The Metalliclike Conductivity of a Two-Dimensional Hole System

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We report on a zero magnetic field transport study of a two-dimensional, variable-density, hole system in GaAs. As the density is varied we observe, for the first time in GaAs-based materials, a crossover from an insulating behavior at low density, to a metalliclike behavior at high density, where the metallic behavior is characterized by a large drop in the resistivity as the temperature is lowered. These results are in agreement with recent experiments on Si-based two-dimensional systems. We show that, in the metallic region, the resistivity is dominated by an exponential temperature dependence with a characteristic temperature which is proportional to the hole density. [S0031-9007(97)05215-0]

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The study of the transport properties of two-dimensional electron systems (2DES's) revealed numerous unique features associated with their reduced dimensionality. A central question is whether a metal-insulator transition (MIT) can occur in two dimensions (2D). Using scaling arguments Abrahams *et al.* [1] stated that noninteracting electrons in 2D systems are localized at zero temperature (T) for any level of disorder, and a MIT is not expected to occur at zero magnetic field (B). This work motivated several experimental studies which investigated the T dependence of the resistivity (ρ) of low-mobility 2DES in Si metal-oxide-semiconductor field-effect transistors (MOSFET's) [2,3] and in In_2O_{3-x} films [4]. The resistivity was found to increase with decreasing T, and its T dependence changed from weak to strong as the density of the 2DES was lowered, or the disorder increased. These experiments seemed to confirm the theoretical notion that no metallic phase exists in 2D.

However, several recent studies presented evidence to the contrary. In these studies 2DES's in Si MOSFET's [5,6] and Si/SiGe heterostructure [7–9] were used, and the resistivity was measured as a function of T for various carrier densities. These studies demonstrated a clear crossover from metallic to insulating behavior at low T. Further, in the metallic region, the resistivity was shown to decrease with decreasing T by as much as a factor of 8, while in the insulating region the resistivity increases sharply with decreasing T. The authors of Ref. [5] took these results as evidence for the existence of a MIT in 2D, and several theoretical works have tried to associate them with modified scaling [10] or raised the possibility of superconductivity [11,12]. The disagreement between these new results and earlier ones is generally attributed to the higher mobility in these samples (reaching a value as high as 75 000 $cm^2/V\,s$) and to the high effective mass of electrons in Si ($m = 0.19m_0$) which, according to the authors, combine to accentuate the effect of carrier-carrier interactions. The possibility that carrier-carrier interactions would lead to qualitative modification of the behavior predicted by theories for noninteracting electrons was actually raised more than a decade ago by Finkel'stein [13]. It was therefore suggested [14] that, due to the heavy mass of holes in GaAs ($0.6m_0, 0.38m_0$) [15,16] and the superior quality of molecular beam epitaxy growth, a similar transition may appear in a two-dimensional hole system (2DHS) embedded in GaAs heterostructures.

In this Letter we report on a low-T, $B = 0$, study of high-quality 2DHS in GaAs that indeed exhibits such a transition. To facilitate this study we chose a p-type inverted semiconductor insulator semiconductor (ISIS) structure [17] grown on (311)A GaAs substrate [18] using Si as a p-type dopant [19]. A schematic layer profile of the p-type ISIS structure used in this work is shown in the inset of Fig. 1. In such an ISIS device the carriers are accumulated in an undoped GaAs layer lying on top of an undoped AlAs barrier, grown over a p^+ conducting layer. This p^+ conducting layer is separately contacted and serves as a back gate. The hole carrier density (p) can be easily varied by applying voltage (V_g) to the back gate resulting in a change in p of $1.1 \times 10^{11}\ cm^{-2}\,V^{-1}$, which is consistent with a capacitively induced charge transfer. The carrier density was determined by direct measurement of the Hall effect. At $T = 50$ mK our samples have a mobility of 150 000 $cm^{-2}/V\,s$ at $p = 0.64 \times 10^{11}\ cm^{-2}$. The high limit of the density in this study was set by gate leakage. The samples were wet etched to the shape of a standard Hall bar and Zn-Au evaporated contacts were carefully alloyed at 370 °C to avoid penetration of the alloyed metal into the p^+ buffer layer. The measurements in this study were performed on a Hall bar with current flowing in the $[01\bar{1}]$ direction.

