Interaction effects in the transport of two-dimensional holes in GaAs

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The power-law increase of the conductivity with temperature in the nominally insulating regime, recently reported for the dilute two-dimensional holes in GaAs heterojunction-insulated-gate field-effect-transistor samples, is found to systematically vary with the carrier density. Based on the results from four different GaAs heterojunction-insulated-gate field-effect-transistor samples, it is shown that the power law exponent depends on a single dimensionless parameter, the ratio between the mean carrier separation and the distance to the metallic gate that screens the Coulomb interaction. This dependence suggests that the carriers form a correlated state in which the interaction effects play a significant role in the transport properties.

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Charge transport in two-dimensional (2D) electron systems 1 provides a unique means of studying the interplay between disorder and electron-electron interactions. This problem is fundamentally important and remains a subject of intense investigation 2. While noninteracting 2D electrons are generally believed to form the Anderson insulator 2, 3, the situation appears to be much more complex in the presence of interactions 2, 4, 5, 6. Recent theoretical studies 4, 6 emphasize the importance of collective phenomena around the so-called metal-to-insulator transition (MIT).

In practice, since the ratio of the Coulomb interaction to the kinetic energy increases with lowering the density, samples with most dilute carriers are best suited for probing the collective phenomena. However, reducing the carrier density n runs into a risk of increasing the carrier separation \( \propto n^{-1/2} \) beyond the single-particle localization length \( \xi \), in which case the interaction effects become overshadowed by the single-particle localization. Thus, a sufficiently clean 2D environment is another requirement that has to be met to uncover the underlying interaction effects.

The experimental progress on studying the transport of 2D systems has been greatly influenced by the sample quality. Very early experimental results in Si-devices demonstrated the activated transport consistent with the Anderson insulator 2. The Arrhenius conductivity \( \sigma \sim e^{-T\Delta/T} \) at high temperatures, and the softer temperature dependence, \( \sigma \sim e^{-T\Delta'/T} \) at lower temperatures, with \( \nu = 1/3 \) corresponding to the variable-range hopping (VRH) scenario 11, and \( \nu = 1/2 \) to the effect of the Coulomb gap 12. However, in the mid-1990’s, experiments performed in much cleaner 2D electrons in Si-MOSFETs showed both metal-like \( (d\sigma/dT < 0) \) and insulator-like \( (d\sigma/dT > 0) \) conductivity behavior, depending on whether the density is above or below a certain critical value \( n_c \). Although the existence of the metallic regime at \( T \to 0 \) is still debated, the transport on the insulating side generally remains activated, in accord with the Anderson localization picture.

The experimental findings on the insulating side of the MIT has radically changed with the adoption of the undoped GaAs/AlGaAs heterojunction-insulated-gate field-effect transistors (HIGFETs). Recent experiments 14, 15 demonstrated that the conductivity can become non-activated, while preserving the “insulating” sign \( d\sigma/dT > 0 \). In 2003, a close-to-linear dependence \( \sigma \propto T \) was first observed in 2D holes in a p-GaAs HIGFET device for densities down to \( p = 1.5 \times 10^9 \text{cm}^{-2} \) 14. Subsequent experiments in the devices of the same kind not only confirmed this observation for similar carrier densities, but also revealed a more general power-law-like temperature dependence, \( \sigma \propto T^\alpha \), with a varying exponent \( 1 < \alpha < 2 \), at sufficiently low temperatures 15. Remarkably, such a behavior persists even for a record-low density of \( p = 7 \times 10^8 \text{cm}^{-2} \), in which case the Coulomb energy is about 100 times greater than the nominal Fermi energy, and the Fermi wavelength \( \lambda_F = \sqrt{2\pi/p} \approx 0.95 \mu \text{m} \) approaches a macroscopic scale.

