Fermi liquid behavior of metallic 2D holes at high temperatures

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The resistivity $\rho$ of high mobility dilute 2D holes in GaAs exhibits a peak at a certain temperature $T^*$ in zero magnetic field ($B=0$). In the $T > T^*$ regime where $d\rho/dT < 0$, we observe for the first time both the $\nu = 1$ quantum Hall(QH) effect and a low field insulator-QH transition which is consistent with the 2D hole system being a Fermi liquid(FL). The known linear $T$-dependent conductivity in this $T$ regime then can be explained by hole-hole Coulomb interactions of this FL. The fact that the system is metallic ($d\rho/dT > 0$) for $T < T^*$ implies that the high temperature FL transforms into the 2D metallic state in the neighborhood of $T^*$.

The effect of disorder on the electronic properties of solids has been one of the central problems in modern condensed matter physics\textsuperscript{1}. Anderson’s pioneering work demonstrated the localization effect of disorder on the electron wavefunctions\textsuperscript{2}. The seminal one-parameter scaling theory of localization by Abrahams et al. made the remarkable conclusion that all non-interacting disordered electronic systems are localized in zero magnetic field in two dimensions(2D)\textsuperscript{3}. However, when a strong perpendicular magnetic field is applied to 2D systems, quantized Landau Levels(LLs) form and extended states can exist around the centers of the LLs. In high quality 2D systems, the integer QH effect can be seen at low temperatures when the Fermi energy moves across the mobility edges which separate the extended states in the centers of LLs from the localized states between LLs\textsuperscript{4, 5}.

To connect the $B=0$ insulating ground state in 2D and the QH states in finite $B$, it was argued that the positions of the extended states should float up in energy as $B \to 0$\textsuperscript{6}. Therefore a zero field insulator-QH transition should be seen when an extended state moves across the Fermi energy by increasing $B$ from zero. The $B=0$ Anderson insulator to QH transition was first demonstrated in a $B=0$ strongly localized 2D electron system\textsuperscript{7} and later in $B=0$ weakly localized 2D systems as well\textsuperscript{8}. Moreover, as predicted by the theory, experiment found the positions of the extended states deviating from the LLs and floating up above the Fermi surface as $B \to 0$ in a 2D electron system with tunable density\textsuperscript{9}.

The recent discovery of the possible $B=0$ 2D metallic state and metal-insulator transition(MIT) in low density 2D electron/hole systems has attracted a lot of attention\textsuperscript{10}. Note that $r_s$, the dimensionless ratio between the Coulomb interaction energy and the Fermi energy of these dilute systems showing a 2D MIT, is much larger than one. This poses the question if the conventional theory of localization is applicable and what is the role of strong Coulomb interactions in these dilute 2D systems. At present, there is still no consensus on either the origin of the metallic behavior or the nature of the insulating state of the $B=0$ 2D MIT. Nonetheless, Shubnikov-de Haas(SdH) oscillations have been seen on both sides of the MIT and the insulating state of the MIT can be turned into a QH conductor by applying a perpendicular magnetic field, that is quite similar to conventional Fermi liquid type insulating 2D systems. The insulator-QH transition in a perpendicular magnetic field was employed on the insulating side of the 2D MIT by different authors to investigate how the extended states behave in the density-magnetic field phase diagram\textsuperscript{11, 12, 13}.

In this paper, we report for the first time the observation of the insulator-QH transition at high temperatures in a dilute 2D hole system that is metallic at low $T$. All previous studies on the insulator-QH transition were done on true $B=0$ 2D insulators, either in the conventional Fermi liquid\textsuperscript{14, 15, 16, 17, 18} or the insulating phase of the 2D MIT\textsuperscript{14, 15, 16, 17, 18}. This paper focuses on the metallic side of the 2D MIT, where the zero field $T$-dependent resistivity $\rho(T)$ changes from metallic to insulator-like above a certain temperature scale $T^*$\textsuperscript{14, 15, 16, 17, 18}. The conductivity of 2D holes was shown to be a linearly increasing function of $T$ in the $T > T^*$ insulating regime\textsuperscript{14, 15, 16, 17, 18}. There exist a few theoretical models to explain the insulating $\rho(T)$ of the 2D metallic state at $T > T^*$. A simple non-interacting picture for the apparent insulating behavior of metallic 2D systems at high $T$ is the $T$-dependent scattering of a non-degenerate system by Das Sarma and Hwang\textsuperscript{19}. On the other hand, Spivak conjectured that Coulomb correlations could be responsible for such an insulating $\rho(T)$\textsuperscript{20}.

