Relative importance of the electron interaction strength and disorder in the two-dimensional metallic state

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The effect of substrate bias and surface gate voltage on the low-temperature resistivity of a Si-MOSFET is studied for electron concentrations where the resistivity increases with increasing temperature. This technique offers two degrees of freedom for controlling the electron concentration and the device mobility, thereby providing a means to evaluate the relative importance of electron-electron interactions and disorder in this so-called ''metallic'' regime. For temperatures well below the Fermi temperature, the data obey a scaling law where the disorder parameter ($k_F l$), and not the concentration (and thus r_s), appears explicitly. This suggests that interactions, although present, do not alter the Fermi-liquid properties of the system fundamentally. Furthermore, this experimental observation is reproduced in results of calculations based on temperature-dependent screening, in the context of Drude-Boltzmann theory.

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The term ''metallic behavior,'' for a two-dimensional (2D) system with concentration n greater than some critical value n_c, has come to designate a drop in the resistivity ρ as the temperature T is decreased, as opposed to ''insulating behavior'' (for $n<n_c$) for which ρ increases exponentially with decreasing temperature. This differs from the purist's definition of a metal, whereby the resistivity is finite at $T=0$, a condition never achieved experimentally. In experiments performed in systems with low disorder and small values of n_c (see Ref. 1, and references therein), the change in ρ in the ''metallic'' regime is considerably greater than was seen in earlier work at higher densities and in more disordered systems.[2] There is still no consensus on the origin of this change. The low values of n_c ($\propto r_s^{-2}$, where r_s is the ratio of the Coulomb interaction to Fermi energy), scaling behavior of transport properties around n_c and the absence of divergence of $\rho(T)$, seen by some authors as $T\rightarrow 0$, (see, e.g., Refs. 3–7) have led to suggestions that the system is a metallic quantum ground state (in the sense that the charge carriers are delocalized at $T=0$). The suggestion is that this novel phase results from strong electronic correlations, and that n_c marks a quantum critical point and a metal-insulator transition (MIT). This contradicts the well-established principle that a 2D system of noninteracting carriers is insulating at $T=0$,[8] but there is no definitive corresponding prediction when interactions are present. Other authors, however, observe a negative magnetoresistance at low magnetic fields B and weak-localization corrections to the resistivity, which are indicative of ''weak localization.''[9–12] Many hypotheses have been put forward to explain the metallic behavior, some invoking exotic interaction effects[13–15] and others advocating a more traditional framework, suggesting that the ''metallic'' behavior is only a finite-temperature effect that is overwhelmed by localization at sufficiently low temperatures.[16–20] To a large extent, the debate hinges on the question of whether the relatively large values of r_s (typically >10), corresponding to n_c, warrant fundamentally new physics.

In motivating our work, we note that as n (r_s) decreases (increases), it is not only the electron-electron interaction that is increasing in the 2D system, but also the effective disorder felt by the carriers. This is because the dominant disorder in semiconductor 2D systems arises from Coulomb scattering by charged impurities, which increases monotonically with decreasing density as the 2D carrier system becomes less effective in screening the Coulomb interaction between the carriers and the charged impurities. Since, in the absence of umklapp processes (not applicable in these systems), electron-electron interactions typically do not affect Ohmic transport, there is good reason to believe that much of the observed ''metallic'' behavior may be arising from the weakening of screening in the disorder potential, rather than from the increasing electron-electron interaction. By carefully studying temperature-dependent 2D transport in high quality Si-MOSFET's, where disorder strength and carrier density are controlled independently using a substrate bias, we hope to shed light on this question of the relative importance of electron-electron interactions and the disorder potential in low density ''metallic'' transport.

A negative substrate bias (V_{sub}) steepens the triangular confining potential normal to the surface, pushing the electron wave function closer to the Si-SiO_2 interface. This can either increase or decrease the mobility.[21] The surface-gate voltage is used to tune n. Without assuming either a specific mechanism for the increase in ρ with temperature or the existence of a quantum phase transition at n_c, this technique probes the density-mobility phase space in a way that is impossible with singly gated devices, and it allows a study of the metal in terms of r_s and the disorder parameter $k_F l$, where k_F is the Fermi wave vector and l is the momentum relaxation length. The value of $k_F l$ can be calculated directly from the relation $\rho \equiv (h/2e^2)/(k_F l)$, while n is measured from the Hall effect at magnetic fields $B<0.5$ T.

