Metal-Insulator Transition at $B = 0$ in a Dilute Two Dimensional GaAs-AlGaAs Hole Gas

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We report the observation of a metal-insulator transition at $B = 0$ in a high mobility two dimensional hole gas in a GaAs-AlGaAs heterostructure. A clear critical point separates the insulating phase from the metallic phase, demonstrating the existence of a well defined minimum metallic conductivity $\sigma_{\min} = 2e^2/h$. The $\sigma(T)$ data either side of the transition can be "scaled" onto one curve with a single parameter T_0. The application of a parallel magnetic field increases $\sigma_{\min}$ and broadens the transition. We argue that strong electron-electron interactions ($r_s \simeq 10$) suppress quantum interference corrections to the conductivity. [S0031-9007(98)05325-3]

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In the mid-1970s experiments on silicon inversion layers produced considerable evidence for the existence of a metal-insulator transition in 2D and a minimum metallic conductance, $\sigma_{\min}$ [1–3]. The decay constants of localized state wave functions were investigated, and it was shown that when the number of localized electrons exceeded 2×10^{11} cm^{-2} the location of the mobility edge was determined by electron-electron interactions and increased with increasing carrier concentration. Subsequent theoretical work in 1979 suggested that all states in 2D were localized [4] and that phase incoherent scattering imposed a cutoff to a localized wave function giving a logarithmic correction to metallic conduction (weak localization) which was widely observed and used to obtain very detailed information on the various types of electron-electron scattering in all three dimensions [5,6]. However, in order to investigate the logarithmic correction at low, but accessible, temperatures it was necessary to use samples with low mobility so that the elastic scattering length l was small [7]. In view of the success of the theory it was then assumed that the earlier high mobility samples did not show a logarithmic correction because the phase coherence length l_ϕ was not greater than the elastic scattering length, but that if experiments could be performed at much lower temperatures (beyond the capability of cryogenics) then the logarithmic correction would be found.

Recent experimental results have raised this issue again and indicate that states in 2D are not always localized with strong evidence for a metal-insulator transition in high mobility Si metal-oxide-semiconductor field-effect transistors (MOSFETs) [8]. It was found that the resistivity on both the metallic and insulating sides of the transition varied exponentially with decreasing temperature, and that a single scaling parameter could be used to collapse the data on both sides of the transition onto a single curve. While the exact nature of the transition is presently not understood, there have been several reports of similar scaling and duality between the resistivity (and conductivity) on opposite sides of the transition, both for electrons in Si MOSFETs [9,10] and for holes in SiGe quantum wells [11]. In all of these reports electron-electron interactions are known to be important, with the Coulomb interaction energy being an order of magnitude larger than the Fermi energy at the transition ($r_s \simeq 10$). The destruction of the metallic state by an in-plane magnetic field has also led to suggestions that spin interactions are important [12,13].

In this paper we present evidence of a metal-insulator transition at $B = 0$ in a high mobility, low density, two dimensional hole gas formed in a GaAs-AlGaAs heterostructure. The conductivity "scales" as a function of temperature on both sides of the transition with a single parameter T_0. A weak temperature dependence of the conductivity similar to that observed in a normal metal is observed for $\sigma > \sigma_{\min}$ in contrast to the exponential behavior recently observed in high mobility Si MOSFETs [8]. A parallel magnetic field suppresses the metallic phase, demonstrating the importance of spin interactions in this system.

The heterostructure used was grown by molecular-beam epitaxy (MBE) on a (311)*A* GaAs substrate, and consisted of a 200 Å GaAs quantum well, modulation doped on one side with Si as the acceptor. The carrier density p_s was varied with a p^+ back gate, formed using a combination of *in situ* ion-implantation and MBE regrowth [14], 360 nm below the quantum well. Samples were processed into 450 by 50 μm Hall bars aligned along the $[\bar{2}33]$ direction, and measurements were performed in a ^{3}He cryostat (with a base temperature of 270 mK) designed for *in situ* rotation of the sample with respect to the magnetic field. Low frequency (4 Hz) ac lock-in techniques were used, with excitations of 500 μV and 2 nA for two and four terminal measurements, respectively. After illumination with a red light-emitting diode (LED) the carrier density could be varied in the

