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Apparent metallic behavior at $B=0$ of a two-dimensional electron system in AlAs

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We report the observation of metalliclike behavior at low temperatures and zero magnetic field in two-dimensional (2D) electrons in an AlAs quantum well. At high densities the resistance of the sample decreases with decreasing temperature, but as the density is reduced the behavior changes to insulating, with the resistance increasing as the temperature is decreased. The effect is similar to that observed in 2D electrons in Si metal-oxide-semiconductor field-effect transistors, and in 2D holes in SiGe and GaAs, and points to the generality of this phenomenon. [S0163-1829(98)50724-2]

The question of whether or not a metal-insulator transition can occur in two dimensions at zero magnetic field has been of great recent interest. Using scaling arguments, Abrahams *et al.*[1] showed that a noninteracting two-dimensional (2D) carrier system with any amount of disorder will be localized at zero temperature. Subsequent experiments provided evidence to support this theoretical prediction.[2] However, recently, various investigators[3–10] have discovered 2D carrier systems that show metallic behavior. They observe that for a range of 2D densities (n), the resistivity of their samples decreases by nearly an order of magnitude as the temperature (T) is decreased. When n is reduced below a critical density (n_c) they observe a transition to insulating behavior. One difference between the earlier and the more recent experiments is that the new samples have a much higher carrier mobility (μ). One theoretical investigation asserts that this higher μ combines with a broken inversion symmetry in the confining potential well to allow spin-orbit effects to create the metallic state,[11] while another hypothesizes that the higher μ allows for stronger electron-electron interaction, and that this interaction causes the metallic state.[12] However, there is still no clear model supported by experimental results to explain this metallic behavior.

So far, the metallic behavior has been observed in 2D electron systems (2DES's) in Si metal-oxide-semiconductor field-effect transistors (MOSFET's),[3,6] 2D hole systems (2DHS's) in GaAs/AlGaAs heterostructures,[4,5,9,10] and SiGe quantum wells (QW's),[7,8] and now in a 2DES in AlAs. To provide an overview, and for further discussion, some of the important parameters of these systems are shown in Table I. AlAs is an interesting material for 2DES's because it combines some of the properties of GaAs with those of Si. Since it is grown in the same molecular beam epitaxy (MBE) systems as GaAs samples, very clean samples can be fabricated. However, it is similar to Si in that the minima of the AlAs conduction band are at the X points of the Brillouin zone. (The minima in Si are near the X points.) In addition, in AlAs QW's like ours, which are grown on the (100) surface of the GaAs substrate, one can cause the electrons to occupy the conduction-band ellipsoids either perpendicular to or parallel to the plane of the 2DES by varying the width of the QW.[13,14] Our data indicate that in our sample, only *one* of the *in-plane* ellipsoids is occupied. By patterning Hall bars along and perpendicular to the direction of the occupied ellipsoid's major axis, we are able to measure the resistance along these two directions. We observe anisotropy in the measured resistance, and the data along both directions show metallic behavior at high n and insulating behavior at low n.

Our sample was grown by MBE on an undoped GaAs (100) substrate. The 2DES is confined to a 150-Å-wide AlAs QW that is separated from the dopant atoms (Si) by a 300-Å-wide front barrier of $Al_{0.45}Ga_{0.55}As$ and a rear barrier consisting of 25 periods of a GaAs/AlAs (10.5 Å/8.5 Å) superlattice. On a sample from this wafer, we patterned two Hall bars oriented perpendicular to each other (L shaped) along the [001] and [010] directions. The Hall bars were patterned by standard photolithographic techniques and a wet etch. Ohmic contacts were made by alloying AuGeNi in an N_2 and H_2 atmosphere for 10 min. A front gate of 350 Å Au on top of 50 Å Ti was deposited on top of the active regions of the Hall bars to control n.

