Linear temperature dependence of conductivity in the “insulating” regime of dilute two-dimensional holes in GaAs

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(Dated: March 22, 2022)

The conductivity of extremely high mobility dilute two-dimensional holes in GaAs changes linearly with temperature in the insulating side of the metal-insulator transition. Hopping conduction, characterized by an exponentially decreasing conductivity with decreasing temperature, is not observed when the conductivity is smaller than $\sigma^2/h$. We suggest that strong interactions in a regime close to the Wigner crystallization must be playing a role in the unusual transport.

PACS numbers: 73.40.-c, 71.30.+h, 73.40.Kp

In recent years, there has been great interest in the transport of low density two-dimensional (2D) charge carrier systems. In contradiction to the the scaling theory of localization, which predicted that all states in 2D in the absence of electron-electron interactions are localized, experimental observations of “metallic” behavior showing increasing conductivity ($\sigma$) with decreasing temperature ($T$) ($d\sigma/dT < 0$) and an apparent metal-insulator transition (MIT) as the carrier density is lowered have been reported on many low density, low disorder 2D systems. Although there have been many experimental and theoretical studies trying to understand this metallic behavior, there is still no consensus on its origin to date.

On the other hand, the “insulating” behavior ($d\sigma/dT > 0$) for lower densities in these low disorder systems has not been studied as extensively as the metallic behavior. In highly disordered systems, the transport in the insulating regime is described by variable range hopping (VRH) among the localized states, and the $T$-dependence of $\sigma$ is expressed as $\sigma(T) = \sigma_0 \exp[-(T_0/T)^{1/x}]$, where $\sigma_0$ is a prefactor and $T_0$ is a characteristic temperature. The exponent $x$ depends on the density of states (DOS) at the Fermi energy. For a constant DOS in the absence of interactions, $x = 1/3$ corresponding to the Mott VRH and for a DOS which has a Coulomb gap at the Fermi energy due to interactions, $x = 1/2$ corresponding to the Efros-Shklovskii VRH. In clean systems with low disorder, however, the origin of the “insulating” behavior ($d\sigma/dT > 0$) in low density regime, where the interactions between carriers are strong, could be significantly different from that described by simple localization. In the ideal case, it was predicted that the ground state of the system in the low density limit is a Wigner crystal which can be pinned by even a tiny amount of impurities in the system.

We have recently studied the MIT of extremely high mobility dilute 2D holes in GaAs and presented a detailed analysis for the $T$-dependence of $\sigma$ on the “metallic” side of the transition. The metallic behavior persisted up to $r_s = 57$, much higher than 37 predicted for Wigner crystallization ($r_s$ is the interaction energy to Fermi energy ratio, given by $r_s = \langle p n \rangle^{-1/2} m^* \epsilon^2 / 4 \pi \hbar^2 \epsilon$, where $p$ is the hole density, $m^*$ effective mass, and $\epsilon$ the dielectric constant). With the persistence of metallic behavior up to such a large $r_s$ value, the question arises regarding the nature of the “insulating” behavior observed in this 2D system for $r_s$ reaching 80. To address this question, we present the $T$-dependence of $\sigma$ of the same sample on the “insulating” side of the MIT in this report. We show that the conductivity exhibits a linear dependence on temperature and does not follow the VRH behavior, and discuss its implications with regard to strong interaction effects close to or in the Wigner crystallization regime.

