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Observation of the metal-insulator transition in two-dimensional *n*-type GaAs

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The observation of a carrier-density driven metal-insulator transition in *n*-type GaAs-based heterostructure is reported. Although weaker than in comparable-quality *p*-type GaAs samples, the main features of the transition are rather similar. [S0163-1829(98)51744-4]

The recent discovery[1] of a metal-insulator transition (MIT) in two-dimensional (2D) Si-based samples has been met with a certain degree of skepticism. This skepticism was largely founded on several successful theoretical studies,[2] which enjoyed a strong support from experiments.[3,4] Therefore, it was only when the pioneering work of Kravchenko and his collaborators was followed by several other groups investigating various other materials[5–12] that the initial objections began to dissolve, and the MIT in 2D has become a mainstream field of study, where old[13] and new[14–21] theoretical approaches are discussed.

Conspicuously missing from the list of semiconducting materials exhibiting the MIT in 2D has been the *n*-type GaAs system. In fact, in a recent study[22] of a high-density *n*-type GaAs/$Al_xGa_{1-x}As$ system, the MIT was clearly shown to be absent down to milli K temperatures. The absence of the MIT in that sample was attributed to the relatively low level of the electron-electron interaction strength. This is because the low mass of the electrons in GaAs, which is a contributing factor in many of the unique phenomena associated with 2D systems, reduces the relative strength of these interactions. It is convenient to express the relative interaction strength in terms of $r_s = E_c/E_F$, the ratio of the typical electron-electron interaction energy, $E_c = e^2/\epsilon r$, to the Fermi energy E_F (e is the elementary charge, ϵ the dielectric constant, and r is the average distance between carriers). The lower mass increases E_F (for a given carrier density) and therefore low carrier-mass systems are usually characterized by small r_s values. With the accumulating evidence for the existence of the MIT in several 2D systems it became clear that a high value of r_s, usually >5, is a prerequisite for the observation of the MIT. In Ref. 22 the system turns (strongly) insulating, presumably due to disorder, at a density $n > 1.4\times10^{11}$ cm^{-2}, corresponding to $r_s < 1.4$, which is clearly too low for the observation of the MIT.

To check these conjectures, and to facilitate a comparison with our *p*-type samples, we grew and measured a low-disorder *n*-type GaAs/$Al_xGa_{1-x}As$ sample. The sample was grown by a molecular-beam epitaxy (MBE) technique on semi-insulating (311)*A* substrate, which is similar to that used for our *p*-type samples. An appealing advantage of the (311)*A* growth orientation in GaAs/$Al_xGa_{1-x}As$ structures is associated with the amphoteric nature of Si on this growth plane.[23] By adjusting the growth parameters one can obtain either *n*-type or *p*-type material: At high growth temperature ($T \geqslant 600$ °C) and low impinging arsenic flux (As/Ga flux ratio of 1/5), the Si will occupy the As sites and turn into a *p*-type dopant, and at low growth temperature ($T \leqslant 500$ °C) and high impinging arsenic flux (As/Ga flux ratio>10) the Si will be forced to occupy the Ga sites and the material will be *n* type. An added advantage of MBE growth on the (311)*A* plane is a reduction in background impurity incorporation, particularly carbon,[24] in comparison with growth on the more common (100) plane. For the (*n*-type) sample in this work our growth comprises a GaAs buffer, followed by a 500-Å $Al_xGa_{1-x}As$ spacer layer, 500-Å Si-doped *n*-type $Al_xGa_{1-x}As$, 150-Å unintentionally doped $Al_xGa_{1-x}As$ capped with a 150-Å GaAs layer. Incorporating a large spacer layer in the growth resulted in a high peak mobility of 2.2×10^6 cm^2/V sec at $n = 13.6\times10^{10}$ cm^{-2}. The measurements in this study were performed using a Hall-bar geometry with current flowing in the $[\bar{2}33]$ direction. A Ti/Au gate was deposited on the top of the sample and was used to control the carrier density, with an effective range of $n = 1.2-13.6\times10^{10}$ cm^{-2}.

As mentioned earlier, mounting evidence indicate that the observation of the MIT in 2D requires high-r_s samples. While the route taken in most previous studies centered around obtaining high r_s by using high carrier-mass systems, we utilized the high quality of our sample to attain low densities, while still maintaining a conducting state. Our ability to reach such low density enabled large values of r_s, $r_s \leqslant 4.8$, to be conveniently studied.

