Universal Behavior of the Resistance Noise across the Metal-Insulator Transition in Silicon Inversion Layers

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Studies of low-frequency resistance noise show that the glassy freezing of the two-dimensional (2D) electron system in the vicinity of the metal-insulator transition occurs in all Si inversion layers. The size of the metallic glass phase, which separates the 2D metal and the (glassy) insulator, depends strongly on disorder, becoming extremely small in high-mobility samples. The behavior of the second spectrum, an important fourth-order noise statistic, indicates the presence of long-range correlations between fluctuators in the glassy phase, consistent with the hierarchical picture of glassy dynamics.

Despite many theoretical and experimental efforts, the metal-insulator transition (MIT) [1] in two-dimensional (2D) systems remains controversial. Since the apparent MIT occurs in the regime where both electron-electron interactions and disorder are strong, it has been suggested that the 2D system undergoes glassy ordering in the vicinity of the MIT. The proposals include freezing into a Coulomb [2,3], Wigner [4], or spin glass [5]. Indeed, a recent study of low-frequency resistance noise in an extremely low-mobility (high disorder) 2D electron system in Si demonstrated [6] glassy freezing, which occurred in the metallic phase as a precursor to the MIT.

Here we report a detailed study of low-frequency resistance noise in a 2D electron system (2DES) in Si in the opposite limit of very low disorder, where the metallic drop of resistivity ρ with decreasing temperature T is most pronounced. Such samples have been studied extensively [1,7] in the context of a 2D MIT using magneto-transport measurements. We find that, similar to the case of low-mobility samples, the behavior of several spectral characteristics of noise in these high-mobility devices indicates a sudden and dramatic slowing down of the electron dynamics at a well-defined electron density $n_s = n_g$, corresponding to the transition to a glassy phase. Since the two sets of devices, Si metal-oxide-semiconductor field-effect transistors (MOSFETs), differ considerably by their peak mobility, which is a rough measure of the disorder, and span essentially the entire range of Si technology, we conclude that the observed glass transition is a universal phenomenon in Si inversion layers. The experiments, however, have also revealed an important difference between low- and high-mobility samples. In low-mobility devices, $n_g \approx 1.5 n_c$ [6], where n_c is the critical density for the MIT determined from the vanishing of activation energy [8], and the temperature coefficient of ρ changes sign at $n_s^* > n_g > n_c$. In high-mobility structures, on the other hand, the onset of glassy dynamics seems almost to coincide with the MIT, i.e., $n_g \approx n_c \approx n_s^*$. It is interesting that the observed strong

dependence on disorder of the size of the metallic glass phase ($n_c < n_s < n_g$), which separates the 2D metal and the (glassy) insulator, is consistent with recent predictions of the model of interacting electrons near a disorder-driven MIT [9]. Furthermore, by analyzing the second spectrum [10,11], an important fourth-order noise statistic, we have established the presence of long-range correlations between fluctuators in the glassy phase, which provides an unambiguous evidence for the onset of glassy dynamics at n_g. The results are consistent with the picture in which noise, in the glassy phase, results from transitions between many metastable states with a hierarchical structure [12] with each transition being a reconfiguration of a large number of electrons.

