I. INTRODUCTION

Landauer’s early work on scattering of particles and waves in random media [2] is still important today, because after decades of work, the physics of transport in disordered systems is still keeping us entertained with unexpected results. The generic “conductivity” that arises from ham-handedly averaging microscopic details and sweeping Coulomb interactions under the rug of effective mass is a poor description of transport in many circumstances. In the past two decades there have been several discoveries in experiments (much of it spurred or explained theoretically by Landauer and his co-workers) that have flown dramatically in the face of the classical conductivity. Response from quantum mechanically phase-coherent carrier excitations have appeared in studies of metals and semiconductors in both the relatively clean and very dirty limits of impurity scattering. In high magnetic fields the re-writing of Ohm’s law has been especially dramatic. Noise from fluctuations in the transport parameters have behaved in ways that contradict the simple models that lead to the generic resistivity. Finally, Coulomb interactions are appearing as large perturbations of the non-interacting carrier models that have dominated thinking for two decades.

Since the appearance of the scaling theory for non-interacting (Fermi-liquid) particles [3], most have accepted the result that there is no minimum metallic conductivity in three dimensions (3D) and no metallic behavior at all in two dimensions (2D). The non-interacting models were developed in terms of a scaling function

$$\beta = \frac{d \ln g}{d \ln L} \quad (1)$$

to hold: $g \propto L^{-2d}$ for cubes of dimension $d$. In weak disorder, perturbative calculations from non-interacting models of carrier transport lead to reduction of $\beta$ indicating a (perfectly plausible) trend toward lower conductance and eventually to an insulator as the amount of disorder increased (illustrated in figure 1). According to this picture, a 3D system is a conductor if the Fermi energy $E_F$ is larger than the characteristic amplitude of the disorder potential $W$. This criterion is equivalent to the Ioffe-Regel criterion that $k_F l > 1$, where $k_F$ is the Fermi wave-number and $l$ is the mean free path. In 2D, there is no metallic behavior for any value of $W \neq 0$. That is, the proposed 2D scaling function $\beta < 0$. Both proclamations are reasonable at first glance, but in both cases the Coulomb interactions among the carriers have largely been swept beneath the rug of effective mass and (often ignored) Fermi liquid parameters. Subsequent work, however, has brought to question the validity of these simple ideas. In particular, the absence of a MIT in 2D has been disputed by Finkelstein [4], who has emphasized that corrections from interacting particles become important as $T = 0$ is approached. These and more recent [5] considerations of interacting systems, have sug-
suggested that $\beta$ can change sign for $d = 2$, i.e. that there can exist a 2D MIT.

In fact, a wide variety of two-dimensional systems exhibit transitions like the MIT. Kosterlitz-Thouless-Berenshinskii transitions in 2D superfluids is an old example. There are more recent examples of proper conductor-insulator transitions in two-dimensional electric transport problems. Granular films of superconducting materials exhibit a transition from insulator to superconductor as the film thickness increases $L$. The transition is driven by the superconducting fluctuations in competition with the Coulomb (charging) interactions between the grains of material $L$. Oxide superconductors, the 2D sheets of oxygen atoms lead to a highly directional order parameter and, depending on doping level, exhibit a superconductor to insulator transition somewhat like that in granular films. Between plateaux in the quantized Hall effect, which demands very high magnetic field $B$ such that the Landau energy $h\omega_c \gg E_F$, there is another 2D MIT manifest as a reversal of the temperature coefficient of the resistivity $\rho$. All of these examples appear in rather exotic circumstances (Landau quantization or Cooper pairing), but there is a manifestation of a 2D MIT in garden-variety conductors and that transition is the subject of the present work.

In generic silicon metal-oxide-semiconductor field-effect transistors (MOSFETs), which comprise strictly 2D electrons (or holes) between reservoirs of 3D carriers, there is a MIT for MOSFETs with sufficiently low disorder and high carrier mobility $L$. In the MOSFETs, the transition occurs among normal (non-superconducting) carriers at zero magnetic field. The transition occurs at relatively low electron densities $n_s$ of the order of $1 \times 10^{15}/m^2$, where the Coulomb energy $(U \sim \sqrt{n_s})$ is larger than $E_F$.

Clear signatures of the 2D MIT have been observed at $B = 0$ in generic 2DES as a reversal of the sign of the temperature coefficient of conductance as the carrier density crosses through some critical value $n_c$: $dG(T)/dT$ changes from positive to negative. The same signature is found in a variety of materials including electrons in Si-MOSFETs, holes in GaAs/AlGaAs heterostructures, holes in SiGe/Si heterostructures, and electrons in Si/SiGe.