The high quality of our sample is attested to in Fig. 1, where we plot magnetic field traces of the longitudinal (ρ_{xx}) and Hall (ρ_{xy}) components of the resistivity tensor, obtained from sample H678D at $T = 35$ and 38 mK. Two densities are shown, $n = 1.3\times10^{10}$ cm^{-2} in Fig. 1(a) and $n = 6\times10^{10}$ cm^{-2} in Fig. 1(b). These traces span nearly the entire

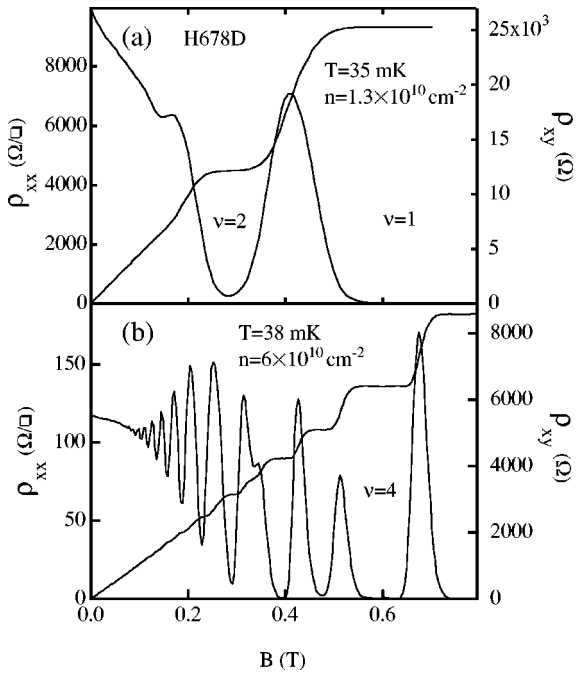

FIG. 1. ρ_{xx} and ρ_{xy} versus magnetic field, at low T, for two densities. (a) Low density traces, $n=1.3\times10^{10}$ cm^{-2} and $\mu=47\,000$ cm^2/V sec (b) High density traces, $n=6\times10^{10}$ cm^{-2} and $\mu=890\,000$ cm^2/V sec.

range of the densities in this low-T study, and it is clear from the appearance of the Shubnikov–de Haas oscillations and the quantum Hall features that homogeneity and uniformity are adequately maintained throughout.

We now turn to our main results. In Fig. 2 we plot the resistivity versus T obtained from sample H678D, for five values of n. Although not as pronounced as in our p-type samples,[9] the main features of the MIT are easily seen. At the lowest density, $n=1.2\times10^{10}$ cm^{-2} [top curve in Fig. 2(a)] the sample appears to be insulating, with ρ monotonically decreasing with T. At slightly higher density, $n=1.3\times10^{10}$ cm^{-2} [bottom curve in Fig. 2(a)], the resistivity is still monotonically decreasing with T, but tends to saturate below 150 mK. We associate the density where the resistivity is T independent at our lowest T's with the metal-insulator transition point. The procedure for identifying the metal-insulator transition point was described in more details in Ref. 25 for our p-type samples. The critical resistivity obtained for the sample in this work is 10.4 kΩ.

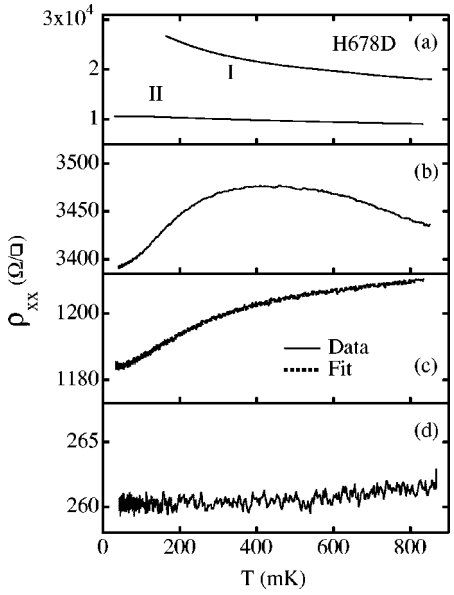

FIG. 2. ρ_{xx} versus T for five different densities. ρ of the 2DES changes from insulating to metallic as the density is increased. (a) Trace I: $n=1.2\times10^{10}$ cm^{-2} ($r_s=4.8$), and trace II: $n=1.3\times10^{10}$ cm^{-2} ($r_s=4.6$). (b) $n=1.9\times10^{10}$ cm^{-2} ($r_s=3.8$). (c) $n=2.5\times10^{10}$ cm^{-2} ($r_s=3.3$), and a fit to Eq. (1), the fit is denoted by a dashed line. (d) $n=4.2\times10^{10}$ cm^{-2} ($r_s=2.5$).

