History-dependent relaxation and the energy scale of correlation in the Electron-Glass

Z. Ovadyahu

The Hebrew University, Jerusalem 91904, Israel

M. Pollak

Department of Physics, University of California, Riverside CA 92651, USA

Abstract

We present an experimental study of the energy-relaxation in Anderson-insulating indium-oxide films excited far from equilibrium. In particular, we focus on the effects of history on the relaxation of the excess conductance $\Delta G$. The natural relaxation law of $\Delta G$ is logarithmic, namely $\Delta G \propto \log(t)$. This may be observed over more than five decades following, for example, cool-quenching the sample from high temperatures. On the other hand, when the system is excited from a state $S_o$ in which it has not fully reached equilibrium to a state $S_n$, the ensuing relaxation law is logarithmic only over time $t$ shorter than the time $t_w$ it spent in $S_o$. For times $t \geq t_w$, $\Delta G(t)$ show systematic deviation from the logarithmic dependence. It was previously shown that when the energy imparted to the system in the excitation process is small, this leads to $\Delta G \propto P(t/t_w)$ (simple-aging). Here we test the conjecture that ‘simple-aging’ is related to a symmetry in the relaxation dynamics in $S_o$ and $S_n$. This is done by using a new experimental procedure that is more sensitive to deviations in the relaxation dynamics. It is shown that simple-aging may still be obeyed (albeit with a modified $P(t/t_w)$) even when the symmetry of relaxation in $S_o$ and $S_n$ is perturbed by a certain degree. The implications of these findings to the question of aging, and the energy scale associated with correlations are discussed.

PACS: 72.80.Ny 73.61.Jc
I. INTRODUCTION

Recently there were several reports on the non-ergodic transport properties of Anderson insulators. These were interpreted as evidence for a glassy phase that was theoretically predicted by several authors. When excited from equilibrium, the conductance of such systems increases - a property inherent to the hopping system. The excess conductance \(\Delta G\) persists for long times (in some cases, days) after the excitation. Vaknin et al argued that such extended relaxation times as well as other glassy aspects are associated with the presence of strong inter-carrier interactions. The various memory effects exhibited by these systems are difficult to explain unless electron-electron correlations play a role.

An intriguing memory effect, common to many other glasses, is aging. This term usually refers to the response of a system when it is under the influence of two differently imposed conditions, the first lasting a macroscopic time \(t_w\), the next (immediately following) a time \(t\). The system is said to age if the response depends on both \(t_w\) and \(t\). That is in fundamental contrast to ergodic systems where the response depends only on \(t\). In the electron glass this may be observed in \(\Delta G(t)\) by, e.g., suddenly changing the gate voltage (employing a MOSFET structure). It turns out that the aging function \(\Delta G(t,t_w)\) in this case is just a function of \(t/t_w\). This so called ‘simple’ or ‘full’ aging behavior has been rarely observed in such a clean form in any other glassy system. It was conjectured that simple aging is associated with the identical dynamics in the ‘old’ and ‘new’ states involved in the experiment. Indeed, the ‘anti-symmetric’ behavior of \(\Delta G(t)\) in the ‘old’ and ‘new’ states, and their logarithmic form are sufficient to guarantee simple-aging for \(t<t_w\). In this paper, we test this conjecture by exploring the changes in the aging function caused by situations where the above symmetry begins to break down. This symmetry is probed by a new experimental procedure described in section III. It is shown that the dynamics in the ‘old’ state is affected by both, the time it takes to switch the external condition that imposes the ‘new’ state, and by the energy difference between the two states. Both contribute to asymmetry in the dynamics. We compare these changes with the respective modifications in the aging function and discuss the implications as to the question of the energy scale for the correlations that presumably control the glassy behavior in the system.
II. EXPERIMENTAL

Samples used in this study are thin films (50Å thick) of crystalline indium-oxide e-gun evaporated on 140µm cover glass. Gold film (500Å thick) was evaporated on the backside of the glass and served as the gate electrode. Conductivity of the samples was measured using a two terminal ac technique employing a 1211-ITHACO current preamplifier and a PAR-124A lock-in amplifier. All measurements reported here were performed with the samples immersed in liquid helium at T=4.11K held by a 100 liters storage-dewar. The ac voltage bias was small enough to ensure Ohmic conditions. Fuller details of sample preparation, characterization, and measurements techniques are given elsewhere. Four different batches of samples were used in the present study. Sample size was typically 1x1 mm and its sheet resistance $R_{\square}$ was 30-80 MΩ at 4K.

