Weak-Localization-Like Temperature-Dependent Conductivity of a Dilute Two-Dimensional Hole Gas in a Parallel Magnetic Field

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We have studied the magnetotransport properties of a high mobility two-dimensional hole gas (2DHG) in a 10 nm GaAs quantum well with densities in the range of $(0.7-1.6) \times 10^{10}$ cm^{-2} on the metallic side of the zero-field "metal-insulator transition." In a parallel field well above B_c that suppresses the metallic conductivity, the 2DHG exhibits a conductivity $\Delta g(T) \approx (1/\pi)(e^2/h)\ln T$ reminiscent of weak localization for Fermi liquids. The experiments are consistent with the coexistence of two phases in our system: a metallic phase and a weakly insulating Fermi liquid phase.

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Since the first report of a metal-insulator transition (MIT) at zero magnetic field in a strongly interacting 2D electron gas (2DEG) in a clean Si metal-oxide semiconductor field-effect transistor (MOSFET), the nature of the transition and the origin of the metalliclike behavior has been a subject of much interest [1]. There are two signatures of the anomalous 2D metallic state. First, above the critical density, the resistivity of the 2D system drops at a temperature scale somewhat below T_F, the Fermi temperature of the system. While many theoretical models are proposed and a tremendous amount of experimental data have accumulated, it is still being widely debated whether the metalliclike resistivity has a semiclassical origin or represents a new 2D metallic ground state violating the well-established scaling theory for noninteracting 2D Fermions [1,2]. Second, the 2D metallic state is known to be unstable against an in-plane magnetic field ($B_\parallel$), suggesting that the spins of the carriers are decisive in the underlying mechanism [1,3,4]. Recently the scaling of the magnetoconductivity of 2DEG in Si MOSFET's for a wide range of densities and temperatures has been taken as evidence for a quantum phase transition in those systems [5]. In Ref. [5] it is further concluded that the MIT is related to a ferromagnetic instability of the 2DEG in Si MOSFET's. Independently, a similar conclusion was reached, from the observation of the vanishing of the magnetic field required to fully polarize the 2DEG at the critical density of the zero field MIT [6]. These observations further stress the importance of spin interactions in the microscopic mechanism responsible for the metallic phenomenon in Si MOSFET's.

Although there exist various explanations for the in-plane magnetic field effect on the 2D metallic state, no consensus has been reached, and the nature of the 2D system on the insulating side of the parallel field driven 2D MIT [4] is also unclear. In this Letter, we report our transport measurements over an extended density range on a dilute 2DHG system when a parallel magnetic field is applied along the $[01\underline{1}]$ or $[\underline{2}33]$ crystallographic directions. The critical field B_c, which fully suppresses the resistance drop, is found to be a linear function of p, the density of the 2DHG, and extrapolates to zero at p_c, the critical density of the zero field MIT, similar to that which was previously reported [4]. The values of B_c with $B_\parallel$ applied along $[01\underline{1}]$ or $[\underline{2}33]$ are found here to be quantitatively correlated with the anisotropic g factor in GaAs QW's over all the density range studied. It is observed that in the high temperature range before the resistance drops, the parallel-field magnetoresistance is negligible. At low temperatures a parallel field less than B_c only suppresses the size of the metallic resistance drop without affecting the characteristic energy scale, as we previously found [7]. When $B_\parallel$ is well above B_c and well aligned in the plane of 2DHG, a logarithmic temperature dependent conductivity reminiscent of weak localization is observed over a wide range of temperature, density, and resistivity (strength of disorder) for a high value of the conductivity $g > e^2/h$. The results show that a parallel magnetic field turns the anomalous 2D metallic state into a Fermi liquid. Finally, we note that these results agree with a two-phase coexistence picture in the anomalous 2D metallic state of our system: a high conductivity metallic phase coexists with a weakly localized "normal" Fermi liquid phase. Under this picture, the thermally activated metallic resistance drop could be due to the formation of metallic liquid droplets at finite temperature [8].

The transport measurements were performed on a high mobility low density 2DHG in a 10 nm wide GaAs quantum well. The measurement driving signals were limited below 3 fW per cm^2 sample area to avoid heating the 2DHG down to 10 mK. The 2DHG has a density of 1.14×10^{10} cm^{-2} from doping, and a low temperature hole mobility of 3.4×10^5 cm^2 V^{-1} s^{-1} without gating. This very same sample was previously used in [7].