Fig.\textsuperscript{1}; to be discussed in detail below, demonstrates the existence of SdH oscillations as well as an insulator-QH transition in the high $T$ insulating regime of metallic 2D holes. The existence of a quantum magnetoresistance minimum and an insulator-QH transition suggest the metallic 2D hole system in fact behaves like a normal insulating Fermi liquid at $T > T^*$. Together with the known linear $T$-dependent zero field conductivity[Fig.\textsuperscript{1a, b}], our results suggest the insulating $\sigma(T)$ at $T > T^*$ is due to the Coulomb interactions of Fermi liquid in the "ballistic" transport regime\textsuperscript{21}. Therefore, the metallicity of the system for $T < T^*$ implies that the 2D metallic state is fundamentally different from the high
Our measurements were performed on a back-gated 2D hole system in a 10nm wide GaAs quantum well made from one of the wafers used in our previous study \cite{22}, a (311)A GaAs wafer using Al$_x$Ga$_{1-x}$As barriers and symmetrically placed Si delta-doping layers. The wafer was thinned to $\approx150$ μm for gating from the back of the sample and prepared in the form of a Hall bar, of approximate dimensions $(2.5 \times 9)$ mm$^2$, with diffused In(5%Zn) contacts. The measurement current was applied along the [2 3 3] direction and kept low such that the power delivered on the sample is less than a few fWatts/cm$^2$ to avoid over heating the holes.

![Image of graph showing temperature dependent resistivity $\rho(T)$ of 2D holes in a 10nm wide GaAs quantum well.](image)

**FIG. 1:** (a) Temperature dependent resistivity $\rho(T)$ of 2D holes in a 10nm wide GaAs quantum well with density $p=1.13 \times 10^{10}$ cm$^{-2}$ in zero magnetic field. Note that $\rho(T)$ changes from insulating-like to metallic below $T^* \approx 0.3K$. (b) The same data as in (a) plotted as conductivity in units of $e^2/h$ vs. $T$. (c) Longitudinal magneto-resistivity $\rho_{xx}(B)$ of 2D holes in (a) and (b) at various temperatures. For temperatures above $T^*$, the $\rho_{xx}(B)$ curves show a low $B$ insulator-$\nu=1$ QH transition at $B^{cl}_c=0.35T$. For comparison, we also show $\rho_{xx}(B)$ curves at 0.11K and 18mK, which are below $T^*$.

Fig.1 presents the zero magnetic field temperature dependent resistivity of 2D holes with density $p=1.13 \times 10^{10}$ cm$^{-2}$ which is on the metallic side of the MIT. For this sample, the MIT happens around $p_c=0.78 \times 10^{10}$ cm$^{-2}$ when the density is changed by the back-gate. It can be seen in Fig.1 that $\rho(T)$ changes from insulating-like($d\rho/dT <0$) to metallic($d\rho/dT >0$) below $T^* \approx 0.3K$. In Fig.1 we plot the data as conductivity $\sigma(T)$, in units of $e^2/h$. For either $T > 1.5T^*$ or $T < 0.5T^*$, $\sigma(T)$ can be viewed as a linear function of $T$, but with a different coefficient $d\sigma(T)/dT$ \cite{17,18}. Fig.1 shows the main result of this paper, the insulator-QH transition in the high temperature insulating regime of the metallic state. The longitudinal magneto-resistivity $\rho_{xx}(B)$ at several temperatures are plotted on Fig.1. For $T > T^*$, there is a low field insulator-$\nu=1$ QH transition at critical field $B^{cl}_c=0.35T$esla, denoted by the crossing of $\rho_{xx}(B)$ curves. The $\rho_{xx}(B)$ curves also cross at a high critical field $B^{cl}_c=0.55T$esla. For comparison, we also include $\rho_{xx}(B)$ curves at 0.11K and 18mK which are below $T^*$. As $T$ drops below $T^*$ the size of the low field negative magneto-resistivity decreases and a sharp resistivity spike develops around $\nu = 5/3$. The large resistivity spike at $\nu \approx 5/3$ and how the $B=0$ 2D metal transforms into QH states at low $T$ need further study. Again, we emphasize that although SdH oscillations are known to exist in the 2D metallic state at low $T$, to the best of our knowledge Fig.1 is the first report of a SdH minimum and an insulator-QH transition in the high $T(>T^*)$ insulating regime of the 2D holes with $p > p_c$.