III. RESULTS AND DISCUSSION

Figure 1 shows the dependence of the sample conductance $G$ following a quench from a high temperature to the measurement temperature $T_m$. The observed $G(t)$ is seen to obey a logarithmic law over more than five decades. Figure 2 illustrates a similar $G(t)$ for the same sample measured after $V_g$ was changed from -50V to +50V. We shall show that the logarithmic dependence characterizes the approach to equilibrium of the electron glass when no history intervenes. The notion of history will become clear below. For now it is emphasized that in both cases depicted in figures 1 and 2, the relaxation is monitored under conditions where the system exhibits no signature of the past; In the first case the system is relaxing from a high-energy state (presumably ergodic, e.g., above its glass temperature), and thus have no long term memory of its old state. In the second case, as will be demonstrated, the system does have a memory of the old state but the signature of this memory does not appear in $G(t)$ during the time of the measurement. This is so because the time the system spent in the old state was much longer than the time over which $G(t)$ was monitored during the experiment shown in figure 2. Indeed, when the time over which $G(t)$ is recorded is comparable or longer than the “waiting” time $t_w$ the system was allowed to equilibrate at the old state, a clear deviation from logarithmic dependence can be observed. An example is shown in figure 3.
Note first that the $\Delta G \propto -\log(t)$ reported here extends the observation of this relaxation law, previously reported, to include more than five decades in time. It seems now plausible to conclude that this is the natural (‘history-free’) relaxation law of the electron glass. Such a law has been explained as being inherent to the hopping system due to its extremely wide distribution of transition rates $\omega$.\[12\]

The $\log(t)$ relaxation law cannot persist for arbitrarily long times even when history does not play a role (e.g., when $t_w=\infty$) because the slope of $\Delta G[\log(t)]$ must vanish asymptotically (or else $G(t)$ will fall below the equilibrium conductance $G(0)$). Physically, the deviation from a $\log(t)$ behavior is expected when $t^{-1}$ approaches the slowest rate $\omega_{\text{min}}$ in the distribution.

The relaxation in figure 3 exhibits a deviation from the logarithmic dependence at time $t_w$, which is evidently much smaller than the ‘natural’ $\omega_{\text{min}}^{-1}$ of the system. It would thus appear that the effect of “history” on the relaxation law is to modify the effective relaxation rate-distribution. Note however that the observed deviation in figure 3 (that falls above the log line) is qualitatively different from departures from log due to a rapid cut-off in a distribution at $\omega_{\text{min}}$.

It was shown in \[10, 13\] that logarithmic behavior results from the exponential dependence of the transition rates $\omega$ on a random variable $x$ with a smooth distribution. Departures from a flat distribution of $x$ introduce only logarithmic corrections to the $1/\omega$ distribution of $\omega$. However, if the distribution of $x$ is not smooth, the deviations from log(t) relaxation can be strong. To explain the observed behavior with a change of the distribution mandates a rise in the distribution around $t_w^{-1}$ (A rise is required for a departure above the log line, as observed in figure 3).

The signature of a previous excitation/relaxation process appearing in a subsequent experiment is a peculiar property of glasses. This history dependent relaxation is one of the aspects of ‘aging’. A typical aging experiment involves the following procedure. The system is allowed to equilibrate under a set of external conditions $\{x^o_i\}$ that control some macroscopic response function $P$. Then, $\{x^o_i\}$ is changed to $\{x^n_i\}$ for a waiting time $t_w$ during which $P(\{x^o_i\})$ evolves towards $P(\{x^n_i\})$. Finally, the ‘old’ conditions $\{x^o_i\}$ are restored, and the response $P$ is monitored versus time $t$ starting from the moment $\{x^o_i\}$ are re-established. In a glassy system it is commonly found that $P(t)$ reflects $t_w$ (as well as $\{x^o_i\},\{x^n_i\}$). Namely, $P(t)$ is in general a function of both $t$ and $t_w$. A special case of aging is when $P(t,t_w)=P(t/t_w)$. Such a behavior of the relaxation (so called ‘simple-aging’), has been recently observed in
Anderson-localized indium-oxide thin films. In these experiments \{x_i\} was the carrier concentration n (controlled via a gate voltage \(V_g\)), and the response P was the electronic conductance G.

