Novel Properties of The Apparent Metal-Insulator Transition in Two-Dimensional Systems

Y. Hanein\textsuperscript{1,2}, D. Shahar\textsuperscript{1,2}, J. Yoon\textsuperscript{2}, C.C. Li\textsuperscript{2}, D.C. Tsui\textsuperscript{2} and Hadas Shtrikman\textsuperscript{1}

\textsuperscript{1} Dept. of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel
\textsuperscript{2} Dept. of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

The low-temperature conductivity of low-density, high-mobility, two-dimensional hole systems in GaAs was studied. We explicitly show that the metal-insulator transition, observed in these systems, is characterized by a well-defined critical density, $p_0$. We also observe that the low-temperature conductivity of these systems depends linearly on the hole density, over a wide density range. The high-density linear conductivity extrapolates to zero at a density close to the critical density.

$\rho(T) = \rho_0 + \rho_1 \exp \left( -\frac{T_0}{T} \right)$

with a characteristic temperature $T_0$, which is proportional to the hole-density ($\rho$). At very low $T$ ($T << T_0$), where the exponential term of Eq. \ref{eq:1} becomes negligible, $\rho(T)$ saturates. While the exponential term of $\rho$ is responsible for the dramatic nature of $\rho$ we will focus in this letter on the saturation value, $\rho_0$ (or $\sigma_0 = 1/\rho_0$), which appears to be more relevant to the ultimate low-$T$ behavior. Instead of analyzing $\rho$, we chose to use $\sigma = 1/\rho$. They are, of course, equivalent but the use of $\sigma$ allowed for an observation of a surprising linear dependence of $\sigma$ on $p$, which is the main finding of this work.

We begin the presentation of our results by pointing out the existence of a MIT in one of our high mobility (\mu), $p$-type, inverted semiconductor insulator semiconductor (ISIS) sample \cite{14,15}. Measurements were done in a dilution refrigerator with base $T$ of 35 mK using a standard lock-in technique. Instead of plotting $\rho$ versus $T$ at various $p$'s we plot, in Fig. 1, isotherms of $\sigma$ versus $p$, at several $T$’s between 57 and 840 mK. At the high-$p$ range, $\sigma$ decreases with $T$ corresponding to a positive TCR. At the low-$p$ end, seen in detail in the inset of Fig. 1, $\sigma$ increases with $T$, and the TCR is negative. In the spirit of previous studies, this sign change of TCR identifies a crossover from an insulating behavior at low-density, to a metallic-like behavior at high-density.

Having established the MIT in our system, we now address the low-$T$ behavior of $\sigma$. As can be seen in Fig. 1, above $\sigma \cong 4e^2/h$, the lower $T$ traces overlap indicating the saturation of $\sigma$ at low $T$’s. Therefore for $\sigma \geq 4e^2/h$, we can regard the 57 mK trace as a good representation
of $\sigma_0$. Focusing on this curve, a linear dependence of $\sigma_0$ on $p$ is observed and $\sigma_0$ can be described by (dashed line)

$$\sigma_0 = \alpha (p - p_0^c)$$

(2)

where $\alpha$ is the linear slope and $p_0^c$ is the density in which the linear fit of $\sigma_0$ extrapolates to zero. This description breaks down for $\sigma < 3e^2/h$, as we approach the transition region. For a set of samples with mobilities varying between 26,000 and 220,000 cm$^2/V$-sec, $\alpha$ changes from 1.8·10$^{-10}$ to 11·10$^{-10}$ e$^2$/h cm$^2$.

To establish the generality of the linear $\sigma_0(p)$ result we show, in Fig. 2, similar data for other 2DHS samples. In Fig. 2a and 2b we show $\sigma$ versus $p$ of a high and low-$\mu$ ISIS structures, respectively, and in Fig. 2c we depict similar data obtained from a 2DHS formed in a 10 nm symmetrically doped quantum well. Indeed, all these samples exhibit a linear $\sigma_0(p)$ dependence, which holds to high values of $\sigma$. It is worthwhile mentioning that $p$ in our samples is obtained directly from a measurement of the Hall effect and is linear with the applied gate bias, consistent with a capacitively induced charge-transfer.

