Nonequilibrium field effect and memory in the electron glass

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We present an experimental study of the nonequilibrium transport in Anderson-insulating indium-oxide films. In particular, we focus on the characteristic features of the cusp that is observed in field-effect (FE) experiments around the gate voltage at which the system has equilibrated. It is shown that the shape of the cusp depends on the temperature history, as well as on the measurement temperature. On the other hand, it is insensitive to the rate and direction of the gate voltage sweeps, disorder, or magnetic field up to 20 T. We discuss a physical picture leading to the appearance of such a cusp and suggest a possible mechanism for memory in the electron-glass system. These findings demonstrate that FE experiments complement the conductance measurements and contribute to a broader perspective on the glassy dynamics.

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I. INTRODUCTION

One of the intriguing properties of glasses is the nonstationary nature of their dynamics. This property is responsible for a variety of memory effects exhibited by the system. A well-known manifestation of memory is the dependence of the relaxation law on the sample history. Specifically, let $\{x_i\}$ be a set of external conditions that control some macroscopic property P of the system. When $\{x_i\}$ is changed from $\{x_i^o\}$ to $\{x_i^n\}$, P will "relax" from $P(\{x_i^o\})$ towards $P(\{x_i^n\})$. The time dependence of the relaxation process $P(t)$ will in general depend on the system itself, $\{x_i^o\}$, $\{x_i^n\}$, and possibly on $P(0)$. In a glassy system, $P(t)$ will also depend on t_W, the time the system has spent under the influence of $\{x_i^o\}$. In a spin glass, for example, the magnetization relaxes with time in a way that reflects the time elapsed since the cooling process, during which the system was under the influence of a magnetic field. This is in contrast to the behavior of a "homogeneous" system like RC circuits; The charge on a capacitor C shunted by a resistor R will decay with the same time constant independent of the time it was connected to a voltage source. The observation that the relaxation law $P(t)$ in glasses is a function of both t and t_W is commonly called "aging."

It has been suggested that glasses can be classified by the specific form of the function $P(t,t_W)$ they exhibit.[1] A particular case is when $P(t,t_W)=P(t/t_W)$ which has been termed "simple,"[1] "naive,"[2] or "full"[3] aging. Such a scaling law for P was recently found in experiments on electron glass.[4] In the electron glass, the property P is associated with the excess conductance ΔG, and the external conditions $\{x_i\}$ may be represented, e.g., by the carrier concentration n. The latter could be modified by fabricating the sample in a metal-oxide-semiconductor field-effect transistor (MOSFET) configuration and using the gate voltage V_g to change the charge in the sample. In our systems, the change in the carrier concentration n due to variations in V_g is relatively small, typically $\Delta n/n \approx 1\%$. Yet this small change in n is effective in terms of bringing about significant nonequilibrium effects.[5] As shown before,[5,6] the field effect $G(V_g)$ in several hopping systems includes a nonequilibrium component in the form of a symmetric, cusplike structure that appears around the gate voltage V_g^o at which the system was allowed to equilibrate. This nonequilibrium feature may persist for hours after a new V_g was applied.[7,8] Drawing on the understanding of the equilibrium FE measurement, the association of ΔV_g with an energy scale seems natural. In this respect, the ability of the system to keep some memory of V_g^o could be interpreted as a memory of information in the energy domain (as opposed to the "aging" phenomenon which reflects memory of an elapsed time, i.e., "age"). However, since these FE measurements were carried out under nonequilibrium conditions the relation to energy is more subtle.

In this paper, we extend the study of aging and other memory effects in the electron glass by focusing on the behavior of $G(V_g,t)$. We show that at a given temperature, the cusp in $G(V_g)$ has a characteristic shape independent of disorder, magnetic field, aging time, and the rate at which V_g is swept. On the other hand, the cusp is found to be narrower the lower the bath temperature. Moreover, it turns out that the amplitude and shape of this characteristic feature reflect the "history" experienced by the sample. The cusp continuously develops with the time elapsed since quench cooling the sample to low temperatures. More intriguingly, $G(V_g)$ measured at $T=T_1$ a short time after it was cooled from T_2, at which the system was allowed to equilibrate, retains the shape it had at T_2.

The results discussed below seem to indicate that some property describing the state of the system contains the memory about the system history and affects the measured $G(V_g)$. We discuss the possibility that this property is associated with correlations in the configuration and motion of carriers due to interactions.

We argue that knowledge of $G(V_g,t)$ gives one a broader perspective on the temporal aspects of the glassy relaxation and complements the information gained by studying just the response $G(t)$ at fixed V_g. As an example, we discuss the temporal evolution of the system properties following quench cooling to low temperatures and the memory of the

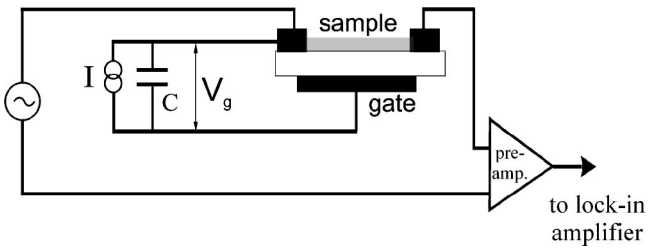

FIG. 1. A schematic drawing of the measurement circuit and the device used in the field-effect measurements.

equilibration temperature that shows up in $G(V_g)$. We also discuss the aging phenomenon, showing what are the requirements to obtain ''simple aging'' in terms of the dynamics involved in $G(V_g)$. We demonstrate that varying the measurement parameters results in deviations from simple aging and discuss the implications of these results.

II. EXPERIMENT

Most of the samples used in this study were prepared in a MOSFET-like configuration schematically shown in Fig. 1 along with a typical measurement circuit. Several variants of the device were used. The active layer was a thin film of indium oxide deposited by an *e*-gun using 99.999% pure In_2O_3. This was either an amorphous film (typically 200 Å thick) or a polycrystalline film (typically 50 Å thick). These will be referred to below as InO_x and In_2O_{3-x}, respectively. As deposited indium-oxide films are usually amorphous. Polycrystalline films were prepared by heating the sample to 250 °C after deposition. Samples lateral dimensions were $1\times1-5\times5$ mm. A fuller description of these materials is given in Ref. 9. For completeness, we present in Fig. 2 transmission electron microscopy (TEM) pictures and diffraction patterns of the In_2O_{3-x} and InO_x active layers demonstrating the difference in their microstructure. All samples measured in this study were in the insulating regime with $R(4.1\ \mathrm{K})/R(300\ \mathrm{K})$ in the range of 10^3-10^4. In the InO_x films, we could change the carrier concentration by varying the deposition rate (0.3–2 Å/sec) and the residual pressure

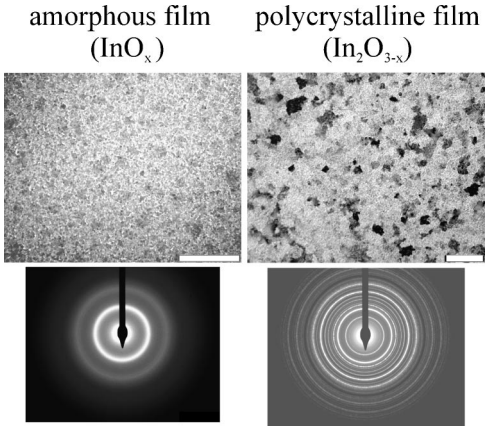

FIG. 2. TEM pictures and diffraction patterns of InO_x and In_2O_{3-x} thin films (200 Å thick), used as the active layers in this study. The white bar corresponds to 200 nm.

of O_2 ($5\times10^{-5}-5\times10^{-4}$ Torr) during deposition. The concentration was determined from Hall effect measurements using magnetic fields up to 0.7 T. Three different spacers were used in this study: microscope cover-glass (140 μm thick), single-crystal Al_2O_3 wafer (100 μm thick, *C*-axis $\langle0001\rangle$ orientation), and SiO_2 (0.5 μm thick) thermally grown on a heavily doped (boron *P*-type, 0.002Ω cm) single-crystal Si wafer $\langle001\rangle$ surface. In the latter case, the Si wafer served also as the gate electrode. In the other two cases a 500-Å-thick gold film was evaporated on the other side of the spacer.