For all versions of the 2D MIT, a scaling of the resistivity data against a control parameter can be accomplished in a form that directly follows from standard scaling considerations. In earlier work, this scaling form has been employed to explain the superconductor-insulator transition in granular metal films. Written in the form appropriate to describe the MOSFET experiment (where the control parameter is $n_s$), the scaling equation is

$$\rho(T, n_s) = f(\delta_n/T^{1/\nu}) = \rho(T/T_0),$$

where $\delta_n = (n_s - n_c)/n_c$ is a distance from the transition and $\nu$ and $z$ are exponents associated with the scaling of a microscopic correlation length $\xi$, which measures the regions over which the quantum interactions are effective $\sim \xi$. $\phi$ is related to the phase coherence length $L_\phi$. In the vicinity of the MIT, the correlation length is assumed to scale to infinity as $\xi = 1/|\delta_n|^{\nu}$. Note that standard scaling arguments are typically formulated in terms of the scale dependence of the conductance at $T = 0$. It is clear that the $T = 0$ limit of the theoretical models is a poor approximation to any experiment, since it assumes that the coherence length for the carrier excitations is infinite. As first emphasized by Thouless, this assumption is false at any finite temperature; more recent arguments question its validity even at $T = 0$. The predicted $\beta$ can be related to more useful observables, by noting that the effective sample size for quantum interactions and interferences is not the patterned sample size but the length-scale $L_\phi$ on which carriers retain phase coherence or phase memory. For most systems, this characteristic thermal length scales as a power of the temperature, viz. $L_\phi \propto 1/T^{1/z}$, where $z$ is the so-called dynamical exponent (in “weak localization” parlance). In this way, the scaling function in the length “domain” can be converted to $\beta_F = -d(\ln g)/d(\ln T)$ in the T “domain” $L_\phi$. We emphasize that if the sample size $L < L_\phi$, then temperature dependence may be “short-circuited” by the finite size effects as illustrated in figure 2.

The use of the quantum phase transition models to explain the 2D MIT carries a certain baggage with it. Such models are generally accepted for a superfluid (boson) ground state and transition only at $T = 0$ to an insulating phase. For the quantized Hall effect or the granular superconductor, there is an obvious choice of ground...
state in the dissipationless ($\rho = 0$) behavior characteristic of these two physical systems. It begs the question, however, of the ground state in the high-mobility MOSFETs: What is going on at $T = 0$? The appearance of the 2D MIT in experiments has led to something of an avalanche of theoretical ideas, with “explanations” of the metallic behavior ranging from valley crossings, \footnote{triplet superconductivity, \footnote{anyon superconductivity \footnote{...}}...} There also have been suggestions that non-interacting models with spin-orbit scattering can explain the data \footnote{These efforts notwithstanding, the nature of the 2D metallic ground state and the 2D MIT remain some of the most challenging open problems of contemporary condensed matter science.}

II. EXPERIMENT

We have studied the conductance $G$ of two different sets of high-mobility n-channel Si-MOSFETs. A set of large area ($\gtrsim 1\text{mm}^2$) FETs were fabricated on the (100) surface of silicon wafers doped with $N_a \approx 8.3 \times 10^{20}\text{m}^{-3}$ acceptors. Corbino channels of length $L = 0.4\ \mu\text{m}$ and width $w = 8\ \mu\text{m}$ were formed with a poly-silicon gate above a 44 nm oxide layer. The measured residual oxide charge for these devices was $\approx 3 \times 10^{14}\text{m}^{-2}$. These samples have been studied only at relatively high temperatures $1.2 < T < 4.2\ \text{K}$. Another set of samples made in a different process run on very similar starting material had a residual oxide charge of $< 10^{14}\text{m}^{-2}$. This run comprised samples of various lengths $1\ \mu\text{m} < L < 256\ \mu\text{m}$ and widths $11\ \mu\text{m} < w < 500\ \mu\text{m}$. For the shorter samples $w \gg L$, so that even though $L$ is small enough to compete with important microscopic process length scales in the material there is some hope of inferring averaged properties as a result of having many “mesoscopic” elements in parallel.\footnote{This later batch of samples have been studied at much lower temperatures $0.01 < T < 4.2\ \text{K}$. All sets of FETs had rather high peak mobilities $\simeq 1\ \text{m}^2/\text{V}$-sec, or they could achieve this regime with substrate bias.}

All measurements of $G$ were conducted in an electrically shielded enclosure with standard lock-in techniques. A source-drain voltage $V_{sd}$ was applied and the resulting current $I_{sd}$ was recorded as a function of the temperature $T$, the magnetic field $B$, or the gate voltage $V_g$, which controls the carrier density $n_s = C_{ox}(V_g - V_{th})$. $V_{th}$ is the threshold for populating the channel, which can be inferred from higher temperature transconductance or from Shubnikov-de Haas measurements at low temperatures, and $C_{ox}$ is the specific capacity of the gate oxide.

