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Weak localization of two-dimensional conduction holes

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We report transport measurements which we interpret as weak localization of two-dimensional conduction holes in a GaSb-InAs-GaSb quantum-well structure. This system is unique in that it has parallel conduction channels containing both holes and electrons. The longitudinal resistance of the sample was measured for temperatures between 0.006 and 25 K; the magnetoresistance was measured in a perpendicular magnetic field. Weak localization of the holes was indicated by negative magnetoresistance and by a large logarithmic correction to the conductivity.

Since the first experiments by Dolan and Osheroff[1] and the scaling theory of Abrahams, Anderson, Licciardello, and Ramakrishnan[2] there has been considerable theoretical and experimental activity in the field of weak localization in two dimensions. The characteristic logarithmic temperature dependence of the resistance has been seen in a wide variety of systems including metal films,[1,3] metal-oxide-semiconductor field-effect transistors (MOSFET's),[4] and GaAs-AlGaAs quantum wells.[5] Further theoretical efforts have resulted in a second mechanism (the interactions among the electrons) which yields a logarithmic temperature dependence of the resistance[6,7] and the calculation of the various effects in a magnetic field.[8,9] The localization contribution to the conductivity and its field dependence have been thoroughly studied in Si-MOSFET's, and recently the interaction term and its magnetoresistance have been measured.[10] Both the localization and the interaction theories were shown to be quantitatively accurate in the relevant magnetic field regimes.

In two dimensions, the weak localization regime is characterized by a logarithmic increase of the resistance as the temperature decreases.[2] This increase arises through the coherent backscattering of carriers which are being scattered by some random potential. The smallest length which enters the calculation is the mean-free-path length l which is just the average distance between scattering events of any kind. The largest length is the inelastic diffusion length $L_\epsilon=(D\tau_\epsilon)^{1/2}$ where D is the diffusion constant for the carriers and τ_ϵ^{-1} is the inelastic-scattering rate. If the inelastic-scattering rate is proportional to the temperature to some power P, then the localization correction to the conductivity will be proportional to the logarithm of the temperature:[2]

$$\Delta\sigma = C\frac{e^2}{2\pi^2\hbar}\ln(T) \quad . \tag{1}$$

The constant C has two factors in it: α, the scattering parameter and P, the temperature exponent of the inelastic-scattering rate. The predicted value of α is between $-\frac{1}{2}$ and $+1$ depending on the relative importance of spin-flip and spin-covering scattering mechanisms. The theoretical prediction for P depends upon the model. For electron-electron scattering,[11,12] it is approximately one at the lowest temperatures.

The interactions among the diffusing carriers also yields a conductivity term identical to Eq. (1) except that C is determined by the interaction strengths.[6,7] If the Coulomb force dominates the interactions, then we can invoke the recent "Fermi-liquid" theory of Alshuler and Aronov.[6] If the inverse screening length κ is small compared with the Fermi wave number k_F, then the Coulomb interaction parameter $F<<1$, and $C=1-3F/4$. When the above condition is not true, C is a complicated function of a parameter F^* [we write F^* rather than F (as Alshuler and Aronov do) to avoid confusion] which is equivalent to F only in the limit of $\kappa << k_F$. In the opposite limit, F^* is not calculable. For arbitrary values of F^*, the interaction correction is

$$C=4-3\left(\frac{2+F^*}{F^*}\right)\ln\left(1+\frac{F^*}{2}\right) \quad .$$

The localization term and interaction terms can be approximately the same size, and therefore they cannot be distinguished through temperature dependence alone.

