Aging Effects Across the Metal-Insulator Transition in Two Dimensions

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Aging effects in the relaxations of conductivity of a two-dimensional electron system in Si have been studied as a function of carrier density. They reveal an abrupt change in the nature of the glassy phase at the metal-insulator transition (MIT): (a) while full aging is observed in the insulating regime, there are significant departures from full aging on the metallic side of the MIT, before the glassy phase disappears completely at a higher density \( n_g \); (b) the amplitude of the relaxations peaks just below the MIT, and it is strongly suppressed in the insulating phase. Other aspects of aging, including large non-Gaussian noise and similarities to spin glasses, also have been discussed.

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It is manifested in the dependence of \( \sigma(t) \) on \( t_w \) such that, in those strongly localized systems, the aging function \( \sigma(t, t_w) \) is just a function of \( t/t_w \). This is known as simple, or full aging. It is interesting that, in spin glasses, full aging has been demonstrated only relatively recently \( 10 \). In general, however, the existence of a characteristic time scale \( t_w \) does not necessarily imply simple \( t/t_w \) scaling \( 11 \). In the mean-field models, in fact, two different cases are distinguished: one, where full aging is expected, and the other, where no \( t/t_w \) scaling is expected \( 12 \). Experimentally, departures from full aging are common \( 12, 13 \). In a 2DES in Si, where \( \tau_{eq} \to \infty \) as temperature \( T \to 0 \) (hence glass transition \( T_T = 0 \) \( 12 \)), aging was also observed for \( t_w \ll \tau_{eq}(T) \) \( 13 \) using the experimental protocol described above. The goal of this study is to investigate that aging regime in detail. In particular, unlike previous work \( 13 \), here \( T \) is kept fixed at 1 K such that \( \tau_{eq} \) is astronomical \( 12 \) and the 2DES is always deep in the \( t_w \ll \tau_{eq} \) limit; \( \sigma(t, t_w) \) are then explored systematically both as a function of final \( n_s \) and of the difference in densities during and after \( t_w \). Our main results include: a) \( \sigma(t) \) obey a power-law dependence for \( t \lesssim t_w \) and a slower relaxation law for \( t \gtrsim t_w \), thus showing a memory of the time ("age") \( t_w \); b) \( \sigma(t, t_w) \) exhibit full aging for \( n_s < n_c \); c) as \( n_s \) increases above \( n_c \), there is an increasingly strong departure from full aging that reaches maximum at \( n_s \approx n_g \); d) for a given \( t_w \), the amplitude of \( \sigma(t)/\sigma_0 \) has a peak at \( n_s \lesssim n_c \), reflecting an interesting and surprising suppression of the relaxations on the insulating side of the 2D MIT.

The experiment was performed in a \(^3\)He system (base \( T = 0.24 \) K) on the same (100)-Si metal-oxide-semiconductor field-effect transistors that were used in previous studies \( 12, 13 \). The two devices (A and B, with \( 1 \times 90 \) \( \mu \)m\(^2\) and \( 2 \times 50 \) \( \mu \)m\(^2\) length \times width, respectively) had a 50 nm oxide thickness, and a relatively large amount of disorder (the 4.2 K peak mobility \( \approx 0.06 \) m\(^2\)/Vs with the substrate (back-gate) bias \( V_g = -2 \) V). \( n_s \) was varied by the gate voltage \( V_g \), such that \( n_s(10^{11} \text{ cm}^{-2}) = 4.31 (V_g [V]) - 0.3 \); \( n_g(10^{11} \text{ cm}^{-2}) = (7.5 \pm 0.3) \) and \( n_c(10^{11} \text{ cm}^{-2}) = (4.5 \pm 0.4) \), where \( n_g \) and \( n_c \) are...
measured for several 13, 21]. It is clear that small amplitude relaxation during $t$ is still visible [12, 21]. The two samples exhibited an almost identical behavior. Unless noted otherwise, the data presented elsewhere [10]. The results do not depend on the cooling time (varied from 30 minutes to 10 hours), nor on $t_1$ and $t_2$ (varied from 5 minutes to 8 hours each). (b) The corresponding $\sigma(t)$. The relaxation of $\sigma$ during $t_w$ is too small to be seen on this scale. (c) $\sigma(t > 0)$ for several $t_w$, as shown; $V_0 = 7.0$ V [$n_0(10^{11}$ cm$^{-2}) = 3.02 < n_c$, $V_1 = 11$ V [$n_1(10^{11}$ cm$^{-2}) = 20.26$]. The data are not shown for the first few seconds (comparable to our sampling time ~ 1 s). The dotted lines are linear fits for $t < t_w$. The dotted line is a fit for $t < t_w$ with the slope $-\alpha = -0.081 \pm 0.005$. Inset: $\sigma(t = 1 s)/\sigma_0$ vs. $t_w$. The dotted line is a fit with the slope $\alpha = 0.076 \pm 0.005$.