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range $(0-3.5) \times 10^{11}$ cm^{-2} ($r_s > 4$), with a peak mobility of 2.5×10^5 cm^2 V^{-1} s^{-1}, over an order of magnitude larger than that used in previous studies. For the carrier densities studied only the heavy hole subband is occupied with $|M_J| = 3/2$ (although for $k_\parallel \neq 0$ there is some mixing between the light and heavy hole bands). The large effective mass ($m^* \approx 0.3 m_e$) quenches the kinetic energy, thereby enhancing the effects of Coulomb interactions. It should also be noted that the asymmetric confining potential in our samples leads to a partial lifting of the twofold Kramer's (spin) degeneracy away from $k_\parallel = 0$.

The transition from insulating to metallic behavior with increasing carrier density can be seen in the temperature dependence of the resistivity in Fig. 1(a). At a critical density $p_c = 5.1 \times 10^{10}$ cm^{-2} ($r_s = 11$) the resistivity is temperature independent for $T \lesssim 1.6$ K with $\rho_c \simeq h/2e^2$, giving a minimum metallic conductance, $\sigma_{\min} \simeq 2e^2/h$. At the lowest carrier densities insulating behavior is observed characterized by an exponential rise in ρ with decreasing temperature. In the strongly insulating regime this behavior fits $\rho(T) = \rho_0 \exp(T_0/T)^{1/2}$ with $\rho_0 \simeq h/2e^2$, characteristic of variable range hopping conduction in the presence of a Coulomb gap [15]. Above this critical density the resistivity changes behavior to that of a normal metal where $\partial\rho/\partial T \geq 0$ for all T. While these curves demonstrate a clear metal-insulator transition, the large decrease in resistivity observed for $T \leq 1.5$ K on the metallic side of the transition in Si MOSFET and SiGe samples [8,11] is not apparent. Figure 1(b) shows the resistivity near the transition for carrier density changes of $\pm 5\%$ and $\pm 10\%$ from p_c. Although no exponential behavior is observed on the metallic side for $T \geq 0.3$ K and $\delta_p = 0.05$, it has been suggested that symmetry is only expected to hold close to the transition where $\delta_p \equiv (p_s - p_c)/p_c \ll 1$ [16]. We cannot therefore exclude the possibility of exponential behavior for $\delta_p \ll 1$ as $T \to 0$.

At high carrier densities, away from the transition ($\delta_p \geq 0.2$) a gradual increase in the conductivity with decreasing temperature is observed characteristic of normal metallic behavior. In Fig. 1(c) the fractional change in conductivity, $\Delta\sigma/\sigma \equiv [\sigma(T) - \sigma(T=0)]/\sigma(T=0)$ is plotted against T/T_F, where T_F is the Fermi temperature ($T_F = \pi p_s \hbar^2/m^* k_B$, $m^* \approx 0.3$) for carrier densities in the range $(0.87-2.6) \times 10^{11}$ cm^{-2} [17]. We find that $\Delta\sigma/\sigma$ scales as T/T_F, and is approximately linear for $T/T_F > 0.04$, consistent with temperature dependent screening in the limit of low disorder [18]. It is noteworthy that a result derived for a weakly interacting system appears to describe our system where many body interactions are known to be strong. Close to the transition ($\delta_p \leq 0.2$) this temperature dependence weakens and $\Delta\sigma/\sigma$ deviates from the behavior shown in Fig. 1(c), with σ becoming completely temperature independent at the critical point.

Figure 2(a) shows the conductivity as a function of carrier density at temperatures between 0.26 and 1.6 K. The curves all intersect at a temperature independent point, confirming the transition from insulating to metallic behavior at a critical conductivity of $\sigma_{\min} = 2e^2/h$.