Vaknin et al. [10, 13] showed that the symmetry of the two-dip experiment (TDE) is sufficient to cause “simple-aging”. In the TDE, the sample is cooled to the measuring temperature with a voltage \(V_o^g\) held at the gate, and is allowed to equilibrate for several hours. Then, a G(\(V_g\)) trace is taken by sweeping \(V_g\) across a voltage range straddling \(V_o^g\). The resulting G(\(V_g\)) exhibits a local minimum centered at \(V_o^g\). At the end of this sweep, a new gate voltage, \(V_n^g\) (differing from \(V_o^g\) by typically few tens of volts for a 100\(\mu\)m spacer), is applied and maintained at the gate between subsequent \(V_g\) sweeps that are taken consecutively at latter times (measured from the moment \(V_n^g\) was first applied). Each such sweep reveals two minima (c.f., figure 1 in reference 9 as an example); one around \(V_o^g\) (with magnitude A1) that fades away with time, and the other at \(V_n^g\) with magnitude A2 increasing with time. It turns out that when \(\delta V_g=|V_n^g-V_o^g|\) is not too large, A1(t) and A2(t) are ‘symmetric’ in the sense that A2(t)=a\cdot\log(t) while A1(t)=A1(t=0) a\cdot\log(t), namely, G at \(V_o^g\) evolves with time at the same rate (and opposite sign) as the change in G at \(V_n^g\).

It is easy to see that these time dependences of A1(t), A2(t) are sufficient to guarantee ‘simple-aging’ in the corresponding aging experiment. Specifically, the excess G observed after \(V_o^g\) is restored (at t=0) relaxes according to the law:

\[
\Delta G(t) = \Delta G(t=0) - a\cdot\log(\omega t) = a\cdot\log(\omega t_w) - a\cdot\log(\omega t) = a\cdot\log(t/t_w).
\]

Note that there are two ingredients in this “derivation”. The first is the basic logarithmic relaxation (which, as discussed above, is obeyed over a limited range in t, and thus poses a similar restriction on the relaxation law in the aging experiment). The second is the symmetry of the A’s. In the following, we wish to look more closely into the relation between the symmetry and simple aging. We shall describe how the symmetry is modified by the experimental procedure, and what implications this has on the question of simple aging.

What does the symmetry (or anti-symmetry) mean? The magnitude A of the cusp formed in G(\(V_g\)) at a newly imposed gate voltage reflects the dynamics of the approach towards the ‘new’ equilibrium value of the conductance G(\(V_n^g\)). Initially (t=0), G exceeds G(\(V_n^g\)) by a certain amount and it slowly decays towards it. We shall refer to this process as “learning”. This is used here mainly to facilitate the discussion below but note that “learning” is an appropriate name for a process where a system adjusts to newly imposed conditions. During
this learning-time, the system begins to “forget” the ‘old’ conditions (i.e., the cusp at $V_{\text{g}}^o$ fading away). The latter process is monitored in the TDE experiment by peeking briefly from time to time at what happens at $V_{\text{g}}^o$ while most of the time the system is allowed to experience $V_{\text{g}}^n$. Both processes are driven by the need to adjust to (the same) change in the external conditions, and on a microscopic level, both involve transitions between states localized in (the same) space. The transition rates are presumably controlled by disorder, and restrictions due to interactions. The processes differ in that they occur in different places on the energy scale (i.e., the energy associated with $V_{\text{g}}^n$ and $V_{\text{g}}^o$). When this difference is small, the two processes should then be symmetric. In the other limit, that of large energy difference, the transition rates could be quite different thus leading to lack of symmetry in the ‘learning’ versus ‘forgetting’ processes. For example, the localization length and/or the relevant density of states may be larger at the higher energy, and this may lead to faster dynamics.

