Onset of Glassy Dynamics in a Two-Dimensional Electron System in Silicon

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The fluctuations of conductivity σ with time have been studied in a two-dimensional electron system in low-mobility Si inversion layers. The noise power spectrum is $\sim 1/f^{\alpha}$ with α exhibiting a sharp jump at an electron density $n_s = n_g$. A huge increase in the relative variance of σ is observed as n_s is reduced below n_g, reflecting a dramatic slowing down of the electron dynamics. This is attributed to the freezing of the electron glass. The data strongly suggest that glassy dynamics persists in the metallic phase.

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The possibility of a metal-insulator transition (MIT) in two dimensions (2D) has been the subject of intensive research in recent years [1,2] but the physics behind this phenomenon is still not understood. It is well established that the MIT occurs in a regime where both Coulomb (electron-electron) interactions and disorder are strong. Theoretically, it is well known [3] that, in the strongly localized limit, the competition between electron-electron interactions and disorder leads to glassy dynamics (electron or Coulomb glass). Some glassy properties, such as slow relaxation phenomena, have indeed been observed in various insulating thin films [4–6]. Furthermore, recent work [7] has suggested that the critical behavior near the 2D MIT may be dominated by the physics of the insulator, leading to the proposals that the 2D MIT can be described as the melting of the Wigner [8] or electron glass [9]. It is clear that understanding the nature of the insulator represents a major open issue in this field. Here we report the first detailed study of glassy behavior in a 2D system in semiconductor heterostructures. The glass transition is manifested by a very abrupt onset of a specific type of random-looking slow dynamics, together with other signs of cooperativity. Our results strongly suggest that the glass transition occurs in the metallic phase as a precursor to the MIT, in agreement with recent theory [10].

While glassy systems exhibit a variety of phenomena [11], studies of metallic spin glasses have demonstrated [12] that mesoscopic, i.e., transport noise measurements are required in order to provide definitive information on the details of glassy ordering and dynamics. Fluctuations of conductivity σ as a function of chemical potential (or gate voltage V_g, which controls the carrier density n_s) have been investigated extensively in the insulating regime [13] and near the MIT [14] in a 2D electron system in mesoscopic Si metal-oxide-semiconductor field-effect transistors (MOSFETs). In order to get reasonably reproducible fluctuations of $\sigma(V_g)$, it was necessary to make very slow sweeps of many hours over a very narrow range of V_g. Thus, all measurements represented a time average. As a matter of fact, it had already been known [15] that, at fixed V_g (or n_s), σ fluctuates as a function of time t. Both high- and low-frequency fluctuations were evident. It was speculated that the time dependence of σ was due to correlated transitions of electrons between different configurations [15] or, in other words, between different metastable states in the glassy phase, but there has been no detailed study of these effects up to now. Here we present the first systematic study of transport and noise in a strongly disordered, mesoscopic 2D system over a wide range of n_s and T.

Most of the measurements were carried out on a 1-μm-long, 90-μm-wide rectangular n-channel Si MOSFET with the peak mobility of only 0.06 m^2/V s at 4.2 K (with the applied backgate bias of -2 V). The samples were fabricated with poly-Si gates, self-aligned ion-implanted contacts [16], substrate doping $N_a \sim 2 \times 10^{17}$ cm^{-3}, oxide charge $N_{ox} = 1.5 \times 10^{11}$ cm^{-2}, and oxide thickness $d_{ox} = 50$ nm. The fluctuations of current I (i.e., σ) were measured as a function of t in a two-probe configuration using an ITHACO 1211 current preamplifier and a PAR124A lock-in amplifier at $\sim$13 Hz. The excitation voltage V_{exc} was kept constant and low enough (typically, a few μV) to ensure that the conduction was Ohmic. A precision dc voltage standard (EDC MV116J) was used to apply V_g. The fluctuations of I as low as 10^{-13} A were measured at $0.13 \leq T \leq 0.80$ K in a dilution refrigerator with heavily filtered wiring. Relatively small fluctuations of T, V_g, and V_{exc} were ruled out as possible sources of the measured noise, since no correlation was found between them and the fluctuations of I. In addition, a Hall bar sample from the same wafer was measured at $T = 0.25$ K in both two- and four-probe configurations, and it was determined that the contact resistances and the contact noise were negligible.

