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Spin-polarization-induced tenfold magnetoresistivity of highly metallic two-dimensional holes in a narrow GaAs quantum well

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We observe that an in-plane magnetic field ($B_{\|}$) can induce an order of magnitude enhancement in the low temperature (T) resistivity (ρ) of metallic two-dimensional (2D) holes in a narrow (10 nm) GaAs quantum well. Moreover, we show the first observation of saturating behavior of $\rho(B_{\|})$ at high $B_{\|}$ in GaAs system, which suggests our large positive $\rho(B_{\|})$ is due to the spin polarization effect alone. We find that this tenfold increase in $\rho(B_{\|})$ even persists deeply into the 2D metallic state with the high $B_{\|}$ saturating values of ρ lower than 0.1 h/e^2. The dramatic effect of $B_{\|}$ we observe on the highly conductive 2D holes (with $B=0$ conductivity as high as 75 e^2/h) sets strong constraint on models for the spin dependent transport in dilute metallic 2D systems.

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The metallic behavior and metal-insulator transition (MIT) in dilute electrons or holes in two-dimensional (2D) semiconductor structures have received much recent interest.[1,2] In these low density 2D systems, when the carrier density is above the critical density, the system exhibits a significant resistivity drop at low temperature, setting a challenge for conventional localization theory. While unique properties (e.g., the dramatic change in compressibility at MIT,[3] the anomalous thermopower,[4] and enhanced phonon coupling[5] effects) are continuing to be discovered in this 2D metallic state, many critical issues still remain unresolved. Outstanding questions include: Does the Fermi liquid (FL) phenomenology still hold for the 2D metallic state where $r_s \gg 1$? Is this MIT a true quantum phase transition or simply a crossover at finite temperature? And most importantly, what is the mechanism for the resistivity drop?

The spin degeneracy is believed to be essential for inducing the metallic resistivity, as it was found that an in-plane magnetic field $B_{\|}$ suppresses the metallicity and in some cases drives the system insulating.[6–10] Recent experiments on GaAs quantum well (QW) further revealed an intriguing $B_{\|}$ insensitivity of the energy scale of the 2D metal as well as the FL-like logarithmically diverging $\rho(T)$ of 2D holes in strong $B_{\|}$.[9] Many theoretical models were proposed to explain the $B_{\|}$ destruction of the 2D metallic transport, such as the superconductivity scenario,[11] the FL-Wigner solid coexisting microemulsion model,[12] or screening model based on conventional FL wisdom.[13,14] It was even noticed that positive $\rho(B_{\|})$ can be induced by the magneto-orbital effect of $B_{\|}$ due to the finite thickness of the sample, without involving any spin effect.[15]

In this paper, we present a study of the in-plane magnetic field induced magnetotransport of a low density 2D hole system (2DHS) in a *narrow* (10 nm wide) GaAs QW down to as low as $T=20$ mK. We show that the resistivity of our 2DHS can increase by nearly an order of magnitude followed by a saturation as $B_{\|}$ increases, similar to the case for Si-MOSFET's. In contrast to previous experiments on GaAs heterostructures or wider QWs,[7,8,10,16] our result clearly disentangles the spin effect from the orbital effect[15] in the $B_{\|}$-dependent transport studies of the 2D metallic state. Moreover, it is striking that this spin polarization induced tenfold magnetoresistivity even persists deeply into the metallic state where the conductivity σ is as high as 75 e^2/h at $B=0$. In-plane magnetotransport has been extensively calculated for low density 2D systems within the screening theory for FL. For weak disorder, semiclassical calculations based on T- and B-dependent screening[14] showed good agreement with highly conductive Si-MOSFET's, in which a factor 3 to 4 increase in $\rho(B_{\|})$ and a weak T dependent $\rho(T)$ in the spin polarized state were observed.[17,18] Refined screening models including exchange and correlation effects may produce a larger increase in $\rho(B_{\|})$, but only when disorder is sufficiently strong and carrier density sufficiently low to be in the vicinity of the MIT.[19] Our observation of such large $\rho(B_{\|})$ for metallic 2DHS with $\sigma \gg$ e^2/h (or $k_F l \gg 1$) calls for further theoretical understanding of spin-dependent transport in dilute metallic 2D systems with strong correlations and weak disorder.

