

Quantum Hall effect in InAs/AlSb quantum wells

P. F. Hopkins,^{a)} A. J. Rimberg, and R. M. Westervelt
Division of Applied Sciences and Department of Physics, Harvard University, Cambridge,
Massachusetts 02138

G. Tuttle and H. Kroemer
Department of Electrical and Computer Engineering, University of California, Santa Barbara,
California 93106

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We demonstrate via low-temperature electron transport measurements the realization of a high-mobility ($> 300\,000\text{ cm}^2/\text{V s}$) two-dimensional electron gas in unintentionally doped InAs/AlSb single 120 \AA quantum wells grown on GaAs substrates by molecular beam epitaxy. Magnetoresistance and Hall measurements at $T \sim 0.4\text{ K}$ show a well-formed quantum Hall effect, with effects due to spin splitting observed at filling factors as high as $\nu = 17$. The electron densities of these wells could be reduced by a factor ~ 5 by using the negative persistent photoconductivity of these samples.

Quantum well structure made from InAs, with barriers made from AlSb, GaSb, or (Al,Ga)Sb alloys, possibly with the addition of As to the barrier, are natural candidates for the study of low-temperature magnetotransport effects such as the quantum Hall effect and the Shubnikov-de Haas effect. Of all binary III/V compounds, InAs has the second highest *intrinsic* electron mobility. Only InSb has a higher mobility, but it suffers from the absence of an approximately lattice-matched barrier material that would permit the construction of quantum wells with low-defect barrier interfaces, necessary for highest mobility transport. In the present work, we report on InAs quantum wells with straight (unalloyed) AlSb barriers, of the kind reported earlier by Tuttle *et al.*^{1,2} Although slightly less well lattice matched and technologically slightly more difficult to grow than GaSb or (Al,Ga)Sb barriers, AlSb barriers have the advantage that they eliminate complications due to a broken-gap band structure at the interface. These complications are of interest in their own right, and were in fact recently studied by MuneKata *et al.*³ but in the present work it was desired to avoid them.

Quantum wells of InAs/AlSb were first studied by Chang *et al.*,⁴ who also reported the first observation of the quantum Hall effect in such structures. However, those early samples still suffered from relatively low mobilities ($\sim 15\,000\text{ cm}^2/\text{V s}$), and the transport measurements were made only down to $T \sim 4.2\text{ K}$, so that much detail remained unresolved. In the years since the pioneering work of Chang *et al.*, great improvements in the technology of the InAs/AlSb have been made. Low-temperature ($\leq 10\text{ K}$) mobilities up to $330\,000\text{ cm}^2/\text{V s}$ were reported by Tuttle *et al.*² in 1989, and more recently, a value as high as $613\,000\text{ cm}^2/\text{V s}$ has been reported by Chalmers *et al.*⁵ in a quantum well with a modified interface structure. The work reported here is a continuation of the earlier work of Tuttle *et al.*, drawing on the same high-mobility samples, and extending the magnetotransport measurements down

to $T \sim 0.4\text{ K}$.

More specifically, we report on low-temperature magnetoresistance and Hall effect data on two 120 \AA InAs/AlSb quantum well samples, with the magnetic field applied perpendicularly and parallel to the plane of the electron layer. These data provide evidence for a high quality, high-mobility, two-dimensional electron gas layer in these wells.

The unintentionally doped 120 \AA InAs/AlSb samples discussed in the present letter were grown by molecular beam epitaxy on GaAs substrates, with InSb-like quantum well interfaces, as described by Tuttle *et al.*² Because of the lattice mismatch (7%) between the InAs/AlSb system and GaAs, we expect the samples to have threading dislocation densities of 10^7 cm^{-2} or higher,¹ and one of the objectives of this study was to see if these dislocations posed a serious obstacle in obtaining high-quality two-dimensional (2D) transport. Hall bars ($7 \times 3\text{ mm}^2$) with three pairs of Hall voltage probes were photolithographically defined, and contacts were made to the electron gas by alloying dots of indium at $300\text{ }^\circ\text{C}$ for 5–10 min. The samples were immersed in He-3 to temperatures $T \sim 0.4\text{ K}$, and measured in magnetic fields to 23 T at the Francis Bitter National Magnet Laboratory. Transverse magnetoresistance and Hall effect measurements were taken with the applied magnetic field B perpendicular to the plane of the electron layer. The two distinct magnetoresistance measurements with B in the plane of the electron layer were taken, with B parallel and perpendicular to the current. All resistance measurements were taken using low-frequency (typically 11 Hz) ac lock-in techniques; the current bias levels ($< 0.2\text{ }\mu\text{A}$) and magnetic field ramp rates ($< 1\text{ T/min}$) were kept low to avoid sample heating. Illumination of the samples to reduce the carrier density via the negative persistent photoconductivity effect² was done at $< 77\text{ K}$ with a red (640 nm measured at 77 K) or green (560 nm at 77 K) light-emitting diode (LED) mounted near the sample. Several sheets of filter paper were used as a diffuser to insure more uniform illumination of the sample; this was checked by comparing data from different contact pairs. In addition, care was taken to insure that no room light reached the