The sample used in this study is a heterojunction insulated-gate field-effect transistor (HIGFET) made on a (100) surface of GaAs. A metallic gate, separated by an insulator (AlGaAs) from the semiconducting GaAs, is used to induce the 2D holes at the interface between the GaAs and AlGaAs. The mobility ($\mu$) of our sample measured at $T = 65$ mK reaches $1.8 \times 10^9$ cm$^2$/Vs for $p = 3.2 \times 10^{10}$ cm$^{-2}$, which is the highest achieved for 2D holes in this low density regime. This high mobility allows us to measure the temperature dependence of conductivity down to very low densities reaching $p = 1.5 \times 10^9$ cm$^{-2}$, with $r_s$ near 80, and the MIT is observed at a critical density of $p_c = 3 \times 10^9$ cm$^{-2}$, i.e. $r_s = 57$. The experiment was done in a dilution refrigerator with a base temperature around 65 mK. The resistivity of the 2D holes were measured by a low-frequency lock-in technique with frequency as low as 0.1 Hz to maintain the out-of-phase signal less than 5 %. Excitation current of as small as 50 pA was used to ensure that the effect of Joule heating is negligible. In addition, the drive current was varied at base temperature to make sure that the linear response was measured.

Figure 1 shows the $T$-dependence of $\sigma$ for five 2D hole densities varying from $5 \times 10^9$ cm$^{-2}$ ($r_s = 44$) to $1.5 \times 10^9$ cm$^{-2}$ ($r_s = 80$). Data for higher densities deep inside the metallic region have been presented in Ref. 6. The top two traces are on the metallic side with $\sigma > \epsilon^2/h$ in the entire $T$ range. For $p = 5 \times 10^9$ cm$^{-2}$, $\sigma$ decreases with...
increasing $T$ from 0.065 K to 0.15 K. This decrease of $\sigma$ with increasing $T$ ($d\sigma/dT < 0$) is typical of the metallic behavior, the physical origin of which has been the focus of much recent research on 2D MIT. For $T > 0.15$ K, $\sigma$ increases with increasing $T$ and the increase becomes linear for $T > 0.25$ K. This linear dependence of $\sigma$ on $T$ continues for $T$ exceeding $T_F$, the Fermi temperature of the 2D hole gas (marked by the vertical bar in Fig. 1), which is 0.36 K for this density. Das Sarma and Hwang explained this change in $T$-dependence of $\sigma$ from $d\sigma/dT < 0$ to $d\sigma/dT > 0$ as a quantum-to-classical crossover. In the classical regime, when $T >> T_F$, scattering of the 2D carriers by charged impurities would give rise to linear increase of $\sigma$ with increasing $T$. We note that the linear dependence starts below $T_F$ in our data, and the crossover happens at a temperature about one third of $T_F$.

For $p = 4 \times 10^9$ cm$^{-2}$ ($T_F = 0.29$ K), similar $T$-dependence of $\sigma$ is observed, although the metallic behavior is much weaker, and the quantum-to-classical crossover occurs at lower $T$ ($\sim 0.1$ K) as expected. The linear dependence sets in at $T = 0.22$ K. However, for $p = 3 \times 10^9$ cm$^{-2}$ ($r_s = 57$), the third trace from the top, $d\sigma/dT > 0$ is observed in all our $T$ range. The metallic behavior ($d\sigma/dT < 0$) is not seen in the data down to the lowest $T$, and for $T < 0.13$ K $\sigma$ becomes smaller than $e^2/h$, suggestive of an insulator, although strictly linear dependence is not seen for $T < 0.1$ K.

The bottom two traces show insulating behavior in that $\sigma$ is observed to decrease with decreasing $T$, albeit only linearly. For $p = 2.3 \times 10^9$ cm$^{-2}$ ($r_s = 65$), $\sigma < e^2/h$ for $T < 0.22$ K and the linear dependence extends down to the base temperature. This linear dependence appears to be the same as that seen in the high hole density metallic side ($5 \times 10^9$ cm$^{-2}$ and $4 \times 10^9$ cm$^{-2}$), and the same linear dependence is seen for $\sigma < e^2/h$ as well as for $\sigma > e^2/h$. Further reducing the density down to $1.5 \times 10^9$ cm$^{-2}$ ($r_s = 80$) does not change the $T$-dependence very much, but simply decreases the magnitude of $\sigma$, making the $T$ range where $\sigma < e^2/h$ wider.