Measurements were carried out on n-channel Si MOSFETs with the peak mobility $\mu \approx 2.5$ m^2/V s at 4.2 K, fabricated in a Hall bar geometry with Al gates, and oxide thickness $d_{ox} = 147$ nm [7]. The resistance R was measured down to $T = 0.24$ K using a standard four-probe ac technique (typically 2.7 Hz) in the Ohmic regime. A precision dc voltage standard (EDC MV116J) was used to apply the gate voltage, which controls n_s. Contact resistances and their influence on noise measurements were minimized by using a split-gate geometry, which allows one to maintain high n_s ($\approx 10^{12}$ cm^{-2}) in the contact region while allowing an independent control of n_s of the 2D system under investigation in the central part of the sample (120×50 μm^2) (Fig. 1 inset). Nevertheless, care was taken to ensure that the observed noise did not come from either the current contacts or the regions of gaps in the gate. For example, since the noise measured across a resistor connected in series with the sample and having a similar resistance was at least 3 times lower than the noise from the central part of the sample, the effect of the contact noise on the excitation current I_{exc} could be easily ruled out. Similarly, the resistance and the noise measured between the voltage contact in the region of high n_s (e.g., No. 5 in Fig. 1 inset) and the one in the central part (No. 6) were much smaller
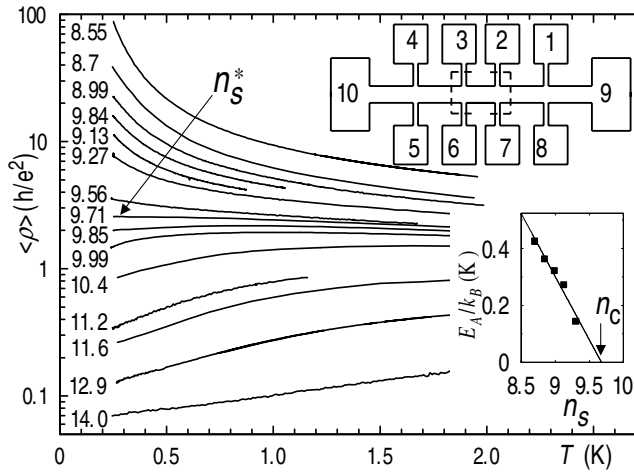
FIG. 1. $\langle\rho\rangle$ vs T for $n_s(10^{10}$ cm$^{-2})$ shown on the plot. Insets: sample schematic (dashed lines represent gaps in the gate), and activation energies vs n_s; $n_c \approx n_s^*$.

than those measured between contacts in the central part (e.g., Nos. 6 and 7). In fact, they were in agreement with what is expected based on the geometry of the sample, which proves that the submicron gap regions did not contribute to either the measured resistance or noise. In order to minimize the influence of fluctuations of both I_{exc} and T, some of the noise measurements were carried out with a bridge configuration [13]. The difference voltage was detected using two PAR124A lock-in amplifiers, and a cross-spectrum measurement was performed with an HP35665A spectrum analyzer in order to reduce the background noise even further [14]. The output filters of the lock-in amplifiers and/or spectrum analyzer served as an antialiasing device. Most of the noise spectra were obtained in the $f = (10^{-4}–10^{-1})$ Hz bandwidth, where the upper bound was set by the low frequency of I_{exc}, limited by the low cutoff frequency of RC filters used to reduce external electromagnetic noise as well as by high R of the sample.

Figure 1 shows the time-averaged resistivity $\langle\rho\rangle$ as a function of T for different n_s; $d\langle\rho\rangle/dT = 0$ at $n_s^* \approx 9.7 \times 10^{10}$ cm^{-2}. For the lowest n_s and T, the data are described by the simply activated form $\langle\rho\rangle \propto \exp(E_A/k_B T)$. The vanishing of E_A is often used as a criterion to determine n_c [8]. This method (Fig. 1 inset) yields $n_c \approx n_s^*$, in agreement with other studies [8].

Figures 2(a) and 2(b) show the time series of the relative changes in resistance $\Delta R(t)/\langle R\rangle$ and the corresponding power spectra $S_R(f) \propto 1/f^\alpha$, respectively. In order to compare the noise magnitudes under different conditions, the spectra were averaged over two octaves $[(0.5 - 2) \times 10^{-3}$ Hz] around $f = 10^{-3}$ Hz. The resulting fraction of power $S_R(f = 1$ mHz$)$ is taken as the measure of noise, and its dependence on n_s is shown in Fig. 3(a) for $T = 0.24$ K. The exponent α is displayed in Fig. 3(b), while Fig. 3(c) shows the dependence of $S_R(f = 1$ mHz$)$ on T for several n_s. Below $T \approx 3$ K, the noise increases with decreasing T, but at high n_s where $d\langle\rho\rangle/$

FIG. 2. (a) $\Delta R/\langle R\rangle$, and (b) the corresponding power spectra $S_R(f)$, for $n_s(10^{10}$ cm$^{-2})$ shown on the plots; $T = 0.24$ K. In (a) traces are shifted for clarity. In (b) $S_R(f)$ are averaged over octaves and multiplied by f, so that the $1/f$ spectrum is horizontal on this scale. Solid lines are linear least-squares fits.

