

HIGH PRESSURE STUDIES OF PERPENDICULAR TRANSPORT IN MULTIPLE
BARRIER SEMICONDUCTOR HETEROSTRUCTURES

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ABSTRACT

In the opening chapter, a review is made of resonant tunnelling in multiple barrier $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterostructures including the important properties, experiments and theories. Although much work has recently been performed on these structures, particularly for the $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ system, a clear and unified picture of the resonant tunnelling mechanism in real structures is still lacking. The majority of experimental work performed for this thesis has used hydrostatic pressure as a means of varying the barrier height for electron tunnelling in the same resonant tunnelling structure.

For the $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ system, the Γ -X barrier and Γ -L barriers decrease under pressure, while the Γ - Γ barrier is thought to be essentially pressure independent. Therefore, pressure is a useful tool for investigating the resonant tunnelling mechanism when a pressure dependent barrier is the lowest in energy. This is the case for the GaAs/AlAs system where the Γ -X barrier is lowest at 1bar. Experimental measurements of negative differential resistance (NDR) have been performed at pressures up to 12Kbar and temperatures down to 4.2K, in double barrier n-i-n structures and multiple barrier p-i-n structures of both GaAs/AlAs and $\text{GaAs}/\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$. Chapter 2 reports the experimental techniques used and describes the fabrication process of resonant tunnelling devices from the wafer.

Chapter 3 reports the effect of pressure on the NDR of a GaAs/AlAs system (five barriers) enclosed in the i-region of a p-i-n device. The five barriers become progressively

thinner and the last three do not significantly influence the electron transport through the structure. Although the results suggest the strong involvement in the electron tunnelling process of X-like states in the barrier, further experiments are shown to be required to eliminate the possibility of other pressure dependent processes. These processes will be related to a non-resonant leakage current associated with a high concentration of active impurity states in the AlAs barriers (thought to be a result of no spacer layers being included in the p-i-n devices) or to hole tunnelling in the valence band.

Chapter 4 reports high pressure measurements on a similar GaAs/AlAs system to that which determines the NDR feature of the device discussed in chapter 3 but the system is enclosed in the i-region of a n-i-n device and spacer layers are included between the undoped barrier layers and the doped cladding layers either side of the GaAs/AlAs structure. The design of this device reduces the non-resonant, impurity contribution to the tunnelling current and eliminates the possibility of hole tunnelling. In addition, magnetoquantum oscillations in the tunnelling current are obtained for this device at pressures of 1bar and 5Kbar. The effect of varying the well and barrier dimensions of the GaAs/AlAs system is also investigated in a different n-i-n device. This device has thicker AlAs barriers and a thinner GaAs quantum well and exhibits no NDR feature. Indeed, the device behaves more like a single barrier structure and, from thermionic emission measurements, an estimate is made of the $\Gamma(\text{GaAs})$ - $X(\text{AlAs})$ barrier height and its variation

with pressure.

Chapter 5 reports the effect of pressure (up to 12Kbar) on a GaAs/Al_{0.33}Ga_{0.67}As system enclosed in the i-region of a n-i-n device. For this system, the Γ (GaAs)- Γ (AlAs) is the lowest until ~ 10 Kbar. Above 10Kbar, the Γ -L and Γ -X barriers become lower in energy. This suggests that the NDR is less sensitive to pressures below 10Kbar than the systems with AlAs barriers, as observed. In addition, the second part of chapter 5 reports the effect of pressure on a symmetric GaAs/AlAs superlattice (five AlAs barriers) enclosed in the i-region of a p-i-n device. This structure is similar to that described in chapter 3 but all the barriers are the same thickness. The pressure behaviour of the NDR features is discussed and contrasted to the behaviour of the feature observed for the structure with progressively thinner barriers.

Finally, a second type of system which exhibits NDR is associated with the Gunn effect, and has been studied as a function of pressure in n-type GaAs. The devices studied include a standard n-i-n GaAs homostructure and structures containing a graded bandgap of Al_xGa_{1-x}As in the i region. In chapter 6, a review is made of the Gunn effect followed by a report of the experiments performed on the devices.

CHAPTER 1

A REVIEW OF RESONANT TUNNELLING IN GaAs/Al_xGa_{1-x}As MULTIPLE BARRIER STRUCTURES

1.1 Formation and Properties of Al_xGa_{1-x}As/GaAs Heterostructures

The rapid advances in the growth of epitaxial layers of semiconducting material by Molecular Beam Epitaxy (MBE) and Metal Organic Chemical Vapour Deposition (MOCVD) have led to a large interest in superlattices, heterojunctions and tunnelling devices. These two growth techniques allow the crystal grower to produce semiconducting heterostructures and multi-layer sandwich structures (such as superlattices) in which the conduction band and valence band potential profiles and/or impurity distributions can be controlled on a scale comparable to the interatomic spacing ($\approx 1\text{nm}$).

When a heterostructure is lattice matched, i.e., when the two semiconductors have almost identical lattice constants, the interfaces formed are virtually free of strain and defects. The most extensively investigated system to date is the GaAs/Al_xGa_{1-x}As heterostructure. It has the advantage of Al_xGa_{1-x}As being closely lattice matched to GaAs throughout the full compositional range $0 \leq x \leq 1$. However, a variety of other systems have also been explored, like the lattice matched systems In_yAl_{1-y}As/In_xGa_{1-x}As and In_xGa_{1-x}As/InP, because of their optoelectronic applications as quantum well lasers and photodetectors. Interest is also currently focused on the II/VI systems and on deliberately non-lattice matched systems, e.g. Si/Ge heterostructures, in which the presence of strain is used as an additional variable.

Fig.1.1 shows the familiar diagram for considering the degree of lattice matching across various heterostructures.

Low dimensional semiconductors are grown when thin layers of different material are grown epitaxially in a single crystal. A quantum well is produced when a thin layer of semiconductor is sandwiched between a material of larger bandgap. By periodically alternating the wide and narrow gap semiconductors, a superlattice can be grown. Quantum effects are seen when the width of the well is comparable to the de Broglie wavelength of the carriers. This requires layers narrower than $200\text{\AA}$. Fig.1.2 shows the potential steps in the conduction and valence band created at the interfaces of a GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructure (1). It is known that the bandgap of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is larger than that of GaAs, the difference in bandgap being distributed between the valence and conduction band. $\text{Al}_x\text{Ga}_{1-x}\text{As}$ has a smaller electron affinity than GaAs so that the conduction band of the narrow bandgap material lies lower in energy than that of the wide bandgap semiconductor. The valence band of GaAs, on the other hand, lies higher in energy than in the wide gap material. For this heterostructure, there is evidence to suggest that most of $\delta E_g = E_g(\text{Al}_x\text{Ga}_{1-x}\text{As}) - E_g(\text{GaAs})$, is accommodated in the conduction band (2,3,4,5,6,). Therefore, confining potential wells are produced for electrons and holes. Typical doping concentrations in the different layers are usually small enough to ensure that band bending can be neglected (2,3). This, with the fact that the transition from one material to another can now occur in one atomic layer, ensures that the sides of the well are steep and so the quantum well can be considered rectangular. In the

quantum well, a number of discrete sub-bands are formed whose energy can be estimated by solving the Schrodinger equation for trapped carriers moving in the direction perpendicular to the layers (z). Effects due to the crystal lattice are accounted for by replacing the carrier mass by an effective mass, m^* . This is called the effective mass approximation. The simplest model takes the conduction band discontinuity (or barrier height) to be infinite. This gives bound solutions:

$$E_n = h^2 n^2 / 8m^* l_z^2 \dots\dots\dots(1.1)$$

where l_z is the width of the well and $n = 1, 2, 3, \dots$

Motion in the x and y directions is uncoupled to that in the z direction so that, ignoring anisotropy in the carrier effective mass, the total carrier energy in the nth sub-band is given by

$$E_{\text{tot}} = E_n + h^2(k_x^2 + k_y^2) / 8\pi^2 m^* \dots\dots\dots(1.2)$$

Fig.1.3 shows the eigenvalues and eigenfunctions for a one dimensional well of infinite barrier height although the two wells shown have finite barriers as for electrons and holes in a $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ system. For a finite barrier height the quantised energy levels are altered considerably, the carriers are no longer perfectly confined and so will suffer a phase change upon reflection at a barrier. The allowed energy levels are those which give constructive interference between successive reflections. It can be shown that the energy levels are given by (7)

$$2l_z \sqrt{(2\pi m_1 E / h)} + 4 \arctan\{\sqrt{[m_2 E / m_1 (V_0 - E)]}\} = 2n\pi \dots\dots\dots(1.3)$$

where $m_{1,2}$ is the carrier effective mass in the well and barrier respectively, and V_0 is the barrier height. The first term is the plane wave phase change on travelling to

and from in the well, and the second term is the phase change due to reflection from both barriers which can be found by matching the wavefunction and particle flux either side of an interface.

In semiconductor heterostructures, the barrier heights are generally of the order of a few hundred meV and the infinite well approximation is not good, except for very thick wells when a large continuum of states results and the system is no longer in the quantum limit. For a thin quantum well (e.g. $l_z \leq 50 \text{\AA}$, for conduction electrons in GaAs quantum wells), the energy spectrum consists of a single bound level and a continuum instead of the increasingly spaced levels given by Eqn.1.3.

Dingle et al. (2,3) computed the confined levels as a function of barrier height. As the barrier height is lowered, the carriers can penetrate more easily into the barriers and so, by analogy with free electrons, the carrier wavelength increases and the energy level drops. The number of bound states also decreases with V_0 , but the $n=1$ level always exists. The electronic structure of a superlattice also depends critically on the width of the barriers. For wide barriers, there is no overlap of the carrier wavefunctions in adjacent wells and so the superlattice can be considered as a collection of single quantum wells and is therefore called a multiple quantum well. Dingle et al. (2,3) considered states in superlattices with narrow barriers. He found that for a superlattice of j quantum wells, the narrow resonances of a single quantum well are split into j closely spaced levels. In the limit of large

j, the levels form a broad band of closely spaced allowed states analogous to the Kronig-Penney model (8).

The bandgap discontinuity (or barrier height) is a critical parameter of quantum wells and superlattices. This discontinuity in the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ system is currently the subject of much discussion and would be very useful to know for the design of devices. It is thought that the ratio $\delta E_C:\delta E_V$ is independent of the Aluminium content (x). Initial experiments by Dingle et al. (2,3) on infrared absorption of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$ multiple quantum well structures, gave $\delta E_C:\delta E_V = 85:15$. However, more recent experiments by Duggan et al. (4), using a similar experimental method, estimate the ratio to be 65:35. By studying photoluminescence in parabolic quantum wells, Miller et al. (5) have measured it to be 57:43, and Wolford et al. (6) have estimated it to be 68:32 by investigating photoluminescence in rectangular quantum wells as a function of hydrostatic pressure for a number of different x-values.

1.2 Proposal and Observation of Resonant Tunnelling

In 1973, Tsu and Esaki computed the resonant transmission coefficient, T^*T , for a multi-quantum well structure (9). Using the effective mass approximation, the three dimensional Schrodinger equation may be separated into longitudinal (l), perpendicular to the layers, and transverse (t) parts; i.e., the total energy is written as

$$E_{\text{tot}} = E_l(V) + \frac{\hbar^2 k_t^2}{8\pi^2 m^*} \dots (1.4)$$

where V is the periodic potential. The wavefunctions are expressed as

$$\Phi_{\text{tot}} = \Phi_l \Phi_t \dots (1.5)$$

By matching the wavefunctions and particle flux at each interface and integrating over the incident carrier energy, an expression for the tunnel current is derived (9). Tsu and Esaki's calculation may be applied to any number of wells.

Fig.1.4 shows $\ln(T \cdot T)$ plotted as a function of energy for one, two and four wells ($l_z = 50\text{\AA}$, $V_0 = 500\text{meV}$ and barrier thickness $= 20\text{\AA}$). The energy positions of the peaks correspond to the energy levels in the quantum wells. In the limit of large j (number of quantum wells) in the coupled well superlattice regime, a band-like condition is achieved, analogous to the one dimensional Kronig-Penney crystal. The superlattice impresses a periodic potential on the structure that is considerably larger than atomic dimensions and the Brillouin zone is reduced into a series of mini-zones and gaps in the E - k dispersion curve in the direction perpendicular to the layers. Tsu and Esaki predicted earlier (10) that an infinite superlattice with a period shorter than the electron mean path should show unusual transport properties such as negative differential resistivity (NDR) and Bloch oscillations, assuming a one dimensional superlattice.

From the calculated $T \cdot T$ coefficient versus energy, the current-voltage (I - V) characteristics can be derived using the assumption of conservation of electron energy and transverse momentum. Fig.1.5 shows how an applied voltage across a double barrier structure creates an electric field which causes the bands to tilt. The I - V characteristics are dependent on the Fermi energy but in each case (one, two and four wells) indicate regions of NDR. The current maxima

occur at voltages such that the resonant energies approach the Fermi energy of the electrons at the left of the barrier. The fall in current on increasing the voltage is a result of the fact that energy and transverse momentum must be conserved in tunnelling.

In 1974, Chang et al. reported the first observations of resonant tunnelling in a double barrier, MBE grown structure at 77K (11). The structure was comprised of a 50Å GaAs well sandwiched between two 80Å $\text{Ga}_{0.3}\text{Al}_{0.7}\text{As}$ barriers. By heavily doping the emitter and collector regions either side of the double barrier n-type, structure in the conductance, dI/dV , versus voltage curve was found to be consistent with two bound electron states in the GaAs well. By looking at a similar structure with 40Å wide barriers and a 40Å wide well, these states were shown to be dependent on the well and barrier widths, as expected. Fig.1.5 illustrates the proposed resonant tunnelling mechanism of Tsu and Esaki for such a double barrier structure. The bound states for the two configurations are computed using the transmission expression in (9). Their assumption of electron tunnelling, $m^* \approx 0.1m_0$, the barrier height, $V_0 \approx \delta E_{cb} \approx 400\text{meV}$, and rectangular barriers appears reasonable.

Esaki and Chang subsequently studied electron transport properties of a fifty period n-type structure comprising 45Å wide wells of GaAs and 40Å wide barriers of AlAs (12). The band structure calculated for this superlattice was found to have two narrow bands at essentially the same energy as the single quantum well structure. Fig.1.6 shows the conductance-voltage characteristic of this structure. At low

temperatures, the current-voltage curve shows a smooth increase with voltage followed by a saturation region and then, at higher voltages, a region of oscillatory behaviour. The low voltage data is interpreted as band conduction but at higher fields, in excess of 10KV/cm, band conduction is no longer sustained through the superlattice and a narrow, high-field domain is spontaneously generated. Fig.1.7 shows the alignment and misalignment of the energy bands across the domain and how this can produce a current oscillation with a period equal to the separation of the energy bands, E_1 and E_2 , in agreement with Esaki et al.'s calculations.

Since the first report of resonant tunnelling in $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ double barrier structures, material quality has improved rapidly. In a similar structure, NDR was observed directly in the I-V characteristic at 77K and in the dI/dV -V characteristic at room temperature by Sollner et al. (13), and Vojak et al. (14) observed NDR in a multilayer $\text{Al}_x\text{Ga}_{1-x}\text{As}$ structure grown by MOCVD using a p-n junction for carrier injection. More recently, NDR has been observed in the I-V characteristic at room temperature (15) and even resonant tunnelling of holes has been reported (16) in AlAs/GaAs double barrier structures sandwiched between heavily doped p-type regions. The better quality of material grown by MBE and MOCVD is also reflected in the ever increasing peak to valley current ratios (A/B) observed, e.g. 3/1 at room temperature (17,18) and 9/1 at 77K (18). However, these ratios are still much smaller than those predicted by the simplest theory.

Initial observations of resonant tunnelling in multiple

barrier $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ structures has stimulated much discussion on the correct theoretical model to use for the resonant tunnelling mechanism. In what follows, the models will be discussed and their relative merits analysed when characterising resonant tunnelling systems against experimental findings.

1.3 Coherent Theory of Resonant Tunnelling

As Tsu and Esaki have shown (9), NDR in double barrier structures is a result of the quantised energy levels in the quantum well and the conservation of electron energy and transverse momentum. Resonance occurs when the electron wavefunction reflected at the walls of the quantum well interfere constructively or, equivalently, when the energy of the electrons in the emitter is degenerate with an unoccupied state in the quantum well. This is analogous to the optical interference in a Fabry-Perot resonator in that coherence of the electron wavefunction is required across the entire double barrier region.

Using this model, Ricco and Azbel consider, in detail, the problem of resonant tunnelling through a one-dimensional double potential energy barrier, of arbitrary dimensions, by considering the global transmission of the whole structure (19). They find that the peak to valley current ratio (A/B) is given by

$$A/B \approx 1/T_{\max}^2 \dots \dots \dots (1.6)$$

where $T_{\max}$ is the larger of T_l (transmission coefficient of left barrier) and T_r (transmission coefficient of right barrier) and is generally expected to be very large. The global transmission coefficient, T_g is given by

$$T_{\text{offres}} \approx T_1 \cdot T_r \dots \dots \dots (1.7)$$

and the resonant transmission (T_{res}) is given by

$$T_{\text{res}} \approx T_{\text{min}}/T_{\text{max}} \dots \dots \dots (1.8)$$

where T_{min} is the smaller of T_1 and T_r . By comparing Eqn.1.7 and Eqn.1.8, a resonance always implies an increased transmission coefficient. This corresponds to a steady state in which the electron wavefunction has attained an appropriate amplitude in the quantum well, i.e., the electron probability density, $\Phi^*\Phi$, must be peaked in the well. Therefore, if initially there are no electrons in the well and the carriers are made to tunnel in response to an applied voltage across the double barrier structure, it takes a certain time constant to build up the probability density in the well, via multiple reflections, and to achieve high transmission at resonance. This resonator charging time is of the order of the resonant-state lifetime, $\hbar/\delta E$, where δE is the width of the resonant state. For a quantum well of GaAs bounded by a 50Å-wide $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ barrier, Luryi (20) estimated the maximum frequency of active oscillations to be in the low gigahertz range. At higher frequencies, the electron wavefunction amplitude in the well cannot readjust itself in response to a variation in the electric field to provide resonant enhancement of the transmission coefficient. The implications of this will be discussed later.

Ricco and Azbel pointed out another important consideration that has previously been neglected when considering resonant tunnelling. The achievement of near unity resonant transmission at all the resonant peaks requires the

transmission of the left and right barriers to be equal at all the sub-band energies in the quantum well ($T_{\min}=T_{\max}$). This condition is not fulfilled for barriers designed to be symmetric in the absence of an applied voltage. Application of a voltage to a symmetric double barrier structure introduces a difference between the transmission of the barriers. Therefore, the overall transmission is significantly decreased below unity at the resonant peaks resulting in a reduced A/B. Unity transmission can be realized if the barriers are designed to be symmetric at the resonant voltage by choosing appropriate barrier widths. However, unity transmission can then only be achieved for one resonance. To counter this, a resonant tunnelling structure was proposed by Capasso and Kiehl (21) in which resonance is achieved, not by applying a voltage to the barriers, but by minority carrier injection into the quantum well. This method does not alter the transmission of the two barriers and should lead to near unity transmission at all resonant peaks and to larger peak to valley ratios. The proposed structure is a heterojunction bipolar transistor with a heavily doped emitter and a symmetric double barrier built into the base. The collector current as a function of the base-emitter voltage exhibits a series of peaks corresponding to resonant tunnelling through the quasi-bound states of the well.

In 1983, Sollner et al. found that a double barrier $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}/\text{GaAs}$ structure that exhibits pronounced NDR at low temperatures ($A/B=6/1$ at 25K), could be used as a detector and mixer of far infrared radiation at frequencies up to 2.5THz (13). Subsequently, Sollner et al.

demonstrated, for the first time, active oscillations of a similar structure mounted in a resonant cavity (22). The device oscillated in the negative differential region at frequencies up to 18GHz with a dc to rf conversion efficiency of 2.4% at temperatures up to 200K. They suggested that the observed frequency was limited by the coaxial circuit and that still higher frequencies could be achieved in a different microwave set up. Observation of oscillations at this frequency is consistent with Luryi's estimate for the frequency limit of such a device using the coherent tunnelling model. However, this estimate rules out the possibility of obtaining active oscillations in a similar device at terahertz frequencies, that is, the time required to store enough carriers in the well to reach the resonant regime appears to be too long to be compatible with the high frequencies detected by Sollner et al.

1.4 Sequential Theory of Resonant Tunnelling

Sollner's anomalous high frequency result and the fact that experimental peak to valley current ratios (A/B) are still far below those predicted by the coherent tunnelling model (CTM) in the presence of an applied electric field, even in good quality materials, led Luryi (20) to propose his sequential tunnelling model (STM). Luryi suggested that the Fabry-Perot coherent tunnelling model (CTM) plays a minor role in the mechanism of negative differential resistance. Instead of calculating a global transmission coefficient of the whole double barrier structure, Luryi considered two successive transitions; one from the emitter electrode into the quasi-bound state in the quantum well, and the other

from the well into the collector electrode, hence the name sequential tunnelling. Fig.1.8 shows the Fermi sea of electrons in a heavily doped emitter. Assuming that the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier is free of impurities and inhomogeneities, the transverse electron momentum (k_x, k_y) is conserved in tunnelling. This means that for $E_C < E_O < E_f$, where E_C is the energy at the bottom of the conduction band in the emitter, E_O is the energy of the sub-band in the quantum well and E_f is the Fermi energy, tunnelling is possible only for electrons whose momentum in the z (longitudinal) direction is equal to k_O (the shaded disk in Fig.1.8), where $\hbar^2 k_O^2 / 8\pi^2 m^* = E_O - E_C$. Only these electrons can tunnel into available states in the quantum well and conserve momentum. Electrons then tunnel out of the well into empty states in the collector electrode. As the emitter-base potential increases, so does the number of electrons which can tunnel into the sub-band at energy E_O . The shaded disk moves downward to the equatorial plane of the Fermi sphere until the number of electrons which can tunnel reaches a maximum, that is $k_O = 0$. When E_C rises above E_O , then at $T=0$, there are no electrons in the emitter which can tunnel into the quantum well while conserving their transverse momentum. Therefore a large fall in the tunnel current is predicted, i.e., negative differential resistance. NDR arises as a result of electrons tunnelling from the three-dimensional states in the emitter into the two-dimensional states in the well. In this model, the current-voltage (I - V) characteristic is approximately triangular; the current starts to rise when the Fermi energy in the emitter coincides with E_O , continues to rise as the bias is

increased, and then falls abruptly when E_0 is biased just below the bottom of the emitter conduction band. That is, for the voltage dropped entirely across a symmetric double barrier structure, the current starts to rise at V_{th} and peaks at V_p such that

$$eV_{th} = 2(E_0 - E_f) \dots \dots \dots (1.9)$$

$$eV_p = 2E_0 \dots \dots \dots (1.10)$$

These theoretical values contrast with Tsu and Esaki's resonance condition (9)

$$eV_p = 2(E_0 - E_f) \dots \dots \dots (1.11)$$

Even though Luryi does not invoke a new physical interaction, he claims that the two models should be experimentally distinguishable. In the CTM, $T_{res} \approx T_{min}/T_{max}$ whereas in the STM, $T_{res} \approx T_1 T_r = T_{max} T_{min}$, since both barriers add their effect independently. Then a change in T_{max} from the case of $T_{min} = T_{max}$ should lead to increased transmission for sequential tunnelling in contrast to the CTM which predicts a decrease in transmission. Also it may initially appear that the two models are distinguishable experimentally. This is because in the CTM, the transmission coefficient can be unity at the resonant tunnelling energy while in the STM, the transmission will be very low since

$$T_1, T_r \sim \exp(-\alpha d) \dots \dots \dots (1.12),$$

where d is the width of the barriers, $\alpha = 2\pi\sqrt{(2m^* \cdot V_0)}/\hbar$ (19) is the decay constant of the barrier, V_0 is the barrier height and generally $\alpha d \ll 1$. However, in the next section, an equivalence between the two models is discussed.

1.5 Comparison of the Sequential Tunnelling Model and Coherent Tunnelling Model

Although the transmission coefficients will differ

substantially in magnitude for the two models, the actual magnitude of the total current has been shown to be equivalent for the two models around the resonance. This was achieved independently by Payne (23) and Weil and Vinter (24). They realised that the equivalence of the two models is realised when the current in the CTM is obtained by integrating the transmission coefficient over a finite energy range around the resonant energy, i.e., the total current is not equal to the square of the transmission coefficient at a single energy but is an integral of the square of the transmission coefficient over the range of energies of the incident electrons. The magnitude of the NDR predicted by the STM (24) is much smaller than that predicted by the CTM with a single incident electron energy. In addition, the STM was able to explain Sollner's terahertz results (25) since rectification of an external signal by a double barrier structure requires readjustment of only the phase of the electron wavefunction and not its amplitude, so that the operation of a detector is not limited by a Fabry-Perot charging time. These two points suggest that Luryi's model has overcome the deficiencies of the CTM.

Buttiker considers coherent and sequential tunnelling in a model in which electrons, scattered during the tunnelling process, are in equilibrium with a "charge reservoir" (26). The reservoir does not draw or supply a net current but permits inelastic events and phase randomisation. He obtains a conductance formula which contains contributions due to coherent tunnelling (in which carriers undergo only elastic scattering and hence reach the collector with a phase which

has a definite relationship to the phase of the incident carriers) and sequential or incoherent tunnelling (in which a carrier tunnels through one of the barriers coherently but in the well is scattered inelastically and loses phase memory). Buttiker considers the limiting regimes of completely coherent tunnelling and completely incoherent tunnelling and the transition between the two. His findings contradict recent assertions that coherent and sequential tunnelling give rise to comparable currents. However, as Payne points out (23), the two models are equivalent for the magnitude of the total tunnel current. If the formula Buttiker derives for the transmission coefficient is integrated over the energy of the incident carriers, then the current would be found to be equivalent for the two models.

Since Luryi's sequential tunnelling model can explain NDR by electrons tunnelling into a two-dimensional system of states whilst conserving their energy and transverse momentum, then NDR should be observable in single barrier structures in which tunnelling occurs into a two-dimensional system of states. This was actually observed by Morkoc et al. using a structure in which electrons tunnel from a heavily doped emitter into a quantum well bounded on the other side by a thick non-tunnelling barrier (18). Electrons are removed from the well by drifting laterally to a specially designed contact outside the emitter area. Further evidence to support Luryi's STM comes from Stone and Lee who consider the effect of intrasub-band inelastic scattering on resonant tunnelling (27). In the CTM, Ricco and Azbel (19) point out that resonant transmission is achieved after a transient

time (of the order of the resonant state lifetime) so that the electron wavefunction can attain an appropriate amplitude in the well. Stone and Lee (27) have shown that, in the presence of intrasub-band inelastic scattering, resonant effects will be negligible in the CTM except at very low temperatures which is contrary to experimental findings. Inelastic scattering occurs on a much shorter timescale than the characteristic time for resonant tunnelling which implies that the magnitude of the resonant current will decrease for scattering frequencies higher than the inverse of the characteristic resonant tunnelling time. The STM does not predict a fall in the magnitude of the resonant current at high frequencies since resonance does not depend on the build up of the electron wavefunction in the well.

Payne has shown, for the STM, that the resonant current through a symmetric double barrier structure flows immediately after opening the resonant tunnelling channel (23) and is constant provided that the resonant tunnelling channel remains open. Thus, the STM provides a more accurate description of resonant tunnelling than the CTM with a single incident electron energy. However, when a range of incident energies is included in the CTM, no decrease in the resonant current is predicted (23) which again establishes the equivalence of the two models.

Inelastic scattering mechanisms can modify the current, however (24). The above inelastic scattering mechanisms considered are intrasub-band events which occur in the direction parallel to the barriers and thus have no effect

on the longitudinal wavefunction. Therefore, the electron wavefunction will remain coherent across the double barrier structure and the STM and CTM lead to the same prediction for the dc current. On the other hand, intersub-band scattering in the well totally destroys the coherence of the longitudinal electron wavefunction so that there is no possibility of a coherent tunnelling current. However, sequential tunnelling is possible but intersub-band scattering can lead to observable changes in the current. Any resonant tunnelling observed in the presence of intersub-band scattering must then be a result of electrons tunnelling sequentially. Payne has also demonstrated that the time dependence of the total current flowing through a system which has two sub-bands in the well can be used to measure the rate of scattering between the sub-bands (28).

1.6 Space-Charge Effects and Current Bistability

Although the two standard models of resonant tunnelling explain many of the experimental observations of resonant tunnelling in double barrier structures, some features of the experimental I-V curves differ from those expected in either approach. In particular, the peak to valley current ratios (A/B) observed are often too small to be well accounted for, even though the STM (and the CTM with a range of incident electron energies) predicts smaller A/B 's than the CTM with a single incident electron energy. In addition, the predicted peak voltages of Eqns.1.10 and 1.11, and the predicted threshold voltage of Eqn.1.9 differ appreciably from the experimental I-V curves. This discrepancy could be due to large voltage drops across a

series resistance caused by contact and parasitic series resistances. To minimise this problem Goldman et al. prepared double barrier structures with relatively low peak current density by employing thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers (29). However, a simple calculation still showed significant deviations from the experimental values for V_{th} and V_p . This led Goldman et al. to consider two previously neglected effects. The first is the space-charge layer created by the electrons which have tunnelled from the emitter into the well. An equal positive charge is induced in the collector electrode resulting in a greater electric field in the collector barrier than the emitter barrier. Thus V_p must be greater than the values predicted by Eqns.1.10 and 1.11. Secondly, the formation of an accumulation and depletion layer in the emitter and collector electrodes must be considered. These are created so that an electric field can be developed across the undoped barriers, as in Fig.1.9. The formation of the depletion layer reduces the electric field in the emitter barrier, which adds to the first effect, increasing the bias required to align E_f and E_o . The accumulation layer lowers the conduction band edge in the emitter close to the barrier lowering E_o relative to E_f . This opposes the effect of the depletion layer and increases the spread of electron energies in the emitter. These two effects, when included in a model calculation by Goldman et al. (29), produce reasonable agreement with the experimental values for V_p and V_{th} .

Goldman et al. subsequently reported "current bistability" in a double barrier $\text{GaAs}/\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ structure (30). This bistability occurs in the region of NDR and was interpreted

as an intrinsic feature arising from the feedback of the electrostatic field, produced by the electrons in the well, on the tunnelling current. However, there has been much discussion about whether this really is an intrinsic feature, caused by charging of the well, or an extrinsic feature due to current oscillations in the device and in the external circuit. In the latter case, bistability arises because of the difference between the turn-on and turn-off points for oscillatory behaviour when sweeping the applied voltage up or down through the NDR region. The range of applied voltage over which the bistability then occurs will depend on the external circuit parameters in addition to the intrinsic characteristics of the device. Sollner believes that the bistability observed by Goldman et al. is a result of oscillations in the NDR region (31). He argues that intrinsic bistability can only be observed if oscillations in the NDR region are completely suppressed. This can be done by placing a capacitor in parallel with the device provided that the magnitude of the NDR, $|dV/dI|$, is large enough. Sollner argues that the bistability observed by Goldman is extrinsic. Since the magnitude of the NDR is rather small, Sollner suggests that the observed bistability is probably due to the device oscillating even though Goldman et al. placed a capacitor across their device. He concludes that to observe intrinsic bistability, Goldman et al. should fabricate devices of smaller diameter to increase the device impedance. This study was performed by Hughes et al. who observed that, by mounting a chip capacitor as close to the sample as possible to minimise the length of the inductive connecting leads, a smooth I-V curve was obtained

with no bistable regions and no oscillations observed throughout the NDR region (32).

The appearance of oscillations does not exclude intrinsic bistability, or the possibility of observing it, provided that the amplitude of the oscillations are small enough. To help suppress the oscillations, Goldman et al. suggested incorporating a Schottky-barrier capacitor within the device (33). Then an external capacitor should easily prevent oscillations occurring. Oscillations may also be suppressed by connecting a small resistance, r , in parallel with the device by way of very short connecting leads such that $r < |dV/dI|$, as observed by Eaves et al. (34). However, no bistability was observed supporting Sollner's objections concerning the observation of intrinsic bistability in double barrier structures.

The accumulation of space charge in the quantum well of a double barrier structure has been considered by Payne (23) and Cahay et al. (35). Cahay et al. used the CTM with a range of incident electron energies and found that space charge modifies the I-V characteristic. The region of NDR is shifted to a higher voltage and is also broadened along the voltage axis. In addition, the peak current is reduced leading to a decrease in the peak to valley current ratio, A/B . These modifications agree with those of Payne, who used the STM, and contrast with those of Ricco and Azbel (19), who used the CTM with a single incident electron energy. Ricco and Azbel suggested that space charge effects will tend to enhance the resonant current leading to a runaway effect which could result in the breakdown of the tunnel

barrier. Payne and Cahay et al.'s modifications of the I-V characteristic support the theory that space charge does accumulate in the well of resonant tunnelling structures since the experimental values of A/B , V_p and V_{th} can be better accounted for.

1.7 Magneto-Quantum Effects

Further evidence for space charge build up in the quantum well of a double barrier resonant tunnelling structure, has been obtained experimentally by Goldman et al. (36) and Payling et al. (37,38). Goldman observed oscillations in the conductance, (dI/dV) -V curves in the presence of a magnetic field, B , applied perpendicular to the barriers of the structure (z direction). Alternatively, oscillations are observed in the dI/dV - B curves at fixed voltages (Shubnikov-de Haas oscillations). The field quantises the motion of the electrons in the x,y plane giving rise to Landau levels. The electrons can move freely along the z direction in the three-dimensional emitter but their motion is completely quantised in the two-dimensional well. The oscillations are a result of the magnetic field splitting the two-dimensional sub-bands in the quantum well into a ladder of Landau levels. The density of states then peaks at the allowed energy values, $E_0 + \hbar w_C(n + \frac{1}{2})/2\pi$, as measured from the bottom of the well, where $w_C = eB/m^*$, $n=0,1,2,\dots$ and E_0 is the energy of the sub-band in the well. For a fixed magnetic field, on increasing the applied voltage, V , resonant tunnelling occurs when the energy of the $n=0$ Landau level in the well is equal to the Fermi energy, E_f , in the emitter. As V is increased further, the current varies slowly until

the next Landau level crosses E_f . This process continues until the $n=0$ level passes the bottom of the emitter conduction band. For higher voltages, direct tunnelling is no longer possible since the transverse momentum is no longer conserved (i.e., the conservation of Landau number, n , in the presence of B). From fan diagrams of the maxima and minima of the oscillations, for both bias polarities, the effective mass, m^* , of the electrons in the well can be estimated. Goldman et al. obtained a value for m^* which was a factor of 2 smaller than expected. By considering the space-charge formation in the electrodes and in the well, a model calculation by Goldman et al. obtained a value for m^* in good agreement with experimental results.

The most convincing evidence for space-charge accumulation in the well comes from experiments performed by Payling et al. (37,38). With a magnetic field, B , applied perpendicular to the barriers, Shubnikov-de Haas (SdH) oscillations in the tunnel current were obtained under constant voltage conditions. Although the double barrier devices investigated exhibit current bistability in the NDR region, (SdH) oscillations were observed over almost all of the voltage range of the I-V characteristic. At low applied bias, where the tunnel current is non-resonant, the Shubnikov-de Haas oscillations are associated with Landau levels passing through the Fermi energy, E_f , of the emitter as the magnetic field is increased. The fundamental field, $B_f = 1/[\Delta(1/B)]$ where B is the magnetic field at the maxima, is then given by $B_f = 2\pi m^* E_f / h e$. These oscillations are three-dimensional in character which is verified by rotating the magnetic field relative to the plane of the barriers. As the bias is

increased to near resonance, a new set of oscillations develop with two-dimensional character, which are associated with the resonant tunnelling of electrons into the first sub-band of the well. This is similar to the effect observed by Goldman et al. (36). The value of B_f increases steadily for these oscillations, until, at the resonant peak voltage, it equals the very low bias value of B_f . By considering space charge build-up in the well and using the STM (39), this second series can be quantitatively explained thus providing evidence for charge build-up in the well when electrons are resonant with the first sub-band.

The sharp fall off in current and small region of bistability beyond the peak are attributed to ejection of electrons from the well (30). In the second region of bistability, the device can be biased in the high and low current modes. At this high applied bias, the conduction band edge in the emitter is lowered, as in Fig.1.9, due to the electric field in the accumulation layer. This leads to two-dimensional quantisation of the electronic states in the emitter close to the barrier. The lowest sub-band is resolved but higher lying sub-bands overlap strongly, mainly on account of the energy broadening produced by the ionised donors (30). These sub-bands are not resolved and can be treated collectively as three-dimensional states. Oscillations in the low current mode of this bistable region are attributed to the Landau level structure of the two-dimensional electronic states in the accumulation layer of the emitter and are shown to have two-dimensional character. Oscillations observed in the high current mode are a

continuation of the series observed near the resonant peak with a high B_f series superimposed. This high B_f series is thought to be related to Landau levels of the first sub-band in the well. Oscillations in the low current mode have a significantly larger value of the fundamental field, $B_f = N_{2D}h/2e$, than the dominant oscillatory series in the high current mode. This indicates that the emitter region adjacent to the barrier is less strongly accumulated in the high current mode than in the low current mode which implies that the bistability is an intrinsic feature caused by space-charge build up in the well. These observations offer support to Goldman et al.'s model of current bistability.

Evidence is also found for the sequential tunnelling model from Shubnikov-de Haas oscillations in the previously considered device (40). Oscillations are considered in the vicinity of the voltage range corresponding to the second resonance. This resonance occurs when electrons tunnel into the second sub-band of the quantum well from the bound two-dimensional state of the accumulation layer in the emitter contact close to the first barrier. Around this resonance, two sets of oscillations are seen with significantly different values of B_f . The smaller B_f series, due to the Landau level structure of the 2DEG (two-dimensional degenerate electron gas) in the accumulation layer, flattens off as the bias is increased to near resonance, indicating that an appreciable density of electrons has built up in the well. The larger B_f series corresponds to intersub-band scattering processes (impurities, electron-electron, longitudinal optic (LO) phonons) which transfer electrons from the second sub-band into the high n Landau states

associated with the first sub-band which overlap in energy the second sub-band. This interpretation of the high B_f series implies that electrons are undergoing intersub-band scattering, i.e., they are tunnelling sequentially. In addition, Eaves et al. (40) can estimate the electron density in the well at the second resonance peak. From this estimate and the measured value of the current at the peak, the mean time that the electron spends in the well is calculated to be approximately 50 picoseconds. This value is significantly longer than the measured mean time for intersub-band scattering by LO phonon emission (10 picoseconds) in quantum wells of similar widths (41). This implies that most of the electrons in the well will be in the lower sub-band offering support for Eave's earlier conclusions.

1.8 Temperature Dependence of Resonant Tunnelling

As mentioned earlier, the improvements in the sample quality of semiconductor heterostructures has extended the temperature range for observation of NDR up to room temperature (15,18) and increased the observed peak to valley current ratios (A/B). The introduction of undoped spacer layers (typically 25 wide) either side of the double barrier region, has also helped to increase A/B (35,42). The spacer layers separate the barriers from the heavily doped contacts reducing the migration of impurities from the contact regions to the resonant tunnelling region thus reducing impurity scattering in the barrier and well regions. In addition, the presence of spacer layers pronounces the upward shift of the CB profile in the undoped region adjacent to the barriers, reducing the component of

region adjacent to the barriers, reducing the component of thermionic emission over the top of the barriers. This thermionic emission component of the current is highly temperature dependent and therefore the resonant tunnelling feature is also. This is because, at high temperatures, most of the current is transported by electrons thermally excited to energies near to the top of the barrier. The tunnelling of the electrons into the sub-bands of the quantum well is then masked by the thermionic emission of carriers over the barrier, i.e., a non-resonant current component. This is reflected in the NDR being usually present but small at room temperature. A/B increases rapidly upon cooling down to 77K, as in Fig.1.10. At these low temperatures, the thermionic emission current is greatly reduced and the current is dominated by the tunnelling of electrons into the sub-bands of the quantum well.

The thermionic emission of electrons at single barrier, $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ structures has been studied extensively by Solomon et al. (43) and Hase et al. (44). Sze (45) considers thermionic emission at a Schottky barrier and derives the standard formula for the current density, J , through the barrier;

$$J/T^2 = A \cdot \exp(-eV_b/k_bT) \quad \dots\dots\dots(1.13)$$

where T is the temperature, V_b is the barrier height for thermionic emission and k_b is the Boltzmann constant. A^* is the Richardson constant and is given by $4\pi e m^* k_b / h^3$, neglecting the effects of optical phonon scattering and quantum mechanical reflections. By plotting $\ln(J/T^2)$ against $1/T$ in the thermionic emission regime (generally $T > 120\text{K}$), the barrier height for thermionic emission of electrons can

be determined.

1.9 Band Structure Effects

At atmospheric pressure, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is a direct gap semiconductor for $x < 0.45$. Thus, for a multiple barrier $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterostructure with $x < 0.45$, the bandgaps of both types of layers are at the same point of the Brillouin zone, Γ , and the minimum potential barrier for electron tunnelling is the $\Gamma(\text{GaAs})-\Gamma(\text{Al}_x\text{Ga}_{1-x}\text{As})$ conduction band offset. For $x > 0.45$, $\text{Al}_x\text{Ga}_{1-x}\text{As}$ becomes an indirect gap semiconductor, the conduction band at X being lower in energy than at Γ . Therefore, the minimum potential barrier for electron tunnelling is the $\Gamma(\text{GaAs})-\text{X}(\text{Al}_x\text{Ga}_{1-x}\text{As})$ conduction band offset. A third barrier of comparable height arises from the $\Gamma(\text{GaAs})-\text{L}(\text{Al}_x\text{Ga}_{1-x}\text{As})$ conduction band offset (46). Fig.1.11 shows the band structure diagrams of GaAs and AlAs.

When considering vertical transport through $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ multiple barrier heterostructures, it is important to know which potential barrier controls the tunnelling of electrons and whether or not the tunnelling is an indirect or direct process. Direct tunnelling conserves transverse (perpendicular to the tunnelling direction) momentum and generally occurs between the same conduction band extrema of GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$, for example, tunnelling via the $\Gamma(\text{GaAs})-\Gamma(\text{Al}_x\text{Ga}_{1-x}\text{As})$ barrier in the [100] direction. Indirect tunnelling does not conserve transverse momentum and requires inelastic scattering with impurities, phonons, interface roughness, etc. This is the case for tunnelling via the L minima, Γ -L barriers, and via the X minima in the

[010] and [001] directions with a Γ -X barrier. However, tunnelling involving the X minima at [100] can occur as a direct process with a Γ -X barrier. From the expression for the transmission probability of a single barrier, eqn.1.12, it is clear that the tunnelling probability depends on the effective mass and barrier height of each path.

For $x < 0.45$, the effective mass of the Γ conduction band minimum, $m^*(\Gamma)$, is the lightest and the Γ - Γ band offset is the minimum potential barrier, hence tunnelling is expected to be direct and to proceed almost exclusively through the Γ - Γ barrier. From tunnelling and thermionic emission measurements on single barrier structures (43,51,52) and resonant tunnelling measurements on double barrier structures (49), all for $x < 0.45$, this is the common consensus. For $x > 0.45$, there are a number of possible tunnelling mechanisms. The possible paths are $\Gamma(\text{GaAs})$ - $\Gamma(\text{Al}_x\text{Ga}_{1-x}\text{As})$ characterised by a large barrier height and light effective mass, $\Gamma(\text{GaAs})$ -X($\text{Al}_x\text{Ga}_{1-x}\text{As}$) characterised by a small barrier height and either a light effective mass in a phonon assisted indirect process, or a heavy effective mass for a direct process. Tunnelling via the $\Gamma(\text{GaAs})$ -L($\text{Al}_x\text{Ga}_{1-x}\text{As}$) barrier is ruled out since indirect tunnelling requires inelastic scattering events, the effective mass of the L conduction band minimum is approximately twice that of the Γ conduction band minimum, (46), and the Γ -L barrier is not the minimum potential barrier. From studies of tunnelling and thermionic emission at a single $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ barrier, Solomon et al. (43) have shown that for large x , close to unity, the Γ -X barrier

with phonon assisted tunnelling can explain their results. By comparing the observed photoconductivity spectrum of a multi-barrier, GaAs/AlAs structure (47) to a transfer matrix model of the quasi-bound states, Singleton et al. conclude that the electronic structure of the device is described by Γ -X barriers and a fitted mass of $0.11m^*$, which is approximately half the mass value associated with the Γ -X indirect tunnelling process. Other single barrier tunnelling measurements, for $x > 0.45$, have also been explained by a Γ -X process (44,48). In a more recent paper by Bonnefoi et al. (49) on NDR in double barrier GaAs/AlAs structures, the NDR features appear to depend solely on the Γ - Γ barrier in some cases, the Γ -X, direct barrier in other cases and sometimes on a mixture of the two, depending on well and barrier dimensions. However, Tsuchiya et al. (50) have studied resonant tunnelling in double barrier structures as a function of x for fixed well and barrier dimensions, and conclude that their results indicate that electron tunnelling is dominated by a Γ - Γ barrier over the whole x -range even when the Γ -X barrier is lower in energy ($0.45 < x < 1$). Therefore, for $x > 0.45$, it is still unclear as to which potential barrier controls the tunnelling of electrons.

From tunnelling experiments on double barrier $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterostructures, the two-dimensional sub-bands in the quantum well are thought to be consistent with a potential configuration defined exclusively by the Γ minimum (53,54) over the whole x -range. This is in agreement with the photoluminescence measurements of Weinstein et al. (55) and Welford et al. (6) on $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ quantum wells and

superlattices for a range of x -values as a function of pressure. This theory, however, conflicts with the latest electroluminescence data of Phillips et al. which is consistent with the confinement of quantum well states between AlAs barriers being determined by a Γ -X potential profile (56). Mendez et al. (57) have shown that the I-V characteristics of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ double barrier structures with $x < 0.45$ show, in addition to resonant tunnelling via quasi-bound Γ states, well defined features corresponding to energies higher than the Γ - Γ barrier height. These features are interpreted as resonant tunnelling through confined states in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ at the X-point of the Brillouin zone since effective mass calculations for the transmission probability through Γ -point barriers cannot explain the observed structure.

The tunnelling of electrons through $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ multiple barrier structures has been theoretically analysed using the one-band model of effective-mass theory coupled with the Wenzel Kramers Brillouin (WKB) approximation. For $x < 0.45$, accurate estimates are obtained for the tunnel current using this model by equating the tunnelling effective mass to that of the Γ -conduction band minimum, e.g., Hickmott et al. (52) have used this approach in analysing the I-V characteristics of a single barrier $\text{GaAs}/\text{AlGaAs}/\text{GaAs}$ structure, $x < 0.45$. Eaves et al. also use this approach when considering the effect of pressure on the tunnelling currents at a single barrier $\text{GaAs}/\text{AlGaAs}$ tunnelling structure in the direct, Γ - Γ regime (51). The current decreases with pressure owing to an increase in $m^*(\Gamma)$. The pressure dependence is accurately

described by the effective mass/WKB model up to 10Kbar. At higher pressures, the observed breakdown of the model indicates the onset of band structure effects associated with the higher X conduction band minima. The application of large hydrostatic pressure is a particularly useful means of studying band structure effects on tunnelling since, in addition to increasing the direct energy gap and hence the Γ - conduction band effective mass, it also decreases the separation of the Γ -X conduction band minima in GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$, respectively. For $x > 0.45$ and heterostructures with $x < 0.45$ under high pressure, more precise models of tunnelling through semiconducting barriers must take into account the full band structure of the semiconductor, i.e., the evanescent waves associated with higher indirect conduction band minima near the L and X points of the Brillouin zone. For $x < 0.45$, they decay faster than those associated with the Γ -minimum and are hence more important for thin barriers. A theoretical analysis of tunnelling currents must now include Γ , X and L states.

Cade has shown that for a GaAs/AlAs system, the X and Γ barrier states in the AlAs give comparable decay lengths in the AlAs with the lower band offset of the X valley being compensated for by the higher mass of these states (58). Thus X and Γ states are expected to give comparable contributions to the tunnelling current, in agreement with Marsh et al. (59,60). From the expression for the decay constant, page 17, and using literature values for the band offsets and effective masses (46), the decay lengths can be estimated for the various tunnelling processes, see chapter 3, page 92. For AlAs barriers, the direct Γ -contribution to

the tunnelling current has a slightly shorter decay length in the barriers than the non-conserving transverse momentum (indirect) Γ -X contribution, and possibly shorter than the transverse momentum conserving (direct) Γ -X contribution. Therefore, for thicker AlAs barriers, the transmission of each barrier may be more strongly X-like. Conversely, for $x < 0.45$, the Γ - Γ process has a slightly longer decay length than the Γ -X process so the transmission of thinner barriers may be more strongly X-like.

