Aging Effects in an Anderson Insulator

A. Vaknin and Z. Ovadyahu
The Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

M. Pollak
Department of Physics, University of California, Riverside, California 92651
(Received 30 August 1999)

Aging, commonly observed in glasses, is a manifestation of breakdown of time-translational invariance. Here we demonstrate experimentally aging effects in the electronic system of an Anderson insulator. The aging phenomenon in the electron glass appears to be much less sensitive to temperature than in other systems. The differences in the behavior of the electron glass and a spin glass system are discussed in terms of some microscopic differences between the two systems.

PACS numbers: 72.80.Ng, 73.61.Jc

Many glassy systems exhibit a nonstationary behavior that has been described as "physical aging" [1]. This term refers to a gradual change in the properties of the glass when it is maintained in some fixed external conditions for a time t_w. When the external conditions that affect a certain property P are changed, P will relax towards its new equilibrium value in a way that reflects the "aging" or waiting time t_w. The particular form of the ensuing $P(t)$ will depend on t_w, and in general the relaxation will be more sluggish the longer the system is "aged." But when plotted as a function of t/t_w, the different $P(t, t_w)$ curves collapse onto a common plot that only weakly depends on other parameters. Such behavior has been reported to occur in a variety of glasses, from structural glass [1] to spin glass [2,3]. In these experiments, t_w is the time interval between the initial quenching of the system and the time at which the external conditions (such as stress or a field) are changed.

This paper reports another variant of an aging experiment performed on an Anderson insulator. Previous experiments established that such systems exhibit characteristic glassy behavior [4]. When excited from equilibrium their conductance G is enhanced, and then slowly decays towards its equilibrium value. In addition to their sluggish relaxation, electron glasses exhibit a peculiar memory effect. When such a system is excited by suddenly changing the carrier concentration [e.g., by applying a new voltage at the gate of a metal-oxide-semiconductor field-effect transistor (MOSFET) structure], a signature of its "old" setting is retained and persists for many hours [5]. This glassy behavior is believed to be associated with the interplay between disorder and electron-electron interactions [6]. Relaxation of such a system involves correlated transitions of electrons between different configurations, and the hierarchical constraints associated with these processes cause the dynamics to be similar to that of other glasses [7].

The work reported here describes another kind of memory, very similar to the aging phenomenon in other glassy systems. It turns out that the scaling of the relaxation with t/t_w is quite accurate, more so than in the spin glass. We present some possible reasons for this difference. They involve differences in the relaxing property that is measured and differences in the microscopic constraints that prohibit rapid relaxation.

The samples used in this study were prepared in a MOSFET-like configuration. The active layer was a 50 Å thick polycrystalline In_2O_{3-x} film, with 1×1 mm lateral dimensions. The film was e-gun deposited using 99.999% pure In_2O_3 onto a 140 μm thick glass substrate. After deposition, the films were crystallized at 250 °C. The gate, a 500 Å thick gold film, was evaporated *vis-a-vis* In_2O_{3-x} film on the other side of the glass. Most of the measurements were carried out at $T = 4.11$ K with the samples immersed in liquid ^{4}He storage Dewar. This enabled high temperature stability over long times. Measurements as a function of temperature were done in a ^{3}He rig. In addition to employing a temperature controller, a Ge thermometer mounted on the sample stage was used to correct for residual temperature fluctuations. The conductivity 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 linear response by use of sufficiently low ac bias.

The main technique used in this work involves the following procedure. The sample is cooled to the measurement temperature T_m with a voltage V_{g0} held at the gate, and is allowed to equilibrate for at least 15 h. Next, still holding V_{g0} fixed, one starts monitoring both the conductance G and the gate voltage V_g as a function of time to obtain a baseline conductance $G_0(V_{g0}, T_m)$. This typically takes 5 min. Then, the gate voltage is switched to V_{gn} and is maintained there for a certain "waiting time" t_w. Finally, the gate voltage is switched back to V_{g0}, and $G(t)$ is measured for an additional period of time of the order of $3 \times t_w$. This experimental procedure is somewhat different from the one that was used in previous experiments in that the time interval t_w starts at the time when a new gate voltage V_{gn} is applied [8]. A typical experimental run is shown in Fig. 1. In the following, we focus