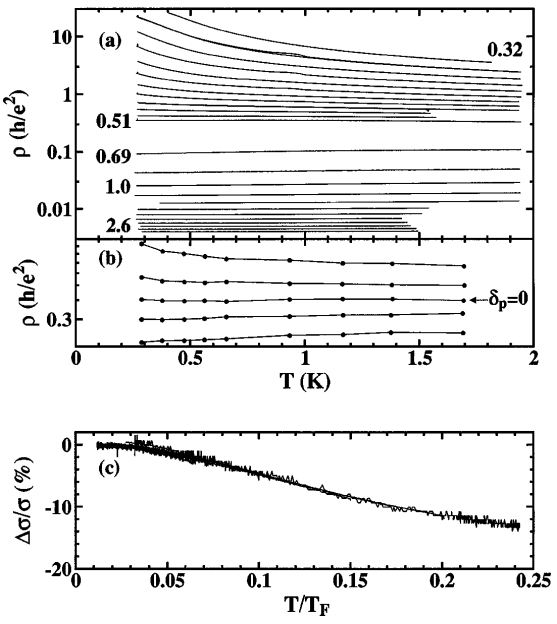

FIG. 1. (a) Temperature dependence of the resistivity as a function of carrier density for $p_s = (0.32-2.6) \times 10^{11}$ cm^{-2}. (b) Closeup of the behavior near the transition, showing the resistivity for $\delta_p = 0, \pm 5\%, \pm 10\%$. (c) Fractional change in conductivity $\Delta\sigma/\sigma$ against the normalized temperature T/T_F for 11 equally spaced carrier densities in the range $p_s = (0.87-2.6) \times 10^{11}$ cm^{-2}.

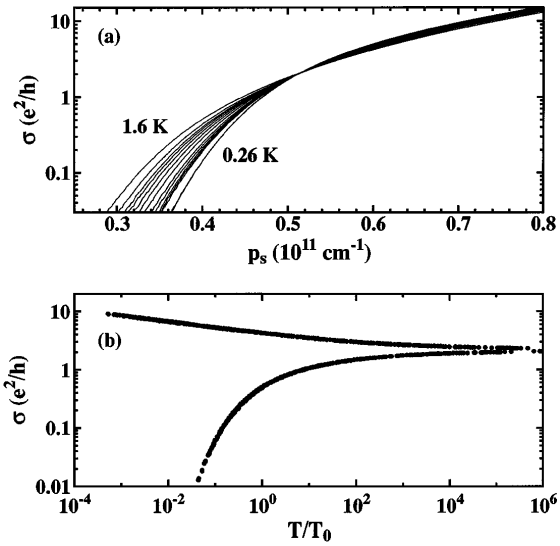

FIG. 2. (a) Conductance as a function of carrier density for different temperatures in the range 0.26–1.6 K, showing a clear $\sigma_{\min} = 2e^2/h$ (a temperature independent contact resistance of 4.15 kΩ has been subtracted from all the data). (b) The scaled data from (a) plotted against T/T_0. Hole densities are in the range $(0.35-0.68) \times 10^{11}$ cm^{-2}, $T < 1.6$ K.

The $\sigma(T)$ curves for different carrier densities on the insulating side were made to overlap by scaling them along the T axis. For the lowest carrier density ($p_s = 0.35 \times 10^{11}$ cm^{-2}) $T_0 = 6$ K was determined by fitting $\sigma(T) = \sigma_0 \exp(T_0/T)^{-1/2}$. Each subsequent curve was then individually scaled along the T axis in order to collapse all the curves onto a single trace, defining T_0 for each curve. The observation that data in the insulating regime can be scaled onto a single curve is not surprising, since it is a direct consequence of variable range hopping with a constant σ_0. The same scaling procedure [8] was applied to the metallic data ($p_s \geq p_c$), in which the initial value of T_0 was chosen to be the same as that on the insulating side of the transition at $|\delta_p| = 0.05$. The results of this scaling are presented in Fig. 2(b). We note that the scaling in the metallic phase is less satisfactory than in the insulating phase (as can also be observed in the data of Refs. [8,19]), since at the higher densities individual traces tend to flatten off at low temperatures, as shown in Fig. 1(c).