1.10 Applications of Resonant Tunnelling Devices

Recently, the resonant tunnelling of electrons in multiple barrier structures has attracted revived interest since NDR characteristics have been substantially improved (large A/B's) permitting their practical application in, for example, the detection and generation of extremely high frequency electromagnetic waves and in the investigation of energy filtering effects of injected carriers into semiconductors.

Schewchuck et al. (61) have demonstrated how a $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ double barrier device can be used as a microwave oscillator. Sollner et al. (13) have shown that they are promising as a source of high frequencies at low power (22) and as self-oscillating mixers since they have demonstrated the ability to mix at submillimeter wavelengths (13). Several three terminal transistor devices have been developed recently which rely on carriers tunnelling through the barriers of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterostructures. For example, the tunnelling hot electron transfer amplifier (62). In this device electrons are injected through a

barrier into a very short base region. The barrier acts as a current limiter and allows the injection of fast, hot electrons into the narrow base. These features combine to make the device potentially very fast. The Stark effect transistor (63) relies on the resonant tunnelling of electrons for operation. The application of a voltage to the base region can drag the device off resonance with a quasi-bound state of a narrow (100Å) quantum well which forms the collector of the device. This produces a transistor action with a small base current which implies high speed. Also, heterojunction bipolar transistors, with a quantum well and symmetric double barrier (or a superlattice) incorporated into the base region, have considerable potential for a variety of signal processing and multiple-valued logic applications (21). Resonant tunnelling transistors, whose main feature is that there are peaks and valleys in the collector current as a function of the base-emitter voltage corresponding to resonant tunnelling through the double barrier structure in the base, are now of practical use since the current gain and peak to valley collector current ratios are sufficiently large.

In order to effectively apply tunnelling transport to new devices a large peak to valley current ratio is essential and minimum parasitic resistances and capacitances (which inhibit the speed of the device). Improvements in I-V characteristics, however, have been achieved mainly at low temperatures since non-resonant current components tend to dominate the I-V characteristics at higher temperatures. Therefore, it is important to suppress non-resonant

components, for example, minimise structural inhomogeneities such as interface roughness and impurities, and optimise structural parameters such as well width, barrier widths and barrier heights.

1.11 Summary

In summary, resonant tunnelling of electrons in multiple barrier heterostructures was first demonstrated in 1974 (11) and is one of the most interesting quantum mechanical phenomena in ultra thin heterostructures. Resonant tunnelling of carriers occurs when two barriers in the conduction (or valence) band profile with transmission coefficients T_L and T_R , which are both a function of incident carrier energy, give rise to quasi-bound states in the potential well formed between the barriers. Ricco and Azbel show in their coherent tunnelling model (CTM) that, as the incident energy of the carriers is increased, or as the electric field across the structure is increased from zero, carriers outside the first barrier reach the same energy as the quasi-bound state in the well and a maximum occurs in the transmission of the whole structure, T_{res} . At higher incident carrier energy (or electric field), the transmission of the whole structure falls and passes through a minimum value, T_{offres} . If the resonance is fully coherent, i.e., $\Gamma_i \ll \Gamma_e$, where Γ_e is the total elastic width of the quasi-bound state and Γ_i is the total inelastic width of the scattering source, the following equations may be used to estimate the maximum transmission and the size of the resonance (19),

$$T_{res} \approx T_{min}/T_{max} \dots\dots\dots(1.8)$$

$$T_{res}/T_{offres} \approx 1/T_{max}^2 \dots\dots\dots(1.6)$$

The CTM with a single incident particle energy predicts extremely large peak to valley current ratios (A/B) since the transmission coefficient is equal to unity at the resonant energy for a symmetric double barrier structure. Theoretical and experimental work show that resonant tunnelling is more accurately described by Luryi's sequential tunnelling model (STM), for example, smaller A/B's are predicted in agreement with experimental findings. In this model, electrons tunnel from the emitter electrode to the resonant state in the well and then from this resonant state to the collector electrode. However, Payne points out (23) that the CTM must be used with a range of incident particle energies to describe resonant tunnelling devices since real devices do not operate with a single mono-energetic electron. Then the two models are found to be equivalent.

For a single tunnelling barrier, the current as a function of voltage does not usually show resonance effects but is a strong function of temperature since there is a competition between tunnelling through the barrier and thermionic emission over the top of the barrier. The thermionic emission current dominates near room temperature and varies as

$$J/T^2 = A^* \exp(eV_b/kT) \dots \dots \dots (1.11)$$

where J is the current density, A^* is the Richardson constant and V_b is the barrier height. From measurements near room temperature it is possible to deduce the barrier height.

Resonant tunnelling devices exhibit a variety of intriguing

properties which have stimulated much theoretical interest (19,20,23,24). These properties includes negative differential resistance, high frequency oscillations, band structure effects, current bistability and magneto-quantum oscillations. The better quality of semiconductor material grown by MBE and MOCVD and the optimisation of structural parameters, has led to a renewed interest in resonant tunnelling devices since NDR characteristics have improved permitting greater practical applications.

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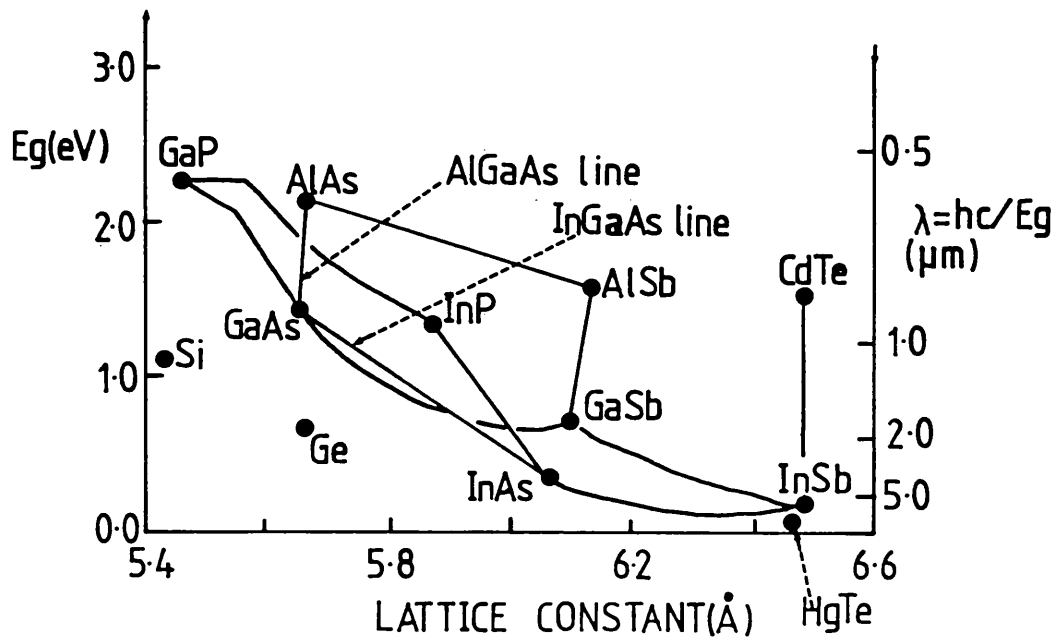


Fig.1.1 The variation of the energy gap (and wavelength) with lattice constant for compositions of III-V binary and alloy semiconductors.

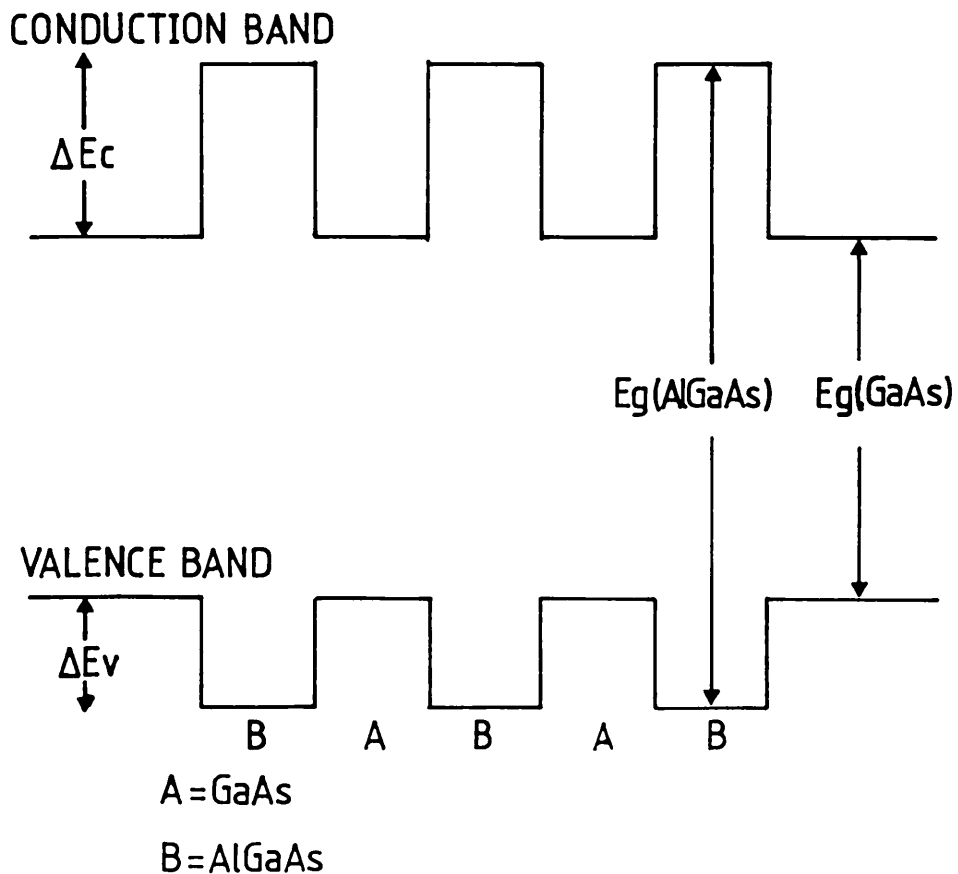


Fig.1.2 Discontinuities of bandedge energies in a GaAs/AlGaAs heterostructure.

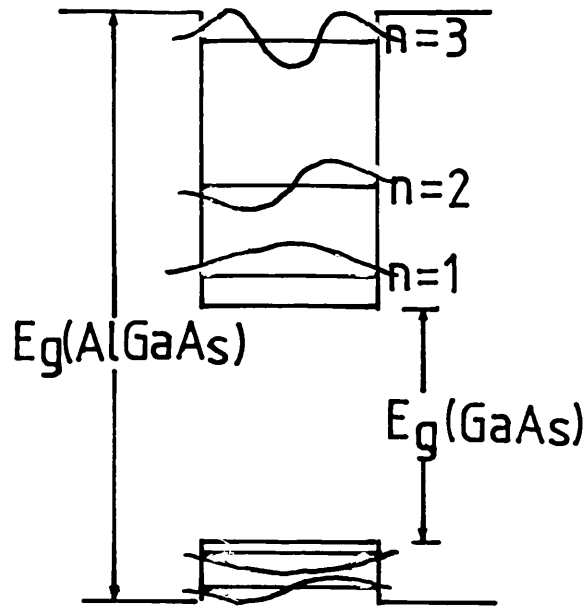


Fig.1.3 The eigenvalues and eigenfunctions for an infinitely deep potential well. As shown, the two wells are of finite depth and apply to electrons and holes in the GaAs layer of a GaAs/AlGaAs heterostructure.

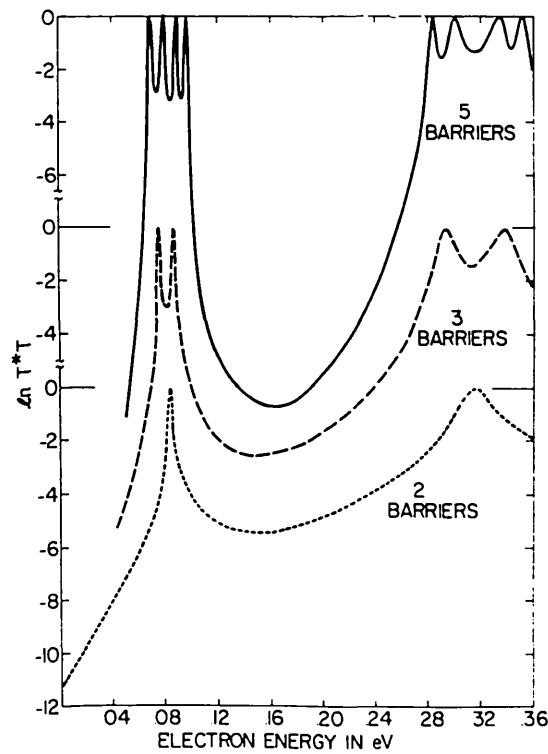


Fig.1.4 Plot of $\ln TT^*$ (electron transmission) versus electron energy showing peaks at the energies of the bound states in the sandwiched potential wells. The traces labelled "2 barriers", "3 barriers", and "5 barriers" correspond to one, two and four wells respectively. Taken from ref.(1.9).

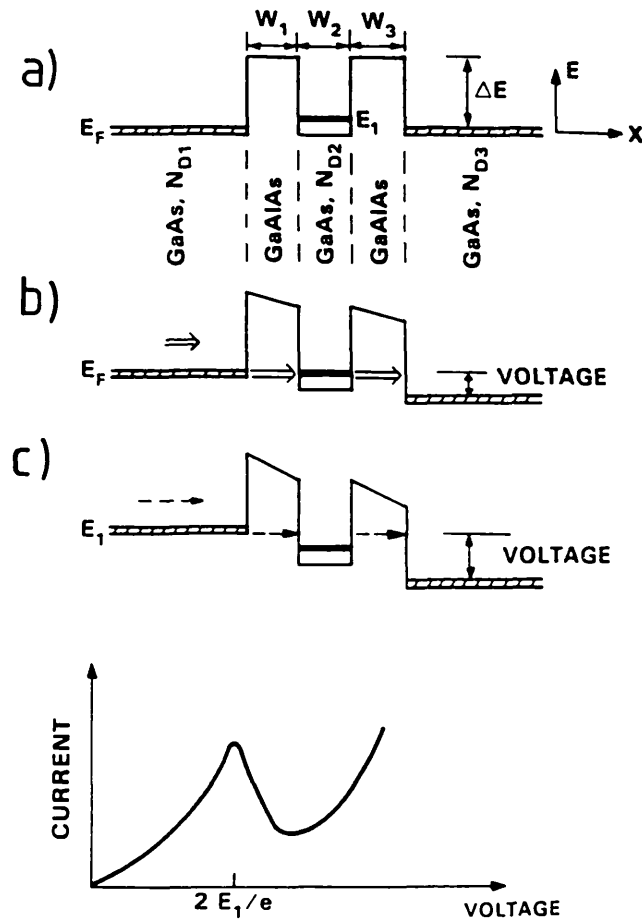


Fig.1.5 Symmetric double barrier GaAs/AlGaAs structure under (a) zero bias, $V=0$, (b) bias at resonance, $V=2E_1$, and (c) bias at "off" resonance.

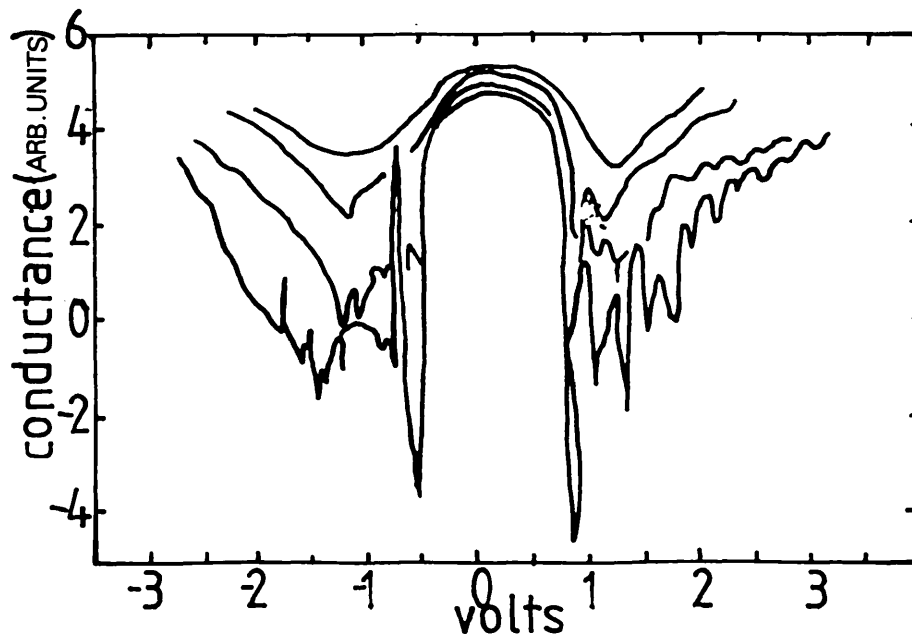


Fig.1.6 Conductance versus applied voltage in a superlattice of fifty periods of 45 GaAs and 40 AlAs at several temperatures. At low temperatures, negative conductance is observed but is supplanted at higher applied fields by an oscillatory behaviour. Taken from ref.(1.12).

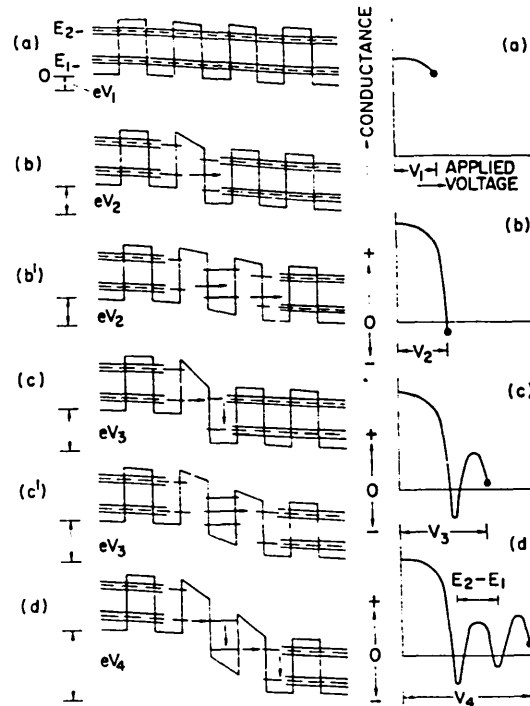


Fig.1.7 Energy diagrams and corresponding conductances for (a) band conductance: (b) and (b') spontaneous generation of a domain; (c), (c') and (d) development of domain expansion. Taken from ref.(1.12).

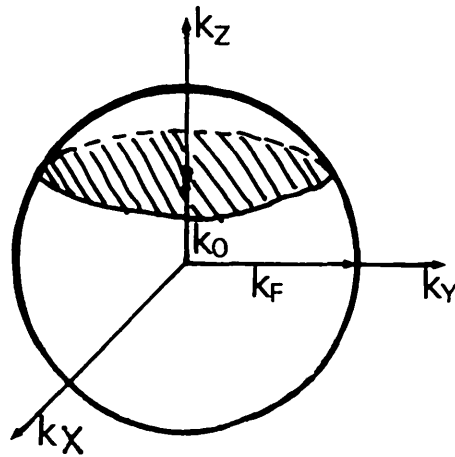


Fig.1.8 The Fermi surface for a degenerately doped emitter. Assuming conservation of the lateral momentum during tunnelling, only those electrons in the emitter whose momenta lie on a disk $k_i=k_0$ (shaded disk) are resonant. Taken from ref.(1.20).

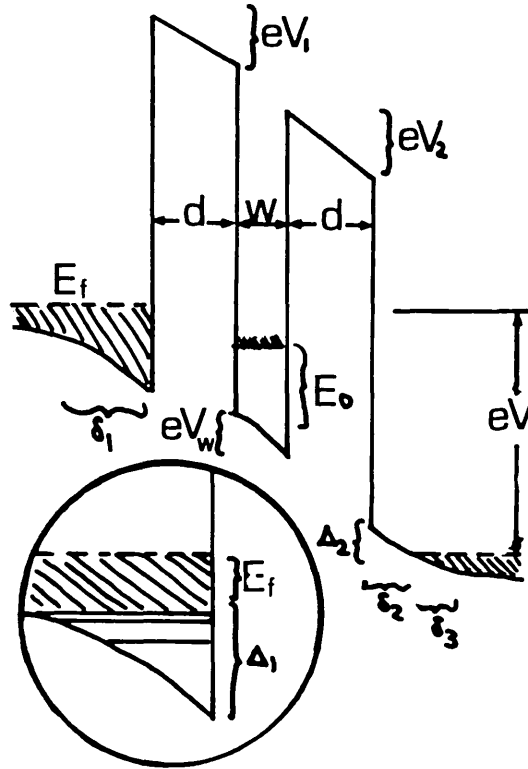


Fig.1.9 Conduction band energy diagram of a double barrier structure under bias. Δ_1 and δ_1 are the parameters of the accumulation layer in the emitter (shown schematically in the inset); Δ_2 , δ_2 and δ_3 describe the depletion layer in the collector. The electrostatic potential drops across the emitter barrier, the well, and the collector barrier are V_1 , V_w and V_2 , respectively. The hatching shows the electron occupation. From ref.(1.31).

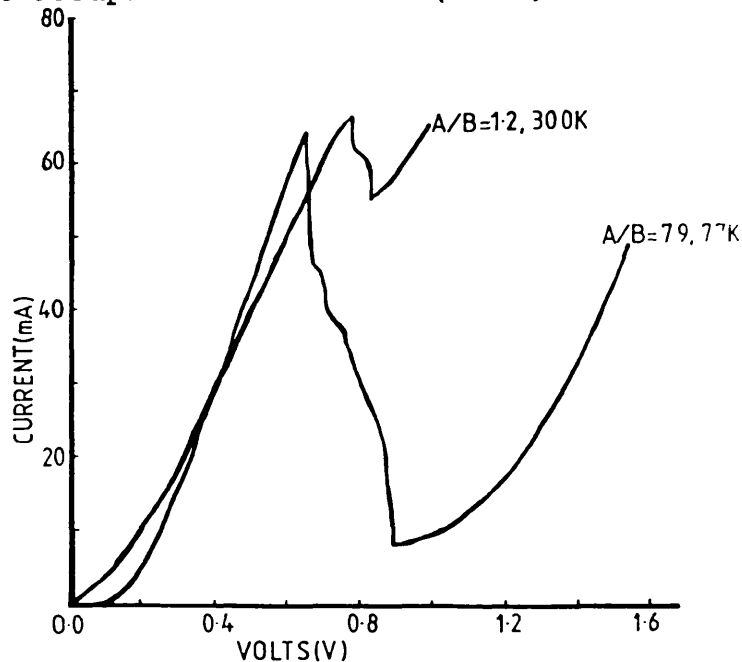


Fig.1.10 I versus V characteristic for the double barrier GaAs/AlAs structure discussed in chapter 4 under reverse bias, for temperatures of 77k and room temperature.

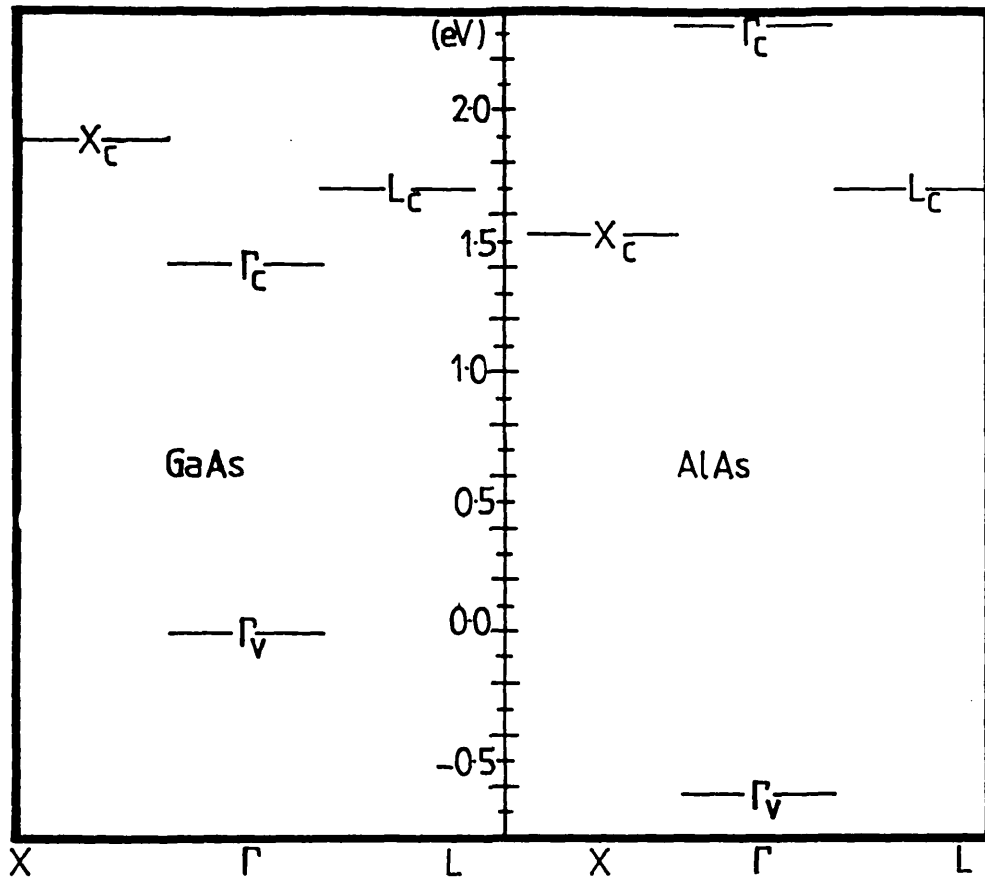


Fig.1.11 Relative positions of the Γ , L and X band extrema in GaAs and AlAs assuming a 60:40 band offset ratio and the bandgaps given in ref.(1.46).

CHAPTER 2

EXPERIMENTAL TECHNIQUES

Experiments performed have been on multiple barrier $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ structures enclosed in the intrinsic region of either a p-i-n device or n-i-n device. The application of hydrostatic pressure has been the most extensively used technique for investigating the I-V characteristics of these devices. For the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ system, the Γ -X barrier is expected to show a large variation with pressure, decreasing at approximately 11meV/kbar, the Γ -L barrier decreases at $\sim 9\text{meV/Kbar}$, while the Γ - Γ barriers for electrons and holes are essentially pressure independent (Chapter 3, pages 84 and 85). This is the predominant effect of pressure and is thus a very useful tool for investigating the possible tunnelling mechanisms, particularly for systems in which the Γ -X potential barrier is the lowest ($x > 0.4$). Consequently, the majority of experiments were performed on multiple barrier structures with AlAs barriers ($x=1$).

This chapter reviews all the experimental techniques used including I, dI/dV and d^2I/dV^2 versus voltage measurements, the system used for performing these measurements as a function of temperature from 300K down to 4.2K, the apparatus used for obtaining Shubnikov-de Haas oscillations up to 12.6 Tesla, and the cells used for attaining hydrostatic pressures up to 14.5kbar. In addition, the fabrication of the n-i-n devices discussed in Chapter 4 is also described.

2.1 I, dI/dV and d^2I/dV^2 versus Voltage Measurements

Current-voltage measurements (I-V) were performed under

constant current conditions (swept current) or constant voltage conditions (swept voltage). Under the constant current conditions, the negative differential resistance (NDR) feature associated with resonant tunnelling through a multiple barrier structure, appears as a hysteresis loop in the I-V characteristic. The upper and lower levels of this loop are equal to the peak and valley currents respectively, as measured under constant voltage conditions.

The majority of experiments were performed under constant voltage conditions and Fig.2.1 shows the experimental set-up for this case. The current is obtained by measuring a voltage across a 1Ω resistor in series with the device, which is equivalent to the current through it. The voltage (or current) was swept manually and with sufficient care to ensure reproducibility, particularly in the region of NDR. For some of the devices investigated, structure in the I-V characteristics appeared at high voltages and currents. To investigate these features, a pulsed voltage source must be used. This is because Joule heating of the devices becomes a problem at high power levels and can lead to device breakdown. The pulsed voltage source used can be swept to a voltage of 30V and the pulse length and frequency can be varied. However, a pulse length of $100\mu\text{s}$ was employed at a frequency of approximately 1Hz to ensure that the effects of sample heating were negligible.

First and second differential measurements, dI/dV and d^2I/dV^2 , versus voltage measurements were performed to investigate weak features in the I-V characteristics of the devices. Constant voltage conditions were used with a small

AC modulation amplitude of 5mV such that the total voltage applied to the device is

$$V_t = V_O + \Delta V \cos \omega t \dots \dots \dots (2.1)$$

where V_t is the total applied voltage, V_O is the DC applied voltage, ΔV is the amplitude of the AC voltage, ω is the frequency of the AC voltage and t represents time. For $\Delta V \ll V_O$, the current, $I(V_t)$, can be expanded in terms of a Taylor series up to second order;

$$I(V_O + \Delta V \cos \omega t) \approx I(V_O) + \Delta V I'(V_O) \cos \omega t + (\Delta V)^2 I''(V_O) \cos^2 \omega t / 2 \dots \dots \dots (2.2)$$

where $I'(V_O) = dI(V_O)/dV$ and $I''(V_O) = d^2I(V_O)/dV^2$. Using $\cos^2 \omega t = \frac{1}{2}(1 + \cos 2\omega t)$ gives

$$I(V_O + \Delta V \cos \omega t) \approx I(V_O) + \frac{1}{4}(\Delta V)^2 I''(V_O) + \Delta V I'(V_O) \cos \omega t + \frac{1}{4}(\Delta V)^2 I''(V_O) \cos 2\omega t \dots \dots \dots (2.3)$$

Therefore, by locking into the "f" and "2f" components of a phase sensitive detector (PSD), signals proportional to $I'(V_O)$ and $I''(V_O)$ were obtained. Any background DC levels were eliminated by feeding the signal from the device through a transformer before inputting it to the PSD. Fig.2.2 shows the experimental arrangement for these measurements.

2.2 Low Temperature Measurements

Experiments were performed by mounting the devices either on a sample holder or onto the sample stage of the pressure cells. The sample holder or pressure cell was then fitted onto the end of an insert designed to fit inside an Oxford Instruments cryostat (CF1200). This is a continuous flow cryostat (CFC) and can be used over a temperature range from 2K to room temperature (2.1).

The continuous flow technique operates on the principle of a continuous and controlled transfer of coolant (helium or nitrogen) from a separate storage vessel to the CFC. The circuit is shown in block form in Fig.2.3. The coolant is delivered to the cryostat via a vacuum-insulated transfer tube inserted in the syphon entry arm of the cryostat. By "sucking" the coolant through a feed capillary on the transfer tube leg in the storage vessel, it is transferred down the length of the cryostat via another feed capillary which carries it down the length of the cryostat to the heat exchanger at the bottom of the sample space. By this method, a gas flow pump drives the flow by creating a pressure difference between the storage vessel and the helium return line. The coolant flows through the heat exchanger of the CFC where the temperature is measured and a heater is used to control this temperature. The heat exchanger may be maintained at any temperature above the boiling point of the coolant; above 77K when using liquid nitrogen and above 4.2K using liquid helium. The coolant flows over the sample holder, or pressure cell, and passes through a second heat exchanger cooling the radiation shield which surrounds the sample tube in the vacuum space to intercept room temperature radiation. Finally, the coolant exhausts to the pump and helium return line through a side hole in the sample tube.

By this method of cooling and controlling the temperature of the sample space, experiments can be performed at any temperature from 4.2K to room temperature. In addition, by filling the sample space with liquid helium, using a high

throughput gas pump, the base temperature can be reduced to below 2K. Some experiments were adequately performed at a temperature of 77K. In these cases, the cryostat sample space was filled with nitrogen through the access port and the insert, with either the sample holder or pressure cell mounted on the end, was slowly lowered into the cryostat.

Although the temperature at the heat exchanger is known, the actual temperature of the devices mounted on the sample holder or inside the pressure cell will be different and must be measured independently. The 1bar sample holder is made of copper and, to obtain an accurate measure of the device temperature when it is mounted, a Germanium diode was embedded in the copper close to the sample space. The diode was supplied with a constant current of $10.00\mu\text{A}$ under forward bias and calibrated against a Rhodium-Iron standard resistor from room temperature to 4.2K with an accuracy of 100mK. However, the main error in evaluating the device temperature during the period of an experiment comes from the temperature drifting rather than the actual measurement of the temperature. It was possible to stabilise the device temperature to within $\pm 0.5\text{K}$ using the temperature controller and the valve in the flow controller unit.

When the device was enclosed in the pressure cell, two thermal germanium diodes and a Gold(Iron)-Chromel thermocouple were used to measure the device temperature. The two thermal diodes are mounted in a constant temperature enclosure using a system similar to that described by Guy and Friend (2.2) and calibrated as for the thermal diode mentioned above. This constant temperature

enclosure is situated on the cryostat insert above the pressure cell. The temperature difference from this enclosure to the device in the cell was measured using the thermocouple. One junction of the thermocouple was attached to the outside of the pressure cell as close to the device as possible, while the other junction was attached to copper leads in the constant temperature enclosure. An accuracy of $\pm 1\text{K}$ was obtained using this method.

2.3 High Pressure Measurements

The devices investigated were pressurised in a "Unipress" clamp cell similar to that described by Wasilewski and Stradling (2.3) and illustrated in Fig.2.4. The cell is made of Beryllium-Copper (2% Be), which has a hardness of 42 on the Rockwell C scale, and can be pressurised up to 12 Kbar at room temperature, with or without an optical window. Be-Cu (2% Be) is a non-magnetic material so experiments may be performed at high magnetic fields under hydrostatic pressure.

The samples are mounted onto a Tufnol specimen holder which holds ten electrical contacting pins, shown in Fig.2.5. Below the sample stage sits the pressure gauge, which requires four electrical contacts for a measurement of the pressure in the cell. Ten copper wires (42 s.w.g.) enter the cell through the piston, by way of a pyrophilite high pressure feedthrough and are attached to the electrical contacting pins of the specimen holder. Petroleum spirit is used as the pressure transmitting medium, since it is a non-crystalline solid when frozen, and therefore very hydrostatic (to about 1%).

Pressure is then applied with a laboratory hydraulic press at room temperature and is retained on removal from the press by a clamping nut attached to the cell. As a result of thermal contraction and of changes in the compressibility of the pressure medium with temperature, the pressure falls by approximately 3Kbar when the cell is cooled to 4.2K. This limits the highest pressure attainable with this cell to approximately 9Kbar at 4.2K.

The pressure gauge is made of a calibrated, highly Te-doped, InSb bar. A four-contact measurement of the InSb gauge resistance is used to determine the pressure. The highly Te-doped InSb exhibits poor metallic behaviour consistent with the high carrier density of approximately 10^{19}cm^{-3} . The resistance of the InSb bar falls when cooled to 4.2K, typically by a factor of approximately five in an almost linear variation with temperature. The pressure dependence of the resistance, $[R(P) - R(1\text{bar})]/R(1\text{bar})$, is slightly non-linear but can be satisfactorily described by a second order polynomial. The change of this characteristic is very small on reducing the temperature from room temperature to 77K and has a negligible variation at lower temperatures. A pressure gauge from the same batch of InSb was calibrated at 300K, to an accuracy of 1% against a manganin coil, using a helium-gas compressor manufactured by Unipress. To estimate the pressure at 77K and 4.2K, the calibration curve, $[R(P) - R(1\text{bar})]/R(1\text{bar})$ versus pressure, measured at room temperature, was used with the appropriate value of R corresponding to the particular temperatures. Following this procedure, the pressure in the cell was obtained with an

accuracy of $\pm 5\%$. In order to obtain a measure of the pressure within the stated tolerance at low temperatures, the temperature must be measured to an accuracy of $\pm 2\text{K}$ in order to ensure that the correct value of R is used with the pressure calibration. As mentioned above, an accuracy of $\pm 1\text{K}$ was obtained when measuring the temperature of the device in the pressure cell.

A second type of pressure system used to generate high pressures was the helium-gas compressor. A Be-Cu cell similar to that described above is used, but the basic principle of attaining high pressures is different to that of the clamp cells. Helium gas is used as the pressure transmitting medium, and is compressed in the cell by way of a flexible, high pressure capillary tube connected to a compressor. The maximum pressure is limited to 14.5Kbar at 77K since the medium solidifies at this temperature and pressure but remains hydrostatic. Within these limitations, the pressure may be varied at any temperature, which allows several measurements at different pressures to be performed immediately. The pressure for this system is measured by two methods; (i) with a highly Te-doped InSb pressure gauge, as before, and (ii) with a manganin resistance coil placed in the third stage of the compressor. The InSb pressure gauge is used when the helium gas has solidified, and a pressure difference exists between the two ends of the high pressure capillary. The temperature range of operation of the gas cell is from room temperature down to 77K. The measurement of the device temperature in this cell is similar to the method used for the clamp cell, except that a copper-constantan thermocouple is used. Also, the thermocouple is

in good thermal contact with the device, rather than being strapped to the side of the cell, as the thermocouple wires are fed through to the sample space.

A third type of pressure system used was a piston pressure cell designed and built by J.Simmonds and R.H.Friend at Cambridge University. The pressure cell system is illustrated in Fig.2.6. The basic method of attaining high pressures is similar to that used in the Be-Cu clamp cells but the design is quite different. Pressures of up to 20Kbar at room temperature have been attained with this cell. However, for the experiments performed, the maximum pressure was limited by the force available from the laboratory hydraulic press, to 14.5Kbar at room temperature. With a suitable alternative press, pressures up to 20Kbar are possible.

The samples are mounted onto a PTFE sample stage, which is secured to a hardened tool steel specimen holder, and holds ten electrical contacting pins. Below the sample stage sits the pressure gauge, as for the Be-Cu clamp cell. The electrical wires enter the cell through the specimen holder to the sample stage by way of a Styecast resin, high pressure feedthrough. The wires are then soldered to the contacting pins of the sample stage. The sample stage, with the sample in place, is covered by a PTFE "top hat" sheath, as shown in Fig.2.6. This sheath is filled to the top with petroleum spirit before being secured onto the specimen holder. The inner bore of the "Cambridge" cell is made of maraging steel tapered on the outer diameter by 1°. This inner part is pushed inside a Be-Cu (2% Be) body. Pressure

is applied at room temperature with a laboratory hydraulic press, as for the Be-Cu liquid cell. A tungsten carbide plunger pushes onto a pressure pad which, in turn, pushes onto a tungsten carbide piston. The piston then compresses the PTFE "top hat" and petroleum spirit through PTFE and brass sealing discs. A brass sealing washer is also placed around the base of the PTFE "top hat", on the tool steel specimen holder. The pressure is retained on removal from the press by a clamping nut attached to the cell. The measurement of the sample temperature in this cell was similar to the method used for the clamp cell, except that a rhodium + 0.5% iron- chromel thermocouple was used (2.2). This thermocouple was in good thermal contact with the device, rather than being strapped to the side of the cell, because the thermocouple wires are fed through to the sample space with the electrical wires.

2.4 High Magnetic Field Measurements

The cryomagnetic field system used was a 14.5 Tesla, Oxford Instruments high field solenoid (S13.6/15/40/13). This comprised a superconducting magnet, mounted to give a vertical magnetic field, with a vacuum insulated cryostat (2.4). The magnet is equipped with a superconducting switch which consists of a length of superconducting wire, non-inductively wound, with a wire electrical heater. The length of superconducting wire is wired in parallel with the three sets of concentric solenoids, wound on separate formers, which comprise the magnet. The superconducting wire is made resistive by raising its temperature using the heater. The switch is then in its "open state" and current, due to a

voltage across the magnet terminals applied when sweeping, will flow in the superconducting magnet windings in preference to the resistive switch element. The switch is in its "closed state" when the heater is turned off and the switch element becomes superconducting again. The switch and quench protection resistors shunt some of the current from the magnet during energisation or de-energisation. The magnitude of this discrepancy depends upon the magnitude of the energising voltage presented to the magnet terminals and therefore, upon the rate of change of energising current. A current of 100 amps through the magnet corresponds to a magnetic field of 12.6 Tesla so a relatively slow sweep rate of 10 amps/min is used to minimise any hysteresis effects associated with energisation or de-energisation of the magnet.

The process of establishing a persistent mode operation for the magnet consists of energising the magnet to give the required field with the switch in the "open state", closing the switch, and then reducing the current flowing through the magnet current leads to zero, leaving the magnet in its previously energised state. The current flowing in the magnet windings remains constant as the current in the magnet current leads is decreased, the current flowing in the closed switch then being the difference between the magnet and lead currents.

The data taken using this system, was stored digitally on a microcomputer and numerically differentiated. A Fourier transform of the data was taken using a fast Fourier transform program written by R.Williams of Imperial College.

2.5 Sample Fabrication

Two wafers of double barrier n-i-n structures were grown by atmospheric pressure metal organic vapour deposition (MOCVD) on n+(100) GaAs substrates at the SERC III-V Growth Facility, Electrical and Electronic Engineering Department, Sheffield University. The specifications for the double barrier structures were either 30Å AlAs barriers separated by a 70Å GaAs well or 50Å AlAs barriers separated by a 50Å GaAs well. The sequence of growth of the wafers was, first, a 1.0µm thick buffer layer of GaAs n-doped to $2 \times 10^{17} \text{cm}^{-3}$. This was followed by a further 25Å of undoped GaAs (spacer layer), the first AlAs barrier, the GaAs well, the second AlAs barrier, a second 25Å spacer layer and 2.0µm of GaAs n-doped to $2 \times 10^{17} \text{cm}^{-3}$. The two different structures were prepared in this way in consecutive growth runs, the first with nominally 50Å barriers and a 50Å well and the second with nominally 30Å barriers and a 70Å well.

The structures were examined by transmission electron microscopy (TEM) to check their layer thicknesses with an accuracy of $\pm 2\text{\AA}$. These measurements were performed at the Materials Science and Metallurgy Department, Cambridge University. Fig.2.8a) and b) shows the relevant micrographs obtained for these two structures. The following values were obtained for the 50Å-50Å-50Å and 30Å-70Å-30Å structures: 50Å-15Å-45Å and 40Å-72Å-43Å respectively. In the case of the nominal 30Å-70Å-30Å structure, the thinner barrier is adjacent to the substrate and for the nominal 50Å-50Å-50Å structure, the thicker barrier is adjacent to the substrate.

The fabrication of the devices from the wafer was carried out at Imperial College. The first stage of the processing involved making a good Ohmic contact to the top buffer layer of n+ GaAs; that is, the contact should have a linear I-V characteristic, be stable over time and temperature, and contribute as little parasitic resistance as possible. The alloy chosen was Ni/Au/Ge (12% by weight of Ge and 5% by weight of Ni) and a Au capping overlayer (2.6). The wafers were cleaned in methanol, 1,1,1-trichloroethane and acetone respectively and then transferred to a conventional evaporation system. A 2500Å layer of Ni/Au/Ge was evaporated onto the wafer, followed, without breaking the vacuum, by a 1000Å capping layer of Au, as measured by a 6MHz quartz crystal placed adjacent to the wafers. The metallisation must then be alloyed into the n+ GaAs. During the alloy and cooling period, the Ge enters the GaAs and highly dopes the surface layer. The Ni is thought to aid the diffusion of the Ge into the GaAs and to prevent the Au/Ge metal from "balling up" during alloying which can result in poor contact resistance, poor morphology and very irregular edges (2.7). With the introduction of a Au capping layer, contact resistivities are found to decrease. The wafer was annealed in a furnace at 440°C for 20 seconds, which is well above the Au-Ge eutectic point of 363°C, and in the presence of an inert forming gas atmosphere (10% Hydrogen, 90% Nitrogen).

The second stage of processing was to define the device mesas. A mask defining square mesas of area $(500\mu\text{m})^2$, $(350\mu\text{m})^2$ and $(200\mu\text{m})^2$ was placed over the wafers after photoresist was spun onto them. The wafer was then exposed

and developed. The devices were then isolated by mesa etching through the Ohmic contact and growth layers of the wafer to the n+ GaAs substrate. The Ohmic Ni/Au/Ge-Au contact layer was etched by placing the wafers in a solution of 4g potassium iodide, 1g iodine and 40ml of distilled water for 1 minute and then rinsing off in distilled water. To etch through the GaAs/AlAs layers, a wet etch solution of 5% ammonia and 95% hydrogen peroxide was used for an etch time of approximately 15 minutes. To verify that the etch is deep enough, i.e., etch depth $>4\mu\text{m}$, the step was measured using a Tallysurf. The photoresist was finally washed off with acetone.

In order to perform experiments using the Be-Cu pressure cells, the devices must be small enough to fit into gold-coated microwave packages which, in turn, are small enough to fit inside the specimen holder of the pressure cell piston. This requires the devices to be smaller than $(1\text{mm})^2$ and no deeper than 2mm. To cleave them from the wafer to these small sizes, the depth of the wafer from top contact to substrate must be of the order of the areal dimensions of the device. Consequently, the substrate of the wafer was thinned by grinding it in a carbon slurry (carborundum) until the thickness of the wafer was approximately 1mm.

After metallising the substrate of the wafer by evaporating a Ni/Au/Ge contact plus gold overlayer as before, the wafer was cleaved into devices of approximately $(1\text{mm})^2$ using a diamond-scribe. The devices were then mounted into the microwave packages, as shown in Fig.2.7. The substrate contact was bonded to the inner electrical terminal of the

package using silver epoxy (Epotech H20E) which also glues the device in place. The top contact of the device was bonded to the other electrical terminal of the package with low inductance gold wire of diameter $25\mu\text{m}$ using an ultrasonic, thermo-compression ball bonder. This method of bonding forms a gold sphere of diameter $120\mu\text{m}$ which bonds to the top contact of the device. This limits the mesa size to areas greater than $(200\mu\text{m})^2$.

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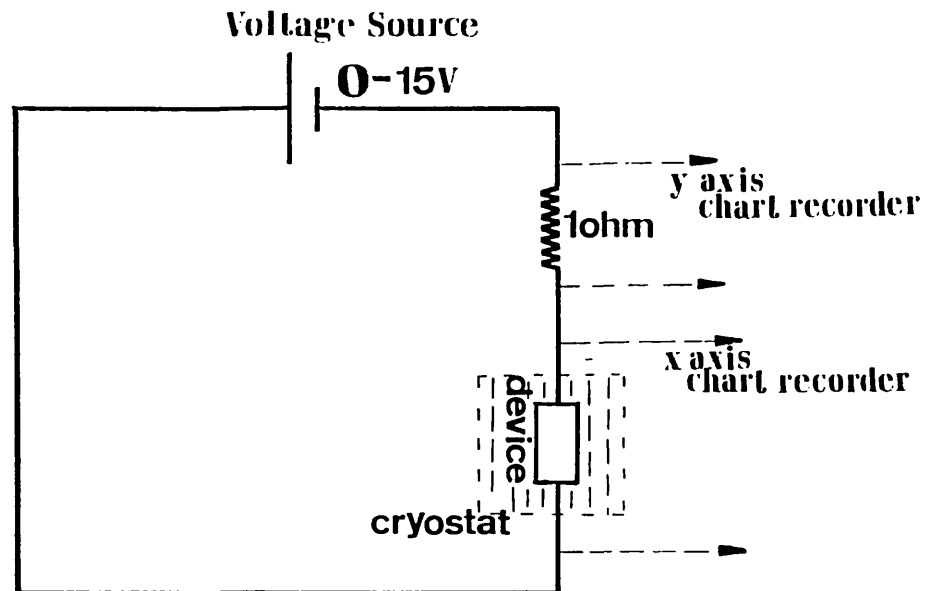


Fig.2.1 Circuit diagram to measure I-V characteristic of device under constant voltage conditions.

