Glassy behavior of a two-dimensional electron system in Si in parallel magnetic fields

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ABSTRACT

Studies of low-frequency resistance noise show that the glassy freezing of the two-dimensional electron system (2DES) in Si in the vicinity of the metal-insulator transition (MIT) persists in parallel magnetic fields B of up to 9 T. At low B, both the glass transition density n_g and n_c, the critical density for the MIT, increase with B such that the width of the metallic glass phase ($n_c < n_s < n_g$) increases with B. At higher B, where the 2DES is spin polarized, n_c and n_g no longer depend on B. Our results demonstrate that charge, as opposed to spin, degrees of freedom are responsible for glassy ordering of the 2DES near the MIT.

Keywords: metal-insulator transition, glass transition, noise, two-dimensional systems, spin

1. INTRODUCTION

The fascinating strong correlation physics exhibited by low-density two-dimensional (2D) electron and hole systems[1] remains the subject of intensive research. In the vicinity of the apparent metal-insulator transition (MIT), in particular, both electron-electron interactions and disorder appear to be equally important. Their competition may lead to the emergence of many metastable states and the resulting glassy dynamics of electrons. Recent experiments[2,3] on a 2D electron system in Si have demonstrated such glassy behavior, lending support to the theoretical proposals that attempt to describe the 2D MIT as the melting of a Coulomb,[4–6] Wigner,[7] or spin[8,9] glass. Even though several features of the data[2,3] are consistent with the model of glassy behavior that occurs in the charge sector,[6,10,11] it is still an open question whether charge or spin degrees of freedom are responsible for the observed glass transition. Since a sufficiently strong magnetic field is expected to destroy the spin glass order,[8,9,12] experimental studies of glassy dynamics in parallel magnetic fields B[*] should be able to distinguish between the proposed models. Here we present such a study, which shows that the glass transition persists even in B such that the 2D system is spin polarized. These results demonstrate that charge, as opposed to spin, degrees of freedom are responsible for glassy ordering of the 2DES near the MIT.

2. SAMPLES AND EXPERIMENTAL TECHNIQUE

Measurements were carried out on a 2DES in metal-oxide-semiconductor field-effect transistors (MOSFETs) that were fabricated on the (100) surface of Si. In such a device, the disorder is due to the oxide charge scattering (scattering by ionized impurities randomly distributed in the oxide within a few Å of the interface) and to the roughness of the Si-SiO$_2$ interface.[13] The so-called peak mobility of the samples was ≈ 2.5 m^2/Vs at 4.2 K, signifying a relatively small amount of disorder. They were fabricated in a Hall bar geometry with Al gates, $N_a \sim 10^{14}$cm^{-3}, and oxide thickness $d_{ox} = 147$ nm.[14,15] The resistance was measured down to $T = 0.24$ K using a standard four-probe ac technique (typically 2.7 Hz) in the Ohmic regime. The DC voltage standard was

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[*]As usual, parallel field is used in order to avoid complications due to the orbital motion of electrons.

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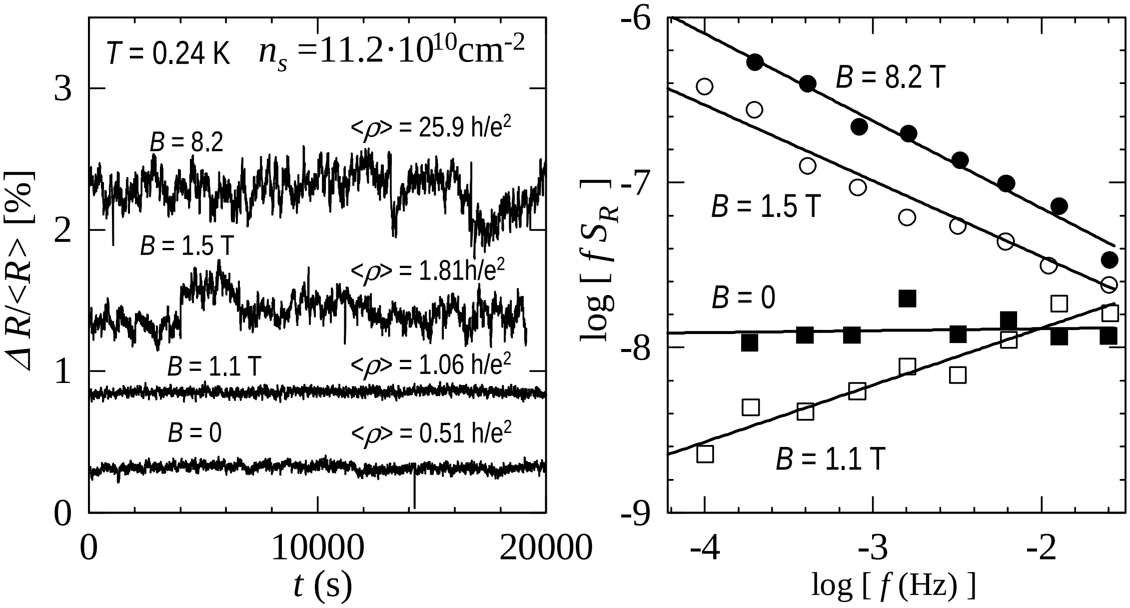

