The Metallic-Like Conductivity of a Two-Dimensional Hole System

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We report on a zero magnetic field transport study of a two-dimensional, variable-density, hole system in GaAs. As the density is varied we observe, for the first time in GaAs-based materials, a crossover from an insulating behavior at low-densities, to a metallic-like behavior at high-density, where the metallic behavior is characterized by a large drop in the resistivity as the temperature is lowered. These results are in agreement with recent experiments on Si-based two-dimensional systems by Kravchenko \textit{et al.}[9] and others [10]. We show that, in the metallic region, the resistivity is dominated by an exponential temperature-dependence with a characteristic temperature which is proportional to the hole density, and appear to reach a constant value at lower temperatures.

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The study of the transport properties of two-dimensional electron systems (2DES's) revealed numerous unique features associated with their reduced dimensionality. A central question is whether a metal-insulator transition (MIT) can occur in two-dimensions (2D). Using scaling arguments Abrahams \textit{et al.} [6] stated that non-interacting electrons in 2D systems are localized at zero temperature ($T$) for any level of disorder, and a MIT is not expected to occur at zero magnetic-field ($B$).

This work motivated several experimental studies which investigated the $T$ dependence of the resistivity ($\rho$) of low-mobility 2DES in Si metal-oxide semiconductor field-effect transistors (MOSFET's) [7] and in In$_2$O$_3$-x films [8]. The resistivity was found to increase with decreasing $T$, and its $T$-dependence changed from weak to strong as the density of the 2DES was lowered, or the disorder increased. These experiments seemed to confirm the theoretical notion that no metallic phase exists in 2D.

However, several recent studies presented evidence to the contrary. In these studies 2DES's in Si MOSFET's [9] and Si/SiGe heterostructure [10] were used, and the resistivity was measured as a function of $T$ for various carrier-densities. These studies demonstrated a clear crossover from metallic to insulating behavior at low $T$.

Further, in the metallic region, the resistivity was shown to decrease with decreasing $T$ by as much as a factor of eight, while in the insulating region the resistivity increases sharply with decreasing $T$. The authors of refs. [9] took these results as evidence for the existence of a MIT in 2D, and several theoretical works have tried to associate them with modified scaling [10] or raised the possibility of superconductivity [11]. The disagreement between these new results and earlier ones are generally attributed to the higher mobility in these samples (reaching a value as high as 75,000 cm$^2$/V-s) and to the high effective mass of electrons in Si ($m = 0.19m_0$) which, according to the authors, combine to accentuate the effect of carrier-carrier interactions. It was therefore suggested [11] that due to the heavy mass of holes in GaAs (0.6$m_0$, 0.38$m_0$) [12,13] and the superior quality of molecular beam epitaxy (MBE) growth, a similar transition may appear in two-dimensional hole system (2DHS) embedded in GaAs heterostructures.

In this letter we report on a low-$T$, $B = 0$, study of high-quality 2DHS in GaAs that indeed exhibits such a transition. To facilitate this study we chose a p-type inverted semiconductor insulator semiconductor (ISIS) structure [14] grown on (311)A GaAs substrate [15] using Si as a p-type dopant [16]. A schematic layer-profile of the p-type ISIS structure used in this work is shown in the inset of Fig 1. In such ISIS device the carriers are accumulated in an undoped GaAs layer lying on top of an undoped AlAs barrier, grown over a $p^+$ conducting layer. This $p^+$ conducting layer is separately contacted and serves as a back-gate. The hole carrier-density ($p$) can be easily varied by applying voltage ($V_g$) to the back-gate resulting in a change in $p$ of $1.1\cdot10^{11}$ cm$^{-2}$V$^{-1}$, which is consistent with a capacitively induced charge-transfer. The carrier density was determined by direct measurement of the Hall effect. At $T = 50$ mK our samples have a mobility of $150,000$ cm$^2$/V-s at $p = 6.4\cdot10^{11}$ cm$^{-2}$. The high limit of the density in this study was set by gate leakage. The samples were wet-etched to the shape of a standard Hall-bar and Zn-Au evaporated contacts were carefully alloyed at 370$^\circ$C to avoid penetration of the alloyed metal into the $p^+$ buffer layer.

