Parallel Magnetic Field Induced Transition in Transport in the Dilute Two-Dimensional Hole System in GaAs

Jongsoo Yoon,[1,*] C. C. Li,[1] D. Shahar,[2] D. C. Tsui,[1] and M. Shayegan[1]

[1]Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

[2]Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel

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A magnetic field applied parallel to the two-dimensional hole system in the GaAs/AlGaAs heterostructure, which is metallic in the absence of an external magnetic field, can drive the system into insulating at a finite field through a well-defined transition. The value of resistivity at the transition is found to depend strongly on density.

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Several years ago, Kravchenko *et al.* [1] observed that the resistivity (ρ) of the high mobility two-dimensional (2D) electron gas in their Si metal-oxide-semiconductor field-effect transistor (MOSFET) samples, decreased by almost an order of magnitude when they lowered their sample temperature (T) below about 2 K with zero external magnetic field. Their observation of such a metallic behavior contradicts the scaling theory of localization [2] which predicts that, in the absence of electron-electron interaction, all states in 2D are localized in the $T \rightarrow 0$ limit and that only an insulating phase characterized by an increasing ρ with decreasing T is possible at low T. They studied the T dependence of ρ as a function of the 2D carrier density (p) and demonstrated from the temperature coefficient ($d\rho/dT$) of ρ a clear transition from the metallic to an insulating behavior at a "critical" density, p^c. This apparent metal-insulator transition (MIT) has since been reported in other low disorder 2D systems [3], and it appears to be a general phenomenon in low disorder dilute 2D systems where the Fermi energy is small and r_s (the ratio of Coulomb interaction energy to Fermi energy) is large ($\gtrsim$10). To date, despite the large number of experimental [3–10] and theoretical [11,12] papers on this zero field MIT in the literature, there is still no consensus on the physics and the mechanisms behind this metallic behavior.

Two factors that strongly influence this MIT have become apparent from the more recent experiments. First, the application of a magnetic field parallel to the 2D system ($B_\parallel$) induces a drastic response [8–10]. A giant positive magnetoresistance is observed in both the metallic and the insulating phases, varying continuously across the MIT. In the case of Si MOSFET's, Simonian *et al.* [8] have made a detailed study of the T and electric field dependences of the magnetoresistance and concluded that "in the $T \rightarrow 0$ limit the metallic behavior is suppressed by an arbitrarily weak magnetic field." Since $B_\parallel$ couples only to the carrier's spin and does not affect its orbital motion, the spin degree of freedom must play a crucial role in the electronic processes that give rise to transport in both phases.

The second factor that has become increasingly clear is the importance of the role played by disorder. A close examination of all 2D systems that exhibit the MIT reveals that p^c is lower in a system with a higher mobility [5]. Typically, the 2D electron system (2DES) in a high quality Si MOSFET has a peak mobility of 1×10^4–5×10^4 cm^2/V s and $p^c \approx 1 \times 10^{11}$ cm^{-2}. On the other hand, the 2D hole system (2DHS) in a GaAs/AlGaAs heterostructure, which has a comparable effective mass at low densities, usually has a peak mobility of about 10 times higher and $p^c \approx 1 \times 10^{10}$ cm^{-2}. It is clear that p^c decreases monotonically with decreasing disorder. In the clean limit, it is well known that the Wigner crystal is the ground state, when p is reduced so that $r_s \geq 37$ [13].

We have recently investigated the transport properties of a 2DHS in the GaAs/AlGaAs heterostructure, which has an unprecedentedly high peak mobility of 7×10^5 cm^2/V s, and observed a zero field MIT at $p^c = 7.7 \times 10^9$ cm^{-2} [5]. The mobility of this 2DHS is over 25 times that of the 2DES in the Si MOSFET whose $B_\parallel$ response has been most extensively studied in Refs. [8] and [9]. In view of the fact that it is not yet clear what specific role the spins play in the two transport regimes and how the small amount of random disorder in high quality 2D systems influences the MIT, we have systematically studied the effect of $B_\parallel$ on the transport in this high quality 2DHS. We find that for $p > p^c$, the metallic behavior persists to our lowest T of 50 mK until $B_\parallel$ reaches a well-defined "critical" value $B_\parallel^c$, beyond which the 2DHS shows an insulating behavior. At $B_\parallel^c$, ρ is independent of T. The nonlinear I-V characteristics across this $B_\parallel$ induced transition are found to be the same as those across the zero field MIT.