$dT > 0$, S_R depends rather weakly on both T and n_s. In the vicinity of n_c, however, a dramatic change in the behavior of S_R is observed. The noise amplitude starts to increase strongly with decreasing n_s, and α rises rapidly from ≈ 1 to ≈ 1.8 [15]. This shift of the spectral weight towards lower f indicates a sudden and dramatic slowing down of the electron dynamics at $n_g \approx 10 \times 10^{10}$ cm^{-2}, which is attributed to the freezing of the electron glass. The same qualitative behavior, together with other manifestations of glassiness (slow relaxations, history dependence), was observed [6] in Si MOSFETs with a much higher amount of disorder: μ was a factor of 40 lower than in the samples studied here, and not surprisingly, n_g was almost an order of magnitude higher. We note that the two sets of devices also differ substantially by their geometry, size, and many fabrication details (see Refs. [6,7]), all of which leads us to conclude that the observed glass transition is a universal phenomenon in Si inversion layers, at least in those with conventional $(d\langle\rho\rangle/dT > 0)$ metallic behavior [16].

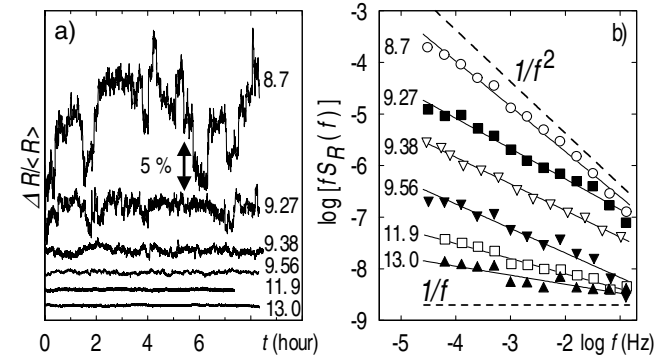In addition to affecting the values of n_c, n_g, and n_s^*, the disorder clearly plays another, nontrivial role. In particular, n_c and n_g were found to differ from each other considerably in low-mobility devices (n_c, n_g, and n_s^* were 5.0, 7.5, and 12.9, respectively, in units of 10^{11} cm^{-2}) [6], whereas in high-mobility devices n_g is at most a few
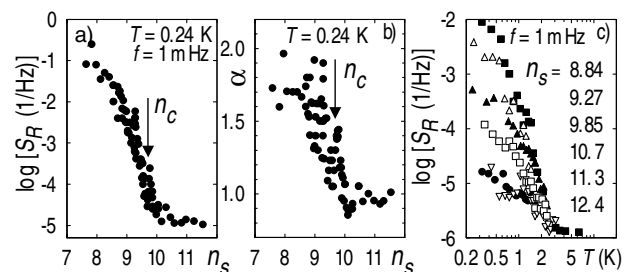

FIG. 3. $S_R(f)$ vs $n_s(10^{10}$ cm$^{-2})$ (a), and vs T (c). (b) α vs n_s. $S_R(f)$ has been corrected for the white background noise. The critical density n_c is shown in (a) and (b).

percent higher than n_c [see Figs. 3(a) and 3(b)]. Therefore, the emergence of glassy dynamics here seems almost to coincide with the MIT. Obviously, the size of the intermediate ($n_c < n_s < n_g$) glass phase depends strongly on disorder, in agreement with theoretical predictions [9].