The question is how small should $\delta V_{\text{g}}$ be to guarantee this symmetry. To answer that experimentally we performed a series of measurements using the following procedure. After allowing the sample to equilibrate under $V_{\text{g}}^o$, the gate voltage was swept to another value $V_{\text{g}}^n$ and kept there for a dwell-time $t_d$. Then, $V_{\text{g}}$ was swept back to $V_{\text{g}}^o$ and kept there for the same $t_d$, and so on. The sample conductance $G$ was continuously monitored during this process. Typical results of such an experiment (which is essentially a repeated aging experiment) are shown in figure 4. Focusing on the G at the end of each dwell-time one identifies two sequences: $G(t_i)$ for $\Delta G = V_{\text{g}}^o$, and $G(t_i)$ for $V_{\text{g}}=V_{\text{g}}^n$ that increases (decreases) with $t$ respectively. Figure 5 shows a similar $G(t)$ for a specific $\delta V_{\text{g}}$ where the time is plotted on a logarithmic scale starting from the time (plus one second, which is the sampling time) $V_{\text{g}}^n$ was first established. The figure includes three straight lines. The first is the initial relaxation curve of the conductance, which is naturally logarithmic just as in figure 2 above. The other two are lines connecting the $G(t_i)$ points of the ‘learning’ and ‘forgetting’ series that also appear to obey rather well logarithmic time dependence. This is not a trivial result; each series ‘accumulates history’ as time goes by but the main effect of it seems to be just a modification of the logarithmic slope. Namely, the absolute value of $\partial G(t_i)/\partial \ln(t)=q_{L,F}$ for the ‘learning’ ($q_L$) and ‘forgetting’ ($q_F$) series is smaller than the respective value for the ‘natural’ relaxation ($q_n$). Either the ratio or difference between $q_L$ and $q_F$ may be used a measure of ‘learning-forgetting asymmetry’. In the experiments described here a fixed
$t_d = 20$ seconds was used and the asymmetry was measured as function of $\delta V_g$ and the gate-voltage sweep-rate $dV_g/dt$. Typical results for $q_{L,F}$ and $q_F/q_L$ are shown in figures 6 and 7 as function of $\delta V_g$ for two of the studied samples. Looking first in figure 6 one observes that both $q$’s increase with $\delta V_g$, which is because the amplitude of the excess conductance grows monotonically with $\delta V_g$. The interesting point here is that $q_F$ increases faster than $q_L$, a trend that becomes clear above a certain $\delta V_g$. As mentioned above, a difference in energies could create a difference in the rate of relaxation, which in turn lead to asymmetry. Note however that the trend observed in figure 6 is independent of the sign of $V_n - V_o$.

Moreover, the relaxation that resulted by switching $V_g$ from, say, $-100V$ to $+100V$ (after allowing equilibration at $-100V$) showed the same logarithmic slope as when the initial $V_g$ was $+100V$ and relaxation was monitored after $V_g$ was swept to $-100V$. The reason for the asymmetry at higher $\delta V_g$ is therefore not due to the difference in the equilibrium energies associated with the different $V_g$. We now show that the asymmetry in these ‘learning-forgetting’ experiments results from the combination of two factors. The first is the finite time it takes $V_g$ to move between the ‘old’ and ‘new’ states. During this travel time, the gate voltage is neither at $V_o$ nor at $V_n$. This naturally contributes to the ‘forgetting’ process and diminishes the rate of ‘learning’. Namely, the conductance at both $V_o$ and $V_n$ changes in the direction to make $q_F/q_L > 1$. This can be seen in figure 7 as an explicit dependence of $\gamma = q_F/q_L$ on sweep rate for four fixed values of $\delta V_g$. The second factor is less trivial. As implied by the data in figure 7, asymmetry increases with $\delta V_g$ even when the effect due to travel-time-delay is taken into account, i.e., for a constant $t_d/[\text{travel time}]$. This contribution to the asymmetry is therefore associated with the change in the state of the system when the gate voltage is swept through $\delta V_g$. Empirically, the effect of $\delta V_g$ in these experiments is to destroy the correlations that are built during the respective $t_d$ for both, the ‘old’ or ‘new’ state. It therefore speeds-up ‘forgetting’ and slows-down ‘learning’.