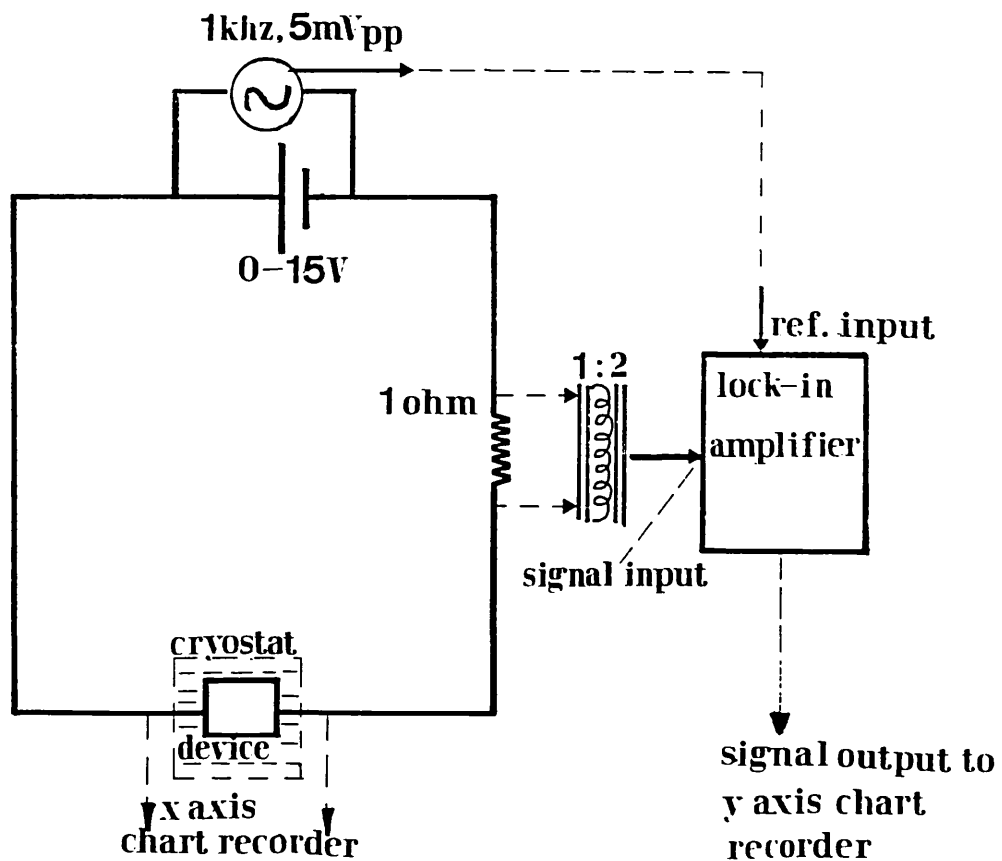


Fig.2.2 Circuit diagram to measure dI/dV -V and d^2I/dV^2 -V characteristics of device.

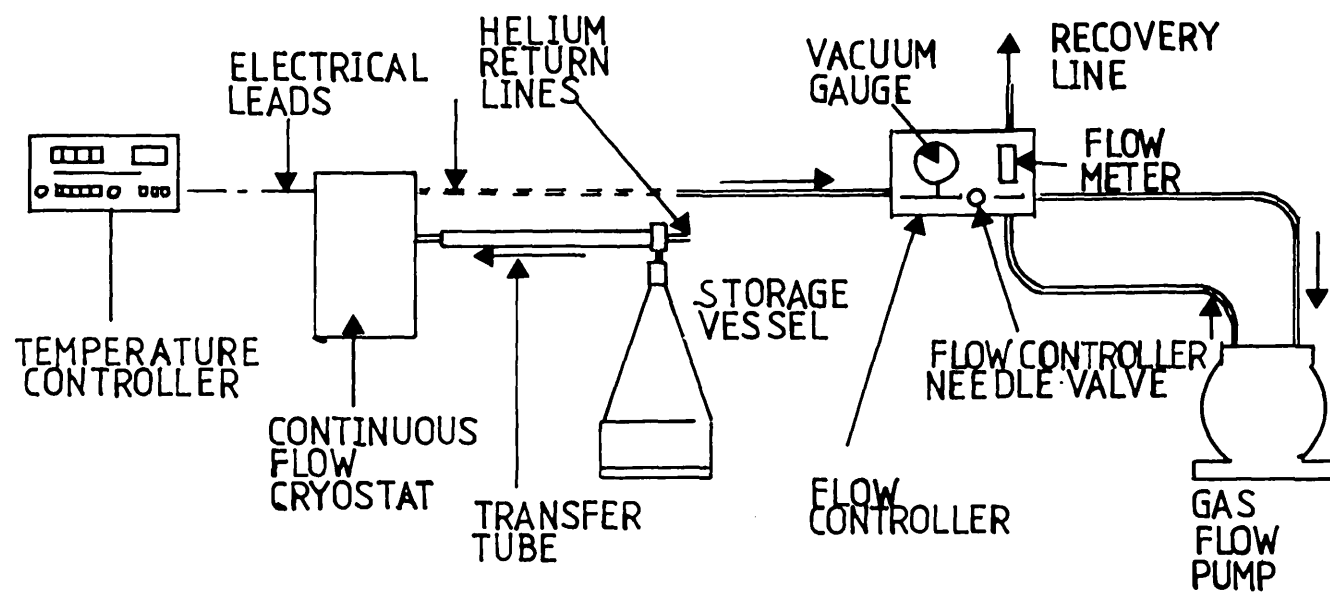


Fig.2.3 Block diagram of continuous flow system.

LOC10 Optical Cell.

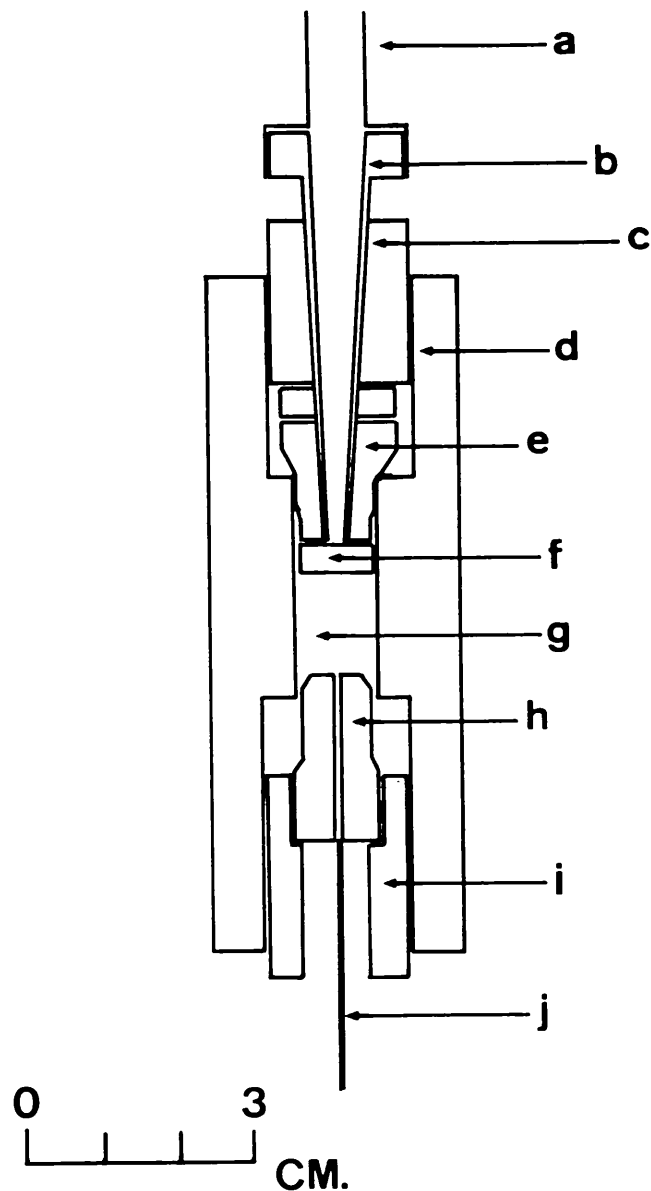


Fig.2.4 LOC10 beryllium-copper optical cell made by Unipress. Maximum pressure is 12Kbar. (a) Stainless steel waveguide, (b) integrating cone, (c) fixed locking ring, (d) Be-Cu cell body, (e) optical piston, (f) sapphire window, (g) sample space - see Fig.2.5 for the sample holder, (h) electrical piston, (i) movable locking ring, (j) electrical leads. For use without the optical window, parts (a) and (b) are not required and parts (e) and (f) are replaced with a blank piston.

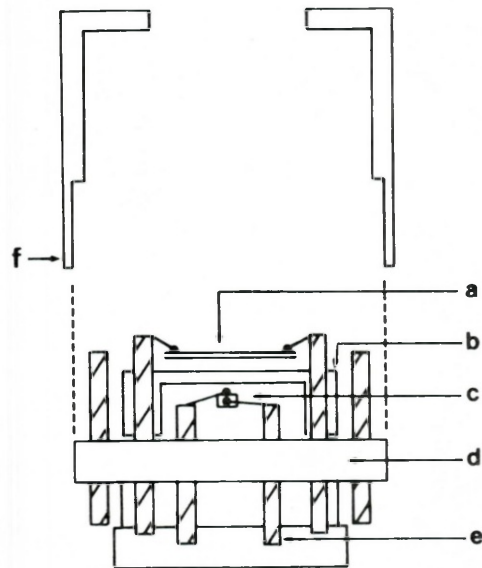


Fig.2.5 The Tufnol sample mounting stage for samples in the 12Kbar Be-Cu optical cell. (a) Device (six pin contacts available), (b) Tufnol stage to protect the pressure gauge, (c) InSb resistance bar pressure gauge, (d) Tufnol block to hold pin connections, (e) enamelled copper pins, (f) Tufnol protection cap held in place with vacuum grease.

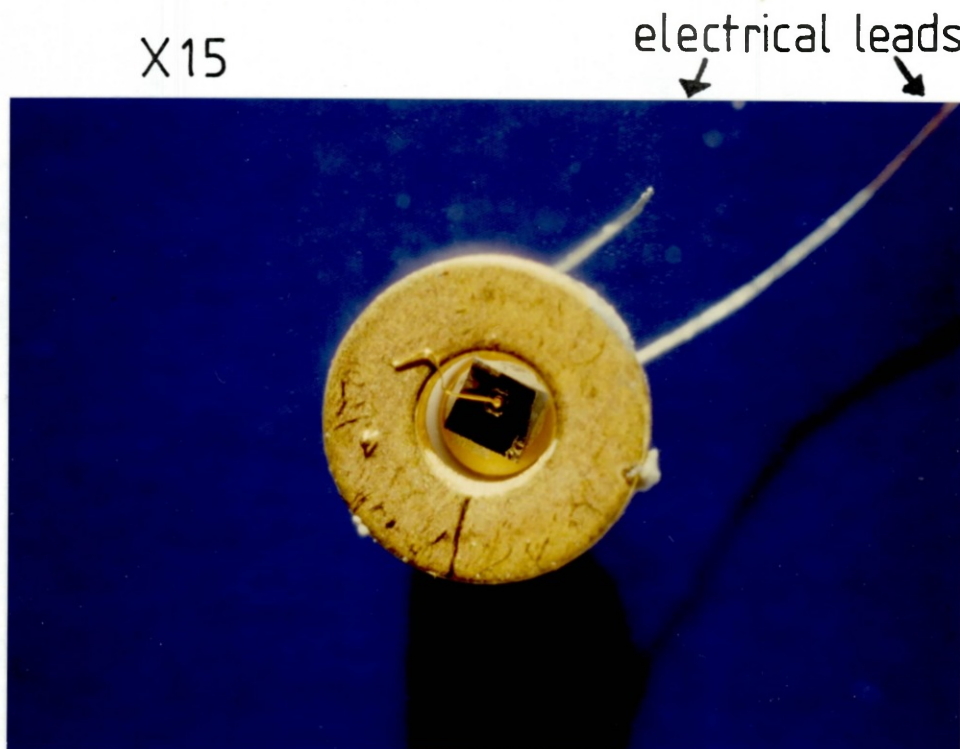


Fig.2.7 Top view of device mounted in microwave packages.

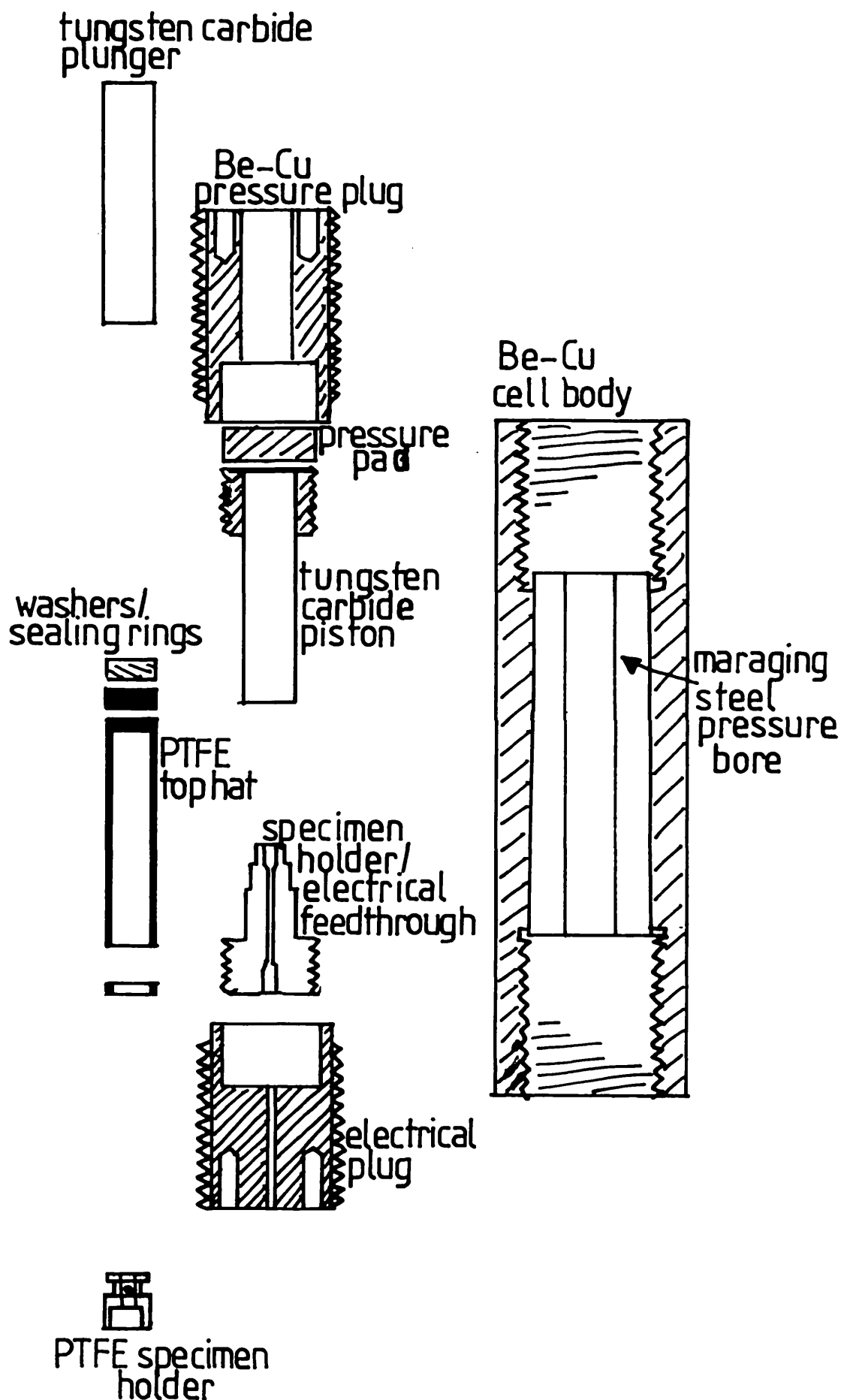
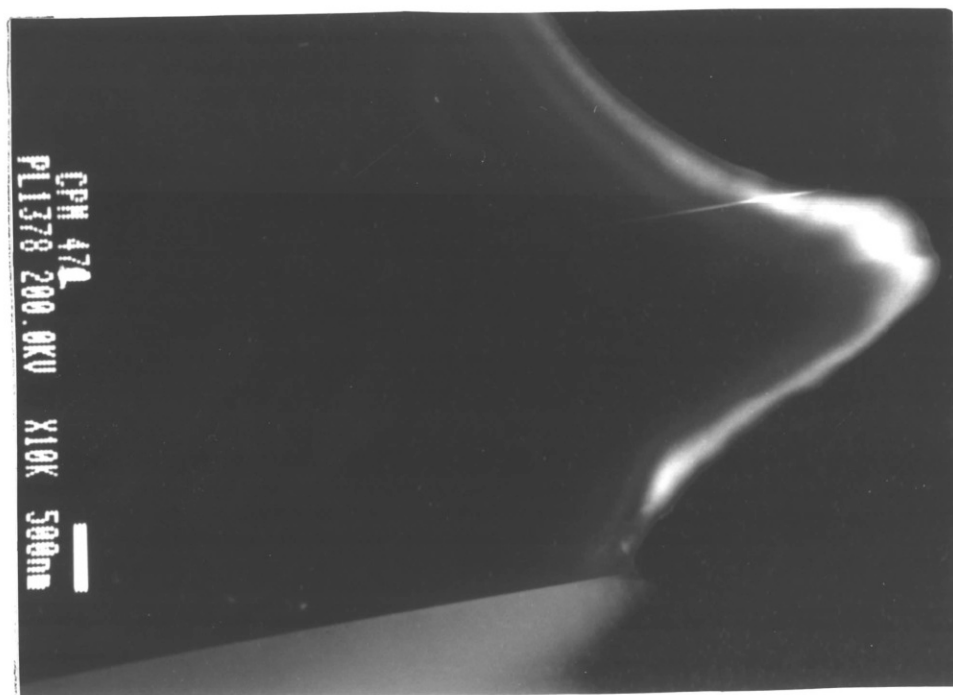


Fig.2.6 Cambridge pressure cell (exploded view).



$2.46\mu\text{m}$
 $\pm 0.2\mu\text{m}$
 TOP SURFACE

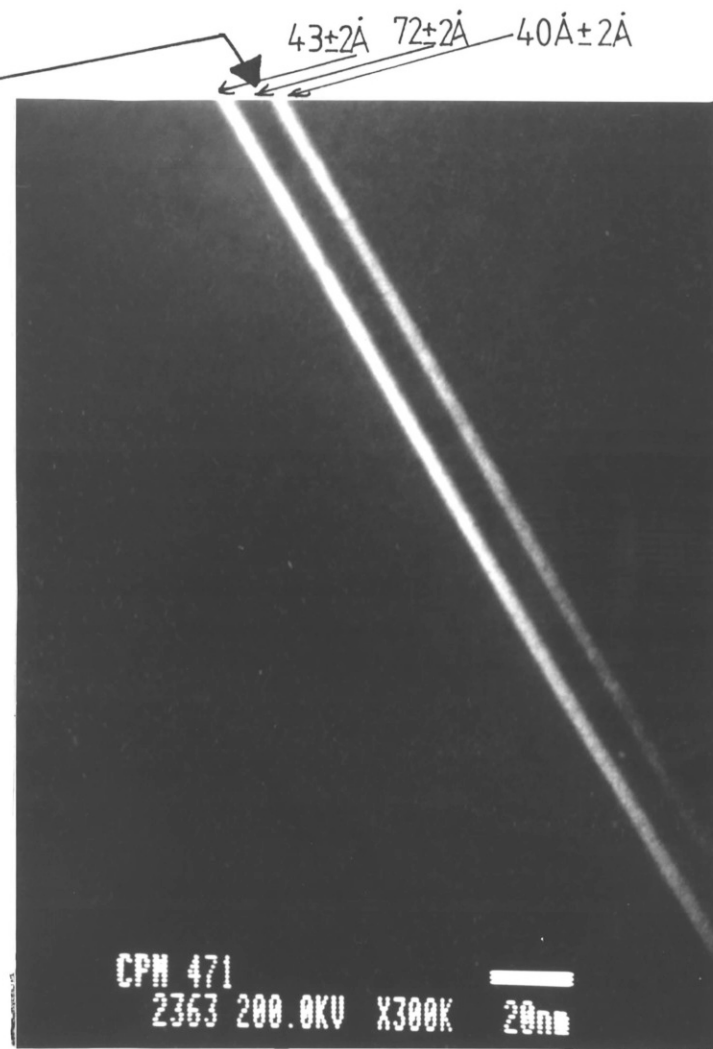


Fig.2.8a) TEM micrographs for the 30Å-70Å-30Å GaAs/AlAs structure. The measured GaAs and AlAs thicknesses are to an accuracy of $\pm 2\text{\AA}$.

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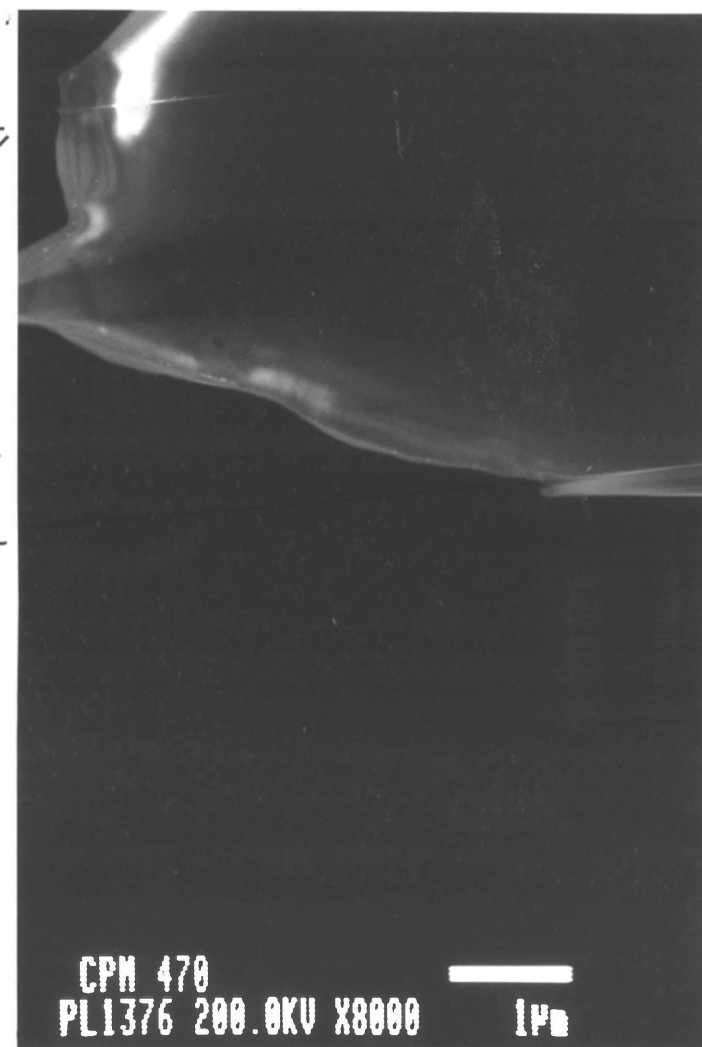
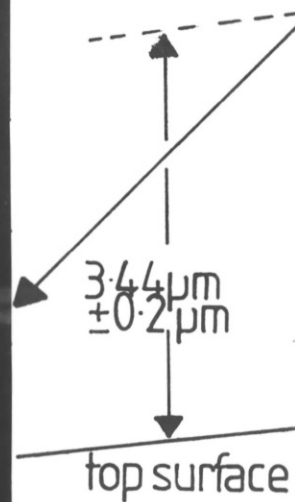
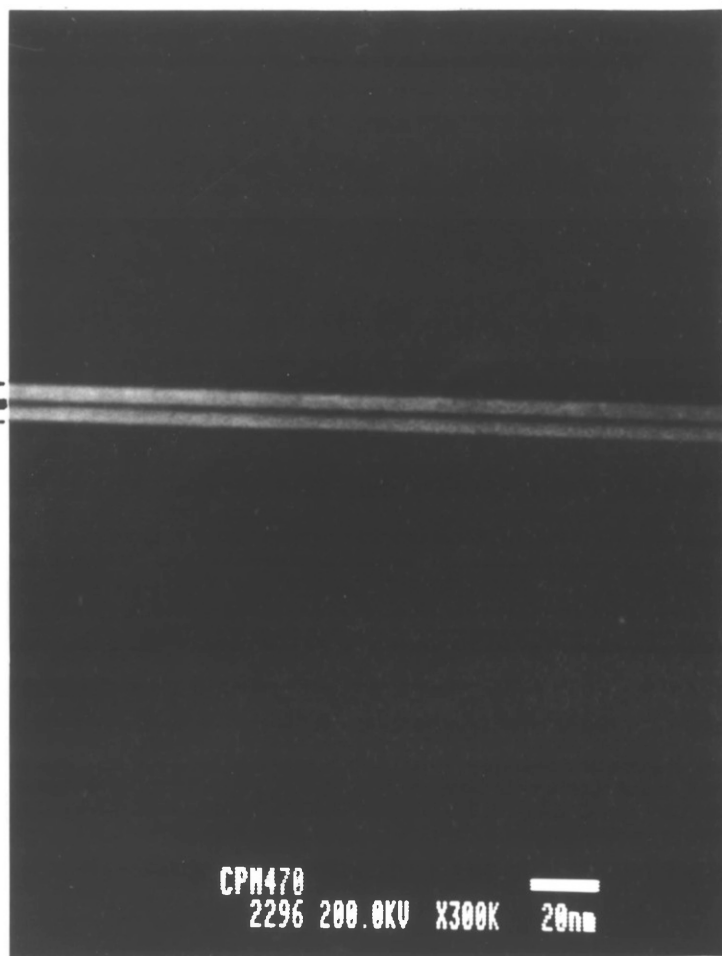
 $50\text{\AA} \pm 2\text{\AA}$ $15\text{\AA} \pm 2\text{\AA}$ $45\text{\AA} \pm 2\text{\AA}$ 

Fig.2.8b) TEM micrographs for the $50\text{\AA}$ - $15\text{\AA}$ - $15\text{\AA}$ GaAs/AlAs structure. The measured GaAs and AlAs thicknesses are to an accuracy of $\pm 2\text{\AA}$.

A LIST OF THE DEVICES INVESTIGATED

Chapter 3 An asymmetric GaAs/AlAs multiple barrier structure enclosed in the i-region of a p-i-n device. Designed by N.R.Couch and grown by MBE by T.Kerr, both of Hirst Research Centre, GEC.

Chapter 4 Double barrier GaAs/AlAs structures enclosed in the i-region of a n-i-n device with either 30Å barriers and a 70Å well, or 50Å barriers and a 15Å well. Grown by MOCVD by J.S.Roberts and P.Mistry, SERC Growth Facility, Department of Electrical and Electronic Engineering, Sheffield University.

Chapter 5 Double barrier GaAs/Al_{0.33}Ga_{0.67}As structure enclosed in the i-region of a n-i-n device. Designed by A.H.Higgs and grown by MBE by G.Smith of RSRE, Malvern.

A symmetric GaAs/AlAs multiple barrier structure enclosed in the i-region of a p-i-n device. Designed by N.R.Couch and grown by MBE by T.Kerr, both of Hirst Research Centre, GEC.

Chapter 6 A standard Gunn device, Gunn device with graded Al_xGa_{1-x}As, hot electron injector, and Gunn device with graded Al_xGa_{1-x}As, hot electron injector and n⁺ spike. All designed by N.R.Couch and grown by MBE by T.Kerr, both of Hirst Research Centre, GEC.

CHAPTER 3

HIGH PRESSURE MEASUREMENTS ON A P-I-N STRUCTURE CONTAINING AN ASYMMETRIC GaAs/AlAs SUPERLATTICE

In this chapter, transport measurements are reported on a quasi-graded gap superlattice at pressures up to 9Kbar. The quasi-graded gap superlattice is enclosed in the intrinsic region of a p-i-n device and consists of an asymmetric GaAs/AlAs structure with four wells and five barriers.

The devices show a negative differential resistance (NDR) feature in their forward bias, current-voltage characteristics which is associated with resonant tunnelling of electrons through the graded gap superlattice. The size of the NDR feature increases with decreasing temperature, the best samples exhibiting a ratio of peak-to valley tunnelling current of 2 at 4.2K and 1bar. On applying hydrostatic pressure, the size of the NDR feature at 4.2K decreases slowly up to 5Kbar and more rapidly at higher pressures, almost vanishing by 8Kbar. These observations are taken as evidence for the strong involvement in the tunnelling process of X-like electron states in the barrier even though the electron states in the quantum wells are expected to be Γ -like.

3.1 Introduction

The device investigated is a p-i-n structure where the intrinsic region consists of a quasi-graded gap GaAs/AlAs superlattice. The well and barrier thicknesses of the quasi-graded gap superlattice vary from 70Å, 30Å, respectively, to 94Å, 6Å so that the average composition and its first moment are equivalent to that of a linearly graded, Al composition

from zero on the p-type side of the junction to 30% on the n-type side, over the same distance. The quasi-graded gap superlattice simulates the grading of the bandgap from that of GaAs to that of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ by varying the well-to-barrier ratio. In the past, this quasi-grading has been proposed as a means of increasing the bandgap linearly without the detrimental effects associated with direct alloy grading (1). Work by Baba et al. (2,3) has overcome the problem of the deep traps created by the doping of AlGaAs with Si. A high carrier concentration and an increased effective bandgap equivalent to that of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ can be retained by growing a short period, GaAs /AlAs superlattice. The p-i-n device was designed, in part, to test these ideas but this aspect is not discussed further in this thesis.

The devices were grown by MBE on an n+ (100) GaAs substrate. The first growth layer was a n+ buffer layer of $0.5\mu\text{m}$ of GaAs doped with Si to $1 \times 10^{18}\text{cm}^{-3}$. This was followed by a lightly n-doped layer of $0.5\mu\text{m}$ of GaAs doped with Si to $1 \times 10^{16}\text{cm}^{-3}$. Then the five period GaAs/AlAs superlattice was grown. The superlattice was nominally undoped and commenced with a $30\text{\AA}$ thick AlAs layer followed by a $70\text{\AA}$ GaAs layer. In the eight consecutive layers, the AlAs thickness was reduced by $6\text{\AA}$ per layer and the GaAs thickness was increased by $6\text{\AA}$ per layer. The fifth and final period of the superlattice comprised an AlAs layer $6\text{\AA}$ thick and a layer of GaAs $94\text{\AA}$ thick. The thicknesses of these layers were subsequently checked by transmission electron microscopy and found to be correct to $\pm 2\text{\AA}$ (4). A $0.5\mu\text{m}$ thick layer of p-type GaAs was grown on top of the superlattice. This layer was doped with

Be to $1 \times 10^{16} \text{cm}^{-3}$. Finally a heavily doped p+ contact layer was grown which was $0.5 \mu\text{m}$ thick and doped to $5 \times 10^{18} \text{cm}^{-3}$ with Be. Standard photolithography and etching techniques produced mesas up to $(180 \mu\text{m})^2$. Au/Zn and Au/Ge metallisations were used to make Ohmic contacts to the p+ layer and the n+ substrate respectively. The devices were then mounted in small, gold microwave packages.

The DC current-voltage (I-V) characteristic of the device exhibits excellent rectifying behaviour with a reverse bias dark current density of less than $6 \times 10^{-8} \text{ A/cm}^2$ at 3V and room temperature. This makes the structure ideal for application as a high sensitivity photodiode (5). In reverse bias, the effect of the superlattice is to prevent tunnelling across the bandgap. This is achieved by increasing the bandgap at the point where tunnelling from the conduction band to the valence band is most likely to occur and by limiting the current when breakdown does occur. For this, it is critical to locate the superlattice at the point of highest field gradient, i.e., the interface of the p-n junction.

At low forward bias (less than 1.7V at 4.2K), a low current is observed since the superlattice greatly reduces the thermally activated current. As the bias is increased, the p-n junction becomes flat band and a rapid increase in current is seen as the junction begins to turn-on. This is expected to be 1.52V at 4.2K and 1.42V at room temperature. At room temperature this expected turn on is observed, while at 4.2K a turn on of approximately 1.7V is observed which is thought to be due to some non-ohmicity in the contacts at

this temperature (4). As the bias is increased further, a weak NDR feature is observed at room temperature which strengthens as the temperature decreases. Fig.3.1 shows the I-V characteristics at 4.2K and 300K at 1bar. At 4.2K, a typical peak to valley ratio of 2 is observed which varies slightly ($\pm 25\%$) between different samples fabricated from the same wafer. This NDR feature occurs when the energies of the electrons in the n-type emitter contact coincide with the $n=1$, quasi-bound state in the first quantum well, Fig.3.2. The device is found to oscillate in this region (4) which is thought to be an artifact of the measurement circuit (see chapter 1, page 23 and appendix 1). A second very weak feature occurs at approximately 0.2V above the principal NDR feature. This is thought to arise from the alignment of the $n=2$ quasi-bound state of the second well with the electrons in the emitter. Beyond the NDR region, the current is dominated by the turning on of the p-n junction after which the measured current is limited by the series resistance of the device ($\approx 10\Omega$).

A number of optical and electrical investigations of the p-i-n structure have already been reported (4,5,6,7,1.47,1.58,1.56). The temperature (T) and magnetic field (B) dependences of the resonant tunnelling feature have been studied in detail by Couch et al. (6). They report a linear variation of the peak to valley ratio (A/B) both with temperature and with magnetic field parallel to the layers ($B \perp J$), both of which suppress the principal NDR feature. It is noted that, in general, the decrease in bandgap of GaAs with increasing temperature is reflected in the reduction of the voltage required to create NDR. For B

perpendicular to the layers ($B||J$), the voltage range over which NDR may be seen broadens but A/B is unaffected.

Using a simple coherent tunnelling model, where the transmission probability is summed up to the Fermi energy to give the tunnelling current, Couch et al. (4) estimated the tunnelling current of this structure using the direct $\Gamma(\text{GaAs})-\Gamma(\text{AlAs})$ bandgap offset value of 1.2eV. This gave a tunnel current three orders of magnitude too small. However, agreement was good between experiment and theory when a band offset of 0.32eV was used for the $\Gamma(\text{GaAs})-\text{X}(\text{AlAs})$ potential barrier. The precise value of the $\Gamma(\text{GaAs})-\text{X}(\text{AlAs})$ barrier is poorly defined with quoted values between 0.14eV (1.47) and 0.4eV (1.12). Nonetheless, $\Gamma-\Gamma$ tunnelling can probably be eliminated. The various tunnelling processes for this structure and their relative probabilities are considered further in section 3.3. Electroluminescence spectra, at 4.2K, has been obtained from the device by Phillips et al. (1.56) and support a $\Gamma(\text{GaAs})-\text{X}(\text{AlAs})$ interpretation for the dominant barrier which gives rise to the quasi-bound states. In addition, by comparing the observed photoconductivity spectrum to a transfer matrix model, Singleton et al. (1.47) conclude that the electronic structure of the device is described by a $\Gamma(\text{GaAs})-\text{X}(\text{AlAs})$ barrier of 0.144eV and a fitted mass of 0.11m, approximately half the mass associated with a parallel wavevector non-conserving process.

In what follows, measurements are presented of the effect of pressure on the NDR feature of the structure. The electrical behaviour of the devices indicates the possible presence of

a high concentration of active impurity states in the AlAs barriers. This is discussed further below and is possibly a result of the fact that in these structures no spacer layer was included between the undoped barrier layers and the doped cladding layers either side of the superlattice. The pressure results provide further support for the Γ -X barrier model of resonant tunnelling in GaAs/AlAs multiple barrier structures.

3.2 Results

DC current voltage characteristics were obtained at pressures up to 8.4Kbar and temperatures down to 4.2K for seven separate p-i-n devices. Typical I-V characteristics at 4.2K are shown in Fig.3.3 for pressures of 1bar and 7.4Kbar, under constant current conditions. Above the principal NDR feature, a second, very weak feature is observed in the I-V trace at low pressures, around 1.97V (not visible in Fig.3.3). This feature, and one at still higher voltage (2.04V) are revealed clearly by both first and second differential measurements and are shown as a function of pressure in Fig.3.4.

All the forward bias characteristics show NDR which appears as a hysteresis loop under the constant current bias conditions used. The voltage at which the NDR feature occurs is somewhat sample dependent and reflects variations in the value of contact and other parasitic resistances. In some samples, a small increase of this voltage occurs with pressure and in others, a small decrease. It was found that, on traversing a hysteresis loop the cycle was repeatable in most cases. However, for some of the seven samples

investigated, consecutive samples showed variations in the NDR region which eventually settled down to a repeatable behaviour. The most likely explanation for this behaviour is that there is also a non-resonant contribution to the current and that this contribution is related to conduction through impurity states located in the barrier, possibly at quite deep energies below the top of the barrier. These states will allow an easier path through the barrier than that offered by tunnelling. The variability in the I-V response on cycling would be due to the changing occupation of these states. Deep metastable states are known to be associated with the X-minimum in GaAs and InSb (9). They can be sensitive to variations in pressure, where the relative positions of the deep states, the conduction and valence bands, and the Fermi energy, may be altered by pressure. Such deep levels may be involved in the present case.

Figures 3.5a and 3.5b show the peak to valley ratio, A/B , plotted as a function of pressure at 77K and 4.2K respectively. The large scatter in the values at each temperature is thought to be caused by the non-resonant leakage current described above. This might be modelled by a resistance, R_p , in parallel with the structure. Provided that the value of R_p is rather larger than the magnitude of the negative differential resistance, the current through R_p changes little over the voltage range of the NDR. Therefore, the main effect will be to offset the values of both the peak (A) and valley (B) currents by approximately the same amount. Thus by plotting the difference between the peak and valley currents, the scatter in the results caused by a

"parallel resistance" whose value varies between samples and with pressure, is expected to be suppressed. The data is plotted in this way in Figures 3.6a and 3.6b for temperatures of 4.2K and 77K respectively. Indeed, a marked reduction in the degree of scatter of the results is observed.

The best samples exhibit a ratio of maximum to minimum tunnelling current in excess of 2 at 4.2K and 1bar. On applying pressure, the size of the hysteresis (or NDR feature) decreases slowly up to 5Kbar and more rapidly at higher pressures, almost vanishing by 8Kbar at 4.2K. The results at 77K are quite similar but there is a reduction of approximately 0.5Kbar in the threshold pressure for loss of NDR.

The features revealed by first and second differential measurements (Fig 3.4) above the principal NDR feature show a rather different pressure dependence. The lower of these features appears to sharpen up to 3Kbar and then to broaden at higher pressures. The feature is not suppressed by 7.5Kbar at 4.2K. In contrast, the higher feature is rapidly suppressed by pressure, vanishing by 5.5Kbar. At room temperature neither feature is observed.

3.3 Discussion

The observation of the rapid loss of NDR with pressure is taken as evidence for the strong involvement of X-like barrier states in the tunnelling process. However, due to the complex design of the p-i-n structure, there are likely to be a number of competing processes taking place and this statement requires some justification. The most important

processes to consider are electron tunnelling, hole tunnelling and the non-resonant leakage currents represented by the "parallel resistance" discussed above. The first two processes depend upon the relevant barrier heights. These and their variations with pressure are considered first.

Recent photoluminescence measurements as a function of pressure on GaAs/Al_xGa_{1-x}As quantum wells and superlattices for a number of different x-values have been performed by Weinstein et al. (1.55) and by Wolford et al. (1.6). In these studies the pressure is obtained at which the X-minimum in the barriers comes into coincidence with the quantum confined Γ state in the well. When this occurs, a sudden loss of luminescence efficiency indicates a switch from direct gap electron-hole recombination to recombination that is indirect both in real space and in reciprocal space. Once this pressure is found, the relative alignment of the band structure in both materials is determined from the known bandgaps and their pressure variations. In the work of Wolford et al. on both low x-values and high x-values, structures exhibiting very different pressure thresholds for Γ -X crossing, the same conduction to valence band offset was determined. This was $\delta E_C : \delta E_V = 68:32$ which suggests that the offset is independent both of pressure and of x. This ratio is also close to the ratio of approximately 60:40 determined at 1bar from the photoluminescence of "parabolic" quantum wells (1.5) and shows some consistency with alternative methods of measurement. One criticism of the high pressure method is that it is difficult to be certain that the loss of luminescence intensity is not caused by an impurity

associated with the X minimum , rather than the minimum itself , crossing the Γ -like well state. However, if this were the case, it would indicate an even more asymmetric band offset in contradiction of the 60:40 result. While the question of band offsets remains controversial, it is considered reasonable to take the ratio to lie between limits of 60:40 and 70:30, in order that some estimate can be made of the degree of uncertainty in the barrier heights for tunnelling obtained.

Fig.1.11 shows the relative positions of the valence band maximum, Γ_V , and the conduction band minima, Γ_C , X_C and L_C for GaAs and AlAs in the 60:40 model. The bandgaps are all obtained from the review by Adachi (1.46) and are due to Casey and Panish (10). It can be seen from the diagram that the following band offsets are obtained: $\Gamma_C(\text{GaAs}) - X_C(\text{AlAs}) = 0.105\text{eV}$ and $\Gamma_C(\text{GaAs}) - \Gamma_C(\text{AlAs}) = 0.957\text{eV}$. For a band offset of 70:30, these values increase to 0.265eV and 1.117eV respectively. In what follows, the values (at 1bar) taken for the $\Gamma_C - X_C$ barrier is $0.2 \pm 0.1\text{eV}$, for the $\Gamma_C - \Gamma_C$ barrier is 1.0eV and for the $\Gamma_V - \Gamma_V$ barrier is 0.5eV. Using the data of Adachi (1.46) and assuming a pressure independent band offset for the Γ band edges, there is negligible pressure shift to the $\Gamma_C - \Gamma_C$ and $\Gamma_V - \Gamma_V$ barriers, and a pressure shift of -11meV/Kbar for the $\Gamma_C - X_C$ barrier. This pressure shift of $\Gamma_C - X_C$ is in exact agreement with the value estimated from thermionic emission measurements on a double barrier AlAs/GaAs structure under pressure, as reported in chapter4. Therefore, on a simple level, our pressure threshold of 8Kbar for loss of NDR appears consistent with a Γ -X barrier height as low as 0.1eV and the

expected pressure variation of -11meV/Kbar . At this pressure the barrier height is almost completely suppressed. An explanation of the "knee" shaped curve of Fig.3.6, however, awaits further theoretical analysis.

The possible tunnelling mechanisms for the structure are considered by estimating the probabilities of various tunnelling processes. A fully incoherent (or sequential) process and a fully coherent process are considered for each possible potential barrier. The results are summarised in Table 1 for various barriers using the lowest possible Γ_C - X_C barrier height of 0.1eV and literature values for the effective masses, determined at the band edges, both for the GaAs and AlAs. Airy functions have been used to calculate the square of the transmission coefficient assuming that all electrons in the "emitter" contact have an energy of 10meV and that they impinge normal to the GaAs/AlAs interface, i.e., a one dimensional calculation. This approximation of a monoenergetic beam of electrons should not be that unreasonable for estimating the total resonant current because the widths of the resonances, which are also listed in Table 1, are all quite broad. The program to calculate the resonant current was designed and written by A.J.Shields, Imperial College. The coherent currents, I' , may then be used directly to give a rough indication of the relative ordering of the various processes. The NDR feature for this structure is assumed to be dominated by the thickest two barriers of width $30\text{\AA}$ and $24\text{\AA}$ respectively. At least two barriers are necessary for NDR and it is expected that the remaining three barriers, being so thin (6, 12 and

18Å), will not affect the gross behaviour of the structure.

For the sequential approach, the first barrier is expected to dominate the overall tunnelling probability since this has a much smaller transmission coefficient than the second barrier. The sequential tunnelling currents are calculated at the same electric fields across the first barrier that exist at the current peaks in the coherent process, for a given tunnelling mechanism. Then some comparison can be made. It is expected that the ordering of the magnitudes of the resonant currents, calculated for various different barrier heights and effective masses, should be the same for both coherent and sequential approaches (1.23).

Inspection of Table 1 shows that the observed experimental pressure dependence of the NDR, which is strongly indicative of X involvement, is consistent with the ordering of the currents: processes 2 and 3, involving X- like barrier states, are predicted by the calculations to be dominant. Since the currents for these processes are so much larger than for any of the other processes, it is expected that they should remain dominant even after allowing for the prefactor associated with the non-conservation of wavevector parallel to the interface. Even if this is not the case, Table 1 shows that process 1, involving X-like states with parallel wavevector conservation, will have, at least, an equal contribution to any other process at 1bar. Furthermore, this process will rapidly come to dominate at higher pressures as the Γ_C - X_C barrier height is reduced.

Two other explanations for the observed pressure variation must also be mentioned. These are (i) a reduction with

pressure of the electron concentration in the emitter contact and (ii) a decrease in the value of the "parallel resistance" with increasing pressure so that it reaches a value equal to the magnitude of the NDR, $|dV/dI|$, at 8Kbar. This could then lead to a pressure variation, even for a process associated with electron or hole tunnelling through their respective Γ - Γ barriers, not otherwise expected to show a pressure variation. It is considered that neither of these explanations applies with the present structure. In the case of (i), Maude et al. (11) have observed a reduction with pressure in the electron density in the emitter contact of a single barrier structure. However, this was for pressures above approximately 10Kbar and an emitter doping of approximately 10^{18}cm^{-3} . This reduction is due to a deep level, associated with a higher minimum, crossing the Fermi level of the emitter electrons above some pressure threshold. For the case of the p-i-n device, the doping of the emitter is much lower ($\sim 10^{17}\text{cm}^{-3}$) and a large pressure variation of the NDR is observed over the whole pressure range up to 8Kbar. In addition, while a shift in the Fermi level will change the absolute value of the current, it will not lead to a total suppression of the NDR.

The second explanation for the loss of NDR in terms of a pressure dependent parallel resistance may be ruled out because of the good agreement obtained for the pressure threshold at which NDR is suppressed in seven different p-i-n devices. Since the parallel resistance is thought to be due to some extrinsic process, it is most unlikely to exhibit the same ratio to the magnitude of the intrinsic NDR

for each device. Thus this mechanism would lead to strong variations in the threshold pressure for loss of NDR between samples, contrary to the results of Fig.3.6.

Next, the origin of the features observed in the differential measurements are discussed. Their most likely origin is either from resonant tunnelling of electrons through the higher quasi-bound electron states of the conduction band or of holes through the quasi-bound hole states of the valence band. A number of quasi-bound electron states are possible including X-like states, located in the barriers and discussed by Mendez et al. (1.57). In view of the constant difference between the voltages of these higher features and the voltage of the principal NDR feature as the pressure is varied, an electron mechanism also involving Γ -X tunnelling is perhaps more likely than a hole tunnelling mechanism.

Finally, the contrasting result of Mendez et al. (8) for a related 50Å-50Å-50Å double barrier GaAs/AlAs structure is considered. NDR is observed for their structure with a similar peak to valley ratio at 1bar but the NDR feature is completely suppressed by 1.5Kbar and 77K. It would appear that NDR may be much more easily suppressed in a 50Å-50Å-50Å structure than a 30Å-70Å-24Å structure. Therefore the suppression of NDR with pressure seems to be a very sensitive function of well and barrier dimensions. This seems plausible since barrier and well dimensions, as well as the barrier height, determine the energy of the quasi-bound states in the well. The difference in pressure sensitivity of NDR in structures with AlAs barriers may thus

be related to the larger confinement energy of the first resonant state in the 50Å-50Å-50Å compared with the 30Å-70Å-24Å one. The larger confinement energy will reduce the energy difference between this state and the X states in the barriers. Assuming that confinement is determined by the Γ - Γ barriers (1.6,1.55), the difference in confinement energies between the p-i-n structure and that of Mendez et al. is only about 42meV. Since the Γ -X barrier height shifts at about 11meV/Kbar, as demonstrated in chapter 4 and elsewhere (1.6,1.46,1.55), this would imply a difference in pressure threshold for loss of NDR of less than 4Kbar. The observed difference is somewhat greater and therefore does not appear to be explained solely by quantum confinement effects.

The sensitivity of NDR to well and barrier dimensions, discussed above, appears to depend on factors other than differences in confinement energy for the two structures. As mentioned in chapter 1, a calculation by Cade et al. (1.58) for this p-i-n structure has been interpreted in terms of almost equal Γ and X contributions to the tunnelling current. He concluded that, for thicker AlAs barriers, the transmission of each barrier might be more strongly X-like, with a correspondingly stronger pressure dependence. Including this consideration could possibly explain the difference in pressure threshold for loss of NDR between the p-i-n structure and Mendez's 50Å-50Å-50Å structure.

To test the above hypothesis, further investigations are required. In particular, experiments on GaAs/AlAs double barrier structures to study the effect of pressure on the NDR feature for various well and barrier dimensions. In

addition, due to the complex behaviour of the p-i-n devices in which both electron and hole tunnelling can take place, it was considered important to perform the same experiments on a double barrier, GaAs/AlAs n-i-n structure of similar well and barrier dimensions to those which determine the NDR feature in the p-i-n devices. For n-i-n devices, the possibility of hole tunnelling is eliminated. Therefore, the conclusions concerning the proposed tunnelling mechanism for the p-i-n device can be substantiated. By including spacer layers either side of the double barrier region for the n-i-n device, the non-resonant impurity contribution to the tunnelling current should be reduced. This would confirm that the non-resonant impurity contribution to the tunnelling current is an extrinsic property of the p-i-n devices associated with impurity states in the barrier. Finally, the effect of pressure on the NDR feature of GaAs/Al_xGa_{1-x}As double barrier structures, with $x < 0.45$, would be an interesting experiment to perform since the Γ_C - X_C potential barrier is no longer the minimum barrier and so the NDR feature is expected to be less sensitive to pressure. These experiments are all attempted in the following chapters.