In the next three graphs [Figs. 2(b)–2(d)] the sample exhibits metallic behavior at low T. In Fig. 1(b), nonmonotonic dependence of ρ is observed, with insulatinglike $\rho(T)$ at higher T changing over to metalliclike behavior at our lower T range. This nonmonotonic behavior invariably appears near the transition to the insulating phase. At the next higher n [Fig. 2(c)] a pure metallic behavior is seen with a pronounced drop in ρ at lower T's. Finally, Fig. 2(d) shows a high-n trace where ρ is only weakly dependent on T over our entire T range. We wish to emphasize that although the qualitative features of these data are very similar to those obtained from Si and p-type GaAs-based materials, the magnitude of the features near the transition are much reduced. For instance, the largest percentage drop in ρ we observe for our n-type GaAs is $<3\%$, to be contrasted with a tenfold drop in the case of the highest mobility Si-MOSFET's (where MOSFET denotes metal-oxide-semiconductor field-effect transistor), or a factor of 3 for our p-type GaAs samples. We note that metallic behavior is observed in the sample of this work down to our lowest T and at $n\leqslant6\times10^{10}$ cm^{-2}. No weak-localization corrections to $\rho(T)$ could be resolved within our experimental accuracy.

An additional similarity between the n-type and the p-type metallic conductivities is the dependence of ρ on T. In both cases it appears to obey the form

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

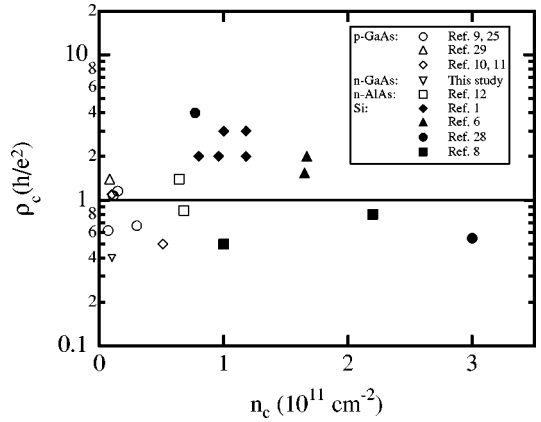

FIG. 3. Resistivity versus density at the transition for various samples from different published studies. The full markers denote Si-based materials that are characterized by large critical densities $n_c>7\times10^{10}$ cm^{-2}. The open markers denote GaAs-based materials, characterized by smaller critical densities, $n_c<7\times10^{10}$ cm^{-2}.

This relation was previously observed in n-type Si-MOSFET's.[5] In Fig. 2(c) we include a fit (dashed line) of the data to Eq. (1). While the quality of the fit is certainly good, we emphasize that the range of the variations in $\rho(T)$ is much too small, and is insufficient to determine the true functional form of $\rho(T)$. The T_0 obtained from the fit is 0.26 K.

The addition of the n-type GaAs-based 2D system to the list of materials that exhibit the MIT serves as a convenient opportunity to consider some general aspects of the transition and their bearing on various material-dependent parameters. In particular, we address the question of the universality of the resistivity value at the transition. In Fig. 3 we plot a compilation of the critical ρ value ρ_c versus critical density n_c, obtained from our samples together with similar published results of several other groups.[1,6,8–12,25,28,29]

In contrast with studies of the quantum Hall to insulator transitions at high magnetic field, where critical resistivities obtained from many samples were within 30% of h/e^2,[26,27] in the MIT-in-2D case the scatter of the data points is significantly larger, even when the somewhat anomalous results from n-type Si/SiGe samples of Refs. 7 are discarded. Further, systematic variations in ρ_c exist, as pointed out in Ref. 28. However, one cannot ignore the impression created by the data that most transition values are scattered around $\rho_c = 1$. The question of whether this is a coincidental observation, or the $\rho_c = 1$ point has some special significance, awaits further experimental as well as theoretical studies.

Summarizing, we demonstrated the existence of a MIT in 2D, n-type, GaAs material. To date, it is the highest mobility sample that exhibits this transition.

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