The change of $V_g$ affects the electrons in two different ways. One is to change the electron population, the other is to change the random potentials of the sites (by $e z_i \delta F$ where $z_i$ is the coordinate across the film of site $i$ and $\delta F$ is the change in the electric field induced by $\delta V_g$). Changing the random potentials constitutes an excitation - say the system was in the ground state prior to the change of $V_g$, this state becomes an excited state just after the change because a change in the Hamiltonian changes the ground state. $\delta V_g$ thus causes a rise in the conductivity because quasi-particles are not fully formed in an excited state; the
motion of particles thus becomes less constrained by correlation. We argue below that this is the dominant effect at small $\delta V_g$ and the one that preserves the observed memory effects. The way in which that comes about has been discussed more fully in [13].

Insertion of electrons (or holes) is a relatively minor effect at small $\delta V_g$ where excitation is smaller than the typical interaction energy (i.e. the typical energy of formation of quasi-particles). This is so because the energy of the particle is larger than the energy of the quasi-particle and therefore the particle density of states at small energies is suppressed. (For example, the Coulomb gap [14] can be viewed as the difference between the energy of particles and quasi-particles.) Furthermore, to leave memory intact, the inserted particles must rapidly enter the system in just the same number and the same degree of dressing as the particles that left the system at the lower $V_g$. There is clearly no reason for this to happen.

When $\delta V_g$ causes an excitation in excess of the typical quasi-particle energy, there is no impediment to electrons entering the system and, since the observed onset of asymmetry happens where $\delta V_g$ corresponds to the interaction energy, we believe that this is a likely cause for loss of memory.

We turn now to the modifications to the aging behavior as function of $\delta V_g$ in these samples. Figure 9 shows the aging functions for two values of $\delta V_g$ measured for the same sample using an identical set of waiting times. At first sight, both sets of data show good scaling with $t/t_w$ despite the fact that the data in 9b is evidently in the asymmetric regime (c.f., figure 7). Therefore, ‘simple-aging’ may apparently be observed even when the symmetry between the ‘old’ and ‘new’ state is no longer obeyed. Closer inspection reveals some differences between the small and large $\delta V_g$ cases; The collapse of data is somewhat worse for the latter case, and more importantly, the extrapolated value of the initial logarithmic slope of $\Delta G(t)$ crosses $\Delta G=0$ at $t/t_w>1$ as opposed to $t/t_w=1$ for the data in figure 9a. These differences, however small are significant; they were consistently observed in all four batches studied as well as in another type of experiments where a large change in the source-drain field $\Delta F$ was used to study aging [15] (instead of “gating” the sample by $\delta V_g$). This allowed a much bigger range of measurements over which asymmetry was apparent and the extrapolation to $\Delta G=0$ kept moving up with $\Delta F$ beyond $t/t_w=1$ reaching a value of $\approx 7$ before a pronounced lack of a collapse of the curves was noticed.

It is illuminating to compare the relatively minor changes in the scaling of the sample in
figure 9 at large $\delta V_g$ with the corresponding behavior of the sample studied by Vaknin et al [10] (c.f., their figure 12). In the latter case, near perfect scaling of $\Delta G(t/t_w)$ was observed for $\delta V_g=40V$ but for $\delta V_g=240V$ the $\Delta G(t/t_w)$ curves completely failed to collapse. Note that in terms of $\delta V_g/\Gamma$ the sample in reference 11 (figure 12b) is $\approx 6$ which is quite similar to $\delta V_g/\Gamma \approx 5$ for the sample in figure 9b which still shows reasonable $\Delta G(t/t_w)$ scaling. There must apparently be a reason for the higher sensitivity of the sample studied by Vaknin et al. Namely, the degree to which the aging behavior is modified when $\delta V_g/\Gamma > 1$ apparently involves another parameter. We suggest that the different sensitivity in the aging behavior between the two samples may be due to the difference in their carrier concentration $n$. The importance of this system parameter in gating experiments can be understood as follows. As noted above, the application of a ‘new’ gate voltage has a number of consequences; the field associated with $V_g$ re-shuffles the random potential of the electronic sites. In the process, the system is re-excited (sometimes referred to as ‘rejuvenation’) and some loss of memory unavoidably occurs. However, an additional factor, peculiar to the gate experiment, takes place – a change of $V_g$ brings into the system particles that are “memory-less” (as they are injected through metallic contacts where they are well equilibrated) thus “diluting” its memory. (This is somewhat analogous to the effect of flushing a “contaminated” vessel with “fresh” substance). All other things being equal, this detrimental effect will be more pronounced in a low-density system. Note that the value of $\Gamma$ for the sample shown in figure 9 is larger by a factor of two than the sample studied by Vaknin et al. Since $\Gamma$ increases monotonically with the carrier concentration $n$, this means that the sample in reference 10 has smaller $n$, and is therefore more susceptible to this additional memory loss by a given $\delta n$. The relevance of this picture can be tested by a Monte-Carlo simulation: An aging ‘experiment’ performed by changing just the random sites energies should yield different results than by inserting new particles.