Our T dependence measurements were performed in a pumped ^{3}He refrigerator at T from 0.28 K to 1.4 K. We measured T using a calibrated RuO_2 resistor. We used the standard low-frequency ac lock-in technique with an excitation current of 1 nA to measure the four point resistance of the sample. The data were taken by fixing the front-gate voltage (V_g), and measuring both the longitudinal (R_{xx}) and transverse (R_{xy}) resistances as a function of a perpendicular magnetic field (B). These magnetoresistance measurements were used to determine n at that V_g. Gate leakage was monitored throughout the experiment and it never exceeded 10 pA. The T was then raised to 1.4 K and continuously lowered back to the base T (0.28 K) over a period of 3 h. The densities and T dependencies were repeatable at the same gate voltages. The results of R_{xx} and R_{xy} magnetoresistance measurements at 0.28 K for $V_g=0$ are shown in Fig. 1. Note the high quality of the data, with the appearance of Shubnikov–de Haas oscillations at a field as low as 0.6 T and the fractional quantum Hall effect at Landau-level filling factor $\nu=\frac{2}{3}$ as well as at $\nu=\frac{1}{3}$ (see Ref. 15).

Before presenting the T-dependence data, we will describe some of the characteristics of our AlAs 2DES. Several observations lead us to believe that in our sample only *one in-plane* conduction-band ellipsoid is occupied. First, previous cyclotron resonance (CR) measurements on samples from this wafer reveal a CR effective mass $m_{CR}=0.46m_e$.[15]

TABLE I. A summary of some of the important parameters in experiments that have reported evidence for a metal-insulator transition in a low-temperature 2DES or 2DHS at zero magnetic field. The listed μ are the peak reported μ. Note that the different systems have a wide range of n_c, the density below which an insulating state ensues, but the resistivity values at the transition (ρ_c) are comparable. Also, all of these systems have a fairly high m^* and a relatively small density, leading to small Fermi energies (E_F) and large r_s values. Listed here are the ranges of E_F and r_s over which the experiments show a metallic behavior.

		μ (m^2/Vs)	n_c (10^{11} cm^{-2})	ρ_c (kΩ/sq.)[a]	m^*/m_e	E_F (K)	r_s
2DES	Si-MOSFET (Refs. 3,6)	7.1–1.0	0.85–1.7	70	0.19	4.3–15	9.6–5.7
	AlAs	7.7	0.7	50	0.46	3.6–16	18–9
2DHS	GaAs (Refs. 9,10)	15	0.1–0.12	40	0.38	0.5–3.7	24–9
	SiGe (Ref. 7)	1.9	1.7	20	0.2–0.32	6–28	~5–9[b]

[a]The values for ρ_c were determined following the method of Ref. 3: by drawing a separatrix between the metallic and insulating curves and then extending that separatrix to $T=0$.

[b]This r_s is a rough estimate because the value of ϵ used for SiGe is an estimate.

This mass is in excellent agreement with the expected CR mass if in-plane ellipsoids are occupied.[16] It is very different from $m_{CR}=m_t=0.19m_e$, which would be observed if an ellipsoid perpendicular to the plane were occupied. Second, the data of Fig. 1 show minima in R_{xx} and plateaus in R_{xy} for both even and odd filling factors, and the Shubnikov–de Haas oscillations show no beating. Moreover, the two R_{xx} traces from the two perpendicular Hall bars show an anisotropy in μ. We conclude from these observations that only one of the two in-plane ellipsoids is occupied: the magnetoresistance data suggest that there is only one occupied subband, while the μ anisotropy indicates that the Fermi surface in the plane of the 2DES can be anisotropic, consistent with a single in-plane ellipsoid being occupied. It is possible that a slight angular deviation from the ideal growth direction could account for the lifting of the expected degeneracy of the in-plane ellipsoids, as a splitting of only a few meV would be sufficient to produce a single occupied subband.[15,17]