One handy advantage of the ISIS structure is that it offers the capability to vary the carrier density continuously over a very wide range, in a similar fashion to Si MOSFET's. We utilize this flexibility to study the T dependence of ρ at a number of densities from the insulating phase to the high-p conducting state. Measurements

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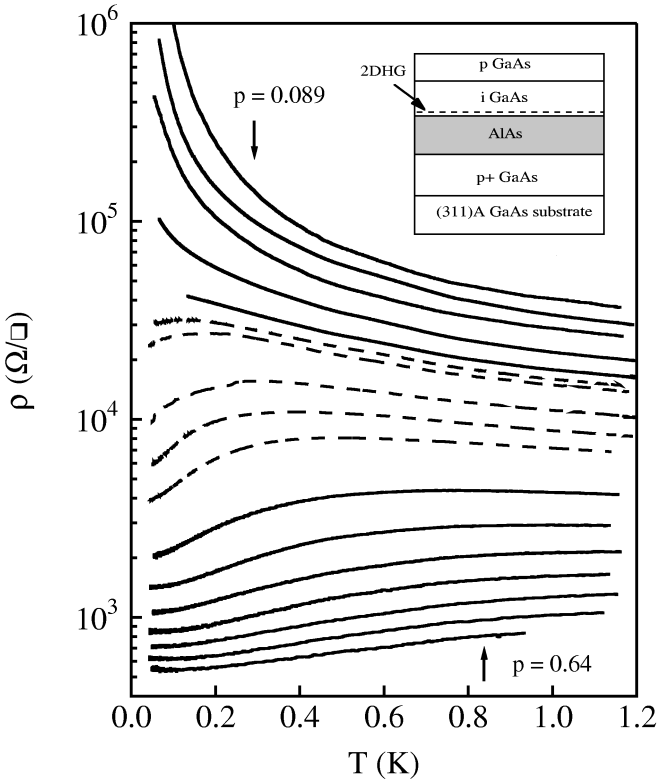

FIG. 1. ρ as a function of T data obtained at $B = 0$ at various fixed densities, $p = 0.089$, 0.094, 0.099, 0.109, 0.119, 0.125, 0.13, 0.15, 0.17, 0.19, 0.25, 0.32, 0.38, 0.45, 0.51, 0.57, and 0.64×10^{11} cm^{-2}. Note the three distinct regimes: insulating regime at low densities, a mixed regime at intermediate densities indicated by dashed lines, and a metalliclike regime at high densities (see text). Inset: Schematic presentation of the p-type ISIS structure grown on a semi-insulating (311)A GaAs substrate, consisting of a thick p^+ buffer, a 300 nm undoped AlAs barrier, a 150 nm undoped GaAs channel layer, and a top 50 nm GaAs layer which is p doped. The 2DHS forms at the lower interface of the channel layer upon application of negative bias to the p^+ conducting layer.

were done in a dilution refrigerator with a base T of 40 mK, using the ac lock-in technique with an excitation current of 0.1 nA. We repeated the measurements with higher excitation current and no effect of heating was found. The collection of the data was done by fixing the density and sweeping T continuously between our base T and 1.2 K. The data were reproducible upon numerous cycles of V_g and T.

Typical results, obtained from sample H315J, are presented in Fig. 1, where we plot ρ vs T at various values of p between 0.089×10^{11} and 0.64×10^{11} cm^{-2}. It is possible to crudely classify the traces in Fig. 1 into three distinct regimes. The first is the low-p regime (top set of solid lines), characterized by insulating behavior, with $\rho(T)$ decreasing rapidly with T. In the second regime (dashed curves), a mixed behavior is observed at our T range, with insulatinglike $\rho(T)$ at high T, turning over to metalliclike behavior at lower T's. Although quite interesting, we defer discussion of these two regimes to a future publication, and center our attention on the high-p region, where the $\rho(T)$ traces exhibit metalliclike behavior characterized by ρ that drops precipitously as T is lowered, followed by an apparent saturation of $\rho(T)$ at yet lower T's.

The results presented in Fig. 1 are very similar to those of Kravchenko *et al.* [5] and others [6], a notable fact considering that we are dealing with two distinct materials. Incidentally, this similarity rules out explanations of the data that are material dependent. We point out that in both Si MOSFET's and p-type GaAs ISIS the low carrier density, coupled with their high effective mass, led to a relatively low Fermi energy (E_F) and high ratio of the typical carrier-carrier Coulomb-interaction energy to E_F, expressed by the dimensionless parameter r_s. In our density range, $E_F = 0.5-3.7$ K and $r_s = 24$ to 9 calculated for the lighter mass, $m = 0.38m_0$. It is not clear whether we can safely deduce the ultimate low-T phase of our system from measurements done at T's that are not much smaller than E_F/k_B.

Of their many findings, Kravchenko *et al.* [5] singled out the existence of an apparent metallic behavior in their samples as the most intriguing. We therefore turn our attention to a detailed analysis of the high-p range of our data where metalliclike behavior is evident. Following the suggestion of Pudalov [20], we fit the $\rho(T)$ data with

$$\rho(T) = \rho_0 + \rho_1 \exp\left(-\frac{T_0}{T}\right) \qquad (1)$$

and plot, in Fig. 2, ρ vs T (solid lines) for several values of p in the metallic regime, together with their fits (dashed lines). A surprisingly good fit (at low T) is obtained especially at high p, where only marginal and hardly noticeable deviations of the fits from the data are seen. In the remainder of this Letter we will explore this form and its possible consequences.