Most of the measurements were carried out at $T=4.1$ K with the samples immersed in liquid ^{4}He. This enabled high temperature-stability over long times. Measurements as function of temperature were performed either in a ^{3}He rig or in a pumped ^{4}He cryostat. In addition to employing a temperature controller or a vapor-pressure controller, a Ge thermometer mounted on the sample stage was used to correct for residual temperature fluctuations. The conductance of the samples was measured using a two-terminal ac technique employing an ITHACO 1211 current amplifier and a PAR 124A lock-in amplifier. Care was taken to ensure a linear response by the use of sufficiently low ac bias. The gate voltage was applied by charging a 10-μF capacitor, connected in parallel with the device, by a Keithley 220 current source. The capacitance of the device (sample and gate) varied in the range 30–200 pF depending on sample area and spacer properties.

As mentioned above, a dominant feature in these field-effect (FE) measurements is the appearance of a cusp in the conductance versus gate voltage $G(V_g)$ traces centered at the equilibrium gate-voltage V_g^o. Examples for such a cusp are shown in Fig. 3 where FE traces for different active layers and spacers are compared. These measurements employed the symmetric sweeping procedure described below. In the inset, the same traces are shown after subtracting the data from a linear part (such as the dashed line in the main figure) and after normalizing the amplitudes. This linear part corresponds to the usual (equilibrium) FE response.[10] In order to allow a comparison between these traces they are plotted against the accumulated surface charge in the sample (Q_s) related to V_g by $Q_s=V_g(\varepsilon/L)$, where ε is the dielectric constant and L is the thickness of the spacer. It can be seen that in terms of $G(Q_s)$ the shape of the cusp is independent of the spacer material. Note also that the cusp in $G(Q_s)$ is nearly identical for InO_x and In_2O_{3-x} samples, which, in the case shown, have comparable carrier concentration.

As explained before,[5] the appearance of the cusp in the $G(V_g)$ traces is due to a nonequilibrium measurement. It is therefore appropriate to specify the different procedures we used to obtain those traces. In this work, we employed two procedures to measure the FE.

(i) *Symmetric sweep.* This measurement is done by sweeping V_g away from V_g^o in a symmetric fashion. Starting at $t=0$ from V_g^o we sweep V_g and record G for $V_g>V_g^o$. Then we bring back V_g to V_g^o and keep it there until $G(V_g^o)$ relaxes to its value at $t=0$. Finally, V_g is swept from V_g^o to record $G(V_g)$ for $V_g<V_g^o$, and the two pieces of $G(V_g)$ are merged.

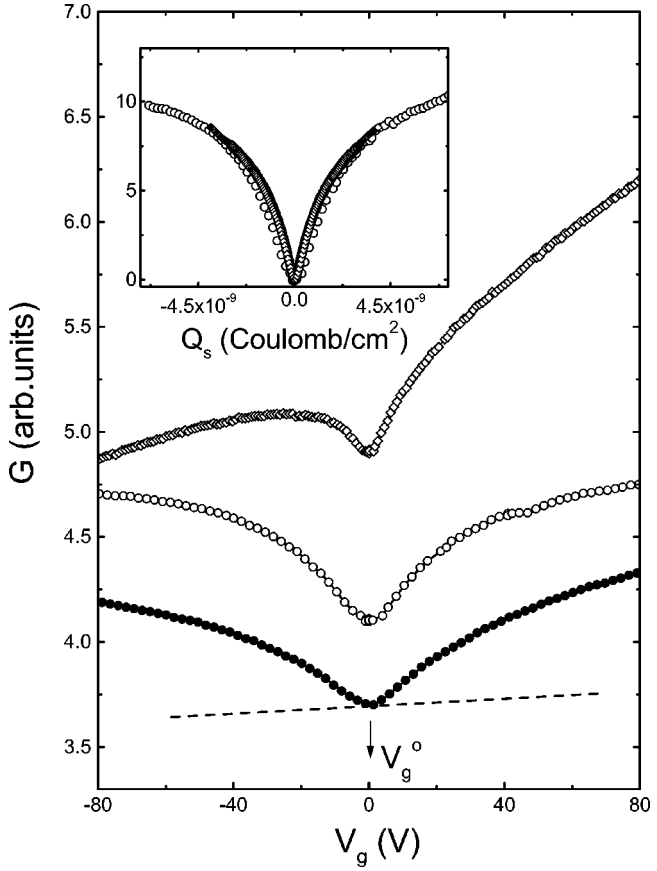

FIG. 3. $G(V_g)$ traces measured using three different devices: In_2O_{3-x} sample on a sapphire spacer ($R_\square = 100$ MΩ, open diamonds), In_2O_{3-x} sample on a microscope cover glass spacer ($R_\square = 16$ MΩ, solid circles), and InO_x sample on a sapphire spacer ($R_\square = 330$ MΩ, open circles). In the inset, the same traces are plotted vs Q_s after subtracting a linear part (e.g., the dashed line) and normalizing their amplitudes. Q_s was calculated using $L = 140$ μm, $\varepsilon = 4.4$ for the cover glass spacer and $L = 100$ μm, $\varepsilon = 9.5$ for the sapphire spacer.

(ii) *Continuous sweep.* V_g is swept continuously through V_g^o, starting from the maximum V_g to its minimum value within the range straddling V_g^o. The cusp in $G(V_g)$ measured in this way is also referred to as a "memory cusp." Naturally, to produce such a scan V_g must be first swept away from V_g^o. Hereafter, unless otherwise mentioned, this was done by sweeping V_g directly from V_g^o to the starting point of the continuous sweep, using the same sweep rate throughout the experiment.

Other experiments that are used in this study are the "two-dip experiment"[7,8] (TDE) and the "aging"[4] experiment that involve the following procedures.

Aging experiment. The system is first equilibrated for about a day at the measurement temperature with a certain gate voltage V_g^o. Then, we shift V_g from V_g^o to some new value V_g^n and then, a time t_W later, shift V_g back to V_g^o. Following the return to V_g^o, at $t \equiv 0$ the excess conductance $\Delta G(t)$ (the conductance in excess of the equilibrium conductance at V_g^o) is measured as function of time for $t > 0$. This procedure is then repeated for varying values of T_W.

TDE. In this case, after the system was equilibrated for about a day with $V_g = V_g^o$ at the measurement temperature, we shift V_g from V_g^o to V_g^n and keep it at V_g^n for the duration of the experiment. At various times after the shift to V_g^n, we sweep V_g rapidly through a voltage domain containing both V_g^o and V_g^n. This allows the observation of the evolution of the dips at those two values of V_g, i.e., the "new" value V_g^n and the "old" one V_g^o.

An important feature in these measurements is the slow evolution of the conductance following a sudden change in the gate voltage. Since changing the gate voltage induces charge on the sample, it is important to know the dynamics of this charging current (I_{ch}) and compare it to the dynamics of the conductance. In Fig. 4, $I_{ch}(t)$ (measured by monitoring the voltage on a 1-MΩ resistor connected in series with the sample) and $G(t)$ are shown during sweeps of V_g using different sweeping rates, at 4.1 K and 77 K. The charging current was found to scale linearly with the sweep rate (see inset), and thus the capacitance of the device C could be deduced using $I_{ch} = C(dV_g/dt)$. This value was found to be similar at both temperatures and is consistent with the room-temperature value (within 2%). Moreover, we could not detect any slowly varying component of I_{ch}, within our experimental time and current resolution. This should be contrasted with the corresponding behavior of the conductance. At high temperatures, $G(t)$ follows V_g in keeping with the charging current. This effect corresponds to the usual (equilibrium) FE.[10] At low temperatures, on the other hand, while I_c behaves in a similar way as at high temperature, the conductance continues to change long after V_g reached a constant value. Obviously, the slow response of G is not due to slow variations in the charging current or the capacitance of the device.

