Shubnikov–de Haas effect and persistent photoconductivity in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$

E. Skuras and C. R. Stanley^{a)}

Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom

A. R. Long

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom

E. A. Johnson and A. MacKinnon

Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, United Kingdom

H. Yaguchi, M. van der Burgt, and J. Singleton

Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

(Received 21 May 1999; accepted for publication 24 August 1999)

The Shubnikov–de Haas effect in InAlAs measured using pulsed magnetic fields up to 50 T is reported. The InAlAs samples were grown by molecular beam epitaxy (MBE) and were either δ or slab doped with silicon at densities up to $7 \times 10^{12} \text{ cm}^{-2}$. Comparison of experimental subband densities with those calculated self-consistently shows that spreading of Si occurs by surface segregation at growth temperatures of $\sim 520^\circ\text{C}$, similar to its behavior in MBE-grown InGaAs . In contrast to InGaAs , the InAlAs exhibits persistent photoconductivity which appears to be caused by a bulk defect rather than $DX(\text{Si})$ states. © 1999 American Institute of Physics. [S0021-8979(99)00423-5]

Shubnikov–de Haas (SdH) measurements combined with self-consistent calculations (SCC) have been used to estimate the spreading of Si as a function of growth temperature in δ - and slab-doped InGaAs .^{1–3} However, the larger electron effective mass in InAlAs and its lower electron mobility mean that substantially higher magnetic fields are required to resolve the individual subbands for structures doped with comparable donor densities. In this communication, we report the observation of the SdH effect in InAlAs δ and slab doped with Si to densities of $N_{\text{Si}} \sim 7 \times 10^{12} \text{ cm}^{-2}$. Pulsed magnetic fields up to 50 T were needed to measure peaks due to depopulation of the Landau levels of the $i=0$ subband. A comparison of the SdH data with SCC provides an estimate of Si spreading at growth temperatures T_S around 520°C . Persistent photoconductivity (PPC) due to deep states in the InAlAs has been observed, and evidence is presented which rules against $DX(\text{Si})$ centers as the cause.

The Si δ - and slab-doped InAlAs layers were grown lattice matched on Fe– $\text{InP}(100)$ by molecular beam epitaxy (MBE) in a constant As_2 flux of $\approx 2.0 \times 10^{15} \text{ molecules cm}^{-2} \text{ s}^{-1}$. The growth rate was $1.0 \text{ }\mu\text{m/h}$ and the growth temperature was varied between $T_S \approx 460$ and 520°C . A series of 0.5 – $2.0 \text{ }\mu\text{m}$ thick InGaAs layers doped uniformly with Si at concentrations ranging from 5×10^{16} to $4 \times 10^{19} \text{ cm}^{-3}$ was grown and analyzed by SdH measurements to calibrate the Si dopant density (N_{Si}) against the Si furnace temperature. The δ - or slab-doped region of the wide range of samples investigated was deposited on $0.5 \text{ }\mu\text{m}$ of undoped (un-) InAlAs and covered by a further $0.5 \text{ }\mu\text{m}$ of un- InAlAs .

A $100 \text{ }\text{\AA}$ cap layer of un- InGaAs was grown to assist the formation of ohmic contacts on Hall bars with a 3:1 length to width ratio. The quantum transport measurements were carried out at 4.2 K with a 0–50 T pulsed magnetic field system⁴ and at 1.2 K in a 0–13 T superconducting magnet. The electron subband densities $n_i = 2e\nu_i/h$ ($i=0,1,2,\dots$) were calculated from the peaks in the fast Fourier transform (FFT) spectra of the SdH data assuming, unresolved spin splitting. ν_i is the magnetic frequency of the i th peak, e is the electron charge, and h is Planck's constant. For the PPC study, the samples were cooled to 4.2 K in the dark, illuminated with a red light emitting diode (LED) until the zero magnetic field longitudinal resistance stopped increasing, and then measured 1 and 14 h after illumination.