The presence of magnetic field perpendicular to the plane of the sample clarifies the situation. The localization contribution is quenched by the field[8] producing negative magnetoresistance. As the size of the cyclotron orbit L_H becomes smaller than the inelastic diffusion length, it becomes the new limiting length in the localization theory. As the magnetic field increases and the cyclotron orbit shrinks, the localization contribution is reduced until the cyclotron orbit becomes smaller than the elastic-scattering length l. For the case of $L_\epsilon, L_H >> l$, the magnetoresistance from the localization calculation is[8]

$$\Delta\sigma=\sigma(H)-\sigma(0)=\frac{\alpha e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{1}{zH}\right)+\ln(zH)\right] \quad , \tag{2}$$

where $z=4eD\tau_\epsilon/\hbar$, H is the magnitude of the magnetic field, and ψ is the digamma function. The interaction effects are generally enhanced by the field and produce a positive magnetoresistance.

The sample was a quantum well composed of two layers of GaSb sandwiching a layer of InAs.[13] Figure 1(a) is a schematic of the bands calculated for carriers with zero wave vector perpendicular to the plane of the layers.[14,15] The conduction band of the InAs extends about 0.15 eV below the valence band edge of the GaSb; this causes electrons to flow from the GaSb valence bands into the InAs conduction band. Hence the electrons are contained in a two-dimensional well of InAs. The flow of electrons distorts the bands of all layers, and the holes left by the donated electrons reside near the interfaces on either side of the InAs layer in the resulting triangular wells. For sufficiently

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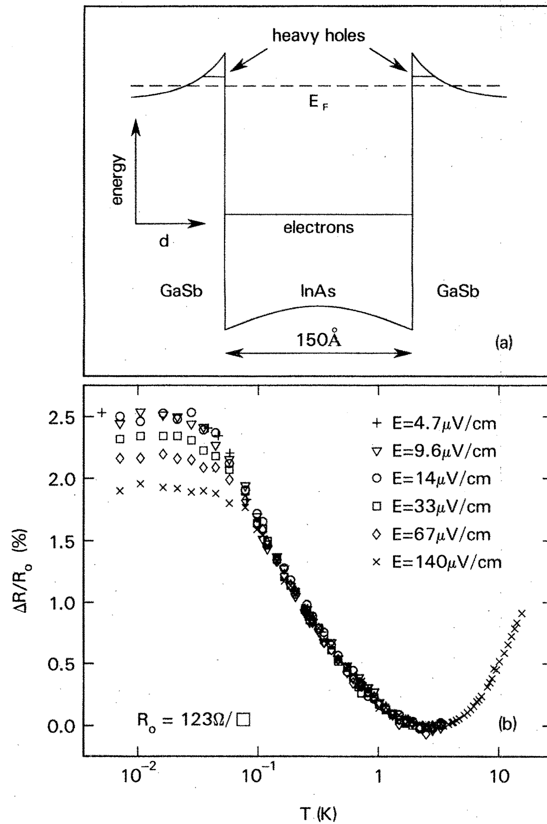

FIG. 1. (a) Schematic view of the band edges on a cross section of the sample. Energy is plotted as a function of distance perpendicular to the conduction plane. The Fermi level is indicated by the dashed line, and the electron and hole-energy levels are indicated by solid lines. (b) Sheet resistance of the sample at several bridge excitations showing the saturation of the resistance at low temperatures regardless of excitation voltage and the electron heating effects.

narrow InAs layers (< 300 Å) there is only one filled band in each layer.[14] (The heavy-hole band is the only one occupied in the GaSb layer.) In the absence of an electron-hole interaction, the structure can be treated as three independent two-dimensional Fermi gases. The electrons are very light: $m_e = 0.023 m_0$, and the holes have an effective mass $m_h = 0.36 m_0$, where m_0 is the free-electron mass. The sample was grown by molecular-beam epitaxy on a semi-insulating Cr:GaAs substrate. First, a deep layer (~ 4000 Å) of GaSb was grown to buffer the lattice mismatch, and then a 150-Å layer of InAs and 200 Å of GaSb completed the well structure. The sample was etched into a "Hall bar" 2 mm long and 0.1 mm wide with current wires on the ends and three, equally spaced voltage probes on either side. Ohmic contract was made simultaneously to all layers of the sample.