3.4 Conclusions

A negative differential resistance and its variation with pressure has been observed in seven samples of a quasi-graded gap superlattice embedded in a p-n junction. Scatter in the results of the peak to valley current ratio as a function of sample and pressure has been strongly suppressed by plotting the peak to valley current difference. This indicates that a non-resonant leakage current is also

present. From the cycling behaviour of the I-V characteristic, this current is thought to be due to impurity levels in the barriers.

It is found that the hysteresis loop associated with the NDR reduces slowly with pressure up to approximately 5Kbar and more rapidly at higher pressures, disappearing by approximately 8Kbar at 4.2K and approximately 7.5Kbar at 77K. A variation with pressure of the leakage "resistance" or of the carrier concentration with pressure is ruled out. The observed behaviour is interpreted as evidence for the dominant role of electrons tunnelling through X-like barrier states. On a simple level, the pressure threshold of 8Kbar for loss of NDR at 4.2K appears consistent with the estimated, low Γ -X barrier height of approximately 0.1eV and its pressure variation of approximately 0.011eV/Kbar.

To substantiate these conclusions, experiments were performed on a GaAs/AlAs, double barrier n-i-n structure of similar well and barrier dimensions to those which determine the NDR feature in the p-i-n device. In addition, experiments were performed on a similar n-i-n structure with different well and barrier dimensions to investigate their effect on the NDR feature. These experiments are reported in Chapter 4.

Table 1: Effective currents for sequential, I , and coherent, I' , tunnelling processes through a 30Å-70Å-30Å double barrier structure. The sequential tunnelling values are calculated for a single barrier under the same electric field as at the peak current for the coherent process. In the calculation, all electrons in the "emitter" contact are assumed to have an energy of 10meV and to impinge normal to the GaAs/AlAs interface.

Barrier	m^*/m_e	V(eV)	I	I'	Res. Width:
GaAs/AlAs	GaAs, AlAs		(arb. units)		FWHM (meV)
<u>1.</u> Γ_C - X_C ($k_{ }$ conserved)	0.07, 1.9	0.1	$2.2 \times 10^{-5}, 9.7 \times 10^{-6}$		4.4
<u>2.</u> Γ_C - X_C ($k_{ }$ not conserved, see note 2)	0.07, 0.19	0.1	0.11, 1.0		4.4
<u>3.</u> Γ_C - X_C (see note 1)	0.07, 0.11	0.1	0.22, 0.9		12.0
<u>4.</u> Γ_C - Γ_C	0.07, 0.15	1.0	$1.1 \times 10^{-5}, 1.9 \times 10^{-6}$		0.4
<u>5.</u> Γ_V - Γ_V (Heavy holes)	0.4, 0.45	0.5	$1.6 \times 10^{-6}, 1.1 \times 10^{-8}$		2.0
<u>6.</u> Γ_V - Γ_V	0.09, 0.26	0.5	$4.3 \times 10^{-5}, 1.1 \times 10^{-5}$		1.9

Note 1: This low mass has been proposed with a similar barrier height by Singleton et al. (1.47).

Note 2: The currents calculated here must be adjusted by a suitable prefactor which takes into account phonon or interface roughness scattering.

Note 3: For process 1, $m^*(\text{AlAs})$ is obtained from references (2.12) and (2.13). For process 2, $m^*(\text{AlAs})$ is obtained from references (2.12) and (2.14).

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Centre)

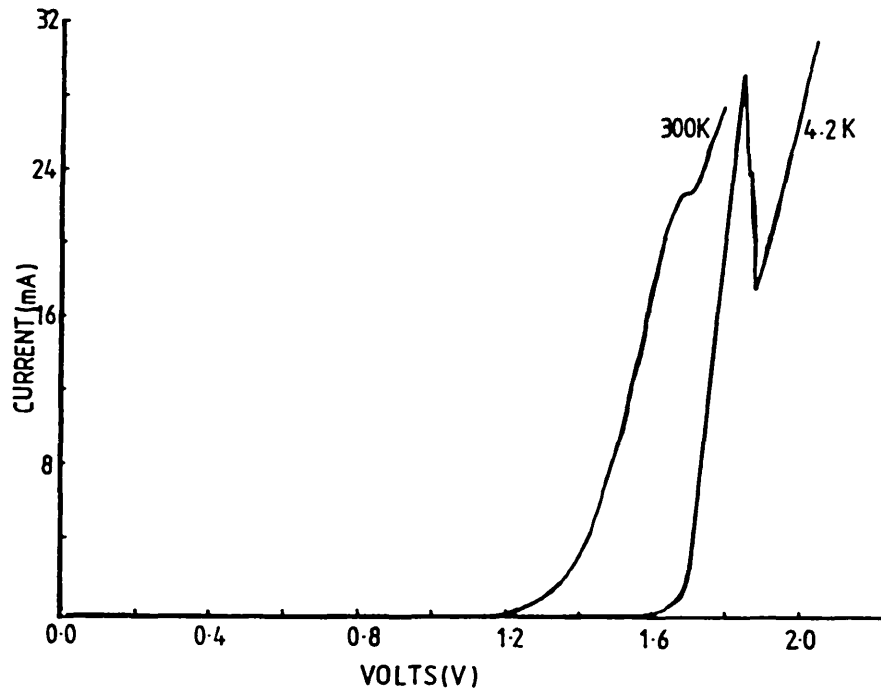


Fig.3.1 Forward bias I-V characteristics at 1bar and temperatures of 300K and 4.2K.

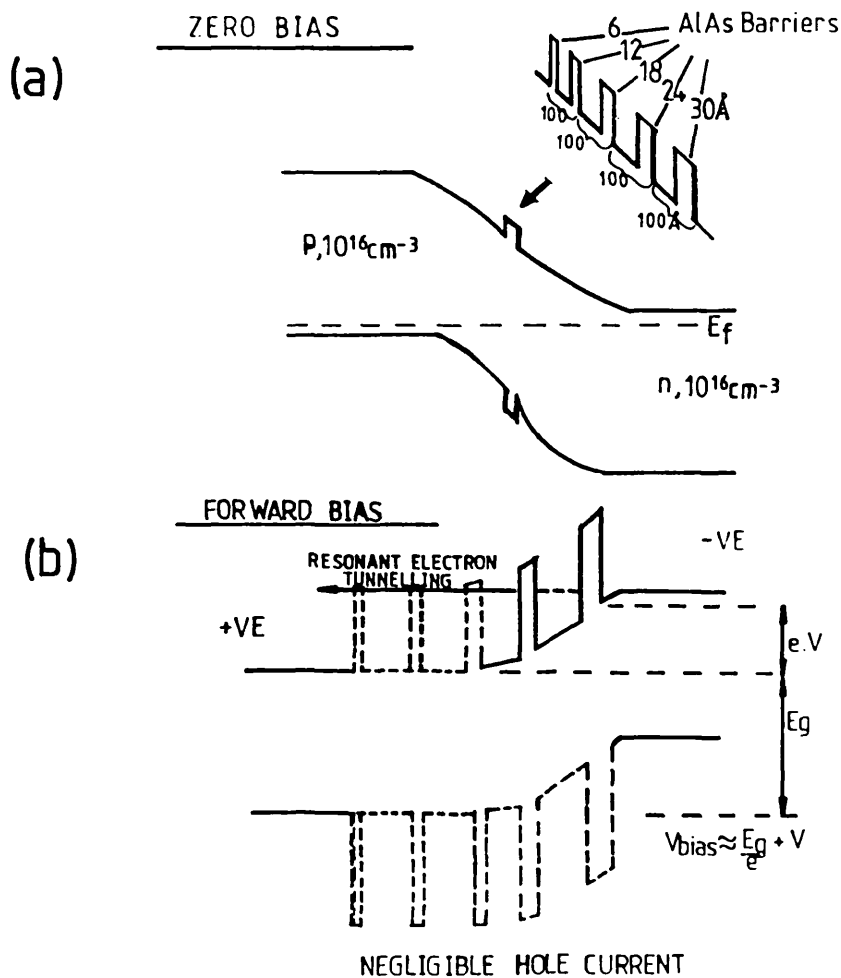


Fig.3.2 A schematic profile of the asymmetric superlattice under (a) zero bias and (b) forward bias at resonance.

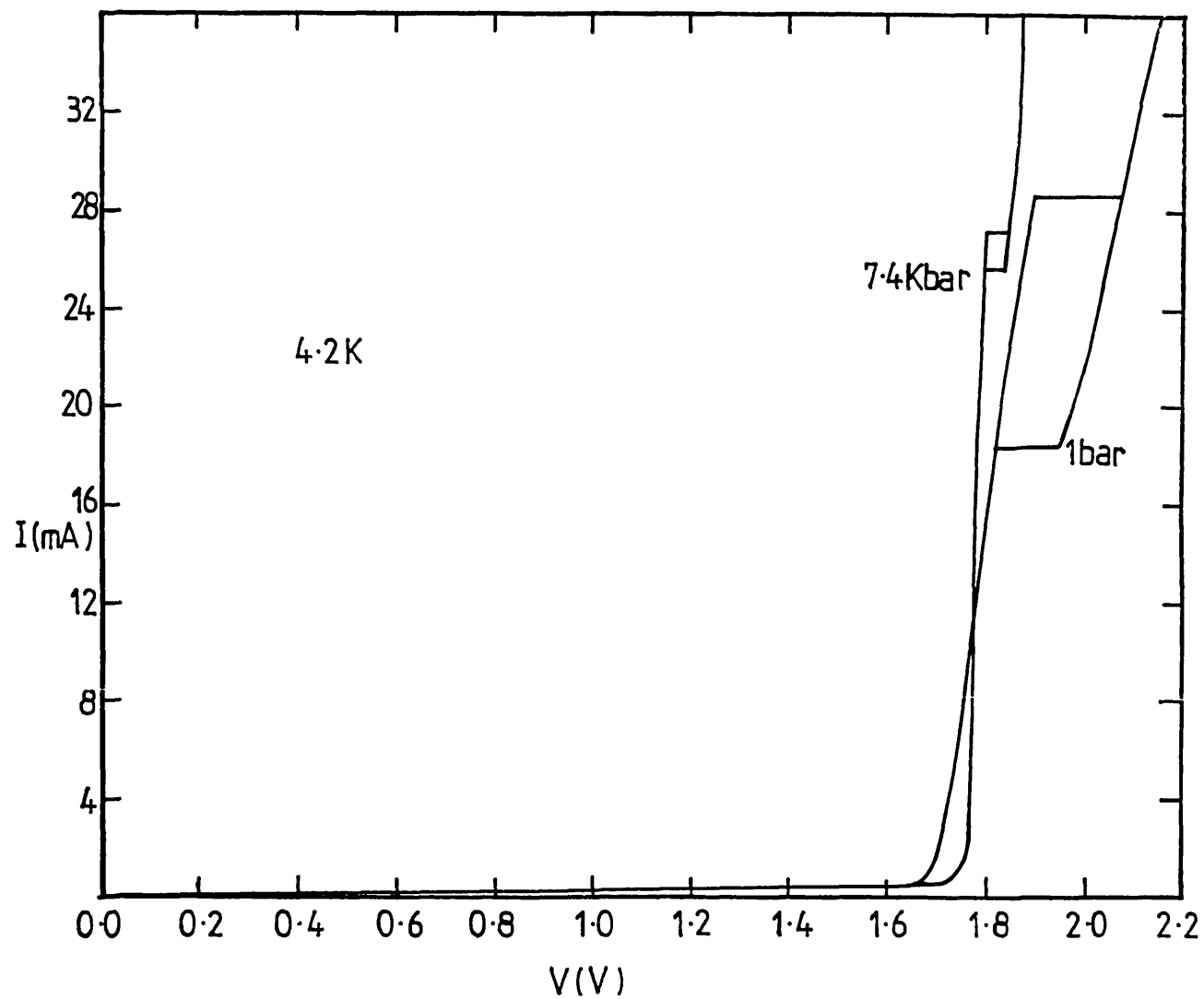


Fig.3.3 I-V characteristics for the device measured at 4.2K under constant current conditions in the same sample at 1bar and 7.4Kbar.

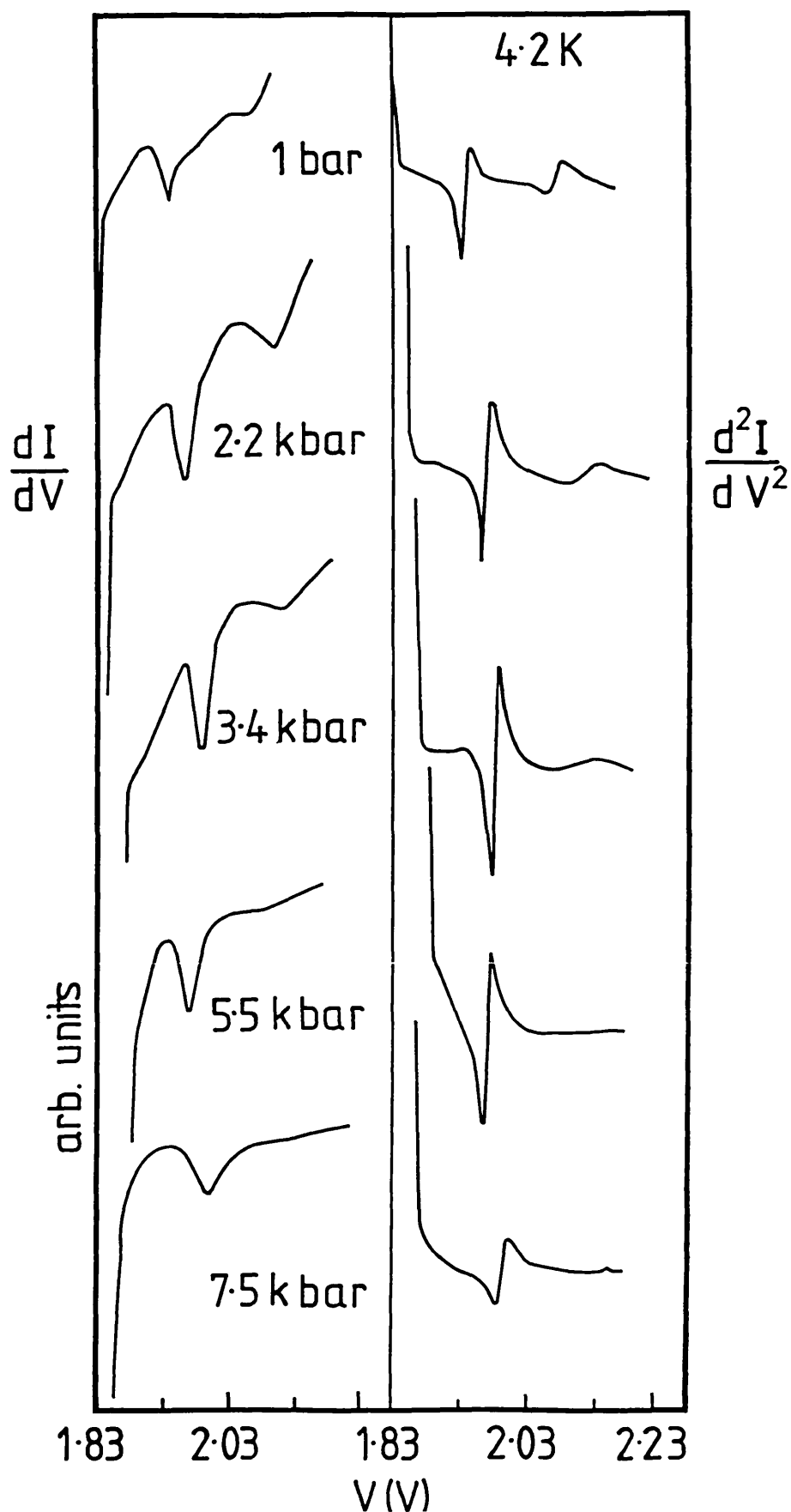


Fig.3.4 First and second derivative characteristics for the device at pressures up to 7.5Kbar. The second derivative was measured with a sensitivity 2.5 times smaller than for the first derivative. 97

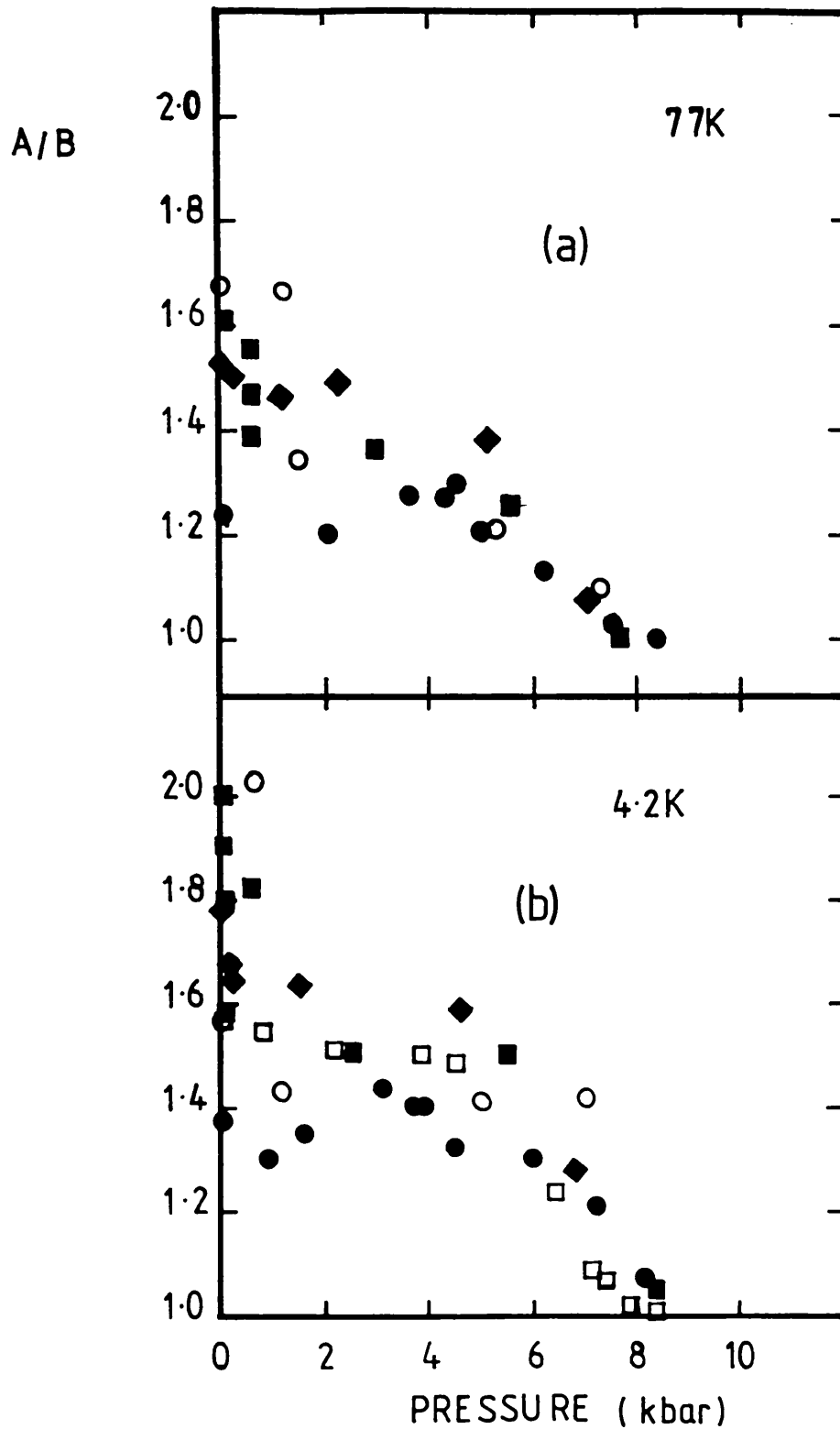


Fig.3.5 Pressure dependence of the peak to valley current ratio, A/B , at (a) 77k and (b) 4.2K, for 5 samples of the p-i-n structure.

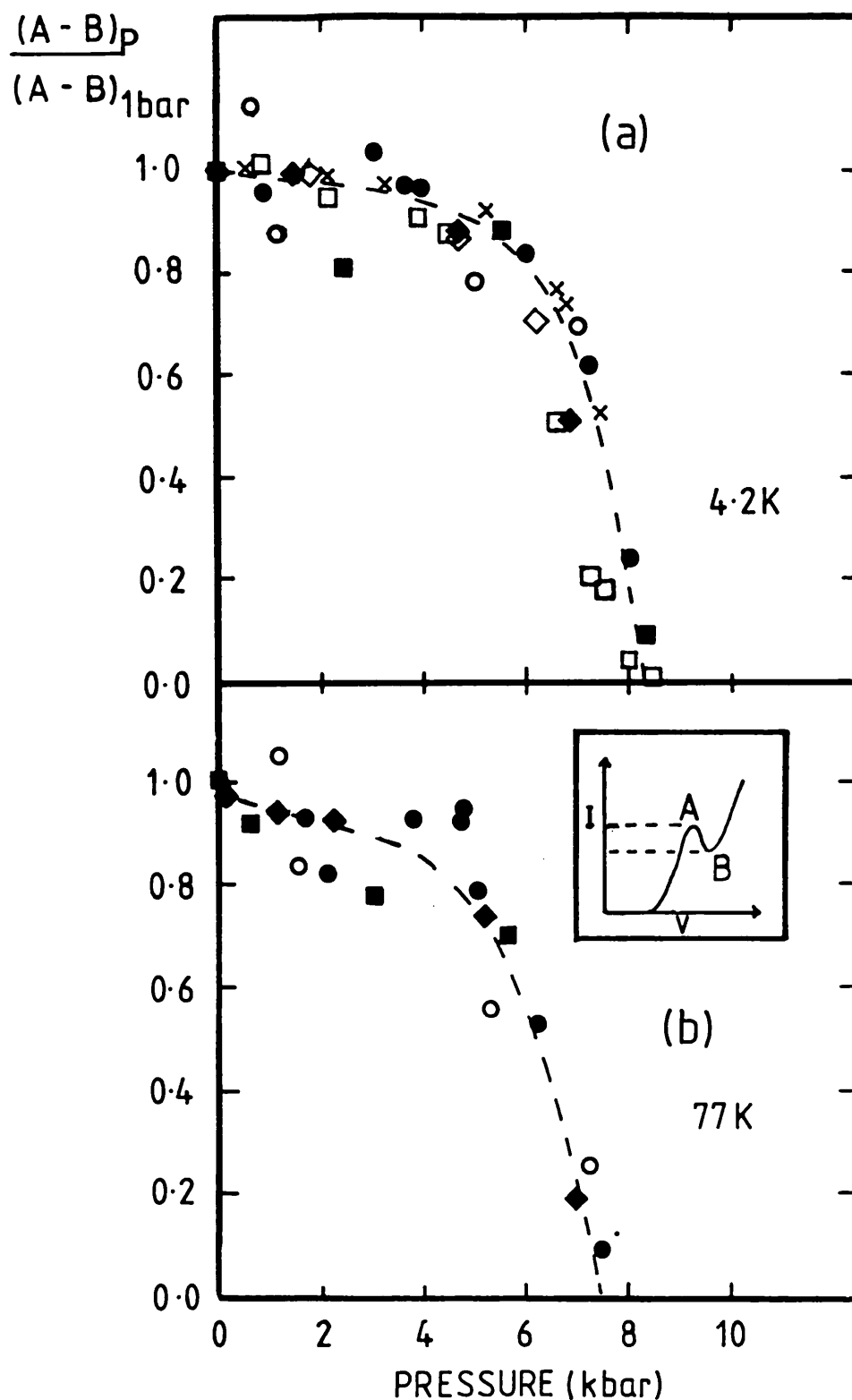


Fig.3.6 Pressure dependence of the peak to valley current difference at (a) 4.2K and (b) 77K, for six samples of the p-i-n structure.

CHAPTER 4

HIGH PRESSURE MEASUREMENTS ON GaAs/AlAs DOUBLE BARRIER

STRUCTURES

Measurements are reported on two n-i-n devices at pressures up to 9Kbar. The intrinsic region of the devices contains a double barrier GaAs/AlAs structure with, nominally, either a 70Å quantum well and 30Å barriers or a 15Å well and 50Å barriers. The 30Å-70Å-30Å double barrier structure shows NDR in both its forward and reverse bias I-V characteristic which have a peak to valley current ratio (A/B) greater than 10 at 4.2K. On applying pressure, the forward bias characteristic of this device exhibits similar behaviour to the p-i-n device discussed in chapter 3, the NDR feature disappearing at just over 8Kbar at 77K. In reverse bias, A/B first increases before falling rapidly above 5Kbar. By 8Kbar, the feature in reverse bias is not completely suppressed. These observations confirm the conclusions of chapter 3 where it was argued that the dominant mechanism of conduction through the multiple barrier GaAs/AlAs structure of the p-i-n device involves electrons tunnelling through X-like barrier states in the two thickest barriers, rather than hole tunnelling. In addition, no scatter in the A/B versus pressure results is observed for this device, in contrast to the results for the p-i-n device. This suggests that the non-resonant leakage current which caused scatter in the results of the p-i-n device, is not present in this case.

For the 50Å-15Å-50Å double barrier structure, no NDR features were at all discernible in the I-V characteristic

at 4.2K, and only a very weak feature could be seen in the first derivative plot ($dI/dV-V$). This indicates that the NDR feature associated with resonant tunnelling depends sensitively on well and barrier dimensions. The device behaved in many respects like a single barrier structure as a function of temperature. From the variation of the current (for a fixed voltage) with temperature, an independent measurement of the barrier height and its variation with pressure were determined. The results suggest that the thermionic emission of electrons over the barriers is controlled by the $\Gamma(\text{GaAs})\text{-X(AlAs)}$ barrier.

Magnetic field measurements ($B \parallel J$) up to 12.6T on the 30-70-30 structure for pressures of 1bar and 5Kbar, reveal magnetoquantum oscillations (Shubnikov-de Haas like) in the tunnelling current. These oscillations are attributed to the Landau level structure of the degenerate two-dimensional electron gas in the accumulation layer of the emitter. The oscillations appear to "strengthen" and "weaken" as the bias across the structure is increased and the oscillations observed at 1bar are "stronger" for a given bias than those observed at 5Kbar. These observations can be explained by considering how the time for ionised impurity scattering in the emitter, the characteristic time for tunnelling through the AlAs barriers, and the time an electron takes to perform a cyclotron orbit, vary with applied bias.

4.1 Experiment

The composition of the two devices and their fabrication are reported in chapter 2. The structures were subsequently measured by TEM to check their layer thicknesses with an

accuracy of $\pm 2\text{\AA}$, (see chapter 2, page 62). The following values were obtained for the nominally $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ and $50\text{\AA}$ - $25\text{\AA}$ - $50\text{\AA}$ structures respectively: $40\text{\AA}$ - $72\text{\AA}$ - $43\text{\AA}$ (thinner barrier adjacent to substrate) and $50\text{\AA}$ - $15\text{\AA}$ - $45\text{\AA}$ (thicker barrier adjacent to substrate). Hereafter, the structures are referred to as the $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ structure and the $50\text{\AA}$ - $15\text{\AA}$ - $50\text{\AA}$ structure.

DC current-voltage characteristics were obtained for two separate n-i-n devices of both the $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ and the $50\text{\AA}$ - $15\text{\AA}$ - $50\text{\AA}$ structures at pressures up to 8.4Kbar and temperatures down to 4.2K. For the $50\text{\AA}$ - $15\text{\AA}$ - $50\text{\AA}$ structure, conductance-voltage (dI/dV -V) characteristics were also obtained since there was no evidence of a NDR feature in the I-V characteristic. The devices were prepared from different parts of each wafer as $200\mu\text{m}$ diameter mesas with Ohmic contacts attached to the top of the mesa and the substrate.

Magnetoquantum oscillations were obtained for the $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ structure using the magnetic field system described in chapter 2. The device was biased at different voltages of its I-V characteristic and oscillations in the current as a function of magnetic field ($B\parallel J$) were observed as the magnetic field was swept up to 12.6T. By numerically differentiating the current signal using a microcomputer, first (dI/dB) and second (d^2I/dB^2) derivatives versus B were obtained. To obtain the fundamental field, B_F , for the SdH oscillations, a Fourier transform of the data was taken using a fast Fourier transform program. These magnetic field measurements were repeated with the device under a pressure of 5Kbar, by attaching the Be-Cu liquid cell to the end of

the insert used for the cryomagnetic field system.

4.2 Results for the 30Å-70Å-30Å Structure

Typical DC I-V characteristics, measured at 4.2K, are shown in Fig.4.1. A certain degree of asymmetry can be observed between the forward bias direction (substrate positive) and the reverse bias direction (substrate negative). A peak to valley current ratio (A/B) of 9.8 is obtained in forward bias and a value of 14.9 is obtained in reverse bias. These values decrease to 6.9 and 8.4 respectively at 77K. This asymmetry is thought to be indicative of the slightly different barrier widths. A larger value in reverse bias of the peak current together with a larger A/B, is consistent with the thinner of the two barriers being adjacent to the emitter contact for this bias (1.19). This is confirmed by the TEM results. An asymmetry could also arise from differences in doping of the n-type layers either side of the double barrier system. This doping has been measured with an electrochemical Polaron plotter and values of $1.4 \times 10^{17} \text{cm}^{-3}$ for the first grown of the two layers, and $1.7 \times 10^{17} \text{cm}^{-3}$ for the other layer were obtained. It is also possible that this difference in doping levels could contribute to the observed asymmetry (1.23).

The I-V characteristics of this device show hysteresis and step-like features in the NDR region which are both an artifact of the measuring circuit. The device is found to oscillate when biased in the NDR region at a frequency of approximately 0.1MHz. To help suppress the oscillations and thus obtain the true I-V characteristic, a smaller diameter mesa was fabricated to increase the device impedance (see

Appendix 1). 40 μ m diameter mesas were processed by N.C.Couch at G.E.C. from the same wafer. However, even with the larger device impedance and, therefore, larger magnitude of negative resistance, the hysteresis and step-like features were not significantly reduced and the device continued to oscillate when biased in the NDR region. This is not altogether surprising since a 10 μ m diameter mesa is required, as discussed below.

Another way of suppressing the oscillations is to place a capacitor, C_p , in parallel with the device via short connecting leads (Appendix 1). This technique was tested using the 40 μ m diameter mesas. Although a variety of capacitors were used, the oscillations and regions of hysteresis were not suppressed. However, the capacitors did remove most of the step-like features to produce a smoother curve, as shown in Fig.4.2a),b) and c). Sketched in Fig.4.2c) is the expected I-V characteristic in the absence of space charge effects (1.19) and current oscillations.

In forward bias at 1bar, a second resonance is observed at 1A and 4.8V, as shown in Fig.4.3. In reverse bias, no second resonance is seen up to 1.4A and 7.2V. The variation with temperature of the peak and valley currents of the first resonance is shown in Fig.4.4. At 300K, the NDR is almost completely suppressed due to the rapid rise of the valley current with increasing temperature.

Fig.4.5 shows the variation of the peak and valley currents with pressure for the first (and second) resonance at 77K. For the first resonance, the peak current (A) increases with pressure while the valley current (B) increases more rapidly

with pressure leading to an overall degradation of A/B, Fig.4.6. The increase of peak and valley currents with pressure can be explained by assuming that the $\Gamma(\text{GaAs})$ - $\text{X}(\text{AlAs})$ barrier controls the tunnelling of electrons. The effect of pressure is to lower this barrier causing an increase in the non-resonant tunnelling component and, therefore, an increase in A and B with pressure and a decrease in A/B with pressure. This is similar to the effect of increasing the temperature which also leads to an increase in non-resonant contributions to the current.

As shown in Fig.4.6, A/B behaves systematically as a function of pressure. In forward bias, the NDR is suppressed by $\sim 8\text{Kbar}$. This behaviour is very similar to that of the p-i-n devices where the thickest barrier is also adjacent to the emitter contact. When the thinner barrier is adjacent to the emitter contact, in reverse bias, the resonance is much stronger and the NDR is not completely suppressed at the maximum pressure applied of 8.5Kbar ($A/B=1.35$). The suppression of NDR with pressure is seen more dramatically in Fig.4.7 where the difference in peak and valley currents, normalised to the 1bar value, is plotted against pressure. A striking similarity is seen between the results for forward bias and the results for the p-i-n device in Fig.3.6, with a more rapid fall at higher pressures and a threshold for complete suppression of $\sim 8\text{Kbar}$. However, for reverse bias the ratio plotted in Fig.4.7 first increases before exhibiting a rapid fall above 5Kbar .

4.3 Discussion

The difficulty found in suppressing the current oscillations

in the NDR region and hence obtaining a smooth I-V characteristic without hysteresis can be explained by considering the device impedance. For the 200 μm diameter mesa, the magnitude of the NDR, $|dV/dI|$, is approximately 10 Ω , and for the 40 μm diameter mesa this increases to approximately 100 Ω . These values are rather small compared to the value of $|dV/dI|$ obtained for the device investigated by Hughes et al. (1.32). Although their device was a 100 μm diameter mesa, it was composed of wide, $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barriers (88 $\text{\AA}$) and a wide GaAs well (56 $\text{\AA}$) giving a device impedance of approximately 600 Ω . They found, by placing a 0.28 μF chip capacitor in parallel with the device via short connecting leads, that a smooth I-V curve was obtained with no hysteresis and no oscillations throughout the NDR region. As Sollner pointed out (1.31), it is difficult to suppress the oscillations when the negative impedance is only approximately 100 Ω . Any series inductance from connecting leads or bond wires often makes it difficult to measure stable negative resistances less than approximately 1K Ω . Therefore, for the 30 $\text{\AA}$ -70 $\text{\AA}$ -30 $\text{\AA}$, GaAs/AlAs structure, the fabrication of a device with a mesa diameter of approximately 10 μm is required to increase the negative resistance to a sufficiently large value. Then current oscillations should be suppressed by a capacitor placed in parallel with the device and a smooth I-V curve obtained.

In the previous chapter it was argued that the dominant conduction mechanism involves electrons tunnelling through X-like states in the two thickest barriers, rather than hole tunnelling. This is confirmed by the similarity in behaviour

between that shown in Fig.3.6 and the forward bias results of Fig.4.7. In addition, since the two sets of samples have very different peak to valley current ratios, the similarity in pressure behaviour of the normalised difference in peak and valley currents would suggest that the pressure effects are intrinsic to the structural parameters of the samples investigated.

Fig.4.7 shows that the resonance in reverse bias is more difficult to suppress than the first resonance in forward bias. The larger value in reverse bias of the peak current together with a larger peak to valley ratio at 1bar, is consistent with the thinner of the two barriers being adjacent to the emitter contact for this bias. The size of the peak to valley current ratio is limited by non-resonant contributions to the current which are inherent to a particular device. For example, the p-i-n device discussed in chapter 3 has a much smaller A/B than the device discussed here in forward bias even though the well and barrier dimensions determining the NDR features are very similar for both devices. This suggests that non-resonant contributions to the tunnelling current which act to degrade A/B, are larger in the p-i-n device than the n-i-n discussed in this chapter. Since non-resonant contributions to the tunnelling current must be very similar for the n-i-n device in forward and reverse bias, it is not surprising that the larger resonance in reverse bias is harder to suppress with pressure than the smaller forward bias resonance.

The n-i-n device shows a smooth variation of the peak to valley current ratio with pressure, Fig.4.6. This indicates

that the device does not contain a non-resonant current component related to conduction through impurity states located in the barrier, in contrast to the p-i-n device. Therefore, this suggests that the presence of the non-resonant component in the p-i-n devices is an extrinsic feature of this device. This is probably a result of the fact that no spacer layer was included between the undoped barrier layers and the doped layers cladding the superlattice.

The second resonance observed in forward bias occurs at approximately 1A and 4.8V at 1bar and 77K. This resonance is suppressed more rapidly with pressure than the first resonance vanishing at approximately 3Kbar, Fig.4.8. Since the second resonance is very sensitive to pressure, this suggests that it is also sensitive to the Γ (GaAs)-X(AlAs) barrier. Therefore, it is possible that this resonance arises from the resonant tunnelling of electrons through X-like states in the AlAs barriers into the second resonant state of the quantum well. However, the second resonant state, assuming that confinement is determined by the Γ barriers (1.6, 1.55), has a larger confinement energy than the first resonant state, by $\sim 200\text{meV}$, and is well above the top of the Γ (GaAs)-X(AlAs) barrier, assuming a Γ -X barrier height of $\sim 0.1\text{eV}$. It would therefore appear that this mechanism is not the most likely origin of the second resonance.

Another possible mechanism by which the resonance occurs is electrons tunnelling through Γ -like states in the barriers into the second resonant state of the well. This could then

explain the decrease of the peak current with increasing pressure (inset of Fig.4.5) which is predicted by Eqn.5.2 for a Γ - Γ tunnelling process, i.e., a decrease in current with pressure is due to the increase in $m^*(\Gamma)$ with pressure. However, the estimated decrease of the normalised peak to valley current difference for this process is only $\sim 2\%/Kbar$. This is somewhat smaller than the observed decrease of $\sim 30\%/Kbar$. However, the situation is rather complicated because the Γ -X barrier is lower in energy than the Γ - Γ barrier and the electron current cannot be explained by simple effective mass theory, Eqn.5.2. Therefore, it would appear that electrons tunnelling through Γ -like states in the barriers into the second quasi-bound state of the quantum well is the most likely origin of the second resonance. However, it should be mentioned that this resonance could be due to resonant electron tunnelling through confined states in the AlAs barriers at the X-point of the Brillouin zone. NDR features attributed to this mechanism have been observed by Mendez et al. (1.57) in a GaAs/ $Al_xGa_{1-x}As$ double barrier structure. This resonant tunnelling mechanism is predicted to occur at high voltages, as observed, but a strong suppression of the NDR is not expected.

In reverse bias, no second resonance is observed up to 1.4A and 7.2V. It seems unlikely that this resonance appears at higher voltages because at such high biases, the energy of the electrons in the emitter will be close to the top of the first Γ - Γ barrier. Therefore, it appears that while this resonance exists in forward bias, it does not exist in reverse bias. Bonnefoi et al. (1.49) have observed this

effect in a 79Å-76.5Å-71Å GaAs/AlAs double barrier structure in which they also observe asymmetry in forward and reverse bias for the first resonance.

4.4 Results for the 50Å-15Å-50Å Structure

Typical I-V and dI/dV-V characteristics at 77K and 1bar are shown for this device in Fig.4.9. As shown, only a very weak NDR feature is discernible in the dI/dV-V curve at 0.83V (forward bias) and 0.96V (reverse bias). Under pressure, this feature still exists up to 8Kbar in the dI/dV-V characteristic at 77K. The device behaved in many respects like a single barrier structure. Fig.4.10 shows the I-V characteristic in forward bias for a series of different pressures at 77K. It can be seen that there is an increase in the current with pressure for a given voltage. At 77K, the thermionic emission of electrons over the barriers is negligible and the measured current is due only to the tunnelling of electrons. In this regime, the change of current with pressure is proportional to (3.8)

$$d(\ln I)/dP \propto -\{ d(\ln m)/dP + d(\ln V_B)/dP \} \dots\dots(4.1)$$

where V_B is the barrier height and m is the effective mass of the electrons. Assuming that the percentage change in $m^*(X)$ with pressure is approximately equal to the percentage change of the Γ_V-X_C energy gap with pressure, i.e., $d(\ln m(X))/dP \sim d(\ln E_G(X))/dP$, then $m^*(X)$ is essentially independent of pressure ($d(\ln E_G(X))/dP \sim -0.03\%$). Therefore, any increase in the tunnelling current must be due to a reduction of the barrier height. This suggests that the tunnelling of the electrons is dominated by the $\Gamma(\text{GaAs})-X(\text{AlAs})$ barrier.

The $\Gamma(\text{GaAs})\text{-X}(\text{AlAs})$ barrier height for thermionic emission can be measured by fitting the temperature dependence of the current density, J , to the standard formula

$$J/T^2 = A^* \cdot \exp(eV_B/k_B T) \dots\dots\dots(4.2)$$

where A^* is the Richardson constant and T represents the temperature. The temperature dependence of the $I\text{-}V$ characteristic for the device was measured from 300K to 4.2K at 1bar and 5Kbar. For a given pressure, the barrier height for thermionic emission is given by the gradient of the I/T^2 versus $1/T$ curve at constant voltage for temperatures between 150K and 300K. In this temperature range, the current is dominated by the thermionic emission of electrons at the barriers and the gradient is, therefore, constant.

The barrier height against bias voltage is plotted in Fig.4.11 for pressures of 1bar and 5Kbar. A pressure change of approximately 1Kbar occurred over the measured temperature range, so the results for 5Kbar, which was the average pressure over this range, are only approximate. Nevertheless, the barrier heights of 0.15eV at 1bar and 0.095eV at 5Kbar are consistent with literature values (1.6,1.12,1.55,3.8). It should be mentioned that the barrier heights at 1bar and 5Kbar obtained from Fig.4.11 are 0.12eV and 0.065eV respectively. 30meV has been added on to these values to take account of the tunnelling current component (1.44). The rapid fall of barrier height with bias is due to electron accumulation and band bending.

One apparent inconsistency is the values of the Richardson constant which were all in the range of $1\text{Am}^{-2}\text{K}^{-2}$. The values are approximately four orders of magnitude smaller than the

formula often used (1.43)

$$A^* = 4\pi em^* k_B^2 / h^3 \quad \dots\dots\dots(4.3)$$

The reason for the large discrepancy is not understood. However, this formula neglects the effect of optical phonon scattering and quantum mechanical reflection and so may not be expected to give precise agreement (1.45). The presence of two barriers in these devices, rather than the usual single barrier arrangement for thermionic emission studies, may also effect the value of the Richardson constant.

4.5 Discussion

The peak to valley current ratio (A/B) is clearly a sensitive function of well and barrier dimensions since measurements on a n-i-n structure, grown consecutively with the 30Å-70Å-30Å structure but with 50Å barriers and a 15Å well, do not show any regions of NDR. Only a very weak feature is revealed in the dI/dV-V characteristic.

The device behaved like a single barrier structure and, from measurements of the current density as a function of temperature, the barrier height is estimated at 1bar and 5Kbar. These values indicate that the $\Gamma(\text{GaAs})$ -X(AlAs) barrier controls the thermionic emission of electrons over the AlAs barriers and has a pressure variation of approximately -11meV/Kbar.

4.6 Magnetic Field Measurements on the 30Å-70Å-30Å Structure

At 1bar, with $B \parallel J$, well resolved magnetoquantum oscillations (Shubnikov-de Haas like), periodic in $1/B$, were observed under constant voltage conditions in forward bias over a limited voltage range of the I-V characteristic,

Fig.4.12. Oscillations are not observed until the device is biased into the NDR region. As the bias is increased, the oscillations appear to "strengthen", i.e., the envelope of the oscillation amplitudes is larger at a given magnetic field, to just beyond the minimum of the I-V curve. As the bias is increased further, the magnetoquantum oscillations weaken and disappear altogether by 1.3V. By repeating the experiment with the device oriented perpendicular to the magnetic field ($\underline{B} \perp \underline{J}$), all the magnetoquantum oscillations vanished. Therefore, the oscillations are two-dimensional in character.

At 5Kbar, magnetoquantum oscillations are not observed until the device is biased at the minimum of the I-V curve. Again, the oscillations appear to strengthen and then weaken on increasing the bias, Fig.4.13. The oscillations disappear altogether by approximately 0.81V. It should be pointed out that the magnetoquantum oscillations observed at 1bar, Fig.4.12a), are plotted on a scale approximately 2.8 times less sensitive than the oscillations observed at 5Kbar.

Magnetoquantum oscillations can be compared directly for a given voltage at 1bar and 5Kbar. This is because the voltage at which the resonant tunnelling feature occurs is essentially pressure independent. This is consistent with the theory that the Γ_C - Γ_C barrier determines the confinement energy of the resonant state associated with this feature (see chapter 1, page 33). Therefore, from Figs.4.12 and 4.13, it can be seen that the oscillations at 1bar are stronger than the oscillations at 5Kbar for a given voltage. Moreover, the magnetoquantum oscillations observed at 5Kbar

weaken and disappear at lower biases than at 1bar. The origin and the behaviour of the oscillations with increasing bias, will now be considered.

The most likely origin of the oscillations is from the Landau level structure of the degenerate two-dimensional electron gas (2DEG) in the accumulation section of the buffer layer (see chapter 1, page 27). This can be justified if the magnetoquantum oscillations observed by Payling et al. (1.37,1.38) in a double barrier GaAs/Al_{0.33}Ga_{0.67}As structure are considered. They attribute a series of oscillations which also commence as the structure is biased into the NDR region of the I-V curve, to the Landau level structure of the 2DEG in the accumulation layer. The fundamental field, $B_F = N_D h / 2e$, of this series increases gradually with bias. This series of oscillations observed by Payling et al. and the oscillations observed for the structure discussed in this chapter, commence at relatively large voltages and are not observed at lower voltages. This is because the lowest sub-band in the accumulation layer is not resolved until high voltages are attained. Since the oscillations are two-dimensional in character, their only other likely origin is from oscillations associated with the resonant tunnelling of electrons into the first sub-band of the quantum well as observed by Payling et al. (1.37) and Goldman et al. (1.36). However, these oscillations are observed around the peak voltage in the I-V curve and so this possibility can probably be ruled out for the magnetoquantum oscillations discussed here.

The oscillations strengthen with bias up to 0.91V at 1bar

and from 0.44V to 0.55V at 5Kbar, Figs.4.12 and 4.13. A larger envelope of the oscillation amplitudes, implies a longer scattering time, τ_I , for the electrons. This is because the electrons can perform more cyclotron orbits before making a collision and the Landau levels are, therefore, sharper since collisions will tend to broaden them ($\omega_C \tau_I > 1$, where $\omega_C = eB/m^*$ is the cyclotron frequency, for well defined Landau levels). This is reflected by a larger amplitude of the oscillations since changes in the resistance of the sample will be larger as the magnetic field is swept and the Fermi level passes through the Landau level structure.

An increase of τ_I , the electron scattering time in the accumulation layer, with bias can be explained by considering the Fermi level in the emitter and assuming that ionised impurity scattering is the dominant mechanism broadening the Landau levels at 4.2K. As the bias increases, the Fermi level, E_F , increases because of the formation of the accumulation layer. This is reflected by the fundamental field, $B_F = N_2 D h / 2e$, increasing as the bias is increased, as indicated in Figs.4.12 and 4.13. Since $V_F \propto E_F^{1/2}$, where V_F is the Fermi velocity, the Fermi velocity also increases with bias. For ionised impurities, the cross section for scattering, $\sigma_I \propto 1/V_F^4$. Thus, as the bias increases, σ_I decreases and the scattering time of the electrons in the emitter, τ_I , increases. The strengthening of the magnetoquantum oscillations as the bias is increased can then be related to the decrease in ionised impurity scattering caused by an increase in the Fermi energy of the electrons in the accumulation layer, as indicated by an

increase in N_{2D} with bias. It should be mentioned that the fundamental fields, and hence carrier concentrations, evaluated for the magnetoquantum oscillations at the highest biases (1.1V at 1bar and 0.81V at 5Kbar) do not show a continuing increase with bias as expected from the increasing value of E_F . This is probably because the oscillations at these biases are rather weak and there is a correspondingly large error in the value of B_F evaluated. This can be seen in the increase in the width of the Fourier transform. A continuing increase in B_F with increasing bias is within the error range of B_F evaluated for these biases.

At higher biases, the magnetoquantum oscillations weaken and eventually disappear altogether. This can be explained by considering the transmission of the barriers as the bias is increased. Under increasing bias, the barriers tilt down and become essentially lower in energy. Thus, their transmission coefficients increase. To obtain magnetoquantum oscillations, the condition $\omega_C \tau_I > 1$, where $\omega_C = eB/m^*$ is the cyclotron frequency, must be met since the separation of the Landau level must be greater than the energy broadening of the levels. The time an electron takes to make one cyclotron orbit is $\tau_C = 2\pi/\omega_C = 2\pi m^*/eB$. If this time is greater than the time it takes an electron to tunnel through the barriers to the collector over the whole magnetic field range, then the magnetoquantum oscillations will not be observed. The time an electron takes to tunnel through one of the AlAs barriers can be estimated from the expression used by Luryi (1.20). By considering the tunnel resistance, R , and capacitance, C , of a barrier, he obtains the expression

$$\tau_T \equiv RC = \epsilon \lambda / \alpha c \cdot \exp(4\pi d / \lambda) \quad \dots\dots(4.4)$$

where ϵ is the dielectric permittivity of the barrier material, $1/\alpha \approx 137$, c is the speed of light, d is the barrier width and $\lambda = h/\sqrt{(2mV_B)}$. Assuming a parallel wavevector conserving tunnelling process such that $m^*/m_e \sim 1.9$ and the barrier height, $V_B \sim 0.1\text{eV}$, and taking $\epsilon \sim 10$, gives $\tau_T \sim 0.4\text{ps}$. From Eq.4.4 it can be seen that as the bias increases, τ_T will decrease.