Measurements were performed on an n-type Si-MOSFET inversion layer with a 200-nm-thick oxide layer with a peak

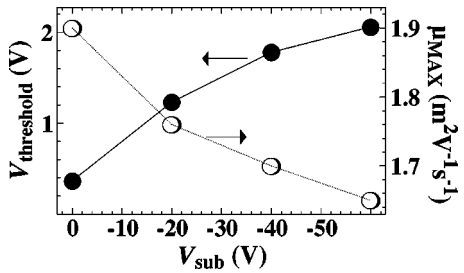

FIG. 1. Threshold voltage and peak mobility versus applied substrate bias for $T=1.4$ K.

mobility (at $T=1.4$ K and with $V_{sub}=0$) of 1.9 $m^2\,V^{-1}\,s^{-1}$ corresponding to $n=4\times10^{15}$ m^{-2} on 100 Ω cm substrate. The mobility *at* the MIT, for $V_{sub}=0$, was 0.24 $m^2\,V^{-1}s^{-1}$, approximately twice the corresponding values in Refs. 3,22. Devices were Hall bars of dimension 1000×100 μm^2. A ^{4}He cryostat was used, covering a range 1.4 K$<T<$70 K. Resistivities were measured using a standard a.c. four-terminal technique, with a constant source-drain current of 100 $nA_{r.m.s.}$ and a frequency of 19 Hz, after ensuring that the magnitude of the current did not induce significant electron heating above the substrate temperature and that the contacts were Ohmic. A substrate bias V_{sub} was applied at room temperature before the sample was lowered into the cryostat and cooled slowly.

One consequence of the (negative) substrate bias is to increase the threshold voltage, which results in the increase of the confining electric field, for a given n. The peak mobility (to be considered here as a rough measure of the disorder) decreases as V_{sub} is made more negative, as shown in Fig. 1, consistent with the enhancement of scattering from interface roughness and the charged impurities located near the SiO_2 interface. The enhancement of spin-orbit scattering is another possible consequence. Negative magnetoresistance is observed in a weak magnetic field perpendicular to the system, in agreement with the prediction for the quenching of weak localization, but no sign of the *positive* magnetoresistance associated with spin-orbit scattering is seen,[23] indicating that this is not a strong effect. No low-temperature resistivity upturn was observed, discarding the possibility of interferences due to local magnetic moments.[21]

The negative magnetoresistance demonstrates that weak localization, which results from quantum interference, is present in the ''metallic'' phase. Figure 2 shows that the

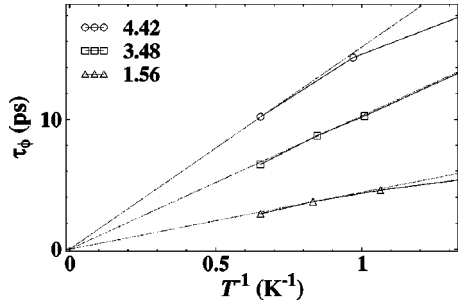

FIG. 2. Phase decoherence time versus T^{-1} for concentrations 1.56, 3.48, and 4.42×10^{15} m^{-2} at $V_{sub}=0$.