Figure 1. (a) $\Delta R(t)/\langle R\rangle = (R - \langle R\rangle)/\langle R\rangle$, and (b) the corresponding power spectra $S_R(f)$, at several B for $n_s = 11.2 \times 10^{10}\mathrm{cm}^{-2}$. In (a) traces are shifted for clarity, and the corresponding $\langle\rho\rangle$ are shown. In (b) $S_R(f)$ are averaged over octaves and multiplied by f, so that $1/f$ spectrum is horizontal on this scale. Solid lines are linear least-squares fits with the slopes $\alpha = 1.53$, 1.45, 0.98, 0.66 (from top).

used to apply V_g. 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). Other experimental details have been described elsewhere.[3, 16, 17]

For a given n_s and B, resistance R was measured as a function of time t at $T = 0.24$ K, although measurements at higher T were also performed at several selected B. At $B = 0$, the temperature coefficient of the time-averaged resistivity $d\langle\rho\rangle/dT = 0$ at $n_s^* \approx 9.7 \times 10^{10}\mathrm{cm}^{-2}$, similar to what was obtained on the previous cooldown of the same sample.[3, 16] In high peak mobility Si MOSFETs such as ours, the so-called "separatrix" n_s^* is often assumed[1] to represent the critical density for the MIT. However, a small but systematic difference of a few percent has been reported[18, 19] such that $n_s^* > n_c$. Here n_c was determined based on both a vanishing activation energy and a vanishing nonlinearity of current-voltage characteristics when extrapolated from the insulating phase. In low peak mobility (high disorder) MOSFETs, n_s^* and n_c are known to differ considerably,[2, 16] such that $n_s^* \gg n_c$.

At a fixed T and in the range of n_s under investigation, $\langle\rho\rangle$ exhibits a dramatic increase with B, followed by a much weaker dependence ("saturation") at higher fields ($B > 2 - 4$ T). This large positive magnetoresistance at low B has been observed and studied extensively in many 2D systems,[1] including other samples from the same source[14, 15] as ours. In the saturation region, it has been shown[20–22] that the 2DES is spin polarized.

3. RESULTS

Figures 1(a) and 1(b) show the time series of the relative changes in resistance $\Delta R(t)/\langle R\rangle$ and the corresponding normalized power spectra $S_R(f)^\dagger$, respectively, for a fixed n_s and several B. It is clear that B has a strong effect on both the amplitude and the character of the noise: the (Gaussian) $1/f$ noise at $B = 0$ is first suppressed by B but, by increasing B further, the noise power increases considerably and noise becomes non-Gaussian. In order

†The normalized power spectra $S_R(f) = S(V,f)/V^2$ (V – voltage) did not depend on the excitation current, indicating that the measured voltage fluctuations result from resistance (excess) noise.