The relative fluctuations $(\sigma - \langle\sigma\rangle)/\langle\sigma\rangle$ (averaging over time intervals of several hours) are shown in Fig. 1 for a few n_s at $T = 0.13$ K. It is quite striking that, for the lowest n_s, the fluctuation amplitude is of the order of 100%. In addition to rapid, high-frequency fluctuations, both abrupt jumps and slow changes over several hours are also evident. The amplitude of the fluctuations decreases with increasing either n_s or T, as discussed in more detail below.

Figure 2 shows the time-averaged conductivity $\langle\sigma\rangle$ as a function of T for different n_s. The behavior of $\langle\sigma(n_s, T)\rangle$

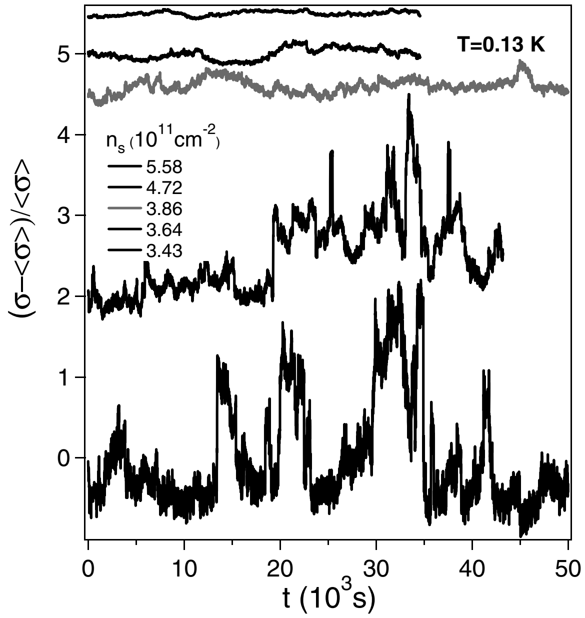

FIG. 1. Relative fluctuations of σ vs time for different n_s at $T = 0.13$ K. Different traces have been shifted for clarity; the lowest n_s is at the bottom and the highest n_s at the top.

in our samples is found to be somewhat similar to that of high-mobility Si MOSFETs. At the highest n_s, for example, our devices exhibit a metalliclike behavior with $d\langle\sigma\rangle/dT < 0$. The change of $\langle\sigma\rangle$ in a given T range, however, is small (only 6% for the highest $n_s = 20.2 \times 10^{11}$ cm^{-2}) as observed in other Si MOSFETs with a large amount of disorder [17,18]. $d\langle\sigma\rangle/dT$ changes sign when $\langle\sigma(n_s^*)\rangle = 0.5e^2/h$, similar to other 2D samples [1]. Even though the corresponding density $n_s^* = 12.9 \times 10^{11}$ cm^{-2} is much higher due to a large amount of disorder in our devices, the effective Coulomb interaction is still comparable to that in other 2D systems ($r_s \sim 4$, r_s ratio of Coulomb energy to Fermi energy).

The density n_s^*, where $d\langle\sigma\rangle/dT = 0$, has been usually [1] identified with the critical density for the MIT. In high-mobility Si MOSFETs, the critical density has also been determined [21] as the density n_c, where activation energy associated with the insulating exponential behavior of $\langle\sigma(T)\rangle$ vanishes. It was established that $n_s^* \approx n_c$, although a small but systematic difference of a few percent has been reported [17,20] such that $n_s^* > n_c$. For the lowest n_s in our experiment, the data are best described by the simply activated form $\langle\sigma\rangle \propto \exp(-T_0/T)$ [Fig. 3(a)], consistent with other studies close enough to the MIT [21]. The data could not be fitted satisfactorily to any variable-range hopping (VRH) law regardless of the prefactor. T_0 decreases linearly with increasing n_s [Fig. 3(a) inset], and vanishes at $n_c \approx 5.2 \times 10^{11}$ cm^{-2}. Close to n_c, the data are best described by the metallic power-law behavior $\langle\sigma(n_s, T)\rangle = a(n_s) + b(n_s)T^x$ with $x \approx 1.5$ [Fig. 3(b)]. The fitting parameter $a(n_s)$ is relatively

