Unexpected Behavior of the Local Compressibility near the $B = 0$ Metal-Insulator Transition

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We have measured the local electronic compressibility of a two-dimensional hole gas as it crosses the $B = 0$ metal-insulator transition. In the metallic phase, the compressibility follows the mean-field Hartree-Fock (HF) theory and is found to be spatially homogeneous. In the insulating phase it deviates by more than an order of magnitude from the HF predictions and is spatially inhomogeneous. The crossover density between the two types of behavior agrees quantitatively with the transport critical density, suggesting that the system undergoes a thermodynamic change at the transition.

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The recent discovery of a two-dimensional (2D) metal-insulator transition (MIT) [1] has raised the fundamental question concerning the existence of metallic 2D systems [2,3]. In contrast to the scaling theory of localization [3], which predicts that only an insulating phase can exist in 2D, there is compelling evidence for metalliclike behavior in a growing number of 2D systems [4,5]. To date, the vast majority of this evidence comes from transport measurements. Clearly, if a true zero-temperature phase transition exists, it may reveal itself also in the thermodynamic properties of the 2D gas, such as the electronic compressibility, $\kappa = n^{-2}\frac{\delta n}{\delta \mu}$ (where μ is the chemical potential and n is the carrier density). For example, a crossover to a gapped insulator would result in a vanishing compressibility at the transition [6], whereas a crossover to an Anderson insulator would involve a continuous evolution of the compressibility across the transition.

The compressibility or $\frac{\delta \mu}{\delta n}$ of a system reflects how its chemical potential varies with density. For noninteracting electrons it simply amounts to the single-particle density of states (DOS), which in 2D is density independent ($\frac{\delta \mu}{\delta n} = \frac{\pi \hbar^2}{m}$). This picture, however, changes drastically when interactions are included. Exchange and correlation effects weaken the repulsion between the electrons, thereby reducing the energy cost, thus leading to negative and singular corrections to $\frac{\delta \mu}{\delta n}$. Within the Hatree-Fock (HF) theory, which includes both the DOS and exchange terms, one gets:

$$\frac{\delta \mu}{\delta n} = \frac{\pi \hbar^2}{m} - \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{e^2}{4\pi \varepsilon} n^{-1/2}, \qquad (1)$$

with the compressibility becoming negative at low enough densities. Measurements of the macroscopic compressibility of 2D electron/hole gases, in the metallic regime, have indeed confirmed this behavior [7,8].

In this work, we have expanded the study of $\mu(n)$ into the MIT regime. Our measurements utilize several single electron transistors (SETs), situated directly above a two-dimensional hole gas (2DHG). This technique allows us to determine the local behavior of $\mu(n)$ as well as its spatial variations. Simultaneous macroscopic transport measurements were conducted to ensure a precise determination of the MIT critical density in the same sample. Our measurements indicate a clear thermodynamic change in $\mu(n)$ at the MIT. In addition, we find that the behavior of $\mu(n)$ in the metallic phase follows the HF model and is spatially homogeneous. The insulating phase, on the other hand, is found to be spatially inhomogeneous. In this regime, $\frac{\delta \mu}{\delta n}$ deviates by more than an order of magnitude from the predictions of the HF model.

The samples are inverted GaAs/AlGaAs heterostructures [9]. A layer of AlGaAs, 2000 Å thick, separates the 2DHG from a p^+ layer that serves as a back gate, and is separately contacted. A GaAs spacer, 500 Å thick, separates the 2DHG from the doped GaAs layer situated just under the surface (see inset in Fig. 1). The mobility of the 2DHGs ranges from 7×10^4 to 1.2×10^5 cm^2/V sec at $n = 5 \times 10^{10}$ cm^{-2} and $T = 4.2$ K. Biasing the back gate enables us to vary the density of holes by 2 orders of

