Glass Transition in a Two-Dimensional Electron System in Silicon

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Abstract

Large fluctuations of conductivity with time are observed in a low-mobility two-dimensional electron system in silicon at low electron densities \( n_s \) and temperatures. A dramatic increase of the noise power (\( \propto 1/f^\alpha \)) as \( n_s \) is reduced below a certain density \( n_g \), and a sharp jump of \( \alpha \) at \( n_s \approx n_g \), are attributed to the freezing of the electron glass at \( n_s = n_g \). The data strongly suggest that glassy dynamics persists in the metallic phase.

Key words: Glassy dynamics, metal-insulator transition

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1 Introduction

The 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 has been established, however, that it occurs in the regime where both Coulomb (electron-electron) interactions and disorder are strong. The competition between these two effects has been suggested [2] to lead to glassy dynamics (electron or Coulomb glass). Therefore, it has been proposed that the 2D MIT can be described alternatively as the melting of the Wigner glass [3], or the melting of the Coulomb glass [4]. The existence of a large number of metastable states in a glass results in fluctuations of conductivity \( \sigma \) with time (conductivity noise) so that mesoscopic samples should be more suitable for studies of glassy properties. Indeed, investigations of metallic spin glasses have shown [5] that mesoscopic measurements

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are necessary in order to provide detailed understanding of glassy ordering and dynamics. Here we report the results of transport and noise studies in mesoscopic samples, which demonstrate for the first time the existence of a glassy phase in a 2D system in semiconductor heterostructures.

2 Experiment

The measurements were performed on a 1 µm long, 90 µm wide rectangular n-channel Si metal-oxide-semiconductor field-effect transistor (MOSFET) with the peak mobility of only 0.06 m²/Vs at 4.2 K. Other sample details have been given elsewhere [6]. The fluctuations of current (i.e. σ) as a function of time were measured using a low-noise current preamplifier and a standard two-probe lock-in technique at ~ 13 Hz with the constant excitation voltage \( V_{\text{exc}} \sim \) a few µV. By changing the gate voltage \( V_g \), the electron density \( n_s \) was varied between 3.4 x 10^{11} cm\(^{-2}\) and 20.2 x 10^{11} cm\(^{-2}\), whereas temperature \( T \) ranged between 0.13 K and 0.80 K. It was established that the current fluctuations were not correlated with (i.e. not due to) the fluctuations of temperature or applied voltage. In addition, another sample from the same wafer was measured in a four-terminal configuration at 0.25 K, and it was determined that the contact resistances and the contact noise were negligible.

3 Results

Fig. 1 (left) shows the time dependence of the relative fluctuations (\( \sigma - \langle \sigma \rangle / \langle \sigma \rangle \) (where \( \langle \ldots \rangle \) denotes averaging over time) for a fixed \( n_s \) at different \( T \). At the lowest \( T = 0.13 \) K, fluctuations are as high as 250 %, and drop rapidly with increasing \( T \). A similar decrease in fluctuations was observed with increasing \( n_s \), as discussed in more detail below.

The time-averaged conductivity \( \langle \sigma \rangle \) was calculated for time intervals of several hours, for all \( n_s \) and \( T \). Fig. 1 (right) depicts \( \langle \sigma \rangle \) as a function of \( T \) at selected \( n_s \). Similar to the behavior of various high-mobility 2D systems [1], the temperature coefficient of conductivity \( d\langle \sigma \rangle /dT \) changes sign when \( \langle \sigma (n_s^*) \rangle = 0.5 \ e^2/h \). 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 samples, the effective Coulomb interaction is still comparable to that in other 2D systems (\( r_s = 4.6 \), \( r_s \) – ratio of Coulomb energy to Fermi energy). The densities \( n_s^* \), where \( d\langle \sigma \rangle /dT = 0 \), have been usually [1] identified with the critical density \( n_c \) for the metal-insulator transition. However, a thorough analysis of \( \langle \sigma (n_s, T) \rangle \) at low \( n_s \) shows [6] that, in our case, \( n_c = (5.0 \pm 0.3) \times 10^{11} \) cm\(^{-2}\), which is more than a
factor of two smaller than \( n^*_s \). The difference between \( n_c \) and \( n^*_s \) in our samples is attributed to a larger amount of disorder.

The root-mean-square (rms) fluctuations \( \delta \sigma = \langle (\sigma - \langle \sigma \rangle)^2 \rangle^{1/2} \) (calculated over the frequency bandwidth from \((10 \text{ hours})^{-1} \) to \((6 \text{ seconds})^{-1} \) increase with \( n_s \), ranging between \((10^{-5} - 10^{-2}) \) \( e^2/h \) at all \( T \). Fig. 2 (left) shows the relative rms, \( \delta \sigma / \langle \sigma \rangle \), as a function of \( n_s \) at three different \( T \). While fluctuations seem to be independent of density at high \( n_s \), a dramatic increase of \( \delta \sigma / \langle \sigma \rangle \) is observed with decreasing \( n_s \) below \( n_g = (7.5 \pm 0.3) \times 10^{11} \text{cm}^{-2} \). Even though an increase in \( T \) causes a substantial reduction of \( \delta \sigma / \langle \sigma \rangle \), the onset of large fluctuations does not seem to depend on temperature.