 0031-9007/00/84(15)/3402(4)$15.00

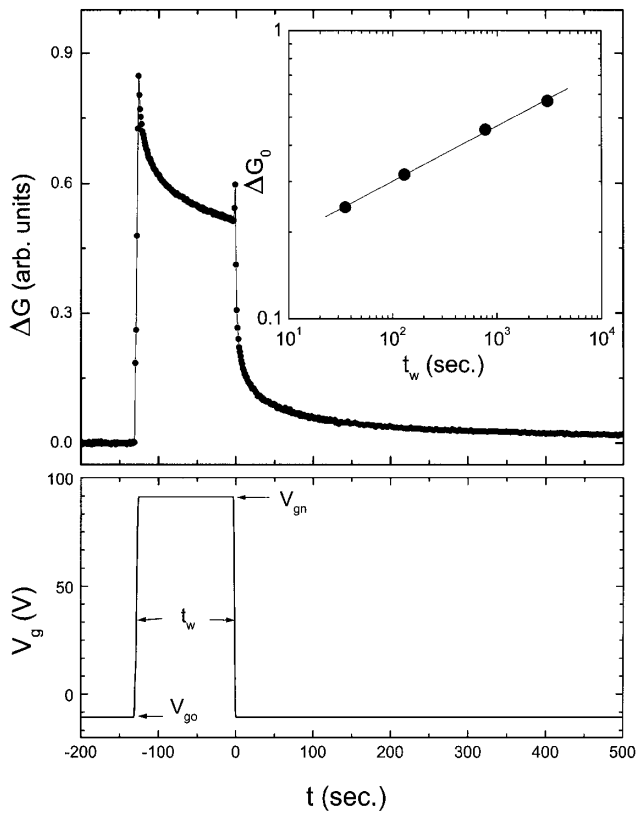

FIG. 1. Bottom graph: The gate voltage versus time in a typical aging experiment (the $V_{g0} \rightarrow V_{gn}$ sweeping time is ≈ 4 s). The upper graph shows the corresponding change of the sample conductance relative to its value at $t < -t_w$. Data are taken with a sampling time $t_s = 1$ s. Results are shown for a sample with $R = 30$ MΩ at $T_m = 4.11$ K. The inset shows $\Delta G(t = 0)$ as a function of t_w.

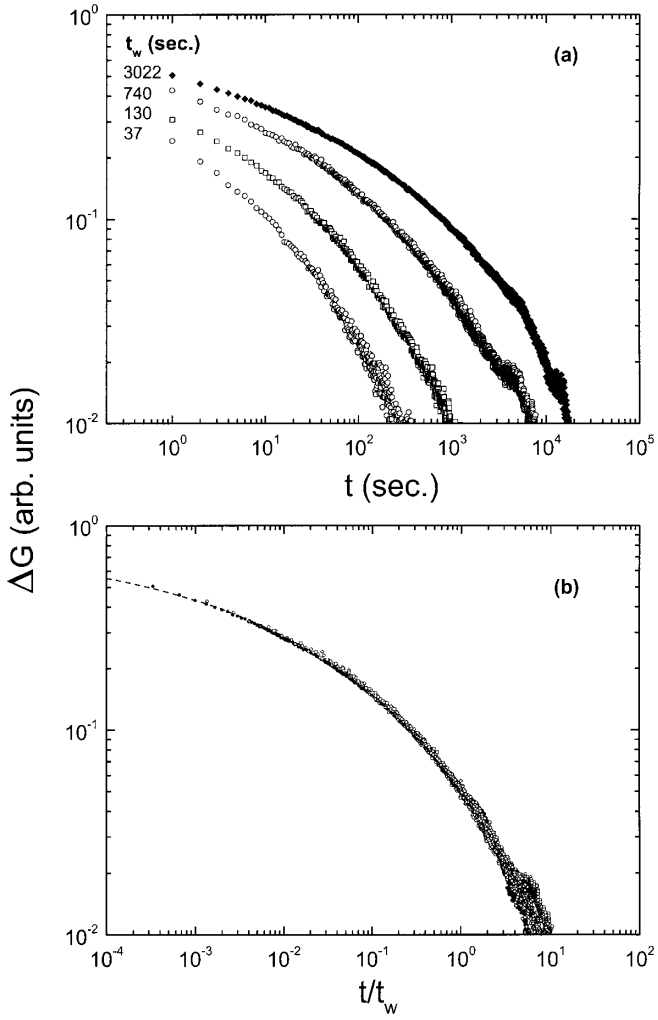

FIG. 2. (a) Relaxation of $\Delta G(t \geq t_s)$ at different values of t_w for the sample in Fig. 1. All traces are taken with $V_{g0} = -10$ V and $V_{gn} = 100$ V. (b) The same data as in (a) but plotted versus the normalized time t/t_w. The dashed curve is a fit to $\exp[-(t/\tau)^{\alpha}]$ with $\alpha = 0.21$ and $\tau = 0.008 \times t_w$.