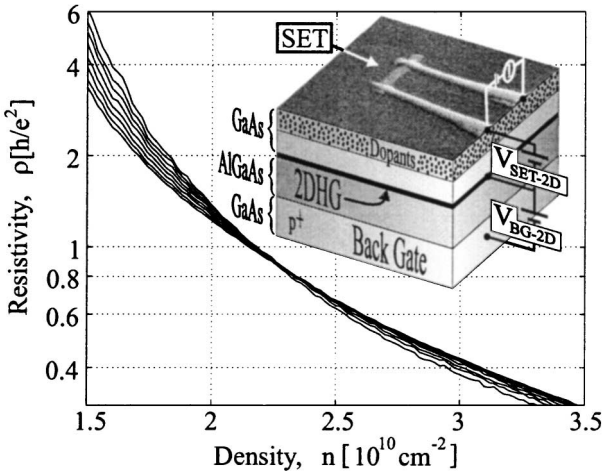

FIG. 1. Density dependence of the resistivity: Traces from top to bottom on the right correspond to $T = 600$, 550, 500, 450, 400, 300, and 250 mK. The low-T crossing point is at $n_c = 2.1 \times 10^{10}$ cm^{-2}. Inset: A scanning electron micrograph of the single-electron transistor (SET), placed on top of a schematic structure along with the measurement circuit.

magnitude, from 2×10^{11} to 2×10^{9} cm^{-2}. Our samples show a clear MIT. A typical plot of the resistivity ρ vs density at various temperatures is shown in Fig. 1. A clear crossing point between metallic and insulating behavior is observed. The critical density and resistivity, determined from the low-temperature crossing point, is $n_c \approx 2.1 \times 10^{10}$ cm^{-2} and $\rho_c \approx 0.9\frac{h}{e^2}$. Transport properties of similar samples were previously used to establish the existence of the MIT in GaAs [5].

A local measurement of μ requires the ability to measure electrostatic potentials with high sensitivity and good spatial resolution. It has been previously shown that both can be achieved using a SET [10–12]. We have therefore deposited several aluminum SETs on top of an etched Hall bar mesa (inset in Fig. 1). This configuration allows us to study simultaneously the local thermodynamic behavior and the macroscopic transport properties and, thereby, trace possible correlation between them. At equilibrium, the Fermi energy is constant across the sample, and therefore a change in μ induces a change in the electrostatic potential, which is readily deduced by measuring the change in current through the SET. A detailed description of the measurement technique has been given in Ref. [11]. The spatial resolution, determined from the size of the SET and its distance from the 2DHG, is 0.1×0.5 μm^2. The measured voltage sensitivity is 10 μV. A similar technique has been previously employed to image the local compressibility of a 2DEG in the quantum Hall regime [11,12].

To demonstrate the strength of our technique, we first employ it to study the magnetic field (B) dependence of μ deep in the metallic regime [$n = 1.96 \times 10^{11}$ cm^{-2} (see Fig. 2)]. Theoretically, the formation of well-separated Landau levels at high magnetic fields is expected to induce sharp sawtoothlike oscillations in μ. The sharp drops are at integer filling factors (ν), and the slopes obey $\frac{\delta\mu}{\delta B} = (j + \frac{1}{2})\frac{\hbar e}{m^*} \pm g^*\mu_B$, where m^* and g^* are the effective mass and g factor, j is the Landau level number, and the $\pm$ relate to the two spin directions. We find good quantitative agreement between this model and the measurement using a single value for $m^* = 0.34m_e$ and $g^* = 2.7$. This value of m^* agrees well with the known effective mass of light holes in GaAs, $m^* = 0.38m_e$ [13]. The position of the jumps allows us to determine the local density of the 2DHG under the SET: $n_l = 1.82 \times 10^{11}$ cm^{-2}, which deviates by only 7% from the density measured macroscopically by transport technique. This small deviation demonstrates that the area beneath the SET is hardly disturbed by its presence.