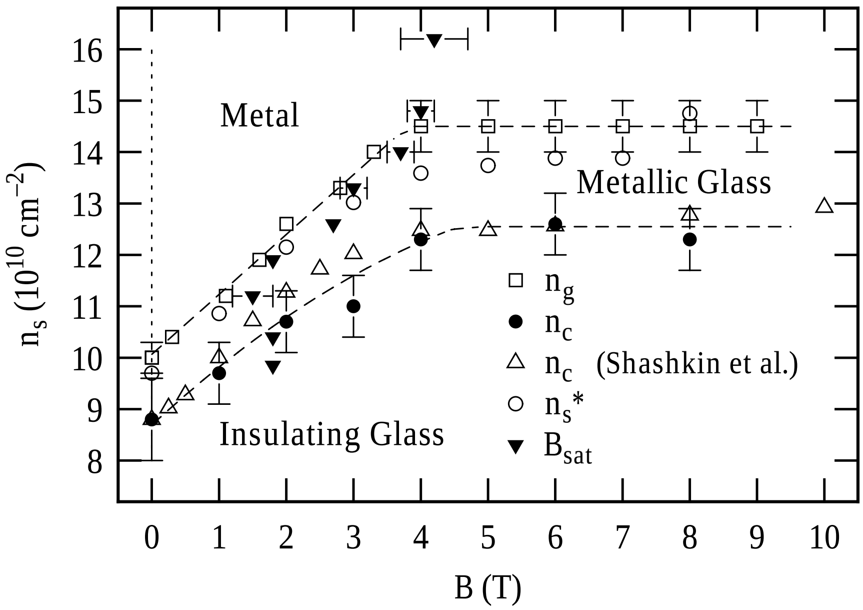

Figure 2. $T = 0$ phase diagram. The dashed lines guide the eye. Open squares: n_g, boundary between phases with fast and slow electron dynamics; solid circles: n_c, boundary between metallic and insulating phases; open circles: n_s^*, location of the "separatrix", *i.e.* density where $d\langle\rho\rangle/dT = 0$; solid triangles: B_{sat}, the magnetic field where noise characteristics become field-independent at $T = 0.24$ K. The Ref. 26 data (open triangles) have been shifted up by $0.85 \times 10^{10}\mathrm{cm}^{-2}$ to make the $n_c(B = 0)$ values coincide. $n_c(B = 0)$ are known[1] to be sample dependent because of the differences in the amount of disorder.

to compare the noise magnitudes under different conditions, the power $S_R(f = 1$ mHz$)$ is taken as the measure of noise. It is determined from the fits of the octave-averaged spectra to the form $1/f^\alpha$ for $10^{-4} < f < 0.07$ Hz [solid lines in Fig. 1(b)]. In addition, we have also analyzed the so-called second spectrum $S_2(f_2, f)$, which is the power spectrum of the fluctuations of $S_R(f)$ with time.[23–25] $S_2(f_2, f)$ provides a direct probe of correlations between fluctuators: it is white (independent of f_2) for uncorrelated, and $S_2 \propto 1/f_2^{1-\beta}$ for interacting fluctuators.[23–25] At $B = 0$, the glass transition in Si MOSFETs was manifested by: (i) a sudden and dramatic increase of S_R, and a rapid rise of α from ≈ 1 to ≈ 1.8,[2,3] indicating an abrupt and striking slowing down of the electron dynamics, and (ii) a change of the exponent $(1-\beta)$ from a white (zero) to a nonwhite (nonzero) value,[3] indicating a change to the sort of correlated statistics characteristic of complicated multistate systems. We adopt similar criteria for the glass transition in B, and determine the values of $B_g(n_s)$ and $n_g(B)$ where glass transition takes place at a fixed density or a fixed field, respectively. This allows us to construct a phase diagram shown in Fig. 2.

In the $(n_s, B, T = 0)$ phase diagram (Fig. 2), the square symbols designate the boundary of the glassy phase, *i.e.* the onset of abrupt and dramatic changes in the noise behavior. At low fields, n_g increases with B, and then it saturates for $B \gtrsim 4$ T, consistent with the fact that the 2DES is here fully spin polarized. The existence of the glass transition in this regime, manifested in the same way as in $B = 0$, strongly suggests that charge, as opposed to spin, degrees of freedom are responsible for glassy ordering. This result imposes a strong constraint on the types of theories that can be formulated to describe this phenomenon.