The sample was grown on a (311)A GaAs wafer using $Al_xGa_{1-x}As$ barriers (typical $x = 0.10$). Delta-doping layers of Si dopants were symmetrically placed above and below the pure GaAs QW in order to minimize the asymmetry-induced spin nondegeneracy. The sample was prepared in the form of a Hall bar, of approximate dimensions (2.5×9) mm^2, with diffused In(5% Zn) contacts. The density of the 2DHG was tuned by a metallic back gate, which is about 100 μm beneath the well. The sample exhibits an apparent MIT at a critical density $p_c \sim 0.6 \times 10^{10}$ cm^{-2}. In this study we report our investigation on the metallic side of the MIT over the density range of $p = (0.7-1.6) \times 10^{10}$ cm^{-2}. This corresponds to a Wigner-Seitz radius $r_s = 12-18$, with hole effective band mass taken as $0.18m_e$ [9]. The measurement current (~100 pA, 4 Hz square wave) was applied along the $[\bar{2}33]$ direction in all our experiments. Independent measurements of the longitudinal resistance per square, R_{xx}, from contacts on both sides of the sample were made simultaneously as the temperature or applied magnetic field was varied. The samples were mounted in a top-loading dilution refrigerator. The temperature was read from a Ge resistance thermometer attached to the refrigerator mixing chamber. The Ge thermometer was calibrated down to 6 mK by He-3 melting curve thermometry [10].

The zero-magnetic field-temperature dependence of R_{xx} for the sample with different 2DHG densities is shown in Fig. 1 from 11 mK to 3 K. All the $R_{xx}(T)$ traces exhibit a nonmonotonic peak, which is frequently observed in high mobility GaAs/AlGaAs heterostructures or quantum wells [11,12]. It can be seen that for $T \sim T_F$, $R_{xx}(T)$ is insulating like, i.e., $dR_{xx}(T)/dT < 0$. This type of increasing resistivity upon lowering T at temperatures around T_F has been understood as the quantum-classical crossover when the 2D system becomes degenerate [13]. At lower temperatures $T < T_0$, the resistance becomes metalliclike, with $R_{xx}(T)$ exhibiting thermally activated behavior. The origin of this thermally activated resistance has been the center of debate over almost a decade [1]. Similar to earlier reports [11,12], T_0, the temperature at which the resistance peaks roughly follows the T_F (or density) of the 2D system.

The 2D metallic state is found to be destroyed by an in-plane parallel magnetic field [3]. For a high mobility GaAs heterostructure, a parallel field driven MIT with critical field B_c was observed [4]. Our magnetotransport data for density $p = 0.99 \times 10^{10}$ cm^{-2} are presented in Fig. 2 with an inset showing the isothermal magnetoresistance at various temperatures. The behavior for other densities is qualitatively similar. Figure 2 shows that a parallel magnetic field $B_\parallel$ has a very small effect at temperatures higher than T_0, while at temperatures lower than T_0, $B_\parallel$ suppresses the metallic behavior and the insulating behavior is "restored" for $B_\parallel > B_c$. We will show later that the resistance at $B_\parallel > B_c$ has a temperature dependence indistinguishable from the $g \sim \ln T$ weak localization effect one would find for a Fermi liquid. From the inset of Fig. 2, the critical field B_c for this density is determined from the crossing point of the low temperature magnetoresistance curves to be (0.62 ± 0.04) T. Moreover, at $T < T_0$, the isothermal magnetoresistance is negative at some field $B_\parallel > B_c$. This nonmonotonic low-temperature magnetoresistance is observed when there is a non-negligible angle between the 2DHG plane and $B_\parallel$. A well-known signature of 2D weak localization is a negative magnetoresistance in a