![FIG. 3. (a) $\sigma(T, n_s)$ of a large MOSFET for $T = 1.32\ \text{K}$ and $n_s$ values: $(-), 1.84\ \text{K}$; $(\nabla)$, $2.30\ \text{K}$; $(\square)$, $2.70\ \text{K}$; $(\triangle)$, $3.00\ \text{K}$; and $(\bigcirc)$, $3.50\ \text{K}$.

(b) The same data re-scaled according to Eq. (2) to form a single function with two branches (bottom branch for the insulating phase and top branch for the metallic behavior). (c) The data re-scaled again in accord with Eq. (3) so that the symmetry for insulating and metallic conductance is evident up to $T = T_0$, which is marked by the dashed line. The dotted line marks the conductivity $\sigma = 0.8e^2/h$ at the MIT. (These data were recorded at finite magnetic field $B = 0.5\ \text{T}$, but this has no bearing on the shapes of any of the curves for this sample.)}
III. RESULTS FOR $B = 0$

Our experiments demonstrate first that the disorder in the devices must be low relative to other important energy scales. For a moderately disordered sample, we find that the slope of $G(T)$ is consistently positive: all values of $n_s$ scale as insulators and the conductivity vanishes as $T \to 0$. For a substantial back-gate bias (e.g., $V_{sub} = -9$ V for the sample shown in Fig. 3(b)), however, the mobility increases enough to permit a MIT at a value of $n_s = n_c \simeq 1.65 \times 10^{15}/m^2$. The MIT appears as a change of sign of the slope of $\sigma(T) = (L/w)G(T)$ at $n_c$ (see Fig. 3(a)). We infer that the peak mobility has increased by about 20%, but this clearly is sufficient to change the behavior of the 2DES dramatically, even though the value of $\sigma$ at $n_s = n_c$ has not changed much.

More importantly, all of the conductance curves $G(V_g, T) = G(n_s, T)$ can be scaled (see figure 3(b)) against $\delta_c = (n_s - n_c)/n_c$ to form a single two-branched function [Fig. 3(b)] as expected from the scaling arguments mentioned above. We take this as a signature of a quantum phase transition in the 2DES. In figure 3(c) we plot

$$\sigma(\delta_n, T) = \sigma_c \exp \left( A\delta_n/T^{1/\nu} \right), \quad (3)$$

for all data from figure 3(b), and find agreement with the theoretical prediction $\sigma_c$ for the temperature dependence in the quantum critical region $T > T_0$ where the crossover temperature $T_0 \propto |\delta_n|^{1/\nu}$ is shown by the dashed line in Fig. 3(c).

Very similar scaling of $\sigma$ has been obtained in other 2DES samples in a variety of physical circumstances. A related scaling of $\sigma(E, T, n_s)$, where $E$ is the electric field applied between the source and drain, has been observed in some 2DES. This collection of experimental results is overwhelming evidence that the MIT is a quantum phase transition, and exhibits similarities with transitions in granular superconducting thin films, oxide superconductors, and plateaux transitions in the quantized Hall effect.

In shorter MOSFETs we find a similar scaling of $\sigma$ for moderate temperatures $1 < T < 4.2$ K. Our results are illustrated in figure 4 which contains measurements from a $L = 1.25 \mu m$, $w = 11.5 \mu m$ MOSFET. The reversal of sign of the slope $dG/dT$ occurs at essentially the same value as for the larger MOSFETs, and the conductivity $\sigma_c$ at the MIT is $\sim e^2/2h$ in agreement with many other experiments on MOSFETs. A similar value of $\sigma_c$ obtains in completely different physical circumstances such as the granular films or the quantized Hall systems, but there the amplitude of $\sigma$ is governed by physics (charging energy and phase fluctuations or the dominance of a particular momentum mode) that are not directly germane to the MIT.