For all B, the glass transition takes place on the *metallic* side of the MIT, *i.e.* $n_g(B) > n_c(B)$, where $n_c(B)$ was determined from the vanishing of activation energy in the insulating regime (for n_c at 1, 2, 3 T, see below). For comparison, $n_c(B)$ obtained on samples almost identical to ours using the same method[26] are also presented. It is seen that the agreement between our results for the form of the $n_c(B)$ dependence and that obtained in Ref. 26 is quite good. The phase diagram shows that the metallic glass (MG) phase actually broadens with B, indicating that its existence is also not due to spin. The increase of n_g and the broadening of the MG phase with B can be understood to result from the suppression of screening by a parallel B,[27,28] which increases the effective disorder. This, in turn, favors glassiness, consistent with theoretical expectations.[11] Analogous to the $B = 0$ case, the critical densities $n_c(B)$ are again consistently lower than the corresponding "separatrices" $n_s^*(B)$ at a given field, with their difference becoming larger with the increasing B. In fact, it is interesting to note that $n_s^*(B) \lesssim n_g(B)$.

At high n_s in the metallic phase, the noise is suppressed by a parallel B (see Ref. 17), suggesting that $1/f$ noise in this regime is probably related to the electrons' spins. For $B \gtrsim$ 3-4 T, all the noise features show saturation or, at least, a very weak dependence on B. For somewhat lower n_s in the metallic phase but not too far from $n_c(B = 0)$ (see, *e.g.* bottom two traces in Fig. 1 and Ref. 17), the noise is suppressed at low B but then it undergoes a dramatic change at $B_g(n_s)$. At a still higher field $B_{sat}(n_s) > B_g(n_s)$, inside the glassy phase, all the noise characteristics $[S_R, \alpha$, and $(1-\beta)]$ again saturate. The corresponding fields $B_{sat}(n_s)$ are also shown in Fig. 2, and they can be interpreted as fields where 2DES becomes fully spin polarized. Magnetotransport studies on other 2D systems at low B have established[20–22] that, for a given n_s, the polarization field is comparable to the field where $d\langle\rho\rangle/dT$ changes sign from metalliclike ($d\langle\rho\rangle/dT > 0$) to insulatinglike ($d\langle\rho\rangle/dT < 0$) behavior. Indeed, Fig. 2 shows that the densities corresponding to B_{sat} are very similar to n_s^* for $2 \lesssim B \lesssim 4$ T. As a function of density, however, B_{sat} exhibits an apparent saturation below $n_s(10^{10}\text{cm}^{-2}) \approx 11$, suggesting that a finite magnetic field is required to fully spin polarize the 2DES at lower densities. This topic has been the subject of some debate, with arguments being put forward[29,30] in support of a spontaneous spin polarization at a finite n_s. Other experiments,[31] on the other hand, have found no evidence for such a ferromagnetic instability. It is interesting that a recent study of a 2DES in GaAs/AlGaAs heterostructures has found[32] that the field for full spin polarization seems to saturate below some density, similar to our results, but this feature needs to be explored in more detail in both experiments. In particular, measurements at lower temperatures might be useful.

Our measurements in both $B = 0$ and $B \neq 0$ show that glassy behavior generally emerges before the electrons localize (*i.e.* $n_g > n_c$). The existence of such an intermediate metallic glass phase is consistent with recent predictions of the model of interacting electrons near a disorder-driven MIT.[11] However, since $n_c(B)$ has been so far determined only based on a vanishing activation energy on the *insulating* side, it is difficult to establish the existence of a true metallic phase (where $\langle\sigma(T = 0)\rangle > 0$, by definition) with certainty. The same result for $n_c(B)$ could be obtained at a crossover between strong and weak localization regimes. The fate of the metallic phase in a parallel B has been one of the major open issues in the studies of dilute, strongly interacting 2D systems. In the presence of scattering by local magnetic moments, experiments on a 2DES in Si MOSFETs have provided strong evidence[33] for a quantum phase transition in both $B = 0$ and $B \neq 0$ by studying $\langle\sigma(T)\rangle$ in the metallic phase. It was also shown that the metallic phase persists even in high parallel B of up to 18 T, where the 2DES is fully spin polarized. However, in high-mobility Si MOSFETs in the absence of such scattering, so far it has not been possible to determine $n_c(B)$ from the data on the metallic side. In this experiment, we have investigated the properties of the metallic glass phase in more detail. In particular, $\langle\sigma(T)\rangle$ was studied at low B of up to 3 T. We find that, in the MG phase, the data are best described by the *metallic* ($\langle\sigma(T = 0)\rangle > 0$) power-law behavior $\langle\sigma(n_s, B, T)\rangle = \langle\sigma(n_s, B, T = 0)\rangle + b(n_s, B)T^{1.5}$ (Fig. 3), similar to what was observed in the MG phase of highly disordered samples at $B = 0$.[2] A detailed analysis of zero-temperature conductivities finds[17] that $\langle\sigma(n_s, B, T = 0)\rangle \propto \delta_n^{\mu}$ with $\mu \sim 1.5$ ($\delta_n = n_s/n_c(B) - 1$). Such a power-law behavior is in agreement with general theoretical expectations near a quantum phase trasition.[34] The critical densities $n_c(B)$ that have been obtained in this way from the data on the *metallic* side for $B = 1, 2, 3$ T are shown in Fig. 2. The agreement between these values and those obtained by using the data from the insulating side is remarkably good, providing for the first time strong evidence for a quantum phase transition in the presence of a magnetic field in high-mobility Si MOSFETs.

