1-15-1985

New Shubnikov-de Haas Effects in a Two-Dimensional Electron-Hole System

S. Washburn

Richard A. Webb
University of South Carolina - Columbia, webbra@mailbox.sc.edu

E. E. Mendez

L. L. Chang

L. Esaki

Publication Info

Published in *Physical Review B*, ed. Gene D. Sprouse, Volume 31, Issue 2, 1985, pages 1198-1201.
Washburn, S., Webb, R. A., Mendez, E. E., Chang, L. L., & Esaki, L. (1985). New Shubnikov-de Haas effects in a two-dimensional electron-hole system. *Physical Review B, 31*(2), 1198-1201. DOI: 10.1103/PhysRevB.31.1198

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 31, NUMBER 2 15 JANUARY 1985

New Shubnikov–de Haas effects in a two-dimensional electron-hole system

S. Washburn, R. A. Webb, E. E. Mendez, L. L. Chang, and L. Esaki
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598
(Received 18 July 1984; revised manuscript received 30 October 1984)

We report the temperature dependence of the Shubnikov-de Haas oscillations from a two-dimensional electron-hole system in GaSb-InAs-GaSb quantum wells at very low temperatures. The samples are double heterostructures containing separate electron and hole layers. The oscillations arising from the electron layer behave regularly with temperature. Additional oscillations, characterized by strong temperature dependence, and relatively large peak widths are believed to arise from the presence of hole layers.

Recently, Mendez *et al.*[1] observed anomalous Shubnikov-de Haas oscillations from a GaSb-InAs-GaSb heterojunction in the quantized Hall regime.[2] In this paper, we describe a detailed study of the temperature dependence of similar magnetoresistance structure. This system contains both two-dimensional electrons and two-dimensional holes.[3] The presence of two species of carrier adds complexity to the usually simple Shubnikov-de Haas spectrum of a two-dimensional gas. From analysis of the temperature dependence and widths of the various oscillations, we conclude that some of them arise indirectly from the layers of two-dimensional holes. These oscillations are broader than the oscillations from the electron layer, and they have an anomalous temperature dependence: They vanish exponentially as the temperature decreases. The oscillations from the electrons have much less temperature dependence. Also, there is evidence for the variation of carrier concentration with magnetic field and for field-dependent enhancement of the effective g factor.

The samples were quantum wells composed of a layer of InAs sandwiched between layers of GaSb.[3] The insert in Fig. 2(b) is a schematic view of the band edges calculated self-consistently for $k_z=0$ (z being perpendicular to the plane of the layers).[4,5] The bottom of the conduction band of the InAs extends about 0.15 eV below the top of the GaSb valence band. When the materials are layered together, the electrons from the GaSb valence band flow into the empty InAs conduction band. These electrons are contained in a quantum well (the conduction band of the InAs layer). The flow of electrons distorts the bands of all layers, and the holes left behind reside near the interfaces in the GaSb layers in the resulting triangular wells. Intrinsically, this system will have $n_s = 2p_s$ where n_s is the electron concentration in the InAs layer, and p_s is the hole concentration in each of the GaSb layers. In this idealized situation, the Shubnikov-de Haas peaks from the hole layers will occur at the same magnetic field as every other peak arising from the electron layer. In the absence of an electron-hole interaction, the structure can be treated as three independent two-dimensional Fermi gases.[6] The electron effective mass is $m_e = 0.023m_0$, and the effective mass of the holes is $m_h = 0.36m_0$ where m_0 is the free-electron mass.