We used the 2DHS created in a Si modulation doped GaAs/Al$_x$Ga$_{1-x}$As heterostructure grown on the (311)A GaAs substrate by molecular beam epitaxy. The samples were Hall bars along the $[\bar{2}33]$ direction, and the measurements were made in the T range from 50 mK to 1.1 K under $B_\parallel$ up to 14 T. The hole density was tuned by a back gate in the range $5.7 \times 10^9 < p < 4.1 \times 10^{10}$ cm^{-2}.

In Fig. 1(a), the T dependence of ρ in the zero field metallic phase is shown on a semilogarithmic plot at several different $B_\parallel$'s for $p = 3.7 \times 10^{10}$ cm^{-2}. The

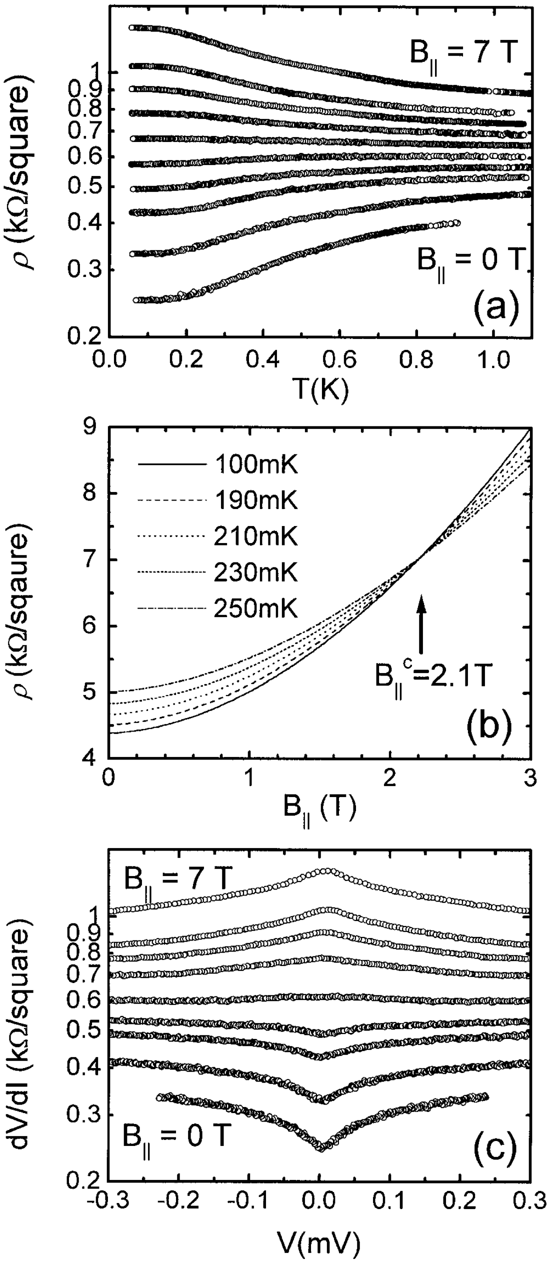

FIG. 1. (a) T dependence of ρ at $p = 3.7 \times 10^{10}$ cm^{-2} and $B_{\parallel} = 0$, 2, 3, 3.5, 4, 4.5, 5, 5.5, 6, and 7 T from the bottom. (b) ρ as a function of $B_{\parallel}$ at five different T's and $p = 1.5 \times 10^{10}$ cm^{-2}. The crossing point at 2.1 T marked by the arrow defines the $B_{\parallel}^c$. (c) dV/dI vs V at 50 mK, $p = 3.7 \times 10^{10}$ cm^{-2}, and at $B_{\parallel} = 0$, 2, 3, 3.5, 4.2, 5, 5.5, 6, and 7 T from the bottom.