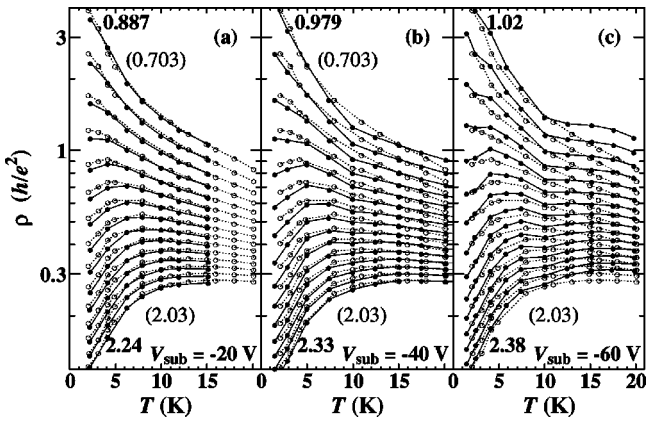

FIG. 3. $\rho(T)$ over a range of densities for three substrate biases -20, -40, and -60 V (solid curves). Dotted curves show $\rho(T)$ for $V_{sub}=0$. Ranges of densities are indicated by bold numbers ($\times10^{15}$ m^{-2}) for $V_{sub}<0$. Numbers in parentheses give the density range of the $V_{sub}=0$ curves. The critical concentration n_c ranges from 0.99×10^{15} m^{-2} (for $V_{sub}=0$) to 1.41×10^{15} m^{-2} (for $V_{sub}=-60$ V). Fermi temperature T_F [K]$=7.25$ $n[10^{15}$ $m^{-2}]$.

phase decoherence time τ_ϕ, obtained by fitting the negative magnetoresistance, is proportional to T^{-1}, in agreement with Fermi liquid theory[23] and with other experimental studies.[24] At sufficiently low temperatures, it is likely that this localization will dominate.

The solid curves in Fig. 3 show $\rho(T)$ for different values of V_{sub} and for a range of densities spanning the ''metal-insulator'' transition. They are superposed on dotted curves, which correspond to $V_{sub}=0$. We point out that the 230% change in resistivity in the lower curves of Fig. 3 is similar to the changes seen in other work (e.g., Ref. 22) over the same ranges of resistivity and temperature. In each figure, the transition from strong localization ($d\rho/dT<0$) to metallic behavior occurs at roughly the same value of the resistivity (or k_Fl), $\rho_c\approx h/e^2$, whereas n_c varies from 0.99×10^{15} m^{-2} (at $V_{sub}=0$) to 1.31×10^{15} m^{-2} (at $V_{sub}=-60$ V). This critical resistivity corresponds to $k_Fl=0.5$, a value below which the Fermi wavelength is poorly defined. It is worth emphasizing that it is k_Fl and not r_s which is the critical parameter. For densities greater than those shown in Fig. 3 (i.e., $n>2\times10^{15}$ m^{-2}), $\rho(T)$ is nonmonotonic, bending downwards in an insulatorlike fashion as T is increased beyond T_F, the Fermi temperature. It also shows signs of saturation as T approaches zero, possibly due to collision broadening or the finite Dingle temperature. The intermediate temperature range shows an approximately linear dependence. The gradients of the curves with $V_{sub}<0$ differ from those of the $V_{sub}=0$ reference curves, showing that the substrate bias does not simply amount to a relabeling of the $\rho(T)$ curves.

With the hope of finding some underlying universality, we follow the work of Hamilton *et al.* on GaAs holes,[25] and consider theoretical studies which take into account the strong temperature dependence of disorder screening. In the Boltzmann transport theory, within the static RPA, screening of the Coulomb disorder potential arising from the charged impurity scattering, $\rho(T)$ at low temperatures is given by[18,19,26,27] the analytic expression

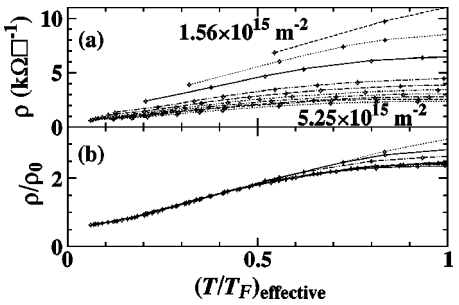

FIG. 4. (a) Experimental $\rho(T/T_F)$ for a range of densities at a constant substrate bias $V_{sub}=0$. T_F ranges from 11.3 to 38.0 K. The effective values of T/T_F displayed include the correction for collisional broadening [see Eq. (3)]. (b) The same data with the vertical axis scaled by a factor ρ_0 determined empirically for each curve.

