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Two-subband transport: A conundrum in scattering

T. P. Smith III, F. F. Fang, U. Meirav,* and M. Heiblum
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

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We present new data concerning the problem of two-subband transport in a two-dimensional electron gas. We find that the ratio of the mobilities of electrons in the two subbands depends on the details of the confinement potential, while the ratio of the relaxation times determined from the Shubnikov–de Haas effect does not. In all samples studied the relaxation time determined from the amplitude of quantum oscillations in the magnetoresistance is longer for electrons in the upper subband. In addition, we see evidence for the repulsion of quantum levels and the inhibition of spin-flip transitions between quantum levels.

Recently there has been a great deal of interest in the relationship between the scattering times and carrier relaxation times of electrons in a two-dimensional electron gas (2DEG).[1-3] The former is determined from the mobility, and the latter is connected with the single-particle self-energy.[1] The observation that relaxation times determined from the Shubnikov–de Haas (SdH) effect are much shorter than the scattering times in high-mobility GaAs-$Al_xGa_{1-x}As$ heterostructures[4,5] has raised several important questions. The current understanding of this problem is that the broadening of Landau levels and cyclotron resonance linewidths are very sensitive to small-angle scattering while the mobility of a 2DEG is not.[1] Although the problem of calculating and interpreting the difference between the single-particle relaxation time τ_S and the scattering time τ_t of electrons occupying only one two-dimensional subband have been addressed quite thoroughly, a related problem has emerged from experiments conducted when two subbands or quantum levels of a 2DEG are occupied.

Interpretation of the earliest data on two-subband transport lead to the conclusion that the mobilities (and presumably both scattering times and single-particle relaxation times) of electrons in the lower subband are larger than those of electrons in excited quantum states.[6] The argument for this is that the Fermi-wave vector is much larger for electrons in the lower subband and Coulomb scattering is less effective yielding a higher mobility. However, recent work indicates that the mobility of electrons in the ground subband can be lower or higher than the mobility of electrons in excited states[7,8] while τ_S for electrons in upper subbands is always longer than that of ground-state electrons.

In order to address this problem in a new light we have studied two-subband transport in an inverted semiconductor-insulator-semiconductor device (ISIS).[9] This type of sample has the advantage that the entire 2DEG is gated (there is no gap between the ohmic contacts and the gate) and that, therefore, the carrier density can be uniformly varied over a fairly wide range. This is in contrast with previous experiments[7,8] where the carrier density was varied by means of the persistent photoconductivity effect, and thus may offer some clues to the two different behaviors mentioned above. The samples are grown on a conducting substrate which acts as the gate. After a doped buffer layer is grown, an undoped barrier layer (nominally 1850 Å of $Al_xGa_{1-x}As$ with an average Al mole fraction of 38%), channel layer (2000 Å of GaAs), and cap layer (300 Å of GaAs doped with 2×10^{18} cm^{-3} Si) are grown. This sample scheme produces a very high-mobility 2DEG ($\mu \gtrsim 5\times10^5$ cm^2/V s at 4.2 K) when grown using interrupted growth techniques.[10] A Hall bar is patterned on the surface and shallow ohmic contacts are alloyed in for transport measurements. The measurements are made at low frequencies using phase-lock-in techniques. All measurements are made at gate biases below 3.2 V where the gate-leakage current is less than 15 μA (at 4.2 K) and does not affect the transport measurements when using an ac detection scheme.

Figure 1 shows the conductance versus gate voltage (V_G). The threshold voltage of the sample is approximately 0.8 V and the conductance increases with V_G. However, this increase is not monotonic. There is an inflection in the conductance at $V_G = 1.9$ V which signals the onset of two-subband transport. When the Fermi energy rises above the first excited subband a new scattering channel (intersubband scattering) opens and the carrier mobility drops. In addition, the average position of the electrons moves farther away from the gate, slightly reducing the capacitance of the device. However, as the carrier density is further increased the mobility recovers and then continues to rise. Because of the high mobility of the 2DEG we can corroborate this by measuring the conductance with a small magnetic field applied perpendicular to the plane of the 2DEG. The lower curve in the upper portion of Fig. 1 shows the conductance at $B = 0.5$ T. The oscillations reflect the filling of successive Landau levels as the Fermi energy increases with V_G. Again, we see an anomaly at $V_G = 1.9$ V confirming that not all the carriers are populating the lowest subband. This can be clarified by labeling the minima in the conductance with their appropriate Landau-level index (assuming a spin degeneracy of 2) and then plotting this index as a function of V_G [see Fig 1(b)]. Below $V_G = 1.9$ V, the plot in Fig. 1(b) is essentially linear, indicating that the carrier density is proportional to the gate voltage, and that the degeneracy of the Landau levels is constant. Above 1.9 V, there is departure from linear behavior indicating the degenera-