Two representative samples, B689 and A1337, have been selected to illustrate the new data. B689 was grown entirely at $T_S \sim 520^\circ\text{C}$ and was δ doped with $N_{\text{Si}} = 7 \times 10^{12} \text{ cm}^{-2}$. A1337 was δ doped to $\sim 5 \times 10^{12} \text{ cm}^{-2}$ and was also grown at 520°C , except for 10 monolayers (ML) of un- InAlAs deposited over the δ doping at 470°C with the aim of inhibiting dopant spreading.^{1,2} SdH curves for A1337 before [curve (a)] and after [curve (b)] illumination are shown in Fig. 1. The two sets of data represent measurements in the pulsed magnetic field system at flux densities up to 50 T, and the 13 T superconducting magnet (inset). Agreement in the 0–13 T range where the two measurement systems can be compared directly is excellent. The $i=0$ subband, which is vital for estimating Si spreading, could only be measured with the 0–50 T magnet.

The experimental values of n_i and the subband density ratio $n_{i=0}/n_{i=1}$ for B689 and A1337 are summarized in Table I. The table includes n_i and the Fermi energy E_F ob-

^{a)}Electronic mail: C.Stanley@elec.gla.ac.uk

FIG. 1. Shubnikov-de Haas oscillations in the range 0–50 T for A1337 (InAlAs δ doped with $N_{\text{Si}} \sim 5 \times 10^{12} \text{ cm}^{-2}$); (a) before and (b) after illumination. The inset shows the equivalent curves recorded between 0 and 13 T in a superconducting magnet.

tained from SCC assuming Si donors distributed uniformly through a thickness w_{Si} . Since the total free electron density in InAlAs ($\sum_i n_i$) increases on illumination, in contrast to InGaAs where it remains unchanged, the ionized Si donor density N_D^+ has been set equal to $\sum_i n_i$ after illumination for the purposes of the SCC. Earlier analysis of InGaAs layers δ and slab doped with Si grown under comparable conditions^{1,2} has shown that Si migrates by surface segregation rather than diffusion at temperatures between $T_S \sim 470$ and 520°C . Similar behavior has been found here for InAlAs, and the estimates for Si spreading in B689 and A1337 are ~ 56 and 2 ML , respectively. A reference sample A1340 with $30 \text{ ML un-InAlAs}-20 \text{ ML Si-InAlAs}$ (uniformly doped)— 30 ML un-InAlAs grown at $\sim 460^\circ\text{C}$ between $0.5 \mu\text{m}$ thick un-InAlAs buffer and cladding layers deposited at 520°C was also analyzed. Agreement between the SdH data and SCC calculations for this sample is good when a uniform distribution of width $w_{\text{Si}} = 20 \text{ ML}$ is assumed, the value expected when Si spreading is absent. We conclude therefore

that surface segregation causes spreading of Si atoms away from the initial doping plane in MBE-grown InAlAs, in a manner similar to that seen in InGaAs. Spreading can be prevented by “encapsulating” the Si-doped region with a thin layer of InAlAs grown at $T_S < 470^\circ\text{C}$, even though subsequent material is deposited at much higher temperatures.

The different Si dopant profiles in B689 and A1337 are also manifest in the discrepancies between the total electron densities deduced from SdH measurements ($n_{\text{SdH}} = \sum_i n_i$) and those calculated from low magnetic field Hall measurements (n_H). The values after illumination are

$$\text{B689: } n_{\text{SdH}} = 6.8 \times 10^{12} \text{ cm}^{-2}, \quad n_H = 6.2 \times 10^{12} \text{ cm}^{-2},$$

$$\text{A1337: } n_{\text{SdH}} = 4.8 \times 10^{12} \text{ cm}^{-2}, \quad n_H = 3.1 \times 10^{12} \text{ cm}^{-2}.$$

Note that there are similar differences before illumination of the samples. The lower values of n_H are a direct result of having spatially confined donors in a multisubband system with different individual subband mobilities. The discrepancy between n_H and n_{SdH} increases for a given density of donors as the impurities become more and more confined, as was discussed in Ref. 5 for δ -doped InGaAs.

The second set of SdH curves for A1337 shown in Fig. 1 [labeled (b)] was recorded 14 h after the sample had been illuminated with a LED; the curves are essentially identical to ones recorded 13 h earlier. A decrease of the zero magnetic field resistivity is measured and a shift to higher magnetic fields is observed for the magnetoresistance minima and maxima, indicating a persistent increase in the electron subband densities.⁶ The effect of this PPC is seen in the FFT spectra of the SdH data; Fig. 2 shows the results for the second sample, B689. The change in the electron density of the $i=0$ subband is very small, $\sim 2 \times 10^{10} \text{ cm}^{-2}$. The $i=1$ and $i=2$ peaks shift to higher frequencies corresponding to increases of $\sim 6 \times 10^{10}$ and $\sim 1 \times 10^{11} \text{ cm}^{-2}$, respectively in the electron density occupying these levels after illumination. The $i=3$ peak is resolved after illumination with $n_3 \sim 3.7 \times 10^{11} \text{ cm}^{-2}$. The general trend is for the change in electron density after illumination to increase with subband index.⁶ Since the $i=3$ level could not be measured in the dark, the change in its electron density cannot be estimated,