Yet a third set of samples with electrons confined at the interface between Si and SiGe has exhibited very similar response. This result (see figure 3) is especially intriguing, because the mobility is very high compared with the MOSFETs experiments in the same range as for electrons in GaAs heterostructures, which have not exhibited the MIT to date. Again the slope $dG/dT$ changes sign at a concentration $n_c = 1.8 \times 10^{15}/m^2$, but owing to the higher mobility, the value of $\sigma_c \approx 80e^2/h$ is very large compared to the MOSFET experiments. This result proves the existence of the MIT in yet another materials system. More interestingly, it lays to rest once and for ever the suggestion (quoted widely and believed even more widely) that the value $\sigma_c$ is a “universal” number. Indeed, subsequent studies of the MIT in a 2D hole systems in SiGe/Si and GaAs/AlGaAs heterostructures have found $\sigma_c \sim 2e^2/h$, almost a factor of seven larger than in some Si MOSFETs.

A much more plausible expectation is that $r_s = U/E_F$ will be a universal number. This, in fact, is not born out across all samples: $r_s \sim 12 - 19$ at the transi-
tion for electrons in Si MOSFETs and Si/SiGe quantum wells, \( r_s \sim 13 \) for holes in SiGe/Si heterostructures and \( r_s \sim 11 - 23 \) for holes in GaAs/AlAs heterostructures. These numbers, however, are much closer to each other (within a factor of two) than the values of \( \sigma_c \), which are distributed across more than two orders of magnitude.

In general, one expects the scaling exponents, such as \( z \) and \( \nu \), to reflect only the symmetry of the problem in question, and thus to be universal numbers. In the experiments, however, a large range of exponents are found. In the Si-MOSFETs at \( B = 0 \), \( z\nu = 1.6 \pm 0.2 \) has appeared in two different sets of samples. The same exponent has been reported for holes in SiGe/Si quantum wells. For holes in GaAs/AlAs heterostructures or electrons in Si/SiGe heterostructures, however, \( z\nu > 4 \). It is worth noting that these two experiments were on samples with very low disorder (\( k_F l \gg 1 \)) by comparison with the MOSFET and p-SiGe samples where the relative effect of disorder is much stronger (\( k_F l \approx 1 \)). In the very short MOSFETs, \( z\nu \) is even larger – \( z\nu = 16 \pm 4 \) for \( L \approx 1 \mu m \). Furthermore, the range of “scalable” temperature dependence is smaller than in the larger samples. In fact for \( |\delta n| > 0.15 \) on the insulating side, the lowest temperature curve (\( \Delta \)) is already failing to scale with the higher temperature data. In the sample of figure 3, the data obeyed Eq. (2) well for \( 1.2 < T < 3.6 \) K (\( T = 1.2 \) K was the lowest temperature studied in that experiment), and for other large MOSFETs the range of temperature extended down to 0.05 K. We attribute this saturation of the \( T \) dependence to the cut-off of \( L_\varphi \), and hence \( \xi \) by the sample length \( L \).

IV. MAGNETOCO nductance

An applied magnetic field \( B \) alters the behavior of the carriers in the 2DES in different ways depending on the angle between the field and the plane of the 2DES. The perpendicular component of the magnetic field tends to bend the path of the carrier (the Lorentz force tends to make the carriers form circular orbits), as well as inducing a splitting of the energies of different spin orientations and consequently to polarize the spins of the carriers out of the plane of the 2DES. A parallel component of the magnetic field probably has little effect on the orbital motion of the carriers, but it still splits spin energies and it polarizes the spins into the plane. Studies of \( G(B) \) have been employed fruitfully for decades as probes of the transport mechanisms of disordered systems. There are detailed calculations of the functional form of \( G(B) \) for various conditions among non-interacting carriers. The contributions from Zeeman interactions (triplet terms in Hartree approximation) have been calculated and for \( \mu_B B \approx k_B T \) (\( \mu_B \) is the carrier magnetic moment and \( k_B \) is Boltzmann’s constant) lead to a negative parabolic magnetoconductance in a perpendicular magnetic field. In contrast, quantum interferences of carriers (orbital effects) can lead to positive slopes of \( G(B) \) near \( B = 0 \).