Our experiments were performed on a high mobility, low-density 2DHS in a 10 nm wide GaAs QW similar to Refs. 5, 9, and 20. The sample was grown on a (311)A GaAs wafer using $\mathrm{Al_{0.1}Ga_{0.9}As}$ barrier. δ-doping layers of Si dopants were symmetrically placed above and below the pure GaAs QW. Diffused In(1% Zn) was used as contacts. The hole density p was tuned by a backgate voltage. The ungated sample has a low temperature hole mobility, $\mu \approx 5 \times 10^5$ cm^2/V s, and a density $\sim 1.6 \times 10^{10}$ cm^{-2} from doping. The sample was prepared in the form of a Hall bar, with an approximate total sample area 0.2 cm^2. With the relatively large sample area and the measuring current induced heating power at the level of f W/cm^2, the low density 2DHS can be reliably cooled down to 20 mK with negligible self-heating.[5] All the data in this paper were taken with the current along the $[\underline{2}33]$ high mobility direction. $B_{\|}$ was also applied along the $[\underline{2}33]$ direction, where the effective g

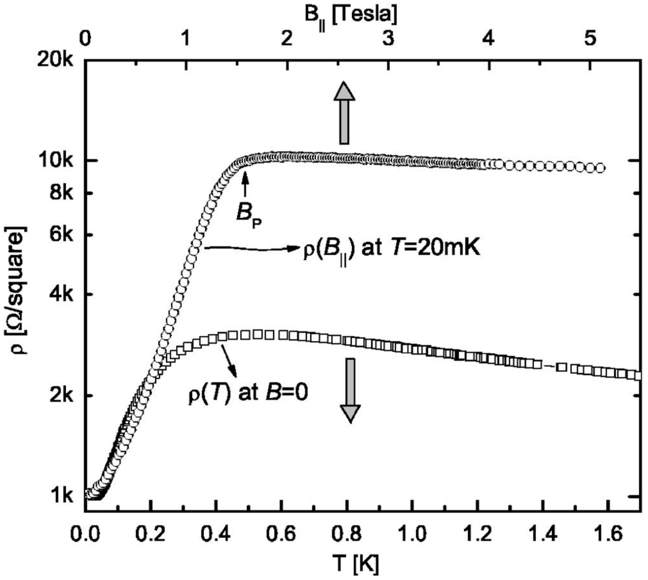

FIG. 1. Resistivity vs T at zero magnetic field and resistivity vs in-plane magnetic field $B_{\|}$ at $T=20$ mK for a 2DHS in 10 nm wide GaAs QW. The hole density $p=1.35\times10^{10}$ cm^{-2}. Similar to Si-MOSFET's, $\rho(B_{\|})$ shows saturation above $B_P=1.5$ T, in contrast to wider GaAs QW's or heterostructures.[7,8,10,16]

factor ~0.6.[9] During the experiments, the sample was immersed in the ^{3}He/^{4}He mixture in a top-loading dilution refrigerator.

Figure 1 shows the $T=20$ mK ρ vs $B_{\|}$ and the zero magnetic field ρ vs T data of our 2DHS with $p=1.35\times10^{10}$ cm^{-2} in the metallic phase of MIT. At $B=0$, ρ shows a factor of three drop below 0.4 K. The $\rho(B_{\|})$ curve shows a very large magnetoresistivity below 1.5 T and a nearly constant ρ at higher $B_{\|}$. This behavior is rather similar to the $\rho(B_{\|})$ data in Si-MOSFET's and the magnetic field B_P at which ρ starts saturating was identified to be the field when the system obtains full spin polarization.[21–23] We mention that all previous $\rho(B_{\|})$ data on GaAs 2D electron/hole systems show somewhat different behavior: the resistivity continuously increases with a reflection point around B_P upon applying $B_{\|}$.[7,8,10,16] We believe that the saturating behavior of our $\rho(B_{\|})$ here at $B_{\|}>B_P$ is due to the smaller thickness of our QW. The constant $\rho(B_{\|})$ above B_P of our QW also suggests that the magnetoorbital effect related scattering[15] is small in our case. For GaAs heterostructures or wider QW's (and low carrier concentration), the magnetic length at several Tesla becomes comparable to or smaller than the width of the 2D electron/hole wave function in the z direction and the magneto-orbital effect can induce a continuous positive magnetoresistivity as discussed by Das Sarma and Hwang.[15] Note that for experiments on Si-MOSFET's the confinement in the z direction is also narrow and a saturation in ρ is often observed after an increasing ρ at low $B_{\|}$.[21–23] Thus our data suggest that the thickness effect is certainly able to explain most of the differences in $\rho(B_{\|})$ behavior between GaAs and Si-MOSFET systems, although the valley degeneracy may play some additional role.