was determined from the onset of slow, correlated dynamics in noise and $n_c$ from $\sigma(n_s, T)$ measurements on both metallic and insulating sides [10, 11]. The devices and the standard ac lock-in technique (typically 13 Hz; 5–10 $\mu$V excitation voltage) were described in more detail elsewhere [10]. The two samples exhibited an almost identical behavior. Unless noted otherwise, the data presented below were obtained on sample A.

We employ the so-called “gate protocol” [4], where $V_g$ is changed from an initial value $V_0$ (density $n_0$), where the 2DES is in equilibrium, to another one, $V_1$ (density $n_1$), where the system attempts to equilibrate during $t_w$, but $t_w < \tau_{eq}$ [Figs. 4(a) and 4(b)]. After $V_g$ is changed back to $V_0$ at $t = 0$, the relaxation of the “excess” conductivity $\sigma(V_0, t)/\sigma(V_0)$ is studied. Figure 4(c) shows some $\sigma(t)$ measured for several $t_w$ and $n_0 < n_c$. Although $n_1 > n_c$, small amplitude relaxation during $t_w$ is still visible [12, 13, 21]. It is clear that $t_w$ has a significant effect on $\sigma(t)$.

In fact, all the $\sigma(t, t_w)$ data can be collapsed onto a single curve simply by rescaling the time axis by $t_w$ [Fig. 1(d)]. Therefore, in this case, the system exhibits full aging at least up to $t \approx (2-3)t_w$. We note that the relaxations can be described by a power law $\sigma(t)/\sigma_0 \propto (t/t_w)^{-\alpha}$ for times up to about $t_w$, followed by a slower relaxation at longer $t$. This means that the memory of $t_w$ is imprinted on the form of each $\sigma(t)$. As a consistency check, the fits to the individual $\sigma(t)$ for $t \leq t_w$ [see Fig. 1(c)] yield the initial amplitudes of the relaxation $\sigma(t = 1 s)/\sigma_0 \propto t_w^{\alpha}$ [22] with the same value of $\alpha$ (Fig. 1(d) inset).

The quality of the data collapse is difficult to estimate with high precision since $\sigma(t)$ are quite noisy. We argue that the large non-Gaussian noise seen in Fig. 1(c) is intrinsic to aging, similar to other materials out of equilibrium [17, 23]. Indeed, Fig. 2 shows that, for $n_s < n_g$, the noise after a temporary $n_s$ change is much larger than the noise before the change. At the lowest $n_0$, this difference amounts to more than an order of magnitude. While a more detailed comparison of the “before” and “after” noise will be presented elsewhere, we note the following. First, the noise in the aging regime grows with decreasing $T$, while at the same time the relaxations $\sigma(t)/\sigma_0$ become smaller. Therefore, in order to optimize the signal to intrinsic sample noise for the study of aging, most of the data were taken at 1 K. Second, they show that the previous noise studies in a 2DES [10, 11] were actually performed in the aging regime, since $V_g$ was varied at $T \sim 1$ K albeit in small steps ($\Delta V_g = 0.1$ and 0.01 V, or smaller, in Refs. [10] and [11], respectively). Such small $\Delta V_g$ did not produce any visible relaxations within the noise, consistent with the results below (Fig. 2).