bottom trace taken at $B_{\parallel} = 0$ clearly shows a positive $d\rho/dT$, which is characteristic of metalliclike transport. This metallic behavior is found to persist to our lowest T of 50 mK in a magnetic field of up to about 4 T. As $B_{\parallel}$ increases from zero, the strength of the metallic behavior measured by the total change in ρ from about 1 K to 50 mK weakens progressively, and for $B_{\parallel} \geq 4.5$ T $d\rho/dT$ becomes negative. We take this negative $d\rho/dT$ as an indication that the 2DHS is insulating, and phenomenologically identify the two distinct transport regimes as "metallic" and "insulating" phases. It is clear from Fig. 1 that there exists a "critical" field $B_{\parallel}^c$ near 4 T where ρ becomes T independent, separating the metallic and insulating phases. Another way of demonstrating the existence of a well-defined $B_{\parallel}^c$ is to plot ρ against $B_{\parallel}$ at different T's, as shown in Fig. 1(b) for $p = 1.5 \times 10^{10}$ cm^{-2}. In this plot, the crossing point marked by the arrow defines $B_{\parallel}^c$. This is the direct consequence of the fact that ρ decreases with decreasing T for $B_{\parallel} < B_{\parallel}^c$, increases for $B_{\parallel} > B_{\parallel}^c$, and is independent of T at $B_{\parallel}^c$.

Across the zero field MIT, the differential resistivity (dV/dI) is known to show an increase with increasing voltage (V) in the metallic phase and a decrease in the insulating phase [4,5]. In Fig. 1(c), the dV/dI measured at 50 mK across the $B_{\parallel}$ induced MIT for $p = 3.7 \times 10^{10}$ cm^{-2} is shown. It is clear that in the metallic phase ($B_{\parallel} < 4.2$ T) dV/dI increases as $|V|$ increases, and in the insulating phase ($B_{\parallel} > 4.2$ T) it decreases. At $B_{\parallel} = 4.2$ T which is the $B_{\parallel}^c$, dV/dI is constant, implying a linear I-V. This result also shows that there is a well-defined critical field $B_{\parallel}^c$ separating the metallic and insulating phases.

We have measured $B_{\parallel}^c$ and the "critical" resistivity (ρ^c) by changing p for $p > p^c$ on two samples cut from the same wafer, and the results are shown in Figs. 2(a)–2(c). Figures 2(a) and 2(b) show that $B_{\parallel}^c$ decreases with decreasing p and approaches zero as $p \rightarrow p^c$. When $B_{\parallel}^c$ is plotted against $p - p^c$ on a log-log scale [Fig. 2(a)], the data from the two samples form two parallel lines, showing that $B_{\parallel}^c \propto (p - p^c)^\alpha$ with $\alpha \approx 0.7$ for both samples. It is interesting to note that Henein *et al.* [7] extracted from the T dependence of ρ in the metallic phase, an energy scale, T_0, in the form of an activation energy. Their T_0 depends linearly on p in the range $p > 2 \times 10^{10}$ cm^{-2} and extrapolates to zero at $p = 0$. We postulate that the magnetic energy at $B_{\parallel}^c$, $g\mu_B B_{\parallel}^c$ (g being the g factor of holes in GaAs and μ_B the Bohr magneton), is equivalent to their $k_B T_0$ (k_B is the Boltzmann constant), and compare the p dependences of $B_{\parallel}^c$ and T_0 by replotting $B_{\parallel}^c$ against p on a linear scale in Fig. 2(b). We find that the data for $p > 2 \times 10^{10}$ cm^{-2} in both samples fall on almost straight lines that extrapolate to zero at $p = 0$, and therefore the dependence of $B_{\parallel}^c$ on p is similar to that of T_0 in the same p range. If we equate our $g\mu_B B_{\parallel}^c$ with their $k_B T_0$ at a $p > 2 \times 10^{10}$ cm^{-2}, we obtain a g factor of 0.1, which is of the same order as the hole g factor in a 100 Å wide GaAs/AlGaAs quantum well [14]. However, we are not able to distinguish whether the p dependence of $B_{\parallel}^c$ for $p > 2 \times 10^{10}$ cm^{-2} is indeed linear or of the power law form because p range covered in our measurements is small.