In this Letter we present a comprehensive study of this surprising power law \( T \)-dependence based on data collected from four different p-type HIGFET samples that only differ by the structural barrier thickness (the distance \( d \) from the 2D layer to the metal gate, Table I). The procedures of sample preparation and the measurement details are described in Ref. 14 for the first three samples, while the data from the fourth sample is drawn from Ref. 14 for comparison. The fitting of the conductivity for the temperatures \( 35 < T < 200 \text{mK} \) to

\[
\sigma/\sigma_Q = G_0 + (T/T_0)\alpha, \quad \sigma_Q = e^2/(2\pi\hbar)
\]

yields a sample-dependent exponent \( \alpha(p) \) that grows with decreasing hole density \( p \), while the \( T \)-independent term remains negligible, \( G_0\alpha \ll \sigma(T) \). Moreover, we find that \( \alpha \) systemically depends on the single dimensionless parameter \( \kappa = a/d \), where \( a = (\pi\rho)^{-1/2} \) is the Wigner-Seitz radius (the mean carrier distance is about 2\( a \)). Such a single-parameter dependence, tied to the screen-
The aim of this work is to analyze the power-law-like temperature dependence $\sigma(T)$ and to examine the relevance of the interaction effects. In Fig. 1 we show the log-log plots of $\sigma(T)$ obtained from four different samples: (a) #2 and (b) #3 are samples from the same wafer, cooled down to the lowest temperature of around 80 mK; (c) sample #4 is cooled down to 35 mK; and (d) is the data from Ref. [14] with the lowest $T$ of 65 mK. Each panel in Fig. 1 contains curves for a number of hole densities. For the density above critical, $p_c \approx 4 \times 10^9 \text{cm}^{-2}$, the transport is metal-like [2]. Below we focus on the opposite, low-density “insulating” regime.

There are three features common to all four samples. (i) Although the sign $d\sigma/dT > 0$, the conductivity never becomes activated [13] because an activated $T$-dependence in a log-log plot would have shown a strong downward bending for $T$ below the activation temperature. (ii) For low densities $p < 2 \times 10^9 \text{cm}^{-2}$, the slopes $d\log \sigma/d\log T$ are roughly temperature-independent at temperatures $\lesssim 200 \text{mK}$ and increase with decreasing density. (iii) Finally, although the non-activated conductivity is a signature of the extended states, the conductivity values are 1-2 orders below $e^2/(2\pi\hbar)$ (the 2D analog of the minimal metallic conductivity [16]).

In what follows we investigate the density dependence of the slope $\alpha = d\log \sigma/d\log T$ by fitting $\sigma(T)$ to the simple formula [1] for the low density curves, $p \leq 3 \times 10^9 \text{cm}^{-2}$. The fitting parameters $G_0$ and $T_0$ are plotted opposite, low-density “insulating” regime.

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in Fig. 2. The $T$-independent term $G_0$ remains around zero up to $p \approx 2 \times 10^9 \text{cm}^{-2}$ for the samples #2, #3, and #4, indicating a fairly good power law dependence: $\sigma \propto T^\alpha$. On the other hand, for the sample from Ref. [14], the constant $G_0$ is more significant. We stress that, although the high-temperature behavior in the sample from Noh et al. looks quite linear, $\sigma \sim A + BT$, as reported in Ref. [14], at $T \lesssim 200 \text{mK}$ the conductivity curve exhibits a noticeable bending at $T < 200 \text{mK}$ as demonstrated in the linear scale plot in the inset of Fig. 1 (d), and is best fitted to Eq. (1) with $\alpha \neq 1$ [see Fig. 3]. The parameter $T_0$ for all four samples has a trend of a slow decrease with increasing density from about $400 \text{mK}$ to about $300 \text{mK}$ for densities up to $p \approx 2 \times 10^9 \text{cm}^{-2}$.

Fig. 3 shows how the exponent $\alpha$ depends on the parameter $2a$, which is approximately the mean carrier spacing. The results from samples #2 and #3 fall approximately onto a single curve in which $\alpha$ varies from 1.1 to about 1.5. The results from both samples #4 and Ref. [14] qualitatively follow the same trend albeit the values of $\alpha$ are greater by about 0.6 and 0.1 respectively. This shift in $\alpha(p)$ relative to that for samples #2 and #3 motivates us to look into the structural differences between the samples, which is primarily in the barrier thickness $d$. As shown in Table I, samples #2 and #3 have the same density, while the values of $d$ for the other two samples are notably different. Furthermore, the values of $\alpha$ increase with the decrease in $d$ for a given density. This trend points at the role of the screening by the metallic gate.