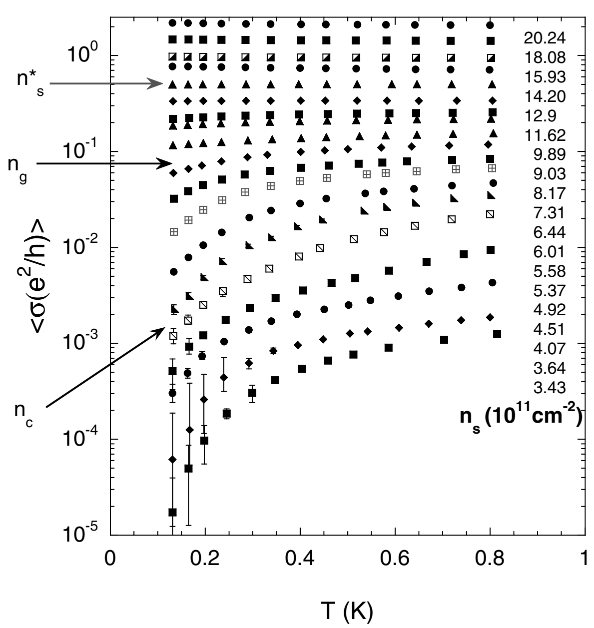

FIG. 2. $\langle\sigma\rangle$ vs T for different n_s. The data for many other n_s have been omitted for clarity. The error bars show the size of the fluctuations. n_s^*, n_g, and n_c are marked by arrows. They were determined as explained in the main text.

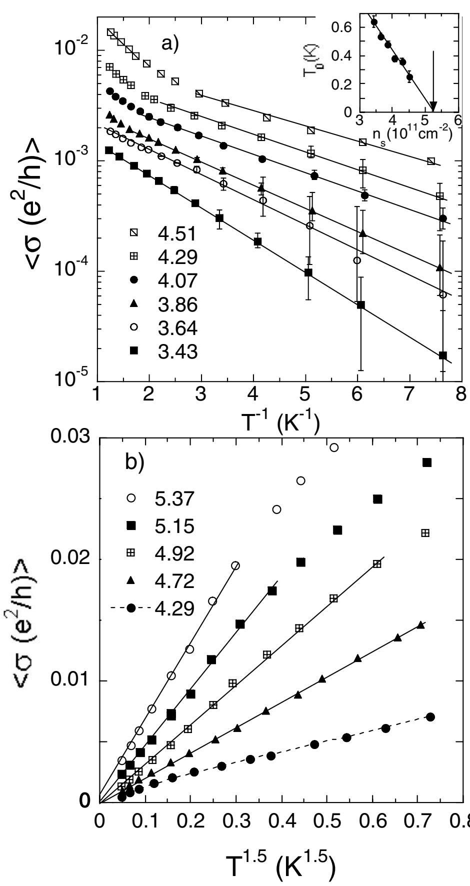

FIG. 3. (a) $\langle\sigma\rangle$ vs T^{-1} for several $n_s(10^{11}$ cm$^{-2})$ in the insulating regime. The error bars show the size of the fluctuations, and the lines are fits to $\langle\sigma\rangle \propto \exp(-T_0/T)$. Inset: T_0 vs n_s with a linear fit, and an arrow showing n_c. (b) $\langle\sigma\rangle$ vs $T^{1.5}$ for a few $n_s(10^{11}$ cm$^{-2})$ near n_c. The solid lines are fits; the dashed line is a guide to the eye, clearly showing insulating behavior $[\langle\sigma(T \to 0)\rangle = 0]$.

small and, in fact, vanishes for $n_s(10^{11}\ \mathrm{cm}^{-2}) = 4.72$ and 4.92. Such a simple power-law T dependence of σ, given by $\langle\sigma(n_c, T)\rangle \propto T^x$, is consistent with the one expected in the quantum critical region (QCR) of the MIT based on general arguments [22], and with the behavior observed in 3D systems [22] and other Si MOSFETs [2] within the QCR. Therefore, based on the analysis of $\langle\sigma(n_s, T)\rangle$ in both the insulating regime and the QCR, we conclude that the critical density $n_c = (5.0 \pm 0.3) \times 10^{11}\ \mathrm{cm}^{-2}$ ($r_s \sim 7$), which is more than a factor of 2 smaller than n_s^*. Such a large difference between n_c and n_s^* is attributed to a much higher amount of disorder in our samples than in high-mobility Si MOSFETs [17,20,21].