The "critical" resistivity ρ^c depends strongly on $B_{\parallel}^c$ and therefore on p. At p^c, where $B_{\parallel}^c = 0$, ρ^c is of the order of 1 resistance quantum, $p_Q = h/e^2$ (where h is Plank's

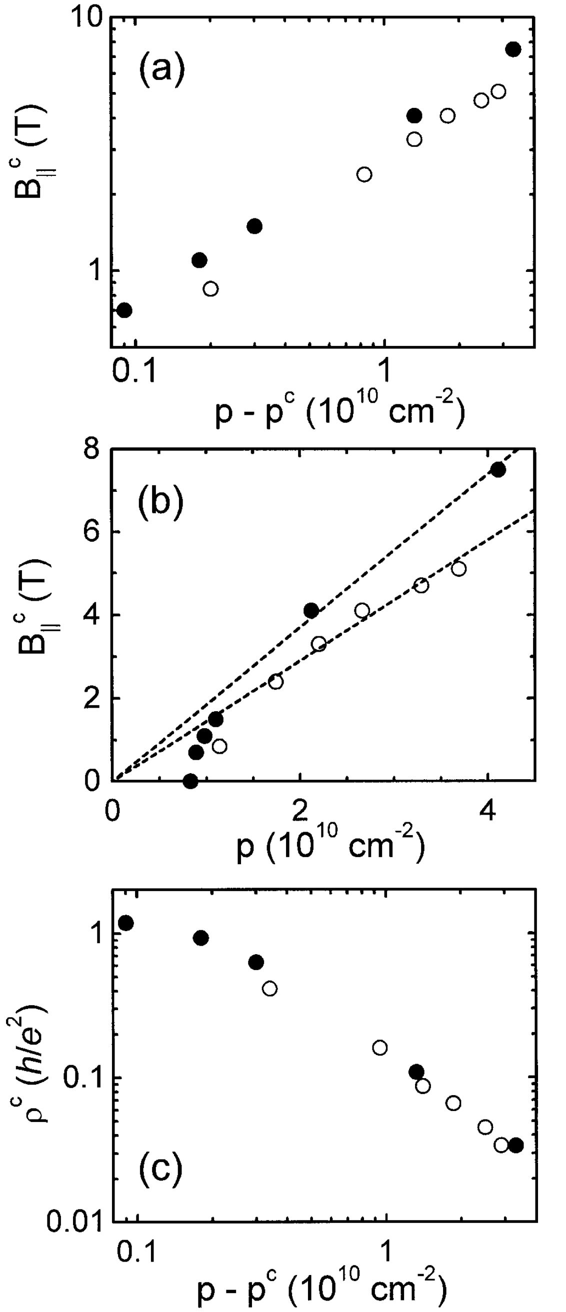

FIG. 2. (a) $B_{\|}^{c}$ vs $p - p^c$. The solid and open circles are for two samples cut from the same wafer. (b) $B_{\|}^{c}$ vs p in a linear scale. The dotted lines are to indicate that $B_{\|}^{c}$ is approximately linear for $p > 2 \times 10^{10}$ cm^{-2}, extrapolating to zero at $p = 0$. (c) ρ^c as a function of $p - p^c$.