In HIGFETs, the metallic gate at the distance $d$ from the 2D hole layer screens the $1/r$ interaction down to $1/r^3$ when $r \gtrsim 2d$. For the lowest densities, the interaction becomes effectively short-ranged, with the relevant parameter being the ratio $\kappa = a/d$ between the carrier spacing $\approx 2a$ and the screening radius $2d$. For our measurements, this ratio can be continuously varied in the range $0.1 < \kappa < 0.85$; the sample of Noh et al. also falls into this range. The effect of the gate screening becomes apparent in Fig. 4 where all the power law exponents $\alpha$ are plotted as a function of $\kappa$. Remarkably, $\alpha(\kappa)$ from all four samples fall onto a single curve within reasonable error bars. This curve tends to saturate for $\kappa \gtrsim 2$, while it most strongly varies when $\alpha \approx 1$. Thus the linear dependence $\sigma \propto T$ reported in Ref. [14] is most probably a crossover into an entirely different transport regime, rather than a universal signature at low $T$. [In the inset we plot $\sigma^{1/\alpha}$ as a function of $T/T_0(p)$ to illustrate the relative insignificance of the constant $G_0$ in Eq. (1).]

The strong sensitivity of the transport to the shape of the interaction potential is not entirely surprising. Indeed, the carriers at these densities are delocalized and are very strongly interacting (the $r_s$ value for $p = 1 \times 10^9 \text{cm}^{-2}$ is 100 if one assumes the hole band mass $m = 0.4m_e$). A plausible way to think about such a system is by imagining a liquid or a strongly-interacting plasma. As it has been recently shown, the kinetic and thermodynamic properties of classical plasmas strongly depend on the same screening parameter $\kappa$ [17], although the classical arguments alone cannot explain the peculiar dependence [11]. It is interesting whether the quantum effects could manifest themselves at lower (so far inaccessible) temperatures, in which case the system could become collectively localized [14], or whether the MIT takes place [14]. The dependence on $\kappa = a/d$, where $a$ and $d$ can be independently controlled, suggests that, by varying the density, one can continuously modify the state of the system. For sufficiently low densities ($a \gtrsim d$), a

![FIG. 3: Density dependence of the exponent $\alpha$ for all the samples. The dotted lines are guides for the eye.](image_url)

![FIG. 4: The exponent $\alpha$ as a function of the ratio $\kappa = a/d$. Inset: $\sigma^{1/\alpha}$ as a function of $T/T_0(p)$.](image_url)
possibility of a reentry into the Fermi-Liquid (FL) was suggested \[15\]. For larger densities, a sequence of mixed phases \[19\] was conjectured.

We finally note that varying \(d\) not only changes the interaction range, but also the correlation length \(\xi_{\text{dis}}\) of the disorder potential. The scattering off the surface imperfections at the gate level is estimated to be negligibly small. In the case when the disorder is dominated by the charge impurities in the bulk, the gate screens the disorder potential harmonics for length scales \(\gtrsim d\), so that \(\xi_{\text{dis}} \sim d\). In such a situation it becomes more difficult to differentiate the electron-electron interaction effects from those due to the change in the distribution of disorder \[20, 21\]. The dependence of the conductivity on \(a/d\), rather than on \(a\) and \(d\) separately, suggests that the electron interactions are probably more important than the change in disorder. One natural possibility for the electron interaction to enter is through the screening of the impurity field (such as via the RPA screening at smaller \(r_s\) \[7, 22\]), in which case the resulting effective disorder would depend on \(a/d\) as long as \(a < d\). Another, equally plausible scenario is provided by assuming the hydrodynamic (viscous) flow of an electron liquid past the impurities whose size \(\xi_{\text{dis}} > a\). In this case the resistivity is proportional to the viscosity of the 2D liquid \[10, 23, 24\] (that depends on \(\kappa\)), and to the number of impurities, while the dependence on their shape and size (that may become affected by varying \(d\)) enters only under the logarithm, according to the well-known Stokes paradox of a 2D flow \[25\].

In summary, by performing transport measurements on high quality 2D holes with densities down to \(7 \times 10^8 \text{ cm}^{-2}\), we established the dependence of the power-law exponent \(\alpha\) [Eq. (1)] on the ratio \(a/d\) between the Wigner-Seitz radius \(a\) and the distance to the metal gate \(d\). We ascribe this dependence to the screening of the Coulomb interaction by the gate. We believe that our results provide direct evidence of the role of the electron-electron interaction in the 2D transport, and suggest that the transport is sensitive to the shape of the interaction potential controlled by the screening distance \(d\). By varying the ratio \(a/d\), one can realize a strongly-correlated state of the 2D carriers with tunable properties.

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