In Fig. 2 we show the $T$-dependence of $\sigma$ for $p = 1.5 \times 10^9$ cm$^{-2}$ in more detail. Clearly, $\sigma$ depends linearly on $T$ (as shown by the solid line) in the entire $T$ range, and $\sigma < e^2/h$ in almost the same range. When we tried to fit the data with the VRH model with exponent $x$ equal to either $1/3$ or $1/2$, none of them produced a good fit, as shown in the insets. This suggests that the transition to an “insulating” behavior as we lower the 2D hole density in our sample, determined from the sign of $d\sigma/dT$, is not a disorder induced transition. While one can argue that further decreasing the density will eventually lead to an exponentially localized behavior, strong interactions (with $r_s = 80$) which must be present for this density make it unlikely that the transport can be described by single particle localization.

For a 2D electronic system with such large $r_s$ value, formation of a Wigner crystal should be considered. When the Wigner crystal is pinned by disorder, the transport is expected through thermal activation of the crystal over the pinning potential. In this case, $\sigma$ should decrease exponentially with decreasing $T$. Our data, on the contrary, shows a linear $T$-dependence in the $\sigma < e^2/h$ insulating regime. Here, we should note that reducing the carrier density not only increases $r_s$, but also decreases $T_F$, thus decreases the quantum-to-classical crossover temperature. In our data, for hole densities $p = 5 \times 10^9$ cm$^{-2}$ and $p = 4 \times 10^9$ cm$^{-2}$, the linear dependence of $\sigma$ on $T$ predicted for the $T >> T_F$ classical regime actually extends down to a $T$ even below $T_F$, suggesting that the crossover from classical to the degenerate regime seems to occur much below $T_F$. In any case, for a classical 2D electronic system, the relevant interaction parameter is $\Gamma$, which is given by $\Gamma = e^2\sqrt{\pi n}/4\pi\epsilon k_B T$, with $n$ being the
carrier density. This parameter is equivalent to $r_s$ in the degenerate regime, with the kinetic energy replaced by $k_B T$. Studies of electrons on liquid helium have shown that transition to the Wigner crystal is around $\Gamma = 127$. In our sample, for the lowest hole density, $p = 1.5 \times 10^9 \text{cm}^{-2}$, $T_F = 0.11$ K. $\Gamma$ is between 80 and 27 for $T$ from 0.11 K to 0.32 K, and equals 146 at $T = 0.06$ K. Therefore, Wigner crystallization is not likely to occur in most of our $T$ range until $T$ reaches close to the base temperature. However, a more recent electron-on-helium experiment has reported residual signature of the Wigner crystal up to a much higher temperature with $\Gamma$ down to 46. Thus, we should expect the 2D holes in our sample to be strongly correlated and the Wigner crystallization physics be important. The $T$-dependence arising from scattering of the 2D hole gas by charged impurities, as considered by Das Sarma and Hwang, even though remarkably similar to that observed in our experiment, cannot be the adequate explanation for the insulating regime.

We should also mention that localization corrections to the conductivity in the weakly interacting classical regime do not explain our data. Experimental study on weak localization in the classical regime has been performed for electrons on solid hydrogen surface. In this case, the correction to the conductivity is proportional to $T_F/T$, and our data are not consistent with this expectation. The interaction correction is proportional to $(T_F/T)^2$. This term is negligible compared with that from the weak localization, and does not explain our data either.

Finally, the linear dependence of $\sigma$ on $T$ observed in the insulating regime of our data must result from strong interaction effects. In this respect, we think that the recent theory by Spivak may be relevant to our data.

In summary, we have studied the temperature dependence of the conductivity in the insulating side of the MIT for extremely high mobility dilute 2D hole system with $r_s$ reaching 80. A linear dependence of conductivity on temperature has been observed in the insulating side. We suggest that strong interaction effects in both degenerate and classical regime close to the Wigner crystallization should be considered to provide an understanding for this unusual transport.

This work has been supported by the NSF and the DOE at Princeton University.

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