The decrease in tunnelling time with increasing bias appears to influence the magnetoquantum oscillations at high biases, $>0.91\text{V}$ at 1bar and $>0.55\text{V}$ at 5Kbar. Consider the oscillations observed at 1bar and a bias of 0.91V . These oscillations, and those observed at lower biases at 1bar, commence at approximately the same magnetic field, 3.2T . This value of magnetic field is assumed to correspond to the case of an electron completing one cyclotron orbit, i.e., $\omega_C \tau \sim 1$. Using this value of magnetic field, τ_C is estimated to be $\sim 0.6\text{ps}$. The magnetoquantum oscillations observed at 1bar and 1.1V commence at a higher magnetic field, $\sim 4.2\text{T}$. This increase in magnetic field for the onset of the magnetoquantum oscillations is thought to be due to τ_T , the characteristic time for tunnelling, decreasing with increased bias such that τ_C , the time taken for an electron to perform one cyclotron orbit, must decrease until it is comparable to τ_T . In this model, the oscillations will weaken on increasing the bias, as observed. This is because, with increasing bias, the electrons perform a smaller number of cyclotron orbits for a given magnetic field, before tunnelling through the barriers. It is clear that τ_T , $\sim 0.4\text{ps}$, is comparable to τ_C , $\sim 0.6\text{ps}$ and so it is possible

that this process is the cause of the magnetoquantum oscillations weakening with increased bias. The disappearance of the oscillations altogether indicates that τ_T has decreased to a value smaller than the minimum value of τ_C attainable.

The decrease of τ_T and, hence increase of τ_C , with increasing bias can also explain the weakening of the magnetoquantum oscillations observed at 5Kbar above 0.55V. The onset of the oscillation at 0.55V (and 0.44V) occurs at $\sim 4T$. At 0.67V, the oscillations have weakened and this value increases to $\sim 5T$. By 0.81V, the oscillations are almost completely suppressed and this value has increased again to $\sim 9T$. The proposed model can explain why the magnetoquantum oscillations observed at 5Kbar are weaker and are completely suppressed at lower biases than at 1bar. At 5Kbar, the barrier height is approximately 55meV lower in energy than at 1bar, assuming a decrease in barrier height of 11meV/Kbar (see section 4.5), and so the barriers have a higher transmission coefficient for a given bias. Therefore, for a given bias voltage, τ_T will be much smaller at 5Kbar than 1bar. This implies that the magnetic field at which the electrons are capable of performing one cyclotron orbit is shifted to higher fields, as observed. Thus, the oscillations will disappear at a lower bias. In addition, for any given magnetic field value, the electrons perform a smaller number of orbits than at 1bar which will weaken the oscillations.

In summary, the magnetoquantum oscillations in the tunnelling current observed for this structure are

attributed to the Landau level structure of the 2DEG in the accumulation layer of the emitter. The apparent "strengthening" and "weakening" of the magnetoquantum oscillations with increasing bias at 1bar and 5Kbar, is thought to be a compromise between a decrease in impurity scattering as the bias increases which will tend to strengthen the oscillations, and a decrease in tunnelling time through the barriers as the bias increases which will tend to weaken the magnetoquantum oscillations. The oscillations seen at 5Kbar are weaker and disappear at lower applied biases than at 1bar. This is thought to be a result of the transmission of the barriers increasing with pressure, due to a reduction of the barrier height. This implies that the characteristic time for electrons to tunnel through the device will be shorter. Therefore, the electrons will preferentially tunnel through the barriers than perform the cyclotron orbits necessary for the occurrence of magnetoquantum oscillations.

4.7 Conclusions

A n-i-n device with similar dimensions to those which determine the NDR feature in the p-i-n device discussed in the previous chapter, has been investigated as a function of pressure. Although the two devices have very different peak to valley current ratios, their normalised peak to valley current difference exhibits very similar behaviour as a function of pressure. This suggests that the observed variation of NDR with pressure is an intrinsic property of a 30Å-70Å-30Å GaAs/AlAs structure and depends on the bandstructures of the well and barrier materials.

The variation of the NDR with pressure for the 30Å-70Å-30Å structure confirms the conclusions of chapter 3. In this chapter it was argued that, for a 30Å-70Å-30Å GaAs double barrier structure, the current is dominated by electrons tunnelling through X-like barrier states. On a simple level, the pressure threshold of 8Kbar for loss of NDR appears consistent with the low Γ (GaAs)-X(AlAs) barrier height of 0.15eV and the pressure variation of approximately -11meV/Kbar. This estimate of the Γ (GaAs)-X(AlAs) barrier height and its pressure variation have been measured directly from the thermionic emission of electrons over the barrier of the 50Å-15Å-50Å structure.

For the 30Å-70Å-30Å structure, a second resonance is observed in forward bias only. This resonance is suppressed by 3Kbar at 77K. It is thought that the most likely origin of this resonance is from electrons tunnelling through Γ -like states in the barriers into the second quasi-bound state of the quantum well.

No NDR is observed for the n-i-n structure with 50Å barriers and a 15Å well. This suggests that NDR is a sensitive function of well and barrier dimensions. Indeed, assuming that the confinement of the resonant states is determined by the Γ barriers, then the confinement energy of the first resonant state for this structure is predicted to be larger than the Γ -X barrier, assuming a Γ -X barrier of approximately 0.15eV. This may explain why the resonance is so weak.

On a more detailed level, a complete understanding of the

variation of NDR with pressure, and with well and barrier dimensions awaits further theoretical analysis. In addition, further investigations are required to test the hypothesis that thicker AlAs barriers are expected to exhibit transmission of more X-like character than thinner AlAs barriers.

Magnetic field measurements on the 30Å-70Å-30Å structure at pressures of 1bar and 5Kbar with $\underline{B} \parallel \underline{J}$, reveal magnetoquantum oscillations in the tunnelling current. These oscillations occur over a limited voltage range of the I-V characteristic and are thought to be due to the Landau level structure of the 2DEG in the accumulation layer of the emitter. By considering the scattering time for ionised impurity scattering, τ_I , the characteristic time for tunnelling through the AlAs barriers, τ_T , and the time an electron takes to complete a cyclotron orbit, τ_C , the apparent "strengthening" and "weakening" of the magnetoquantum oscillations can be accounted for as the bias applied to the structure is increased. In addition, by taking the same considerations into account, the "weakening" of the magnetoquantum oscillations with increasing pressure for a fixed applied bias can be explained.

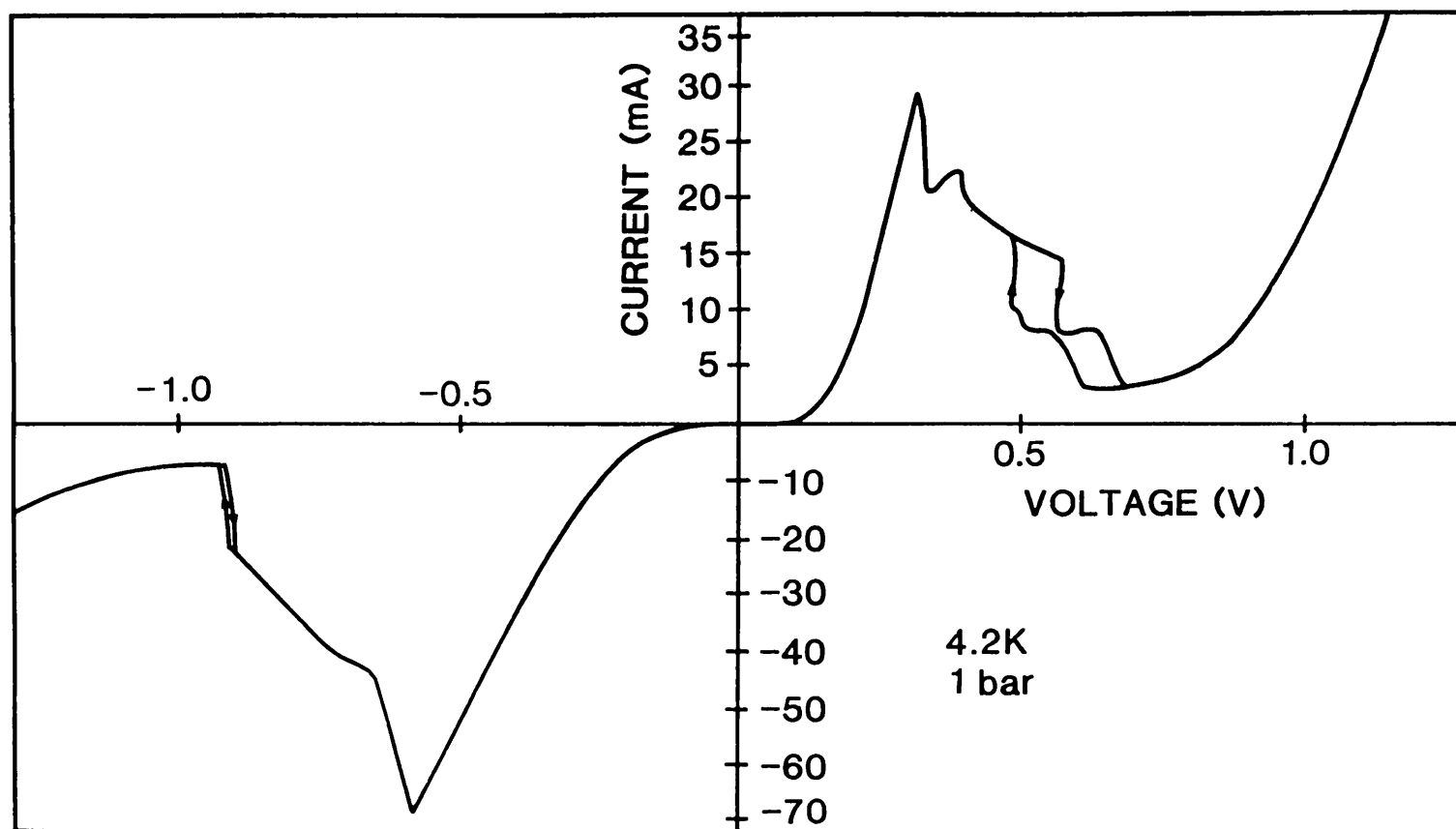


Fig.4.1 4.2K, I-V characteristic for the first resonance of the 30Å-70Å-30Å double barrier structure in forward bias (substrate positive) and reverse bias (substrate negative).

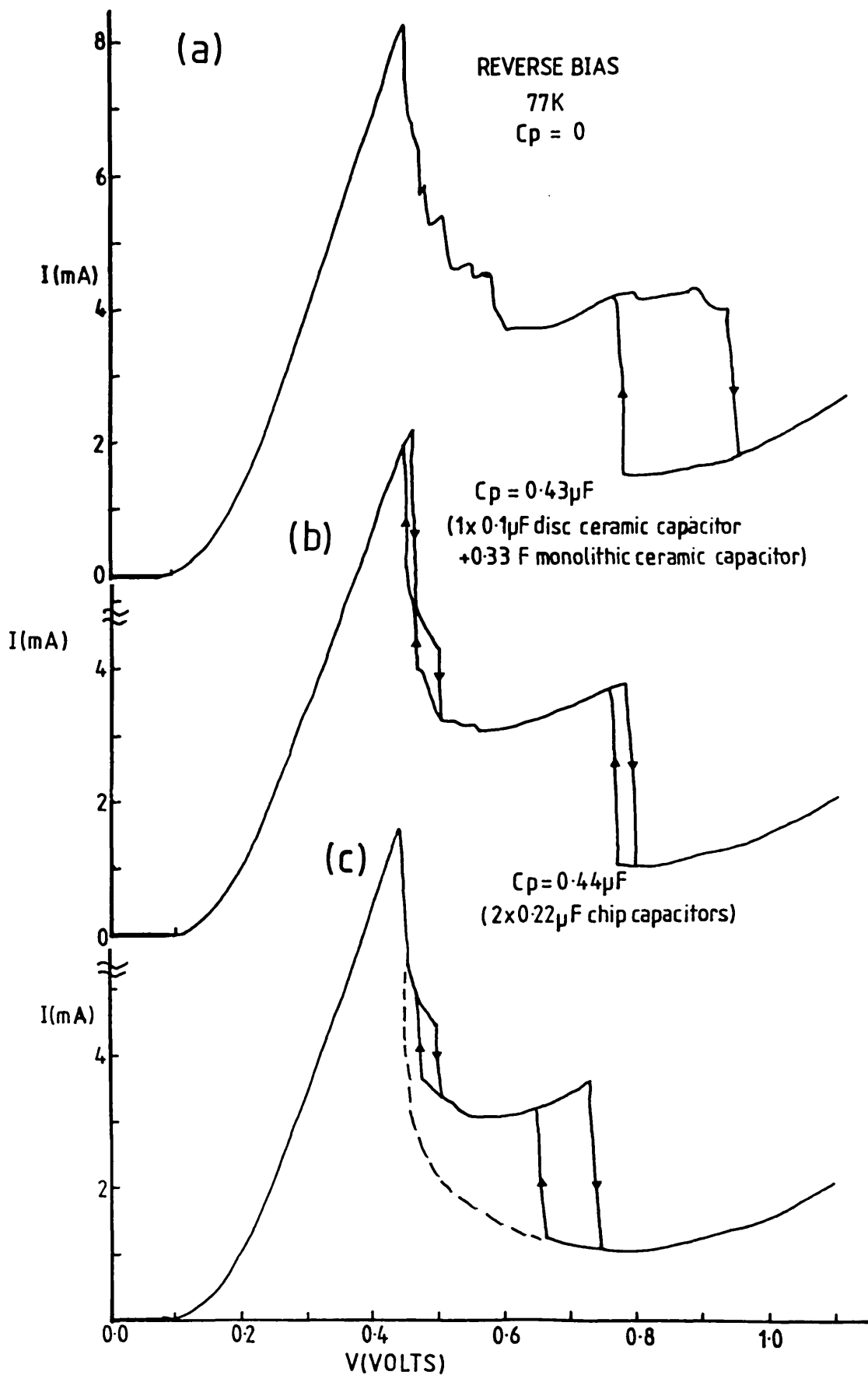


Fig.4.2 Reverse bias, I-V characteristic of 30Å-70Å-30Å structure at 77K with (a) $C_p=0$, (b) $C_p=0.43 \mu\text{F}$ and (c) $C_p=0.44 \mu\text{F}$. Shown in Fig.4.2c) is the expected I-V characteristic in the absence of space charge effects and current oscillations.

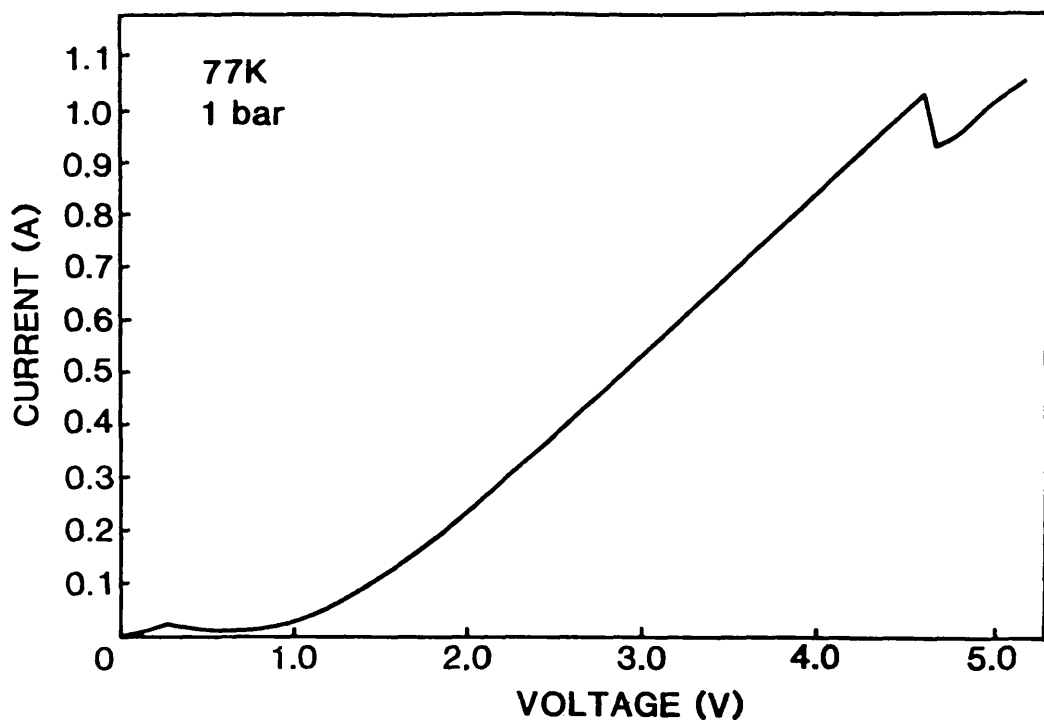


Fig.4.3 77K, forward bias I-V characteristic of 30Å-70Å-30Å structure showing both the first and second resonance.

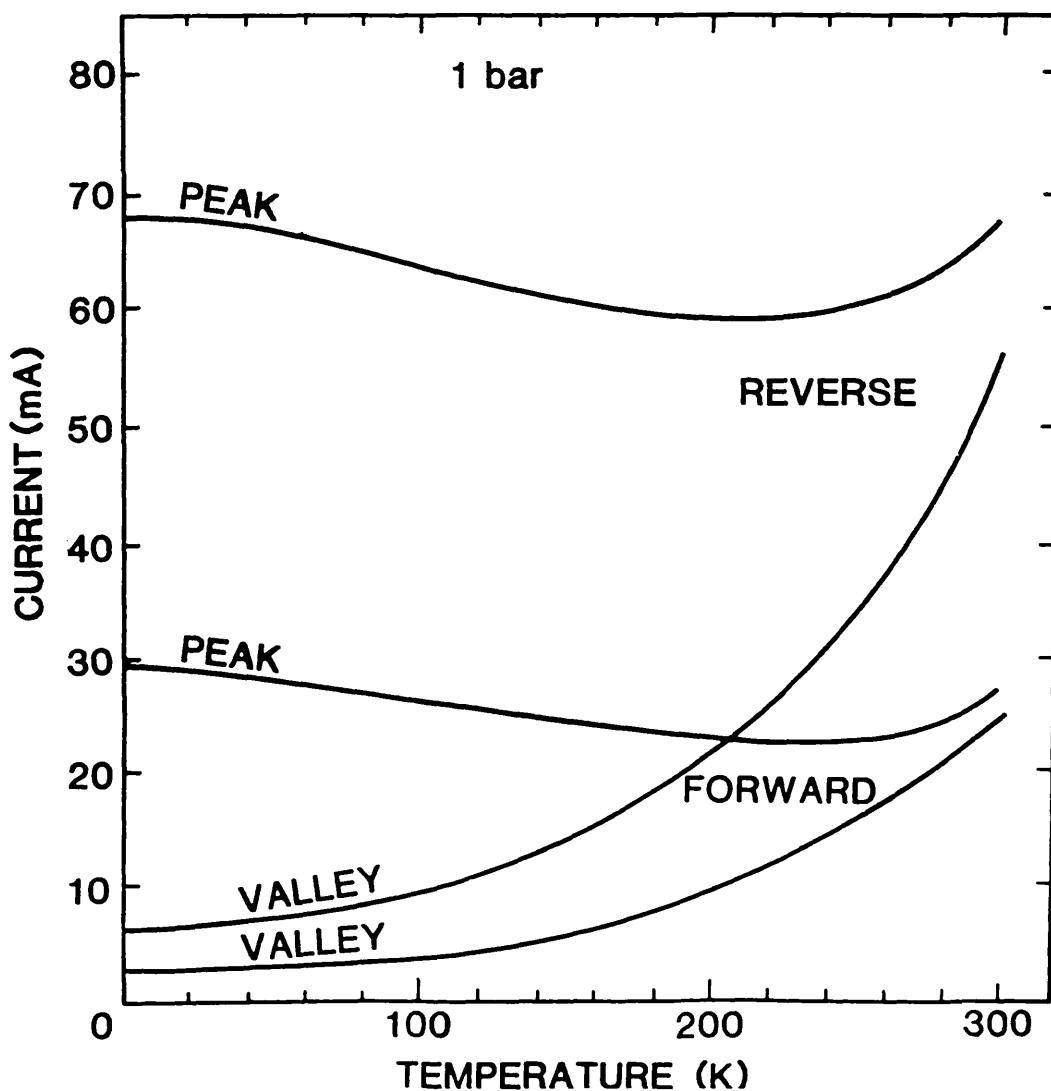


Fig.4.4 The peak, A, and valley, B, currents of the first resonance for the 30Å-70Å-30Å structure in forward and reverse biases, as a function of temperature.

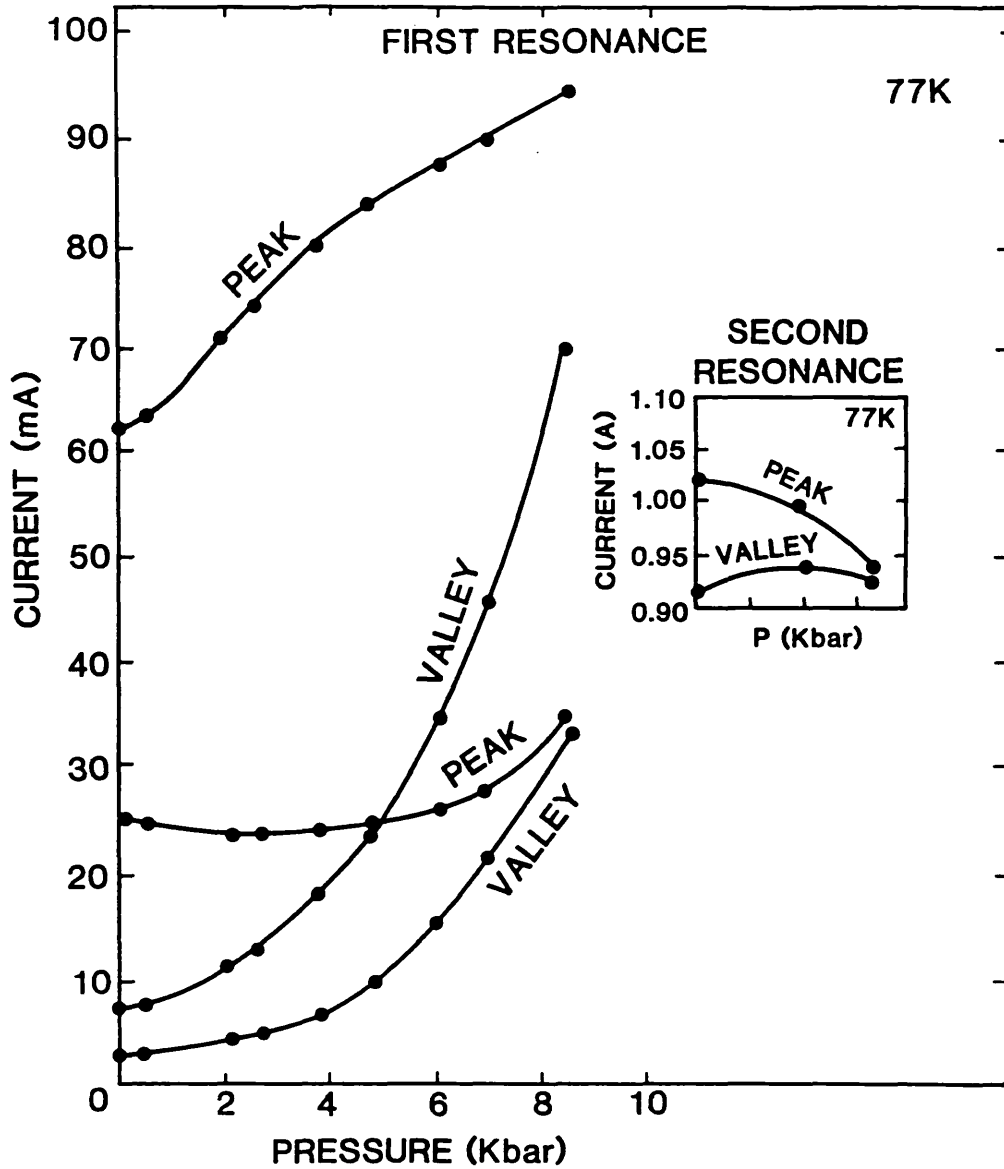


Fig.4.5 The peak, A, and valley, B, currents of the first resonance for the 30Å-70Å-30Å structure in forward and reverse biases, and for the second resonance in forward bias (inset: 0-4Kbar), at 77K, as a function of pressure.

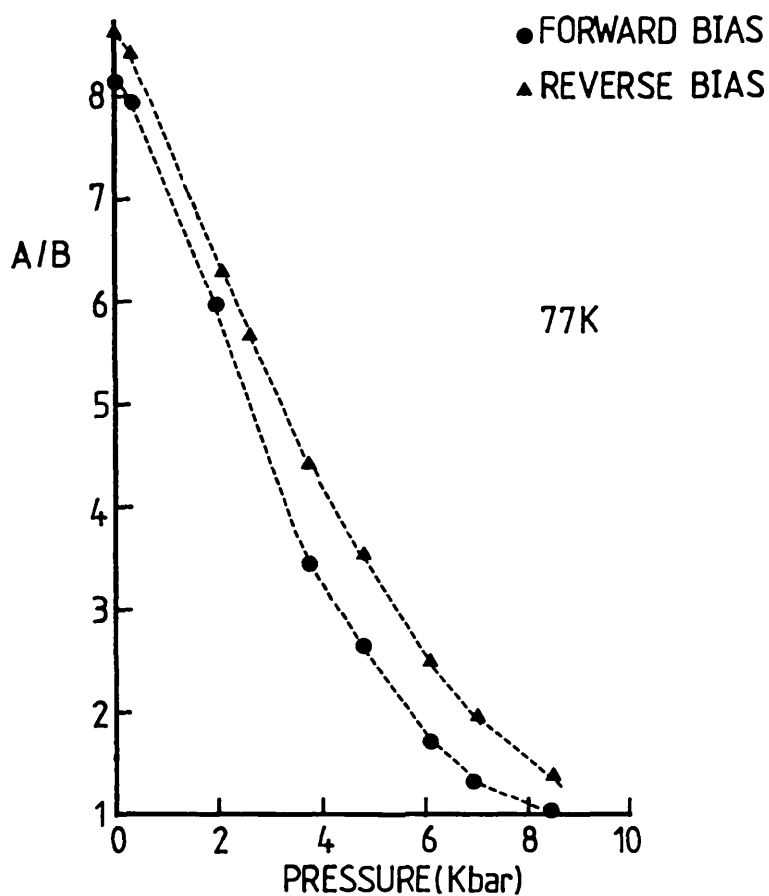


Fig.4.6 Pressure dependence at 77K, of the peak to valley current ratio, A/B , in forward and reverse bias for the first resonance of the $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ structure.

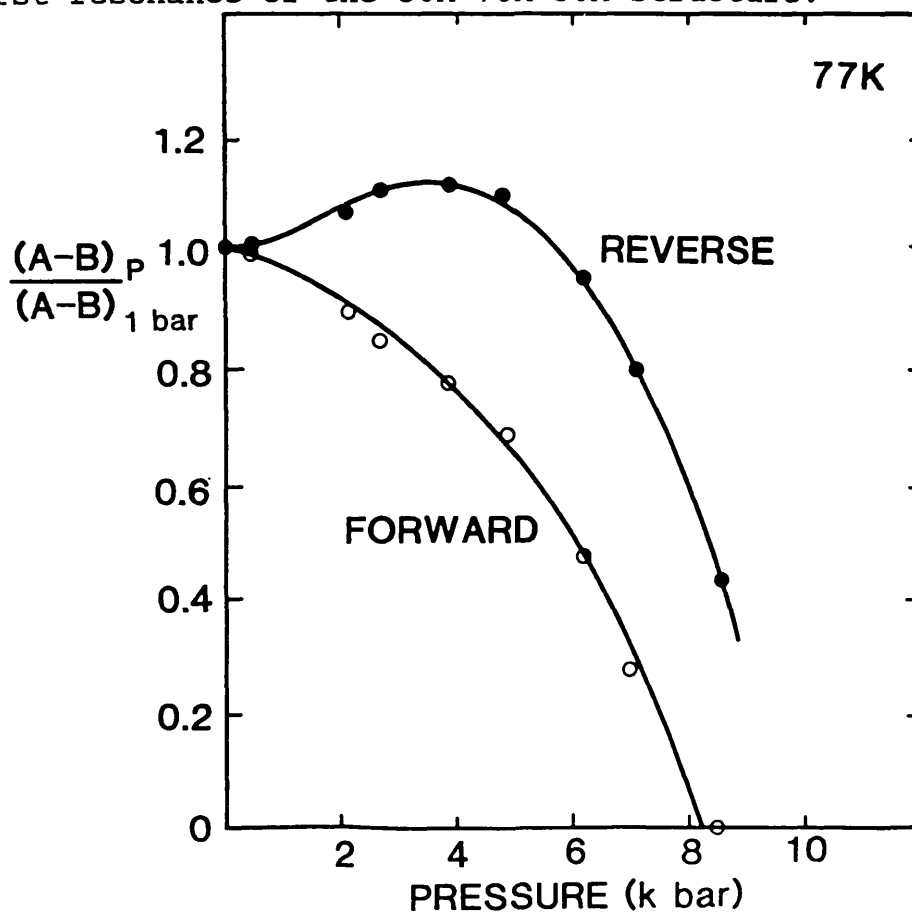


Fig.4.7 Pressure dependence at 77K, of the peak to valley current difference for the first resonance of the $30\text{\AA}$ - $70\text{\AA}$ - $30\text{\AA}$ structure in forward and reverse biases.

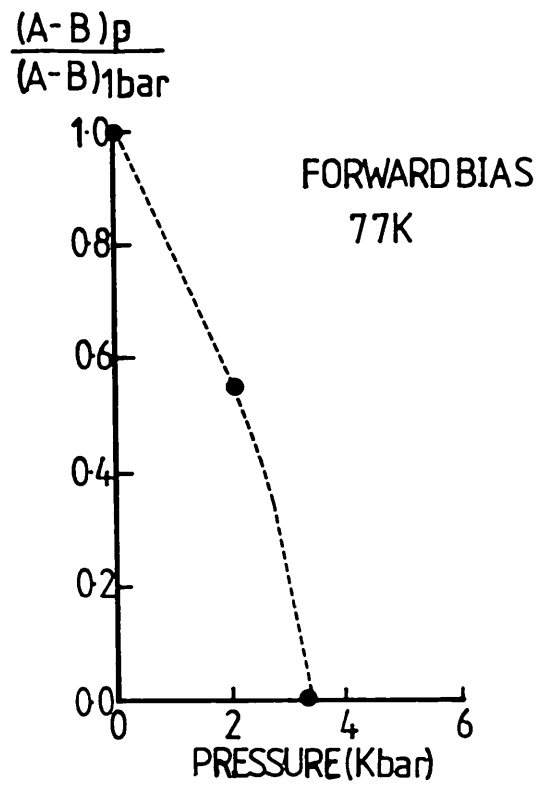


Fig.4.8 Pressure dependence at 77K, of the peak to valley current difference for the second resonance of the 30Å-70Å-30Å structure in forward bias.

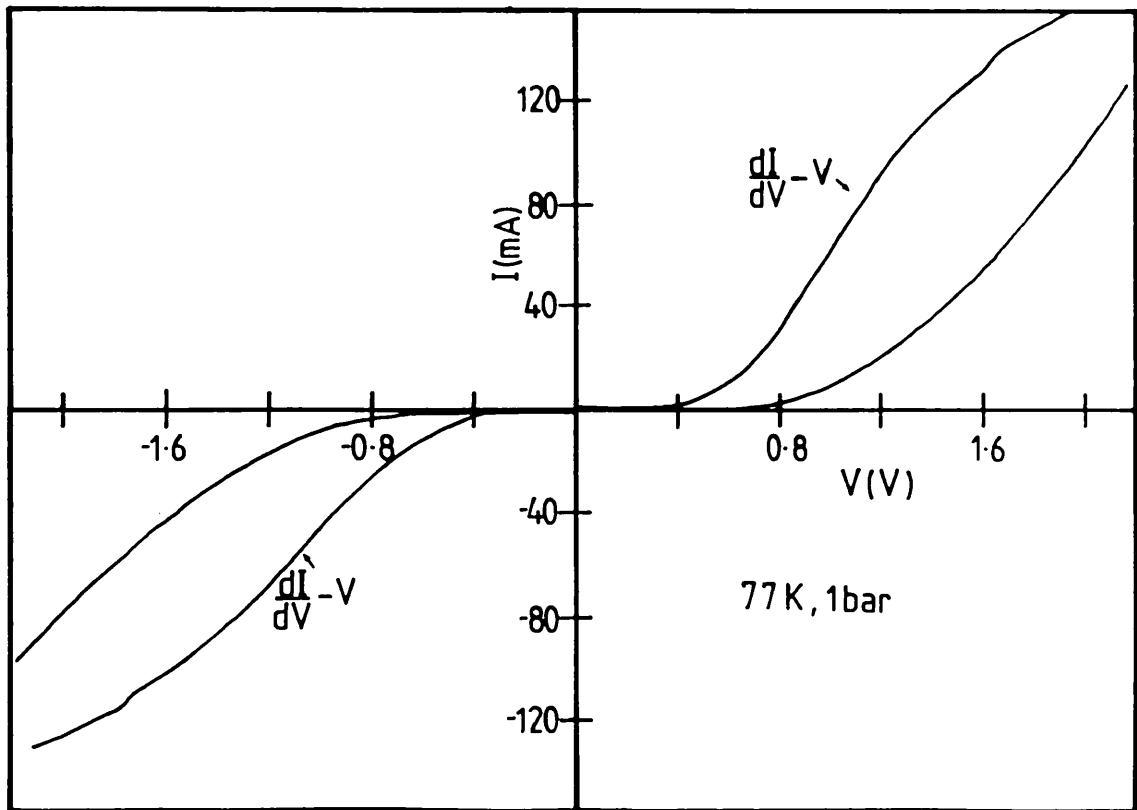


Fig.4.9 I-V and dI/dV characteristic at 77K for the 50Å-15Å-50Å structure.

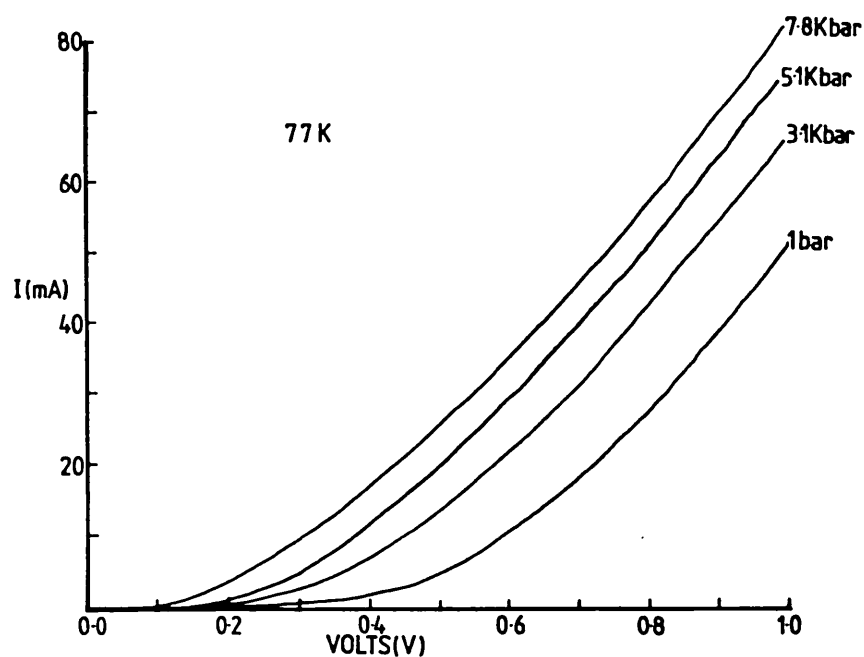


Fig.4.10 Forward bias I-V characteristic of the 50A-15A-50A structure at 77K for a series of pressures.

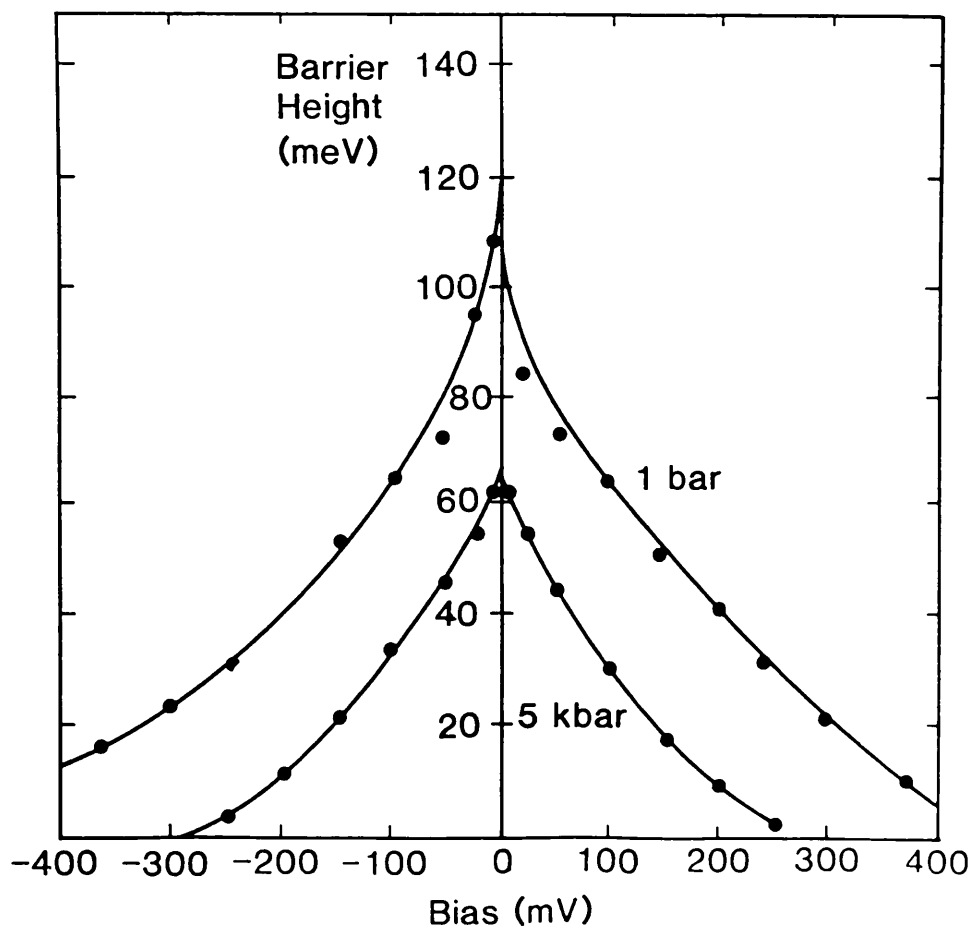
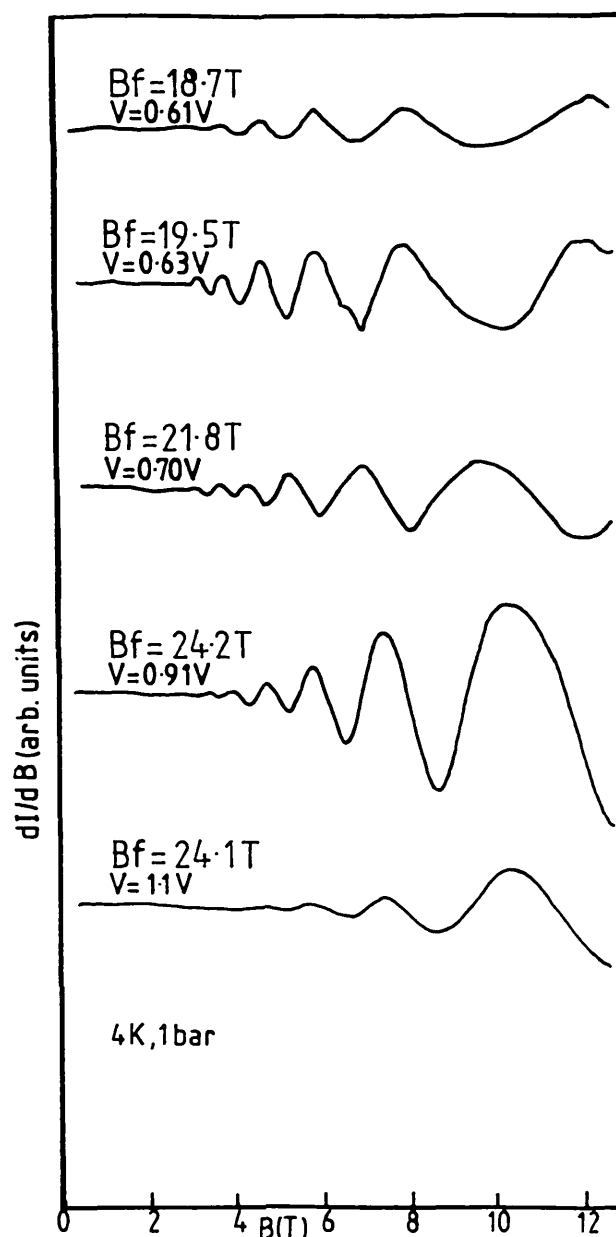


Fig.4.11 Barrier height, determined from thermionic emission measurements, of the 50A-15A-50A structure as a function of bias and pressure.

(a)



(b)

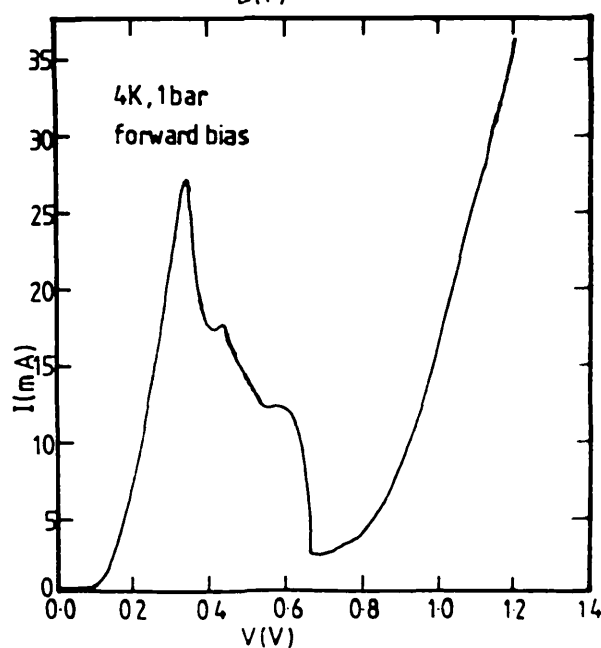
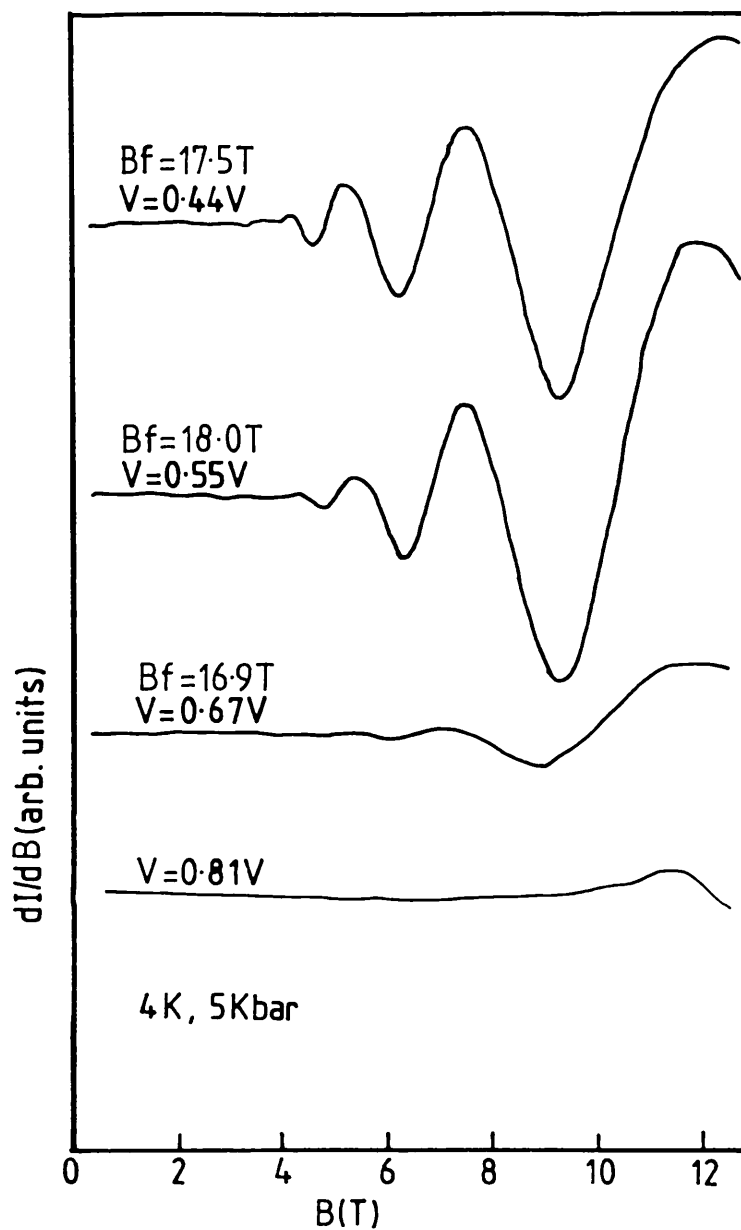


Fig.4.12 (a) The first derivative of $I(B)$ at 4.2K and 1bar showing the Shubnikov- de Haas oscillations at various parts of the $I(V)$ curve, (b).

(a)



(b)

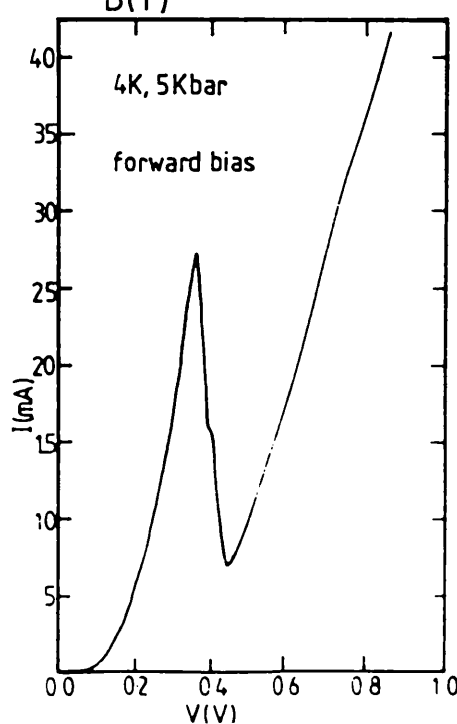


Fig.4.13 (a) The first derivative of $I(B)$ at 4.2K and 5Kbar showing the Shubnikov- de Haas oscillations at various parts of the $I(V)$ curve, (b). 130

CHAPTER 5

ADDITIONAL HIGH PRESSURE STUDIES OF RESONANT TUNNELLING IN MULTIPLE BARRIER GaAs/Al_xGa_{1-x}As STRUCTURES

PART A: A Double Barrier GaAs/Al_{0.33}Ga_{0.67}As Structure

High pressure measurements are reported at pressures up to 12Kbar on a n-i-n device in which the i-region consists of a double barrier GaAs/Al_{0.33}Ga_{0.67}As structure. The device was grown by MBE and consists of a 68Å GaAs well and two 85Å Al_{0.33}Ga_{0.67}As barriers.

The device shows NDR in both its forward and reverse bias characteristic, the size of which increases as the temperature decreases. At 4.2K and 1bar, the peak to valley ratio (A/B) is approximately 10 in forward and reverse bias. On applying pressure, the size of the NDR decreases slowly up to 10Kbar and more rapidly at higher pressures. The observation of the weak pressure dependence below 10Kbar is taken as evidence for the dominant role of the $\Gamma(\text{GaAs})$ - $\Gamma(\text{Al}_{0.33}\text{Ga}_{0.67}\text{As})$ potential barrier in the electron tunnelling process. Above 10Kbar, the stronger suppression of NDR with pressure suggests that the tunnelling process is no longer dominated by Γ -like electron states in the barrier but has a significant contribution from X-like and (or) L-like electron states.