Now we discuss how the temperature affects the magnetotransport. In Fig. 2(a) we plot the $\sigma(B_{\|})$ for $p=1.35\times10^{10}$ cm^{-2} at 20 mK, 0.15 K, 0.26 K, and 0.40 K. All the isothermal $\sigma(B_{\|})$ curves cross around 1.2 T, indicating the "$B_{\|}$ induced MIT".[7–9] As suggested by Vitkalov *et al.*,[24] we can determine the magnetic field B_P for the onset of

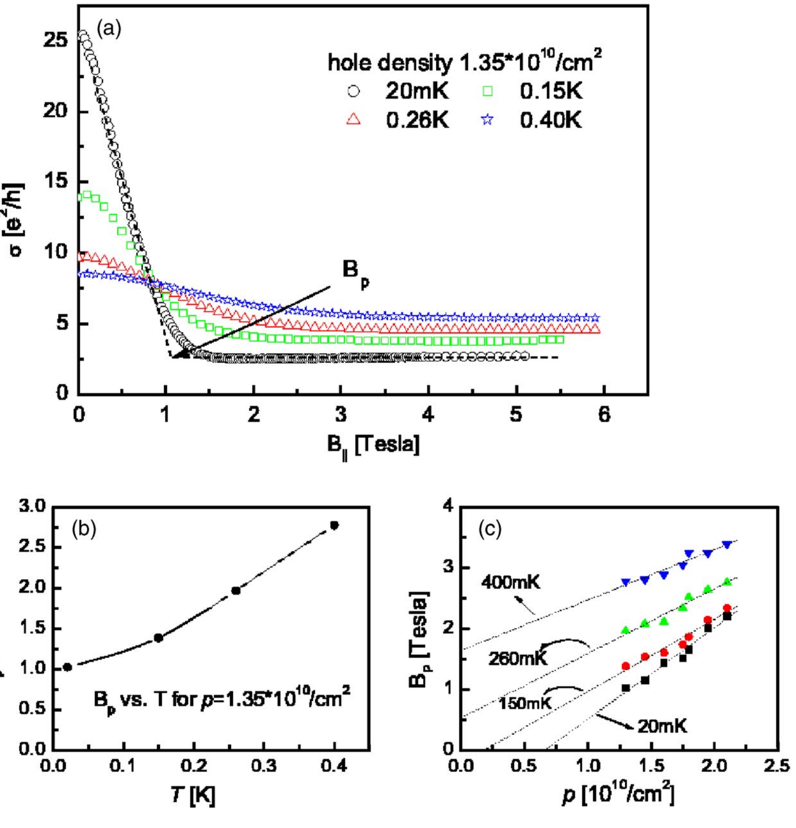

FIG. 2. (Color online) (a) The conductivity σ of 2DHS with $p=1.35\times10^{10}$ cm^{-2} as a function of the in-plane magnetic field $B_{\|}$ at 20 mK, 0.15 K, 0.26 K, and 0.40 K. The magnetic field B_P above which all the spins are polarized is determined by the intersection of linear extrapolations of $\sigma(B_{\|})$ at low and high field regions. (b) The temperature dependence of B_P, with the dashed line as a guide to the eye. (c) B_P as a function of hole density p at 20 mK, 0.15 K, 0.26 K, and 0.4 K. The dotted lines are the linear fittings to the data. It can be seen that finite temperature strongly affects the behavior of $B_P(p)$, and it is only at the lowest temperatures $B_P(p)$ linearly extrapolates to zero at a finite density.

full spin polarization of *delocalized* holes by the intersection of linear extrapolations of $\sigma(B_{\|})$ at low and high field regions. Nonetheless, we obtain a B_P only 10% higher if the extrapolating process is applied to $\rho(B_{\|})$, suggesting that most holes are delocalized. We find that B_P is strongly temperature dependent. As one can see in Fig. 2(b) where $B_P(T)$ is plotted for this density, B_P at $T=20$ mK is only 40% of its value at 0.4 K. Since the B_P is generally regarded as the magnetic field required to fully polarize the spins of delocalized carriers,[21,22] one natural interpretation of the T dependent B_P is that *the spin susceptibility* χ *is largely enhanced as* T *is reduced*. This strong T dependent B_P has implications in other models as well. For instance, in the "microemulsion" model it would mean that it requires much less Zeeman energy to solidify the FL phase at lower temperatures.[12]