The scaling factor T_0 is shown in Fig. 3(a) as a function of carrier density. For the lowest carrier densities T_0 is comparable to that observed in Si MOSFETs [8], but falls more rapidly as the transition is approached. Previous reports have found that the conductivity near the transition scales as

$$\sigma(T, \delta_p) = f(T/T_0) = f'(|\delta_p|/T^{1/z\nu}), \qquad (1)$$

with a single parameter $T_0 \propto |\delta_p|^{z\nu}$, where z is the dynamical exponent and ν is the correlation length exponent [8–10]. Figure 3(b) shows T_0 against $|\delta_p|$. For $\delta_p < 0.1$ we find $z\nu = 4.8 \pm 0.4$, although the uncertainty in T_0 and δ_p makes it difficult to comment on the symmetry of $z\nu$ about the transition. At larger $|\delta_p|$ the asymmetry is clearly visible, with $z\nu = 3.8 \pm 0.4$ in the insulating regime, and 7 ± 1.5 in the metallic regime. In all cases the values of $z\nu$ obtained are much larger than that observed in Si-based samples where a universal value of $z\nu = 1.6 \pm 0.2$ on both the insulating and metallic sides of the transition has been widely reported [8–11]. Physical insight into the variation of T_0 with δ_p is obtained by considering the localization length in the strongly insulating regime, $\xi = e^2/\epsilon k_B T_0$ [15]. The localization length therefore diverges as the transition is approached. The large value of $z\nu$ shows that ξ grows more rapidly with increasing carrier density than in lower mobility Si-based samples. The reason for this difference is unclear, but may be due to the long range of the random impurity potential in modulation doped GaAs-AlGaAs heterostructures.

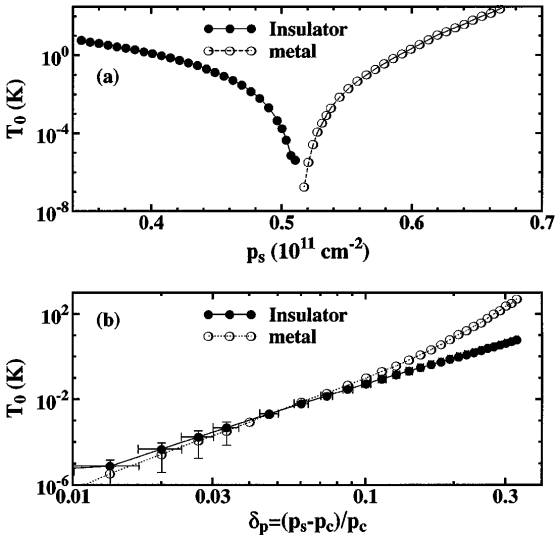

FIG. 3. Scaling parameter T_0 (a) as a function of the hole density and (b) as a function of δ_p.

The scaling theory of localization [4] argues that there is no $\sigma_{\min}$ in the absence of spin-orbit scattering, as weak localization always takes over as $T \to 0$. The introduction of spin-orbit scattering leads to weak antilocalization and the possibility of a metal-insulator transition. Although spin-orbit scattering is strong in p-GaAs, in these measurements a negative magnetoresistance is always observed in a perpendicular magnetic field in contrast to the positive magnetoresistance expected for antilocalization. In fact, in the temperature range of this study no evidence of weak localization or antilocalization is observed in the temperature dependence of the magnetoresistance near the transition. We suggest that the strength of the electron interactions suppresses the quantum interference corrections to the conductivity [20]. The absence of these weak localization corrections thus restores the metal-insulator transition originally envisaged by Mott [21,22], where $\sigma(T = 0) = 0$ at $\sigma < \sigma_{\min}$ and $\sigma(T = 0) > 0$ for $\sigma \geq \sigma_{\min}$, consistent with our data.