We now compare the characteristics of the 2DES in our sample with those of Si MOSFET's. First, the conduction-band ellipsoids in bulk Si and AlAs are comparable, with similar values for m_l and m_t.[18] However, in contrast to our sample, the Si-MOSFET 2DES's that have been studied so far occupy *out-of-plane* ellipsoids. As a result, transport in the plane is isotropic with an effective mass $m_t=0.19m_e$. The mobilities at base T of our sample for the trace shown in Fig. 1 ($n=2.08\times10^{11}$ cm^{-2}) are 6.1 m^2/V s for the high-μ direction and 4.2 m^2/V s for the low-μ direction. The highest mobilities we measure, for the highest density ($n=2.73\times10^{11}$ cm^{-2}), are 7.7 m^2/V s and 4.7 m^2/V s. These mobilities are comparable to the highest mobilities reported for Si-MOSFET 2DES's (see Table I).[3] Finally, as seen in Fig. 1 and Ref. 15, our sample exhibits clear fractional quantum Hall effect, an effect rarely seen in Si MOSFET's.

Figure 2 summarizes the T dependence of the zero-B resistivity (ρ) for a range of n from 2.73×10^{11} cm^{-2} to 0.59×10^{11} cm^{-2}. The results for both high- and low-mobility directions are shown. As with other experiments,[3,6–10] the data can be split into three regimes. In the lowest n traces, the behavior is insulating throughout the T range measured, with ρ rising monotonically as T is reduced. The highest n traces show metallic behavior throughout the T range, with ρ decreasing monotonically as T is reduced. For intermediate n, ρ exhibits a nonmonotonic dependence on T: it initially rises as T is lowered, shows a maximum, and then decreases with decreasing T. These data are very similar qualitatively to the results of previous experiments.

As already mentioned, a theoretical explanation for data like these, with experimental evidence to support it, does not exist. We expect, though, that the Fermi energy (E_F) might be an important parameter. In our sample, E_F at the highest density is 16 K and at the lowest density is 3.6 K. Our T range in these measurements (0.28 K to 1.4 K) is only about an order of magnitude smaller than E_F. Most of the 2D carrier systems investigated so far also have E_F comparable to the T range over which the experiment is done. This raises the possibility of finite-T effects causing the metalliclike behavior. In fact, Henini *et al.*[4] have fitted to their GaAs 2DHS data an expression $[\mu/\mu_0\sim1-(T/E_F)^2]$ describing the temperature dependence of screening[19] and found that the fit was very good. Our data is not fit well by this equation, but we cannot rule out this effect because the exact expression for temperature-dependent screening depends on details of disorder and material parameters.

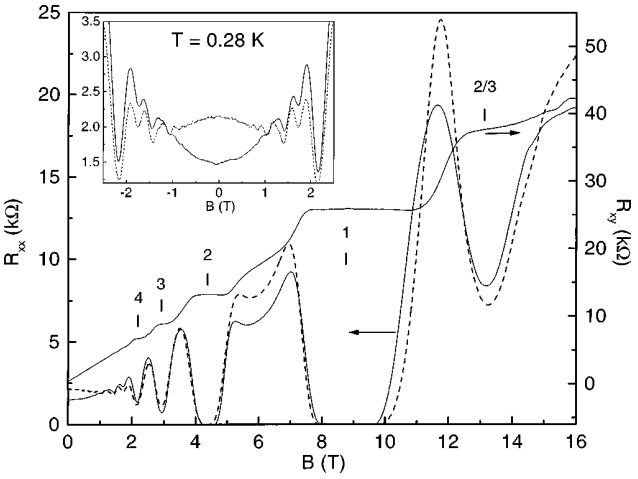

FIG. 1. R_{xx} and R_{xy} data for an AlAs 2DES ($n=2.08\times10^{11}$ cm^{-2}) confined to the (100) plane. R_{xx} is shown along two perpendicular ([010] and [001]) directions. Some of the Landau level filling factors at which the quantum Hall effect is observed are marked by vertical lines. The inset is a closer view of the low field data, demonstrating the resistance anisotropy at $B=0$.