TABLE I. Experimental electron subband densities n_i ($\times 10^{12} \text{ cm}^{-2}$) for samples B689 and A1337 before and after illumination, calculated from the peaks in the FFT spectra of the Shubnikov-de Haas data. The values of n_i calculated self-consistently are also listed, together with the subband density ratio $n_{i=0}/n_{i=1}$, the estimated Si spreading in monolayers (ML) for a best fit between the SdH and SCC subband densities (assuming a uniform distribution of dopant atoms), and the Fermi energy (E_F).

Parameter	B689			A1337		
	Before illumination	After illumination	Calculated	Before illumination	After illumination	Calculated
$n_{i=0}$	3.25	3.27	3.252	3.25	3.27	3.298
$n_{i=1}$	2.06	2.12	2.114	1.06	1.11	1.094
$n_{i=2}$	0.94	1.04	1.038	0.36	0.45	0.412
$n_{i=3}$	?	0.37	0.385	...	...	0.096
$n_{i=4}$	...	...	0.11	...	...	...
Total ($\sum n_i$)	6.25(?)	6.80	6.90	4.67	4.83	4.90
$n_{i=0}/n_{i=1}$	1.578	1.542	1.538	3.066	2.945	3.015
Spreading (ML)			56 ML			2 ML
E_F (meV)			104.5			153.4

FIG. 2. Fast Fourier transform (FFT) spectra for B689 (a) before and (b) after illumination. The two curves have been displaced vertically for clarity. Note that the $i=3$ subband is only measured after illumination, and that the change in subband densities following illumination increases with subband index.

but it is expected to be comparable to that for the $i=2$ level. This is a result of the wide dopant distribution in B689 and the correspondingly closer energy separation between states near the top of the potential well. The total increase in the free electron density for sample B689 is thus $>2 \times 10^{11} \text{ cm}^{-2}$ while that for A1337 ($N_D \sim 5 \times 10^{12} \text{ cm}^{-2}$) is $1.6 \times 10^{11} \text{ cm}^{-2}$, comparable to the increase after illumination in the two dimensional electron density of an InGaAs–InAlAs modulation doped heterostructure reported by Lo et al.⁷

PPC in InAlAs has been ascribed to both intrinsic^{8–10} and extrinsic defects;^{11,12} for example, native defects involving an As antisite⁹ and deep acceptor states¹⁰ have both been proposed. Recently, Sari and Wieder¹¹ have observed PPC in $\text{In}_{1-x}\text{Al}_x\text{As}$ ($0.1 \leq x \leq 0.34$) due to DX centers which pin the Fermi level (E_F) to an average energy 0.3 eV below the lowest conduction band minimum. The DX center is resonant with the Γ -conduction band for $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, with an energy at ambient pressure ~ 180 meV above the Γ minimum.¹² Negatively charged DX centers in the samples analyzed here would be confined in the vicinity of the Si donor atoms. Therefore, an increase in the electron density of all occupied subbands should be observed after illumination as the DX centers revert to singly ionized shallow donor states.^{13,14} In contrast, electron trapping states not connected to Si but distributed uniformly throughout the InAlAs will pin E_F in a manner similar to background acceptors.^{15–18} Such states will cause preferential removal of free electrons from the higher subbands of the δ -doped region; this is the observed response for the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ samples discussed here. In addition, the calculated Fermi energies for B689 and A1337 after illumination are 104.5 and 153.4 meV, respec-

tively, much lower than the estimate of 180 meV when DX centers are occupied.¹² A Si density of $6 \times 10^{12} \text{ cm}^{-2}$ distributed uniformly in 2 ML would be needed to produce $E_F = 180$ meV. Although B689 was doped to a higher Si density ($N_{\text{Si}} \approx 7 \times 10^{12} \text{ cm}^{-2}$), Si spreading of ~ 56 ML reduces E_F to 104.5 meV (Table I). The value of E_F for the same concentration of Si donors distributed in 2 ML is 196 meV. We conclude therefore that the centers responsible for the PPC in our δ - and slab-doped InAlAs layers are more likely to be bulk defects rather than DX(Si).