III. RESULTS AND DISCUSSION

As is evident from Fig. 4 above, the anomalous features associated with nonequilibrium effects are observable only at low temperatures (typically below 50–5 K, depending on the sample disorder[11]). We start this section by demonstrating that after quench-cooling the sample to a sufficiently low temperature its properties keep changing for a long time. Figure 5 shows a typical example of $G(t)$ following quench cooling of the sample from ~100 K to liquid ^{4}He bath at 4.1 K (cooling time is roughly 2 min). The figure reveals that while the bath temperature (as indicated by the resistance of the thermometer) is stationary, the conductance of the sample is not—it continues to change a long time after quenching. This demonstrates that the conductance of the sample does not merely depend on the temperature but also on the time that elapsed since the quench. This behavior is quite general. It is observed in all our insulating samples whether they have a gate or not. Such phenomenon of time-dependent response measured after a cooldown occurs in a variety of other systems such as spin glasses,[3] supercooled liquids,[12] and polymers.[13] The underlying reason for this behavior is presumably a gradual microscopic change within the system that alters its response properties.

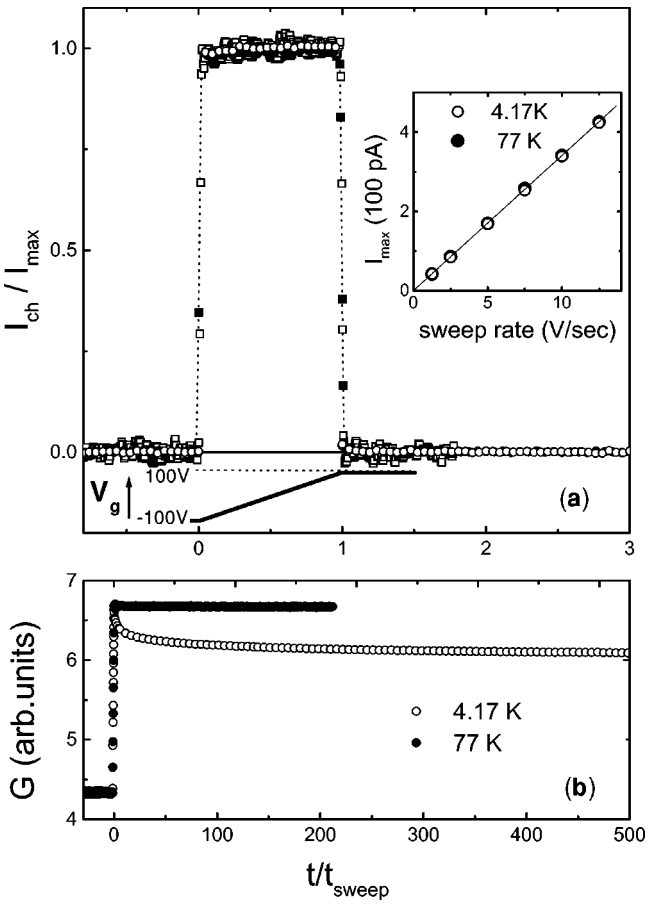

FIG. 4. The charging current I_{ch} and the sample conductivity G, during and after sweeps of V_g from -100 V to 100 V, plotted vs t/t_{sweep}, where t_{sweep} is the sweep duration. (a) $I_{ch}(t/t_{sweep})$ is shown for sweeping rates of 10 V/sec and 1 V/sec (circles and squares, respectively), and at temperatures of 4.1 K and 77 K (full and empty symbols, respectively). The Y axis is normalized by the maximal charging current (I_{max}). A representative trace of $V_g(t/t_{sweep})$ is also shown in the lower part of the figure. Sweeps in the reversed direction yielded the same behavior. In the inset, I_{max} is plotted vs the sweep rate. (b) $G(t/t_{sweep})$, following a sweep of V_g at $t=0$ (12 V/sec). In_2O_{3-x} sample on a sapphire spacer. $R_\square$ is 100 MΩ and 140 kΩ at 4.1 K and 77 K, respectively.

To gain more insight into the changes occurring in the system after cooling, we measured the FE at various time intervals τ after the cooldown. In the experiments shown in Fig. 6, while keeping $V_g=0$, the temperature was lowered from ~ 100 K to 4.1 K. The FE was then measured a time τ after the cooldown using both the symmetrical and the continuous sweeping procedures of V_g (see Sec. II). These $G(V_g)$ traces show a cusp around $V_g=0$ whose magnitude increases gradually as τ increases. As shown in the figure this development of the cusp is independent of the sweeping procedure used in the experiment, i.e., symmetrical or continuous. It can be seen that the $G(V_g)$ traces for different τ coincide far from the equilibrium V_g. Thus, $G(t)$ does not represent a homogeneous decrease of $G(V_g)$. This may indicate that the gradual change in the response of the system (Fig. 5) is intimately connected with the creation of the cusp in $G(V_g)$. Therefore, we may interpret these results in the

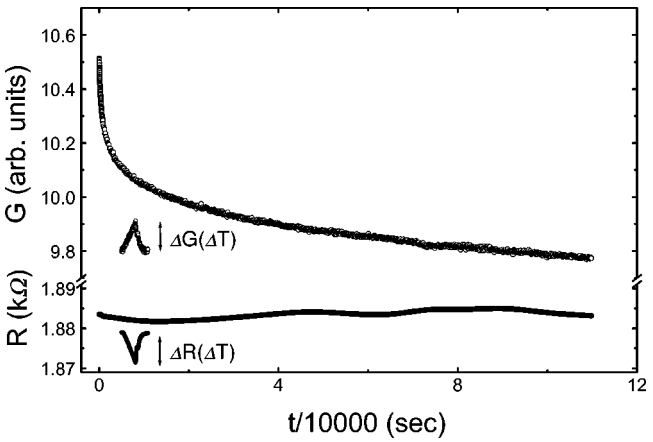

FIG. 5. The conductance of the sample G and the resistance of the Ge thermometer R, following quench cooling to 4.1 K. Also shown is the response of G and R to a temperature change $\Delta T \sim 1$ mK, induced by varying the ^{4}He vapor pressure. Using this calibration, variations in G due to temperature instability during the measurement could be corrected. In_2O_{3-x} sample on a sapphire spacer, $R_\square = 100$ MΩ.

following way. Immediately after the quench, the system is not yet in equilibrium and hence there is no modulation in $G(V_g)$, and the conductance is high as compared with the conductance at equilibrium. As time elapses, a cusp develops in $G(V_g)$ which means that $G(V_g=0)$ diminishes with time.

This slow dynamics of the system after cooling made it imperative to allow the system to equilibrate under fixed external conditions for a long time before other measurements could be done. It was found that this equilibration time should be long in comparison with the duration of any subsequent experiment, e.g., t_W in the aging experiment.

Following quench cooling, while the amplitude of the cusp in $G(V_g)$ evolves with time the *shape* of the cusp *does not* (inset of Fig. 6). The shape of this cusp is found to be insensitive also to the rate or direction in which the gate voltage is swept. FE traces measured using various scan rates of V_g are shown in Fig. 7. The figure reveals that the cusp amplitude depends on the scan rate, in keeping with the notion that the cusp is a nonequilibrium effect. Obviously, no cusp can be observed in the limit of a scan rate so slow that equilibrium persists throughout the entire scan. But the shape of the cusp in the vicinity of V_g^o is independent of the scan rate over a range of rates in excess of two orders of magnitude. A comparison of the cusp shape in various scanning modes is presented in Fig. 8. Evidently, the shape of the cusp is essentially identical for both the symmetric and continuous scanning modes [Fig. 8(a)]. Furthermore, in the experiment shown in Fig. 8(b) a symmetric sweep was first carried out (lower trace) followed by a continuous and periodic sweep of V_g between -100 V and $+100$ V for several hours. During this sweep we observe cusplike minima with an amplitude that decays logarithmically in time, but with a similar shape and in the same position.[14] In addition, changes in the structural disorder or an application of magnetic field (up to 20 T) also do not affect the shape of the cusp (Fig. 9). Therefore, it seems that for a given sample[15] at a given tempera-