The samples were grown by molecular-beam epitaxy on a semi-insulating Cr:GaAs substrate. First, a thick layer of GaSb was grown to buffer the lattice mismatch with GaAs. Then a 150-Å layer of InAs and 200 Å of GaSb completed the well structure. Ohmic contact was made to all layers of the sample simultaneously. The samples were mounted inside the mixing chamber of a dilution refrigerator, and the resistance was measured by a four-probe bridge comprising two PAR-124 lockins, a room-temperature standard resistor, and an HP-3456 digital voltmeter. The carrier concentration of sample I (determined from low-fields Hall resistance) was $n_s = 7.8\times10^{15}/\mathrm{m}^2$ and the electron mobility was $\mu = 17.1$ $\mathrm{m}^2/(\mathrm{V\,sec})$. For sample II, $n_s = 7.4\times10^{15}/\mathrm{m}^2$ and $\mu = 17.4$ $\mathrm{m}^2/(\mathrm{V\,sec})$.

In Fig. 1 we display representative magnetic field sweeps at four temperatures for sample II. (The magnetoresistance

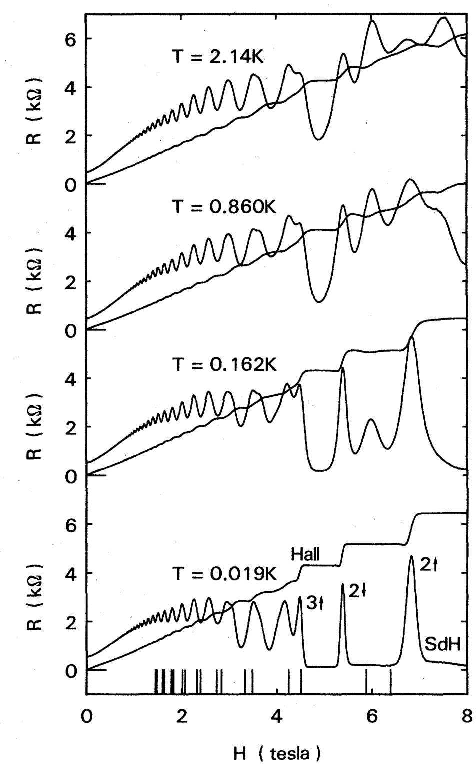

FIG. 1. Representative traces of the magnetoresistance and Hall resistance of sample II at four temperatures. The magnetoresistance was measured across a sample of length 10 squares. The vertical bars at the bottom of the figure indicate the positions of Landau levels that would be expected if the carrier concentration were a constant $n_s = 7.4\times10^{15}/\mathrm{m}^2$, and the g factor a constant $g^* = 18$.

data for sample I are equivalent except that all features are shifted to higher magnetic field by the increased carrier concentration.) In contrast with lower mobility samples of the InAs-GaSb system,[6] these samples have only positive magnetoresistance at low fields which is nearly temperature independent. This probably results from the presence of two very mobile species of carrier.[7] At low temperatures and magnetic fields greater than 5 T, the electrons are in the quantized Hall limit. The Hall plateaus are well developed, and the Shubnikov–de Haas peaks from the electron layer are sharp. Immediately, we see the evidence of two effects. First, the carrier concentration varies with magnetic field, and second, the g factor is enhanced at high field. The vertical bars at the bottom of the figure indicate where the Shubnikov–de Haas peaks would be if the carrier concentration were a constant $n_s = 7.4 \times 10^{15}/\mathrm{m}^2$ over the entire range of magnetic field and if the g factor were a constant. This value of carrier concentration is a good approximation in the field range 4–8 T. (The predicted locations of the center of the spin-split Landau levels for $n = 2, 3$ are in agreement with the observed resistance oscillations.) Inspection of the magnetoresistance curve for $T = 0.019$ K makes clear that this is *not* a valid approximation from 2 to 4 T. In the field range $H = 1.5$–3 T, the theoretical peak positions coincide more with minima in the experimental curve than with maxima (notice, for instance, that the predicted peak at 2.75 T falls at a minimum in the magnetoresistance). In this range, standard analysis of the oscillation spacing yields $n_s = 8.82 \times 10^{15}/\mathrm{m}^2$. A variation in the carrier concentration near the $n = 0$ Landau level was predicted in Ref. 4. We do not know if we are observing a related effect here. The peaks at 5.3 and 6.7 T are the spin-split Landau level $n = 2$. Their splitting indicates an enhancement over the value of 15 measured in bulk InAs.[8] Others have observed large g factors ($g^* = 19$–23) in InAs-GaSb superlattices at higher temperatures.[9] Furthermore, the splitting of the peaks at $H \simeq 4.2$ T is approximated well by $g^* \simeq 18$ indicating that the g factor depends on magnetic field. We believe that the enhancement results from the exchange mechanism described by Ando and Uemura,[10] and observed by Englert, Tsui, Gossard, and Uihlein in GaAs-AlGaAs heterojunctions.[11]