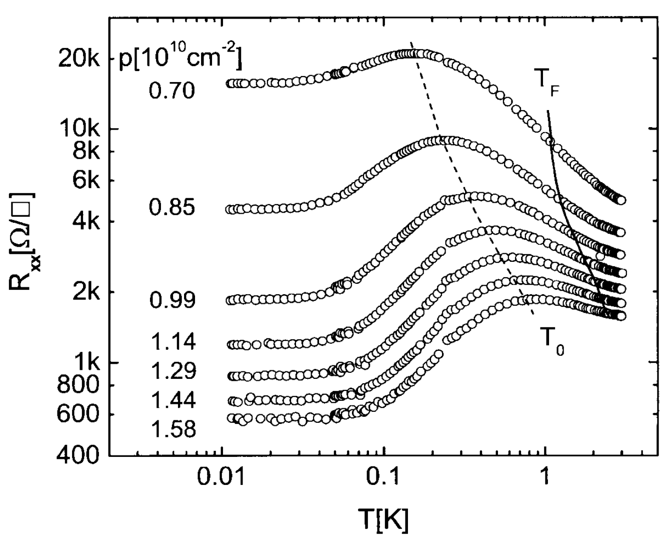

FIG. 1. Resistance per square, R_{xx} vs T for 2DHG with various densities in a 10 nm wide GaAs quantum well at zero magnetic field. The black solid line marks corresponding T_F's, the Fermi temperatures of the 2DHG's. The dashed black line connects the characteristic temperature T_0, below which the system exhibits a thermally activated metallic resistance.

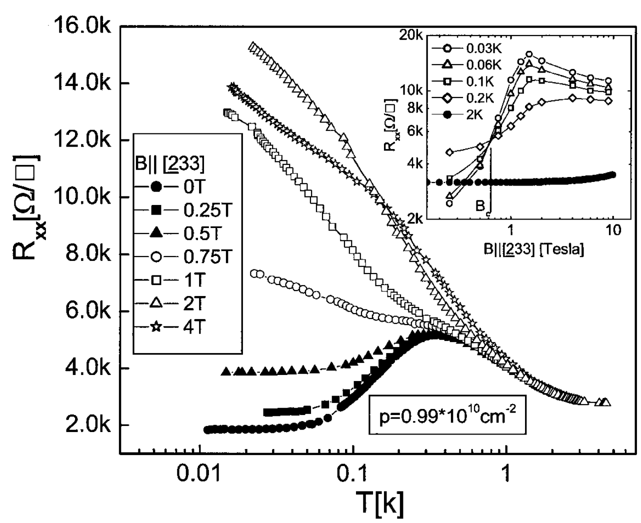

FIG. 2. R_{xx} vs T at various $B_\parallel$ for $p = 0.99 \times 10^{10}$ cm^{-2}. $B_\parallel$ was along the $[\bar{2}33]$ direction, the same direction as the current. It was determined that $B_\parallel$ was tilted from the 2DHG plane about 0.1° by Hall resistance measurements. The inset shows the isothermal magnetoresistance at different temperatures.

perpendicular magnetic field and the tendency for the negative magnetoresistance to get sharper upon lowering T [14]. We propose that the negative magnetoresistance for $T < T_0$ and $B_\parallel > B_c$ here might be caused by the suppression of the weak localization by the small increasing perpendicular magnetic field from the small misalignment between $B_\parallel$ and the 2DHG plane. In principle, since the weak localization suppression by a perpendicular field is well known, more insight can be gained by carefully tuning the angle between $B_\parallel$ and the sample to introduce an adjustable small perpendicular field at constant $B_\parallel > B_c$ to avoid the mixing of magnetoresistance induced by $B_\parallel$ and the negative magnetoresistance due to weak localization. It would be a hard experiment because extreme care must be taken as a few hundred gauss of perpendicular field may be enough to destroy the weak localization effect for a 2DHG in a high mobility GaAs quantum well.

In Fig. 3a, we present the temperature dependent conductivity $g(T)$ in units of e^2/h at 4 T in-plane magnetic field along the [$\underline{2}33$] direction, under which field the metallic resistance is well suppressed. Figure 3b shows corresponding $R_{xx}(T)$ data in a log-log plot. For the upper five curves in Fig. 3a with $g(T) \gg 1$, all the $g(T)$ traces follow $g(T) \propto \ln T$ over almost a decade of temperature, 15 mK–0.14 K. Fitting the five $g(T)$ curves of Fig. 3a for densities $(0.99-1.58) \times 10^{10}$ cm^{-2} in the temperature range 15 mK $< T <$ 0.15 K by the function $g(T) = g_0 + a^{-1} \ln T$ yields $a = 3.09 \pm 0.08$, in agreement with the value $a = \pi$ predicted by the established weak localization theory [15–17]. In the latter theory, the low-temperature conductivity correction from quantum interference for our symmetrically doped GaAs QW at small constant perpendicular field can be approximated as