The main focus of this work is the density dependence of μ across the $B = 0$ MIT. Both the theory and previous macroscopic measurements [7,8] show that at low densities μ should increase monotonically as n is decreased

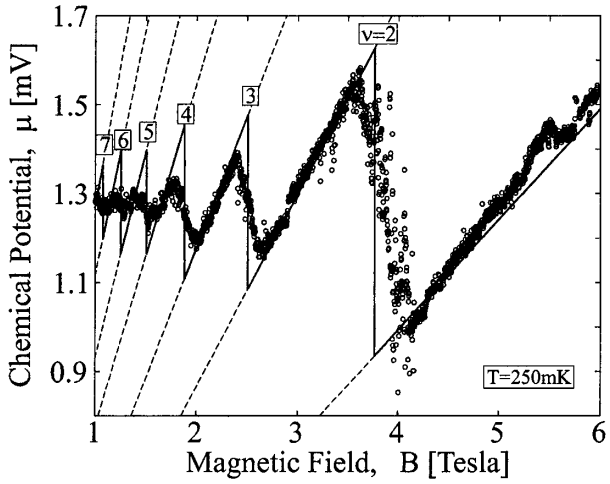

FIG. 2. Measured B dependence of μ. The solid line is the predicted Landau fan with $m^* = 0.34m_e$ and $g^* = 2.7$. Oscillations in μ are observable up to $\nu = 7$. The *local density* extracted from the magnetic field values at integer ν is $n_l = 1.82 \times 10^{11}$ cm^{-2} which deviates by only 7% from the transport-measured macroscopic density, $n = 1.96 \times 10^{11}$ cm^{-2}.

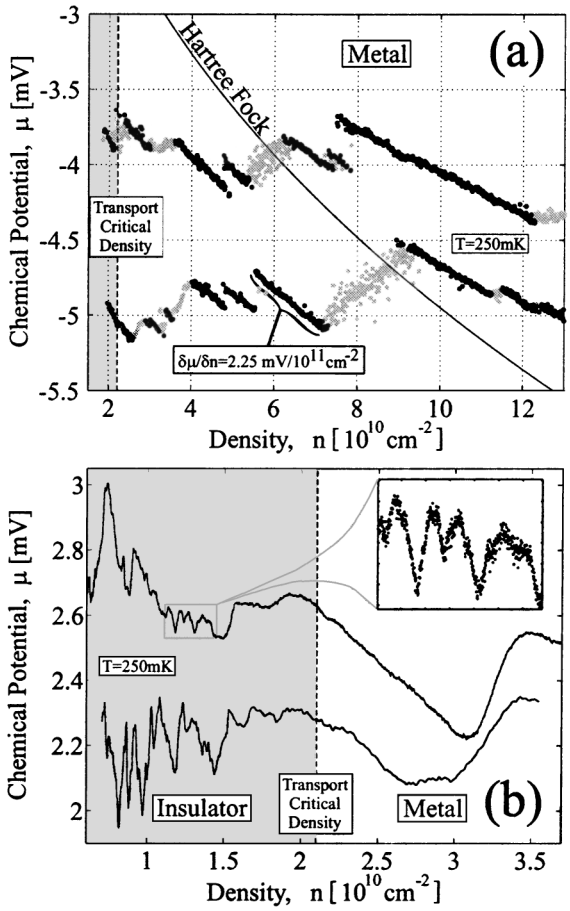

FIG. 3. (a) Measured $\mu(n)$ in the metallic regime (dots) together with the HF theory [Eq. (1)] (solid line). The measured negative slopes are highlighted (dark symbols) to demonstrate their resemblance to the HF model. (b) Measured $\mu(n)$ across the MIT and in the insulating region. Inset: A closer look at the data in the insulating regime. Each slope is composed of many data points allowing an accurate determination of the slopes.