The degree of deviations from simple aging behavior, and the relevance of the sample parameters could be likened to other phenomena where, due to a large drive, the response gets out of the linear regime. Ohm’s law, for example, is obeyed when the energy imparted by the applied voltage to the charge carriers is smaller than $k_B T$. The conductance will become voltage dependent when the voltage is higher than this limit, but the degree of deviation from Ohm’s law will depend on many factors in particular, the temperature coefficient of resistivity. Likewise, the linear-response regime (defined experimentally by the condition
that simple aging is strictly obeyed), of the aging experiment has the limitation that $\delta V_g/\Gamma$ should not exceed a certain value of order unity. We showed that the degree of deviation when this condition is violated depends on the system.

The asymmetry created by a large $\delta V_g$ impairs the precise scaling of the aging function $\Delta G(t/t_w)$ by a smaller degree than that revealed in the ‘learning-memory’ experiments (compare figure 6 and 9). The main reason is probably the cumulative effect produced in the latter type of experiment. As mentioned before, the reason for the destructive effect is the energy associated with $\delta V_g$ and therefore the ‘critical’ $\delta V_g$ at which the symmetry begins to fade away marks the typical energy of the correlations. Inasmuch as the question of this important factor is concerned, the ‘learning-memory’ experiment is a much more sensitive tool than the aging experiment. It would be of interest to apply a similar technique to other glassy systems.

In summary, we presented and discussed experimental data pertaining to the effect of history on relaxation processes in the electronic glassy phase of indium-oxide samples. It was shown that the natural relaxation law in these systems is logarithmic over a wide range of times provided the excitation is performed following ample equilibration period. Partial equilibration, for a finite $t_w$, leads to a deviation from the logarithmic law, beginning from times $t \approx t_w$. This aging phenomenon takes a simple form such that the relaxation of the excess conductance can be described by $\Delta G(t/t_w)$. It was further demonstrated that this simple-aging behavior could still be observed (albeit somewhat impaired) even when $\delta V_g$ was large enough such that the symmetry in the dynamics of the ‘old’ and ‘new’ states was considerably impaired. The robustness of the simple aging under these seemingly unfavorable conditions is remarkable and deserves further studies.

This research was supported by a grant administered by the US Israel Binational Science Foundation and by the German-Israeli Science Foundation.

[1] M. Ben Chorin, Z. Ovadyahu and M. Pollak, Phys. Rev. B48, 15025 (1993).
[2] G. Martinez-Arizala, D. E. Grupp, C. Christiansen, A. Mack, N. Markovic, Y. Seguchi, and A. M. Goldman, Phys. Rev. Letters, 78, 1130 (1997). G. Martinez-Arizala, C. Christiansen, D. E. Grupp, N. Markovic, A. Mack, and A. M. Goldman, Phys. Rev. B57, R670 (1998).
[3] Z. Ovadyahu and M. Pollak, Phys. Rev. Letters, 79, 459 (1997).

[4] S. Bogdanovich and D. Popovic, Phys. Rev. Letters, 88, 23641 (2002); T. Grenet, Eur. Phys. J, 32, 275 (2003).

[5] J. H. Davies, P. A. Lee, and T. M. Rice, Phys. Rev. Letters, 49, 758 (1982); M. Pollak, Phil. Mag. B50, 265 (1984); M. Pollak and M. Ortuño, Sol. Energy Mater., 8, 81 (1982); M. Grünewald, B. Pohlman, L. Schweitzer, and D. Würtz, J. Phys. C, 15, L1153 (1982).

[6] A. Vaknin, Z. Ovadyhau, and M. Pollak, Phys. Rev. Letters, 81, 669 (1998).

[7] The relevance of interactions to long relaxation times was considered theoretically by: C. C. Yu, Phys. Rev. Lett., 82, 4074 (1999).