As the temperature increases, new peaks appear and grow at magnetic fields of 5.9 T and $\simeq 7$ T. At temperatures of 1 K or more, these peaks are comparable in amplitude to those from the electron layers, and at higher temperatures, the electron oscillations and the anomalous oscillations have approximately the same rate of decrease as the temperature increases. It was such an array of oscillations from this system that was reported in Ref. 1. The experiment was limited to temperatures $T > 0.5$ K, where the amplitudes and temperature dependences of the anomalous oscillations are still comparable to the oscillations from the electron layer. From the arguments given below, we conclude that the extra features reported in Ref. 1 do not indicate fractional quantization of the Hall resistance but, rather, the indirect effects of the holes in the GaSb layers of these samples. In spite of the complexity of the Shubnikov-de Haas spectrum at $T > 0.1$ K, all of the anomalous effects vanish at low temperature and $H \gtrsim 4.5$ T, and the system becomes a well-behaved two-dimensional electron gas with integer spacing of the Hall plateaus. There is one contrast with the single carrier systems [GaAs-AlGaAs and Si-MOSFET's (metal-oxide semiconductor field-effect transistors)]. In our samples, in the region between the peaks, the resistance does not go completely to zero. This may be due to leakage current from the hole layers, and it is one more piece of evidence that the holes play an important role in our samples.

In addition to the peaks at $H = 5.9$ T and $H \simeq 7$ T, more subtle irregularities in the Shubnikov-de Haas spectrum can be found at fields of $H \simeq 3.1$ T and $H = 3.6$ T; at $T = 0.019$ K, these are apparent as "shoulders" on the electron oscillations at $H \simeq 3.0$ and 3.5 T. Because these peaks are imbedded so deeply in the oscillations from the electron layers, simple quantitative analysis (as for the anomalous peaks at $H = 5.9$ T and $\simeq 7$ T) is difficult. However, from the sequence of magnetoresistance curves we can see the qualitative temperature dependence of the shoulder at $H = 3.6$ T. It is similar to that exhibited by the anomalous peaks at 5.9 T and $\simeq 7$ T.

The anomalous peaks are broader than the peaks from the electron layer. For a random, short-range potential, $\tau \propto H/\Gamma^2$ where τ is the mean free time in zero magnetic field, and Γ is the width of the peak.[10] Viewed naively, this implies that the carriers which are responsible for the anomalous peaks have a shorter scattering time than the electrons have. Implicit in this view is the unjustified assumption that the Shubnikov-de Haas peak width is proportional to the Landau level width or, in other words, that the ratio of the number of extended and localized states is the same for both species of carrier. Nevertheless, the larger width indicates that the anomalous oscillations are representative of carriers with a different characteristic scattering time.

We emphasize the contrast with the temperature dependence seen in other systems with only one carrier[12] where the relative rate of the conductivity decrease with temperature is a monotonic function of the magnetic field. (That is, the $n = 1\uparrow$ level decays more rapidly than the $n = 1\downarrow$ level and so on.) However, for our samples, the $2\uparrow$ peak ($H = 6.7$ T) from the electron layer is still prominent at $T < 0.019$ K when the anomalous peaks have been completely quenched. The anomalous peak shrinks by about two orders of magnitude while the height of the electron peaks changes by only $\sim 15\%$. This, along with the difference in widths of the peaks, is very strong evidence that we are seeing effects from two separate species of carrier. We may further contrast these data with results on lower mobility samples of this system where no such anomalous behavior is observed.[1] This may imply that not only must the holes be present, but that they must be fairly mobile. In samples with lower zero-field mobilities, presumably the holes become localized at higher temperatures before $\hbar\omega_c \sim k_B T$, and the Shubnikov-de Haas oscillations appear.