At high bias, a second resonance is observed in reverse and forward bias with $A/B \sim 1.3$ at 77K and 1bar, and a third resonance is observed in forward bias with $A/B \sim 1.2$. The origin of the second resonance is from electrons tunnelling into the second quasi-bound electron state in the well. The

origin of the third resonance, only observed in forward bias, is rather ambiguous. It could be due to electrons tunnelling into the third quasi-bound state of the well, or is possibly an artifact of the sample fabrication process which causes a repeat of the second resonance. Both of these resonances are strongly suppressed at pressures above ~ 8.5 Kbar.

5.1 Experimental

The structure investigated was grown by MBE on a n^+ (100) GaAs substrate. A $0.75\mu\text{m}$ thick buffer layer of GaAs n-doped to 10^{17}cm^{-3} with Si was grown first. This was followed by a $0.5\mu\text{m}$ buffer layer of GaAs n-doped with Si to 10^{17}cm^{-3} grown at a temperature 40°C higher than the first layer. The sequence of growth was then the first $85\text{\AA}$ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barrier, the $68\text{\AA}$ GaAs well, followed by the second $85\text{\AA}$ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barrier. Finally a top contact layer of $0.5\mu\text{m}$ of 10^{17}cm^{-3} Si doped GaAs was grown. Devices were prepared from different parts of the same wafer as $400\mu\text{m}$ diameter mesas with Ohmic contacts attached to the top of the mesa and the substrate. The devices were then mounted into standard microwave packages.

DC current-voltage characteristics were obtained for two separate devices at pressures up to 11.5 Kbar using the gas cell system and the "Cambridge" cell described in chapter 2. I-V characteristics were also obtained as a function of temperature down to 4.2 K at 1 bar.

5.2 Results

Typical DC I-V characteristics are shown in Fig. 5.1 at 77 K and 1 bar for the first resonance. A/B is observed to be 7.5

in the forward bias direction (substrate positive) and 8.5 in the reverse bias direction (substrate negative). The peak occurs at approximately the same current in reverse and forward bias, but the voltage at which NDR occurs is approximately twice as large in reverse bias as in forward bias. In addition, the voltage at resonance in forward bias is much larger than that predicted by theory, Eq.1.10. The large asymmetry in voltage and large additional voltage drop in forward bias, is thought to be due to an accumulation of impurities at the interface of the substrate and the first, buffer layer. This produces a p-type layer. A similar device grown subsequently but including a Si doped spike between the substrate and the first buffer layer, showed a highly symmetric I-V characteristic and resonance occurring at approximately the predicted voltage.

The I-V characteristic, Fig.5.1, shows that there is a sharp, almost vertical fall in current after the peak as the device is biased into the region of NDR. The NDR occurs over a narrow voltage range, approximately 40mV, indicating that the magnitude of the negative resistance is small. Indeed, the negative resistance is only approximately 10Ω . This is probably due to the large mesa diameter of $(400\mu\text{m})^2$. The device was found to oscillate in the NDR region at a frequency of 0.1-1MHz which is determined by the external circuit parameters and the magnitude of the negative resistance. To suppress the oscillations, a smaller diameter mesa is required to increase the device impedance (Appendix 1).

A large region of hysteresis is found in the I-V

characteristic between sweeping up in voltage and down in voltage, Fig.5.1. Similar hysteresis has been observed many times before, particularly for large diameter mesas and mesas with poor Ohmic contacts, and is distinctly different from the hysteresis observed for the devices discussed in chapter 4 which occurred over a limited voltage range within the NDR region. However, this type of hysteresis has been seen in the devices discussed in chapter 4 with a series resistance ($\sim 20\Omega$) included in the measuring circuit. A problem arises when deciding which ramping direction (sweeping voltage up or down) gives the true peak and valley currents when this type of hysteresis is present. By comparing the I-V characteristics of the device of chapter 4 with and without a series resistance, it is clear that sweeping up in voltage gives the true peak current and sweeping down in voltage gives the true valley current. This is confirmed by the fact that for the device discussed here and the device of chapter 4, these currents are constant on consecutive ramps but the valley current on sweeping up in voltage and the peak current on sweeping down in voltage, vary on consecutive ramps. Therefore, the origins of this hysteresis are completely different from that discussed in chapter 4. It is thought to be due to the series resistance of the Ohmic contacts which causes additional voltage drops when the current is high. The series resistance also affects the bias positions of the peak and valley currents. This may explain why the NDR is seen to occur over a very narrow voltage range. Therefore, the magnitude of the negative resistance may be larger than the value estimated from the I-V characteristic.

At higher bias, a second resonance can be observed at 148mA and 2.96V in forward bias and at 4.2V and 145mA in reverse bias, Fig.5.2. In addition, a third resonance is observed in forward bias at 3.5V and 190mA for temperatures below 100K. This resonance is not seen up to 5V and 200mA in reverse bias.

The variation with temperature of the peak and valley currents of the first resonance are shown in Fig.5.3. The NDR is completely suppressed by 240K due to the rapid rise of the valley current with increasing temperature. The second resonance is completely suppressed by 140K and the third resonance by 100K. This behaviour presumably reflects the increase of non-resonant, thermionic components to the tunnelling current as the bias increases and the electron energy in the emitter approaches the top of the potential barrier. Therefore, it is expected that resonances occurring at higher voltages will be suppressed more rapidly with increasing temperature than the resonance occurring at lower voltages.

In Fig.5.4 the variation of the peak and valley currents with pressure are plotted for the first resonance. Below 10Kbar, the valley current is essentially constant as a function of pressure while the peak current decreases resulting in an overall slow decrease of A/B. Above 10Kbar, the valley current begins to increase and the peak current begins to decrease more rapidly leading to a more rapid decrease of A/B. Typical I-V characteristics at 77K are shown in Fig.5.5 for pressures of 1bar and 10.5Kbar. In

forward bias, the peak to valley current ratio (A/B) decreases from 7.5 at 1bar to 5.7 at 10.5Kbar. The rapid suppression of NDR with pressure above 10Kbar is seen more dramatically when the normalised peak to valley current difference is plotted, Fig.5.6. The size of the NDR decreases slowly up to 10Kbar but is then suppressed rapidly at higher pressures.

Fig.5.7 plots the normalised difference between the peak and valley currents for the second resonance. The size of the NDR decreases slowly up to 8.5Kbar but then is suppressed rapidly at pressures above 8.5Kbar. For this resonance, the behaviour of the peak and valley currents under pressure is similar, as shown in Fig.5.8. Below ~ 8.5 Kbar, they both decrease at approximately the same rate followed by a sharp drop in current and then an increase in current. The third resonance exhibits very similar pressure behaviour to that of the second resonance. Again, the size of the NDR decreases slowly up to ~ 8.5 Kbar followed by a rapid suppression above this pressure.

It has been assumed that the third resonance is due to electrons tunnelling into the third quasi-bound state of the quantum well. However, I-V measurements performed by A.Higgs at RSRE on devices fabricated from the same wafer, do not reveal a third resonance in forward bias. The devices investigated by A.Higgs were defined from the wafer by mesa etching, whereas, the devices discussed here were cleaved from the wafer. Therefore, it is possible that the third resonance, observed in the devices investigated in this chapter, is a result of sample damage during the fabrication

process. Since it exhibits very similar behaviour to the second resonance under pressure, the third resonance could be a repetition of the second resonance. Nevertheless, the mechanism by which the repetition occurs is not understood and the possibility of the third resonance being a genuine feature is not ruled out.

5.3 Discussion

The high pressure measurements show that in a double barrier GaAs/Al_xGa_{1-x}As structure with x=0.33, the NDR is much less sensitive to pressures below 10Kbar than a structure with AlAs barriers. This is a consequence of the much larger $\Gamma(\text{GaAs})-\text{X}(\text{AlAs})$ potential barrier in these samples. Consider Fig.5.9 where the relative positions of the valence band maximum Γ_V and the conduction band minima Γ_C , X_C and L_C are drawn for GaAs and Al_{0.33}Ga_{0.67}As in the 60:40 model. The bandgaps are all obtained from the review by Adachi (1.46) and are due to Casey and Panish (3.10). It can be seen from Fig.5.9 that the following band offsets are obtained:

$$\Gamma_C(\text{GaAs})-\Gamma_C(\text{Al}_{0.33}\text{Ga}_{0.67}\text{As})=0.247\text{eV}, \quad \Gamma_C(\text{GaAs})-X_C(\text{Al}_{0.33}\text{Ga}_{0.67}\text{As})=0.368\text{eV}$$

$$\text{and } \Gamma_C(\text{GaAs})-L_C(\text{Al}_{0.33}\text{Ga}_{0.67}\text{As})=0.331\text{eV}.$$

Since $\Gamma_C-\Gamma_C$ is the minimum potential barrier and $m^*(\Gamma)$ is the lightest, electron tunnelling is expected to proceed almost exclusively through the $\Gamma(\text{GaAs})-\Gamma(\text{Al}_{0.33}\text{Ga}_{0.67}\text{As})$ barrier at 1bar. X and L contributions to the tunnelling may become more important for thin barriers since X- and L- like states in the barrier have a larger decay constant than Γ -like states. For the structure discussed here, quite wide barriers are employed (85Å) so it is most likely that the tunnelling current is dominated by the Γ minimum at 1bar.

Using the data of Adachi (1.46) and assuming a pressure independent band offset for the Γ band edges, there are negligible pressure shifts to the Γ_C - Γ_C and Γ_V - Γ_V barriers, a pressure shift of $\sim -11\text{meV/Kbar}$ for the Γ_C - X_C barrier and a pressure shift of $\sim -8.5\text{meV/Kbar}$ for the Γ_C - L_C barrier. Therefore, for $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barriers, the Γ_C - X_C barrier becomes the minimum potential barrier at $\sim 11\text{Kbar}$ and the Γ_C - L_C barrier becomes the minimum potential barrier at $\sim 10\text{Kbar}$. Below 10Kbar , it is expected that Γ_C -like electron states in the barrier will continue to dominate the tunnelling current. Since this barrier is almost independent of pressure, it is also expected that the size of the NDR will not change substantially. Above 10Kbar , it is possible that a substantial amount of current may now tunnel through L_C - and X_C - like electron states in the barrier. If this is the case, it will manifest itself by the size of NDR exhibiting a pressure dependence. The size of the NDR should then decrease as the potential barrier decreases and the non-resonant, thermionic contributions to the current increase.

The model described above appears to be consistent with the observation of a more rapid suppression of NDR above $\sim 10\text{Kbar}$ for the first resonance, Fig.5.6. The second and third resonances show a rapid suppression of NDR above $\sim 8\text{-}9\text{Kbar}$, Figs.5.7 and 5.8. However, it is not clear as to which tunnelling mechanism is dominant at high pressures in this structure. The rapid suppression of NDR for pressures above 10Kbar indicates that a pressure sensitive barrier is involved. Therefore, the possible mechanisms are; (i) a Γ_C - X_C barrier with a heavy effective mass in a parallel

wavevector conserving process, (ii) a Γ_C - X_C barrier with a light effective mass, $m^*(X) \sim 3m^*(\Gamma)$, in a parallel wavevector non-conserving process and (iii) a Γ_C - L_C barrier with a light effective mass, $m^*(L) \sim m^*(\Gamma)$, in a parallel wavevector non-conserving process. It is possible that there are comparable L and X contributions to the tunnelling current at high pressures. A precise theoretical model which takes into account the Γ , X and L minima is required to discover the relative contributions to the tunnelling current for this structure at pressures greater than 10Kbar.

Mendez et al. (3.8) have performed high pressure measurements on a similar device. Their device comprised a double barrier GaAs/ $Al_xGa_{1-x}As$ structure with 100Å barriers and a 40Å well and $x=0.4$. With this x composition, the Γ_C - X_C barrier becomes the minimum potential barrier at ~ 4.5 Kbar and the Γ_C - L_C barrier always lies higher in energy than the Γ_C - X_C barrier but is lower than the Γ_C - Γ_C barrier at ~ 5 Kbar. However, at 1bar, the Γ , X and L conduction band minima in the barrier are quite close in energy. Mendez et al. find that NDR is observed at 1bar but the size of the NDR begins to decrease rapidly above ~ 4 Kbar and is completely suppressed by 10.8Kbar at 77K. The increase in pressure sensitivity of the NDR feature above 4Kbar is well explained when the relative positions of the conduction band minima in the barrier are considered. The rapid suppression of NDR with pressure is attributed by Mendez to the dominant role of X-like electron states in the barrier on the tunnelling current for pressures greater than ~ 4 Kbar.

For the structure investigated, the peak current of the

first resonance is found to decrease as a function of pressure while the valley current decreases slightly, for pressures less than 8.5Kbar. However, the rate of change of current with pressure, $d(\ln I)/dP$, is the same for both peak and valley currents, $\sim -0.017/\text{Kbar}$. At 77K (negligible thermionic current), the change of current with pressure is proportional to

$$d(\ln I)/dP \propto -\{ d(\ln m)/dP + d(\ln V_B)/dP \} \dots\dots\dots(5.1)$$

Since pressure slightly decreases the barrier height, V_B , below 8.5Kbar, any decrease in current is due to an increase in the effective mass. Indeed, for the second and third resonance, the peak and valley currents also decrease at approximately the same rate of $0.017/\text{Kbar}$. The value of $d(\ln I)/dP$ can be estimated from the following equation (1.51) derived from effective mass theory,

$$\beta = -d(\ln I)/dP = \alpha f(V)/2 \{ d(\ln m)/dP + d(\ln V_B)/dP \} \dots\dots\dots(5.2)$$

where $\alpha = 2b(2m^*V_B/h^2)^{\frac{1}{2}}$, b is the total barrier width and $f(V)$ describes the effect that an increasing electric field in the barrier has in increasing the tunnelling transmission probability. It is assumed that $f(V) \sim 1$. This is because, in the sequential tunnelling model, the first barrier is expected to dominate the overall tunnelling probability since it has a much smaller transmission coefficient than the second barrier under bias. An increasing electric field in the barriers is expected to have a larger influence on the transmission probability of the second barrier. Therefore, to first order, it is assumed that the transmission of the first barrier is not greatly increased as the bias is increased. Taking the values used in

reference (1.51) of $d(\ln I)/dP=7.4 \times 10^{-3}/\text{Kbar}$ and $d(\ln V_B)/dP=-1.1 \times 10^{-3}/\text{Kbar}$, gives $\beta = 0.014/\text{Kbar}$. This is in reasonable agreement with the observed value of $0.017/\text{Kbar}$. The departure of the data from the linear dependence of $\ln I$ on pressure above $\sim 8.5\text{Kbar}$, is taken as evidence for the increasing role of X- and L-like electron states in the barrier on the tunnelling current. Then the effective mass theory of tunnelling breaks down and tunnelling can no longer be explained in terms of a wavefunction described by a single effective mass.

Above 8.5Kbar , the peak and valley currents of the second and third resonances begin to increase with pressure. This reflects a decrease of barrier height with pressure indicating that electrons are beginning to tunnel through X- and/or L-like states in the barrier above 8.5Kbar . Higher pressures than 11Kbar are required to observe the expected increase of peak current with pressure for the first resonance although the valley current is found to increase sharply at 11Kbar . Mendez et al. observe an increase of peak and valley current with pressure over the whole pressure range employed. This suggests that for their structure, the decrease of the Γ_C-L_C and Γ_C-X_C potential barriers with pressure is influencing the tunnelling current even when these barriers are not below the $\Gamma_C-\Gamma_C$ barrier at low pressures.

The second and third resonances are almost completely suppressed by 11Kbar . Extrapolating from Fig.5.7 indicates a pressure threshold for complete suppression of NDR of $\sim 12.5\text{Kbar}$ for these resonances. Extrapolating from Fig.5.6

indicates that the first resonance will be completely suppressed by ~ 14.5 Kbar at 77K. These estimates are at pressures rather lower than expected. At 10 Kbar, the Γ -L and Γ -X barrier heights are quite large, ~ 0.25 eV, and the first and second resonances are ~ 200 meV and ~ 50 meV below the top of the minimum barrier, respectively. At 14.5 Kbar, the Γ -X barrier is predicted to be ~ 0.2 eV and the Γ -L barrier ~ 0.21 eV, and so the first resonant state is still well below the top of the barriers. At this pressure, the second resonant state is approximately at the energy position of the top of the Γ -X barrier and ~ 0.1 eV below the Γ -L barrier. For the GaAs/AlAs systems discussed in chapters 3 and 4, the pressure threshold for complete loss of NDR appears to be consistent with the complete suppression of the Γ -X barrier, i.e., when the quasi-bound state in the well associated with the resonance is coincident with the top of the Γ -X barrier. Therefore, it is somewhat surprising that the first resonance for this structure appears to be suppressed so rapidly above 10 Kbar with an extrapolated pressure value for complete suppression of ~ 14.5 Kbar. For the second resonance, it is expected, using the above criterion, that the resonance will be suppressed by ~ 15 Kbar, which is above the extrapolated value of ~ 12.5 Kbar. It should also be mentioned that the results of Mendez et al. (3.8), discussed above, also show that the complete suppression of the NDR occurs at pressures well below the pressure at which the Γ -X barrier for their sample is completely suppressed.

As pointed out earlier, there is a difference in pressure

sensitivity between the first and second resonance. This may be related to the larger confinement energy of the second (E_2) resonant state compared to the first one (E_1), $E_2 - E_1 \sim 0.15\text{eV}$. This implies a difference in pressure threshold for loss of NDR of $\sim 12\text{Kbar}$ for a Γ -X barrier and a difference in pressure threshold of $\sim 16\text{Kbar}$ for a Γ -L barrier. This is somewhat larger than the estimated difference of $\sim 2\text{Kbar}$ (see above).

Although the pressures at which the NDR features begin to be more easily suppressed are consistent with a pressure dependent barrier becoming the lowest in energy, the subsequent rapid suppression of NDR is not expected. In addition, the estimate of the difference in pressure threshold for complete loss of NDR between the first and second resonances is not explained well by the differences in confinement energy of the resonant states. However, measurements at higher pressures are required to confirm that the first resonance is suppressed by approximately 14.5Kbar and the second resonance by $\sim 12.5\text{Kbar}$.

Another explanation for the observed pressure variation above 10Kbar must also be mentioned. This is a reduction with pressure of the electron concentration in the emitter contact. Maude et al. (3.11) have observed a reduction with pressure of the electron density in the emitter contact of a single barrier structure for pressures above 10Kbar and an emitter doping of $\sim 10^{18}\text{cm}^{-3}$. This reduction is due to a deep level, associated with the X minimum, crossing the Fermi level of the emitter electrons above some pressure threshold. For the structure discussed in this chapter, the

doping of the emitter is much lower ($\sim 10^{17} \text{cm}^{-3}$). Also, a decrease in the Fermi level with increasing pressure would cause the peak and valley currents to decrease. This is in conflict with the observed behaviour above 10Kbar. For the second resonance, the peak and valley currents increase with pressure above 8Kbar and the valley current of the first resonance increases with pressure above 10Kbar.

5.4 Conclusions

Negative differential resistance and its variation with pressure have been observed in two samples of a double barrier structure embedded in the i-region of a n-i-n device. The barriers are composed of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with $x=0.33$. This low aluminium concentration means that the $\Gamma_C-\Gamma_C$ potential barrier is the lowest up to 10Kbar, in contrast to the devices discussed in chapters 3 and 4. Above $\sim 10\text{Kbar}$, the $\Gamma_C-\Gamma_C$ barrier is no longer the minimum potential barrier.

The observed variation of NDR with pressure for the first resonance indicates that X-like or L-like electron states in the barriers, or both, are strongly involved in the tunnelling process above 10Kbar. This is consistent with the X and L minima in the barrier becoming lower in energy than the Γ minimum. To estimate the relative contributions of X-like and L-like electron states to the tunnelling current at high pressures, a full band structure calculation is required.

The pressure behaviour of the second resonance indicates that X-like and (or) L-like states in the barrier become

important at lower pressures, ~ 8.5 Kbar. This is probably because the quasi-bound state associated with the second resonance has a larger confinement energy than the first resonance and is therefore closer in energy to X and L states in the barrier. However, considering the difference in confinement energies, the observed difference in pressure sensitivity between the first and second resonances is not quantitatively well explained.

The estimated pressure thresholds for complete loss of NDR for the first and second resonance, are not consistent with the pressure thresholds at which the Γ -X or Γ -L barriers are completely suppressed. Additional experiments at pressures greater than 12 Kbar are required as the reason for this discrepancy is not, at present, understood.

By comparing the experimentally determined value of $d(\ln I)/dP$ at the peak and valley currents with the theoretically determined value, it is clear that effective mass theory accurately describes the tunnelling current for pressures below ~ 8.5 Kbar. This confirms that, at low pressures (< 8.5 Kbar), Γ -like electron states in the barriers dominate the tunnelling current. At higher pressures, the currents are no longer accurately described by effective mass theory. This confirms that X- and (or) L-like contributions to the tunnelling current are dominant at pressures greater than ~ 8.5 Kbar for this structure.

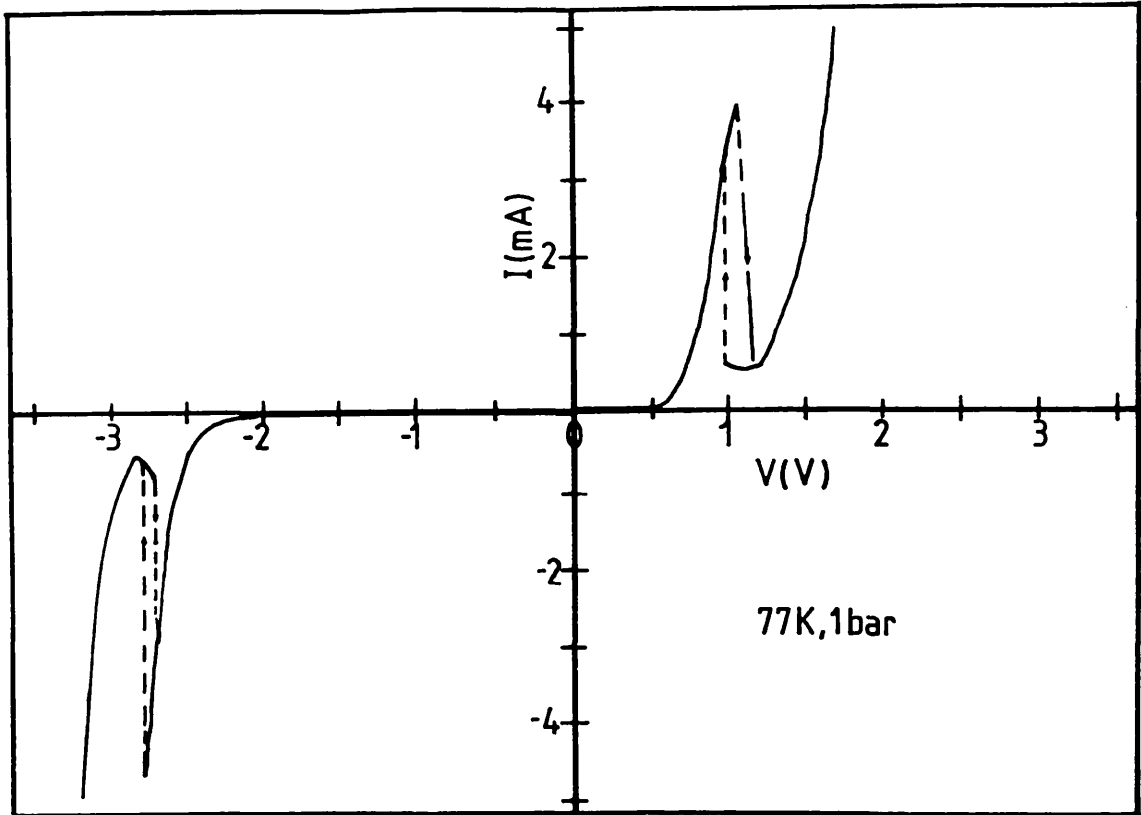


Fig.5.1 I-V characteristic at 77K and 1bar showing the first resonance for the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure in reverse and forward bias.

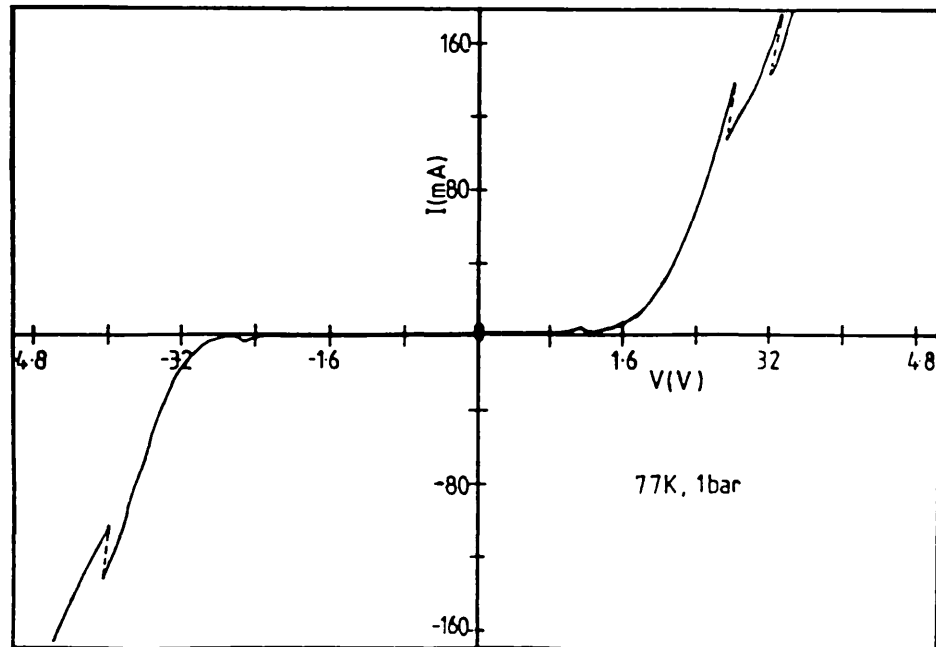


Fig.5.2 I-V characteristic at 77K and 1bar showing the first, second and third resonances for the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure in reverse and forward bias.

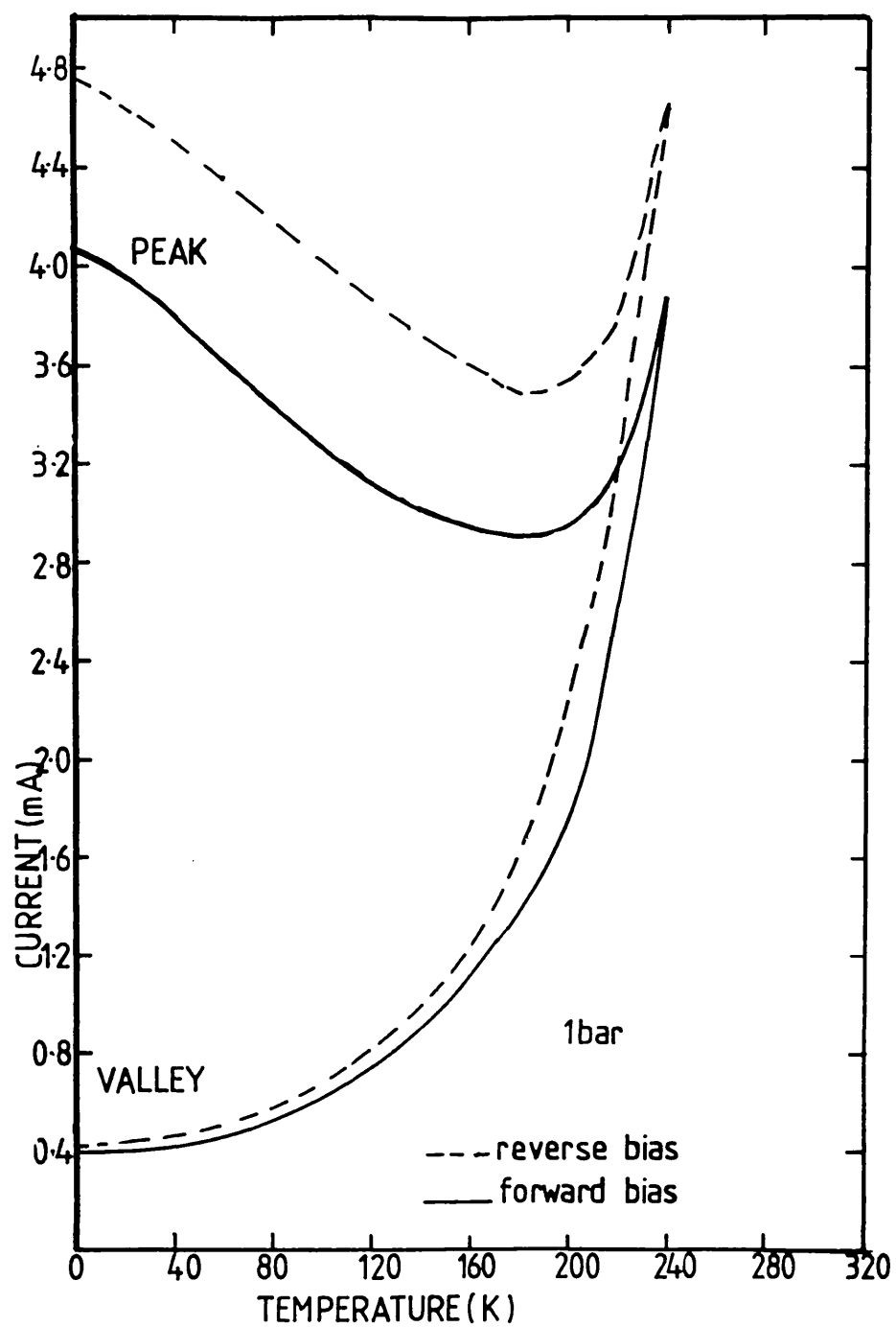


Fig.5.3 The variation with temperature of the peak and valley currents in forward and reverse bias for the first resonance of the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure.

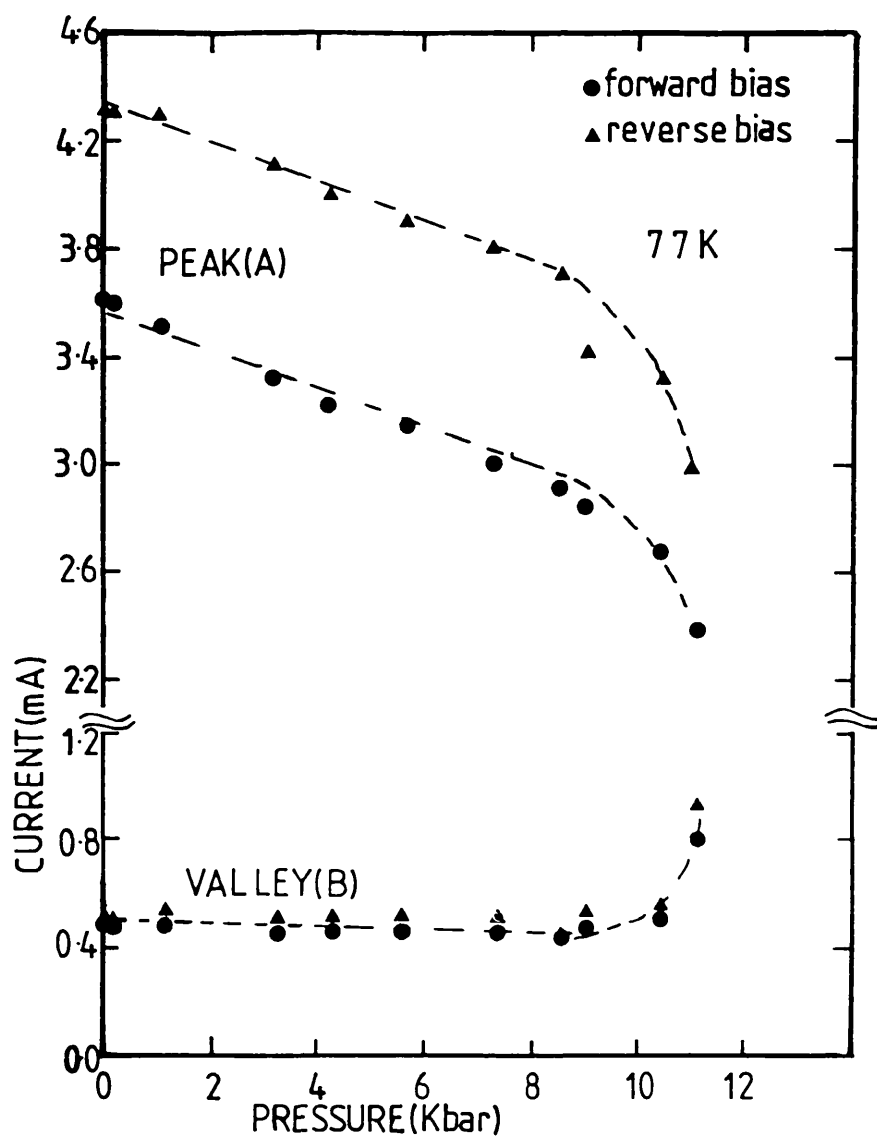


Fig.5.4 The variation with pressure of the peak and valley currents in forward bias and reverse bias for the first resonance of the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure at 77K.

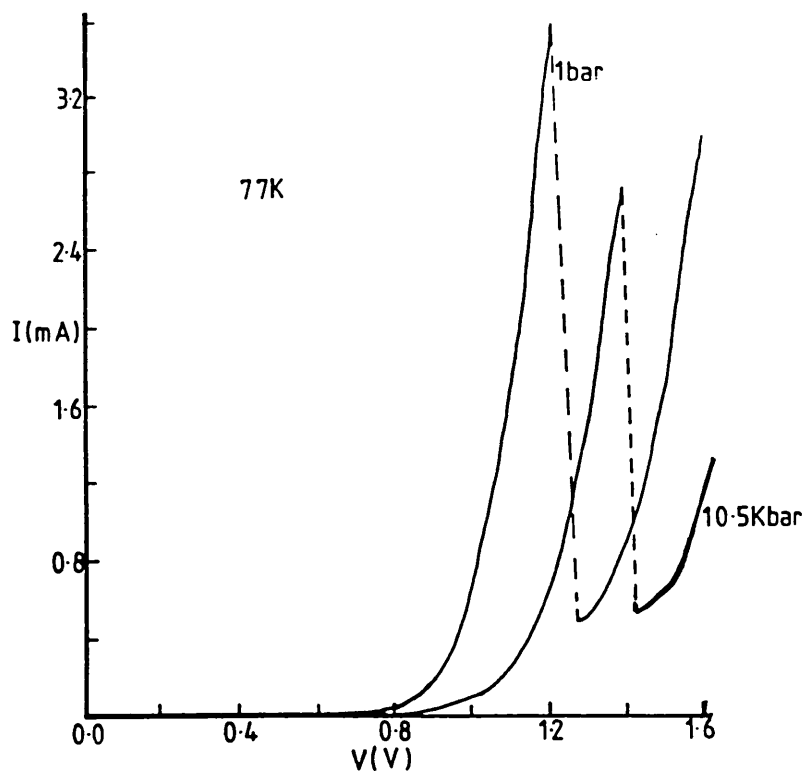


Fig.5.5 Typical forward bias I-V characteristics at 77K showing the first resonance at 1bar and 10.5Kbar for the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure.

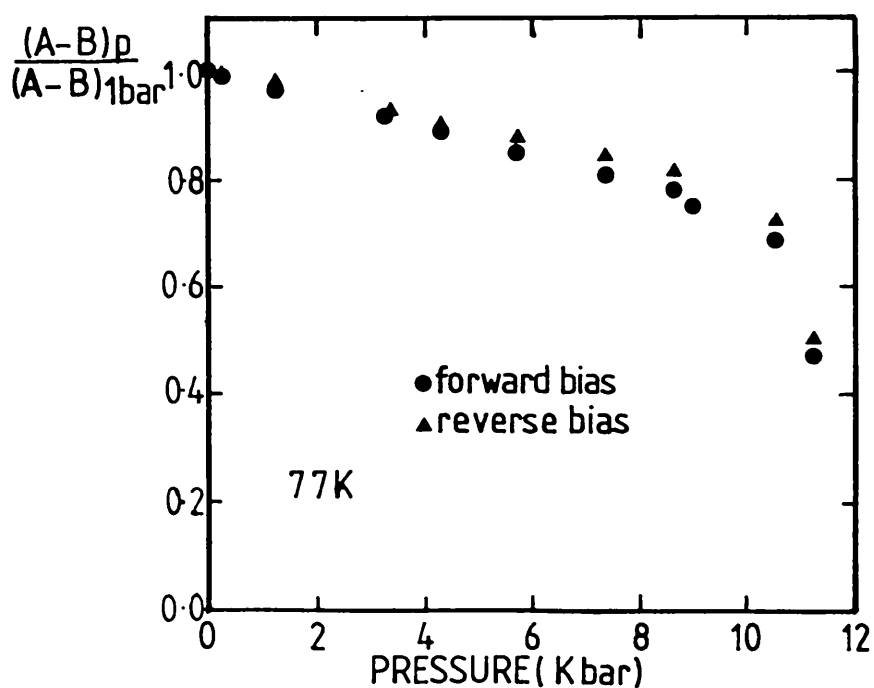


Fig.5.6 Peak to valley current difference as a function of pressure at 77K for the first resonance of the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure.

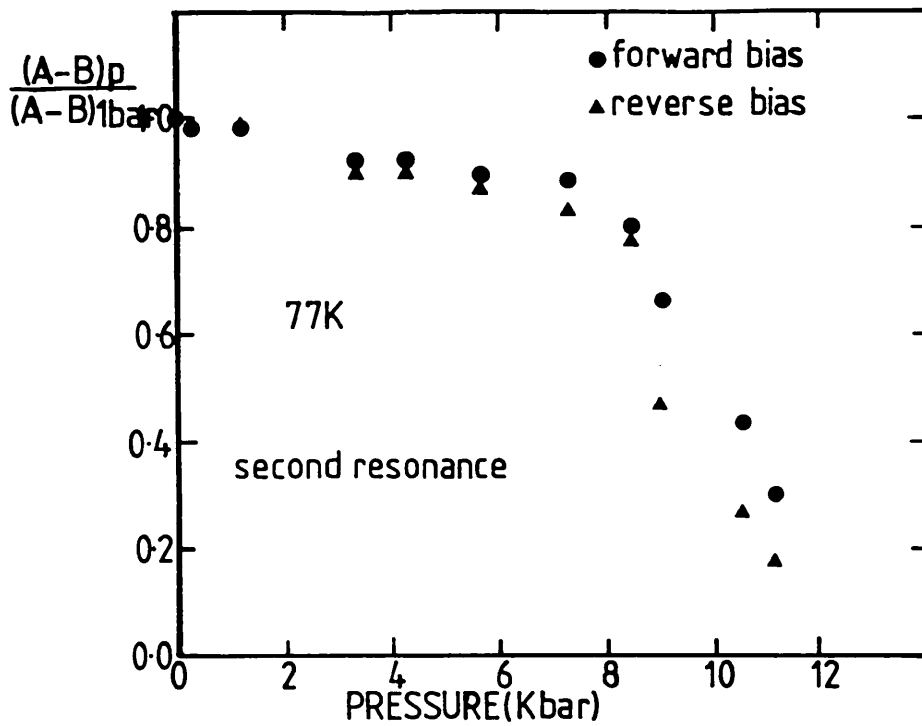


Fig.5.7 Peak to valley current difference as a function of pressure at 77K for the second resonance of the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure.

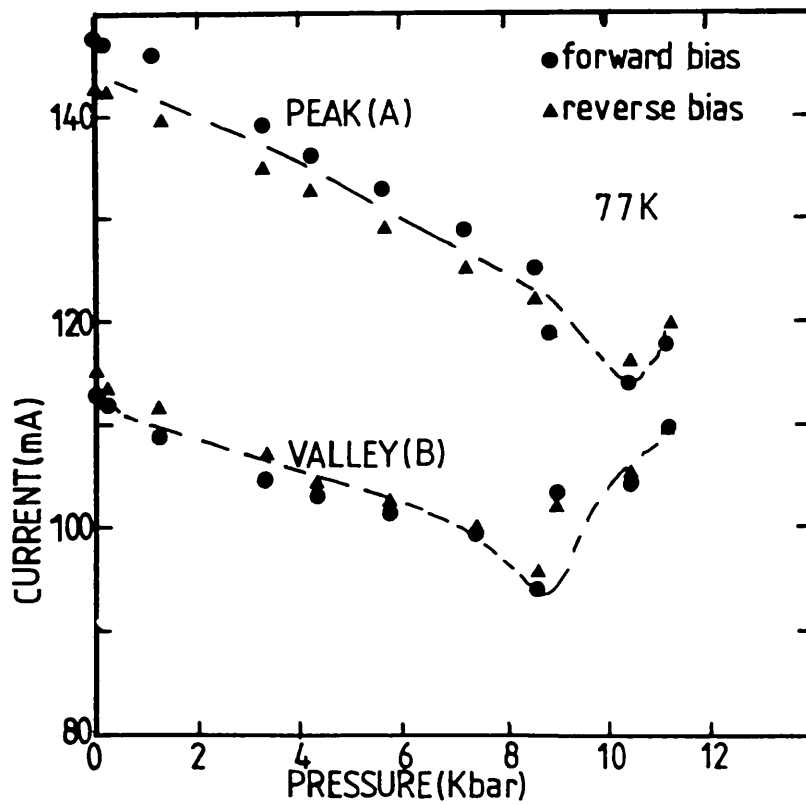


Fig.5.8 The variation with pressure of the peak and valley currents for the second resonance of the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ structure at 77K.

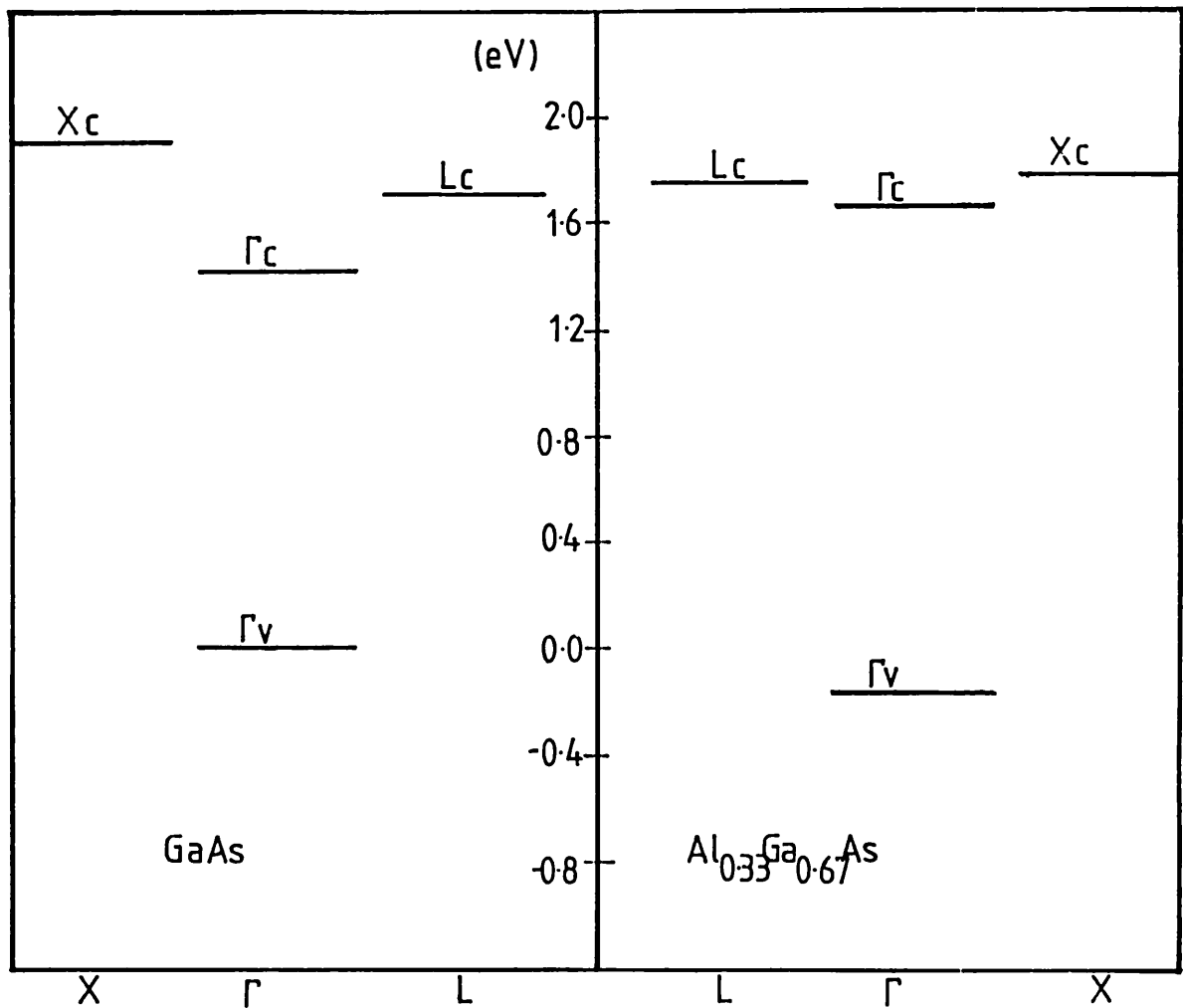


Fig.5.9 Relative positions of the Γ , X and L band extrema in GaAs and $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ assuming a 60:40 band offset ratio and the bandgaps given in ref.(1.46).

PART B: A Symmetric GaAs/AlAs Superlattice

High pressure transport measurements are reported on a GaAs/AlAs superlattice at pressures up to 9Kbar. The superlattice is enclosed in the intrinsic region of a GaAs p-i-n device and consists of a symmetric GaAs/AlAs structure with four 70Å GaAs wells and five 30Å barriers. Measurements on these devices present an interesting comparison to those discussed in chapter 3. In chapter 3, high pressure measurements on a p-i-n device containing an asymmetric GaAs/AlAs superlattice were reported, the first barrier being 30Å wide and the first well being 70Å wide. The barriers grew progressively thinner by 6Å per period (100Å) and the wells grew wider by an equal amount per period. Five barriers and four wells were grown for both devices.

The asymmetric superlattice structure showed a NDR feature in forward bias associated with electrons tunnelling into the $n=1$ level of the first quantum well. Under pressure, this feature is completely suppressed by 7.5Kbar at 77K. This is taken as evidence for the strong involvement in the tunnelling process of X-like electron states in the barrier. A second weaker feature is observed at higher bias and is associated with electrons tunnelling into the $n=2$ level of the first well. Since the barriers become progressively thinner, it is thought that the last three do not significantly affect the tunnelling current.

The symmetric superlattice, in addition to exhibiting NDR features associated with electrons tunnelling into the $n=1$ and $n=2$ state of the first well, shows NDR features associated with electron tunnelling into the $n=1$ and the $n=2$

state of the second well. The behaviour of these NDR features under pressure confirm the results of the earlier chapters, that X-like electron states in AlAs barriers strongly influence the tunnelling processes even though the electron states in the quantum wells are expected to be Γ -like. In addition, the difference in pressure sensitivity between the different NDR features and their difference in size at 1bar, appears to be influenced by the other barriers of the structure, not directly involved in the resonant tunnelling process.

5.5 Experimental

The structure investigated was grown by MBE on n+ (100) GaAs substrates. The structure consisted of a p-i-n diode where the i-region comprised the short period GaAs/AlAs superlattice. The layers in order of growth were 0.5 μm of GaAs n-doped to $1 \times 10^{18} \text{cm}^{-3}$, 0.5 μm of GaAs lightly n-doped to $1 \times 10^{16} \text{cm}^{-3}$, followed by the superlattice. Next was 0.5 μm of GaAs p-doped to $1 \times 10^{16} \text{cm}^{-3}$, and finally a capping layer of 0.5 μm of GaAs p-doped to $1 \times 10^{18} \text{cm}^{-3}$. The n dopant was Si and the p dopant Be. The superlattice was of alternate layers of AlAs and GaAs with a repeat period of 100Å. The five AlAs barriers were 30Å thick and the four GaAs wells were 70Å thick.

Standard photolithography and etching techniques produced mesas of 55 μm diameter square. The mesas were diced and mounted in small, gold microwave packages. Au/Zn and Au/Ge metallisations were used to make Ohmic contacts to the p+ layer and n+ substrate respectively.