[8] L.C.E. Struik, Physical aging in amorphous polymers and other materials (Elsevier, Amsterdam, 1978); L. M. Hodge, Science, 267, 1945 (1995).

[9] A. Vaknin, Z. Ovadyhau, and M. Pollak, Phys. Rev. Letters, 84, 3402 (2000).

[10] A. Vaknin, Z. Ovadyhau, and M. Pollak, Phys. Rev. B63, 235403 (2002).

[11] Z. Ovadyahu, J. Phys. C: Solid State Phys., 19, 5187 (1986).

[12] A. Vaknin, Z. Ovadyhau, and M. Pollak, Phys. Rev. B61, 6692 (2000).

[13] A. Vaknin, M. Pollak and Z. Ovadyahu, Springer Proc. in Physics 87, 995 (2001).

[14] M. Pollak, Discuss. Faraday Soc. 50, 11 (1970).

[15] V. Orlyanchik, A Vaknin, and Z. Ovadyahu, Phys. Stat. Sol., b239, 67 (2002).

A. Figure Captions.

1. The dependence of the conductance $G$ on time following a quench from $T=120K$ to $T_m=4.11K$.

2. The conductance $G$ as function of time after the gate voltage was changed from 50V to +50V. Prior to this change, the sample was under $V_g=50V$ for six days. The sample has $R_{\square}=52M\Omega$.

3. Same as in figure 2 except for the following history: The sample was equilibrated under $V_g=+50V$ for six days, then $V_g$ was switched to -50V and maintained there for 1600 seconds before the final switch back to +50V was affected. Note that the deviation of $G(t)$ from the initial logarithmic dependence (dashed line) is already evident after $\approx 300sec$.

4. The dependence of the conductance on time while the gate voltage changes periodically
between two values differing by $\delta V_g$. The first change occurs at the end of the short horizontal line at small $t$. The solid line is for $\delta V_g=100V$, the dashed line for $\delta V_g=400V$, both on the same sample ($R\Box=52M\Omega$).

5. Same as the dashed line ($\delta V_g=400V$) in figure 4 but on a log time scale. The long-dashed line represents $G(t)$ following the first change of $V_g$. The short-dashed line (“memory” curve) connects the dots just before the changes from “old” to “new” $V_g$. The thick solid line (“learning” curve) connects the dots just before the changes from “new” to “old” $V_g$. The difference in the (absolute) values of the slopes of these two lines is the measure of asymmetry (see text).

6. The (absolute) value of the “learning” and “memory” slopes (in percent change of $\Delta G$ per decade in time) as function of $\delta V_g$. Circles and triangles are for “learning” and “memory” respectively. Full symbols data points were taken by going from $-V_g$ to $+V_g$ and vice versa for the empty symbols. The sample has $R\Box=40M\Omega$.

7. The ratio $\gamma=q_F/q_L$ for different values of $\delta V_g$ as a function of the transition rate between $V_{g}^n$ and $V_{g}^o$. The dashed line in this figure indicates a particular choice of equal transition-times. Sample with $R\Box=52M\Omega$.

8. An example of the cusp in $G(V_g)$ (for the sample with $R\Box=40M\Omega$) measured using different sweep-rates. Note that the characteristic width of the cusp $\Gamma$ ($\approx 50V$) is independent of the sweep-rate used (c.f., reference 6).

9. Two sets of “aging” experiment each using five identical values of waiting-times $t_w$ and employing two different values of $V_{g}^o$ and $V_{g}^n$: (a) $V_{g}^o=-50V$, $V_{g}^n=+50V$ (b) $V_{g}^o=-200V$, $V_{g}^n=+200V$. Notice the extrapolation of the logarithmic part to $t_w$ for the smaller $\delta V_g$ but a failure to do so for the larger $\delta V_g$. Also, the collapse of the data is somewhat worse in (b). Sample with $R\Box=52M\Omega$. 
Figure 1
Ovadyahu&Pollak
Figure 2
Ovadyahu & Pollak
Figure 3
Ovadyahu&Pollak
Figure 4
Ovadyahu&Pollak
Figure 5
Ovadyahu&Pollak
Figure 6
Ovadyahu & Pollak
Figure 7
Ovadyahu&Pollak
Figure 8
Ovadyahu&Pollak
Figure 9
Ovadyahu&Pollak