One handy advantage of the ISIS structure is that it offers the capability to vary the carrier density continuously over a very wide range, in a similar fashion to Si MOSFET's. We utilize this flexibility to study the $T$-dependence of $\rho$ at a number of densities from the insulating phase to the high-$p$ conducting state. Measurements were done in a dilution refrigerator with a base $T$ of 40 mK, using AC lock-in technique with an excitation current of 0.1 nA. We repeated the measurements with higher excitation current and no effect of heating was found. The collection of the data was done by fixing the density and sweeping $T$ continuously between our base $T$ and 1.2 K. The data were reproducible upon numerous cycles of $V_g$ and $T$. 

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Typical results, obtained from sample H315J, are presented in Fig. 1, where we plot \( \rho \) vs. \( T \) at various values of \( p \) between 0.089-10^{-11} \text{ and } 0.64-10^{11} \text{ cm}^{-2}. \) It is possible to crudely classify the traces in Fig. 1 into three distinct regimes. The first is the low-\( p \) regime (top set of solid lines), characterized by insulating behavior, with \( \rho(T) \) decreasing rapidly with \( T \). In the second regime (dashed curves), a mixed behavior is observed at our \( T \)-range, with insulating-like \( \rho(T) \) at high-\( T \), turning over to metallic-like behavior at lower \( T \)-s. Although quite interesting, we defer discussion of these two regimes to a future publication, and center our attention on the high-\( p \) region, where the \( \rho(T) \) traces exhibit metallic-like behavior characterized by \( \rho \) that drops precipitously as \( T \) is lowered, followed by an apparent saturation of \( \rho(T) \) at yet lower \( T \)-s.

The results presented in Fig. 1 are very similar to those of Kravchenko et al. and others, a notable fact considering that we are dealing with two distinct materials. Incidentally, this similarity rules out explanations of the traces in Fig. 1 into three regimes. The first is the low-\( T \) range, with insulating-like \( \rho \)-vs.-\( 1/T \) at high-\( T \), and with metallic-like behavior at lower \( T \)-s. Although quite interesting, we defer discussion of these two regimes to a future publication, and center our attention on the high-\( p \) region, where the \( \rho(T) \) traces exhibit metallic-like behavior characterized by \( \rho \) that drops precipitously as \( T \) is lowered, followed by an apparent saturation of \( \rho(T) \) at yet lower \( T \)-s.

The results presented in Fig. 1 are very similar to those of Kravchenko et al. and others, a notable fact considering that we are dealing with two distinct materials. Incidentally, this similarity rules out explanations of the additional terms in \( \rho(T) \) with relatively weak (logarithmic) \( T \)-dependence. Moreover, the existence of the exponential term in \( \rho \) will effectively mask any possible \( T \)-dependence of \( \rho \) as long as \( T \) is not much smaller than \( T_0 \).

More relevant to the determination of the quantum nature of the transport is the low-\( T \) range. Following Eq. 1 \( \rho \) seems to approach a constant, \( \rho_0 \). We note that this apparent saturation is not likely to be caused by heating since, at the same \( T \)-range, lower-\( p \) traces (Fig. 1), where the dissipation induced by the constant probing-current is more than 10 times larger, are distinctly \( T \)-dependent. At face value, a finite \( \rho_0 \) may indicate a true metallic zero \( T \) behavior. We stress that this is not necessarily the case for finite-size samples, a fact that had been previously recognized regarding high-mobility 2DES’s. Furthermore, due to the limited accuracy of our measurements, we are unable to exclude the existence of additional terms in \( \rho(T) \) with relatively weak (logarithmic) \( T \)-dependence. Moreover, the existence of the exponential term in \( \rho \) will effectively mask any possible \( T \)-dependence of \( \rho \) as long as \( T \) is not much smaller than \( T_0 \).

Between these two extremes of Eq. 1, a remarkable behavior is observed. In this intermediate \( T \)-range, the second term of Eq. 1 dominates and \( \rho \) is exponentially increasing with \( T \). To further emphasize this behavior we plot, in Fig. 3, \( \rho - \rho_0 \) vs. \( 1/T \) using an Arrhenius plot, for the data of Fig. 2. A clear exponential dependence is seen which covers over 2 orders of magnitude in \( \rho \). It is this exponential behavior which underlies the abrupt drop in \( \rho \) seen in Figs. 1 and 2.

Clearly, the physical origin of \( T_0 \) is one of the main issues that need to be addressed. We therefore plot, in Fig. 4, the characteristic \( T \) of the conduction process, \( T_0 \), as a function of \( p \) for our sample. \( T_0 \) increases monotonically with \( p \) and reaches 0.78 K for our highest \( p \). With the limited accuracy of these measurements we are unable to determine the functional dependence of \( T_0 \) on \( p \), although a linear dependence is reasonable. We note that from the linear fit \( T_0 \) extrapolates to \( T_0=0 \) as \( p \) approaches zero. This implies that the exponential \( T \)-dependence of \( \rho \) persists to \( p=0 \). In reality it is overcome by the insulating behavior that sets-in at low-\( p \).