$$\rho(T;n)=\rho(T=0;n)[1+C(n)T/T_F], \tag{1}$$

where $C(n)$ is a weakly varying function of n that also depends on the dominant scattering mechanism. Equation (1) is valid in the range $T/T_F \ll 1 \ll T/T_D$, where T_D is the effective Dingle temperature. In a recent diagrammatic perturbation calculation, it has been suggested[28] that the linear temperature dependence in Eq. (1) is preserved (in the ballistic regime, i.e., for $\hbar/\tau \ll k_BT \ll k_BT_F$) even in the presence of higher-order electron-electron interaction terms (at least within a systematic r_s expansion for a zero-range impurity scattering potential, which was the only case considered in Ref. 28). The coefficient $C(n)$ of the linear temperature coefficient in this theory[28] is, however, renormalized by Fermi-liquid interaction effects, which are unknown at the large r_s values used in the experiment. In particular, $C(n)$ in this theory is apparently renormalized[28] by the factor $-[1+3F_0^\sigma/(1+F_0^\sigma)]$, where F_0^σ is the triplet channel Fermi-liquid renormalization parameter which, in general, is a function of density, temperature, and momentum, but taken to be a constant factor in the theory. It is noteworthy that, in this interaction theory, the renormalized $C(n)$ could become negative at small values of r_s(i.e., high densities) where F_0^σ exceeds -0.25. Such a situation, with $\rho(T)$ decreasing with increasing T in the low-temperature ballistic regime, has never been observed experimentally to the best of our knowledge. We note also that the interaction theory is only valid in the $T \ll T_F$ regime, and therefore cannot provide an explanation for the nonmonotonicity manifestly obvious in the data for $\rho(T)$ at high temperatures (Fig. 3).

Figure 4 shows $\rho(T)$ for a range of n in the metallic regime with $V_{sub}=0$. Following Eq. (1), the temperature was normalized to T/T_F, where T_F is the Fermi temperature calculated for each curve individually. The Dingle temperature was estimated from $T_D=\hbar/2\pi k_B\tau_q$, where τ_q is the quantum lifetime, measured from the amplitude of Shubnikov–de Haas oscillations.[29] For a range of concentrations $n=4.6-5.4\times10^{15}$ m^{-2} ($T_D\sim35$ K), we obtain $T_D\approx1.1$ K, i.e., below the experimental temperatures. $\rho(T/T_F)$ is generally linear with a gradient that increases with decreasing n (or T_F), in agreement with Eq. (1). It is remarkable that another scaling factor ρ_0, applied to the *vertical* axis and determined by eye for each curve, succeeds in collapsing the linear portion of all of the curves onto the bottom (high-density) curve [Fig. 4(b)], at least for a range of T well away from T_F. Indeed, this scaling factor must equal the ratios of *both* the gradients of the lines and their intercepts

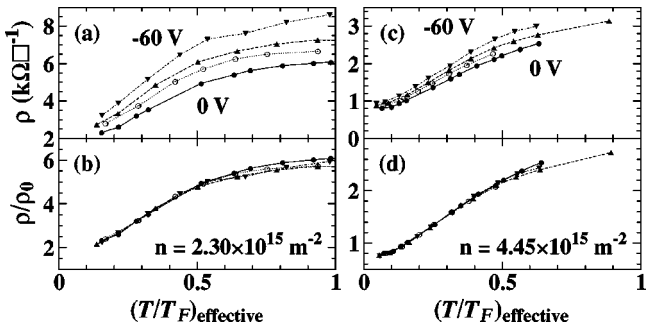

FIG. 5. (a), (c) $\rho(T/T_F)$ for fixed densities 2.30×10^{15} m^{-2} ($T_F=16.7$ K) and 4.45×10^{15} m^{-2} ($T_F=32.3$ K) for substrate biases 0, -20, -40, and -60 V. (b) and (d) show the same data after scaling by $\rho_0(V_{sub})$.

