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Properties of the apparent metal-insulator transition in two-dimensional systems

Y. Hanein and D. Shahar
Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel
and Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

J. Yoon, C. C. Li, and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

Hadas Shtrikman
Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel

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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^c. 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. [S0163-1829(98)50536-X]

The development of the scaling theory of localization[1] contributed a great deal to the understanding of the transport properties of electron systems. For the case of two-dimensional (2D) systems this theory, which neglects carrier-carrier interactions, predicts that the electrons are always localized at zero temperature (T). This theory stood until, Kravchenko *et al.*[2] presented experimental evidence supporting the existence of a metal-insulator transition (MIT) in 2D. The presence of strong electron-electron interactions[3–6] was proposed to account for the discrepancy between these results and the noninteracting theory.[1] This discrepancy implies the possible revival of other concepts that were abandoned following the successes of the scaling theory of localization. One such concept is that of minimum metallic conductivity, introduced by Mott,[7] suggesting that metallic systems can only have a conductivity (σ) higher than a minimal value, $\sigma > \sigma_{min}$. By exploring, in this communication, the low-T conductivity characteristics of the apparent MIT in 2D, we show that it is consistent with the existence of a minimum metallic conductivity. In several samples, σ_{min} is close to e^2/h.

At the absolute zero of temperature the fingerprint of an insulator is a diverging resistivity (ρ) while that of a metal is a ρ that reaches a constant value. At finite T's however, all materials (except superconductors) have a finite ρ. Consequently, in order to distinguish between insulating and metallic phases in experimental situations, one has to rely primarily on the extrapolation of the measured ρ to $T=0$. The temperature coefficient of resistivity (TCR), defined as $\mathrm{TCR}=d\rho/dT$, can be used to determine whether the extrapolated value of ρ is likely to be infinite or finite, and therefore the sign of the TCR is commonly taken to differentiate between insulating and metallic phases. Namely, we label a state as insulator if it has a negative TCR (ρ appears to diverge as $T\rightarrow 0$) and a metal if it has a positive, or zero TCR (ρ extrapolates to a finite value at $T=0$). A change of the TCR from positive to negative as the density was lowered was observed by all researchers of Refs. 2, 8–13 for various 2D systems, and was considered indicative of a MIT. Although simple and convenient, this procedure is not unambiguous, and we shall stress the difficulties associated with it below.

Attempts to characterize the new metallic state revealed[11,8] that the metallicke resistivity of high-mobility two-dimensional hole system (2DHS) in GaAs, and of electrons in Si MOSFET's, is dominated by an exponential T dependence and follows

$$\rho(T)=\rho_0+\rho_1\exp\left(-\frac{T_0}{T}\right) \tag{1}$$

with a characteristic temperature T_0, which is proportional to the hole density (p). At very low T ($T \ll T_0$), where the exponential term of Eq. (1) becomes negligible, $\rho(T)$ saturates. While the exponential term of ρ is responsible for the dramatic nature of ρ we will focus in this letter on the saturation value, ρ_0 (or $\sigma_0=1/\rho_0$), which appears to be more relevant to the ultimate low-T behavior. Instead of analyzing ρ, we chose to use $\sigma=1/\rho$. They are, of course, equivalent but the use of σ allowed for an observation of a surprising linear dependence of σ 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 (μ), p-type, inverted semiconductor insulator semiconductor (ISIS) samples.[14,15] Measurements were done in a dilution refrigerator with base T of 35 mK using a standard lock-in technique. Instead of plotting ρ versus T at various p's we plot, in Fig. 1, isotherms of σ versus p, at several T's between 57 and 840 mK. At the high-p range, σ decreases with T corresponding to a positive TCR. At the low-p end, seen in detail in the inset of Fig. 1, σ 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 metalliclike behavior at high density.

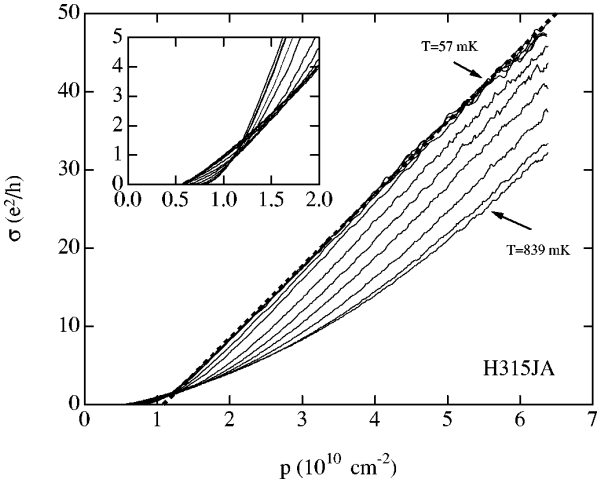

FIG. 1. σ versus p of a high-μ p-type ISIS sample at various fixed T's, $T=57$, 69, 71, 104, 138, 226, 308, 405, 571, 740, 839 mK. The dashed line is the fit of the 57 mK data to $\sigma=\alpha(p-p_0^e)$. The inset shows a focus on the low density range of the data shown in Fig. 1.