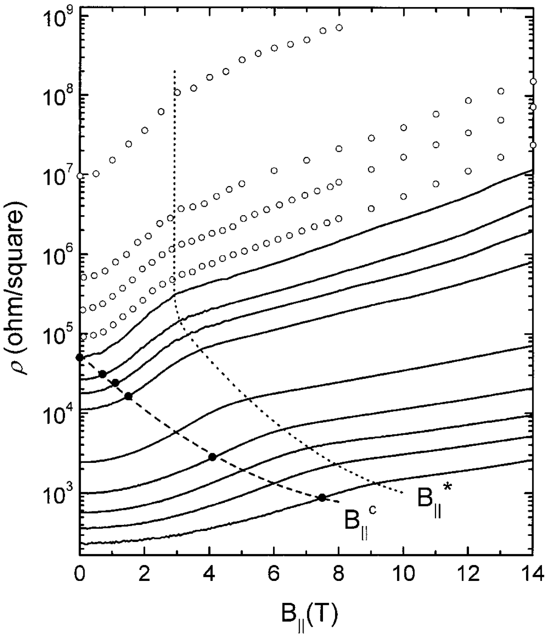

FIG. 3. The $B_{\|}$ dependence of ρ at 50 mK and $p = 4.11$, 3.23, 2.67, 2.12, 1.63, 1.10, 0.98, 0.89, 0.83, 0.79, 0.75, 0.67, and 0.57×10^{10} cm^{-2} from the bottom. The solid lines are for $p > p^c$ and the open circles for $p < p^c$. The solid circles denote measured $B_{\|}^{c}$'s, and the dashed line is a guide to the eye. $B_{\|}^{*}$, the boundary separating the low and high field regimes, is marked as the dotted line.

constant and e the electron charge). For $p > p^c$, ρ^c decreases steeply as $B_{\|}^{c}$ increases and drops to $\sim 0.03\rho_Q$ at $B_{\|}^{c} = 7$ T, as shown by the solid circles in Fig. 3. Figure 2(c) shows the ρ^c data from both samples as a function of $p - p^c$, and it is clear that for $p - p^c > 2 \times 10^9$ cm^{-2} ρ^c decreases exponentially with increasing p. This strikingly strong p dependence of ρ^c is not anticipated within the MIT framework. It suggests that the observed insulating behavior for $B_{\|} > B_{\|}^{c}$ cannot be the result of thermally activated processes in a simple Anderson type of insulator. However, it is reminiscent of the magnetic field driven superconductor-insulator transition reported by Yazdani and Kapitulnik [15] in their experiments on thin films of amorphous MoGe, where a similar decrease in critical resistivity with increasing critical B field is observed. They have attributed this lack of universality in their critical resistivity to the conduction by unpaired electrons. In this context, we should also note that Phillips *et al.* [11] have proposed that the metallic behavior observed in high mobility 2D systems is that of a superconductor, and the existence of a critical B field is to be expected. However, for $p > p^c$ ρ is known to saturate to a finite value instead of vanishing as $T \rightarrow 0$, and the relation of the metallic behavior to superconductivity is not known at present.

Now, we turn to the discussion on the overall in-plane magnetoresistance. In Fig. 3, the in-plane magnetoresistance in the zero field insulating phase is shown as open circles and in the metallic phase as solid lines. Regardless of whether the zero field transport is metallic or insulating, we observe a strong positive magnetoresistance. According to the $B_{\|}$ dependence of ρ, we can divide the entire ρ-$B_{\|}$ plane into two regimes: a low field regime and a high field regime. In the low field regime, we find that the magnetoresistance is well described by $\rho = \rho_1 \exp(B_{\|}^2/B_1^2)$, where ρ_1 and B_1 are the fitting parameters. As the open