The MIT in MOSFETs is quenched by a large parallel magnetic field (\( B > 1 \) T) \( [33,34] \), which in turn implies that polarizing the electron spins in the plane of the carrier motion has a dramatic effect on the correlations of the carriers. The conductance of nominally metallic 2DES \( (i.e. \; n_s > n_c) \) decreases by orders of magnitude and the slope of \( G(T) \) reverses from negative to positive, indicative of insulating samples. The application of \( B \) perpendicular to the plane of the 2DES also quenches the metallic phase \( [3,39] \). Moreover, careful measurements of magnetoconductance in the quantum critical region in the presence of a perpendicular \( B \) provide quite a bit of insight into the relative importance of spin interactions and orbital motion at the MIT. \( [15] \)

Figure 6 contains representative plots of magnetoconductance (MC) \( \Delta \sigma/\sigma(B=0) \), where \( \Delta \sigma = \sigma(B)-\sigma(B=0) \). Clearly, there is a positive magnetoconductance and a negative magnetoconductance contribution to each curve, and the positive contribution is more accentuated near \( n_s = n_c = 1.65 \times 10^{15}/m^2 \). As we will see below, this is because the negative contribution has dropped to a minimum value at this point.

Each curve in figure 6 can be written

\[
\Delta \sigma/\sigma(0) = pf(B) - qB^2, \tag{4}
\]

where \( p, q > 0 \). The assumption of parabolic form for the negative term is justified because (1) it fits the data and (2) it is the form expected for the electron-electron interaction contribution for \( B \approx k_B T/\mu_B \approx 0.8 \) T. \( [37] \). We have decomposed the data following formula (4) and find that the positive component \( pf(B) \) of the magnetoconductance does not depend on \( n_s \) within the scatter of data. These contributions are plotted in figure 7 and fall atop one another for \( B < 0.8 \) T. The coefficient \( p \) is
therefore a constant. The coefficient $q$, i.e. the electron-electron interaction contribution to MC, exhibits a minimum near $n_s = n_c$ as is obvious in figure 7(b). We have found exactly the same behavior of MC in short MOSFETs [30,38] at temperatures down to 0.04 K, in spite of the presence of sizable conductance fluctuations.

Both positive and negative MC have been observed in other MOSFETs as well [34]. Since orbital effects (positive magnetoconductance) are absent in an applied parallel field, our results show clearly that MC of a 2DES does depend on the angle between the magnetic field and the plane of a 2DES, at least in the quantum critical region. Away from the critical region, the orbital effects at low fields become small compared to spin effects [see Fig. 7(b)], and only negative MC is observed. Therefore, a recent claim [33] about the absence of any angular dependence of MC is valid only far from the critical regime, in the metallic phase where the experiment [36] was carried out.

V. SCALING OF THE CONDUCTANCE

We can extract $\beta_T \propto \beta$ from our data by using the assumption of power-law dependence of the correlation scale (the phase coherence length) on $T$. One such plot for four of our samples is given in figure 8. Anticipating the dependence of $L_\phi$ suggested in the introduction, we have scaled the bare $\beta_T$ multiplying it by $z\nu$. The two large MOSFETs have $z\nu = 1.6$, and the two short MOSFETs yielded $z\nu = 16$. In spite of the disparity, all four curves produce the same scaled scaling function indicating that the underlying $\beta$ is the same for all samples. A noteworthy feature is that $\beta$ is essentially linear as it crosses through $\beta = 0$ as expected from recent scaling arguments [5]. For non-interacting particles, $\beta < 0$ as illustrated by the dotted lines in figure 1. Our experiment (which corroborates other measurements [33]) proves that $\beta$ extends into the metallic region and thus provides clear evidence as to the inadequacy of noninteracting models of charge carriers.

An even more striking feature is evident from the present data: $\beta$ decreases towards zero at large $g$, as proposed in Ref. [5]. Although this is by no means a necessary condition for such an exotic metallic state, it seems as if the system tries to restore Ohm’s law in the large conductance (weak disorder) limit.

VI. SUMMARY

Our experiments corroborate other experiments on 2DES and prove the existence of a metal-insulator transition in two-dimensions for sufficiently low disorder. The conductances can be reduced to a single (two-branched) scaling function that is consistent with recent proposals for Coulomb driven quantum phase transitions. Measurements for different sample lengths and different levels of disorder demonstrate certain universal features of the transition. The transition occurs near a certain value of $n_c$ for a given density of states (carrier effective mass). The conductance at the transition is not a universal constant. Magnetoconductance experiments suggest that spin polarization and Coulomb interactions of the carriers have a dramatic effect on the transition. The product of conductance scaling function $\beta_T$ and the correla-
tion scale exponents $\nu$ shows that the underlying scaling function $\beta$ is the same for all MOSFETs. The inferred $\beta$ violates the predictions from non-interacting models and supports recent predictions based on interacting carriers.

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