Earlier studies of noise in R in Si MOSFETs were performed mostly at $T > 4.2$ K and $n_s > 10^{12}$ cm^{-2} [17,18]. The observed random telegraph and $1/f$ noise were attributed to charging and discharging of traps in the oxide close to the Si/SiO$_2$ interface, leading to $dS_R/dT > 0$ [19]. On the other hand, studies carried out at lower n_s and T demonstrated [20,21] clearly that the observed $1/f$ noise was an intrinsic property of the conduction in a 2D channel and not due to charge trapping. Moreover, $dS_R/dT < 0$ was found [21] for $T = 1.5, 4.2$ K. Our measurements at much lower T reveal a dramatic *increase* of S_R with decreasing T. This rules out models of thermally activated charge trapping [11,19,22], noise generated by fluctuations of T [23], and a model of noise near the Anderson transition [24], as possible explanations. Likewise, the models of noise in the Mott and Efros-Shklovskii variable-range hopping regimes [25] do not describe the data because they predict either $dS_R/dT > 0$ or a saturation of S_R below 10–100 Hz, both in clear disagreement with the experiment. Therefore, the observed noise cannot be a result of single electron hops even when Coulomb interactions are included through the Coulomb gap. We note that no such low-frequency saturation of S_R was found in computer simulations of a Coulomb glass, where $1/f$ noise was a result of transitions between many metastable states, with each transition being a reconfiguration of a large number of electrons [26].

We have established that the exponent $\alpha \approx 1$ in the 2D metallic phase (above n_g) in both low- and high-mobility samples. On the other hand, $\alpha \approx 1.8$ in the glassy phase, similar to α found in some spin glasses [27,28], and submicron wires in the quantum Hall regime [29]. In general, such noise with spectra closer to $1/f^2$ than to $1/f$ is typical of a system far from equilibrium, in which a step does not lead to a probable return step. Such high values of α may be also obtained if noise results from a superposition of a small number of independent two-state systems (TSS) [11,22]. However, even though some distinguishable discrete events can be seen at low n_s [Fig. 2(a)], they do not show the characteristic repetitive form of stable TSS. On the contrary, both the shape and the magnitude of noise exhibit random, nonmonotonic (which exclude aging) changes with time. A quantitative measure of such spectral wandering is the so-called second spectrum $S_2(f_2, f)$, which is the power spectrum of the fluctuations of $S_R(f)$ with time [10], i.e., the Fourier transform of the autocorrelation function of the time series of $S_R(f)$. If the fluctuators (e.g., TSS) are not correlated, $S_2(f_2, f)$ is white (independent of f_2) [10,11] and equal to the square of the first spectrum. Such noise is called Gaussian. On the other hand, S_2 has a nonwhite character, $S_2 \propto 1/f_2^{1-\beta}$, for interacting fluctuators [10,11].

Therefore, the deviations from Gaussianity provide a direct probe of correlations between fluctuators.

We investigate S_2 using digital filtering [30] in a given frequency range $f = (f_L, f_H)$ (usually $f_H = 2f_L$). The normalized second spectra, with the Gaussian background subtracted, are shown in Fig. 4(a) for two n_s, just above and just below n_g. It is clear that there is a striking difference in the character of the two spectra. Similar differences are observed between various spin glasses [Fig. 4(a) inset], where S_2 is white [27] in the absence of long-range interactions, and nonwhite [10] when long-range RKKY interaction leads to hierarchical glassy dynamics [12]. A detailed dependence of the exponent $(1 - \beta)$ on n_s has been determined for both high- and low-mobility samples [Figs. 4(b) and 4(c), respectively]. In both cases, S_2 is white for $n_s > n_g$, indicating that the observed $1/f$ noise results from uncorrelated fluctuators. It is quite remarkable that S_2 changes its character in a dramatic way exactly at n_g in both types of samples. For $n_s < n_g$, S_2 is strongly non-Gaussian, which demonstrates that the fluctuators are strongly correlated. This, of course, rules out independent TSS (such as traps) as possible sources of noise when $n_s < n_g$. In fact, a sudden change in the nature of the fluctuators (i.e., correlated vs uncorrelated) as a function of n_s rules out *any* traps, defects, or a highly unlikely scenario that the observed glassiness may be due to some other time dependent changes of the disorder potential itself. Instead, it provides an unambiguous evidence for the onset of glassy dynamics in a 2D electron system at n_g.