The sample was mounted inside the mixing chamber of a dilution refrigerator. The resistance was measured by an ac, four-probe bridge operated at 200 Hz. To prevent heating of the electrons, it was necessary to keep the electric field across the sample to a minimum—usually near 10 μV/cm. The resistance was measured as a function of temperature at zero magnetic field and as a function of perpendicular magnetic field at several temperatures. The carrier concentration (determined from Hall resistance and from Shubnikov–de Haas oscillations) was $n_s = 8.5\times10^{15}/\text{m}^2$ and the electron mobility was $\mu = 5.9\ \text{m}^2/(\text{V sec})$.

In Fig. 1(b) we show the resistance of the sample as a function of temperature in zero magnetic field. At temperatures greater than a few kelvins, the resistance increases with temperature: $R(300\ \text{K})/R(4\ \text{K}) = 1.8$. From a few hundred mK to ~ 40 mK, we see the logarithmic temperature dependence from the weak localization and interactions, and below 30 mK, the resistance is constant. We do not know the origin of the saturation at low temperature. For excitations less than 10–15 μV/cm the saturation of the resistance with decreasing temperature was independent of excitation. Similar effects have been seen in several experiments at very low temperatues.[1,4,10] We are not certain of the explanation for this. It might be decoupling of the carriers from the phonon thermal bath as has been proposed elsewhere.[10] It may instead by noise heating, but similar experiments in our apparatus using the same measurement circuit have shown temperature dependence in the resisitance down to 0.005 K.[16] One possibility is that it is the result of spin-orbit scattering. As each layer in our sample is strictly two dimensional, the spin-orbit interaction causes no spin-flip processes (i.e., $\tau_{\text{s.o.},x}^{-1} = 0$), but it does contribute to the conductivity correction. If we assume no paramagnetic impurities are present, then we have

$$\Delta\sigma \propto \ln\frac{(\tau_\epsilon^{-1} + 2\tau_{\text{s.o.},z}^{-1})^{-1}}{\tau} ,$$

where τ is the mean free time, and $\tau_{\text{s.o.},z}$ is the spin-orbit scattering time.[8] If $\tau_{\text{s.o.},z}^{-1}$ is an appreciable fraction of τ^{-1}, then at sufficiently low temperatures, the logarithm will be dominated by the second term and the resistance will saturate. Saturation below 40 mK would imply $\tau_{\text{s.o.},z}^{-1} \sim 0.02\tau^{-1}$ for our sample. Since both indium and antimony are relatively large atoms, we expect that the spin-orbit intraction will contribute to the corrections to the Drude conductivity. The saturation of the resistance may be the signature of this effect.

Figure 2 shows a typical curve of the conductivity versus

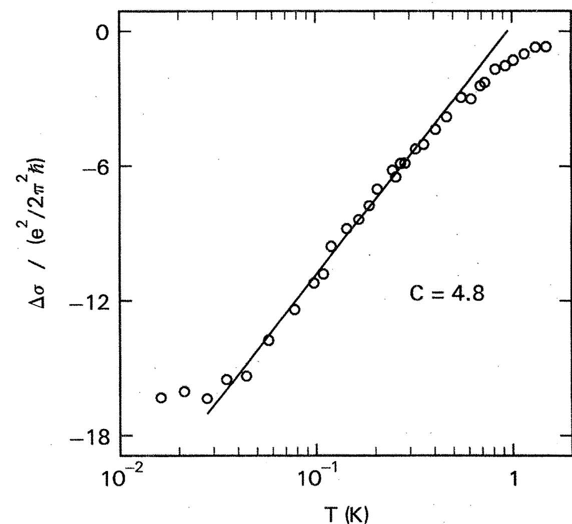

FIG. 2. Results of one experiment which measured the resistance as a function of temperature for $E = 14\ \mu$V/cm and in the absence of a magnetic field. The slope $C = 4.8$ is the magnitude of the logarithmic correction to the conductivity Eq. (1).

temperatuure in natural units. The slope of 4.8 includes the interaction terms and the localization terms for all three layers. The total conductivity is the sum of the conductivities from all the layers of the sample in analogy with parallel resistors. Therefore we expect that the total conductivity will be

$$\sigma=\sigma_0^e+\Delta\sigma_q^e+2(\sigma_0^h+\Delta\sigma_q^h) ,$$

where the subscript 0 refers to Drude conductivity, and q refers to quantum contributions to the conductivity (both localization and interactions), and the superscripts e and h refer to electron and hole contributions.