Figure 2(c) shows the density dependence of B_P at 20 mK, 0.15 K, 0.26 K, and 0.4 K. Previously, extrapolating $B_P(p)$ to $B_P=0$ was used as a way to determine if a ferromagnetic instability exists in the system.[2,16,23] If $B_P(p)$ extrapolates to zero at a finite density, then such density corresponds to the ferromagnetic instability. It can be seen in our Fig. 2(c) that our $B_P(p)$ data taken at different T extrapolate to zero at different densities. Only at low temperatures $B_P(p)$ linearly extrapolates to zero at a finite density. At $T=20$ mK, $B_P(p)$ extrapolates to zero at a density very close to the critical density of the $B=0$ MIT.[25] Our T dependent study of $B_P(p)$ is consistent with Si-MOSFET's.[26] Although the meaning of a diminishing B_P at finite p is controversial and may actually be associated with other physics (e.g., the instability to crystallization instead of ferromagnetism),[12,27] our experiment on p-GaAs corroborates the universal existence of this behavior.

Figure 1 has shown that the narrow p-GaAs QW responds to $B_{\|}$ quite similarly to Si-MOSFET's, where $\rho(B_{\|})$ shows large increase at low $B_{\|}$ and a saturation at high field. It is striking that for our p-GaAs, this order of magnitude positive $\rho(B_{\|})$ even persists deeply into the metallic phase where $\rho \ll \mathrm{h/e^2}$ for both the $B_{\|}=0$ low spin polarization phase and the high $B_{\|}(>B_P)$ spin-polarized phase.[28] Figure 3 shows $\rho(B_{\|})$ at 20 mK for seven densities up to 2.1×10^{10} cm^{-2}. The large enhancement and saturation in $\rho(B_{\|})$ are observed for all these densities. Note that for $p=2.1$ (the lowest curve) the high field $(B>B_P)$ value of ρ is clearly below 0.1 h/e^2. *For Si-MOSFET system with comparable resistivity*, ρ *usually shows only a factor of 3–4 increase below* B_P,[19,22,23] in agreement with the screening model.[13,14,19] Note that the screening model predicts at most a factor of four increase in ρ due to reduced screening from the lifted spin degeneracy for $\rho \ll \mathrm{h/e^2}$.[13,14] Only very near the critical density of the MIT can the Si-MOSFET show $\rho(B_{\|})/\rho(0)>4$, resulting from many body and strong disorder effects in the screening model.[19] Moreover, the original publication of screening theory predicts a weak metalliclike $\sigma(T)$ at $B_{\|}>B_P$,[14] in disagreement with our data in Fig. 4. It is possible that exchange (Fock) term of the electron-electron interaction[29] could account for the difference; however, to date, the only FL theory including both Hartree and Fock interactions[29] is perturbative, valid only at $T \ll T_F$ and not applicable to our experimental regime. More sophisticated nonperturbative Fermi liquid calculations are needed for further comparison with our data.

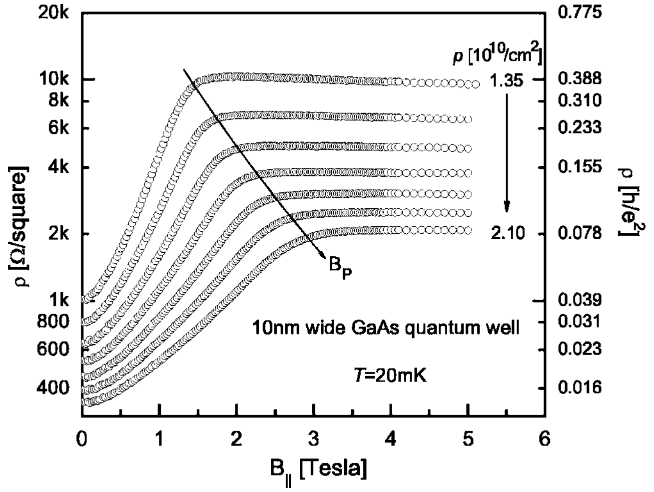

FIG. 3. Resistivity ρ vs $B_{\|}$ at $T=20$ mK of 2D holes in a 10 nm wide GaAs quantum well. The hole densities are 1.35, 1.48, 1.60, 1.73, 1.85, 1.98, and 2.10×10^{10} cm^{-2} from top to bottom. The arrow marks the positions of B_P, the magnetic field above which $\rho(B_{\|})$ shows saturation. Note that the almost factor of 10 increase in ρ persists deeply into the metallic phase with high $B_{\|}$ values of $\rho<0.1$ h/e^2.