DC current-voltage characteristics were obtained at 77K for

two separate devices at pressures up to 9Kbar using the Be-Cu liquid cell described in chapter 2. Device breakdown sometimes occurred at high bias, above $\sim 3\text{V}$, due to Joule heating effects. Therefore, some difficulty was found in investigating the fourth resonance as a function of pressure as it occurs at $\sim 3.18\text{V}$ at 77K and 1bar. Since this is a weak NDR feature, a pulsed voltage technique does not clearly reveal this resonance. However, I-V characteristics were obtained up to $\sim 3.4\text{V}$ for pressures of 1bar, 7Kbar and 8.5Kbar.

5.6 Results

Typical DC I-V characteristics at 77K and 1bar are shown in Fig.5.10. The characteristic shows four NDR features as indicated by the arrows. The first feature is weak and occurs at $\sim 2.05\text{V}$ and 2.3mA . The second feature is also weak with $A/B \sim 1.06$ and occurs at $\sim 2.32\text{V}$ and 5.8mA . The third NDR feature is relatively large with $A/B = 1.2$ and occurs at $\sim 2.6\text{V}$ and 6.8mA . Finally, the fourth resonance is also weak and occurs at $\sim 3.18\text{V}$ and 147mA . These features are revealed more clearly in the conductance- voltage (dI/dV -V) characteristic, Fig.5.11. The p-n junction turns on at approximately 1.5V which is the predicted value for the p-n junction to become flat band, i.e., the bandgap of GaAs at 77K.

Fig.5.12 shows typical I-V characteristics at 77K for a pressure of 1bar and 8.5Kbar and Fig.5.13 shows typical dI/dV -V characteristics at 1bar and 8.5Kbar. The NDR features appear to be completely suppressed by 8.5Kbar. In Fig.5.14 the peak to valley ratio, A/B , is plotted as a

function of pressure for the third resonance at 77K. Although the I-V characteristic exhibits repeatable behaviour for consecutive cycles, the large scatter in values is thought to be caused by the non-resonant leakage current which caused scatter in the results of the device discussed in chapter 3. This scatter in values is also observed in the A/B versus pressure plot for the second resonance, and the first resonance shows large scatter in the values of its current position versus pressure (this feature is not resolved into peak and valley currents). Since this device is of very similar design to that of chapter 3 and, again, no spacer layers were included between the undoped barrier layers and the doped layers cladding the superlattice, the scatter in results is thought to be due to a significant presence of impurity states in the barriers (see chapter 3, pages 80 and 81).

Following the procedure of chapter 3 to remove this scatter in results, the normalised peak to valley current difference is plotted as a function of pressure in Fig.5.15a) and b) for the second and third resonances respectively. As shown, a marked reduction in the degree of scatter is observed. The pressure behaviour of the four resonances will now be considered. To avoid confusion, they are clearly labelled resonances 1,2,3 and 4 in Fig.5.10.

Resonance 1 is a very weak feature at 1bar and, on applying pressure, dI/dV -V characteristics show that the resonance is not significantly altered up to 7Kbar but appears to be slightly weaker at 8.5Kbar, Fig.5.13. The apparent slight sharpening of the feature at some pressures is not an

indication of the strength of the resonance but reflects changes in the "off-resonance" current associated with barriers not directly involved in the resonance, as discussed in the next section. However, the most important observation is that this feature is not substantially affected by pressures below 8.5Kbar.

Resonance 2 is also weak at 1bar but has a resolved A/B of approximately 1.06 at 1bar. As shown in Fig 5.15a), the size of NDR is constant up to ~5Kbar and is rapidly suppressed at higher pressures, vanishing by 8.5Kbar at 77K. This feature is still visible, however, in the dI/dV -V curve at 8.5Kbar.

Resonance 3 is the largest resonance of this structure with A/B ~1.2 at 1bar and 77K. As shown in Fig.5.15b), the size of the NDR decreases up to 4Kbar and more rapidly at higher pressures. It is completely suppressed by 7Kbar at 77K. This feature is not revealed in the dI/dV -V curve at 8.5Kbar.

Finally, resonance 4 is present as a weak feature at 1bar and 4K. At 7Kbar and 8.5 Kbar, no feature is observed in the I-V characteristic or dI/dV characteristic in the voltage range at which this resonance occurs at 1bar. This suggests that the resonance is not present at these high pressures.

5.7 Discussion

The transmission probability for this structure has been calculated by Couch et al. (5.1) using effective mass approximation simulations (EMA). It was calculated by matching wavefunctions and the product of the reciprocal effective mass and the derivative of the wavefunction at each interface for the transfer matrix. For a simple

approximation, the masses and bandgap offsets appropriate to the X states were used for the AlAs. The experimental values measured by Solomon et al. (1.43) were used. These simulations have been shown to be very accurate at predicting the I-V characteristics of this structure and the structure of chapter 3. However, the modelling of well energies for optical measurements performed on these structures are not so precise. This may reflect the results of Cade et al. (1.58), that the properties of thin AlAs barriers ($\leq 30\text{\AA}$) are due to a combination of both Γ and X states.

Fig.5.16 (taken from reference 5.1) shows the current, I , and the conductance, dI/dV , against voltage for the symmetric GaAs/AlAs superlattice. The broken line shows the EMA simulation of I-V for this structure. Two NDR features are seen. These are attributed to tunnelling into the $n=1$ state of the first well (resonance 2) and the $n=2$ state of the second well (resonance 3). The calculation shows much weaker features for tunnelling into all of the $n=1$ and 2 states of the second, third and fourth well. Experimentally, evidence is found only for the $n=1$ state of the second well (resonance 1). The simulation also predicts a large peak in the current at 4, for tunnelling into the $n=2$ state of the first well (resonance 4 which is not shown on this experimental I-V characteristic).

In Fig.5.17 (from ref.5.1) a schematic profile is shown of the symmetric superlattice under increasing forward bias. The top profile shows the superlattice under flat band conditions. The subsequent profiles, numbered 1,2 and 3, are

the resonant conditions for tunnelling from the Fermi level of the bulk GaAs to the left of the superlattice, to the $n=1$ level in the second well, to the $n=1$ level in the first well and to the $n=2$ level in the second well respectively, as the bias increases. The table below summarises the experimentally observed resonances:

RESONANCE	WELL	LEVEL
1	2	$n = 1$
2	1	$n = 1$
3	2	$n = 2$
4	1	$n = 2$

Now that the resonant states associated with each of the four resonances have been established, the size of the NDR features and their pressure variation can be considered. From the results of chapters 3 and 4, the Γ_C-X_C offset is assumed to be the potential barrier for electrons tunnelling through the AlAs barriers with a pressure variation of $\sim 11\text{meV/Kbar}$.

For resonance 1, the electrons have to tunnel non-resonantly through the first barrier, tunnel resonantly through the second and third barriers, and finally tunnel through the remaining two barriers non-resonantly, since at this low bias, the transmission of the last two barriers is still quite low, Fig.5.17a). Therefore, this resonance is expected to be rather weak, as observed. Under pressure, the situation is quite complicated. On the one hand, a decrease of barrier height for the first, fourth and fifth barriers will increase the transmission coefficients of these

barriers. This will tend to increase the size of the resonance. On the other hand, a decrease in barrier height with pressure of the second and third barriers will increase the non-resonant contributions to the current through these two barriers, decreasing the size of the resonance associated with well 2. The observed pressure behaviour of this resonance is difficult to quantify since it is only revealed clearly in the dI/dV - V characteristic. However, it appears to weaken at ~ 8.5 Kbar suggesting that the suppression of the resonance associated with the second and third barriers begins to play a dominant role at ~ 8.5 Kbar.

For resonance 2, the electrons resonantly tunnel through the first two barriers and non-resonantly through the remaining three. At this higher bias, the last three barriers become increasingly narrow and lower in energy, Fig.5.17b), with a resulting increase in transmission. However, the last three barriers still obstruct much of the resonant current, so the NDR feature is small ($A/B \sim 1.06$ at 77K and 1bar). Under pressure, the size of this feature is constant up to ~ 5 Kbar and then decreases rapidly at higher pressures, disappearing completely by 8.5 Kbar. However, it is still visible in the dI/dV - V characteristic. Below 5 Kbar, it would appear that a decrease with pressure in the size of the NDR due to an increase in the non-resonant tunnelling current through the first two barriers, is balanced by an increase in tunnelling current due to the increased transmission of the last three barriers with pressure. Above 5 Kbar, the rapid suppression of NDR reflects the dominant role of electrons tunnelling through X-like states in the first two barriers. The remaining three barriers have a decreasing effect on the

tunnelling current as the pressure increases above 5Kbar, because their transmission coefficients become very large.

The pressure behaviour of the second NDR feature is similar to that of the principal NDR feature observed in the I-V characteristics of the asymmetric GaAs/AlAs superlattice, Fig.3.6. This is expected because both features are associated with resonant tunnelling of electrons into the $n=1$ level of the first well of their respective structures and the confinement energies of these states are the same. The fact that the NDR feature for the asymmetric superlattice is suppressed at a slightly lower pressure (~ 7.5 Kbar at 77K) than for the symmetric superlattice (~ 8.5 Kbar at 77K), is probably because the three barriers not involved in resonant tunnelling for the asymmetric structure, are much thinner ($18\text{\AA}, 12\text{\AA}, 6\text{\AA}$) than those of the symmetric structure (all $30\text{\AA}$). Therefore, the thinner barriers of the asymmetric superlattice are not expected to significantly affect the tunnelling current. Thus X-like states in the first two barriers will dominate the tunnelling current even at low pressures. This implies a lower pressure threshold for loss of NDR, as observed. In addition, the value of A/B is much smaller for the symmetric superlattice than the asymmetric superlattice. This is also thought to be due to the last three barriers, not directly involved in the resonant tunnelling process, being thicker in the symmetric superlattice than the asymmetric superlattice.

For the third resonance, the electrons in the emitter tunnel non-resonantly through the first barrier and then resonantly

through the second and third barrier before reaching the collector. The remaining two barriers effectively disappear under the high bias and are not expected to influence the tunnelling current, Fig.5.17c). Therefore, the NDR feature is relatively large ($A/B \sim 1.2$ at 77K and 1bar) compared to the other features. However, it is a small feature when compared to the size of the NDR feature of the asymmetric superlattice. This is expected because, firstly, electrons must tunnel non-resonantly through the first barrier and, secondly, the NDR feature occurs at quite high bias which introduces a large asymmetry in the transmission coefficients of the second and third barriers. As Ricco and Azbel pointed out (1.19), asymmetry in the transmission coefficients degrades A/B . Under pressure, the size of the NDR feature decreases up to 4Kbar and more rapidly at higher pressures. This feature is completely suppressed by 7Kbar at 77K and is not visible in the dI/dV - V characteristic at 8.5Kbar. The suppression of NDR with pressure indicates that X-like states in the second and third barriers dominate the tunnelling current. The increase in pressure sensitivity of this feature compared to resonance 2 is probably related to the larger confinement energy of the resonant state associated with this feature. However, considering differences in confinement energy, it is expected that this resonance should be suppressed at pressures lower than 7Kbar at 77K. The reason why it does not could be due to the increase in the transmission coefficient of the first barrier as the pressure increases. Therefore, this mechanism will tend to increase the resonant tunnelling current through the second and third barriers with increasing

pressure. This suggests that the NDR feature will be suppressed at higher pressures than it would be if the first barrier were not present, as observed. Nevertheless, the size of the NDR feature decreases over the whole pressure range indicating that X-like states in the second and third barrier are dominating the tunnelling current.

Resonance 4 occurs when electrons resonantly tunnel through the first and second barrier. The remaining barriers do not influence the current at this high bias. The resonance is weak at 77K and 1bar since it is masked by the large, non-resonant tunnelling contribution to the current through the first two barriers. Moreover, the transmission coefficients of these barriers will be highly asymmetric. This resonance is not present at 7Kbar and probably disappears at lower pressures since the confinement energy of the resonant state is close to the top of the Γ_C - X_C barrier.

5.8 Conclusions

Four negative differential resistance features and their variation with pressure have been observed in two samples of a symmetric GaAs/AlAs superlattice embedded in the i-region of a p-i-n device. Scatter in the results of the peak to valley current ratios of resonances 2 and 3 as a function of pressure, has been strongly suppressed by plotting the normalised peak to valley current difference. This indicates that a non-resonant leakage current, similar to that discussed in chapter 3, is also present.

All four NDR features are sensitive to pressure confirming that X-like electron states in the barriers are dominating

the tunnelling current through the superlattice. AlAs barriers not directly involved in the resonant tunnelling process appear to play an important role in determining the size and pressure behaviour of the different NDR features.

Resonance 2 of this structure shows very similar pressure behaviour to the principal NDR feature of the 30Å-70Å-30Å double barrier structure discussed in chapter 4, and the principal NDR feature of the asymmetric superlattice discussed in chapter 3. All these NDR features are associated with electrons tunnelling through two ~ 30Å AlAs barriers into the first quasi-bound state of a 70Å GaAs well. Therefore, it is quite clear that the observed pressure behaviour of the normalised peak to valley current difference, which is very similar for each of these devices even though their respective peak to valley current ratios are vastly different, is intrinsic to a 30Å-70Å-30Å GaAs/AlAs structure.

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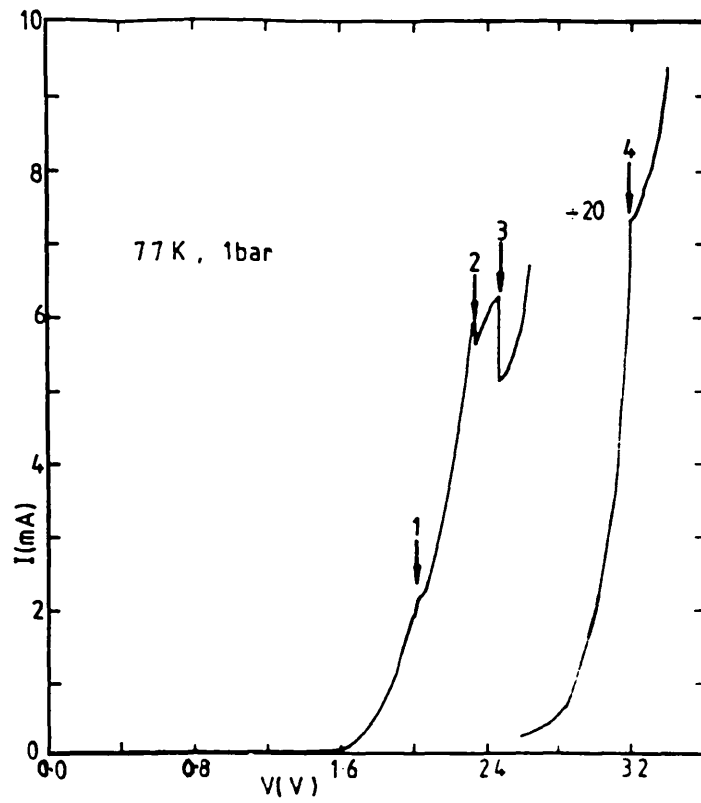


Fig.5.10 I-V characteristic at 77K and 1bar of the symmetric GaAs/AlAs superlattice.

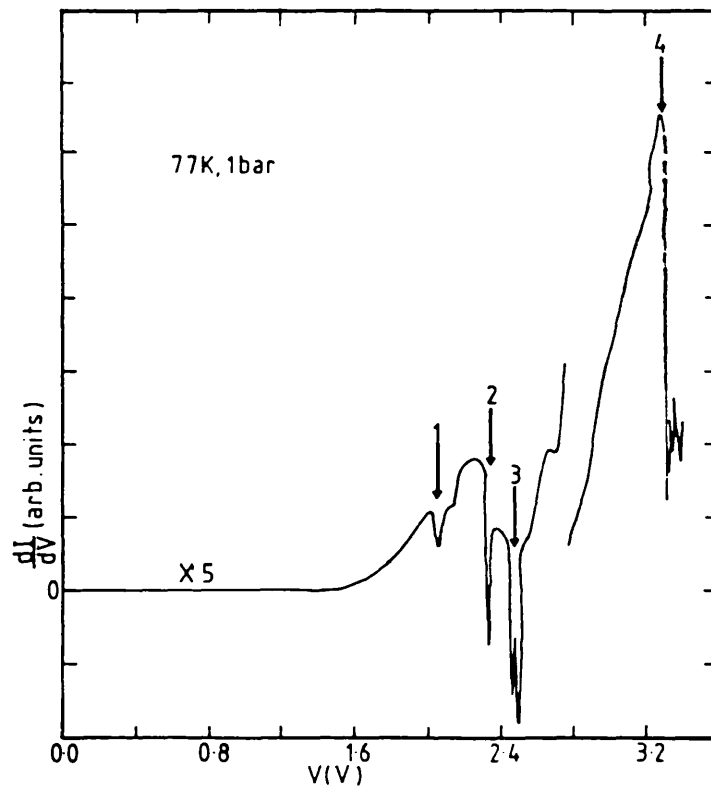


Fig.5.11 dI/dV -V characteristic at 77K and 1bar of the symmetric GaAs/AlAs superlattice.

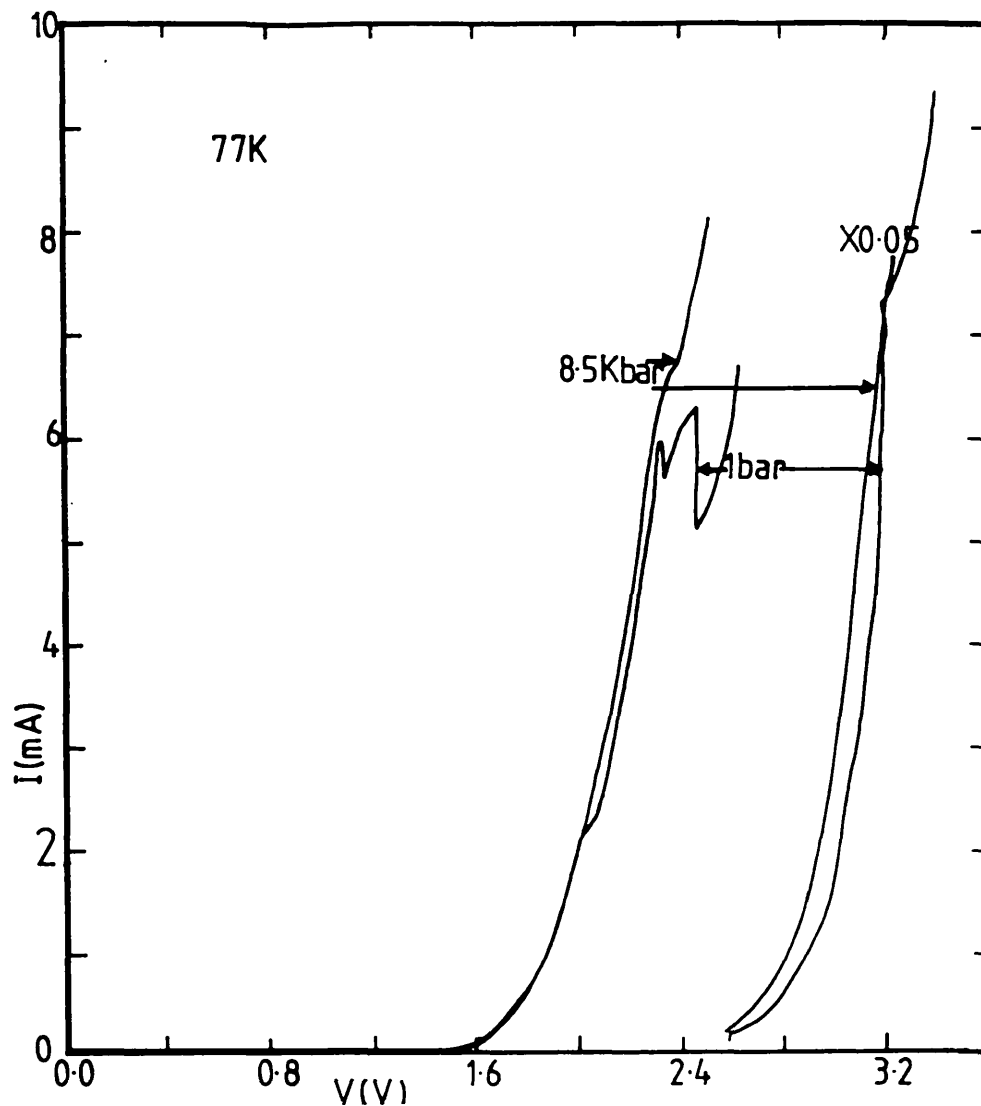


Fig.5.12 I-V characteristic at 77K and pressures of 1bar and 8.5Kbar for the symmetric GaAs/AlAs superlattice.

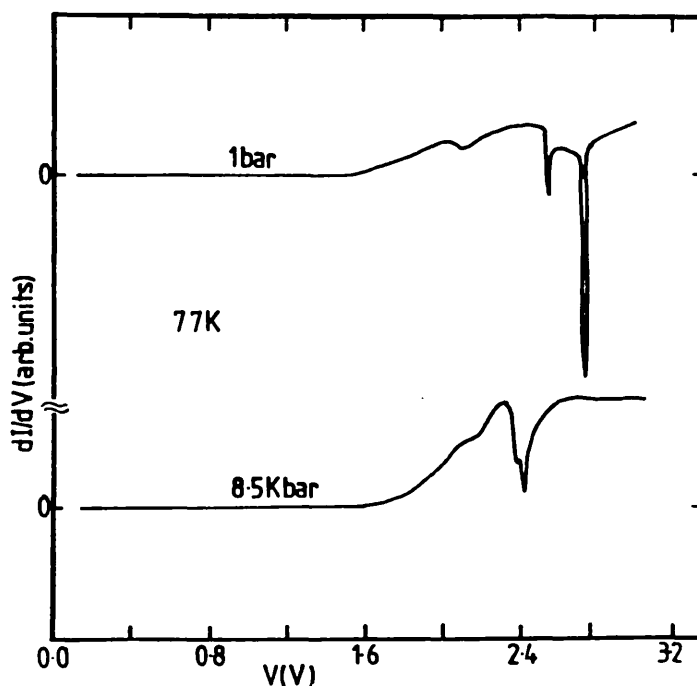


Fig.5.13 dI/dV -V characteristic at 77K and pressures of 1bar and 8.5Kbar for the symmetric GaAs/alAs superlattice.

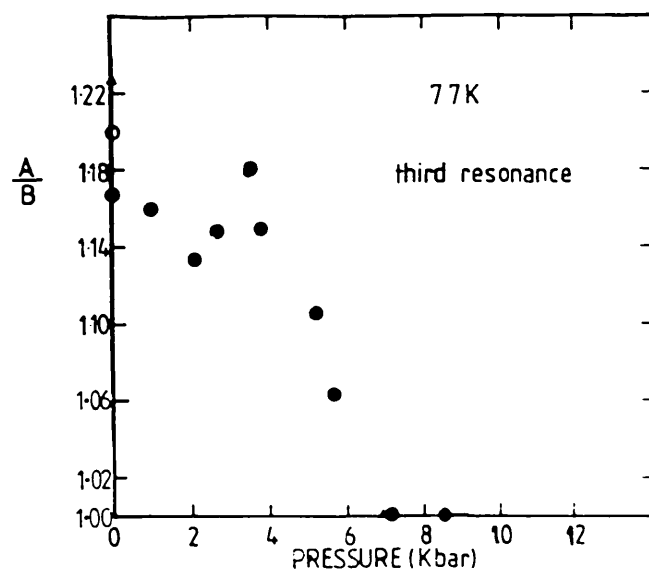


Fig.5.14 Peak to valley current ratio as a function of pressure at 77K for the third resonance of the GaAs/AlAs superlattice.

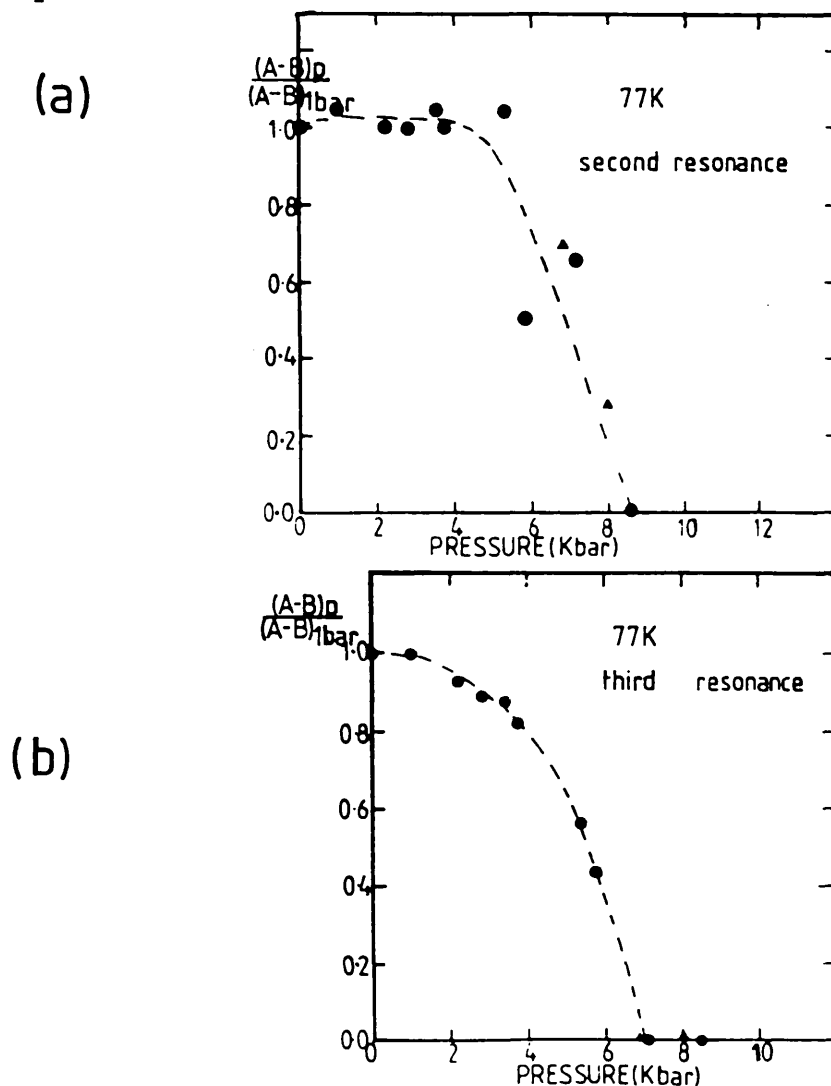


Fig.5.15 Peak to valley current difference at 77K as a function of pressure for (a) the second resonance and (b) the third resonance of the symmetric GaAs/AlAs superlattice.

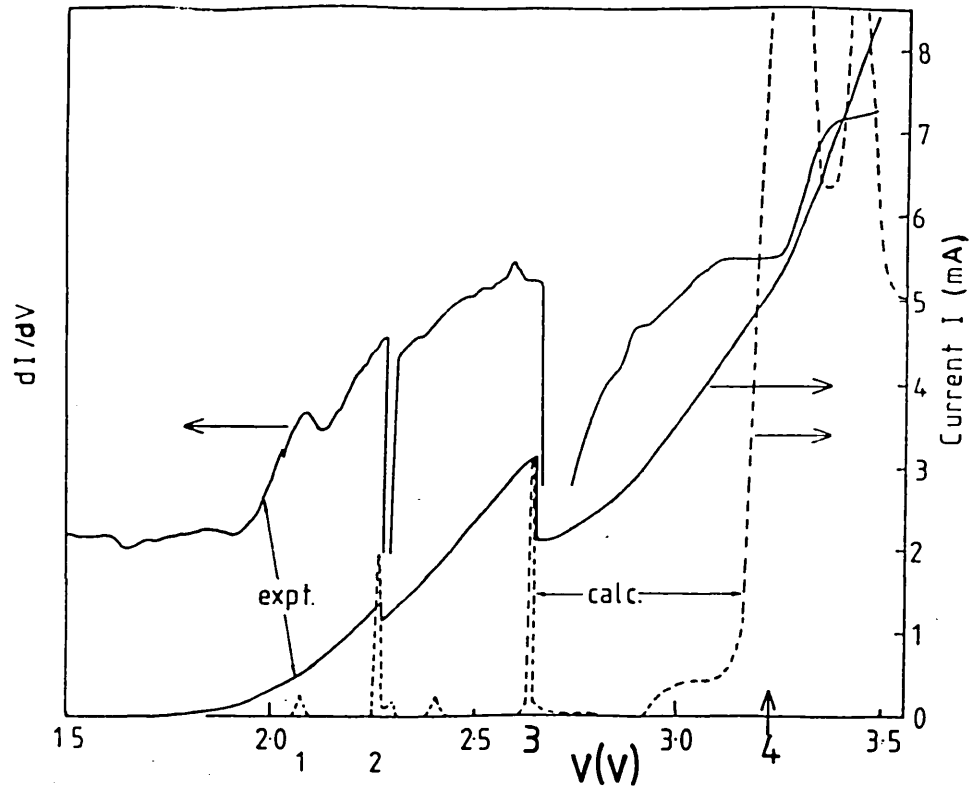


Fig.5.16 I-V and dI/dV -V characteristic at 4.2K and 1bar for the symmetric GaAs/AlAs superlattice. The broken line shows the EMA simulation of I-V for this structure. Taken from ref.(5.1).

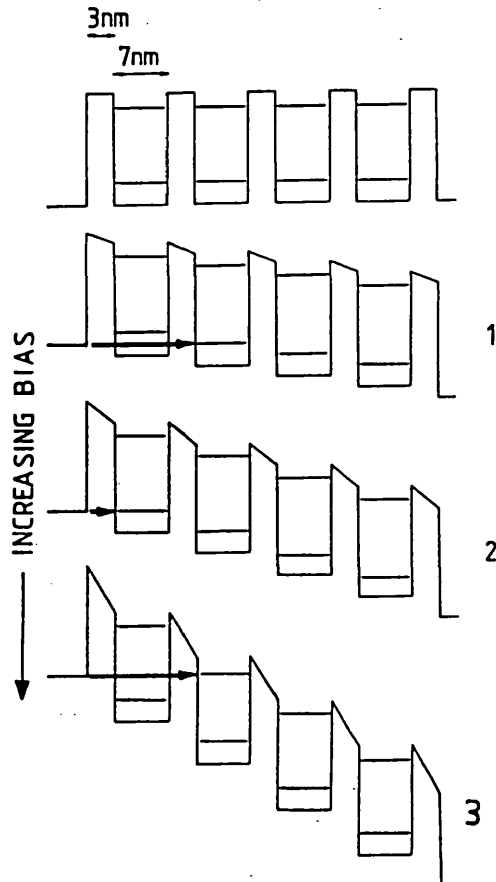


Fig.5.17 A schematic profile of the symmetric GaAs/AlAs superlattice under increasing forward bias. The top profile is at the flat band condition and the subsequent profiles, numbered 1,2 and 3, are the resonant conditions for tunnelling from the Fermi level of the bulk GaAs to the $n=1$ level of the second well, the $n=1$ level of the first well, and the $n=2$ level of the second well respectively.

CHAPTER 6

THE GUNN EFFECT: A GENERAL REVIEW AND HIGH PRESSURE MEASUREMENTS ON A GaAs GUNN DEVICE WITH AND WITHOUT A HOT ELECTRON INJECTOR

A second type of system, other than the resonant tunnelling structures, which exhibits negative differential resistance (NDR) is associated with the Gunn effect, and has been studied as a function of hydrostatic pressure in n-type GaAs. Under pressure, the Γ , L and X conduction band minima shift relative to one another. The Gunn effect depends critically on the relative positions of the conduction band minima, therefore, the I-V characteristics exhibit a pressure dependence. Since high pressure facilities were available, it was thought that this would be an interesting system to study and would also present an interesting contrast to the NDR mechanism observed in resonant tunnelling structures.

In this chapter, a review is made of the Gunn effect followed by a description of the devices and the experiments performed. The devices studied include a standard n-i-n GaAs homostructure and structures containing a graded bandgap of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ in the intrinsic region. Finally, the experimental results are discussed.

6.1 Review of the Gunn Effect

In 1963, Gunn reported the first observation of current oscillations in n-type GaAs at high, DC electric fields (1). The current oscillations occur when the electric field exceeds a threshold field of approximately 3kV/cm. There is then a sharp fall in the time-averaged value of the current

and the current waveform consists of a periodic train of spikes separated by plateau regions. The period of oscillation is close to the specimen length ($\approx 100\text{--}2500\mu\text{m}$ long) divided by the electron drift velocity corresponding to the plateau regions ($\approx 10^7\text{cm/s}$). This relation implies that something is drifting through the sample with the electrons. Subsequent voltage probe measurements by Gunn of the spatial variation of the electric field within the GaAs, showed that each current oscillation was accompanied by the propagation of a high electric field region (domain) from the cathode to the anode. The spiky current waveform is due to the periodic passage of the domains through the sample.

Following the original observations, the physical mechanism responsible for this effect was the subject of considerable debate. An important experiment by Hutson et al. (2) proved that the electron transfer mechanism proposed by Ridley and Watkins (3) and independently by Hilsum (4), must be the correct one. By applying hydrostatic pressure to GaAs, Hutson et al. observed that the threshold pressure for the Gunn effect decreased. This is predicted by the electron transfer mechanism which points out that semiconductors having multi-valley band structures could exhibit negative differential mobility (NDM) at high fields as a result of the transfer of hot electrons from high mobility conduction band minima to low mobility minima at higher energies. GaAs has a conduction band of the required type and the energy separation between the high mobility and low mobility minimum decreases with pressure. Ridley considered theoretically the type of space charge instability which

would develop when a material having a region of NDM in its velocity-field characteristic was biased in this region. He showed that high field domains would develop and propagate uniformly through the sample which is precisely what is observed in the Gunn effect.

Consider the conduction band of GaAs shown in Fig.6.1. In equilibrium the majority of electrons reside in the minimum at the Γ point in the Brillouin zone, (000). However, the electrons can be heated by an applied electric field and transferred into states in the 4 subsidiary minima (intervalley transfer) at point L in the zone (111) which are the lowest subsidiary minima. Until 1976, it was believed that the X (100) minima were lower than the L (111) minima but Aspnes (5) showed that the L minima were lower in energy. Because of the small effective mass, m^* , in the Γ minimum, electrons are heated very effectively by an electric field and gain an energy of magnitude $E(L)-E(\Gamma)=0.29\text{eV}$ at $E\approx 3\text{kV/cm}$. Before reaching this energy, the mobility is limited by polar optical mode scattering. At $E\approx 3\text{kV/cm}$, electrons are transferred to the subsidiary minima where they are heavier and have a reduced momentum relaxation time because of scattering between the minima and because of the higher density of states in these minima. Therefore, the mobility in the L minima is estimated to be only $920\text{cm}^2/\text{Vs}$ while the mobility in the Γ minimum is between 6000 and $7350\text{cm}^2/\text{Vs}$ depending on purity; these estimates are valid for room temperature (9). The momentum change at electron transfer is supplied by an intervalley phonon which is either absorbed or emitted, Fig.6.2. For high enough fields a large enough number can be transferred

into these minima so that the mobility of the sample will be affected. Infact, if the intervalley coupling is strong enough, NDM can result, Fig.6.3. For NDM to occur, three requirements must be met: (1) the lattice temperature must be low enough so that, in the absence of a field, most of the electrons are in the lower minimum, i.e., $\delta E_{TL} > kT$. (2) In the lower minimum the electrons must have a high mobility and small effective mass, and in the upper minimum the electrons must have low mobility and high effective mass. (3) The energy separation between the two minima must be smaller than the semiconductor bandgap so that avalanche breakdown does not occur before the transfer of electrons to the upper valley. N-type GaAs and n-type InP satisfy these requirements and are the most extensively investigated to date.

If the electron transfer mechanism is occurring, then a variation in the relative positions of the conduction band minima should alter the threshold field of the Gunn effect. As a function of pressure, the energy separation of the conduction band minima decreases at a rate of approximately 9meV/Kbar (1.46). Hutson et al. (2) found that the field at threshold decreased with increasing pressure and at 26Kbar the oscillations disappeared completely.

The shape of the velocity-field curve suggests that a DC bias in the NDM region would allow generation of AC power in a circuit connected to the device. This mode of operation is possible and is called the LSA (limited space-charge accumulation) mode but can only be realised under certain conditions (6). One difficulty arises from internal

instabilities. A semiconductor exhibiting NDM (or NDR) is inherently unstable because a random fluctuation of carrier density at any point in the semiconductor produces a momentary space charge that can grow exponentially with time. The one-dimensional continuity equation is given by

$$q \cdot dn/dt = dJ/dx \quad \dots\dots\dots(6.1)$$

where $n(x,t)$ is the space and time dependent mobile charge density and J is the current density. If there is a small local fluctuation of the majority carriers from the uniform equilibrium concentration, n_0 , the locally created space charge density is $n-n_0$. Poisson's equation and the current density equations are

$$dE/dx = -q(n - n_0)/\epsilon_s \quad \dots\dots(6.2)$$

$$J = qn_0\mu E + qD \cdot dn/dx \quad \dots\dots(6.3)$$

where μ is the average mobility, E is the electric field, ϵ_s is the dielectric permittivity and D is the diffusion constant. Differentiating Eq.6.3 with respect to x and using Poisson's equation gives

$$1/q \cdot dJ/dx = -qn_0\mu(n - n_0)/\epsilon_s + Dd^2n/dx^2 \quad \dots\dots(6.4)$$

Substituting this expression into Eq.6.1 gives

$$dn/dt = -qn_0\mu(n - n_0)/\epsilon_s + Dd^2n/dx^2 \quad \dots\dots\dots(6.5)$$

This equation can be solved by separation of variables, i.e., let $n(x,t) = n_1(x)n_2(t)$. The solution of Eq.6.5, for the time equation is

$$n - n_0 = (n - n_0)_{t=0} \exp(-t/\tau_R) \quad \dots\dots\dots(6.6)$$

where τ_R is the dielectric relaxation time given by

$$\tau_R = \epsilon_s/qn_0\mu \quad \dots\dots\dots(6.7)$$

τ_R represents the time constant for growth or decay of the space charge. Thus, if there is a region of NDM in the velocity-field curve and the sample is biased in the

positive mobility region, e.g. $V = \mu E$, then the space charge will decay with time. However, if the sample is biased in the NDM region, the space charge will grow with a time constant equal to τ_R .

To illustrate the response of a semiconductor exhibiting NDM to this charge fluctuation, consider a uniform field with a domain of greater field in the centre of the semiconductor as shown in Fig.6.4a). The charge distribution that produces this field fluctuation is shown in Fig.6.4b). There is a net accumulation of charge on the left side of the domain and a depletion of charge on the right. If the carriers are considered to have a positive charge, the carriers and therefore the domain will move to the right. Assuming that the field within the domain is within the NDM range and the field outside the domain is within the positive mobility range, then the field fluctuation will initially grow with time. This is because the higher upstream field in the domain means that carriers move more slowly inside than outside the domain. Charge will therefore deplete on the right edge of the domain and accumulate at the left edge of the domain, increasing the field in the domain. If the semiconductor is in a resistive circuit the increasing voltage across the domain will decrease the current in the circuit and lower the field outside the domain.

This situation leads to a runaway process. Given enough time, the domain field will grow until the domain velocity is equal to the velocity of carriers outside the domain. The final velocity depends on the circuit load line (6). If the original fluctuation in field was produced by a doping non-

uniformity, then the decreased field around this region which occurs when the domain moves from this region prevents the nucleation of subsequent domains. This situation prevails until the domain reaches the right hand edge of the semiconductor (anode) where it disappears. The field can then rise to nucleate another domain, resulting in a periodic current oscillation whose period is determined by the transit time of the domain. This was the phenomenon observed by Gunn. The domain usually forms near to the cathode because this region often has the greatest non-uniformity due to crystal damage occurring in the contact process (7).

It was discovered that an NDM-induced current instability could occur in ways other than those associated with a domain moving from the cathode to the anode (7). It could also be accompanied by the formation of stationary charge layers at the cathode or anode, moving accumulation or depletion layers, or uniform or non-uniform excursions of the electric field through the NDM region. It has been found that the occurrence of the current instability observed in a semiconductor exhibiting NDM depends on three things (7); (1) the electrical characteristics of the semiconductor, (2) the operating circuit, (3) the conditions at the boundaries of the active region (in particular the conditions at the cathode contact).

The criterion for instability of a semiconductor exhibiting NDM can be established by considering the growth of space charge fluctuations. Assuming that Eq.6.6 remains valid for the growth of the charge fluctuation throughout its transit

of the sample, the growth, $G=(n-n_0)_t/(n-n_0)_{t=0}$, is given by

$$G = \exp(l/V\tau_R) = \exp(lqn_0\mu/V\epsilon_S) \dots(6.8)$$

where l is the sample length and V is the average drift velocity of the domain. For space charge instability, G must be greater than unity, or

$$n_0l > \epsilon_S V/q\mu \dots\dots\dots(6.9)$$

For GaAs,

$$n_0l > 10^{12}\text{cm}^{-2} \dots\dots\dots(6.10)$$

Gunn devices with $n_0l < 10^{12}\text{cm}^{-2}$ exhibit a stable field distribution. Even though Eq.6.10 gives the criterion for instability, it is not a criterion for domain formation, which may take many dielectric relaxation times, since no account is taken of the domain formation time. If this time is longer than the space charge transit time, l/V , through the sample then domain formation cannot occur. However, an important boundary which separates the various modes of operation is the product of carrier density and device length.

The transit time of a domain is $\tau_d = l/V$ and so the transit time frequency is V/l . In a long sample ($\sim 100\mu\text{m}$), the domain drifts at a velocity of $\sim 10^7\text{cms}^{-1}$ and so, provided $n_0l \gg 10^{12}\text{cm}^{-2}$, the transit frequency is $\sim 1\text{GHz}$. Many practical devices have a length of $\sim 10\mu\text{m}$ but their n_0l product is close to 10^{12}cm^{-2} . In this case, the domain (or space charge) velocity can be greater than 10^7cms^{-1} and the transit time is modified by the finite time of domain growth. Transit frequencies usually lie between 7GHz and 25GHz for such a device, depending on the bias voltage (6). In addition, a Gunn device in a resonant circuit can operate

at frequencies higher than the transit time frequency if the domain can be quenched before it reaches the anode (8). The domain width generally decreases with decreasing biasing voltage. If the biasing voltage is reduced sufficiently below the threshold for NDM during a domain cycle, the domain will vanish (or is quenched). When the biasing voltage swings back above threshold, a new domain is nucleated and the process is repeated. Therefore, the oscillations occur at the frequency of the resonant circuit rather than the transit time frequency.

Many Gunn devices make use of the cathode to anode domain transit time mode in long samples. However, thermal limitations restrict the use of long samples in continuous DC operation. Therefore, short samples ($< 10\mu\text{m}$ active region length) that can be sufficiently well heat sunk so as to be capable of DC operation, have become the major Gunn effect devices. Short samples are used almost always as simple oscillators or amplifiers when incorporated into a variety of microwave circuits. Short samples exhibit different behaviour in many ways to that of the long samples mainly because they have lower n_0l products and the cathode and anode are in close proximity. In particular, circuit controlled oscillations may be obtained in short samples in which the minimum voltage exceeds the sustaining voltage (the minimum bias which can sustain domain propagation). In long samples circuit control ceases under this condition. Short samples ($n_0l < 10^{12}\text{cm}^{-2}$) are used as amplifiers in the LSA mode (9). Superimposed on the DC electric field, E_0 is an AC field, $E_1 \cos 2\pi \nu t$. The amplitude of the AC field is so large that for a short part of its cycle, the mobility is

positive as shown in Fig.6.5. At a high enough frequency, ν , almost no space charge is generated. As a result of the decrease of current with increasing voltage, it is possible that the power, P_{tot} , which an electron gains from the total field, $E_0 + E_1 \cos 2\pi \nu t$, during one cycle, is smaller than the power P_0 which it would gain from the DC field alone:

$$P_{tot} = e\nu \int_0^{1/\nu} E v dt < P_0 = e\nu E_0 \int_0^{1/\nu} v dt \quad \dots\dots\dots(6.11)$$

that is, the yield, $(P_0 - P_{tot})/P_0$, is positive.

6.2 Hot Electron Injectors

Over the past few years the injection of hot electrons into GaAs has been demonstrated using hot-electron spectroscopy which is a technique employed for investigating non-equilibrium transport in narrow regions of GaAs (10,11). Triangular barriers of compositionally graded $Al_xGa_{1-x}As$ are used to inject the hot electrons so that the energy of the electrons is equal to the conduction band offset between the $Al_xGa_{1-x}As$ and GaAs at the heterojunction formed between the two materials (12). This is typically between 200meV and 300meV. The conduction band offset energies in this heterojunction system can be chosen to be nearly equal to the Γ -L energy separation in GaAs (~ 290 meV). Therefore electrons may be injected at the cathode with an energy equal to the energy difference $E(\Gamma) - E(L)$. A modification of the intervalley scattering is anticipated immediately after the GaAs/AlGaAs heterojunction.

The injection of hot electrons at the cathode may improve the performance of a standard Gunn device (12). This is because, firstly, the dead zone, the distance over which electrons must drift before acquiring enough energy to

scatter into the L minima, is reduced to approximately the mean free path for intervalley scattering, 30nm. Therefore, electrons may be heated more efficiently to the L minima. Secondly, the variance in distance from the cathode of the first intervalley scattering event for electrons entering the drift region is reduced. Associated with this is a reduction in the variance in position at which the charge instabilities are formed. Therefore, improvements in the noise of Gunn devices are expected (12).

The three structures studied in this chapter are; (i) a standard Gunn diode, (ii) a Gunn diode with a graded AlGaAs hot electron injection cathode and (iii) a Gunn diode with a graded AlGaAs hot electron injection cathode plus a thin, heavily doped region placed between the AlGaAs barrier and the GaAs drift region. The third diode was designed by Couch et al. to include a thin heavily doped region for the following reason(12): The doping profile near the cathode must also be carefully controlled so that the field from the ionised impurities in the depletion layer set up when the AlGaAs injector is forward biased, does not suppress the formation of charge instabilities. The charge and field instabilities generated in Gunn oscillations require the opposite field gradient to that occurring in this depletion region, so without the thin n^+ spike the Gunn diode with hot electron injector will not lead to enhanced Gunn effects. By including the n^+ spike, the depletion region may be confined to a much smaller length. The thickness of this spike must be less than the mean free path for the hot electrons injected over the barrier.

Couch et al. have performed self-consistent Monte-Carlo simulations on these structures to confirm their ideas discussed above (12). They find that the field profiles across diodes (i) and (ii) are spatially inhomogeneous, but temporally stable. Conversely, the field profile across structure (iii) is unstable and associated with this instability are current oscillations. Subsequent experiments performed on this device reveal, from an evaluation of the activation energies for small forward and reverse biases, that the barrier height of the injector is 220meV. Fig.6.6 shows the I-V characteristic at room temperature. A region of NDR due to intervalley transfer occurs beyond 1V and ~ 1 A. Fig.6.7 illustrates the device with zero applied bias and under forward applied bias. The device was found to oscillate at microwave frequencies at a few milliWatts power.

The experiments discussed in this chapter report the effect of hydrostatic pressure on the I-V characteristics of devices (i) and (ii). With pressure, the predominant effect is to decrease the energy separation $E(L)-E(\Gamma)$, at a rate of ~ 9 meV/Kbar, $\sim 3\%$ /Kbar, (13) and increase the effective mass in the Γ minimum by $\sim 0.6\%$ /Kbar (14). The triangular barrier of the injector decreases at a much slower rate of ~ 0.39 meV/Kbar, $\sim 0.1-0.2\%$ /Kbar, and is not expected to influence the pressure behaviour of device (ii). However, the injector may play some role in the I-V characteristics as a function of pressure. Device (iii), with the hot electron injector and n+ spike, was found to be unstable under pulsed DC voltage at high biases. Device breakdown

occurred just before the onset of NDR even when a variety of capacitors was placed in parallel with the device via short connecting leads. The reasons for this instability will be discussed.