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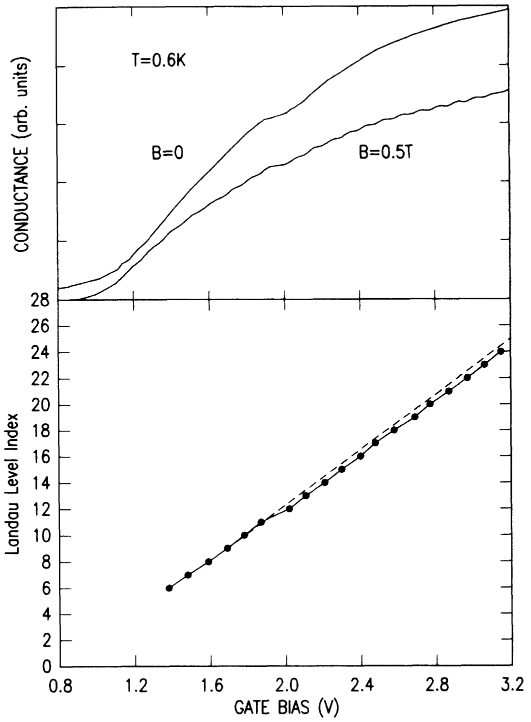

FIG. 1. (a) The conductance of an inverted heterostructure as a function of gate bias at 0 and 0.5 T. The data at $B=0.5$ T have been offset and expanded for clarity. (b) The Landau-level index vs gate voltage taken from the transconductance at 0.4 T.

cy of the 2DEG has changed due to filling of the next higher subband.

One surprise is that the separation between the two subbands is fairly small. Using the degeneracy of a Landau level at 0.5 T, we find that the carrier concentration and Fermi energy are 2.7×10^{11} cm^{-2} and 9.5 meV, respectively, at the onset of upper-subband filling ($V_G=1.9$ V). This carrier density is about a factor of 2 smaller than the carrier density at the onset of two-subband transport in our previous experiments.[7] We believe this is because our ISIS sample configuration produces a 2DEG that is accumulation-layer-like rather than inversion-layer-like. This conclusion is supported by modeling of the sample using a classical two-dimensional Poisson solver and by theoretical calculations of Ando[11] showing that filling of the upper subband of an accumulation layer can occur at carrier densities as low as 3×10^{11} cm^{-2}.

Before the onset of two-subband occupancy the change in carrier density as a function of V_G is lower than expected from the capacitance of the barrier layer. Based on the nominal thickness of the $Al_xGa_{1-x}As$ barrier layer (1850 Å) the carrier density should change by about 3×10^{11} cm^{-2} per volt change in V_G. At low-gate voltages (below 1.9 V) we observe a change of only 2.4×10^{11} cm^{-2} V^{-1}. This discrepancy may result from any one or a combination of several effects. (1) Charge is accumulating in traps or deep levels in the $Al_xGa_{1-x}As$ barrier as the gate bias is changed. This would result in a smaller charge being induced at the heterojunction, and is supported by the observation that there is some hysterisis in the capacitance if V_G is swept quickly. (2) Charge is induced at the surface layer. As V_G increases, acceptorlike surface states on the surface of the device or donors in the cap layer may be proportionally charged as the Fermi energy of the 2DEG increases. (3) There could be some error in our estimate of the thickness of the barrier, the mean position of the 2DEG with respect to the heterojunction, and depletion of the doped GaAs gate.

Turning to the data at gate voltages above 1.9 V, we see evidence for the "push-up" effect. The idea that the subband separation is significantly modified as the first excited subband is occupied was first discussed by Howard and Fang.[12] They proposed that changes in the rate of filling the ground subband reflect the self-consistent rearrangement of the electrostatic potential, defining the 2DEG as the upper subband is populated. At 2.1 V, the slope of the curve in Fig. 1(b) increases and at higher biases the slope approaches a constant value close to its initial value. This is similar to the observations of Ensslin.[13] Whereas, they conclude that the carrier density in the upper subband is roughly constant after initial filling, we see a gradual increase in the upper-subband carrier density from our magnetic field sweeps at different biases. Since the number of electrons in the upper subband is only about 5% of the electron density in the lower subband at $V_G=3.2$ V, the change in slope of the curve in Fig. 1(b) due to the filling of the upper subband is very small and cannot be resolved.

