Shubnikov–de Haas effect and persistent photoconductivity in In$_{0.52}$Al$_{0.48}$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 $7 \times 10^{12}$ 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 $\sim 520^\circ$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(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 $N_{Si} \sim 7 \times 10^{12}$ 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(Si) centers as the cause.

The Si δ- and slab-doped InAlAs layers were grown lattice matched on Fe–InP(100) by molecular beam epitaxy (MBE) in a constant $A_S$ flux of $\sim 2.0 \times 10^{15}$ molecules cm$^{-2}$ s$^{-1}$. The growth rate was 1.0 μm/h and the growth temperature was varied between $T_S \sim 460$ and 520°C. A series of 0.5–2.0 μm thick InGaAs layers doped uniformly with Si at concentrations ranging from $5 \times 10^{16}$ to $4 \times 10^{19}$ 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 μm of undoped (un-) InAlAs and covered by a further 0.5 μm of un-InAlAs.

A 100 Å 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 system$^4$ and at 1.2 K in a 0–13 T superconducting magnet. The electron subband densities $n_i = 2e\nu_i/h$ ($i = 0,1,2,...$) were calculated from the peaks in the fast Fourier transform (FFT) spectra of the SdH data assuming, unresolved spin splitting. $\nu_i$ 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 down 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 $T_S \sim 520^\circ$C and was δ doped with $N_{Si} \sim 7 \times 10^{12}$ cm$^{-2}$. A1337 was δ doped to $\sim 5 \times 10^{12}$ 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.$^{1,3}$ 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 $n_i/\nu_i$ 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
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 \( T_s < 470 \) °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 \( (n_{\text{SdH}} = \Sigma n_i) \) 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 \( n_{\text{SdH}} \) increases for a given density of donors as the impurities become more and more confined, as was discussed in Ref. 5 for \( \delta \)-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. 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, \(~2 \times 10^{10} \text{ cm}^{-2}\). The \( i=1 \) and \( i=2 \) peaks shift to higher frequencies corresponding to increases of \( \sim 6 \times 10^{10} \) and \(~1 \times 10^{11} \text{ cm}^{-2}\), 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. 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 \( (E_F) \).

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

FIG. 1. Shubnikov–de Haas oscillations in the range 0–50 T for A1337 (InAlAs, \( \delta \) doped with \( N_{\text{Si}} = 5 \times 10^{12} \text{ cm}^{-2} \)); (a) before and (b) after illumination. The inset shows the equivalent curves recorded between 0 and 13 T in a superconducting magnet.
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 $> 2 \times 10^{11}$ cm$^{-2}$ while that for A1337 ($N_D \sim 5 \times 10^{12}$ cm$^{-2}$) is $1.6 \times 10^{11}$ 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 antisite$^9$ and deep acceptor states$^{10}$ have both been proposed. Recently, Sari and Wiedner$^{11}$ have observed PPC in In$_{1-x}$Al$_x$As ($0.1 \lesssim x \lesssim 0.34$) 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 $\Gamma$-conduction band for In$_{0.52}$Al$_{0.48}$As, with an energy at ambient pressure $\sim 180$ meV above the $\Gamma$ 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 $\delta$-doped region; this is the observed response for the In$_{0.52}$Al$_{0.48}$As samples discussed here. In addition, the calculated Fermi energies for B689 and A1337 after illumination are 104.5 and 153.4 meV, respectively, much lower than the estimate of 180 meV when DX centers are occupied.$^{12}$ A Si density of $6 \times 10^{12}$ 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 ($N_{Si} \sim 7 \times 10^{12}$ cm$^{-2}$), Si spreading of $\sim 56$ 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 $\delta$- 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 $\delta$ 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 $\sim 520$ °C with $N_{Si} \sim 7 \times 10^{12}$ cm$^{-2}$, similar to the values observed in InGaAs.$^3,2$ Spreading can be prevented by “encapsulating” the Si-doped region with a thin layer of InAlAs grown at $T_S \lesssim 470$ °C, even though subsequent material is grown at higher temperatures. In contrast to MBE-grown InGaAs, InAlAs $\delta$ 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.