6.3 Experiment

The Gunn devices with hot electron injector, outlined above, were grown by molecular beam epitaxy (MBE) on an n^+ (100) GaAs substrate. A $0.5\mu\text{m}$ thick n^+ GaAs buffer layer doped at $1 \times 10^{18} \text{cm}^{-3}$ with Si was grown first. Then the transit region of GaAs doped at $1 \times 10^{16} \text{cm}^{-3}$ also with Si was grown. The thickness of this layer was $1.0\mu\text{m}$ for device (iii) and $0.5\mu\text{m}$ for device (ii). For device (iii), this was followed by a 10nm n^+ GaAs spike doped with Si to $1 \times 10^{18} \text{cm}^{-3}$. Then, for both devices, the sequence of growth continued with the graded composition $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer. This layer was nominally undoped, starting at a composition of $x=0.3$ and reducing to $x=0$ over 50nm . Examination by transmission electron microscopy (TEM) has confirmed the shape and thickness of this layer (12). For device (ii), the following layer was $0.5\mu\text{m}$ of GaAs doped to $1 \times 10^{16} \text{cm}^{-3}$. Finally, for both devices, this was followed by a $0.5\mu\text{m}$ thick n^+ GaAs contact layer doped to $5 \times 10^{18} \text{cm}^{-3}$ with Si. The devices were fabricated using standard photolithography and etching techniques and the top and bottom layers were metallised with Ni/Au/Ge Ohmic contacts. The devices were mounted in standard microwave packages and bonded with low inductance gold wire. Device (iii) was processed into mesas of nominal diameters of $100\mu\text{m}$ and $200\mu\text{m}$ and device (ii) was processed into mesas of nominal diameter of $180\mu\text{m}$.

The standard Gunn device was comprised of the following layers grown on a n^+ (100) GaAs substrate: Firstly, a $1\mu\text{m}$ thick buffer layer of GaAs doped to $2 \times 10^{18} \text{cm}^{-3}$. Then the transit region of $1.7\mu\text{m}$ of GaAs doped to $2 \times 10^{16} \text{cm}^{-3}$ and finally a $1\mu\text{m}$ thick layer of GaAs doped to $2 \times 10^{18} \text{cm}^{-3}$. Si was used as the dopant. These devices were processed as above with a nominal mesa diameter of $80\mu\text{m}$.

Two terminal DC I-V characteristics were obtained at 77K and 1bar for the three devices using a pulsed voltage supply, as shown in Fig.6.8. The bias was increased to just beyond the onset of NDR since device breakdown occurs if the NDR region is probed too far. This is a result of the current oscillations associated with the Gunn effect. The I-V characteristics of devices (ii) and (iii) show non-linearity near the origin which reflects the diode-like behaviour of the graded gap, in contrast to the I-V characteristic of device (i). As mentioned above, device (iii) was found to be unstable at high bias, close to the onset of NDR. This is thought to be a result of the fact that this device was specifically designed to enhance Gunn effects, i.e., to increase the power output of current oscillations. To quench these oscillations, a capacitor was placed across the terminals of the device in parallel. However, although a variety of capacitors was employed ($0.1\mu\text{F}$ disc ceramic, $0.33\mu\text{F}$ monolithic ceramic, $1\mu\text{F}$ polycarbonate and $100\mu\text{F}$ electrolytic), the device was found to break down close to NDR. An I-V characteristic showing the onset of NDR, was eventually obtained for this device at 1bar and 77K without an external capacitor placed across the terminals.

Devices (i) and (ii) were found to be relatively stable to just beyond the onset of NDR without a capacitor in parallel. These two devices were investigated as a function of hydrostatic pressure. For device (ii), the Be-Cu gas cell was used up to 14Kbar at 77K and for device (i), the Be-Cu liquid cell was used up to 9Kbar at 77K.

6.4 Discussion

At 1bar, the current peaks corresponding to the onset of NDR occur at currents of 1.76A, 2.22A and 1.38A for (i) the standard Gunn device, (ii) the Gunn device with hot electron injector and (iii) the Gunn device with hot electron injector and n_+ spike, respectively. Since the current depends on mesa diameter and doping concentration, the peak currents cannot be compared directly between devices. The peak electric fields can be compared provided that the widths of the transit regions are known and negligible voltage drops occur outside this region. However, large voltages can develop across parasitic resistances due to the contacts and connecting leads. Even though these resistances are small (of the order of an Ohm), large voltage drops are found to occur because very high currents (~ 1 A) and high voltages (~ 1 V) have to be realised in order to observe NDR. This makes it difficult to estimate the electric field at threshold for NDR and particularly to discover if the electrons are heated more efficiently by the hot electron injector.

Fig.6.9 shows the threshold voltage for NDR against pressure for device (ii). The threshold voltage decreases as a

function of pressure, as expected from the electron transfer mechanism, at a rate of approximately 0.5%/Kbar. This is rather slower than the rate at which the energy separation, $E(L)-E(\Gamma)$ decreases with pressure which is approximately 3%/Kbar. The difference could be due to the effective mass of the electrons in the Γ minimum increasing with pressure which will tend to increase the threshold voltage, V_t , for NDR ($d\ln m^*(\Gamma)/dP = 0.6\%/Kbar$, from ref.6.14). The L minimum effective mass is expected to have little effect because the majority of electrons reside in the Γ minimum, even at threshold, and $m^*(L)$ is thought to have a low pressure coefficient of approximately 0.16% (assuming $d\ln E_G(L)/dP \sim d\ln m^*(L)/dP$). The increase of $m^*(\Gamma)$ with pressure could, therefore, mask some of the decrease in threshold voltage associated with the decrease in energy separation between the Γ and L minima with pressure. Hutson et al. (2) find, from experiments on a standard GaAs Gunn device, that V_t falls at approximately the same rate as that of device (ii) for pressures below 15Kbar. Above 15Kbar, they find that V_t drops rapidly which suggests that the decrease in the intervalley energy separation is beginning to play a dominant role. However, an alternative explanation for the low pressure behaviour is discussed below.

From Fig.6.8 it can be seen that devices (ii) and (iii) show diode-like behaviour at low bias indicating the presence of the graded gap at 77K in contrast to device (i) which behaves like a resistor in forward (substrate bias positive) and reverse bias. Device (i) exhibits NDR in forward and reverse bias at the same voltages and currents (to within $\pm 2\%$). However, the threshold voltage as a function of

pressure shows a large scatter in values although there is a general increase of threshold voltage with pressure, Fig.6.10. Pickering et al. (15) have found that for a specific type of contact which they believe to be perfectly "Ohmic", the field at threshold increases with pressure up to 15Kbar followed by a rapid decrease with pressure. They attribute the initial increase to the increase in effective mass in the Γ minimum with pressure being the dominant effect at low pressures rather than the decrease in the intervalley separation. This behaviour contrasts to the results for device (ii) and Hutson et al.'s observations. The decrease of V_t with pressure below 15Kbar in Hutson's data is attributed, by Pickering et al., to the presence of high fields at the cathode contact rather than the effects of a decrease in intervalley separation.

The difference in low pressure behaviour for devices (i) and (ii) can be explained along similar lines to those used by Pickering to explain his type 1 and type 2 behaviour. Pickering's type 1 behaviour agrees with the device (i) behaviour in that an increase in E_t occurs with pressure ($\sim 0.5\%/Kbar$) at pressures below 15Kbar. Type 2 behaviour shows the usual decrease with pressure as observed by Hutson et al. and the data of device (ii). Pickering found that type 1 behaviour shows a linear variation of I against V and that in forward and reverse bias E_t agreed to within $\pm 5\%$. This is in agreement with our device (i) characteristic which shows a linear characteristic and then a sharp turn over at the threshold voltage for NDR and good agreement for V_t in forward and reverse bias. Conversely, type 2 diodes

show non-linear I-V curves, as for our device (ii) curve up to threshold, and large differences in E_t for forward and reverse bias ($\pm 20\%$). Thus, device (i) exhibits typical type 1 behaviour and device (ii) exhibits typical type 2 behaviour. Hutson et al's samples exhibit non-linear I-V characteristics below threshold and, therefore, typical type 2 behaviour.

The use of the pre-threshold I-V plot to indicate whether the devices are exhibiting low or high field cathodes has been discussed by Shaw et al. (16) and Grubin et al. (17) for GaAs. They found good linearity prior to threshold on samples with uniform fields and showed that the effect of a high cathode field, relative to that in the bulk, was to cause non-linearity and to reduce the threshold field. It is probable, therefore, that the onset of oscillations (and therefore NDR) in the type 2 devices is controlled by contact effects. It should be mentioned that Pickering et al. and Hutson et al. define E_t to correspond to the onset of oscillations, whereas, for the data of devices (i) and (ii), the threshold voltage refers to the voltage at which NDR begins. This is not expected to influence the analysis.

To explain the difference in type 1 and type 2 behaviour, Pickering considers the formation of Ohmic contacts with a metal on a semiconductor. He finds that Type 2 behaviour can be explained by the formation of a Schottky barrier at the metal-semiconductor contact which gives rise to a high cathode field. In addition, the Schottky barrier will produce hot electrons, assuming thermionic emission is the dominant conduction mechanism. Type 1 behaviour is

believed to reflect purely band structure effects. Therefore, an increase in threshold field with pressure at low pressures indicates that the increase in effective mass in the Γ minimum is probably the dominant effect at low pressures rather than the decrease in the Γ -L energy separation and that any deviations from this behaviour can be explained in terms of a Schottky barrier at the cathode contact. At high pressures, above 15Kbar, Pickering finds that type 1 and type 2 devices show a rapid decrease in threshold field with pressure indicating that the decrease in the Γ -L energy separation with pressure is the dominant effect at high pressures. Since devices (i) and (ii) were contacted by the same procedure, it seems unlikely that the presence of a Schottky barrier at the cathode contact of device (ii) is the cause of the type 2 behaviour. It is more likely that the presence of the hot electron injector is causing this behaviour. This is because it forms part of the cathode of the device and, from Monte-Carlo simulations (12), creates a high electric field at the cathode. Moreover, the injector acts as a barrier and therefore produces hot electrons in the transit region.

The pressure dependences of the peak currents corresponding to the onset of NDR for the two devices may also be compared directly, Fig.6.11. It is clear that the two devices exhibit very similar behaviour. The decrease of peak current with pressure is expected if the following equation is considered;

$$J(E) = (n_1\mu_1 + n_2\mu_2)E \quad \dots\dots\dots(6.11)$$

where $J(E)$ is the field dependent current density, n_1 , μ_1 are the number of electrons and mobility in the Γ minimum

respectively and n_2 , μ_2 are the number of electrons and mobility in the L minima. Assuming that the ratio n_1/n_2 remains constant at the pressure dependent threshold, the predominant effect of pressure on the current density is through the mobilities which depend on m^* . The Γ mobility will decrease since it is proportional to $m^{*-3/2}$ for polar optical mode scattering (6.9). Since the majority of electrons are in the Γ minimum even near threshold, the pressure dependence of the current density should be close to the pressure dependence of the mobility on $m^*(\Gamma)$. The observed pressure dependence is $\sim 0.85\%/Kbar$, which agrees well with the value of $0.9\%-0.8\%/Kbar$ for the mobility decrease, using $d\ln m^*(\Gamma)/dP = 0.6\%/Kbar$ (6.14), over a pressure range from 0 to 14Kbar.

Another subtle comparison can be made from the shape of the I-V characteristics. Immediately after the threshold voltage for NDR, device (i) appears to show a sharp fall in current whereas devices (ii) and (iii) show a gradual turning over of the characteristic up to NDR followed by a gentle decrease in current, Figs.6.6 and 6.8. This contrasting behaviour may be explained by considering the two possible velocity-field characteristics plotted in Fig.6.12. At low fields, the slope is the high mobility, μ_1 , in the Γ minimum while at high fields, the slope is the low mobility, μ_2 , in the L minima assuming all electrons have been transferred. Curve 2 shows a region of NDR while curve 1 has a positive slope everywhere. The type of curve observed depends on the ratio of $\delta E_{\Gamma L}$ to the thermal energy of the electrons. A curve 2 characteristic is realised when this ratio is very

high and a characteristic more like curve 1 as this ratio decreases. Device (ii) and (iii) show characteristics with more curve 1 behaviour than device (i). This could be accounted for by the presence of the hot electron injector which will decrease this ratio since the thermal energy of the electrons is increased.

6.5 Conclusions

The Gunn effect has been studied in three different devices which include; (i) a standard Gunn device, (ii) a Gunn device plus a hot electron injector at the cathode and (iii) a Gunn device plus a hot electron injector with a n^+ spike directly after the injector. The hot electron injector is thought to improve device performance by heating electrons more efficiently into the subsidiary minima since the distance over which electrons must drift before gaining sufficient energy to scatter into the L minima is reduced.

Device (iii), with the graded $\text{Al}_x\text{Ga}_{1-x}\text{As}$ injector as the cathode followed by an n^+ spike, was found to be unstable at biases close to the onset of NDR. This is thought to be because the device was specifically designed to enhance microwave oscillations in a GaAs Gunn device by the inclusion of an n^+ spike. Devices (i) and (ii) were studied as a function of pressure up to 15Kbar. The threshold voltage exhibited different behaviour with pressure for the two devices, device (i) exhibiting typical "type 1" behaviour and device (ii) exhibiting typical "type 2" behaviour. Type 1 behaviour is characterised by the threshold field for the Gunn effect increasing with pressure. In contrast, previous results (6.2) have exhibited

type 2 behaviour, characterised by the threshold field decreasing with pressure. Any deviations from type 1 behaviour can be explained in terms of a Schottky barrier at the cathode contact. However, in device (ii), the type 2 behaviour is thought to be a consequence of the hot electron injector forming the cathode. The increase in threshold field with pressure for device (i) indicates that the increase in effective mass in the Γ minimum, rather than the decrease in the intervalley separation, is probably the dominant effect at low pressures.

The peak current as a function of pressure shows very similar behaviour for the two devices. The predominant effect of pressure on the current is through the mobility, which depends on the effective mass of the electrons. The expected pressure variation is found to be in close agreement with the variation obtained experimentally from the devices.

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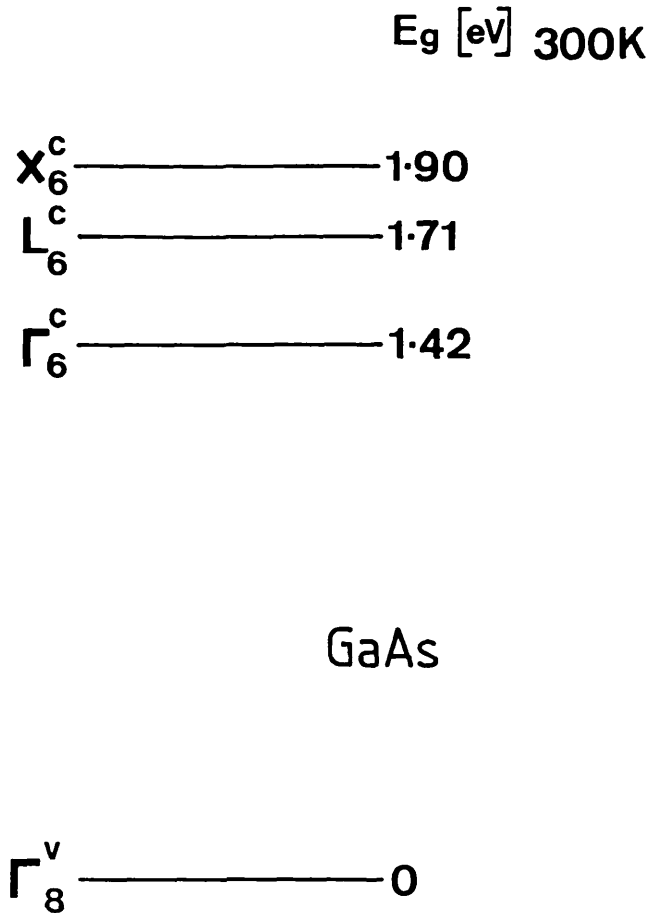


Fig.6.1 Conduction band diagram of GaAs at 300K. The energy gaps are taken from ref.(1.46).

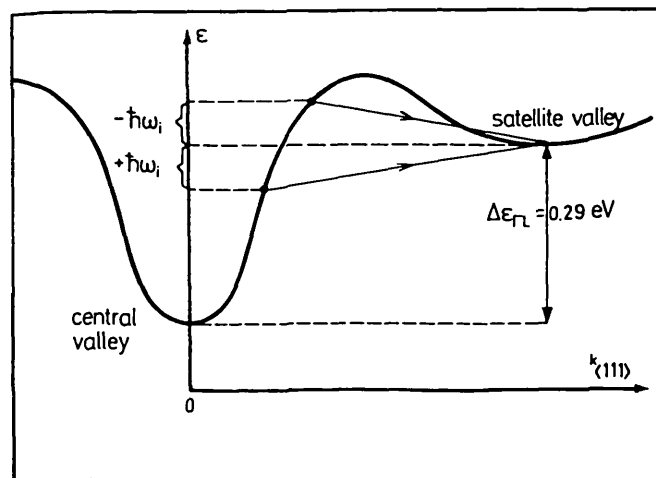


Fig.6.2 Central and satellite minima in the conduction band of GaAs. The full straight lines indicate electron transitions between the valleys with emission or absorption of an intervalley phonon. Taken from ref.(6.9).

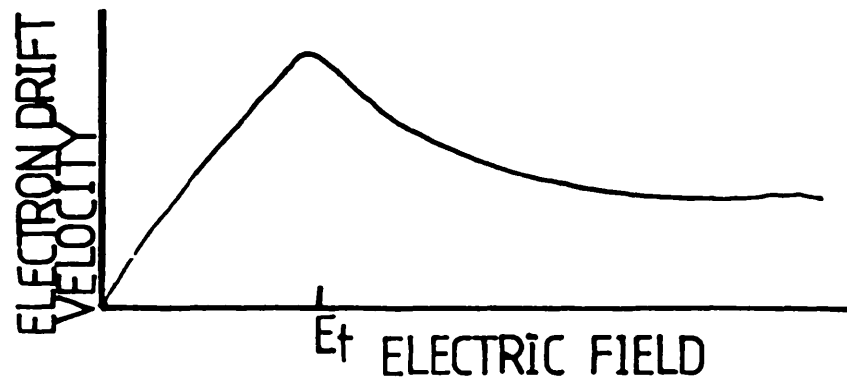


Fig.6.3 Drift velocity-field characteristic of electrons in GaAs.

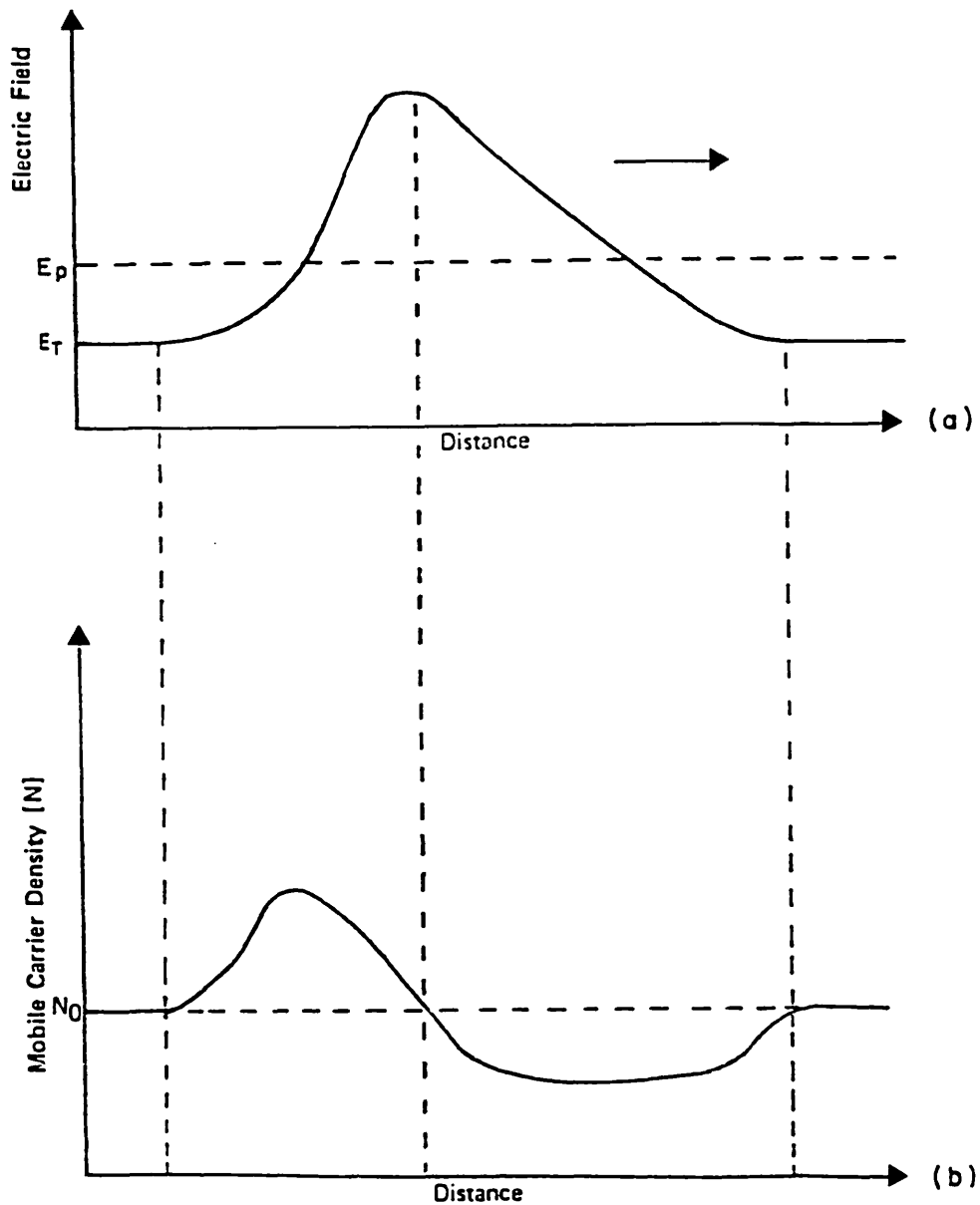


Fig.6.4 Illustration of a charge fluctuation (b) required to produce a local increase in electric field (a). The arrow denotes the direction of carrier drift. Taken from ref.(6.7).

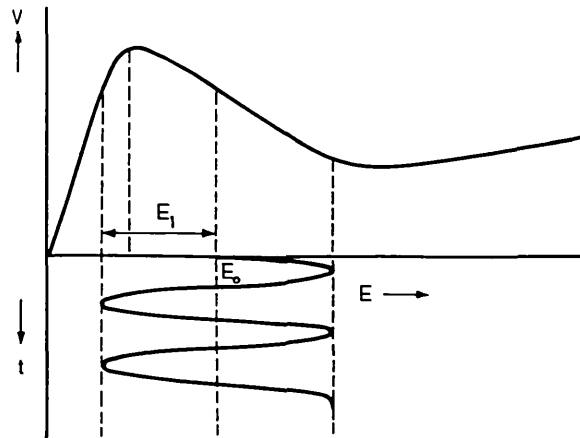


Fig.6.5 The field variation as a function of time in a LSA oscillator. Taken from ref.(6.9).

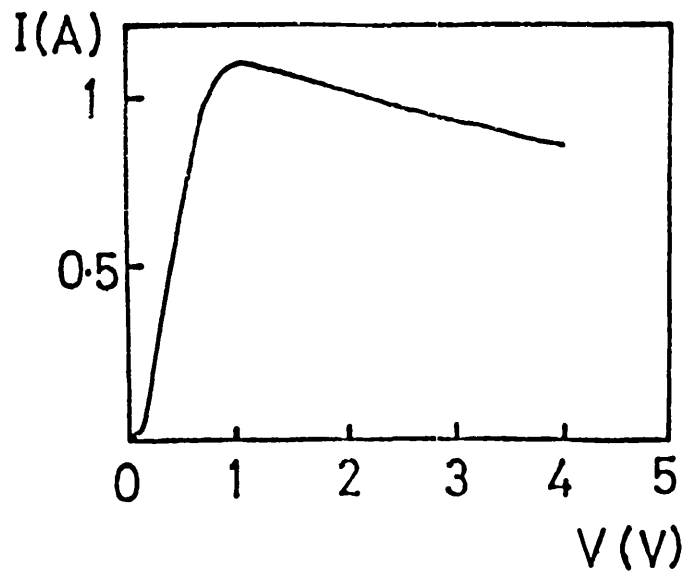


Fig.6.6 I-V characteristic at room temperature for device (iii). Taken from ref.(6.12).

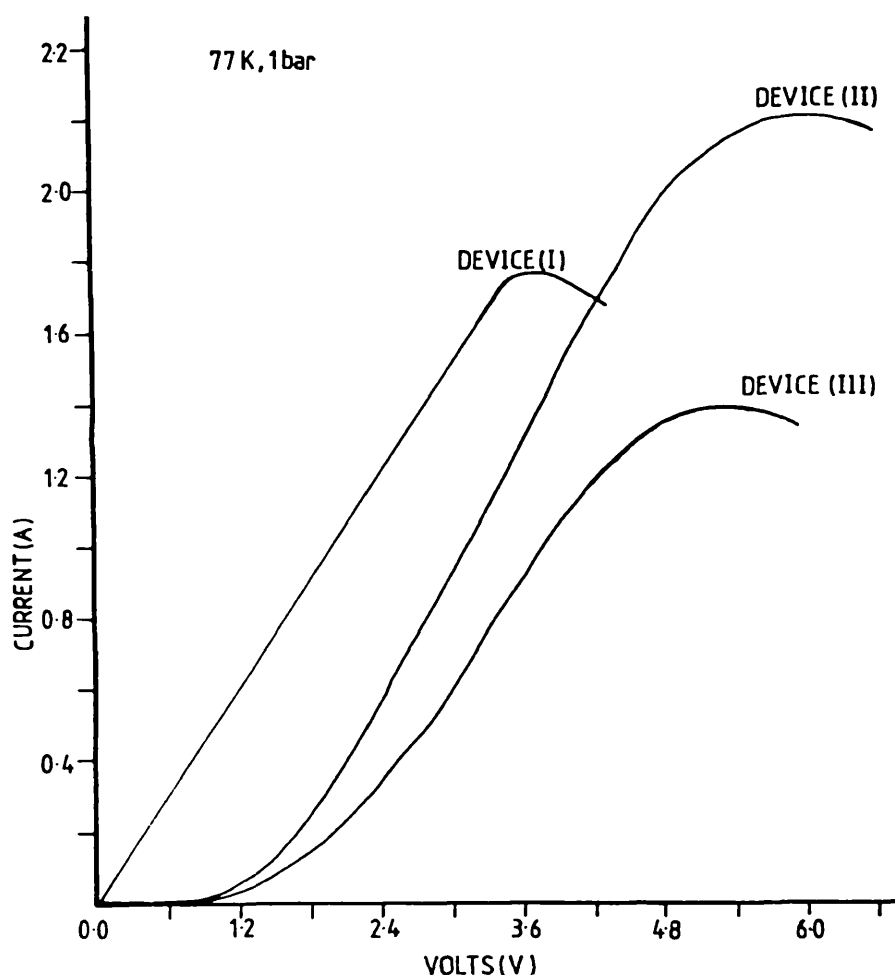


Fig.6.8 I-V characteristics at 77K and 1bar for devices (i), (ii) and (iii).

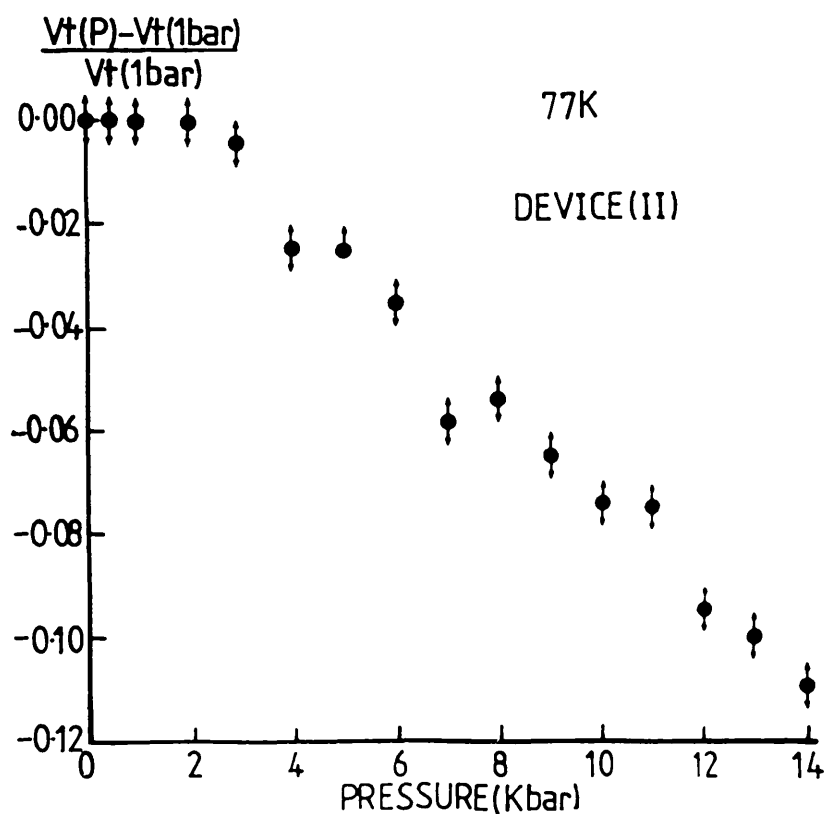


Fig.6.9 Fractional change in threshold voltage with pressure at 77K for device (ii).

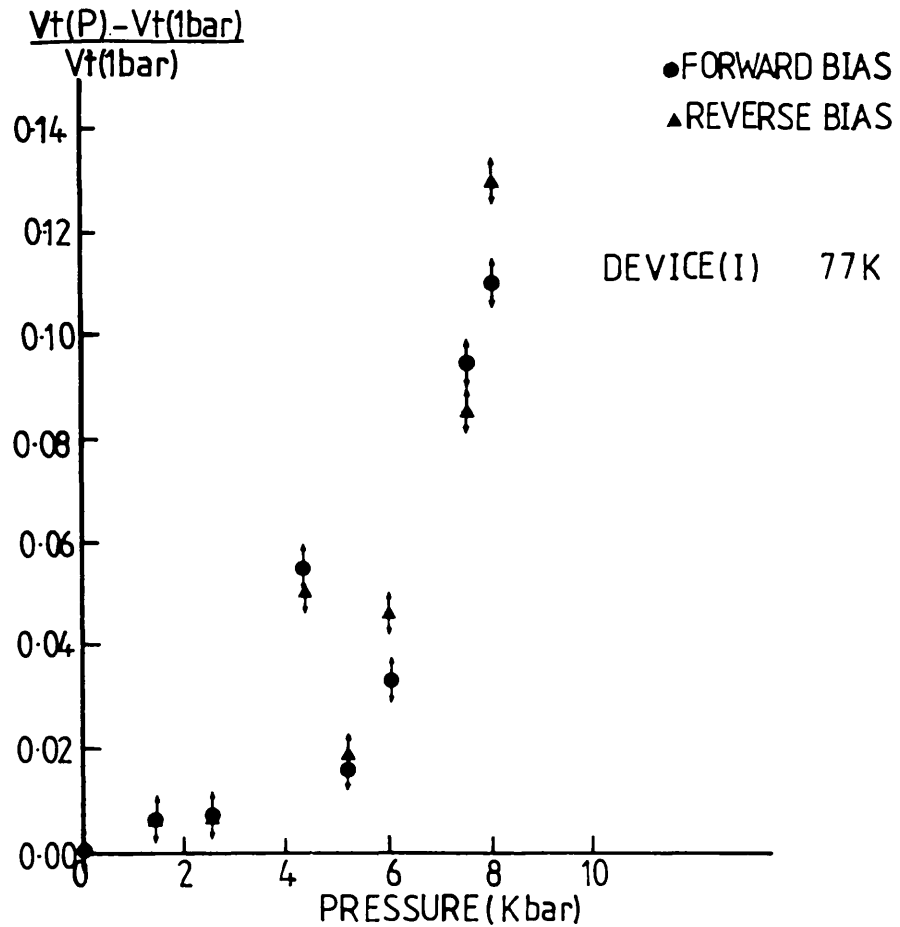


Fig.6.10 Fractional change in threshold voltage with pressure at 77K for device (i).

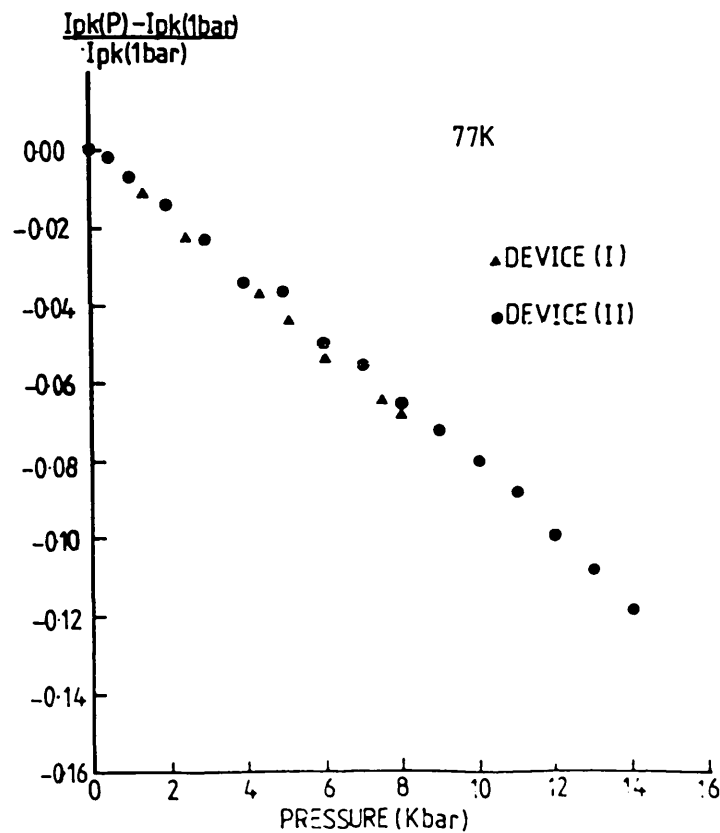


Fig.6.11 Fractional change in peak current with pressure at 77K for devices (i) and (ii).

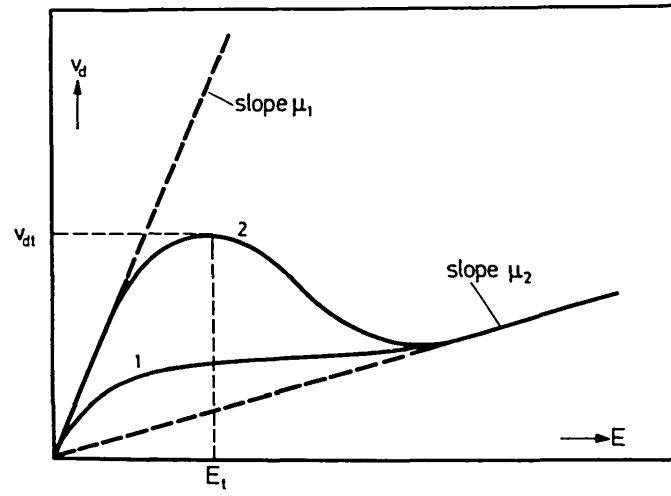


Fig.6.12 Drift velocity versus field characteristics for electron transitions from the central minimum (mobility μ_1) to the satellite valley (mobility μ_2).

CONCLUSIONS

The experiments performed in this thesis have used hydrostatic pressure as a means of varying the barrier height for electron tunnelling in double barrier and multiple barrier GaAs/Al_xGa_{1-x}As systems. The majority of experiments have been performed on GaAs/AlAs structures since the pressure sensitive $\Gamma_C(\text{GaAs})\text{-}X_C(\text{AlAs})$ barrier is the lowest in energy for this system. Pressure has been shown to have a profound effect on the size of the negative differential resistance (NDR), associated with electrons tunnelling into the quasi-bound states of the GaAs quantum well, when a pressure sensitive barrier is involved in the electron tunnelling process.

Experiments on a GaAs/AlAs system enclosed in the i-region of a p-i-n device have been performed under pressure. This GaAs/AlAs structure includes five AlAs barriers which become progressively thinner (asymmetric superlattice). The last three barriers do not significantly influence the electron transport through this device. A problem arose when analysing the data for these structures. This is caused by impurities, probably residing in the barriers, which introduce a non-resonant component in the I-V characteristic. This non-resonant component produced scatter in the results when the peak to valley current ratio versus pressure is plotted. This contribution is eliminated when the peak to valley current difference is plotted versus pressure. Then the pressure behaviour intrinsic to the GaAs/AlAs system can be analysed.

The results show that the size of the NDR is very sensitive

to pressure, the NDR is completely suppressed by ~ 8 Kbar at 77 K. This behaviour indicates that X-like states in the AlAs barriers are strongly involved in the electron tunnelling process even though the quasi-bound states in the quantum well are expected to be Γ -like.

To substantiate the above conclusions, pressure experiments were performed on a double barrier GaAs/AlAs structure of similar barrier and well dimensions to those which determine the NDR feature for the p-i-n device (i.e., 30 Å-70 Å-30 Å). This structure is enclosed in the i-region of a n-i-n device and includes spacer layers which separate the undoped barriers from the doped cladding layers. This device eliminates the possibility of a pressure dependent hole tunnelling process causing the loss of NDR. In addition, the spacer layers, not included in the p-i-n device, reduce the non-resonant impurity contributions to the tunnelling current. Therefore, the possibility of this process causing the loss of NDR with pressure is eliminated. Indeed, the scatter in results is reduced for this device. Moreover, although the p-i-n device and n-i-n device have very different peak to valley current ratios, their normalised peak to valley current differences exhibit very similar behaviour as a function of pressure. Therefore, it can be asserted that, for structures with AlAs barriers, the current is dominated by electrons tunnelling through X-like states in the barriers. The actual pressure threshold for complete loss of NDR is thought to be an intrinsic property of the GaAs/AlAs structure, depending on the well and barrier dimensions.

The pressure threshold for complete loss of NDR for a 30Å-70Å-30Å GaAs/AlAs double barrier structure is found to be ~8Kbar at 77K. On a simple level, this pressure threshold is consistent with the pressure at which the Γ -X barrier is approximately at the same energy as the quasi-bound state of the well associated with the NDR. For a 50Å-50Å-50Å GaAs/AlAs double barrier structure, Mendez et al. (3.8) have found that the pressure threshold for complete loss of NDR is ~1.5Kbar at 77K. This difference in pressure threshold cannot be explained solely in terms of the difference in confinement energy of the quasi-bound states in the well between the two structures. It is possible that the difference in pressure threshold can be explained by including the consideration that the transmission of thicker AlAs barriers is more strongly X-like, with a corresponding stronger pressure dependence. A complete understanding of the relationship between the pressure threshold for complete loss of NDR and the well and barrier dimensions of a GaAs/AlAs double barrier system, awaits further theoretical analysis. Moreover, an extensive experimental study of this relationship is also required.

High pressure experiments were also performed on a symmetric GaAs/AlAs superlattice enclosed in the i-region of a p-i-n device. This device is similar to the p-i-n device discussed above, but the barriers are of equal thickness rather than becoming progressively thinner. Four NDR features are observed for the symmetric superlattice, all of which are sensitive to pressure and, therefore, to the Γ -X barrier. Indeed, one of the NDR features exhibits very similar

pressure behaviour to the principal NDR feature of the asymmetric GaAs/AlAs superlattice and the principal NDR feature of the n-i-n GaAs/AlAs double barrier structure, discussed above. This is not surprising since this feature arises from the same intrinsic double barrier system (i.e., the same barrier and well dimensions) as the other two, and is associated with the same quasi-bound state of the quantum well ($n=1$). In addition, it is found for this symmetric superlattice that AlAs barriers not directly involved in the resonant tunnelling process appear to play an important role in determining the size of the different NDR features at 1bar, and their pressure behaviour.

For the GaAs/AlAs n-i-n device discussed earlier, Shubnikov-de Haas-like oscillations in the magneto-tunnelling current, at pressures of 1bar and 5Kbar, were obtained. The magnetoquantum oscillations observed occur over a limited voltage range of the I-V characteristic and are attributed to the Landau level structure of the degenerate two-dimensional electron gas (2DEG) in the accumulation layer of the emitter. By considering the time for ionised impurity scattering, the characteristic time for tunnelling through AlAs barriers, and the time of an electron cyclotron orbit, the apparent "strengthening" and "weakening" of the oscillations as the bias is increased, and the "weakening" of the oscillations with increased pressure for a given bias, are explained.

No NDR is observed for a double barrier GaAs/AlAs n-i-n device similar to the one discussed above but with thicker barriers and a thinner well ($50\text{\AA}$ - $15\text{\AA}$ - $50\text{\AA}$). The structure

behaves more like a single barrier system. From thermionic emission measurements at pressures of 1bar and 5Kbar on this structure, a value of 0.15eV is obtained for the $\Gamma_C(\text{GaAs})\text{-}X_C(\text{AlAs})$ barrier height with a pressure variation of -11meV/Kbar.

The effect of pressure on resonant tunnelling has been investigated in a system with a large $\Gamma_C(\text{GaAs})\text{-}X_C(\text{Al}_x\text{Ga}_{1-x}\text{As})$ barrier. This is a GaAs/ $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ double barrier structure. Up to ~10Kbar, the $\Gamma\text{-}\Gamma$ barrier is the lowest in energy for this system. This barrier is thought to be essentially independent of pressure. This is confirmed by the high pressure experiments: Below 10Kbar, the slow decrease in the size of the NDR, associated with electrons tunnelling into the first quasi-bound state of the well, is accounted for by the increase in $m^*(\Gamma)$ with pressure and a pressure independent $\Gamma\text{-}\Gamma$ barrier. Above 10Kbar, the pressure sensitive $\Gamma\text{-}X$ and $\Gamma\text{-}L$ barriers become lower in energy than the pressure insensitive $\Gamma\text{-}\Gamma$ barrier. This is reflected by the NDR exhibiting a strong pressure dependence: Above 10Kbar, the size of the NDR is suppressed rapidly with pressure indicating that X-like and/or L-like states in the $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ barriers are making a significant contribution to the electron tunnelling current. As mentioned above, the critical pressure of 10Kbar is approximately the pressure at which the L and X minima in the barriers become lower in energy than the Γ minimum. Therefore, an overview of the pressure measurements on GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ systems investigated, suggests that the resonant tunnelling process is determined by the lowest energy minimum in the barriers (Γ , L or X) even though the

states in the well are expected to be Γ -like. However, it is necessary to perform further investigations on systems with different well and barrier dimensions to this one, and on systems with different Al composition, x , in the barriers (varying x , changes the size of the different potential barriers). This is because, for the GaAs/Al_{0.33}Ga_{0.67}As system discussed here and for the GaAs/AlAs systems discussed above, it is not clearly understood how the pressure threshold for complete loss of NDR varies with these parameters.

Finally, experiments have been performed under pressure on GaAs Gunn devices, with and without a graded Al _{x} Ga_{1- x} As hot electron injector. The results suggest that the pressure behaviour of the NDR, associated with the Gunn mechanism, depends on the mechanism for electron heating as well as the bandstructure of GaAs.

APPENDIX 1

A NDR ELEMENT IN A RESONANT CIRCUIT

When investigating the I-V characteristic of a device exhibiting NDR, the device is found to oscillate when biased in the NDR region. These oscillations are controlled by the parameters of the electrical circuit. Consider the circuit in Fig.1. L represents any series inductances from the electrical leads connecting the circuit to the device, C represents a capacitor connected in parallel with the device, r refers to any series resistances due to the electrical leads, R_N represents the negative resistance of the device and V_O represents the constant applied voltage required to bias the device into the NDR region. The impedance of the circuit is

$$Z_{in} = A + Bj \quad \dots\dots\dots(A1)$$

$$= Z_O \cdot e^{j\phi} \quad \dots\dots\dots(A2)$$

where $Z_O = (A^2 + B^2)^{\frac{1}{2}}$ and $\tan\phi = B/A$. Resonance occurs when the current (I) through the circuit is a maximum, that is, when

$$I = V/Z = V/Z_O \cdot e^{-j\phi} \quad \dots\dots\dots(A3)$$

is a maximum, where V represents the applied voltage. For the circuit shown

$$LdI/dt + q/C + Ir = V_O \quad \dots\dots\dots(A4)$$

Differentiating this equation with respect to time gives

$$Ld^2I/dt^2 + i/C + r dI/dt = 0 \quad \dots\dots(A5)$$

Rearranging Eq.A5 gives

$$i = -rC \cdot dI/dt - LC \cdot d^2I/dt^2 \quad \dots\dots (A6)$$

$V_C = V_{RN}$, therefore

$$q/C = -R_N(I-i)$$

and differentiating this with respect to time gives

$$i/C = -R_N(dI/dt - di/dt) \dots\dots(A7)$$

Rearranging Eq.A7 gives

$$R_N.dI/dt = R_N.di/dt - i/C \dots(A8)$$

Substituting the expression for i in terms of I (Eq.A6)

$$R_N.dI/dt = -rCR_N.d^2I/dt^2 - LCR_N.d^3I/dt^3 + r.dI/dt + L.d^2I/dt^2 \dots\dots(A9)$$

Integrating Eq.A9 with respect to time and rearranging gives

$$d^2I/dt^2 + (r/L - 1/R_NC)dI/dt + (1/LC - r/R_NLC)I = 0 \dots(A10)$$

Since the current is oscillating at a frequency ω , $I = I_0.e^{j\omega t}$ can be substituted into Eq.A10 to give

$$\omega^2 - j\omega.(r/L - 1/R_NC) - (1/LC - r/R_NLC) = 0 \dots(A11)$$

If $r/L = 1/R_NC$, then the current will continue to oscillate with simple harmonic motion (SHM). That is, the circuit resonates when $r/L = 1/R_NC$ at a frequency $\omega = (1/LC)^{\frac{1}{2}}$.

The condition for which the oscillations are damped, that is the oscillations are suppressed, or the current is constant, can be found by solving Eq.A11. It is clear that for a damped or steady current, ω must be complex and positive or equal to zero respectively. Solving Eq.A11 gives

$$2\omega = j.(r/L - 1/R_NC) \pm 1/LR_NC.\{4LCR_N^2 - (rR_NC + L)^2\}^{\frac{1}{2}} \dots\dots(A12)$$

Since C is an external parameter of the circuit, it can be treated as a variable. For ω to be positive and complex, certain conditions can be placed on the value of C. They are

$$rR_NC \gg L \quad \text{and} \quad 4L/C \ll r^2 \dots\dots(A13)$$

With these conditions, Eq.A12 becomes

$$2\omega \approx j.(r/L) \pm j(r/L) \dots\dots(A14)$$

Therefore, $\omega = 0$ or $\omega = 2jr/L$. For $\omega = 0$, $I = I_0$ and so the current is constant. For $\omega = 2jr/L$, $I = I_0.exp(-2rt/L)$ and the oscillations are damped.

To suppress oscillations in a resonant circuit containing a NDR device biased in its NDR region, the conditions in Eq.A13 must be met. This requires a large capacitor in parallel with the device and a large value of R_N , the magnitude of the negative resistance. Typically, for $L \sim 10^{-6} \text{H}$, $r \sim 1\Omega$, and $C \sim 1\mu\text{F}$, this requires $R_N \gg 1\Omega$. This inequality is in good agreement with the value estimated by Sollner (1.31) who suggests that it is difficult to suppress the oscillations for negative resistances of less than $1\text{k}\Omega$.

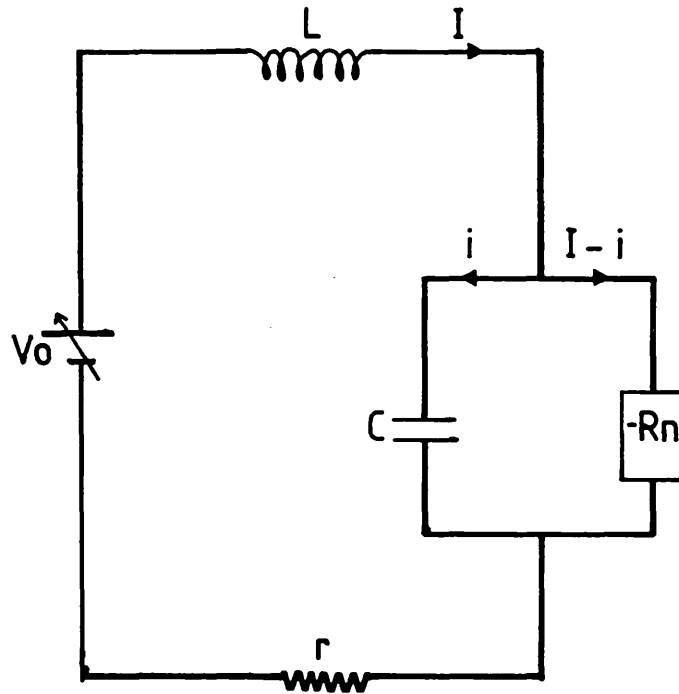


Fig.A1 Electrical circuit for measuring the I-V characteristic of the NDR element, $-R_N$. V_0 represents the voltage required to bias the element into the NDR region.