^{a)}Current address: Materials Department, University of California, Santa Barbara, CA 93106.

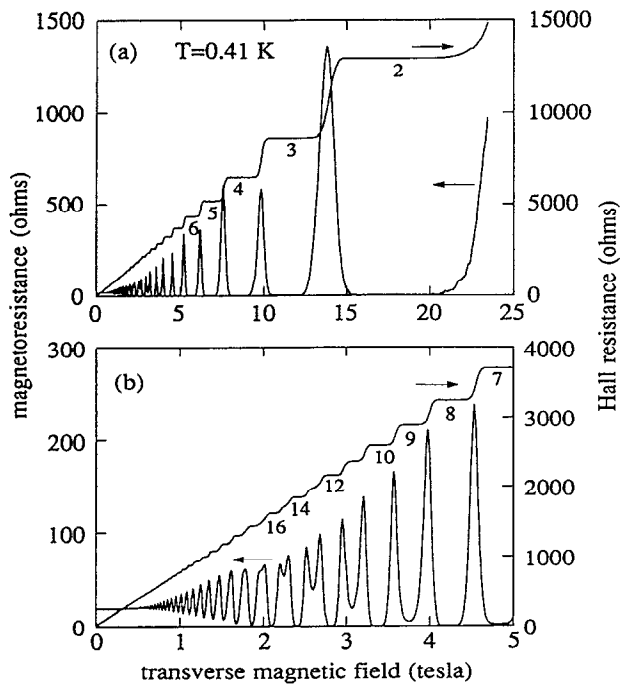


FIG. 1. Transverse magnetoresistance and Hall resistance at $T = 0.41$ K for the unilluminated sample with $n_s = 8.3 \times 10^{11} \text{ cm}^{-2}$: (a) 0–23 T; (b) 0–5 T.

sample when cooled down; this was verified by the reproducibility of the unilluminated magnetoresistance and Hall data over several cooldowns.

The low-temperature magnetoresistance and Hall resistance for the unilluminated sample with the magnetic field applied perpendicular to the electron layer is shown in Figs. 1(a) and 1(b). Figure 1(a) shows the $T = 0.41$ K data up to 23 T for the sample, which has a low-temperature carrier density $n_s = 8.3 \times 10^{11} \text{ cm}^{-2}$ and a zero magnetic field mobility $\mu = 320\,000 \text{ cm}^2/\text{V s}$. Figure 1(b) shows the 0–5 T range from Fig. 1(a) in more detail. At this temperature, well-formed quantized Hall plateaus and zeroes in the magnetoresistance can be observed; resistance minima touch zero as low as $B = 2.2$ T, corresponding to the filling factor $\nu = 16$. The quantized Hall resistance plateaus occur at the values $R_{xy} = h/\nu e^2$, to the accuracy of the measurements. Spin splitting is apparent in Fig. 1(b) up to a filling factor $\nu = 17$ at $B \sim 2.0$ T, indicating a spin splitting large compared to the thermal broadening of the Landau levels. This is what one might expect from the large effective bulk g factor⁶ for InAs, $g = -15$ (compared to $g = -0.44$ for GaAs). Magnetoresistance measurements in tilted magnetic fields could be used to check the magnitude of the g factor quantitatively, and to determine whatever exchange enhancement it might exhibit.⁷ Note that the data in Figs. 1(a) and 1(b) show no evidence for the fractional quantum Hall effect.

The Fourier transform of the low-field (< 2 T) magnetoresistance versus $1/B$ data shows a strong peak at a single frequency f_b , indicating a single occupied subband; this frequency $f_i = (h/2e)n_s$ corresponds to the same total density as that given by the slope of the Hall resistance.