$$\Delta g(T) \approx (1/\pi)\ln(T/T_\varphi), \tag{1}$$

where T_φ is the characteristic temperature below which the logarithmic temperature-dependent conductivity from quantum interference starts. Equation (1) is thus in good quantitative agreement with the fit for low T curves in Fig. 3a with $g \gg 1$. When g is close to or less than 1, Eq. (1) is no longer obeyed as the carriers are in a strongly localized regime. T_φ in Eq. (1) depends on the ratio of the phase breaking time T_φ and the momentum relaxation time τ of the carriers (holes). Without information on T_φ of our system we cannot determine whether the logarithmically decreasing conductivity for all the $g > e^2/h$ curves on Fig. 3a is associated with $\tau_\varphi > \tau$ or not. As a comparison, we mark the temperature range $T < h/(2\pi\tau k_B)$ where transport becomes diffusive. It is seen that the logarithmic conductivity does appear in the diffusive transport regime, where the weak localization theory could be applicable.

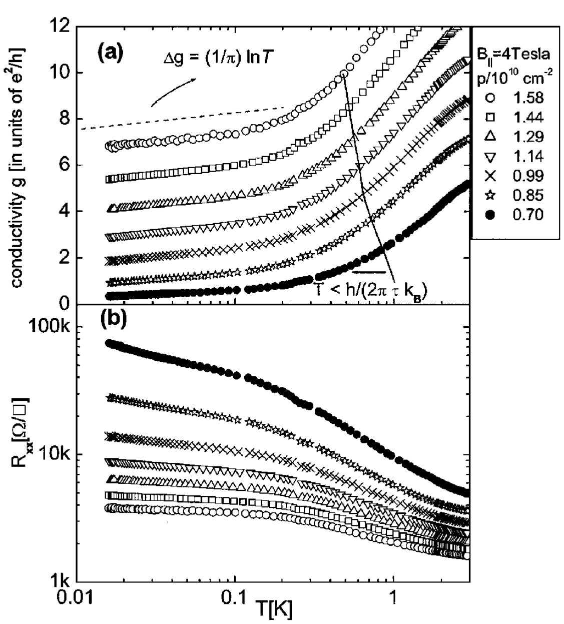

FIG. 3. (a) Temperature dependent conductivity $g(T)$ in units of e^2/h of the 2DHG at various densities with a 4 T in-plane magnetic field along the [$\underline{2}33$] direction. The perpendicular field is roughly 70 G estimated from the Hall resistance. The dotted gray line represents $g(T) \sim (1/\pi)\ln T$, the logarithmical temperature dependent conductivity from 2D weak localization theory. The solid black line connects the temperatures below which the transport become diffusive. (b) For comparison, the same data of (a) are shown as R_{xx} vs T.

The density dependences of the critical field B_c for the [$01\underline{1}$] and the [$\underline{2}33$] directions are plotted in Fig. 4a. It is obvious that $B_c \propto (p - p_c)$ for both directions. Statistics on the data yields $\langle B_{c[01\underline{1}]}/B_{c[\underline{2}33]}\rangle \approx 4.3$, consistent with the known highly anisotropic g factor for holes in GaAs QW's [19], and suggesting the destruction of the 2D metallic state is associated with the Zeeman energy. In Fig. 4b the T_0's are plotted as a function of 2DHG density. T_0 also extrapolates linearly to zero at the critical density. Note that Ref. [6] reported a linearly vanishing full spin polarization field at p_c and inferred a ferromagnetic instability of the 2DEG in Si MOSFET's. The linearly vanishing B_c we observe probably needs a different interpretation since $g\mu_B B_c$ is not related to E_F. The possibility of a ferromagnetic instability for 2D holes in GaAs needs further study.