The noise was studied in more detail using normalized power spectra \( S_I(f) = S(I,f)/I^2 \), most of which were obtained in the \( f = 10^{-4} - 10^{-1} \text{ Hz} \) bandwidth. They were found to follow the well-known power-law frequency dependence \( S_I \propto 1/f^\alpha \) (Hooge’s law) [7]. In all measurements, the device noise was extracted from the total measured noise by subtracting the background noise present with no current flowing, \( i.e. \) by setting \( V_{exc} = 0 \). The power spectrum of the background noise was always several orders of magnitude smaller than sample noise and had no \( f \)-dependence (white noise). Fig. 2 (center) shows \( S_I \) as a function of \( n_s \) at \( f = 3.16 \times 10^{-4} \text{ Hz} \) and \( T = 0.13 \text{ K} \). At high \( n_s \), \( S_I \) does not depend on \( n_s \) within the scatter of data. For \( n_s < n_g \), however, an exponential rise of \( S_I \) by six orders of magnitude is observed with decreasing \( n_s \). This striking increase of the slow dynamic contribution to \( \sigma \) is consistent with the behavior of \( \delta \sigma / \langle \sigma \rangle \) (Fig. 2, left). In fact, since \( (\delta \sigma)^2 / \langle \sigma \rangle^2 = \int S_I(f) df \), it is clear that the observed enormous increase of the relative rms as \( n_s \) is reduced below \( n_g \) (Fig. 2, left) reflects a dramatic slowing down of the electron dynamics. This is attributed to the freezing of the electron glass.

Fig. 2 (right) shows another striking feature of our data. The exponent \( \alpha \), which describes the frequency dependence of the noise power \( S_I \propto 1/f^\alpha \), exhibits a sudden jump at \( n_s \approx n_g \). While \( \alpha \approx 1 \) for \( n_s > n_g \), \( \alpha \approx 1.8 \) for \( n_s < n_g \); similar large exponents \( \alpha \) have been observed in metallic spin glasses [8]. In general, it is possible to obtain such high values of \( \alpha \) if telegraph noise is superimposed on flicker (1/f) noise [9]. However, our data exhibit many abrupt jumps rather than two-level switching (see Fig. 1, left).

For \( n_s < n_g \), a rapid decrease of \( S_I \) is also observed with increasing \( T \) (inset to Fig. 2, center), consistent with other studies on Si MOSFETs [10] at higher \( T \) (\( T = 1.5, 4.2 \text{ K} \)). The observed \( T \)-dependence of noise disagrees with the models of thermally activated charge trapping-detrapping fluctuations [9,11,12], noise generated by temperature fluctuations [13], and in the vicinity of the Anderson transition [14], all of which predict an increase of noise with increasing \( T \). Models of noise in the hopping regime [15] predict either a \( T \)-independent noise or a power-law decrease of noise with \( T \). In
our experiment, however, $S_T$ follows an exponential rather than power-law $T$-dependence. On the other hand, the observed $S_T(T)$ does agree with the behavior found in mesoscopic spin glasses [16,8,17].

4 Summary

Measurements of the time dependence of $\sigma$ in low-mobility Si MOSFETs have shown that, with decreasing $n_s$, a sudden, enormous increase in the low-frequency conductivity noise and a sudden shift of the spectral weight towards lower frequencies occur at a well-defined density $n_g$. In addition, a dramatic increase of noise with decreasing $T$ have been observed for $n_s < n_g$. Similar behavior in metallic spin glasses was attributed to spin glass freezing [16,8,17]. For $n_s < n_g$, we have also observed long relaxation times and history dependent behavior characteristic of a glassy phase, but these effects will be described in detail elsewhere. These observations are interpreted as signatures of the freezing of the electron glass at $n_s = n_g$. The metal-insulator transition occurs at the density $n_c < n_g$ indicating the existence of a metallic electron glass, as predicted in [18].

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5 Figure captions

Figure 1

Left: Relative fluctuations of $\sigma$ vs. time for $n_s = 3.64 \times 10^{11} \text{cm}^{-2}$ at several different $T$ (lowest $T$ at bottom, highest $T$ at top). Different traces have been shifted for clarity. Right: $\langle \sigma \rangle$ vs. $T$ for different $n_s$. The data for many other $n_s$ have been omitted for clarity. $n_s^*$ and $n_g$ are marked by arrows. They were determined as explained in the main text.

Figure 2

Left: Relative rms $\delta \sigma / \langle \sigma \rangle$ vs. $n_s$ at different $T$. $n_c$, $n_g$, and $n_s^*$ are marked by arrows. Center: The normalized noise power $S_I$ at $3.16 \times 10^{-4} \text{ Hz}$ vs. $n_s$ at $T = 0.13 \text{ K}$; inset: $S_I$ vs. $T$ for three different $n_s (10^{11} \text{ cm}^{-2})$. Right: The exponent $\alpha$ ($S_I \propto 1/f^\alpha$) vs. $n_s$.
This figure "fig1a.gif" is available in "gif" format from:

http://arxiv.org/ps/cond-mat/0212460v1
glass-like behavior

\[ \frac{\delta \sigma}{\langle \sigma \rangle} \]

\( n_s \left(10^{11} \text{ cm}^{-2}\right) \)

-  \( T=0.130\text{K} \)
-  \( T=0.455\text{K} \)
-  \( T=0.805\text{K} \)

\( n_c \)
\( n_g \)
\( n_s \)
\( n^*_s \)
log(S_I (1/Hz))

T=0.13K
f=3.16x10^{-4} Hz

n_s (10^{11} cm^{-2})