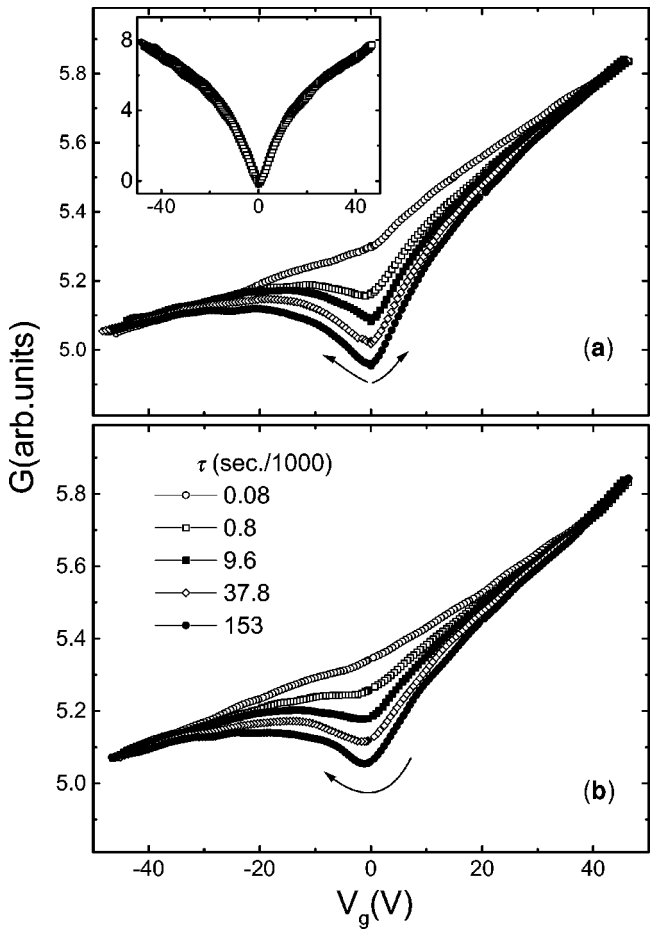

FIG. 6. $G(V_g)$ traces, measured at various times τ after the sample was quench cooled to 4.1 K. For each value of τ a separated cooling cycle was done. At each cycle, traces were measured using both symmetric and continuous sweeping procedures, shown in (a) and (b), respectively. In the inset, the same traces shown in (a) are plotted after subtracting a linear part and normalizing their amplitude. The sweep rate is 0.8 V/sec. The sample is the same as in Fig. 5.

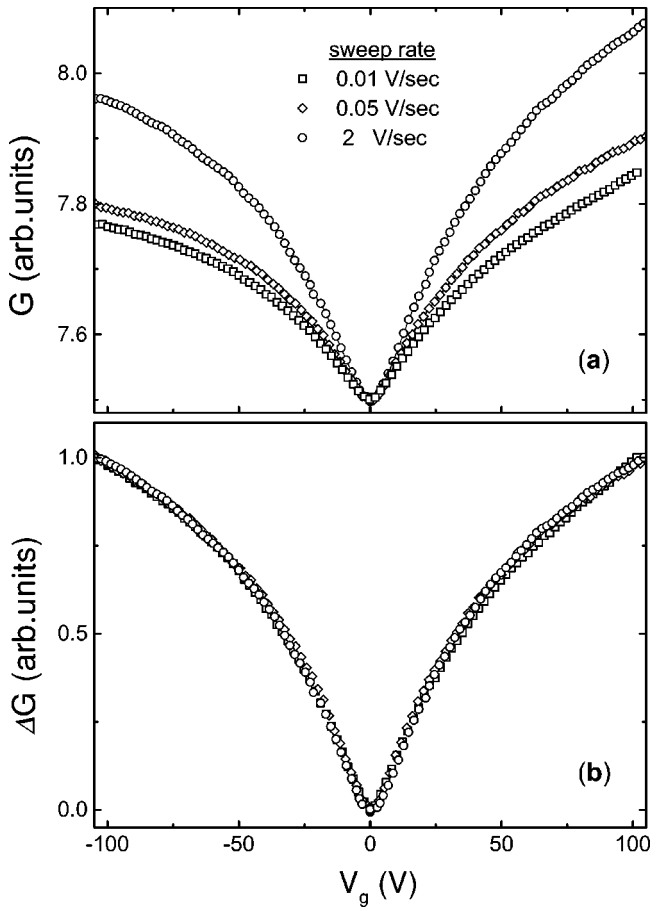

FIG. 7. $G(V_g)$ traces measured using the symmetric sweeping procedure with various sweep rates of V_g. (a) Raw data. (b) The same data after subtracting a linear part and normalizing the amplitude. In_2O_{3-x} sample on a microscope cover glass spacer, measured at 4.1 K. $R_{\square}=16$ MΩ.

ture the cusp has a *characteristic shape*.

On the other hand, Fig. 10 shows that the shape of the cusp does depend on the temperature at which it is measured provided the experiment is performed after the system is allowed to equilibrate at this temperature. Figure 10(a) presents $G(V_g)$ traces produced in a regime of temperatures between 0.7 K and 7 K. Measurements were done in two runs: from 4 K to 9 K and from 0.7 K to 1.5 K. Between runs, the sample was taken out of the cryostat and its resistivity was lowered[16] by UV treatment (see Ref. 9 for details). The curves are scaled such that they all coincide far from $V_g=0$. It can be seen that the cusp sharpens with decreasing temperature. This point is exhibited somewhat differently in Fig. 10(b) where $G(V_g)$ traces measured at two different temperatures (1.6 K and 4.1 K) for both the symmetric and continuous types of scanning are plotted. In this case the curves are scaled such that the amplitudes of the minima that correspond to the same type of scan coincide. In the continuous scans, the sample was first kept with $V_g=-30$ V for 5 h at the temperature of measurement. Then, V_g was swept to $+30$ V where it was kept for 8 min and then swept back to -100 V. It is again seen that lowering the temperature sharpens the cusp, equally so in both types of scan. In Fig. 10(c) such continuous sweep experiments (done at constant temperature) are compared with a similar experiment but where the sample was cooled from 4.1 K to 1.6 K during the 8 min pause at $V_g=30$ V (combined procedure). The interesting feature revealed by the figure is that the shape of the memory cusp measured after such cooling procedure is characteristic of the temperature that preceded the cooling.

In summarizing the above experimental results we may say that although the appearance of the cusp in the FE measurements is a nonequilibrium feature, we find several properties of this cusp that are insensitive of the way we measure $G(V_g)$. These are the evolution of the cusp after cooling the sample, the position and shape of this cusp at a given temperature, and the narrowing of this cusp at lower temperatures. It was also shown that the shape of the memory cusp might depend on the temperature at which the system was equilibrated, which could be quite higher than the temperature prevailing during its actual measurement. This demonstrates a *memory of the equilibration temperature.*

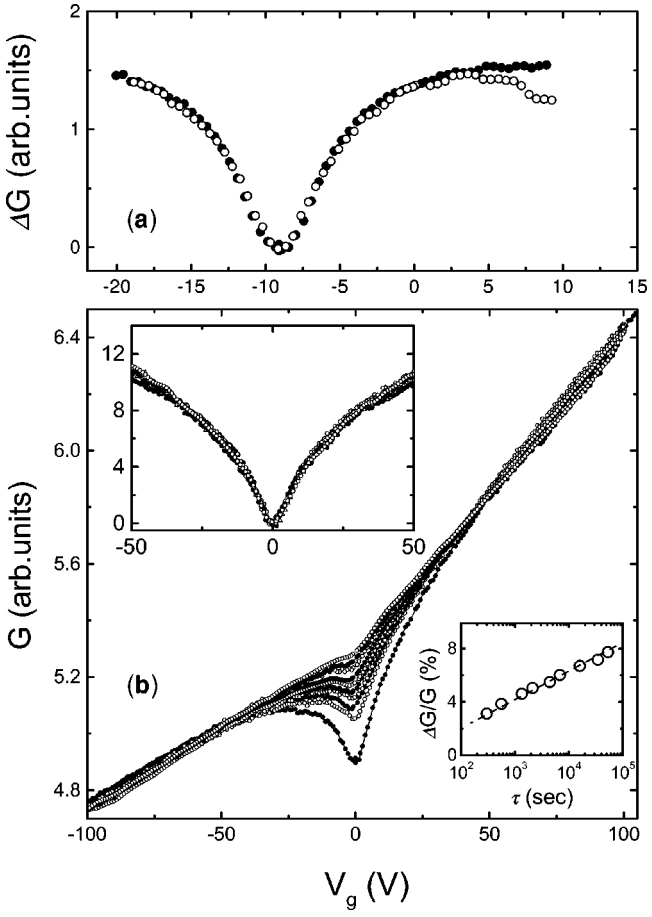

FIG. 8. (a) $G(V_g)$ traces, measured using the symmetric and the continuous sweeping procedures (solid and open circles, respectively). Between scans V_g was kept at 10 V for 30 sec. Traces are shown after normalizing their amplitude. InO_x sample on a SiO_2 spacer. $R_\square = 71$ MΩ. (b) Selected $G(V_g)$ traces, measured at different times τ during a continuous and periodic sweep of V_g. $\tau/1000$ (sec) = 0, 3, 5.6, 13.4, 21.2, 44.4, 68, 160, 346, 532 (bottom to top), labeled by the time at the beginning of trace. The sweep rate is 0.8 V/sec. The dependence of the conductance at $V_g = 0$ on τ is plotted in the lower-right inset. In the upper-left inset, the first eight $G(V_g)$ traces are shown after subtracting a linear part and normalizing their amplitudes. In_2O_{3-x} sample on a sapphire spacer, measured at 4.1 K. $R_\square = 100$ MΩ.