A complementary way to examine two-subband transport is to fix the carrier density (by fixing V_G) and vary the magnetic field applied perpendicular to the 2DEG. Figure 2 shows a spectra of this type. Several important features arise as a result of occupying the upper subband. Simple analysis of two-carrier transport predicts the pres-

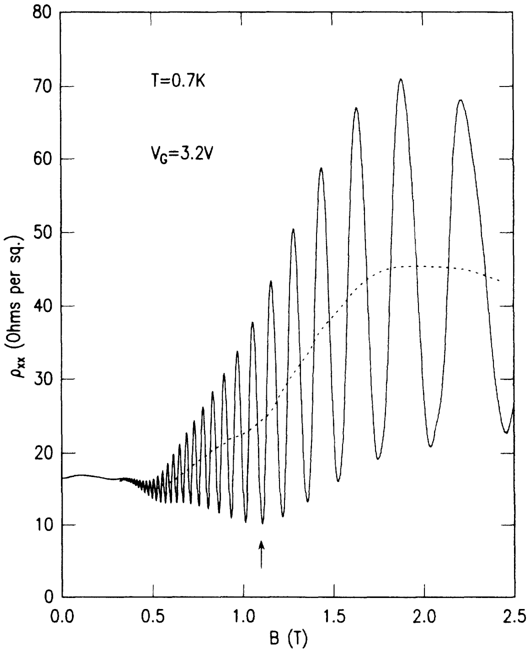

FIG. 2. Magnetoresistance at 0.7 K with two subbands occupied. The slow oscillations (dotted curve) are due to the upper subband and the small period oscillations to the lower subband.

ence of a positive magnetoresistance when two carrier systems with different mobilities are present.[14] We see the development of this effect as the carrier density increases and the upper subband becomes more populated. At higher magnetic fields there are two superimposed SdH periods. The frequency of these oscillations can be used to determine the carrier concentration in each subband. At $V_G=3.2$ V, the carrier densities in the lower and upper subbands are 5.8×10^{11} cm^{-2} and 2.8×10^{11} cm^{-2}, respectively. These carrier densities can be used to determine the mobilities of the two subbands by fitting the low-field positive magnetoresistance.[7] Figure 3 shows the best fit to the data taken at $V_G=3.2$ V. In contrast to our previous results,[7] but consistent with those of van Houten *et al.*,[8] the best fit occurs when the mobility of electrons in the upper subband is lower than the mobility of those in the ground state. Specifically, $\mu_0=625000$ cm^2/Vs and $\mu_1=280000$ cm^2/Vs corresponding to scattering times τ_t of 24.1 and 10.8 ps, assuming the effective mass for electrons in the 2DEG is $0.068m_0$ and neglecting nonparabolicity effects.

The fact that scattering times determined by fitting the low-field magnetoresistance do not exhibit any universal behavior may be related to the specific configuration of the samples studied. In our previous study,[7] the sample had a very thin spacer layer (15 Å) and was inversion-layer-like. We concluded that, since the average position of electrons in the upper subband was almost twice as far away from the ionized donors in the $Al_xGa_{1-x}As$ barrier as the average position of the electrons in the lowest subband, the mobility could be higher. However, in our ISIS sample there are no intentional ionized donors except in the back gate and cap layer. Since they are very far away from the 2DEG, their contribution to scattering is fairly small. Nonetheless, there are some ionized impurities throughout the 2000-Å GaAs channel layer. Since the 2DEG is accumulation-layer-like, the electrons in the upper subband will be spread to a greater extent in the channel and not be as effectively screened as electrons in the lower subband which are held more tightly to the heterointerface. The data of van Houten *et al.*,[8] also seem to indicate that their sample is accumulation-layer-like since the upper subband is occupied at lower-carrier concentrations.