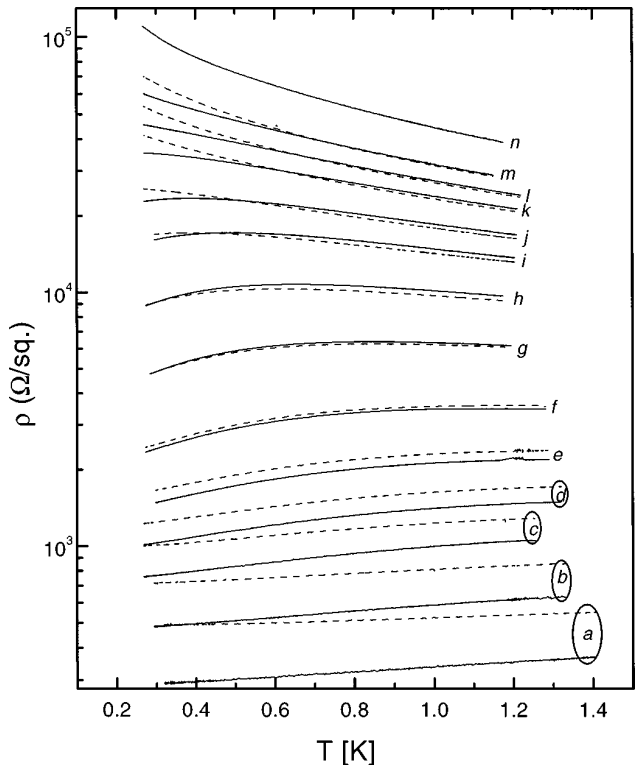

FIG. 2. Resistivity vs temperature data from our AlAs 2DES. The high (low)-mobility direction data are shown by solid (dashed) curves. The densities, in units of 10^{11} cm^{-2}, are *a*: 2.73, *b*: 2.08, *c*: 1.42, *d*: 1.22, *e*: 1.02, *f*: 0.82, *g*: 0.74, *h*: 0.72, *i*: 0.70, *j*: 0.65, *k*: 0.64, *l*: 0.63, *m*: 0.60, *n*: 0.59. The low-mobility curve for case *n* is not shown because the Ohmic contacts failed at such a low density.

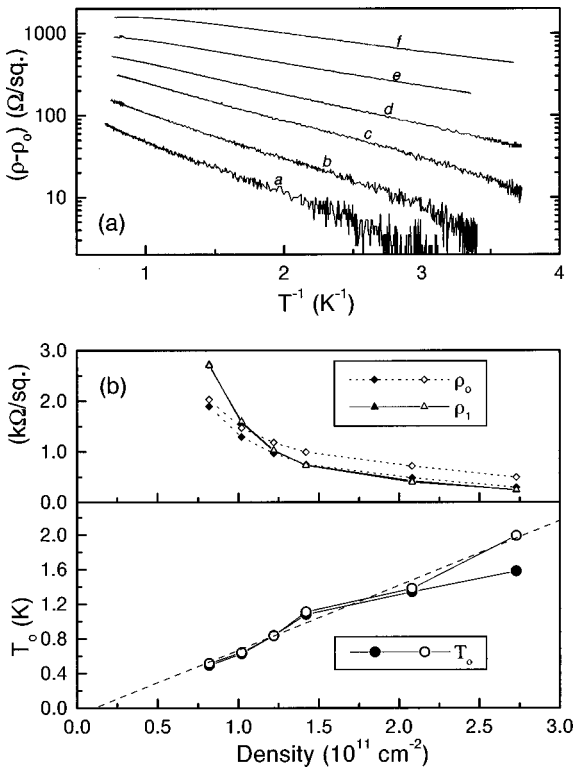

FIG. 3. (a) Arrhenius plots of $(\rho-\rho_0)$ vs $1/T$ for traces *a* through *f*. Only the high-μ direction curves are shown. (b) Values of ρ_0, ρ_1, and T_0 from fits of Eq. (1) to the data (traces *a* through *f* of Fig. 2). The open (closed) symbols are from fits to the low (high)-μ direction data. The dashed line in the lower plot is a least-squares fit to the open circle points. The least-squares fit to the closed circle points (not shown) also extrapolates to very close to $T_0=0$ at $n=0$.