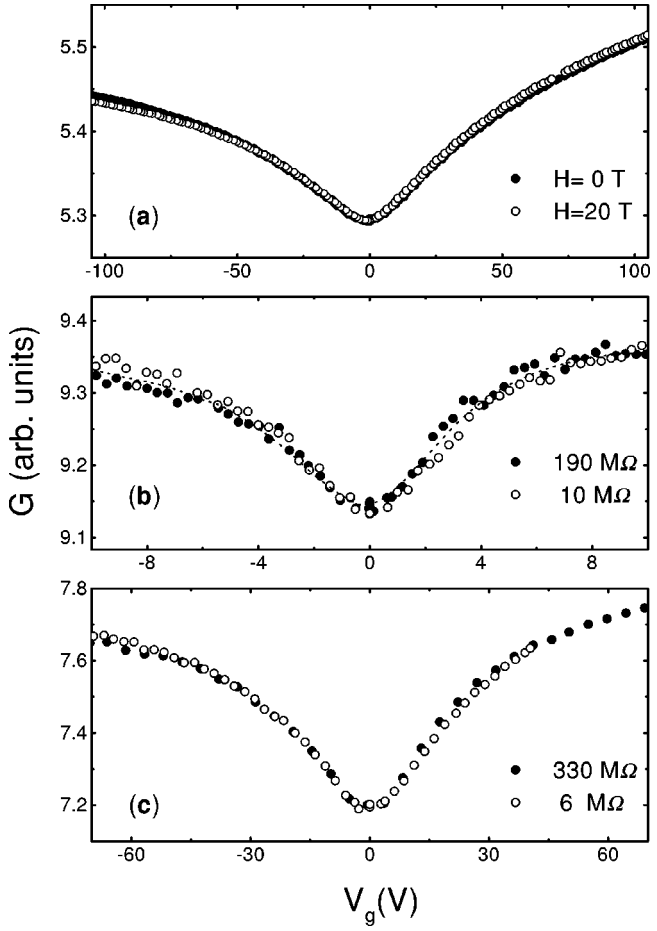

FIG. 9. (a) $G(V_g)$ traces, measured at different magnetic fields (using a Bitter magnet). In_2O_{3-x} sample on a microscope cover glass spacer. $R_\square = 10$ MΩ. (b) $G(V_g)$ traces, measured before and after thermal annealing of the sample, and thus having different structural disorder, labeled by the resistance. InO_x sample on a SiO_2 spacer. (c) The same as in (b) for a different amorphous sample on a sapphire spacer. All traces were measured using the symmetric sweep procedure, at 4.1 K.

One may try to explain the existence of the cusp based on two premises. First, in the Anderson-insulating phase the conductivity of a system with a nonequilibrium distribution of electrons is always larger than its equilibrium conductivity.[17] Second, sweeping V_g away from its equilibrium value produces a nonequilibrium situation if electrons are inserted (extracted) into (from) the sample at a rate that exceeds the rate of decay to equilibrium. For a symmetrical sweep, such dynamical considerations might indeed explain the existence of a minimum in $G(V_g)$ around the equilibrium gate voltage. On this basis, one may also understand the temperature dependence of the cusp shape—that is, by assuming that the excitation must exceed a certain energy (which in this scenario is related to the temperature) before a notable change in G occurs.[7] However, it is hard to see how such a picture alone can explain other features of this phenomenon. In particular, there seems to be no natural way to account for the following findings: the appearance of a memory cusp that is similar in position and shape to the symmetric cusp, the appearance of memory of the equilibration temperature, and the aging behavior.[4]

We suggest that the cusp in $G(V_g)$ reflects some internal property of the system. In equilibrium, such a property should characterize the external conditions felt by the sample, e.g., V_g or temperature, and retain a specific memory of these conditions a long time after they were altered. Considering the dynamics seen in Figs. 6 and 8 one may conclude that equilibrating at a specific gate voltage, say, V_g^o, has an effect only on a restricted region of V_g around V_g^o. This may imply that each value of V_g is associated to a different and distinct equilibrium state of the system. Later we examine the possibility that the property that characterizes the state of the system is associated with the correlation in the configuration and motion of carriers that arises due to

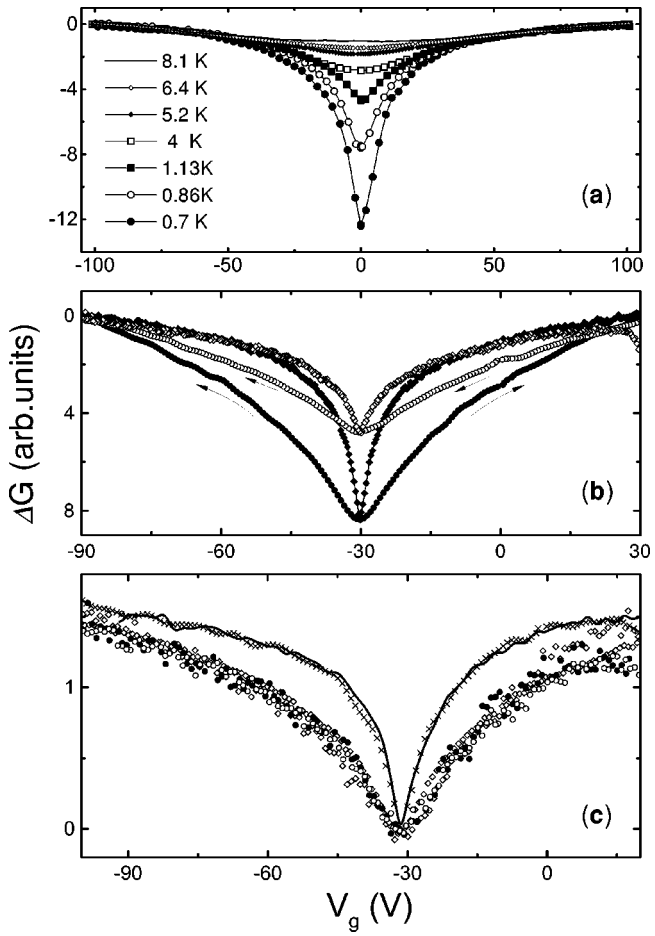

FIG. 10. (a) $G(V_g)$ traces, measured using the symmetric sweeping procedure at different temperatures (as indicated in the figure). In_2O_{3-x} sample on a microscope cover glass spacer. $R_\square$ varied in the range 3×10^5–$3\times10^8\Omega$. (b) $G(V_g)$ traces, measured at 4.1 K ($R_\square=4.8$ MΩ, circles) and 1.6 K ($R_\square=360$ MΩ, diamonds), using both the symmetric and the continuous sweeping procedures (solid and open symbols, respectively). In_2O_{3-x} sample on a sapphire spacer. (c) $G(V_g)$ traces, measured on the same sample as in (b) using either the ''combined'' procedure (solid circles) or the constant temperature procedure at 4.1 K (open diamonds) and 1.6 K (line). Also shown is a trace measured after carrying out the combined procedure and another waiting period of 3 h at 1.6 K and $V_g=-30$ V before the sweep (crosses). All traces are shown after subtracting a linear part and normalizing their amplitudes.

the mutual interaction between them. Evidence for the role of interactions in this system was already presented[7,8] before. One would expect then that such correlations would be diminished by a strong excitation presumably above an energy that characterizes the strength of the interaction. In the following, we show that this is indeed the case in two complementary experiments: the ''two-dip experiments'' and the ''aging'' experiments. The strength of the excitation relates here to the magnitude of the shift in the gate voltage $\Delta V_g \equiv |V_g^o - V_g^n|$ (see Sec. II).