The linear $\sigma$ by itself may not have been too surprising, as it is a natural result of the Drude model, $\sigma = ne^2\tau/m^*$, where $n$ is the carrier density, $e$ is the electron charge, $\tau$ is the elastic scattering time and $m^*$ is the carrier effective mass. However, in our data, $\sigma_0$ (see Eq. 2) does not extrapolate to zero at $p = 0$, but has an offset, $p_0^c$, of unclear origin. We will show below that $p_0^c$ is equal, within experimental uncertainty, to the critical point of the MIT.

To determine the critical point of the MIT, we use the vanishing-TCR criterion discussed before. Inspecting the inset of Fig. 1, we see that each two consecutive isotherms of $\sigma(p)$ cross each other at some value of $p$ ($p^c$). Since at these points the TCR=0, a natural tendency is to identify them as transition points between the metallic and the insulating phases. Accepting this point of view leads to a possible conflict as these TCR=0 points are clearly $T$ dependent, and an unambiguous determination of the transition is therefore impossible. Fortunately, at the lower $T$ range typically below 150 mK, the crossing point appears to be independent of $T$. This can be seen more readily in Fig. 3, where only low-$T$ traces from Fig. 1 are presented. A $T$-independent crossing point, marked by an arrow in Fig. 3, emerges at a well-defined $p$ ($p_0^c$), which clearly separates the conducting and insulating phases. Another way of seeing the settling of $p^c$ is by plotting it as function of averaged $T$ of each two consecutive curves, as we do in the inset of Fig. 3. Here, $p^c(T)$ decreases monotonically with $T$ for $T$'s above 150 mK, but for lower $T$'s $p^c$ appears to saturate to its final value $p_0^c$.

Based on the results presented above we can safely argue the following three points. First, at low enough $p$, $p << p_0^c$, the system is insulating with a vanishingly small $\sigma_0$. Second, for $p > p_0^c$, metallic-like $\sigma$ is observed down to our lowest $T$. And third, a fixed transition-point does exist, and its $p$-value can be identified. Having identified a low-$T$ transition point, it is tempting to associate it with a MIT. But before we explore the interesting consequences of this association we wish to alert the reader to a serious caveat that must be born in mind: For $p$ values close to $p_0^c$ the saturation is not as clear and an unambiguous determination of the phases is impossible. This is an unavoidable difficulty common to all phase transitions, and is not particular to the transition at hand. Further, for the MIT in three-dimensions (3D), the sign of the TCR is certainly not a good indication of the phases, and metallic samples can exhibit negative TCR [16,17]. Nevertheless, it is still possible that the 2D MIT will be different in that respect. With these reservations kept in mind we will proceed with our discussion assuming that the low-$T$ fixed point is indeed the MIT.

The first interesting question is the $\rho$ value of the transition point, $\rho_c$, and whether it is universal. For the three different samples for which we were able to reliably extract $\rho_c$, it occurs at $\sigma_0$ 0.83, 0.9, and 1.58 e$^2$/h, which is close to the Yoffe Regel criterion, $k_F \cdot l = 1$. This result is similar to the universality found in the diagonal $\rho$ for the quantum Hall liquid to Hall insulator transition [18]. This result as well as the observation of a fixed transition point may indicate the existence of minimum metallic conductivity in 2D.

If we now focus on the extrapolation of the linear fit of $\sigma_0$ to $\sigma_0 = 0$, denoted in Fig. 3 by a dashed line, we can clearly see that $p_0^c$ is close to $p_0^c$, the low-$T$ crossing point. The fascinating consequence of this result is that the MIT can be identified by an extrapolation from $\sigma_0 > 40e^2/h$, much larger than $\sigma_0$ at the transition itself. To further characterize $p_0^c$ (recall that $p_0^c \approx p_0^c$), we plot, in Fig. 4, $p_0^c$ for different samples as a function of their mobilities at $p = 5 \cdot 10^{10}$ cm$^{-2}$. While $\mu$ changes from 220,000 to 26,000 cm$^2$/V-sec, the transition point changes from 0.67 to 2·10 cm$^{-2}$. Namely, higher mobility samples remain conducting until lower values of $p$. An important consequence of this result lies in the relation between the density and the effective strength of the carrier-carrier interaction $r_s$ ($r_s \equiv k_F^2 \rho_e \propto 1/\mu$). The dependence of $p_0^c$ on $\mu$ indicates that, while the strong interactions in these samples are important to the observation of the transition, the disorder still plays a significant role, at least in determining the $r_s$ value where the transition takes place.