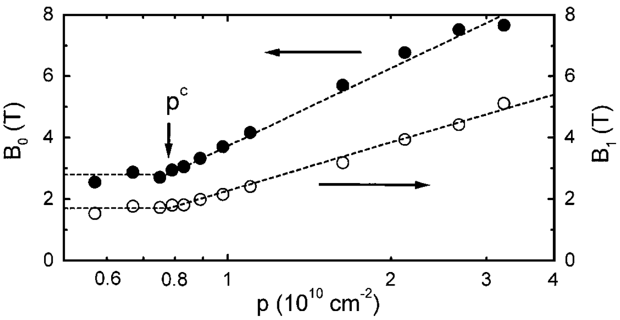

FIG. 4. B_0 and B_1, obtained from fitting the data in Fig. 3 in the form $\rho = \rho_1 \exp(B_\parallel^2/B_1^2)$ at low fields and $\rho = \rho_0 \exp(B_\parallel/B_0)$ at high fields, are plotted as a function of p. The dashed lines are guides to the eye.

circles in Fig. 4 show, the value of B_1 decreases as p is reduced towards p^c (marked by the vertical arrow in Fig. 4) reflecting that the $B_\parallel$ dependence of ρ becomes stronger. However, it is clearly visible in Fig. 4 that B_1 saturates to a constant value of ~1.5 T as the 2DHS is brought into the zero field insulating phase. The $B_\parallel$ induced transition occurs in this low field regime, and the measured $B_\parallel^c$'s are marked by the solid circles in Fig. 3 (the dashed line is a guide to the eye). As the magnetic field is increased beyond $B_\parallel^*$ (the dotted line in Fig. 3), the dependence of ρ on $B_\parallel$ changes. In this high field regime, the magnetoresistance is of the form $\rho = \rho_0 \exp(B_\parallel/B_0)$, where ρ_0 and B_0 are the fitting parameters. The p dependence of B_0 is similar to that of B_1; B_0 also decreases as p is reduced towards p^c and saturates to ~3 T for $p < p^c$ (the solid circles in Fig. 4). While the overall magnetoresistance evolves smoothly as p is changed across p^c, it is obvious from Fig. 3 that $B_\parallel^*$ decreases with decreasing p for $p > p^c$, but is independent of p for $p < p^c$. It is interesting to note that all three characteristic fields, B_0, B_1, and $B_\parallel^*$, become independent of p when p is reduced below p^c.

The low field magnetoresistance at $B_\parallel < B_\parallel^*$ is very similar to that observed in the Si MOSFET's [8–10], where a positive magnetoresistance at low fields is followed by a saturation at high fields. Mertes *et al.* [9] have interpreted the magnetoresistance in Si MOSFET's by the hopping model of Kurobe and Kamimura [16], in which hopping becomes more difficult as spins align with $B_\parallel$ resulting a positive magnetoresistance. This interpretation is supported by the observation of Okamoto *et al.* [10] that the field for magnetoresistance saturation coincides with the field expected for full spin alignment. We can apply such a hopping model to explain our data for $p < p^c$, where our 2DHS is insulating. However, for $p > p^c$, transport is metallic and hopping is not relevant; some other mechanisms must be operative.

The exponential divergence of the magnetoresistance in the high field regime, on the other hand, has not been observed in other 2D systems before, and cannot be explained by existing models. The model by Lee and Ramakrishnan [17] for a weakly disordered system, where the in-plane magnetoresistance arises from spin splitting, predicts a logarithmic divergence. In the hopping model by Kurobe and Kamimura, the magnetoresistance is expected to saturate with full spin alignment. In our data, the exponential dependence of ρ on $B_\parallel$ is observed up to our highest field of 14 T, and B_1 varies continuously with p across p^c (Fig. 4). Also, it appears that the influence of $B_\parallel$ on the energy structure of our 2DHS is not the cause of such strong but simple $B_\parallel$ dependence in both transport regimes. It is possible that new electronic processes in the dilute 2D system in its clean limit are responsible for the behavior of the high field magnetoresistance.

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*Present address: Department of Physics, UC Berkeley, Berkeley, CA 94720.

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