Another possible model has been put forth by Pudalov.[11] He suggests that the metalliclike data may be fitted by an empirical dependence

$$\rho(T)=\rho_0+\rho_1\exp(-T_0/T). \quad (1)$$

The second term is intended to account for an energy gap caused by a spin-orbit interaction. For *n* where our 2DES exhibits a metallic behavior throughout the measured *T* range (traces *a* to *f* of Fig. 2), this equation fits our data well through the whole *T* range. The fits are not shown in Fig. 2 because they are indistinguishable from the data. To show the accuracy of the fits, we present representative Arrhenius plots of $(\rho-\rho_0)$ vs $1/T$ in Fig. 3(a). For clarity, only the curves for the high-μ direction data are shown; the curves for the low-μ direction are very similar. Clear exponential behavior is observed for more than a decade of $(\rho-\rho_0)$ for the highest density traces, but as the density is reduced, the range over which exponential dependence is observed reduces to about a factor of 5. In Fig. 3(b) we show, as a function of *n*, the values of ρ_0, ρ_1, and T_0 deduced from fitting Eq. (1) to the data. As expected, ρ_0 rises monotonically as *n* is reduced. Also, ρ_1 is seen to rise smoothly and monotonically, which is more evidence that the fits are meaningful. The T_0 vs *n* dependence seen in the lower part of Fig. 3(b) is qualitatively the same as what Hanein *et al.*[9] observe for their 2DHS data. Both show a dependence that is close to linear, and that extrapolates to $T_0=0$ at $n=0$. We note that a decreasing T_0 with *n* is consistent with T_0 being related to spin-orbit interaction: the spin-splitting energy in 2D carrier systems due to interface inversion asymmetry indeed typically decreases with decreasing 2D density.[11,20] It is also interesting to compare the dimensionless ratio T_0/E_F in our measurements to those of Hanein *et al.*[9] Since both E_F and T_0 vary approximately linearly with *n* in the range where the behavior is metallic, this ratio is a constant for each experiment. For the data of Hanein *et al.*, $T_0/E_F\simeq 0.2$, while for ours, $T_0/E_F\simeq 0.1$. Despite a factor of 2 difference, these ratios are similar enough to suggest that T_0 and E_F may be important physical parameters in all of the systems that show metallic behavior.

Taken together, the results of recent experiments make it very difficult to overlook the anomalous low-*T* behavior in these systems. The similarity of the data and the parameters from various systems, and the inability of any current theory to describe them all, strongly suggest that there is new and interesting physics here. A look at Table I shows the similarities among some relevant parameters. The large values of the dimensionless parameter r_s (the interparticle spacing measured in units of the effective Bohr radius) and of μ support the idea that electron-electron interaction plays a role in stabilizing the metallic state. The combination of rather small densities and large effective masses that leads to large r_s values, on the other hand, also means small values of E_F. Ironically, precisely because of these small E_F values, it is still questionable if it is meaningful to infer the existence of

a zero-T metallic state from the available finite-T data: phenomena such as temperature-dependent screening[4,19] can indeed lead to a decrease in ρ with decreasing T at temperatures that are not negligible compared to E_F.

In conclusion, we present data from a 2DES that shows the same metalliclike behavior and apparent metal-insulator transition recently observed in other 2D carrier systems. The generality of this phenomenon begs theoretical explanation.

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