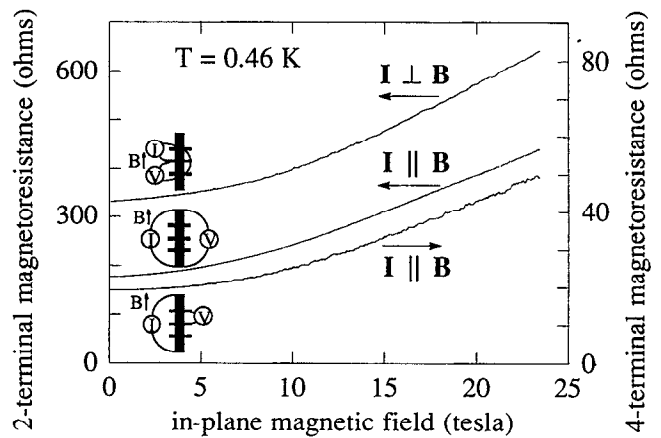


FIG. 2. Magnetoresistance and Hall resistance for the unilluminated sample at $T = 0.46$ K and 0–23 T with the magnetic field applied in the plane of the electron layer. Data were taken both for the current I along B , $I \parallel B$, and perpendicular to B , $I \perp B$. The two-terminal and four-terminal resistances for $I \parallel B$ and the two-terminal resistance for $I \perp B$ are shown.

This agreement and the presence of zero-resistance minima both argue against the existence of parallel conducting paths in these samples under these experimental conditions. In addition, the constant average slope of the Hall resistance and the observed field positions of the zero resistance minima indicate that in the range 0–23 T no apparent loss of carriers is occurring with increasing magnetic field.

Figure 2 shows the magnetoresistances up to 23 T for two orientations with of magnetic field applied in the plane of the electron layer: (a) current I parallel to the field, $I \parallel B$, and (b) current perpendicular to the field, $I \perp B$. For the orientation $I \parallel B$, the Hall bar was oriented lengthwise along B , with the current biased along the sample and the voltage measured across the current probes (two-terminal resistance) and across two voltage probes (four-terminal resistance). To obtain the $I \perp B$ measurement, the sample was left in the same orientation with respect to B but current biased through the middle Hall voltage probe pair.

The data in Fig. 2 show a weak monotonic increase, and suggest that the magnetoresistance with applied field in the plane is isotropic with respect to the current direction. The four-terminal resistance increases roughly as B^2 . The absence of oscillations in the magnetoresistances for B in the plane demonstrate the two-dimensional behavior of the electron gas. Using the measured sheet density and effective mass $m^*/m_e = 0.023$, we obtain a Fermi energy of 90 meV, much less than that needed to occupy a second subband in these wells in zero magnetic field,⁸ in agreement with the data. We note that the magnetic length $l_m = \sqrt{\hbar/eB}$ is equal to one-half the well width of 120 Å at $B = 18$ T.

Using the negative persistent photoconductivity of these samples, we were able to reduce the carrier density of the wells. With increasing illumination the zero-field resistance increases along with the slope of the Hall resistance and the period of the Shubnikov–de Haas oscillations, all corresponding to the decrease in electron density in the

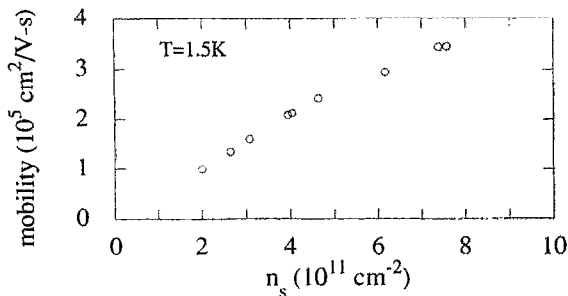


FIG. 3. Hall mobility vs sheet density measured at $T = 1.5$ K for a series of illuminations with both the red and green LEDs.

wells. Magnetoresistance and Hall resistance data for two pairs of contacts were compared and were found to agree for all illumination levels.

Figure 3 shows a composite plot of the $T = 1.5$ K measured Hall mobilities versus sheet densities, for illuminations at low temperatures with both the red and green LEDs separately; the sample was warmed to room temperature between the red illuminations and the green illuminations. With the red LED we were able to reduce n_s by a factor of ~ 2 , and with green by a factor of ~ 5 . The mobility has an sublinear dependence on sheet density; such a sublinear dependence is expected in GaAs/(Al,Ga)As heterostructures when the scattering is dominated by the background doping in the well.⁹ We found that the mobility does not depend on the illumination photon energy, but that the $\mu(n_s)$ carrier density after saturation with illumination does.