The $\sigma_0$ of Eq. 2 is suggestive of a two-component model where a portion of the carriers, $\rho_0^c$, contributes only to the Hall voltage and not to the longitudinal resistivity. These carriers may be in a Hall insulator state which is characterized by a vanishing $\sigma$ and a Hall resistivity close to its classical value. We note that all samples used in this study are characterized by very large separation (> 150 nm) between the conducting channel and
any intentional doping. This large separation minimizes the scattering from ionized dopants.

To summarize, we used various samples to investigate the density dependence of $\sigma$ of 2DHS’s in GaAs. We provided evidence that, at low-$T$, $\sigma$ changes from metallic-like to insulating at a well-defined $p$ value, $(p_0^c)$. If identified correctly as the MIT, $p_0^c$ may describe a point of minimum metallic conductivity with a value close to $e^2/h$. We see that for all of our samples, above a critical value of density, the low-$T$ conductivity has a linear dependence on density. The density in which the linear fit of $\sigma_0$ extrapolates to zero is finite $(p_0^c)$. We show that the value of $p_0^c$ scales with the high-$p$ mobility of the 2D system. We find that $p_0^c \sim p_0^c$. These results suggest that the transition as well as the physics near it are related to the physics far away from the transition.

This work was supported by the NSF and by a grant from the Israeli Ministry of Science and The Arts.

[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).
[2] 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).
[3] A.M. Finkel’stein, Zh. Eksp. Teor. Fiz. 84, 168 (1983) [JETP 57, 97 (1983)].
[4] V. Dobrosavljevic, Elihu Abrahams, E. Miranda, and Sudip Chakravarty, Phys. Rev. Lett. 79, 455 (1997).
[5] D. Belitz, T. R. Kirkpatrick, cond-mat/9705023 (1997).
[6] P. Phillips, Y. Wan, I. Martin, S. Knysh, D. Daldovich, cond-mat/9709168 (1998)
[7] N.F. Mott, Phil. Mag. 26, 1015 (1972).
[8] V. M. Pudalov, JETP Lett. 66, 175 (1997).
[9] D. Popovic, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. 79, 1543 (1997).
[10] P.T. Coleridge, R.L. Williams, Y. Feng, and P. Zawadzki, Phys. Rev. B 56, 12764 (1997).
[11] Y. Hanein, U. Meirav, D. Shahar, C.C. Li, D.C. Tsui, and H. Shtrikman, Phys. Rev. Lett. 80, 1288 (1998).
[12] M.Y. Simmons, A.R. Hamilton, M. Pepper, E.H. Linfield, P.D. Rose, and D.A. Ritcie, Phys. Rev. Lett. 80, 1288 (1998).
[13] S. J. Papadakis, and M. Shayegan, To be published in Phys. Rev. B.
[14] U. Meirav, M. Heiblum, and F. Stern, Appl. Phys. Lett. 52, 1268 (1988).
[15] Y. Hanein, H. Shtrikman, and U. Meirav, Appl. Phys. Lett. 70, 1426 (1997).
[16] B. W. Dodson, W. L. McMillan, J. M. Mochel, and R. C. Dynes, Phys. Rev. Lett. 46, 46 (1981).
$\sigma (e^2/h)$

$p \left( 10^{10} \text{ cm}^{-2} \right)$

$T=57 \text{ mK}$

$T=839 \text{ mK}$

H315JA
\[ \sigma \left( \frac{e^2}{h} \right) \]

\[ p \left( 10^{10} \text{ cm}^{-2} \right) \]

\[ T = 57 \text{ mK} \]

\[ T = 138 \text{ mK} \]

H315JA
\[ P_0^e \text{ (cm}^2\text{)} \]

\[ \mu \text{ (cm}^2\text{/Vsec)} \]