In conclusion, Shubnikov–de Haas oscillations in lattice-matched InAlAs δ and slab doped with Si have been reported. The Si donors spread by an estimated 56 ML via surface segregation at a growth temperature of $\approx 520^\circ\text{C}$ with $N_{\text{Si}} \approx 7 \times 10^{12} \text{ cm}^{-2}$, similar to the values observed in InGaAs.^{1,2} Spreading can be prevented by “encapsulating” the Si-doped region with a thin layer of InAlAs grown at $T_S < 470^\circ\text{C}$, even though subsequent material is grown at higher temperatures. In contrast to MBE-grown InGaAs, InAlAs δ and slab doped with Si exhibits persistent photoconductivity. The available experimental and theoretical data suggest that its origin is a bulk defect(s) rather than DX(Si) states.

The authors acknowledge financial support for the work from the U.K. Engineering and Physical Sciences Research Council.

- ¹M. McElhinney, B. Vögele, M. C. Holland, C. R. Stanley, E. Skuras, A. R. Long, and E. A. Johnson, Appl. Phys. Lett. **68**, 940 (1996).
- ²B. Vögele, C. R. Stanley, E. Skuras, A. R. Long, and E. A. Johnson, J. Cryst. Growth **175/176**, 229 (1997).
- ³M. Zervos, A. Bryant, M. Elliott, M. Beck, and M. Illegems, Appl. Phys. Lett. **72**, 2601 (1998).
- ⁴H. Jones, R. G. Jenkins, M. van Kleemput, R. J. Nicholas, W. J. Siertsma, and M. van der Burgt, Physica B **201**, 546 (1994).
- ⁵E. Skuras, A. R. Long, B. Vögele, M. C. Holland, C. R. Stanley, E. A. Johnson, M. van der Burgt, H. Yaguchi, and J. Singleton, Phys. Rev. B **59**, 10712 (1999).
- ⁶G. Li and C. Jagadish, Appl. Phys. Lett. **70**, 90 (1997).
- ⁷I. Lo, D. P. Wang, K. Y. Hsieh, T. K. Wang, W. C. Mitchel, M. Ahoujja, J.-P. Cheng, A. Fathimulla, and H. Hier, Phys. Rev. B **52**, 14671 (1995).
- ⁸W. P. Hong, S. Dhar, P. K. Bhattacharya, and A. Chin, J. Electron. Mater. **16**, 271 (1993).
- ⁹E. Calleja, A. L. Romero, S. Fernández de Avila, E. Muñoz, and J. Castagné, Semicond. Sci. Technol. **8**, 206 (1993).
- ¹⁰J. P. Praseuth, L. Goldstein, P. Henoc, J. Primot, and G. Danan, J. Appl. Phys. **61**, 215 (1987).
- ¹¹H. Sari and H. H. Wieder, J. Appl. Phys. **68**, 3380 (1999).
- ¹²F. E. Fruth, J. M. Sallese, M. Beck, D. K. Maude, U. Wilke, M. Rabary, J. C. Portal, and M. Illegems, Solid State Commun. **89**, 323 (1994).
- ¹³E. Skuras, R. Kumar, R. L. Williams, R. A. Stradling, J. E. Dmochowski, E. A. Johnson, A. MacKinnon, J. J. Harris, R. B. Beall, C. Skierbiszewski, J. Singleton, P. J. van der Wel, and B. P. Wisniewski, Semicond. Sci. Technol. **6**, 535 (1991).
- ¹⁴A. Zrenner, F. Koch, R. L. Williams, R. A. Stradling, K. Ploog, and G. Weimann, Semicond. Sci. Technol. **3**, 1203 (1988).
- ¹⁵E. A. Johnson and A. MacKinnon, Superlattices Microstruct. **9**, 441 (1991).
- ¹⁶G. Q. Hai, N. Studart, and F. M. Peeters, Phys. Rev. B **52**, 8363 (1995).
- ¹⁷A. B. Henriques, Phys. Rev. B **53**, 16365 (1996).
- ¹⁸E. Skuras, A. R. Long, B. Vögele, M. C. Holland, C. R. Stanley, E. A. Johnson, and A. MacKinnon, Appl. Phys. Lett. **74**, 973 (1999).