$\sigma(t)$ was studied first by analyzing $\delta\sigma = \langle(\sigma - \langle\sigma\rangle)^2\rangle^{1/2}$. The Fig. 4 inset shows that, while $\delta\sigma$ does not depend on T, it increases with n_s by 3 orders of magnitude. The most striking feature of the data, however, is the sudden and dramatic change in the rate of its n_s dependence (see "kink" in Fig. 4 inset), which occurs near n_c. Although we are not aware of any theoretical work relevant to this problem, we note that the observed $\delta\sigma(n_s)$ is plausible: once electrons enter the localized (i.e., insulating) phase by reducing n_s below n_c, their ability to change configurations will be severely impaired, resulting in a much more rapid drop of $\delta\sigma$ with decreasing n_s.

Figure 4 shows that, for high n_s, $\delta\sigma/\langle\sigma\rangle$ is independent of n_s and T. However, below a certain density $n_g = (7.5 \pm 0.3) \times 10^{11}\ \mathrm{cm}^{-2}$, which does not seem to depend on T, an enormous increase of $\delta\sigma/\langle\sigma\rangle$ is observed with decreasing either n_s or T. It is interesting that $\delta\sigma/\langle\sigma\rangle$ does not exhibit any special features near n_c or n_s^*. The onset of strong noise at $n_g > n_c$ is, in fact, consistent with the observation [23] that, in some materials, a considerable increase in noise occurs in the metallic phase as a precursor to the MIT. We show below that here n_g represents the density below which the 2D electron system freezes into an electron glass.

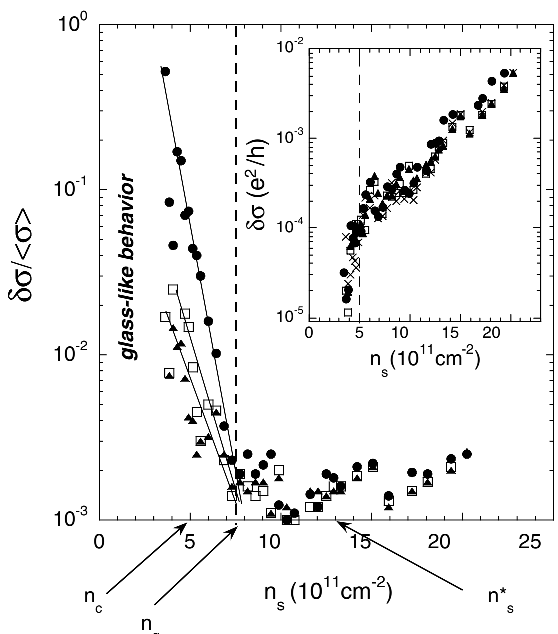

FIG. 4. $\delta\sigma/\langle\sigma\rangle$ (main) and $\delta\sigma$ (inset) vs n_s at different T (●: 0.130 K; ×: 0.196 K; □: 0.455 K; ▲: 0.805 K). Main: n_s^*, n_g, and n_c are marked by arrows. The vertical dashed line shows the region of densities $n_s < n_g$, where various glassy properties have been observed. Inset: the vertical dashed line shows the location of the critical density n_c.

The normalized power spectra $S_I(f) = S(I, f)/I^2$ (f frequency) of $(\sigma - \langle\sigma\rangle)/\langle\sigma\rangle$ were also studied for all n_s and T. Most of the spectra were obtained in the $f = (10^{-4}\text{–}10^{-1})$ Hz bandwidth, where they follow the well-known empirical law $S_I \propto 1/f^\alpha$ [24,25] (usually, $\alpha \sim 1$). The background noise was measured by setting $I = 0$ for all n_s and T. It was always white and usually several orders of magnitude smaller than the sample noise. Nevertheless, a subtraction of the background spectra was always performed, and the power spectra of the device noise were averaged over frequency bands ($\lesssim$ an octave). Some of the resulting S_I are presented in Fig. 5(a). At the highest n_s (not shown), $S_I(f)$ does not depend on n_s. However, it is obvious that, by reducing n_s below n_g, S_I increases enormously, by up to 6 orders of magnitude at low f. This striking increase of the slow dynamic contribution to the conductivity is consistent with the behavior of $\delta\sigma/\langle\sigma\rangle$ (Fig. 4). In fact, since $(\delta\sigma)^2/\langle\sigma\rangle^2 = \int S_I(f)\,df$, it is clear that the observed giant increase of $\delta\sigma/\langle\sigma\rangle$ for $n_s < n_g$ (Fig. 4) reflects a *sudden and dramatic slowing down of the electron dynamics*. This is attributed to the freezing of the electron glass. In addition, for $n_s < n_g$, $S_I(f)$ *increases* exponentially with decreasing T. The observed T dependence of noise (obvious from Fig. 4) is consistent with early studies on Si MOSFETs [26], and it shows that the noise in our system cannot be explained by the models of thermally activated charge trapping [25,27,28], noise generated by fluctuations of T [29], noise in the hopping regime [30], and noise in the vicinity of the Anderson transition [23]. On the other hand, a similar increase of noise at low T has been observed in mesoscopic spin glasses [31,32], in wires in the quantum Hall regime for tunneling through localized states [33], and in Si quantum dots in the Coulomb blockade regime [34].