The observation that $B_\parallel$ gradually suppresses the magnitude of the metallic resistance and eventually restores weak localization is consistent with a two-phase coexistence scenario: A high conductivity metallic phase coexists with an insulating phase in the 2D potential landscape at low T, and the metallic phase is gradually driven insulating by the parallel magnetic field. The consistency between the prediction of weak localization theory and the observed low-temperature transport of our 2DHG at high $B_\parallel$ suggests that the insulating phase is a Fermi liquid. Thus our data allow the possibility that the metallic state of our 2DHG system consists of mixed regions of anomalous metallic phase and 2D Fermi liquid phase. Local compressibility measurements by Ilani *et al.* also point to a two-phase coexistence picture for metallic 2D holes in GaAs [20]. Previously we reported the observation of a negative low field ($B_\perp$) magnetoresistance in the

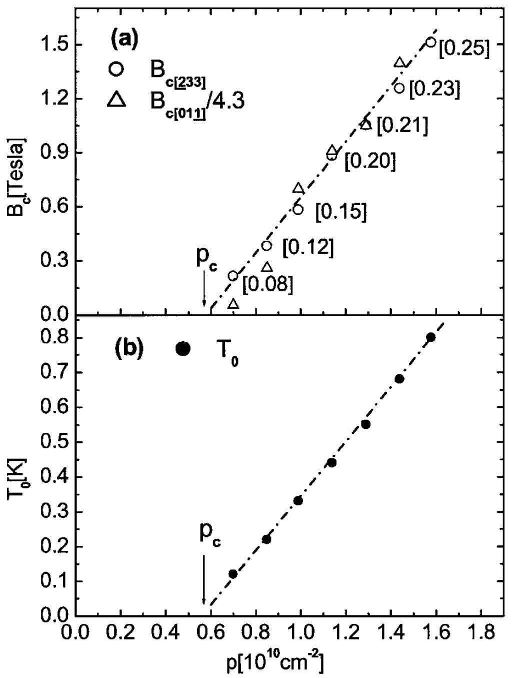

FIG. 4. (a) B_c vs p for $B_\parallel$ along the $[01\underline{1}]$ and $[\underline{2}33]$ directions. B_c is determined from the crossing point of the low temperature isothermal magnetoresistance. Note that $B_{c[01\underline{1}]}$ should have larger error bars than $B_{c[\underline{2}33]}$ since for the $[01\underline{1}]$ configuration, $B_\parallel$ was tilted from the 2DHG plane by a relatively large angle, 2°. $B_\parallel$ was only tilted from the 2DHG plane for 0.1° for the $[\underline{2}33]$ configuration. For $B_\parallel$ along $[\underline{2}33]$, $g\mu_B B_{c[\underline{2}33]}/E_F$, the ratio of the Zeeman energy at B_c and the Fermi energy is noted in brackets, taking $g_{[\underline{2}33]} = 0.6$ for all densities [18]. (b) T_0 vs hole density p, where T_0 represents the temperature where the metallic resistance emerges as shown in Fig. 1. The dash-dotted lines are a guide to the eye.

2D metallic state at ~10 mK without any sign of weak localization in the temperature dependence of the resistivity [21]. This might be explained if a weakly insulating Fermi liquid phase, which does have a negative magnetoresistance, is intermingled with the anomalous metallic phase and carries a non-negligible portion of the current. Our measurements are thus in agreement with theoretical models [8] and simulations [22] suggesting the existence of phase separation in disordered 2D systems with high r_s [23]. However, both the mechanism behind the 2D metallic phase and the physical origin of the parallel magnetic field effect on the metallic phase remain unclear.

In summary, we have studied the effects of a parallel magnetic field on a high mobility dilute 2DHG in a GaAs quantum well over an extended density range. At $B_\parallel > B_c$, we observed a temperature-dependent conductivity $\Delta g(T) \sim (1/\pi)(e^2/h)\ln T$ independent of g at low T for $g > e^2/h$, which is reminiscent of weak localization. B_c is found to be anisotropic and a linear function of density. The results can be interpreted in terms of a high conductivity metallic phase coexisting with a Fermi liquid phase in the metallic 2D hole gas in GaAs.

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[23] We note that studies of the homogeneity of the system upon increasing $B_\parallel$ would shed more light on our picture here. We expect that the 2DHG becomes very inhomogeneous around B_c, as it changes from a state consisting of mainly the metallic phase at $B_\parallel \ll B_c$ into a state consisting of mainly Fermi liquid for $B_\parallel \gg B_c$.