We begin by considering the limits of applicability of Eq. (1). At higher T's we observe significant deviations from the behavior prescribed by Eq. (1) and indicate their approximate T's by arrows in Fig. 2. These deviations may be expected when $T > T_0$. Several other factors may also combine to cause additional deviations, among them the aforementioned approach towards E_F and the influence of the insulating regime at low p.

More relevant to the determination of the quantum nature of the transport is the low-T range. Following Eq. (1), ρ seems to approach a constant, ρ_0. We note that this apparent saturation is not likely to be caused by heating since, at the same T range, lower-p traces (Fig. 1), where the dissipation induced by the constant probing current is more than 10 times larger, are distinctly T dependent. At face value, a finite ρ_0 may indicate a true metallic zero T behavior. We stress that this is not necessarily the case for finite-size samples, a fact that had been previously recognized regarding

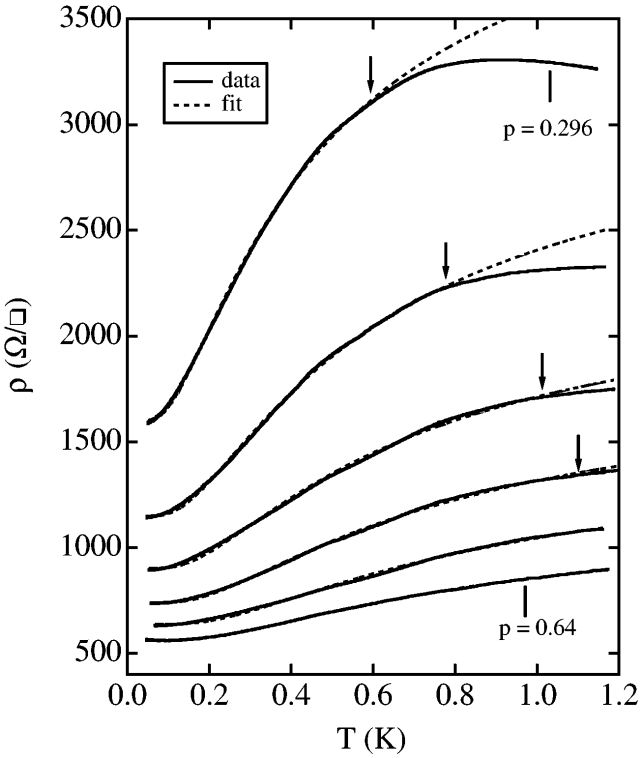

FIG. 2. Metalliclike curves at $p = 0.30$, 0.36, 0.43, 0.50, 0.57, and 0.64×10^{11} cm^{-2} plotted using a linear ordinate (solid lines). Also shown are the fits to the empiric formula: $\rho_0 + \rho_1 \exp(-\frac{T_0}{T})$ (dashed lines). Because of the high fidelity of the fits, they are hardly distinguishable from the data at some higher densities. Arrows indicate the approximate T where the fits start to deviate significantly from the data.

high-mobility 2DES's. Furthermore, due to the limited accuracy of our measurements, we are unable to exclude the existence of additional terms in $\rho(T)$ with relatively weak (logarithmic) T dependence. The existence of the exponential term in ρ will effectively mask any possible T dependence of ρ as long as T is not much smaller than T_0. We are therefore in a situation where our ability to extrapolate $\rho(T)$ to $T = 0$ is limited to a very narrow T range between $\approx T_0/5$ (where the exponential term becomes negligible) and our base T, 40 mK. Clearly, much lower T's are essential for unveiling the ultimate zero T behavior of the system.

Between these two extremes of Eq. (1), a remarkable behavior is observed. In this intermediate T range, the second term of Eq. (1) dominates and ρ is exponentially increasing with T. To further emphasize this behavior we plot, in Fig. 3, $\rho - \rho_0$ vs $1/T$ using an Arrhenius plot, for the data of Fig. 2. A clear exponential dependence is seen which covers over 2 orders of magnitude in ρ. It is this exponential behavior which underlies the abrupt drop in ρ seen in Figs. 1 and 2.