The application of a parallel magnetic field $B_\parallel$ couples directly to the spin, altering many body interactions and spin-orbit coupling by introducing a spin splitting of the "spin-up" and "spin-down" particles. Although the in-plane factor $g_\parallel$ is zero for purely heavy hole states, mixing between the light and heavy hole bands at nonzero $k_\parallel$ leads to a finite $g_\parallel$. We have measured the four terminal resistivity $\rho = 1/\sigma$ as a function of $B_\parallel$, and observe a negative magnetoconductance for all carrier densities on both sides of the transition [Fig. 4(a)]. The effect of $B_\parallel$ on $\sigma_{\min}$ is shown in Fig. 4(b), where we plot $\sigma(p_s)$ at different temperatures for $B_\parallel = 0$, 0.5, 1, and 3 T. The critical point at which $\sigma = \sigma_{\min}$ and is T independent can be seen to move to larger conductances as $B_\parallel$ increases, until at $B_\parallel = 3$ T there is no distinct transition between the metallic and insulating phases. Increasing $B_\parallel$ also makes the sample more insulating below the transition (σ is more T dependent for a given p_s), and weakens the metallic state on the other side of the transition [$\sigma(p_s)$ becomes less T dependent]. In attempting to scale the data according to Eq. (1) we find that the scaling exponents increase from $z\nu = 3.75 \pm 0.25$ to

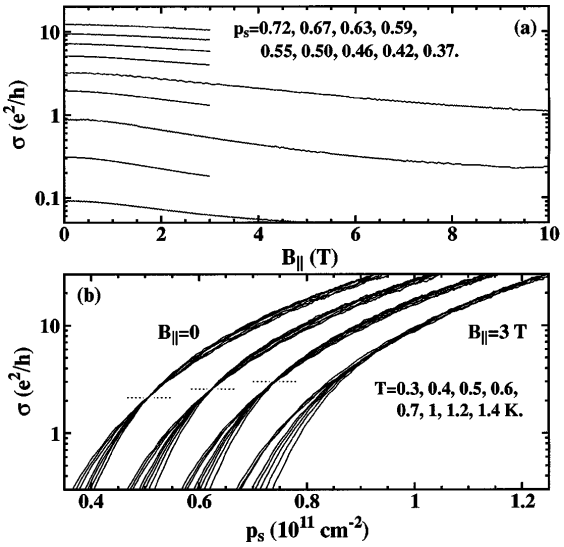

FIG. 4. (a) Conductance as a function of applied parallel magnetic field $B_\parallel$ at $T = 0.27$ K for the hole densities indicated on the graph (in unit of 10^{11} cm^{-2}). (b) The conductance as a function of carrier density, with magnetic fields of $B_\parallel = 0$, 0.5, 1, and 3 T. Curves for different $B_\parallel$ have been offset horizontally by 0.1×10^{11} cm^{-2}; the horizontal dotted lines mark the T-independent $\sigma_{\min}$.

4.5 ± 0.25 in the metallic regime, and from 6.5 ± 1 to 8 ± 2 in the insulating regime, as $B_\parallel$ increases from 0 to 1 T, with a corresponding decrease in the quality of the scaling. In a system with weak electron-electron interactions and strong spin-orbit scattering the destruction of the metallic phase by the application of a parallel magnetic field can occur as the spin degeneracy is lifted and a transition from weak antilocalization to weak localization occurs. However, in our samples electron interactions should be strong, and no evidence for weak antilocalization is observed. The destruction of the metallic state in a parallel field both in Si MOSFETs [12,13] and in our samples does, however, point to a spin related origin of the metallic phase.

In summary, we have reported the observation of a metal-insulator transition at $B = 0$ in a high mobility two dimensional hole gas formed in a GaAs/AlGaAs heterostructure, with a minimum metallic conductance of $\sigma_{\min} = 2e^2/h$. On either side of the transition a single scaling parameter can be used to collapse the resistivities onto a single curve in both the conducting and insulating phases separately. The critical exponents were found to be 7.0 ± 1.5 and 3.8 ± 0.4, respectively. On the metallic side of the transition we observe apparently normal metallic behavior, with $\Delta\sigma/\sigma = f(T/T_F)$. We suggest that this is a consequence of the strength of the electron-electron interactions ($r_s \approx 10$) which suppress quantum interference corrections to the conductivity. The spin related origins of the metallic state are, however, revealed by the application of a parallel magnetic field which suppresses the metallic phase and causes an increase in $\sigma_{\min}$.

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Note added.—After the initial observation reported here we have since learned of a related work by Y. Hanein *et al.* [23].

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