In the case of small ΔV_g the following results were obtained. In the aging experiments, it is found[4] that $\Delta G(t) \propto f(t/t_W)$, i.e., simple aging. In Fig. 11 result of aging experiments, i.e., $\Delta G(t)$, are shown for different samples including polycrystalline and amorphous samples, samples with different carriers concentration (3×10^{19}–3×10^{21} cm^{-3}) and thickness (50 Å, 200 Å, and 2000 Å). It can be seen that $f(t/t_W)$ is, to a good approximation, the same for all measured samples. Interestingly, for $t/t_W<1$, $f(t/t_W)\propto\ln(t/t_W)$, such that if this logarithmic dependence would persist to the end (dashed line), ΔG would have relaxed to its original (equilibrium) value after a time t_W, i.e., the decay and buildup times of ΔG would be the same. This behavior is apparent also in Fig. 12(a) where the relaxation plots $\Delta G(t/t_W)$ corresponding to different t_W's are shown for a specific sample.

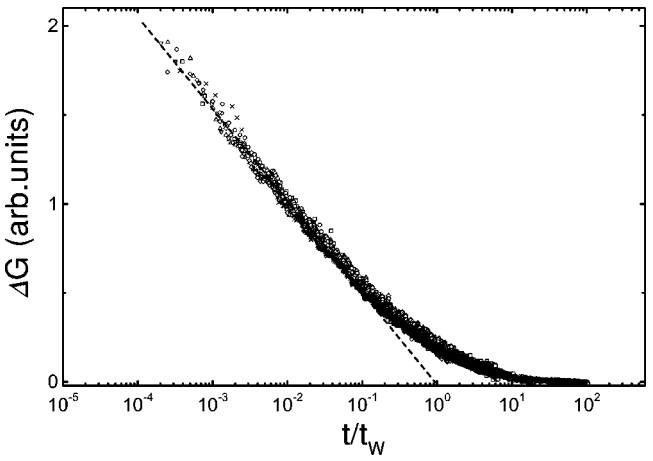

FIG. 11. $\Delta G(t/t_W)$, measured for different samples, during an aging experiment after V_g is switched back to V_g^o. For each sample, traces corresponding to different t_W were averaged and are presented as a single curve. Traces are shown after normalizing their amplitudes. Temperature is 4.1 K.

In the TDE, for the same values of ΔV_g we observe an antisymmetrically related time dependence of the buildup of the cusp at V_g^n and the decay of the cusp at V_g^o. This can be seen from the raw data in Fig. 13(a) or with the aid of Fig. 14, where the amplitude of the ''old'' dip A^o and that of the ''new'' one A^n are plotted as a function of time.

In both experiments, applying large enough ΔV_g causes a deviation from the behavior described above. As shown in Fig. 12(b) the simple-aging law is no longer obeyed. This deviation of the relaxation curves from the ''universal'' relaxation law (dashed line) increases with decreasing T_W. Thus, it seems that the effect of large ΔV_g on the relaxation curves is more pronounced for shorter T_W. This is presumably due to the fact that after long T_W the memory of the state that corresponds to V_g^o is considerably diminished even for small ΔV_g, and thus the additional effect of the large change in V_g is less prominent. With increasing ΔV_g there is a tendency for $\Delta G(t)$ to become independent of t_W. These findings are consistent with the hypothesis that a large shift in V_g causes degradation in the memory of the system regarding its voltage history. This may be more directly seen by considering the effect of the same ΔV_g on the TDE [Figs. 13(b) and 14]. Here, the antisymmetrically related time dependence of the buildup of the new cusp and the decay of the

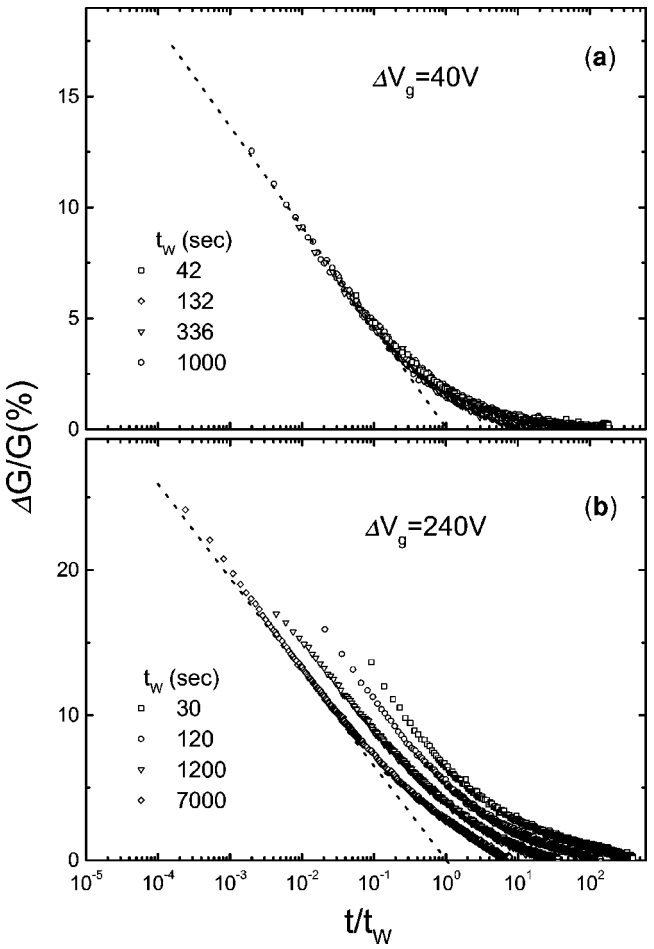

FIG. 12. $\Delta G(t/t_W)$, measured during an aging experiment after V_g is switched back to V_g^o. Data are shown for two series of experiments (a) and (b), employing different ΔV_g's (see text). In each series, different values of t_W were used. InO_x sample on a sapphire spacer. $R_\square = 330\ \mathrm{M}\Omega$.

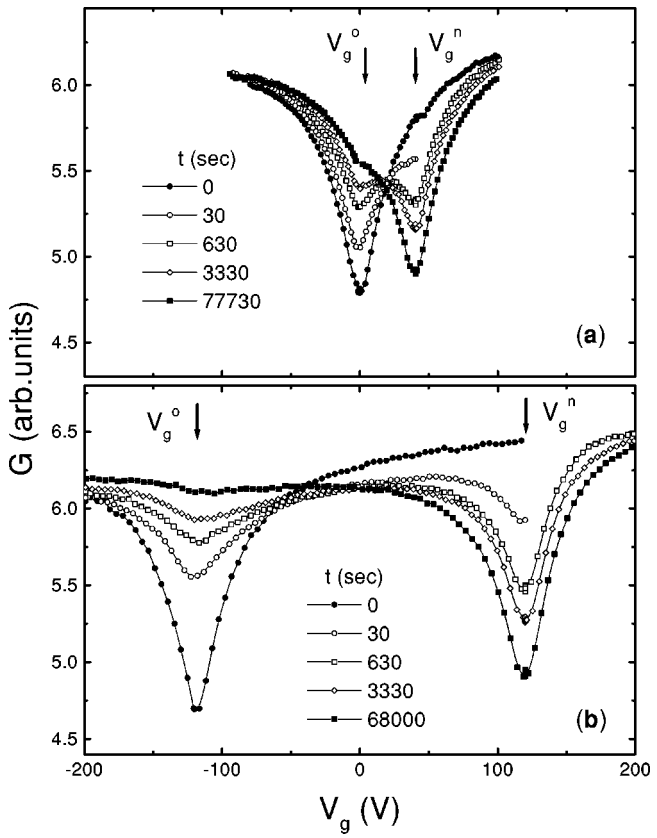

FIG. 13. $G(V_g)$ traces, measured during two TDE, (a) and (b), using the same sample and the same ΔV_g's as in Fig. 12 ($\Delta V_g \equiv |V_g^o - V_g^n|$). Before the experiments began, the sample was kept at the measurement temperature 4.1 K with $V_g = V_g^o$ for about 20 h. The sweep rate is 2 V/sec and 4 V/sec in (a) and (b), respectively.

old one is destroyed. A closer inspection of these figures shows that this destruction involves mainly the dynamics of the old dip. Namely, a short time after moving V_g to the new location the amplitude of the old cusp has diminished substantially, while the new cusp still evolves with time at the same rate as in the small ΔV_g limit. In other words, it is the memory of the old dip that is weakened by the large ΔV_g. It is important to note that this effect is independent of the sign of ΔV_g, as we ascertained by repeating this experiment sweeping V_g to either direction. It was also checked that this effect is not due to the longer time spent in sweeps to farther V_g (by varying the sweep rate for the same ΔV_g and getting similar results). This degradation of the memory is more noticeable as ΔV_g increases, suggesting that the memory cusp would disappear in the limit of sufficiently large ΔV_g.

