Transport and percolation in a low-density high-mobility two-dimensional hole system

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We present a study of the temperature and density dependence of the resistivity of an extremely high quality two-dimensional hole system grown on the (100) surface of GaAs. For high densities in the metallic regime ($p \gtrsim 4 \times 10^8$ cm$^{-2}$), the nonmonotonic temperature dependence ($\sim 50 \sim 300$ mK) of the resistivity is consistent with temperature dependent screening of residual impurities. At a fixed temperature of $T=50$ mK, the conductivity vs. density data indicates an inhomogeneity driven percolation-type transition to an insulating state at a critical density of $3.8 \times 10^9$ cm$^{-2}$.

The low temperature conduction properties of an interacting two-dimensional (2D) electron gas in the presence of disorder remains a topic of fundamental interest and some controversy. It has been understood for some time that all non-interacting electronic states are localized in the presence of disorder at $T=0$ [1]. This model was challenged by the observation of Kravchenko and coworkers [2] of an apparent metal-to-insulator transition in Si MOSFETs. Subsequently a variety of models have been put forth [3, 4, 5, 6] to explain a wealth of experimental data. The 2D metal-to-insulator transition (MIT) has now been studied in a variety of semiconductor systems [2, 7, 8, 9, 10, 11, 12, 13, 14]. Yet the question remains: does the transition from insulating to metallic behavior observed in certain 2D systems represent a quantum phase transition, since the interaction parameter ($r_s \sim 45$) for our sample are among the lowest and highest ever respectively recorded in the 2D MIT literature, we find that the data are well explained within this simple framework. The fact that our critical density is similar to the critical density for 2D MIT found in ref. [11] suggests that the effective 2D MIT in GaAs electron and hole systems at experimentally accessible temperatures is a disorder-driven crossover phenomenon and not an interaction driven quantum phase transition, since the $r_s$ value for our hole system is four times larger than the corresponding $r_s$ in the electron system of ref. [11].

Our experiments utilize recently developed structures in which the 2DHS resides in a 20nm GaAs/AlGaAs quantum well grown on the (100) surface of GaAs that has been modulation-doped with carbon [16]. Back-gated Hall bar geometry is used in this experiment to tune the density from $2.9 \times 10^{10}$ cm$^{-2}$ to $2.9 \times 10^9$ cm$^{-2}$ in single sample. Cyclotron resonance studies of similarly grown carbon-doped quantum wells indicate that the hole effective mass is large, $m_h \sim 0.3m_e$, where $m_e$ is the free electron mass [17]. To give a comparison with other 2D systems studied in the literature, we mention that the 2D n-GaAs samples of refs. [10, 11] have an electron mobility of $5 \times 10^6$ cm$^2$/Vs at the carrier density of $3 \times 10^{10}$ cm$^{-2}$ compared with our hole mobility of $2 \times 10^{10}$ cm$^2$/Vs at the same density. Taking into account the effective mass difference ($m = 0.07 m_e$ for electrons in refs. [10] and [11] and $m \approx 0.3 m_e$ for holes in our samples) and remembering that mobility $\mu \propto \tau / m$, where $\tau$ is the transport relaxation time, we conclude that our 2D hole samples are comparable in quality to the corresponding 2D electron samples of refs. [10, 11], while $r_s$ is significantly larger. In this manner the data presented here probe a regime inaccessible to the experiments of refs. [10, 11].

Figure 1 displays magnetotransport at $T=50$ mK. The exceptional quality of these samples is evident in the strength of the fractional quantum Hall state at $\nu = 2/3$ at B=1 Tesla and the nascent features observed at $\nu = 5/3$ and $4/3$ at even lower values of magnetic field. Figure 2 displays the temperature dependence of the resistiv-
In order to understand the low temperature 2D transport properties in the metallic regime we have carried out a microscopic transport calculation using the Boltzmann theory. In our calculation we assume that the 2D carrier resistivity is entirely limited by screened impurity scattering. We neglect all phonon scattering effects because our theoretical estimate shows phonon scattering to be negligible for 2D holes in GaAs structures in the $T < 1K$ regime of interest to us. Formally, this approach is well-controlled in the regime of small $r_s$ and $k_F l \gg 1$, where $k_F$ is the Fermi wavevector and $l$ is the mean free path. While our Fermi liquid approach is not well controlled at high interaction, it has been proven to work at relatively large $r_s$ which substantiates its use in the high density, large conductance regime $k_F l > 1$. We therefore mostly show our theoretical results in the $k_F l > 1$ metallic regime except for the lowest density (dashed) curve in Fig. 3(a). We emphasize that by adjusting the charged impurity density and by including disorder effects in the screening function, it is possible to get reasonable quantitative agreement between our Boltzmann-Fermi liquid theory [Fig. 3(a)] and the experimental data (Fig. 2) even in the insulating low-density $k_F l < 1$ regime.