[Eq. (1)]. Unexpectedly, our local measurements demonstrate quite a different behavior. Several typical traces of μ vs n are shown in Fig. 3. Figure 3a shows the behavior in the metallic regime and Fig. 3b shows the behavior across the MIT and in the insulating regime. Instead of the expected monotonic dependence, μ exhibits a rich structure of oscillations. All the oscillations, including the fine structure seen on the left side of Fig. 3b, are completely reproducible and do not depend on the measurement rate or sweeping direction. Two distinct types of oscillations are observed: In the metallic regime (Fig. 3a) we observe long sawtooth oscillations with a typical period in density of $(1-2) \times 10^{10}$ cm^{-2}. Superimposed on them and starting in close proximity to the MIT, a new set of rapid oscillations emerges (Fig. 3b). Their typical period is an order of magnitude smaller: $(1-2) \times 10^{9}$ cm^{-2}, and their amplitude grows continuously from their point of appearance to lower densities. Similar behavior has been measured on seven different SETs placed on five separate Hall bars from two different wafers. Although the specific pattern of oscillations varies between these Hall bars and changes also after thermal cycling, they all have the same general characteristics. The qualitative change in the oscillation pattern of $\mu(n)$ near the critical density suggests that the system experiences a thermodynamic change at the MIT.

Out of the two types of oscillations, the easier ones to explain are these on the metallic side. In Fig. 3a we compare the measured oscillations with the expected monotonic behavior of the HF model. In contrast to the model, the measured μ has a density independent average which suggests that some kind of screening mechanism is present in the system. While the negative slopes of $\mu(n)$ (black symbols) follow the HF theory, there are apparent additional drops (some of which are extremely sharp) between them (gray symbols). This sawtooth profile is reminiscent of the behavior of the chemical potential of a quantum dot as a function of its density [14] and suggests the existence of discrete charging events in the dopant layer, situated between the 2DHG and the SET. Thus, the measured μ of the 2DHG varies undisturbed along the negative slopes, until a certain bias is built between the 2DHG and the SET that makes the charging of an intermediate localized state energetically favorable. This causes a screening charge to pop in, which results in a sharp drop in the measured electrostatic potential, after which μ continues to vary undisturbed until the next screening event occurs. Because screening occurs only at discrete points we can reconstruct the underlying $\mu(n)$ from the unscreened segments in the measurement. We do this in Fig. 4, by collecting the slopes of these segments from the sawtooth profiles of five different SETs placed on three separate Hall bars. Each single point in this graph represents the slope of a well-defined segment, like the ones emphasized in Fig. 3a. In the metallic side all the data collapse onto a single curve (the dashed line in Fig. 4 is a guide to the eye). The prediction of the HF model is depicted by the solid line in Fig. 4.

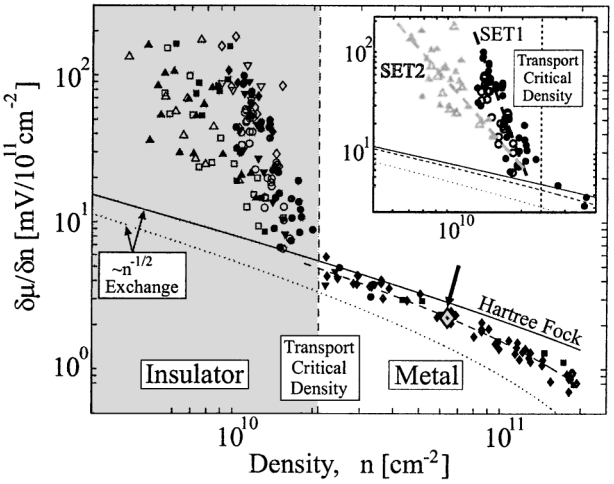

FIG. 4. $|\delta\mu/\delta n|$ collected from five SETs on three different Hall bars from two different wafers. In the insulating regime, both negative and positive slopes are shown (closed and open symbols, respectively). Each point corresponds to a well-defined segment in the $\mu(n)$ trace. The point marked by an arrow corresponds to the marked segment in Fig. 3a. Inset: Results from two SETs on the same device (●, ▲) demonstrating the spatial dependence of $|\delta\mu/\delta n|$ in the insulating side.