What is the reason for the difference between small versus large ΔV_g? The degradation of the memory takes place because V_g is swept to a (far away) new value. Previous experiments established that a sudden change of V_g excites the system, presumably by imparting certain energy to the electrons. It thus seems natural to look for an energy scale in the problem that, once exceeded by some external means, the memory is destroyed. Such a conjecture is consistent with the results of another experiment in which we exposed the samples to an IR radiation. It turns out that a brief (few seconds) exposure of the sample to a 1-μm radiation effectively eliminated the memory cusp. On the other hand, briefly raising the sample temperature by few tenths of a degree (such as to produce the same increase in G as in the IR burst) left the memory intact. A detailed description of the IR irradiation experiments will be published elsewhere.[18] It seems therefore plausible to assume that it takes a certain energy to destroy the memory. The IR experiments are not very useful in terms of telling what this energy is since the energy $h\nu$ by which electrons get excited in the IR experiment is much larger than any other energy in the problem. However, they support the assumption that the application of large ΔV_g destroys the memory because it imparts a sufficiently large energy to the electrons. We can then use the observed value of ΔV_g where simple aging is no longer obeyed to estimate this energy. A simple estimate of the energy associated with ΔV_g can be obtained by evaluating the corresponding equilibrium shift of the Fermi-energy: $\Delta E_F \approx (\partial E/\partial n)\Delta n(\Delta V_g) = C\Delta V_g/[N(0)e\lambda A]$ where $N(0)$ is the system density of states (DOS) at the Fermi energy, C is the sample-to-gate capacitance, A is the area of the sample, and λ is its screening length. Using this procedure,[19] we estimate that ΔE_F associated with the value of ΔV_g at which

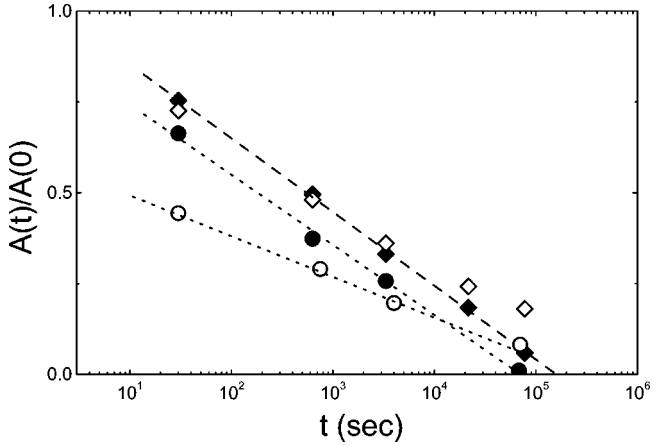

FIG. 14. $A(t)$, representing either $A^o(t)$ or $A^n(t)$ (open and solid symbols, respectively), corresponding to the experiments shown in Fig. 13(a) and 13(b) (diamonds and circles, respectively). A^o is the amplitude of the cusp at V_g^o, and A^n is defined as 1 minus the amplitude of the cusp at V_g^n, where both amplitudes are normalized with respect to initial cusp amplitude at V_g^o.

the memory cusp is affected to be 3–5 meV. Note that this energy is of the same order of magnitude as the temperature above which glassy effects disappear in our systems.[11] It is thus tempting to speculate that it is the correlation energy that is responsible for the observed glassy phenomena. However, note that this energy is considerably smaller then the estimated Coulomb gap energy.[8]

The effect of memory degradation described above is consistent with the suggestion raised above that the cusp in the FE measurements and the memory of the sample history are related to the correlation between electrons due to their mutual interaction. These correlations are at the heart of the phenomenon known as the Coulomb gap.[20] The glassy nature of Anderson insulators with interactions was anticipated by several authors.[21] Numerical simulations of the dynamics in these systems[22] (based on the Coulomb gap model) show glassy behavior such as the slow and nonexponential dynamics of various properties. Yu[23] developed a theory for the temporal evolution of the density of states and of the conductance, following an excitation that corresponds to a spatially random arrangement of electrons. The calculation was based on the Coulomb gap model of Baranovskii *et al.*[24] and on single-electron hopping with hopping rates based on weak electron-phonon interactions (Miller-Abrahams,[25] Mott[26]) at $T=0$. These results exhibited the buildup of the cusp in the density of states and thus in $G(E;t)$ that bears considerable resemblance to our evolution of the cusp obtained in $G(V_g,t)$ (Fig. 6). This similarity may support the association of the FE cusp with the Coulomb gap. Such an association is appealing and would explain, for example, why a cusp in $G(V_g)$ is formed at any V_g where the system equilibrates. However, it is important to realize that the Coulomb gap (like some other correlation gaps of the Fermi-edge singularity type) refers to a single-particle DOS. A modulation in the FE, on the other hand, usually reflects the thermodynamic DOS. In our experiments, neither situation is realized. Rather, the modulation in $G(V_g)$ is due to partially dressed quasiparticles. Therefore, at best, one may loosely refer to the cusp shape as reflecting a ''nonthermodynamic DOS.''

In a different approach to the problem, we wanted to see how much of the observations could be explained by a slow formation of quasiparticles.[27] For that purpose, we assumed interactions between particles to be, in a certain sense, strong, but without specifying their specific nature. In this framework, the strength of the interaction may be characterized by the typical self-energy of a quasiparticle. In the regime where the interaction is the dominant energy (i.e., at sufficiently small ΔV_g), the model can explain several features of the experiments. These are the following.

The logarithmic temporal relaxation of ΔG. The relaxation of particles corresponds to a buildup of correlations, i.e., ''dressing,'' which is quite slow because it is relies on hopping. Correlation in the motion of particles amounts to a decrease in mobility, i.e., in a gradually decrease of conductance. The rate of dressing of particles is controlled by a distribution $N(w)$ of transition rates w. For hopping processes w depends exponentially on a random variable x made up of a hopping distance and of a hopping energy, i.e., $w=w_0\exp[-x]$. The distribution of w is related to the distribution of x by $N(w)dw=N[x(w)]dx$, resulting in $N(w)=-(w_0/w)N[-\ln(w/w_0)]$. Assuming that x has a smooth distribution,[25,28] then $N[-\ln(w/w_0)]$ can be approximated by a constant since the argument of N moderately changes for a large change of w. A natural assumption regarding the distribution is a rapid drop of $N(w)$ around some minimum value of w, say, w_m. Then one can show that the time-dependent reduction in energy $\Delta E(t)$ is given by the integral $\int_{w_m t}^{\infty}(x^{-1})e^{-x}dx$, which gives

$$\Delta E(t)\sim\gamma-\ln(w_m t)-\sum\frac{(-1)^n(w_m t)_n}{(nn!)}. \tag{1}$$

For $t<1/w_m$ the logarithmic term dominates the time dependence. The more the system relaxes in energy, the smaller the conductance. So $G(E)$ is monotonic. Expanding $G(E)$ and taking the linear term only (the constant term does not affect ΔG), we get

$$\Delta G(t)\sim-\ln(w_m t). \tag{2}$$

The antisymmetric behavior observed in the TDE. This behavior can be obtained with the assumption that a change of V_g constitutes a small perturbation of the potential energy and of the electron concentration. Thus, its main role is to alter the structure of quasiparticles. Imagine two spectra of states corresponding to V_g^o and to V_g^1, where each state is defined by the site occupations. Neglecting the change in the number of electrons, any state in one spectrum corresponds to a state in the other spectrum but at a different energy. On the other hand, since there is nothing particular about a given V_g (within the limits of the assumption), the DOS of the two spectra are similar. Now consider a change in V_g, say, at $t=t_0$, from V_g^o to V_g^1. At $t<t_0$ the system is in an equilibrium state in the spectrum of V_g^o. At $t=t_0$ the same state (the same configuration of electrons) becomes an excited state in the spectrum of V_g^1, and thus gradually relaxes to a new equilibrium state in the spectrum of V_g^1. If during this evolution one

would follow the corresponding states in the spectrum of V_g^o, one would observe a climbing in energy at the same rate at which the energy in V_g^1 decreases. This can be justified on the basis of similarity of the two spectra and the assumption of a small perturbation in energy.