To measure the temperature dependence of the conductivity at a given magnetic field, we simply invert the resistivity matrix: $\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)$. The results for the peak at 5.9 T in sample II and the corresponding peak at 6.45 T in sample I are shown in Fig. 2(a). The dashed lines in the figure are fitted exponential functions:

$$\sigma_{xx} = (3.2 \times 10^{-5}) e^{-(0.17/T)}$$

for sample I and

$$\sigma_{xx} = (3 \times 10^{-5}) e^{-(0.20/T)}$$

for sample II. This is a large, rapid decrease in the conductivity which cannot be explained by weak disorder and the

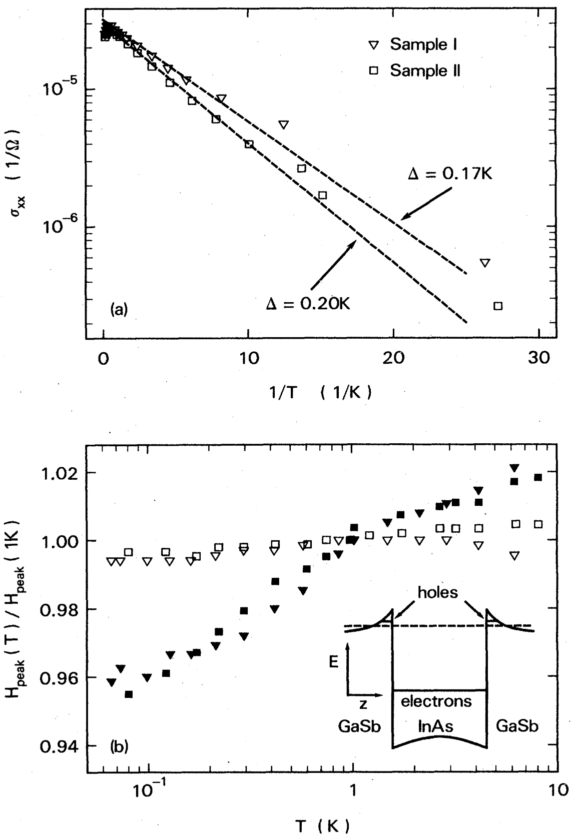

FIG. 2. (a) Temperature dependence of the longitudinal conductivity σ_{xx}^{peak} of the conductivity maximum at 6.45 T for sample I and of the maximum at 5.9 T for sample II. The dashed lines are the fitted exponential decays. (b) The positions of the anomalous peaks from both samples, relative to their positions at $T=1$ K, as a function of temperature. Open symbols refer to the same peaks as in (a), and the solid symbols refer to the higher-field peaks. The insert is a schematic view of the band edges on a cross section of the sample. Energy is plotted as a function of distance perpendicular to the conduction plane. The Fermi level is indicated by the dashed line, and the electron and hole energy levels are indicated by solid lines.

Coulomb interactions among the carriers in the Landau levels.[13] (The logarithmic temperature dependence of the conductivity which results from the Coulomb interactions is observed in the sharp oscillations which arise from the electron layer.) Therefore, we might attribute the decrease in the conductivity to trapping or "freezing out" of the carriers which give rise to the anomalous oscillations. From the exponential law, we see that the nonconducting state is ~ 0.2 K below the normal conducting state. We might just as plausibly explain the data as an exponential of $-(T_0/T)^{1/2}$ as would be expected if the quenching of the conductivity were the result of variable range hopping in the presence of Coulomb interactions.[14] Regrettably, our data can be fitted just as convincingly to this formula in a slightly lower range of temperature. The experiment does preclude the pure variable range hopping prediction[15] of $\sigma \sim \exp[-(T_0/T)^{1/3}]$. The temperature dependence of the peak near 7 T in sample I was somewhat stronger than that of the peak at 5.9 T, but since it is observable as a separate peak only over smaller ranges of temperature $(0.9 < T < 8)$ and relative amplitude (35%), equivalent analysis of its height is more risky. In sample II, over the range in temperature where comparison was possible, both anomalous peaks had approximately the same temperature dependence.