Since the elastic-scattering length for the electrons is so large ($l=0.91$ μm), the negative magnetoresistance from the localization of the electrons can be present only at fields of 4 G or less. (That is, when the Landau orbit is larger than l.) We found no negative magnetoresistance in this region. We did see a small positive magnetoresistance over a range of 15 G or so [see the insert in Fig. 3(a)]. We cannot explain the positive magnetoresistance at these low fields. It resembles the spin-orbit effects seen in metal films.[3,8,17] However, if the layers in our sample are independent, then $\tau_{\mathrm{s.o.},x}^{-1}=0$, and theory predicts no magnetoresistance from the spin-orbit interactions.

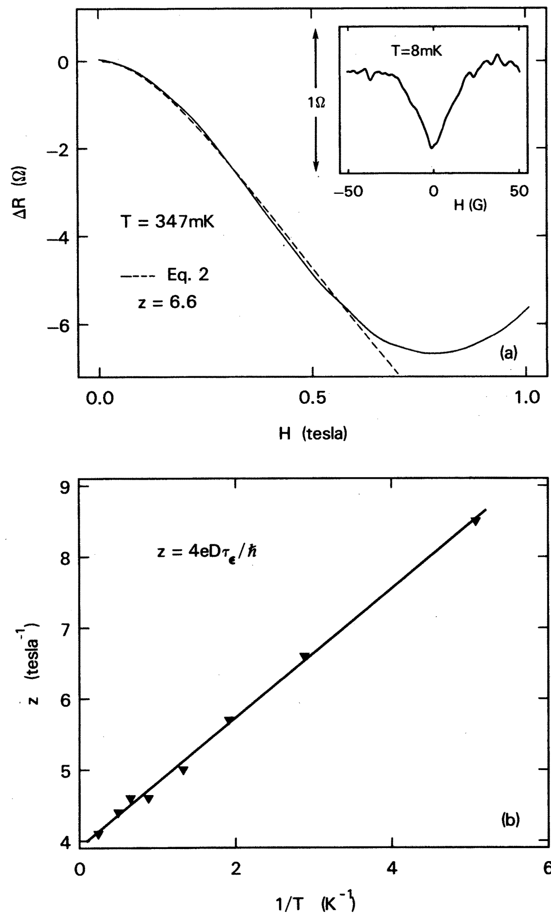

FIG. 3. (a) Negative magnetoresistance which results from the localization of the holes. The solid line represents the experimental data, and the dashed line is the fit from Eq. (2). The tail at $H\geq 0.8$ T shows that interactions have begun to dominate the conductivity. The insert shows the small positive magnetoresistance near $H=0$. (b) The parameter z (which is proportional to the inelastic-scattering time τ_ϵ) as a function of inverse temperature. This demonstrates that for the holes, $P=1$.