The observation that the shape of the cusp is independent of the sweep rate. This, however, is under the assumption of a symmetric sweep mode; the continuous sweep mode has not yet been considered in this model. In measuring the field-effect traces the change in V_g is linear in time, i.e., $\Delta V_g(t) = ct$ where c is some constant. Considering the sweep of V_g as a succession of evenly spaced identical infinitesimal step functions, $d[\Delta V_g(t)] = c\,dt$. Then $d\Delta G(t,t') = [d\Delta G(t,t')/dt']dt'$ and, writing $\tau = t - t'$ and using $\Delta G(t) \sim -\ln(w_m t)$ we find that the amplitude of the dip changes with sweep rate c but the shape does not.

An interesting issue in these measurements is the ability of the system to memorize the history of the external conditions to which it was subjected, such as V_g, t_W, and temperature. In this picture, after changing the external conditions, the electronic configuration retains a certain memory of the quasiparticle structure appropriate for the old external conditions prevailing during equilibration. This memory then will gradually diminish with time. Loosely speaking, one may say that the memory resides in the correlations involved in the makeup of quasiparticles. One would expect then that once the quasiparticles are fully ''dissociated'' into particles, all traces of memory are wiped out from the system. This may happen when the energy of excitation becomes larger than the formation energy of quasiparticles. This is consistent with the observation of memory degradation by large excitation. The reduction of mobility, as the gradual dressing of carriers by other carriers enhances the correlation in their motion, provides a possible mechanism by which such processes may affect the conductance.

Next, we want to elaborate on the advantages in following the glassy dynamics by measuring the function $G(V_g;t)$, i.e., by performing the FE experiments. Obviously, $G(V_g;t)$ carries more information about the nonequilibrium dynamics than that obtainable from just monitoring the response $G(t)$ at fixed V_g. Consider the following examples.

(i) As noted above, $G(V_g)$ has a typical shape that depends on the temperature at which the system was allowed to equilibrate [Figs. 10(a) and 10(b)]. This correlation between the cusp shape and the temperature enabled us to identify [Fig. 10(c)] a new kind of memory: a memory of the ''equilibration temperature.''

(ii) The FE experiments show that the evolution of the response $G(t)$ after cooling is just part of a development of a cusp in $G(V_g)$ (Fig. 6). Namely, most of the evolution occurs over a limited range of gate voltages around V_g^o. It is plausible then that this limited range of gate voltages reflects the existence of an energy range in which most of the dynamics takes place. Moreover, as noted above, following quench cooling the shape of the cusp does not change with time (inset of Fig. 6). This should be contrasted with the observation that the cusp shape does reflect the equilibrium (or near-equilibrium) temperature. We may thus conclude that the evolution of the cusp (and therefore the decay of the response after cooling) cannot be viewed as a slow ''cooling'' of the electronic system.[29] In this context it is interesting to note the similarity between the time evolution of the cusp in these FE experiments and the corresponding behavior of the DOS in the numerical results shown in Ref. 23.

Finally, we show how monitoring $G(V_g;t)$ using the TDE may help to understand the various aging phenomena from a different perspective. In particular, the reason for the deviation from simple-aging behavior when ΔV_g is not small can be identified. In the aging experiment, the conductance is continuously measured versus time while switching V_g from the equilibrium cusp at V_g^o to the new cusp at V_g^n, and then back after t_W (at a time defined as $t=0$). Then, one focuses on the behavior of the excess conductance $\Delta G(t)$ for $t>0$. During this time, G relaxes towards its equilibrium value. This process is a rebuilding of the old cusp at V_g^o that diminished in magnitude during the time the system spent at V_g^n. Obviously, $\Delta G(0)$ depends on the dynamics that takes place at V_g^o, namely, the decay rate of A^o. This dependence, however, is concealed in the aging experiments. It is precisely this missing information that can be retrieved via the TDE. In particular, the following features can be established from these experiments. First, for small ΔV_g, both $A^o(t)$ and $A^n(t)$ evolve antisymmetrically with $t, \Delta[A^o(t)] \propto -a\ln(t)$ and $\Delta[A^n(t)] \propto a\ln(t)$ (Fig. 14). Second, the process of rebuilding the cusp at V_g^o is also of the same form albeit only for $t \ll t_W$.[30] Let us now see how these features lead naturally to simple-aging behavior. The relaxation $\Delta G(t>0)$ can now be written as $\Delta G(t>0) = \Delta G(t_0) - A^n(t) = \Delta G(t_0) - a\ln(t/t_0)$, where $\Delta G(t_0)$ is the initial amplitude at t_0 (say, the sampling time). Then, from the relation between $\Delta G(t_0)$ and $A^o(t)$ discussed above and from the first feature we can write $\Delta G(t_0) = A^o(0) - A^o(t_W) = a\ln(t_W/t_0)$. Thus, we find

$$G(t>0) = a\ln(t_W/t_0) - a\ln(t/t_0) = -a\ln(t/t_W), \qquad (3)$$

consistent with a simple-aging behavior at this limit of small ΔV_g. When ΔV_g is not small we observe deviation from simple aging (Fig. 12). The TDE show that this deviation is due to the degradation of the memory cusp amplitude A^o. This degradation of A^o is apparent already in the first $G(V_g)$ trace taken after sweeping V_g to V_g^n (Figs. 13 and 14). Although at later times $A^o(t)$ is still logarithmic, it has a different slope than that of $A^n(t)$ due to the weakened amplitude at early times. Thus, there is no symmetry between the evolution of A^o and A^n in this case.

For $0<t<t_W$, the consistently observed relaxation law $\Delta G(t) \propto f(t/t_W)$ in our aging experiments is logarithmic and extrapolates to zero at $t=t_W$ (Fig. 11, dashed line). This is in agreement with the above expression (3) that is based on the antisymmetry in the evolution of the two dips in the TDE. Therefore, it seems that this common relaxation function $f(t/t_W)$ for $t/t_W<1$ actually reflects the underlying antisymmetry between the decay and the creation of the cusp in the $G(V_g)$ traces. On the other hand, for $t \geqslant t_W$, $f(t/t_W)$ deviates from the logarithmic relaxation law. This may indicate that

the explanation for this relaxation law over the whole time domain (and thus to the simple-aging behavior) is probably more involved.

In summary, we have presented results of the nonequilibrium transport properties of insulating InO_x and In_2O_{3-x} samples with special emphasis on field-effect experiments. Some properties of these experiments are robust against variations in the way we do the measurements, i.e., sweep the gate voltage. These properties are the shape of the cusp in $G(V_g)$, its temperature dependence, and its time evolution following quench cooling. It was also shown that the shape of the cusp reflects not only the measurement conditions but also retains a certain memory of the equilibration temperature. We proposed that the cusp in $G(V_g)$ reflects an internal property of the system that characterizes the specific external conditions experienced by the sample during equilibration. These conditions are memorized and may be retrieved long after the external conditions are changed. We discussed the correlation between electrons as a possible candidate for such a property. In this framework, memory appears since the evolution of these correlations after altering the external conditions is very sluggish. It will be interesting to find whether this slow evolution also affects other measurements than the conductance or the field effect.

Finally, the advantage in measuring the temporal evolution of $G(V_g)$ rather than just monitoring $G(t)$ at a fixed V_g has been emphasized. It would be of interest to study the properties of the analogous function in other glassy systems. Here we draw attention to the resemblance between the cusp in our $G(V_g)$ and the similar features found in the ac capacitance measurements versus dc electric field in structural glasses[31] and in magnetic susceptibility versus magnetic field in spin glasses.[32]

ACKNOWLEDGMENT

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