The electron oscillations and one of the anomalous peaks are fixed on the magnetic field axis: they do not move as a function of temperature. However, the remaining anomalous oscillation moves dramatically as the temperature increases. The peak near 7 T moves by $\sim 6\%$ in magnetic field (while the amplitude of the peak decays by more than 90%). In sample II, the feature near 7 T changes from a shoulder on the electron peak at 6.7 T to a separate oscillation at 7.4 T. The same is true of the corresponding feature $(H \simeq 8$ T) in sample I. The peak positions are given for both anomalous features from both samples in Fig. 2(b). These data were obtained by approximating the Shubnikov-de Haas spectrum as a sum of a series of Gaussian peaks. With this method the behavior of the anomalous peaks can be observed without distortion from the surrounding electron peaks. The lower-field anomalous peak position is constant (to within 1% or so) as the temperature varies, as are the electron peak positions. Only the higher-field anomalous peak moves substantially. That the oscillation moves consistently away from $H=0$ as the temperature rises is an indication that the carrier population is growing. Naively, if the number of carriers were decreasing, then we would expect both oscillations to move toward $H=0$ as they decreased in amplitude. This discrepancy between the temperature dependences of the two peaks may indicate that they originate in different parts of the sample; perhaps one of the GaSb layers has a rougher interface, and the holes in that layer trap more readily as the temperature decreases.

The temperature dependence of the $i=5$ Hall plateau is illustrated in Fig. 3. The Hall conductivity is accurately quantized (to within the 0.5% limit of our measuring circuit) at $T < 0.03$ K. That is, at very low temperature, the sample behaves as a one carrier system. As the temperature increases and the anomalous peak grows at $H=5.9$ T, a dimple appears in the plateau, and below $T=1$ K, the Hall conductivity is higher than the plateau value. If the new os-

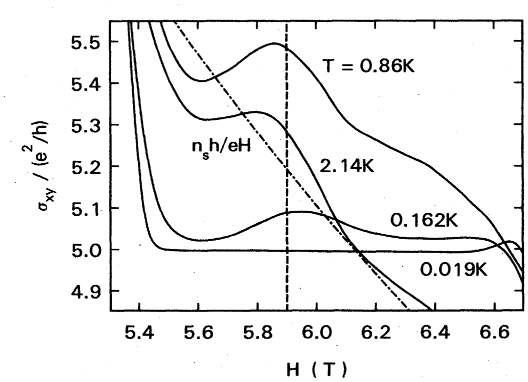

FIG. 3. Hall conductivity near the plateau for occupation number $i=5$. The conductivity is normalized by the fundamental conductance $e^2/h = 1/25\,812.8\ \Omega$, and the dashed line indicates the position of the anomalous Shubnikov-de Haas peak. The dash-dot line is the classical Hall conductivity $\sigma_{xy} = n_s e/H$ with $n_s = 7.4 \times 10^{15}/\mathrm{m}^2$.

cillation were the result of a new state being populated, then we would expect to see the conductivity form a new step (at $i=6$) for $H<5.9$ T. However, the experiment at $T=0.16$ K indicates that after passing through the disturbance near $H=5.9$ T, the Hall conductivity tends back towards the plateau. We also note that the dimple in the Hall step does not coincide with the anomalous peak but is at a slightly higher magnetic field. At $T=0.86$ K, the data have structure near $i=5\frac{1}{2}$. In Ref. 1, a similar feature observed on a coarser resistance scale near $i=2\frac{1}{2}$ was mistaken for fractional quantization of the Hall resistance. For $T>2$ K, the plateau is thermally smeared, and the Hall conductivity approaches the classical value $\sigma_{xy}=n_s e/H$.