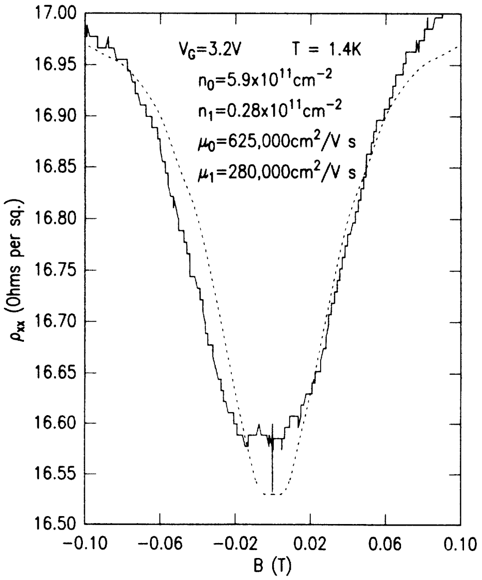

FIG. 3. The best fit (dotted curve) to the low-field positive magnetoresistance (solid curve).

Having said this, a very puzzling result emerges from analysis of τ_S. To determine τ_S for carriers in each of the subbands we analyzed the magnetic field dependence of the amplitude of the SdH oscillations.[2,15] The results of this analysis are shown in Fig. 4. In contrast to the scattering times, we find that τ_S is longer for electrons in the upper subband. This is consistent with our previous results.[7] Our analysis of the magnetic field damping of the SdH oscillations in the data published by van Houten *et al.*[8] also yields the same result. In fact, we have looked at two-subband transport in a number of samples and this is the case in all the samples we have studied. The τ_S of electrons in the upper subband is always about three times longer than that of electrons in the ground state. Similar conclusions have also been drawn from cyclotron resonance studies of wide quantum wells with two subbands occupied. Ensslin, Heitmann, and Ploog[16] find that the cyclotron resonance linewidth is narrower for electrons in the upper subband.

This result is very perplexing. There seems to be no well-defined relationship between τ_t and τ_S. The τ_t for electrons in the upper subband can be larger or smaller than the τ_t for electrons in the lowest subband, whereas the τ_S is always longer for electrons in the upper subband. While the τ_S is always smaller than the corresponding scattering time, no simple relationship connects them. It would seem that the relationship between the amplitude of the SdH oscillations and the mobility is not as simple as

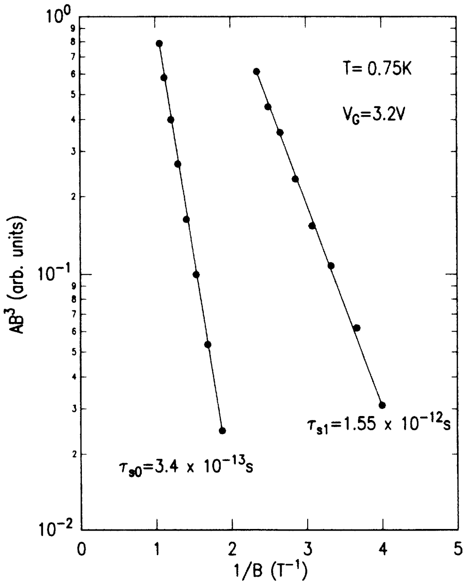

FIG. 4. A plot of the amplitude of the SdH oscillations times the cube of the magnetic field vs $1/B$. The values for τ_{S0} and τ_{S1} are the results after correcting for the finite-measurement temperature.

assumed in the past. There may be a salient factor which enters the problem at finite magnetic field when two subbands are occupied.

Finally, careful analysis of the SdH oscillations associated with the upper subband reveals structure at 1.1 T due to spin splitting of the lowest Landau level (see arrow in Fig. 2). However, there is no comparable splitting observed for Landau levels associated with the lower subband. Spin splitting at such low magnetic fields is very surprising and confirms, first of all, that τ_S for electrons in the upper subband is fairly long. It also suggests that the g factor is significantly enhanced above its bulk value. Enhancement of the g factor is generally attributed to an increase in the exchange energy due to a large imbalance in the number of spin-up and spin-down electrons.[17] However, the number of electrons in the upper subband is a small fraction of the total number of electrons at the heterointerface. Since there is no observable spin splitting in the lower subband, the total number of spin-up and spin-down electrons is practically equal. Only the electrons in the upper subband have a large spin polarization. The fact that we observe spin splitting in the upper subband indicates that the exchange energy of the electrons in the upper subband is not affected by the presence of a large number of electrons in the lower subband. Thus, there are essentially no spin-flip transitions between the two subbands.

In summary, we have attempted to resolve the question of two-subband scattering in a 2DEG. We find that, while the relationship between the mobilities of electrons in the lowest- and first-excited subband of a 2DEG can be explained in terms of sample configuration, the fact that τ_S is always longer for electrons in the upper subband is not well understood, and a more complete theoretical analysis of this problem is warranted.

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[*] Permanent address: Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139.

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