Clearly, the physical origin of T_0 is one of the main issues that need to be addressed. We therefore plot, in Fig. 4(a), the characteristic T of the conduction process,

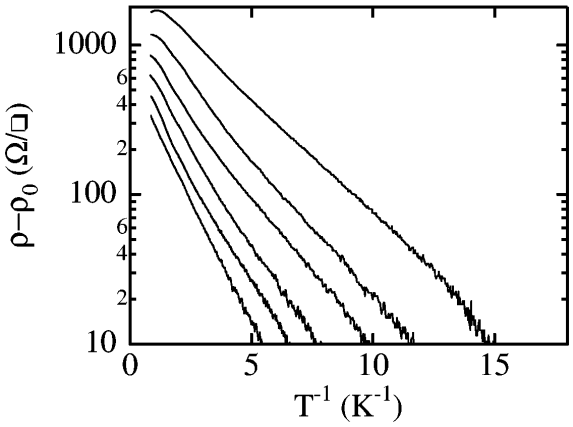

FIG. 3. $\rho - \rho_0$ [ρ_0 is obtained from fitting the data to Eq. (1)] as a function of T^{-1} at the same p values as in Fig. 2. The T was varied between 50 mK and 1.2 K.

T_0, as a function of p for our sample. T_0 increases monotonically with p and reaches 0.78 K for our highest p. With the limited accuracy of these measurements we are unable to determine the functional dependence of T_0 on p, although a linear dependence is reasonable. We note that from the linear fit T_0 extrapolates to $T_0 = 0$ as p approaches zero. This implies that the exponential T dependence of ρ persists to $p = 0$. In reality it is overcome by the insulating behavior that sets in at low p.

In Fig. 4(b) we show ρ_0 and ρ_1 vs p. Clearly, both have a very strong dependence on p, and appear to be diverging near $p = 1.1 \times 10^{10}$ cm^{-2}. Because of the importance of ρ_0 we are currently studying in detail its behavior.

At present, we do not have a theoretical understanding of the physics which underlies this intriguing regime. We note that this behavior reveals itself under the condition of low E_F, where carrier-carrier interactions should play a more significant role in the dynamics of the system. This may explain why in systems with lower r_s, such as 2DEG in GaAs, no analogous behavior is observed [21]. The observation of an exponential term in ρ may be taken as evidence for the existence of an energy gap, which inhibits scattering at low T. Pudalov suggested a spin-orbit gap as the origin of T_0. As he stated, this gap is likely to be too small in n-type GaAs [20]. However, it may not necessarily be small in p-type GaAs.

To summarize, we used a p-type ISIS to investigate the T dependence of the resistivity of two-dimensional hole gas in GaAs. We observed a transition from metallic to insulating behavior at low T's. The results in this Letter are similar to other experiments facilitating different 2D systems. We have shown that the resistivity at the metallic phase is determined by two terms. The first appears to be independent on T, while the second has a rather surprising, exponential, dependence on T_0/T and T_0 increases monotonically with p. We emphasize that much lower T's are needed to safely determine the ultimate low-T phase of the system.

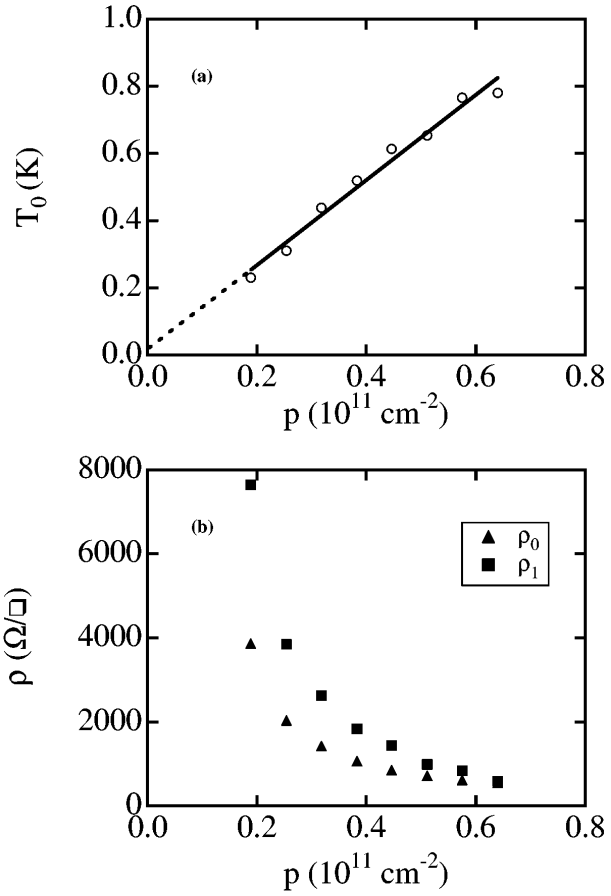

FIG. 4. (a) The T_0's, obtained by fitting the metallic data of Fig. 2 to Eq. (1), vs p. The solid line indicates the linear fit of T_0. The dashed line indicates the extrapolation of the fit to $p = 0$. (b) The fitting parameters ρ_0 and ρ_1 as a function of p.

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Note added.—After the submission of this Letter we became aware of a similar study of the metal-insulator transition in 2DHS in GaAs [22].

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