$$\rho(T;n)/\rho_0(n)=f(T/T_F), \quad T/T_F<0.5. \tag{2}$$

This simple transformation holds well for $n>3\times10^{15}$ m^{-2} (where $\rho<1.4$ kΩ/□ at $T=1.4$ K) but fails at densities closer to the MIT. However, a much better scaling is recovered by including a correction

$$(T/T_F)_{\text{effective}}=[(T/T_F)^2+A/(k_Fl)^2]^{1/2}. \tag{3}$$

The value of the coefficient A was set to 1.0, but the overall quality of the fit was not sensitive to its exact value. The correction term $1/k_Fl$ represents the broadening of the Fermi circle due to the finite scattering length (collisional broadening).[30] Alternatively, it may be viewed as a lowering of the effective density (or T_F) resulting from carrier freeze-out, a possibility envisaged by some authors.[19] With this correction, Eq. (2) is obeyed down to $n=1.56\times10^{15}$ m^{-2} (for which $\rho=8$ kΩ/□ at $T=1.4$ K), i.e., considerably closer to the MIT. At even lower values of n, the correction term is much more significant compared with T/T_F, so that this first order correction is no longer sufficient. Our focus, however, is on the *metallic* regime, and not on the localizing effects relevant close to the MIT. For the higher-density data ($n\geqslant3\times10^{15}$ m^{-2}), the broadening correction to the temperature requires small modifications to the empirical ρ_0 values in order to achieve a satisfactory collapse, but the quality of the collapse is not significantly altered.

Figure 5 shows the same procedure, applied to a set of curves corresponding to different values of V_{sub} but with the same density (2.30 and 4.45×10^{15} m^{-2}). Again, Eq. (2) is obeyed, but with $\rho_0=\rho_0(V_{sub})$. The similarity in the forms of Eqs. (1) and (2) is notable, but the scaling factors ρ_0 of Eq. (2) may be equated with the $\rho(T=0)$ of Eq. (1) only in so far as (a) $\rho(T;n)$ remains linear outside the strict range $T \ll T_F$, (b) the saturation observed at low temperatures may be discarded as due to the finite T_D, and (c) C is a sufficiently weak function of n.

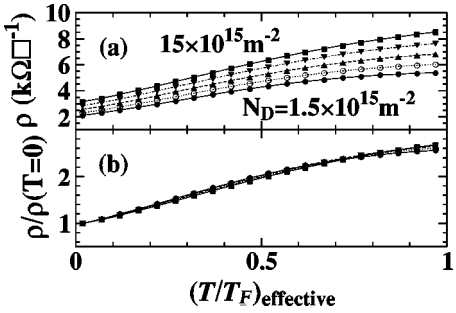

FIG. 6. (a) Numerical calculation of $\rho(T/T_F)$ due to temperature-dependent screening, for constant $n=2.3\times10^{15}$ m^{-2} ($T_F=16.7$ K) and $N_D=1.5,2.5,4.5,8.0$, and 15.0×10^{15} m^{-2}, with $T_D/T_F=0,0.06,0.12,0.18$, and 0.24 respectively. (b) The same data, with ρ scaled by $\rho(T=0)$.

Experimentally, $C\approx8$ is observed, considerably greater than the values 2.0–3.0 predicted by the simple screening theory. It is, however, consistent with the arbitrary choice $F_0^\sigma\approx-\frac{3}{4}$ in the interaction calculation. (The importance of F_0^σ has been highlighted elsewhere for *p*-GaAs,[31] although those data were fitted with a lower value of $F_0^\sigma\approx-0.4$.) Note that, in general, F_0^σ is strongly density dependent. If we assume that F_0^σ is independent of n and, therefore, of r_s, then scaling follows. The scaling thus suggests that the value of ρ (or k_Fl) at finite T is determined solely by its value at low T, with the concentration appearing only implicitly in T_F. Combining Eq. (2) with the identity $\rho\equiv(h/2e^2)/(k_Fl)$ we obtain

$$\frac{k_Fl(T=0)}{k_Fl(T)}=\frac{f(T/T_F)}{f(0)}. \tag{4}$$

This conclusion, drawn from the observed scaling laws, follows from theory [Eq. (1)] regardless whether interaction effects are considered or simple screening theory is used.