The data of Fig. 3 are consistent with the model of the negative persistent photoconductivity effect given by Tuttle *et al.*,¹ according to which the illumination creates electron-hole pairs in the AlSb barriers [$E_g(300\text{ K}) = 1.55\text{ eV} \rightarrow 800\text{ nm}$]. The holes are attracted and captured by the well, where they recombine with electrons inside the well to reduce n_s . The electrons in the AlSb fail to overcome the repulsive barrier at the edges of the well, and are captured by ionized deep donors in the AlSb. However, this model does not readily explain why the green LED has a larger effect on the carrier density than the red LED when both are used to saturation. No attempt was made to resolve this question.

To study the extreme quantum limit in these samples at obtainable magnetic fields, one sample was illuminated with the green LED until saturation to obtain the lowest carrier density $n_s = 1.7 \times 10^{11}\text{ cm}^{-2}$ ($\mu = 88\,000\text{ cm}^2/\text{V s}$). Figure 4 shows the $T \sim 0.5\text{ K}$, 0–23 T magnetoresistance and Hall resistance data for this carrier density. Data were taken in both transverse magnetic field directions (normal and reversed) and subtracted to remove any re-

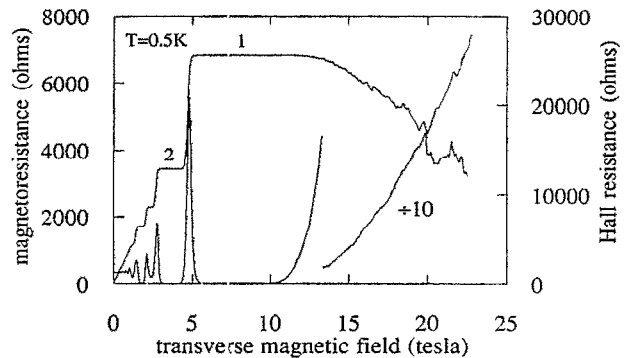


FIG. 4. Transverse magnetoresistance and Hall resistance at $T = 0.5$ K for the illuminated sample with $n_s = 1.7 \times 10^{11}\text{ cm}^{-2}$.

sidual magnetoresistance pickup in the Hall voltage probes due to misalignment. For fields above the $\nu = 1$ plateau, this pickup was substantial ($\sim 50\%$ of the Hall signal) because of the sharply increasing magnetoresistance. Beyond the $\nu = 1$ Hall plateau, both the magnetoresistance and the Hall resistance become “noisy”, with the magnetoresistance increasing sharply and the Hall resistance dropping. No evidence of the fractional quantum Hall effect can be seen in these data.

In conclusion, we have investigated the low-temperature magnetoresistance and Hall effect of 120 \AA InAs/AlSb single quantum wells grown on GaAs substrates by Tuttle *et al.*^{1,2} We find that the wells contain a high-mobility 2D electron gas which shows quantum Hall effect behavior.

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¹G. Tuttle, H. Kroemer, and J. English, in *III-V Heterostructures for Electronic/Photonic Devices*, edited by C. Tu, V. D. Motta, and A. C. Gossard, MRS Symposia Proceedings, San Diego, Aug. 1990, Vol. 145 (Materials Research Society, Pittsburgh, 1989), p. 393.

²G. Tuttle, H. Kroemer, and J. H. English, *J. Appl. Phys.* **65**, 5239 (1989).

³H. Munekata, T. P. Smith, and L. L. Chang, *J. Cryst. Growth* **95**, 235 (1989).

⁴C. A. Chang, L. L. Chang, E. E. Mendez, M. S. Christie, and L. Esaki, *J. Vac. Sci. Technol. B* **2**, 214 (1984).

⁵S. A. Chalmers, H. Kroemer, and A. C. Gossard, Proceedings of the 7th International Conference on Molecular Beam Epitaxy, *J. Cryst. Growth* (to be published).

⁶J. Konopka, *Phys. Lett. A* **26**, 29 (1967).

⁷See, for example, T. Ando, A. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 551 (1982).

⁸For an empty 120 \AA well with infinite barriers, the energy level spacing is $E_2 - E_1 \sim 260\text{ meV}$, ignoring nonparabolicity.

⁹A. Gold, *Appl. Phys. Lett.* **54**, 2100 (1989).