Although the $\rho_{xx}(B)$ data and insulator-QH transition in Fig.1 appear to be similar to previously studied Anderson insulator-QH transitions \cite{17,18}, the underlying physics should be very different. Most of the previous experiments were performed in the low temperature diffusive regime such that $k_B T < h/\tau$, where $k_B, h, \tau$ are the Boltzmann constant, Planck’s constant divided by $2\pi$ and the scattering time, respectively. Thus the low $B$ insulating $\rho(T)$ was likely to be mainly driven by single particle quantum interference (Anderson localization). In the temperature regime($T>T^*$) where our high mobility metallic sample shows the "insulator-QH transition", there is no single particle interference effect due to strong dephasing, and the sample is actually in the ballistic regime ($k_B T > h/\tau$) \cite{21}. Recent interaction theories on the conductivity of 2D Fermi liquids in the ballistic regime predict a linear $T$-dependent zero field conductivity $\sigma(B)$ and a parabolic negative magneto-resistivity at $\omega_c \tau > 1$ \cite{23,24}. The data in Fig.1 show that our sample behavior is qualitatively consistent with the predictions of ref.\cite{21,23} at $T>T^*$ \cite{24}. Recently, some authors have attempted to interpret the $T<T^*$ metallic behavior using the Fermi liquid theory in ref.\cite{21}. Under this interpretation, we found the fitted Fermi liquid parameters to be inconsistent between 2D hole samples with similar densities but different mobilities.\cite{25}. Note that since $d\sigma(T)/dT$ changes sign at $T^*$, it is not a priori known whether the $\sigma(T) \sim T$ at $T=T^*$ or at $T < T^*$ is due to interaction corrections. We believe that the $\sigma(T) \sim T$ at $T>T^*$ is related to interaction effects of a ballistic Fermi liquid, where both the parallel field and perpendicular field effect are consistent with theoretical expectations \cite{25}.

Observing the SdH oscillation and an "insulator-QH transition" in the $T > T^* \sim T_F$ insulating regime of low density 2D holes is somewhat unexpected, since it was originally believed that the insulating $\rho(T)$ at $B = 0$ in...
FIG. 2: The lower critical field $B^L_c$ and higher critical field $B^H_c$ of the high $T$ insulator-QH-insulator transition for 2D metallic holes with various densities. Black lines connecting data points are only guides to the eye. As a reference, we show the positions of SdH dips for $\nu = 1, 2, 3$ as dotted lines on the density-magnetic field diagram.

This temperature range is related to the non-degenerate nature of the low density hole gas\[1\]. Note that if the insulating $\rho(T)$ at $T > T^*$ has a classical origin as in ref.\[12\], it would be unlikely for the sample to show a negative magneto-resistivity and the "insulator-QH transition" in Fig1 because the classical Drude magneto-resistivity is zero. At present, it is unclear if a more elaborated semi-classical model can reproduce a non-monotonic $T$ dependent zero field $\rho(T)$ and an "insulator-QH transition" at high $T$ at the same time. To further elucidate the high $T$ "insulator-QH" transition of metallic 2D holes, we plot both $B^L_c$ and $B^H_c$ for five densities on the density-magnetic field diagram shown in Fig2. The values of $B^L_c$ and $B^H_c$ are obtained from the crossing of the $\rho_{xx}(B)$ curves at temperatures $T > T^*$. For $p=0.93, 1.13, 1.32 \times 10^{10}$ cm$^{-2}$, the insulator-$\nu = 1$ QH transition is observed at $B^L_c$, while for higher densities the sample enters the QH state with $\nu > 1$ at $B^H_c$. As a reminder, the density dependence of $B^L_c, B^H_c$ in Fig2 is related to the nature of the high $T$ insulating phase of 2D holes on the metallic side ($p > p_c$) of the MIT, differing from all previous insulator-QH studies which were on the insulating ($p < p_c$) side of the $B = 0$ MIT\[11, 12, 13\]. As we suggest above, the zero field localization exhibited by the sample at $T > T^*$ could be due to the Coulomb interactions of a "ballistic" Fermi liquid. Thus, the trace of $B^L_c, B^H_c$ in Fig2 represents a metal-insulator boundary in $p, B$ space for a Fermi liquid in which localization is prompted merely by interactions. Zhang et al. has constructed a global phase diagram for a 2D system in a magnetic field\[24\], considering only the disorder induced Anderson localization. An extended theoretical phase diagram like ref.\[24\] including the interaction effect has yet to be developed to make comparison with Fig2.