Having established the MIT in our system, we now address the low-T behavior of σ. As can be seen in Fig. 1, above $\sigma\cong 4e^2/h$, the lower T traces overlap indicating the saturation of σ at low T's. Therefore for $\sigma\geqslant 4e^2/h$, we can regard the 57 mK trace as a good representation of σ_0. Focusing on this curve, a linear dependence of σ_0 on p is observed and σ_0 can be described by (dashed line)

$$\sigma_0=\alpha(p-p_0^e) \tag{2}$$

where α is the linear slope and p_0^e is the density in which the linear fit of σ_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, α changes from 1.8×10^{-10} to $11\times10^{-10}e^2/h$ 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 Figs. 2(a) and 2(b) we show σ versus p of high- and low-μ ISIS structures, respectively, and in Fig. 2(c) 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 σ. 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 σ 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, τ is the elastic scattering time and m^* is the carrier effective mass. However, in our data, σ_0 [see Eq. (2)] does not extrapolate to zero at $p=0$, but has an offset, p_0^e, of unclear origin. We will show below that p_0^e 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

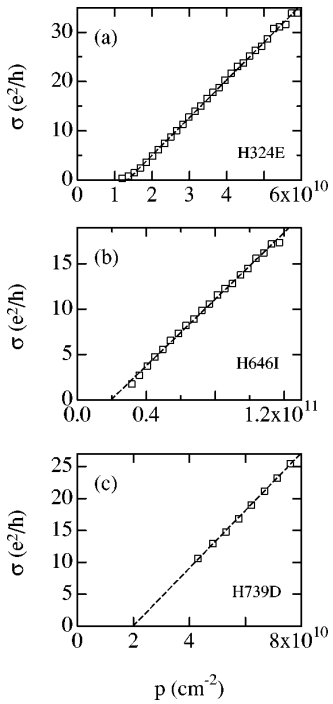

FIG. 2. (a) σ versus p of a high-μ ($\mu=134\,000$ cm^2/V sec at $p=5\times10^{10}$ cm^{-2}), p-type ISIS at $T=50$ mK. (b) σ versus p of low-μ ($\mu=26\,000$ cm^2/V sec at $p=5\times10^{10}$ cm^{-2}), p-type ISIS at $T=48$ mK. (c) σ of 2DHS formed in a 10 nm thick symmetrically doped quantum well versus p at $T=35$ mK ($\mu=65\,000$ cm^2/V sec at $p=5\times10^{10}$ cm^{-2}).

points the TCR$=0$, a natural tendency would be 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,

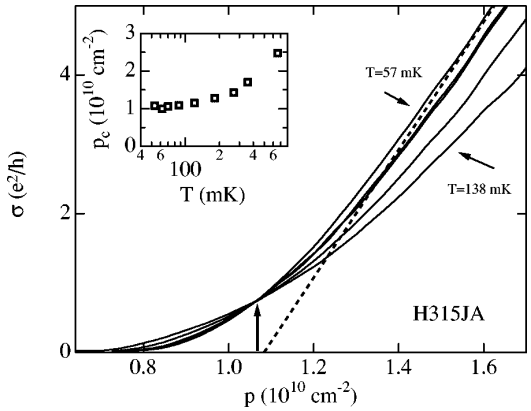

FIG. 3. Focus on the low density range of the data shown in Fig. 1, only low T's are shown, $T=57$, 69, 71, 104, 138 mK. The dashed line is the extrapolation of the fit of the high-p data to $\sigma=\alpha(p-p_0^e)$. The arrow marks the low T crossing point, p_0^c. The inset shows the crossing point between each two consecutive isotherms of $\sigma(p)$, plotted versus the averaged T of each two curves.

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 $p, p \ll p_0^c$, the system is insulating with a vanishingly small σ_0. Second, for $p > p_0^c$, metallic-like σ 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 ρ value of the transition point, ρ_c, and whether it is universal. For the three different samples for which we were able to reliably extract ρ_c, it occurs at σ_0 0.83, 0.9, and $1.58e^2/h$, which is close to the Yoffe Regel criterion, $k_F \times l = 1$. This result is similar to the universality found in the diagonal ρ 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 σ_0 to $\sigma_0 = 0$, denoted in Fig. 3 by a dashed line, we can clearly see that p_0^e 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 σ_0 at the transition itself. To further characterize p_0^e (recall that $p_0^e \approx p_0^c$), we plot, in Fig. 4, p_0^e for different samples as a function of their mobilities at $p = 5 \times 10^{10}$ cm^{-2}. While μ 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 [$r_s \equiv (U/E_F) \propto (1/\sqrt{p})$]. The dependence of p_0^e on μ 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.

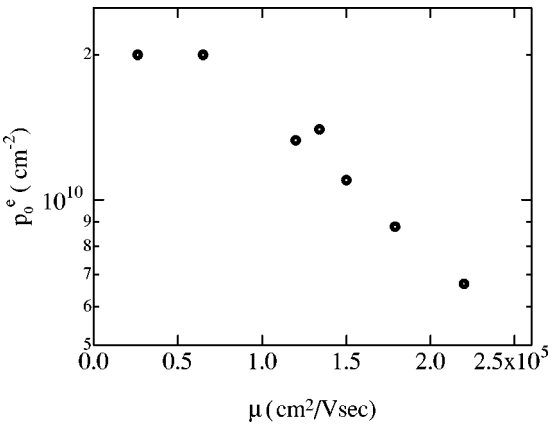

FIG. 4. The critical density, p_0^e, vs μ (at $p = 5 \times 10^{10}$ cm^{-2}) for various 2DHS samples. p_0^e appears to decrease monotonically with μ.

The σ_0 of Eq. (2) is suggestive of a two-component model where a portion of the carriers, p_0^e, 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 σ 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.[19]

To summarize, we used various samples to investigate the density dependence of σ of 2DHS's in GaAs. We provided evidence that, at low-T, σ changes from metalliclike 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 σ_0 extrapolates to zero is finite (p_0^e). We show that the value of p_0^e scales with the high-p mobility of the 2D system. We find that $p_0^e \sim p_0^c$. These results suggest that the transition as well as the physics near it are related to the physics far away from the transition.

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