Figure 6 shows the results of a numerical calculation of the temperature-dependent screening for experimental conditions analogous to those in Figs. 5(a), 5(b). It includes the temperature dependence of static RPA screening at finite temperature, the finite extent of the wave function in the direction normal to the interface (using a Fang-Howard distribution,[32]) and a variable effective disorder, parametrized by the collision-induced Dingle temperature T_D. (Here T_D measures the strength of impurity scattering and is, by definition, temperature independent.) Carrier freeze-out was not assumed. The penetration depth of the wave function below the interface is determined by the depletion concentration N_D, which increases as $V_{\rm sub}$ is made more negative. The range of N_D indicated in Fig. 6 is consistent with the range of $V_{\rm sub}$ (0 to -60 V) used in the experiment. By setting suitable values of T_D, the calculation reproduces the features of the experimental with reasonable accuracy: (1) $\rho(T)$ increases in a metallic fashion, with a weaker temperature dependence appearing (at low T) as T/T_D decreases and (at high T) as T/T_F increases, (2) The scaling law, Eq. (2), is obeyed [with $\rho_0=\rho_0(N_D)$], although the ability to scale the theoretical curves as was done with the experimental data relies on the correct combination of N_D and T_D. We emphasize, however, that the theoretical results presented here are not intended to give a fully quantitative description of the experimental results. Rather, we demonstrate that, to a very large extent, temperature-dependent screening can account for the main features of $\rho(T)$ in the so-called metallic regime in the absence of a magnetic field. The absence of r_s in Eq. (4) argues against a novel strongly correlated ground state in the metallic regime and suggests that the system retains its Fermi-liquid character.

Before concluding, we point out that the direct unbiased conclusion following our experimental data is that disorder (as characterized by the dimensionless parameter k_Fl) is at least as important a parameter as interaction (i.e., r_s) in determining the temperature dependence of $\rho(T)$ for $T/T_F\leqslant1$. This conclusion confirms, generalizes, and extends to *n*-Si MOSFET's a similar conclusion reached earlier in Ref. 25 for 2D holes in *p*-GaAs systems. We believe that this conclusion is consistent with the Fermi-liquid theory-based interpretation of the 2D finite-temperature ''metallic'' state, as discussed, for example, in Refs. 18,19,28. At $T=0$, this ''metal'' should, in principle, become an insulator, in keeping with Ref. 8. We have carried out an explicit numerical calculation within the screening theory[18,19,26,27] to obtain qualitative agreement between theory and experiment, but the same is also true at a qualitative level for the interaction theory (in its regime of validity) of Ref. 28, provided F_0^σ is reasonably independent of r_s. The issue of a quantitatively reliable theory for $\rho(T)$ at large r_s remains open at the present time, and is probably a formidable theoretical challenge because of nonperturbative effects arising from both disorder and interaction, neither of which is small in this problem. We emphasize in this context that the screening theory and the interaction theory are complementary theories, as discussed in Ref. 28. In particular, the screening theory uses a realistic impurity potential by regularizing the Coulomb disorder potential due to charged impurity scattering by phenomenologically screening the long-range bare impurity potential, whereas the interaction theory includes higher-order interaction corrections through a systematic r_s expansion, using an unrealistic zero-range impurity potential. Both theories are, in fact, uncontrolled theories at large r_s, where no systematic perturbative analysis applies in principle, but our data show that these theories catch the essential qualitative features of the temperature dependence of $\rho(T)$ very well, even for rather large values of r_s.

In summary we have demonstrated that a simple empirical scaling law, where the concentration (and therefore r_s) does not appear explicitly, is applicable on the metallic side of the MIT when either the concentration or the mobility is varied. A similar effect has been observed in GaAs heterostructures.[25] The quality of the scaling is improved, and is obeyed down to lower concentrations, by taking into account collision-broadening effects which enhance the effective temperature. The magnitude of r_s is irrelevant, suggesting that the effect of the interactions is to modify the effective disorder, expressed as k_Fl, by screening. We observe a striking similarity with the prediction of Drude-

Boltzmann transport theory in the presence of temperature-dependent screening. Although quantitative agreement between this theory and our experimental results is only approximate, possibly because it neglects the interaction effects, it is clear that many features of the ''metallic'' behavior can be understood in terms of screening and disorder, without the need to resort to fundamentally new physics originating from electron-electron interactions.

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