The dramatic effect of spin polarization induced by $B_{\|}$ on our dilute 2DHS also exhibits in the temperature dependence of the conductivity. In Fig. 4 we plot $\sigma(T)$ at various $B_{\|}$ for $p=2.1\times 10^{10}$ cm^{-2}. At $B=0$, the 2DHS shows a factor of three increase in the conductivity below 0.8 K, and the low T conductivity is as high as 75 e^2/h. With the application of $B_{\|}$, the metallic conductivity enhancement becomes smaller and eventually $\sigma(T)$ turns into insulatinglike, $(d\sigma/dT>0)$

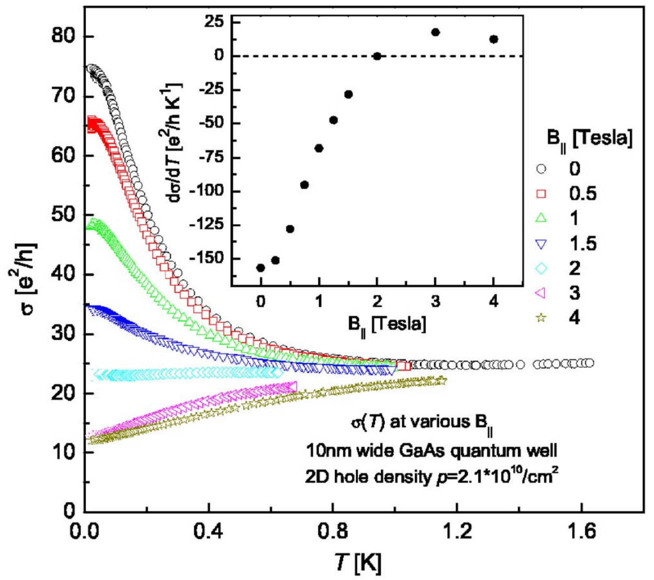

FIG. 4. (Color online) 2D hole conductivity σ vs T at various in-plane magnetic field $B_{\|}$'s. The density p is 2.1×10^{10} cm^{-2}. The inset shows the slope of $\sigma(T)$ as a function of $B_{\|}$. The slope of $\sigma(T)$ is obtained by fitting data linearly between 0.06 K and 0.2 K.

above 2 T. In the inset of Fig. 4 we plot $d\sigma/dT$, the slope of $\sigma(T)$, as a function of $B_{\|}$ to demonstrate this strong effect of $B_{\|}$ on the 2D metallic transport. It can be seen that the absolute values of the slope of $\sigma(T)$ differ by about a factor of ten between the zero and high field regimes. A similar effect was also seen in Si-MOSFET's.[17]

The $B_{\|}$ suppression of 2D metallic transport was attributed to the FL interaction correction effects in the ballistic regime[29] in various recent experimental papers.[30] Here we do not attempt to fit our data to extract the FL parameter F_0^σ since we believe that the perturbative FL calculation should not be taken as a quantitative theory for our order of magnitude increase in $\rho(B_{\|})$. Recent Hall coefficient measurements on similar samples also provide experimental evidence against the interaction correction interpretation for the metallic $\sigma(T)$ at $B=0$,[20] further reflecting the fact that the $T \ll T_F$ theory is inapplicable to our data.[31] A nonperturbative FL calculation including both the Hartree and Fock interaction terms and extending to temperatures $T > T_F$ would be required to make a direct comparison with our data. Another possible explanation for our large magnetoresistivity effect comes from a nonperturbative non-FL approach: it has been theoretically argued that intermediate phases (microemulsions) exist in clean 2D systems between the FL phase and the Wigner solid phase.[12,27] In such a scenario, the dramatic suppression of the slope of $\sigma(T)$ by an in-plane magnetic field $B_{\|}$ would be analogous to the magnetic field effect on the Pomaranchuk effect in ^{3}He.[12] It will be of interest to develop more quantitative calculations based on such models for a direct comparison with our experimental data.

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