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

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The time-dependent fluctuations of conductivity $\sigma$ have been studied in a two-dimensional electron system in low-mobility, small-size Si inversion layers. The noise power spectrum is $\sim 1/f^\alpha$ with $\alpha$ exhibiting a sharp jump at a certain electron density $n_s = n_g$. An enormous increase in the relative variance of $\sigma$ 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 a subject of intensive research in recent years [1], but the physics behind this phenomenon is still not understood. It is well established that the MIT occurs in the regime where both Coulomb (electron-electron) interactions and disorder are strong. Theoretically, it is well known [2] 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 been indeed observed in various insulating thin films [3]. Furthermore, recent work [4] 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 may be dominated by the physics of the insulator, leading to the proposals that the 2D MIT can be described alternatively as the melting of the Wigner glass [8], or the melting of the 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 [1, 2], studies of metallic spin glasses have demonstrated [3] 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 $\sigma$ 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 [3] and near the MIT [4] in a 2D electron system in mesoscopic Si metal-oxide-semiconductor field-effect transistors (MOSFETs). The latter study indicated that Coulomb interactions dominate the physics near the MIT. In order to get reasonably reproducible fluctuations as a function of $V_g$, 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 been already known [11] that, at fixed $V_g$ (or $n_s$), $\sigma$ fluctuates as a function of time. Both high- and low-frequency fluctuations were evident. It was speculated that the time dependence of $\sigma$ was due to correlated transitions of electrons between different configurations [12] 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 $\mu$m long, 90 $\mu$m wide rectangular n-channel Si MOSFET with the peak mobility of only 0.06 $m^2/Vs$ at 4.2 K (with the applied back-gate bias of $-2$ V). The samples were fabricated using standard 0.25 $\mu$m Si technology [13] with poly-Si gates, self-aligned ion-implanted contacts, 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 $I$ ($i.$ $e.$ $\sigma$) were measured as a function of time 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 $\mu$V) to ensure that the conduction was Ohmic. A precision DC voltage standard (EDC MV1163J) was used to apply $V_g$. The current fluctuations 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 current fluctuations. 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. [4] for a few selected $n_s$ 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
FIG. 1. Relative fluctuations of $\langle \sigma \rangle$ vs. time for different $n_s$ at $T = 0.13$ K. Different traces have been shifted for clarity, starting with the lowest $n_s$ at bottom and the highest at top.

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. $n_s^*$, $n_d$, and $n_c$ are marked by arrows. They were determined as explained in the main text. 

periods of 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 $\langle \sigma(n_s, T) \rangle$ 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 metallic-like behavior with $d(\sigma)/dT < 0$. 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 [15,18]. $d(\sigma)/dT$ changes sign when $\langle \sigma(n_s^*) \rangle = 0.5 e^2/h$ similar to other 2D samples [8]. 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 $d(\sigma)/dT = 0$, has been usually identified with the critical density for the MIT. In high-mobility Si MOSFETs, the critical density has been also 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 [22]. $T_0$ 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 small and, in fact, vanishes for $n_s(10^{11}$ cm$^{-2}) = 4.72$ and 4.92. Such a simple power-law $T$-dependence of
samples than in high-mobility Si MOSFETs \cite{17,20,21}. The fluctuations of \( \sigma \) with time have been studied first by analyzing \( \delta \sigma = \langle (\sigma - \langle \sigma \rangle)^2 \rangle^{1/2} \). Fig. 4 inset shows that, while \( \delta \sigma \) does not seem to depend on \( T \), it increases with \( n_s \) by three 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 the fluctuation amplitude \( \delta \sigma \) with decreasing \( n_s \).

The critical density \( \delta \sigma/\sigma \) keeps decreasing with \( T \) and \( n_s \), which is consistent with the observation \cite{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 \( n_{s} \) represents the density below which the 2D electron system freezes into an electron glass.

The normalized power spectra \( S_1(f) = S(I,f)/I^2 \) (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 \( f = (10^{-4} - 10^{-1}) \) Hz bandwidth, where they follow the well-known empirical law \( S_1 = \beta/f^{\alpha} \) \cite{23,24} \((\beta \text{ is inversely proportional to the number of fluctuators and, usually, } \alpha \approx 1)\). 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 \((\lesssim \text{ an octave})\). Some of the resulting \( S_1 \) are presented in Fig. 5(a). At the highest \( n_s \) (not shown), \( S_1(f) \) does not depend on \( n_s \). However, it is obvious that, by reducing \( n_s \) below \( n_g \), \( S_1 \) increases enormously, by up to six orders of magnitude at low \( f \). This striking increase of the slow dynamic contribution to the conductivity is consistent with the behavior of \( \sigma(n_s, T) \) \cite{23}. The observed \( T \)-dependence of noise (obvious from Fig. 5) is consistent with early studies on Si MOSFETs \cite{27}, and it shows that the noise in our system cannot be explained by the models of thermally activated charge trapping \cite{26,27,29}, noise generated by fluctuations of \( T \) \cite{20,21}, noise in the hopping regime \cite{34}, and in the vicinity of the Anderson transition \cite{24}. On the other hand, similar increase of noise at low \( T \) has been observed in mesoscopic spin glasses \cite{20,24,34}, in wires in the quantum Hall regime for tunneling through localized states \cite{33}, and in Si quantum dots in the Coulomb blockade regime \cite{35}.

Another remarkable result, shown in Fig. 5(b), is a sharp jump of the exponent \( \alpha \) 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 \( \alpha \) have been observed in spin glasses above the MIT \cite{24}, and in submicron wires \cite{33}. In general, such noise with spectra closer to \( 1/f^{\alpha} \) 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 \cite{12,26}) of the noise, showing an abrupt change to the sort of statistics characteristic of complicated multi-state systems just at the density \( n_g \) at which \( \alpha \) jumps. This will be described in detail elsewhere.
We note that in order to obtain reproducible values of addition, for glasses was attributed to spin glass freezing [32,33]. In T of noise with decreasing spectral weight towards lower in the low-frequency noise in glass freezing at a well-defined density low system in silicon, in agreement with theoretical predictions [8,9]. Glassy freezing occurs in the regime of very is consistent with theoretical predictions [10].

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We have demonstrated that the transition to a glassy phase is characterized by a sudden, enormous increase in the low-frequency noise in \( \alpha \), 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 [22,23]. 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. 3(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 \( 4.3 \times 10^{10} \text{cm}^{-2} \) at the highest \( T \) (0.8 K).

In summary, we present the first evidence of electron glass freezing at a well-defined density \( n_d \) in a 2D electron system in silicon, in agreement with theoretical predictions [24]. 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 \( (n_e < n_s < n_g) \) glass phase is consistent with theoretical predictions [25].

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FIG. 5. (a) The averaged noise power spectra \( S_f \propto 1/f^\alpha \) vs. \( f \) for several \( n_s \). Solid lines are linear least-squares fits with the slopes equal to \( \alpha \). (b) \( \sigma \) vs. \( n_s \). (c) Relaxation of \( \sigma \) following a slow change in \( n_s (10^{13} \text{cm}^{-2}) \) from 15.93 to 6.01, carried out at \( T = 0.8 K \) and \( T = 0.13 K \) over a period of \( \approx 4.5 \) hours each. After \( \sigma \) reached a stationary value \( \langle A \rangle \) at 0.8 K, the sample was cooled down to 0.13 K. The resulting \( \sigma \) (B) differs from \( \sigma \) (C) obtained using a different cooling procedure by a factor of two, clearly demonstrating history dependent, i.e. non-ergodic behavior. Such behavior is not observed for \( n_s > n_g \).

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