Full $t/t_w$ scaling is exhibited for all $n_s < n_c$. However, as soon as $n_s \gtrsim n_c$, we find systematic deviations from full aging [e.g. Figs. 3(a) and 3(c)]. In other glassy mate-
of trying to collapse very small (pears as if the full aging is restored, but this may be an noise of comparable magnitude [Fig. 3(e)]. There are no partures from full scaling are seen. It is striking that the data [Figs. 3(b) and 3(d)] shows a clear distinction between the full aging regime and of the step size $\Delta V$ (provided $\sigma(t) > 1$ s)/$\sigma_0$ may become negative. This corresponds to $\sigma(t)$ approaching $\sigma_0$ from “below” instead of from above as in Fig. 4(c) [25]. Indeed, we have observed instances of such behavior, as shown in Fig. 4(d) for the case where both $V_0$ and $V_1$ happen to be in the insulating regime. The nonmonotonic dependence of the system response, here characterized by $\alpha$ and $\sigma(1)$/$\sigma_0$, on the perturbation $\Delta V_g$, bears a remarkable resemblance to the results of negative $T$ cycle spin glass experiments (see Figs. 1–3 in Ref. [24]), where the so-called “memory anomaly” at low $\Delta T$ was interpreted [26] based on the hierarchical distribution of states in the free energy landscape. The noise studies in the aging regime [11] have already provided support for the hierarchical picture of glassiness in the 2DES. Unfortunately, it is not possible to perform systematic studies of aging for small, including negative, $\Delta V_g$ in a 2DES, because then $\alpha$ is typically comparable to the large noise that is intrinsic to aging. The raw data [e.g., Figs. 3(a), 3(c), and 3(e)], as well as Figs. 4(b) and 4(c), indicate also large variations in $\sigma(1)$/$\sigma_0$ and $\alpha$ as a function of $V_0$ for fixed $t_w$ and $\Delta V_g$. This was explored in detail by varying $V_0$, while keeping $t_w$ and $V_1$ fixed [Fig. 4(a)]. We expect, based on Fig. 4 to see an increase of both quantities with decreasing $V_0$, since $\Delta V_g$ is getting larger. While an increase is observed [Fig. 4(b)], it is much stronger than expected. For example, even for the same $\Delta n_s(10^{11}$ cm$^{-2}$) = 13.79 and $t_w = 1000$ s, $\log(\sigma_0(10^{11}$ cm$^{-2}$) = 3.88, $t = 1$ s)/$\sigma_0$ ≈ 0.4

![FIG. 3: (color online) (a), (c), (e) Relaxations for different $n_s(10^{11}$ cm$^{-2}$) and a fixed $n_s(10^{11}$ cm$^{-2}$), scaled with the waiting time $t_w$. (b), (d) Scaling with $t_w^2$ improves the collapse of the data. (f) $\mu$ vs. $n_0$. $\mu$ does not depend on $n_1$.](image)

![FIG. 4: (color online) (a) $\sigma(t)$ for fixed $n_0(10^{11}$ cm$^{-2}$), $t_w$, and several $n_1(10^{11}$ cm$^{-2}$). The dashed lines are fits. (b), (c) Slopes $\alpha$ and amplitudes $\sigma(t = 1)$/$\sigma_0$ of the relaxations, respectively, vs. $\Delta n_s(10^{11}$ cm$^{-2}$) for two fixed $n_0$ and several $t_w$. The values corresponding to $n_0(10^{11}$ cm$^{-2}$) = 6.46 were multiplied by 10. Open symbols: device B. Dotted lines guide the eye. (d) Sample B. $\sigma(t)$ for small $\Delta V_g$ scaled with $t_w$.](image)
FIG. 5: (color online) (a) $\sigma(t)$ for fixed $t_w$, $n_1$, and several $n_0$. (b) Relaxation amplitudes vs. $n_0$ for several $t_w$. Dotted lines guide the eye. The error bars typical of low and high $n_0$ values are also shown.

[Fig. 4(c)], i.e. still an order of magnitude larger than for $n_0(10^{11}\text{cm}^{-2}) = 6.46$. Even more striking, however, is the dramatic decrease of $\sigma(1\text{s})/\sigma_0$ [Fig. 3(b)] as $n_0$ is reduced further, contrary to simple expectations based on Fig. 4. The slopes $\alpha$ exhibit the same nonmonotonic behavior [Fig. 3(a)]. Again, the abrupt change in the aging properties occurs at $n_s \approx n_c$: the relaxation amplitude peaks just before the system becomes metallic, and it is suppressed upon going deeper into the insulator. This is reminiscent of the suppression of the fluctuations of $\sigma(t)$ observed earlier in the same system at $n_c$ (Ref. [11], Fig. 4 inset). While a clear understanding of these two effects is lacking, it is plausible that collective charge rearrangements that are responsible for the slow dynamics will be suppressed as the 2DES becomes strongly localized. It is interesting to speculate whether this is related in any way to the problem of many-body localization [27]. It would be also of interest to study aging deeper in the insulator, in the variable-range hopping regime, but that is not possible because of the small relaxation amplitudes and the large intrinsic sample noise. The effects of disorder could be explored further by extending the relaxation studies to cleaner 2DES, where $n_0 \gtrsim n_c$ [11].

In summary, a detailed study of aging in a 2DES in Si shows an abrupt change in the nature of the glassy phase at the 2D MIT before it vanishes entirely at a higher density $n_g$. The results put constraints on the theories of glassy freezing and its role in the physics of the 2D MIT.

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