on the behavior of $\Delta G(t) = G(t) - G_0$ for $t \geq 0$ (taking $t = 0$ as the time when V_g reattains the original value V_{g0}). Note that the quantities [$G(t \geq 0)$ and G_0] that determine $\Delta G(t)$ are measured under the *same* external conditions. This ensures that the relaxation of the conductance embodied in $\Delta G(t \geq 0)$ excludes spurious contributions such as the common equilibrium field effect. As a check on this point, we show that, as $t_w \rightarrow 0$, $\Delta G(t = 0) \rightarrow 0$ (inset of Fig. 1).

The behavior of $\Delta G(t \geq 0)$ for a given sample depends on several parameters. These are t_w, T_m, and $\Delta V_g = (V_{gn} - V_{g0})$. The most important one turns out to be the waiting time t_w. Results for $\Delta G(t, t_w)$ at constant T_m and ΔV_g are shown in Fig. 2. The top graph shows $\Delta G(t)$ for four different t_w's and illustrates that the waiting time significantly affects both the magnitude and shape of the relaxation. Our main result is that when the relaxation data are plotted as $\Delta G(t/t_w)$ all curves collapse onto a single curve (bottom graph of Fig. 2). It is emphasized that this scaling does not involve any parameter except for the measured t_w. No rescaling of the amplitude can make the $\Delta G(t)$ curves collapse; this is accomplished entirely by $t \rightarrow t/t_w$.

By contrast, varying either ΔV_g or T_m affects the *amplitude* of $\Delta G(t)$ but not its shape. Results of such experiments are shown in Figs. 3 and 4, respectively. The relaxation curves can be well described by $f(\Delta V_g) \cdot \Delta G(t)$ or by $h(T_m) \cdot \Delta G(t)$, respectively. In either case, the common relaxation law can be fitted by the stretched-exponent function $\Delta G(t) = A \exp[-(t/bt_w)^{\alpha}]$. Such a relaxation law is often found in the dynamics of glasses [9], and it is usually attributed to the process of hierarchical relaxation [10] with a wide distribution of relaxation times. Such hierarchical behavior in the Anderson insulator can result from the combination of disorder and interactions as also happens in other glasses.

The unique role of t_w in determining the relaxation law is worth noting. The simple scaling demonstrated by Fig. 2

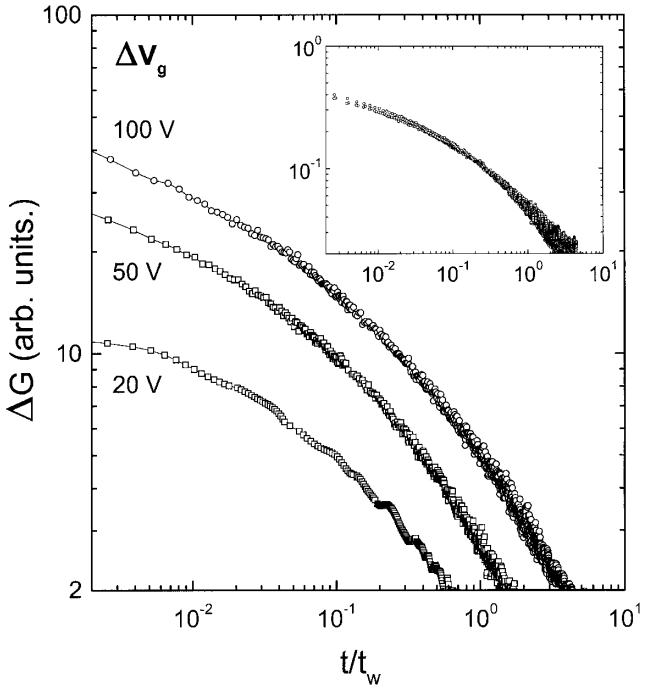

FIG. 3. Relaxation of $\Delta G(t \geq t_s)$ as a function of ΔV_g for the sample in Fig. 1. A fixed waiting time $t_w = 770$ s was used for all three runs. $T_m = 4.11$ K. The inset shows that the data can be made to collapse on a single curve when $\Delta G(t, \Delta V_g)$ is multiplied by an appropriate constant $f(\Delta V_g)$