We arrive finally at the question of whether or not we are directly observing the conductivity of the holes. If both the electrons and the holes were in the quantized Hall limit, then we would not expect to find the plateaus in the Hall resistance at the values predicted for a pure electron system. This leads us to the conclusion that the extra oscillations arise from an indirect process between the electrons and holes. One possibility is that the tendency for the electrons and holes to bind results in an "impurity band" in the electron density of states. In this case, *every* electron peak should be attended by a satellite peak a fixed energy below it. This interpretation, when applied to the electron peak at $H=5.3$ T and the extra peak at $H=6.4$ T, yields an energy shift of about 6.5 meV. This number is in (possibly fortuitous) agreement with the calculated binding energy for a hydrogenic impurity.[16] However, at least one of the electron oscillations ($3\uparrow$) does *not* have an anomalous satellite. We also doubt that the anomalous peaks mark the positions of the Landau levels of the holes. In the intrinsic situation (with $n=2p$), one would expect to see extra structure coming from the hole density of states only for every *other* peak in the electron density of states. This condition is clearly violated in Fig. 1 by the electron peaks at $H=5.3$ and 6.7 T, and the anomalous peaks at $H=6.4$ and $\simeq 7$ T.

In summary, we have measured the temperature dependence of the Shubnikov–de Haas oscillations in GaSb-InAs-GaSb quantum wells down to 10 mK and magnetic fields up to 8.5 T. We find that the g factor is enhanced at fields above 4 T, and that the electron concentration varies with the intensity of the field. Furthermore, the amplitudes of some of the Shubnikov oscillations decrease exponentially as the temperature goes to zero. The oscillations which vanish as $T\to 0$ are broader than the peaks which arise from the electron gas. We conclude that the extra oscillations arise indirectly from the presence of holes. The interactions that cause this behavior are still under investigation.

We are grateful to P. A. Lee for several instructive conversations. The molecular-beam epitaxy was performed by Chin-An Chang, and the samples were etched by Leo Alexander. This work was partly sponsored by the Army Research Office.

[1]E. E. Mendez, L. L. Chang, C.-A. Chang, L. F. Alexander, and L. Esaki, Surf. Sci. **142**, 215 (1984).
[2]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[3]L. L. Chang and L. Esaki, Surf. Sci. **98**, 70 (1980).
[4]G. Bastard, E. E. Mendez, L. L. Chang, and L. Esaki, J. Vac. Sci. Technol. **21**, 531 (1982).
[5]M. Altarelli, Phys. Rev. B **28**, 842 (1983).
[6]S. Washburn, R. A. Webb, E. E. Mendez, L. L. Chang, and L. Esaki, Phys. Rev. B **29**, 3752 (1984).
[7]R. A. Smith, *Semiconductors* (Cambridge Univ. Press, Cambridge, 1961), p. 107 ff.
[8]C. R. Pidgeon, D. L. Mitchell, and R. N. Brown, Phys. Rev. **154**, 737 (1967).
[9]L. L. Chang, E. E. Mendez, N. J. Kawai, and L. Esaki, Surf. Sci. **113**, 306 (1982).
[10]T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **36**, 959 (1974).
[11]T. Englert, D. S. Tsui, A. C. Gossard, and C. Uihlein, Surf. Sci. **113**, 295 (1982).
[12]M. A. Paalanen, D. C. Tsui, and A. C. Gossard, Phys. Rev. B **25**, 5566 (1982).
[13]A. Houghton, J. R. Senna, and S. C. Ying, Phys. Rev. B **25**, 2196 (1982); **25**, 6468 (1982); S. M. Girvin, M. Jonson, and P. A. Lee, *ibid.* **26**, 1651 (1982).
[14]A. L. Efros, J. Phys. C **9**, 2021 (1976).
[15]N. H. Mott, J. Non-Cryst. Solids **1**, 1 (1969).
[16]G. Bastard, Surf. Sci. **113**, 165 (1982).