The finite width of the 2DHG adds a positive contribution to the compressibility as shown by the dotted line. It is evident that both theories describe the data to within a factor of 2 over more than an order of magnitude in density, throughout the metallic regime. The fact that different Hall bars and different SETs (namely different locations within the same Hall bar) produce the same dependence, suggests that the metallic phase is *homogeneous in space*.

The sudden appearance of rapid oscillations as the system crosses to the insulating side already signifies that something dramatic happens at the transition. Assuming that this new set of oscillations is caused by the same mechanism, namely screening by traps, we can proceed and extract their slopes and add them to the same plot of $\delta\mu/\delta n$ (see Fig. 4). Unlike in the metallic phase where the system clearly has a negative $\delta\mu/\delta n$, namely negative compressibility, in the insulating phase we *a priori* do not know the sign of the compressibility. We, therefore, plot in the left side of Fig. 4 the absolute value of both negative and positive slopes, all of which deviate considerably from the expected $n^{-1/2}$ power law. The deviation becomes greater than an order of magnitude at our lowest density [15]. We see that $|\delta\mu/\delta n|$ starts deviating from the theoretical curve in close proximity to the transport-measured critical density, signifying a change in the screening properties of the 2DHG at the transition. Another intriguing result is the nonuniversal behavior of the slopes on the insulating side. It should be emphasized that each slope is determined from a complete segment in the $\mu(n)$ curve (see inset in Fig. 3b) and is, therefore, determined very accurately. The fluctuations in the slopes, seen even in a measurement done using a single SET, are

completely reproducible and suggest that mesoscopic effects are present. Furthermore, the average behavior of $\delta\mu/\delta n$ in this fluctuating regime is seen to be position dependent. An example of that is shown in the inset in Fig. 4 where we plot $|\delta\mu/\delta n|$ measured by two separate SETs on the same Hall bar. Such dependence on position indicates that once the system crosses into the insulating phase it *ceases to be spatially homogeneous*.

The charge traps have a clear signature in our measurements, emphasizing their important role in the thermodynamic ground state of the system. It was recently suggested by Altshuler and Maslov [16] that a gas that is in electrochemical equilibrium with charge traps might show metalliclike behavior of the resistivity due to temperature-dependent scattering by the ionized traps. Although it is clear from our measurements that charging of traps takes place as the density of holes is varied, we are currently unable to determine experimentally whether this coupling is responsible for the metallic behavior seen in our samples.

The mesoscopic behavior and the inhomogeneities observed in the insulator side emphasize the important role of disorder in the MIT. This might explain why theories that do not take full account of strong disorder, such as the clean Wigner crystal [17] or the more elaborate theory of the metallic state [2], do not account for the large divergence seen in $|\delta\mu/\delta n|$. These theories predict that $\delta\mu/\delta n$ would remain *negative* after the transition and would increase only as $n^{-1/2}$. Strong disorder theories, on the other hand, support the possibility of a *positively* diverging $\delta\mu/\delta n$: Positive correction [6] and even a change in sign of $\delta\mu/\delta n$ [18] were suggested to result from disorder. A conceivable scenario is the formation of voids [19] and puddles [20] in the 2DHG. The inability of the voids to screen the back gate voltage results in an added large and positive contribution to $\delta\mu/\delta n$, whereas the discrete screening of puddles contributes to the rapid oscillations. In this scenario, the size and shape of the voids as functions of decreasing density are responsible for the large and seemingly random set of positive slopes observed. This scenario suggests a percolative-like transition [19,21,22], and is in accord with our observation that the 2DHG becomes inhomogeneous in the insulating phase.

In conclusion, we have measured the dependence of $\mu(n)$ across the MIT. Our measurements clearly indicate a thermodynamic change in the screening properties of the 2DHG at the transition. We find the metallic phase to be spatially homogenous and to behave according to the predictions of the HF model. The insulating phase, on the other hand, deviates significantly from the HF predictions and is spatially inhomogeneous.

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