Over the range of a few kilogauss, we observed negative magnetoresistance which we believe is the signature of weak localization in the hole layers. At the lowest temperatures, the negative magnetoresistance persisted out to $\sim$9–10 kG which leads us to an estimate for the hole mean free path $l\sim 0.01$ μm. This agrees with an estimate from the ratio of bulk, room-temperature mobilities which gives $l=0.015$ μm. We fitted the magnetoresistance data at various temperatures using Eq. (2). Since we cannot measure the resistance of each layer of the sample separately, we cannot determine the scattering parameter α for the holes. This is because we cannot determine the bare conductivity of the hole layers as they are being "shorted out" by the electron layer. However, under the assumption of a temperature-independent elastic-scattering rate for the holes, we can determine the temperature dependence of inelastic scatttering. A representative fit of Eq. (2) to the magnetoresistance data is shown in Fig. 3(a) and the temperature dependence of the parameter z is shown in Fig. 3(b). The fitting process consisted of picking one of the magnetoresistance curves and fitting both z ($\propto\tau_\epsilon$) and α, and then for the rest of the curves, only the parameter z was fitted. We found that the inelastic-scattering rate is proportional to the temperature, that is, $P=1$ for the holes. The above estimates for l and the experimental value of z lead us to an inelastic-scattering time of 3×10^{-12} sec at 350 mK. For comparison we also used the estimate for l and the theory of Abrahams *et al.*[11] to calculate the scattering time and obtained 5×10^{-12} sec. We emphasize here that this only is a rough estimate; the major point is the determination of P.

In principle, two other mechanisms might account for the negative magnetoresistance. Houghton, Senna, and Ying,[18] predict that interactions can cause a negative magnetoresistance $\Delta R\propto 1-(\omega_c\tau)^2$, and they predict that there is a logarithmic temperature correction in the Hall constant. However, our negative magnetoresistance is not parabolic in magnetic field, and we see no variation of the Hall constant with temperature. Therefore we discard this source for the negative magnetoresistance. The second candidate is the Kondo effect. The Cr^+ from the substrate is quite mobile in GaAs,[19] and it can contribute to a Kondo effect. This would give rise to a negative magnetoresistance which is isotropic in magnetic field and to yet another logarithmic correction to the conductivity.[20] Measurements of the resistance in a parallel magnetic field indicate that the negative magnetoresistance is not isotropic. A sample of the substrate and buffer layer was analyzed with secondary ion emission spectroscopy. The level of Cr^+ in the GaAs layer was quite high (from the doping), but the amount of Cr^+ was at or below the background level of the spectrometer (0.005 ppm) in the GaSb layer. The drop-off in Cr^+ concentration was quite abrupt (<100 Å). Calculations show that this low level of Cr^+ cannot account for our temperature dependence of negative magnetoresistance. Therefore we can neglect the Kondo effect as well.

We can estimate the correction that should be present from the localization and interaction theories. As there was no negative magnetoresistance at low fields, we assume that there is no localization in the electron layer. Here we also assume that $\alpha=1$ in the hole layers. Further, we set

$F^* = F$. This approximation is marginally valid for the electrons, but it may be in error for the hole layers. However, there is no theoretical estimate for F^*. We calculate F in the Thomas-Fermi approximation; we obtain $F = 0.22$ for the electrons and $F = 0.81$ for the holes. Summing all corrections, we estimate the total logarithmic slope for the sample $C = 0 + 0.8 + 2(1 + 0.5) = 3.8$. The value of the slope which we obtain from all of the experiments on this sample is 4.8 ± 0.2 which is somewhat larger than the above estimate. We do not know how much of this difference will be absorbed by the unknown parameter F^*. Some of the difference might be due to the electron-hole interaction in this system which has been ignored by the theory to date. If, however, we assume that there exists localization in the electron layer (and that for some reason it did not appear as negative magnetoresistance), then $C = 4.8$. Here we have assumed that $P = 1$ for the electrons as well, and that again α takes its maximum value; that is, we are stretching the theory to obtain the largest slope that we can from it. Considering the approximations (both in the electron localization and in the interaction terms) that were necessary to obtain this estimate, it is probably fortuitous that it agrees so well with the experimental slope.

In summary, we believe that we have made the first measurements of the effects of weak localization in two-dimensional gases of conduction holes. The experiments were performed on a heterostructure quantum well of InAs-GaSb. We have also used the localization effect to measure the temperature exponent of the inelastic-scattering time for the holes, and we find that $\tau_\epsilon \propto T^{-1}$.

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