The persistence of the $\nu = 1$ QH effect into the $T \sim T_F$ regime suggests a large energy gap $\Delta_1$ of the $\nu = 1$ QH state for the low density 2D hole gas. We plot $\rho_{xx}(T)$ at the center of the $\nu = 1$ QH state for 2D holes with different densities on Fig3. The black lines are fitted curves using the activated function $\exp(-\Delta_1/2T)$. The density dependence of $\Delta_1$ is presented in the inset of Fig3. The Fermi temperature $T_F$ is also plotted using effective hole masses $m^* = 0.38m_e$ and $0.19m_e$ to compare with $\Delta_1$. Fig3 shows that the energy gap in the $\nu = 1$ QH state could be 2-3 times larger than the Fermi energy of 2D holes in the low density regime. Many body effects have been known to be important in the $\nu = 1$ QH state where novel collective spin excitations named Skyrmions may exist\[27, 28\]. Therefore $\Delta_1$ should be related to the interaction energy, which is much larger than the Fermi energy in low density holes. Interestingly, the inset of Fig3 shows a sharp non-monotonic density dependence of $\Delta_1$. We suspect the sharp drop of $\Delta_1$ at lower density is due to the competition between the QH liquid and Wigner solid at the lowest Landau level\[29\].

Finally we would like to comment on the contradictory results concerning the fate of the lowest extended states as $B \rightarrow 0$ in low density GaAs 2D electron/hole systems in ref.\[11, 12, 13\]. Both Hanein et al.\[11\] and Yasin et al.\[13\] used the low $B$ insulator-QH transition to track the positions of the in 2D GaAs systems in the insulating side of MIT. The low $B$ insulator-QH transition in the $T > T^*$ regime observed in this paper suggests that caution must be taken while interpreting the finite temperature insulator-QH transition. Due to the
non-monotonicity of $\rho(T)$ in dilute 2D GaAs systems, the critical density/resistivity of the MIT is not well defined and could depend on the experimental temperature. If an experiment is done at high temperature, the critical density could appear to have a higher value with a correspondingly lower value of critical resistivity. As a result, for experiments where temperature is high or the electrons/holes are overheated, the insulator-QH transition for $p$ slightly lower than $p_c$ could be only the insulator-QH transition of metallic holes at $T \geq T^*$. In fact, the $B^p_c$ of the high $T$ insulator-QH transition increases with $p$ for $p$ just above $p_c$, as Fig.2 shows, which may cause the $B^p_c$ to appear to "float up" for $p < p_c$ in a sample with high $T$. Thus, the positions of extended states extracted from the insulator-QH transition depend critically on the sample temperature around the region $p \sim p_c$, which is exactly the crucial density region where the extended states appear to float up or saturate. We note that $T^*$ for 2D holes in GaAs was found to be linearly dependent on density and to extrapolate to zero at some density $p^*$ [22]. Practically the positions of extended states determined from insulator-QH transitions can only be reliably extrapolated to $T \rightarrow 0$ for densities below $p^*$ but not the $p_c$ determined from the temperature coefficient of zero field $\rho_{xx}(T)$. In our opinion, the different behavior of the lowest extended states as $B \rightarrow 0$ around the $p_c$ of the 2D MIT in ref. [11,12,13] might be simply related to the different base temperatures of the 2D systems.

In summary, we demonstrate for first time that there exist SdH oscillations and an insulator-QH transition in the high temperature insulating regime of low density (low $T$-metallic) 2D holes in a GaAs quantum well. We also show that the energy gap of the $\nu = 1$ QH state has a large value, attesting the strong interactions in the low density GaAs hole system. These results together with the linear $T$ dependent conductivity suggest the 2D metallic hole system behaves like a localized Fermi liquid in the ballistic transport regime for $T$ higher than $T^*$, the temperature at which zero field resistivity changes from insulating to metallic.

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