We show our calculated results in Fig. 3 for various hole densities. In our calculation the overall resistivity scale depends on the unknown charge impurity density, but the qualitative trends in $\rho(T, p)$ arise from basic aspects of the underlying scattering mechanism. Our calculated resistivity, Fig. 3(a), shows a non-monotonicity (as seen in Fig. 2 of the experimental data) where it increases with $T$ at first and then decreases with increasing T after going through a maximum at a density-dependent temperature $T_m$ where $d\rho/dT$ changes sign. This non-monotonicity is a non-asymptotic finite temperature “quantum-classical” crossover phenomenon, and arises from the competition between two contributions to transport [4], i.e. the temperature dependence of the dielectric screening function and the thermal averaging of the scattering rate. The screening effect decreasing with increasing temperature gives rise to increasing effective disorder with increasing $T$, and hence increasing $\rho(T)$ with $T$. Based on the Boltzmann theory, however, in the higher temperature classical non-degenerate regime the thermal averaging of the scattering rate becomes quantitatively more important and shows stronger temperature dependence than screening, which gives rise eventually to a $\rho(T)$ decreasing with $T$ for $T > T_m$. Thus, if the system is homogeneous and not strongly localized this crossover behavior appears in the transport measurements as can be seen in Fig. 2. We note that as the density is reduced significantly be-
Temperature dependence ($\rho$)

The calculated resistivities for p-GaAs quantum well system ($a = 200 \, \text{Å}$) for various hole densities $p = 0.4, 0.5, 0.6, 0.7, 0.9, 1.1 \times 10^{10} \, \text{cm}^{-2}$ (from the top) with linearly screened charge impurity scattering. (The dashed curve is in the $k_F l < 1$ regime.)

FIG. 3: (a) Calculated resistivities for p-GaAs quantum well system ($a = 200 \, \text{Å}$) for various hole densities $p = 0.4, 0.5, 0.6, 0.7, 0.9, 1.1 \times 10^{10} \, \text{cm}^{-2}$ (from the top) with linearly screened charge impurity scattering. (The dashed curve is in the $k_F l < 1$ regime.) (b) Calculated mobility as a function of hole density at $T=50 \, \text{mK}$. The dashed straight line indicates the $\mu \sim p^{0.7}$ behavior. We only show mobility in the $k_F l > 1$ regime.

We emphasize that the quantitative and qualitative discrepancies between the lowest density data of Fig. 4a and the calculation of Fig. 3b indicate that the screened charge impurity scattering. (The dashed line in (a) indicates the $\mu \sim p^{0.7}$ behavior.

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FIG. 4: (a) Mobility vs. density at fixed temperature $T=47 \, \text{mK}$. (b) Conductivity vs. density (solid squares) along with the fit generated assuming a percolation transition. The dashed line in (a) indicates the $\mu \sim p^{0.7}$ behavior.

FIG. 5: a) Variation of the derived critical density $p_c$ as a function of temperature. b) Variation of $\delta$ with temperature.

Screening properties of the system at low carrier density. We emphasize that the quantitative and qualitative discrepancies between the lowest density data of Fig. 4a and the calculation of Fig. 3b indicate that the screening theory which captures the essential experimental features at higher densities does not fully describe the transition to insulating behavior.

For high mobility n-type GaAs, Das Sarma et al. [11] interpreted the density driven crossover from metallic...
conductivity to an insulating regime as a percolation-type transition. The importance of interactions as parameterized by \( r_s \) for the MIT in GaAs remains an open question. In high mobility n-type 2D layers, the regime of \( r_s \sim 10 \) can be reached at low density. Due to the higher effective mass in our 2DHS, \( r_s \) reaches approximately 45 at low density in this study. It is an interesting question if a percolation type analysis can also be applied to our ultra high mobility 2DHS in the regime of large \( r_s \). We mention that there have also been various percolation analyses of 2D MIT in other n- and p-GaAs systems [14, 21] for low mobility (a factor of 10 lower than our mobility) systems where the temperature dependent metallic behavior is much weaker than what we see in our high-mobility system.

To describe the transition of the resistivity from metallic behavior to an apparent insulating behavior at lowest densities, we fit our data using a percolation transition model [22]. The physical motivation for a percolation transition is readily apparent. As the density of the 2DHS is reduced, the system can no longer fully screen the random disorder potential. The 2DHS breaks up into “puddles” of carriers isolated from one another by peaks in the disorder potential. Transport then takes place through percolating conduction paths in the disorder potential network. In the percolation model, the conductivity near the percolation threshold density is described by:

\[
\sigma(p) = A(p - p_c)^\delta
\]

where \( \sigma(p) \) is the density dependent conductivity, \( p_c \) is the critical density, and \( \delta \) is the critical exponent describing the transition. \( A \) is a constant of proportionality. The 2D percolation exponent is expected to be 1.31 [11, 21, 22]. The results of such an analysis applied to our sample is shown in Figure 4(b). The extracted exponent for our sample is \( \delta = 1.7 \pm 0.1 \) and the critical density \( p_c = 0.38 \times 10^{10} \text{cm}^{-2} \pm 0.01 \times 10^{10} \text{cm}^{-2} \). Formally, the preceding analysis is valid for \( (p - p_c) \ll p_c \). While the quality of the fit does not depend sensitively on the number of data points included, clearly the restriction \( (p - p_c) \ll p_c \) must be relaxed somewhat to make connection with the experimental data. Interestingly, the extracted conductivity parameters from the percolation analysis are consistent with known behavior of very high mobility n-type GaAs 2D systems as reported in ref. [11]. In particular, our extracted percolation exponent of 1.7 at \( T = 47 \text{mK} \) is almost identical with the corresponding exponent value at a somewhat higher temperature (\( \sim 100 - 200 \text{mK} \)) in ref. [11], which is consistent with equivalent values of the dimensionless temperature \( T/T_F \) for the two systems, where \( T_F \) is the Fermi temperature, and our critical density of \( 3 - 4 \times 10^9 \text{cm}^{-2} \) is consistent with the corresponding critical electron density in ref. [11]. The temperature dependences of the fit parameters are detailed in figure 5. To conclude, we find that the temperature dependence of the metallic phase is well-described by assuming the conductivity to be limited by temperature and density dependent screened charged impurity scattering whereas the apparent low-density (\( \sim 3.8 \times 10^9 \text{cm}^{-2} \)) transition from the metal to the insulating phase is well-described by a density-inhomogeneity driven percolation transition.

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