4. CONCLUSION

By studying the statistics of low-frequency resistance noise in Si MOSFETs in the presence of magnetic fields parallel to the plane of the 2DES, we have established that the glass transition persists even in fields such that the 2DES is fully spin polarized. Therefore, our results provide strong support to the theoretical proposals that attempt to describe the 2D metal-insulator transition as the melting of a Coulomb glass.[6,10,11] The intermediate, metallic glass phase ($n_c < n_s < n_g$) broadens by a parallel B, suggesting that its origin is also not due to spin. In the metallic phase ($n_s > n_g > n_c$), however, noise is suppressed by a parallel B, suggesting that electrons'

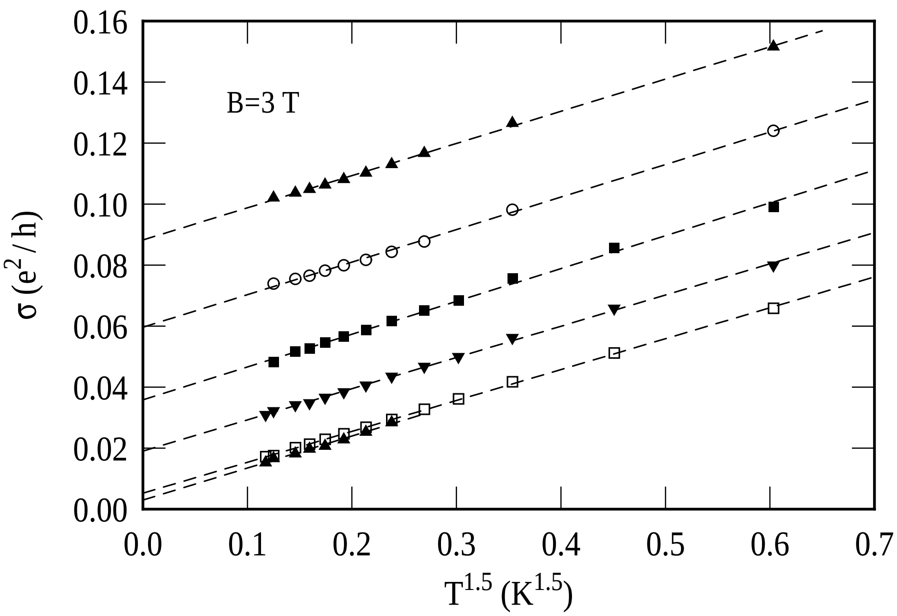

Figure 3. $\langle\sigma(T)\rangle$ in the metallic glass phase for $n_s(10^{10}\mathrm{cm}^{-2}) = 12.4, 12.2, 11.9, 11.6, 11.3, 11.2$ from top; $B = 3$ T. The extrapolated zero-temperature conductivities go to zero at $n_c(B = 3\ \mathrm{T}) = 11.00 \times 10^{10}\mathrm{cm}^{-2}$.

spins may play a relevant role. Finally, the evidence for a metal-insulator transition in a magnetic field has been obtained for the first time from the temperature dependence of conductivity on the *metallic* side of the MIT.

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