In the studies of spin glasses, the scaling of S_2 with respect to f and f_2 has been used [10] to unravel the glassy dynamics and, in particular, to distinguish generalized models of interacting droplets or clusters (i.e., TSS) from hierarchical pictures. In the former case, the low-f
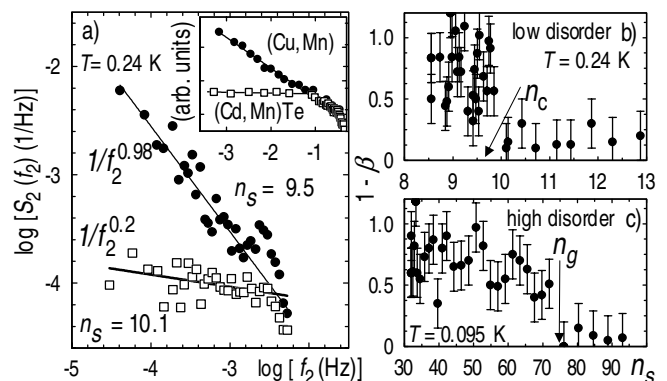

FIG. 4. (a) Second spectral density $S_2(f_2)$ vs f_2 for $n_s(10^{10}$ cm$^{-2})$ shown on the plot; $f_L = 1$ mHz. Inset: $\log[S_2(f_2)]$ for spin glasses Cu$_{0.91}$Mn$_{0.09}$ [10] and Cd$_{0.93}$Mn$_{0.07}$Te [27]. Solid lines are fits. Exponent $1 - \beta$ vs $n_s(10^{10}$ cm$^{-2})$ for (b) high-mobility and (c) low-mobility samples. The low-mobility device is the same as the one studied in Ref. [6].
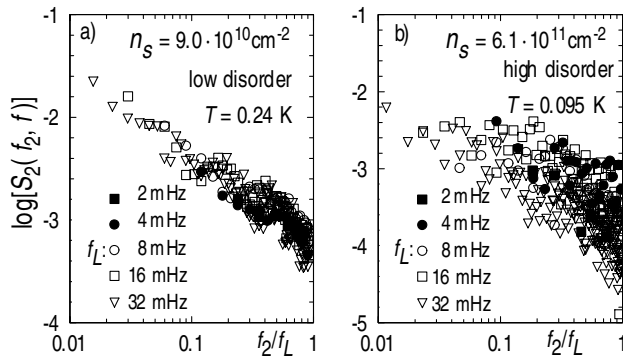
FIG. 5. Scaling of S_2 measured at frequency octaves $f = (f_L, 2f_L)$ for (a) high-mobility and (b) low-mobility samples.

noise comes from a smaller number of large elements because they are slower, while the higher-f noise comes from a larger number of smaller elements, which are faster. In this picture, which assumes compact droplets and short-range interactions between them, big elements are more likely to interact than small ones and, hence, non-Gaussian effects and S_2 will be stronger for lower f. $S_2(f_2, f)$, however, need to be compared for fixed f_2/f, i.e., on time scales determined by the time scales of the fluctuations being measured, since spectra taken over a fixed time interval average the high-frequency data more than the low-frequency data. Therefore, in the interacting "droplet" model, $S_2(f_2, f)$ should be a decreasing function of f at constant f_2/f. In the hierarchical picture, on the other hand, $S_2(f_2, f)$ should be scale invariant: it should depend only on f_2/f, not on the scale f [10]. Figure 5 shows that no systematic dependence of S_2 on f is seen in our samples, which signals that the system wanders collectively between many metastable states related by a kinetic hierarchy. Metastable states correspond to the local minima or "valleys" in the free energy landscape, separated by barriers with a wide, hierarchical distribution of heights and, thus, relaxation times. Intervalley transitions, which are reconfigurations of a large number of electrons, thus lead to the observed strong, correlated, $1/f$-type noise, remarkably similar to what was observed in spin glasses with a long-range correlation of spin configuration [10]. We note that, unlike droplet models [31], hierarchical pictures of glassy dynamics [32] do allow for the existence of a finite T (or finite Fermi energy) glass transition in the presence of a symmetry-breaking field, such as the random potential in an electron glass.

In summary, by studying the statistics of low-f resistance noise, we have established that the glassy ordering of a 2DES near the MIT occurs in all Si inversion layers. The size of the metallic glass phase, which separates the 2D metal and the glassy insulator, depends strongly on disorder, becoming extremely small in high-mobility samples. The properties of the entire glass phase are consistent with the hierarchical picture of glassy dynamics, similar to spin glasses with long-range correlations.

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