At present, we do not have a theoretical understanding of the physics which underlies this intriguing regime. We note that this behavior reveals itself under the condition of low \( E_F \), where carrier-carrier interactions should play a more significant role in the dynamics of the system. This may explain why in systems with lower \( r_s \), such as 2DEG in GaAs, no analogous behavior is observed. The observation of an exponential term in \( \rho \) may be taken as evidence for the existence of an energy gap, which inhibits scattering at low \( T \). Pudalov suggested a spin-orbit gap as the origin of \( T_0 \), but, as he stated, this gap is likely to be too small in GaAs.
To summarize, we used a p-type ISIS to investigate the $T$-dependence of the resistivity of two-dimensional hole gas in GaAs. We observed a transition from metallic to insulating behavior at low $T$’s. The results in this letter are similar to other experiments facilitating different 2D systems. We have shown that the resistivity at the metallic phase is determined by two terms. The first appears to be independent on $T$, while the second factor has a rather surprising, exponential, dependence on $T_0/T$ and $T_0$ increases monotonically with $p$. We emphasize that much lower $T$’s are needed to safely determine the ultimate low-$T$ phase of the system.

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[1] S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D’Iorio, Phys. Rev. B 50, 8039 (1994); S. V. Kravchenko, W. Mason, G. E. Bowker, J. E. Furneaux, V. M. Pudalov, and M. D’Iorio, Phys. Rev. B 51, 7038 (1995); S. V. Kravchenko, D. Simonian, M. P. Sarachik, W. Mason, and J. E. Furneaux, Phys. Rev. Lett. 77, 4938 (1996).
[2] D. Popovic, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. 79, 1543 (1997).
[3] K. Ismail, J.O. Chu, Dragana Popovic, A.B. Fowler, and S. Washburn, preprint cond-mat/9707061 (1997).
[4] P.T. Coleridge, R.L. Williams, Y. Feng, and P. Zawadzki, preprint cond-mat/9708118 (1997).
[5] J. Lam, M. D’Iorio, D. Brown and H. Lafontaine, preprint cond-mat/9709201 (1997).
[6] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).
[7] D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. 44, 5737 (1980).
[8] M. J Uren, R. A. Davies, M. Kaveh, and M. Pepper, J. Phys. C. 14, 5737 (1981).
[9] Z. Ovadyahu, and Y. Imry, J. Phys. C16, L471 (1983).
[10] V. Dobrosavljevic, Elihu Abrahams, E. Miranda, and Sudip Chakravarty, Phys. Rev. Lett. 79, 455 (1997).
[11] P. Phillips and Y. Wan, preprint cond-mat/9704209 (1997).
[12] D. Belitz, T. R. Kirkpatrick, cond-mat/9705023 (1997).
[13] S. V. Kravchenko (private communication).
[14] H. L. Stormer, Z. Schlesinger, A. Chang, D. C. Tsui, A. C. Gossard, and W. Wigmann, Phys. Rev. Lett. 51, 126 (1983).
[15] K. Hirakawa, Y. Zhao, M. B. Santos, M. Shayegan, and D. C. Tsui, Phys. Rev. B. 47, 4076 (1993).
[16] U. Meirav, M. Heiblum, and F. Stern, Appl. Phys. Lett. 52, 1268 (1988).
[17] Y. Hanein, H. Shtrikman, and U. Meirav, Appl. Phys. Lett. 70, 1426 (1997).
[18] L. Pavesi, M. Henini, and D. Johnston, Appl. Phys. Lett. 66, 2846 (1985).
[19] V. M. Pudalov, preprint cond-mat/9707076 (1997).
[20] A. J. Dahm, F.W. Van Keuls, H. Mathur, and H. W. Jiang, Proc. Intern. Conf. on Electron Localization and Quantum Transport in Solids, Jaszowicz, Poland, 1996. (Ed. by T.Dietel), Inst. of Physics PAN, Warsaw (1996).
Fig 1.
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Fig 2.
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The graph shows the relationship between resistivity ($\rho$) and temperature ($T$) with two sets of data points and a fit line. The fit line has an equation of $p = 0.296$ and $p = 0.64$. The data points are indicated by arrows on the graph.
Fig 3.
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Fig 4. Hanein et al.