Another remarkable result, shown in Fig. 5(b), is a sharp jump of the exponent α at $n_s \approx n_g$. While $\alpha \approx 1$ for $n_s > n_g$, $\alpha \approx 1.8$ below n_g, reflecting a sudden shift of the spectral weight towards lower frequencies. Similar large values of α have been observed in spin glasses above the MIT [32], and in submicron wires [33]. 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. We also have the analysis of higher order statistics (non-Gaussianity or second spectra [12,25]) of the noise, showing an abrupt change to the type of statistics characteristic of complicated multistate systems just at the density n_g at which α jumps. This will be described in detail elsewhere.

We have demonstrated that the transition to a glassy phase is characterized by a sudden, enormous increase in

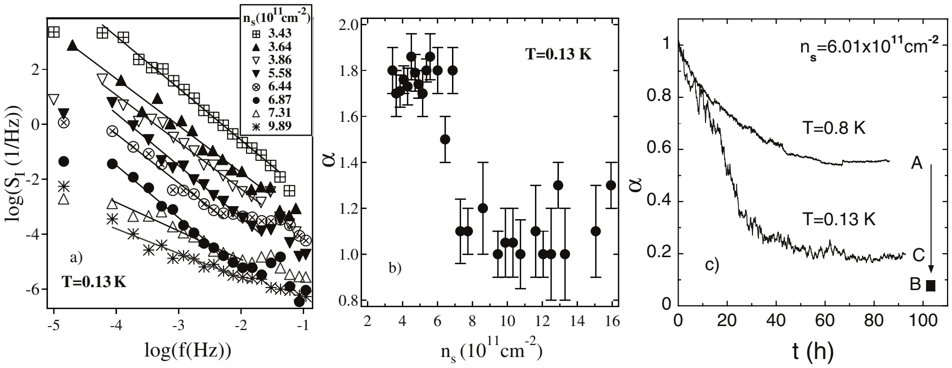

FIG. 5. (a) The averaged noise power spectra $S_I \propto 1/f^{\alpha}$ vs f for several n_s. The solid lines are linear least-squares fits with the slopes equal to α. (b) α vs n_s. (c) Relaxation of σ following a slow change in $n_s(10^{11}\ \mathrm{cm}^{-2})$ from 15.93 to 6.01, carried out at $T = 0.8$ and $T = 0.13$ K over a period of $\approx$4.5 hours each. After σ reached a stationary value (A) at 0.8 K, the sample was cooled down to 0.13 K. The resulting σ (B) differs from σ (C), obtained using a different cooling procedure, by a factor of 2, clearly demonstrating history-dependent, i.e., nonergodic behavior. Such behavior is not observed for $n_s > n_g$.

the low-frequency noise in σ, a sudden shift of the spectral weight towards lower f, and a dramatic increase of noise with decreasing T. Similar behavior in spin glasses was attributed to spin glass freezing [31,32]. In addition, for $n_s < n_g$, we have observed long relaxation times following a large change in V_g, and history-dependent behavior characteristic of a glassy phase [Fig. 5(c)]. We note that, in order to obtain reproducible values of $\langle\sigma(n_s, T)\rangle$ shown in Fig. 2, it was necessary to vary n_s in small steps of $4.3 \times 10^{10}\ \mathrm{cm}^{-2}$ at the highest T (0.8 K).

In summary, we present the first evidence of electron glass freezing at a well-defined density n_g in a 2D electron system in silicon, in agreement with theoretical predictions [8,9]. Glassy freezing occurs in the regime of very low $\langle\sigma\rangle$, apparently as a precursor to the MIT. The existence of such an intermediate ($n_c < n_s < n_g$) glass phase is consistent with theoretical predictions [10].

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