means that one can tell how long the system was allowed to relax at V_{gn} (for $t < 0$) just by monitoring $\Delta G(t)$ for $t \geq 0$ [11]. This breakdown of time-translational invariance has been described in other glassy systems as an "aging" effect [3]. The basic idea behind the explanation given for the aging effect is the following [3,12]. During the waiting time (in our case when V_{gn} is applied), the system relaxes towards an equilibrium state compatible with the new conditions imposed on the system. The system will relax by overcoming barriers [13] with heights that are compatible with the elapsed time. The height of the barriers that the system can overcome during this time increases with t_w. When changing the conditions after t_w (in our case by changing V_{gn} back to V_{g0}), the system will have to go over the same barriers to return to *status quo ante*. The time for this thus will scale with the aging time t_w. (Notice that such an argument would also explain the symmetry in the growth and shrinkage of the two dips observed in previous experiments [6].) The aging effect is expected to break down if the highest barriers in the system are lower than the barriers with the height compatible with t_w. Also, the symmetry of the process hinges on the assumption that the external conditions (V_{g0} and V_{gn} in our case) do not greatly affect the system itself, so effective barriers and the hopping distances remain nearly the same. The latter requirement is fulfilled in our experiments because the fields associated with the applied V_g's are rather small and amount to a very small change in any of the relevant parameters (such as the localization length ξ and the carrier concentration n).

The observation that $\Delta G(t \geq 0)$ increases with t_w can be also naturally explained. The longer the system waits at V_{gn} the closer it approaches a new equilibrium state. Then the switching back to V_{g0} reexcites the system to a larger degree.

We turn now to the set of experiments of Fig. 4. It is apparent that the magnitude of the effect, namely, $\Delta G(0)$, decreases with increasing T_m. This is in line with the observations of Vaknin *et al.* [14]. In this range of temperatures, the equilibrium conductivity changed by 2 orders of magnitude, and the amplitude of the effect decreases by more than an order of magnitude. Yet, as seen in Fig. 4, the amplitudes of these plots can be scaled to reveal that the relaxation law does not change with temperature. We briefly comment on this puzzling feature in our closing remarks.

The glassy behavior in spin glasses (measuring magnetization) differs in certain respects from the observations reported here [8]. The salient differences are that in spin glasses the observed scaling is more involved than simply normalizing t by t_w. Moreover, the rate of relaxation in

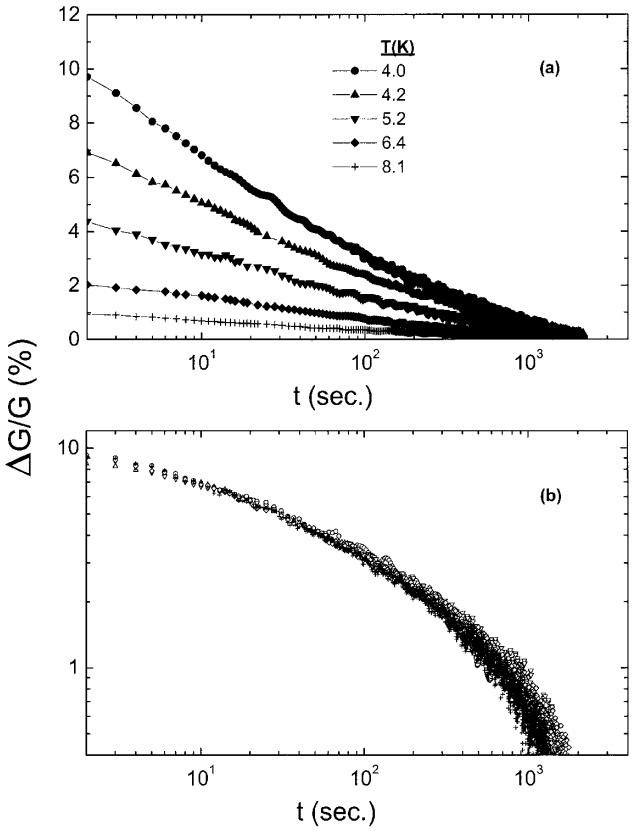

FIG. 4. (a) Relaxation of $\Delta G(t \geq t_s)$ for several values of T_m. All traces are taken with $V_{g0} = -10$ V and $V_{gn} = 100$ V, and for a fixed $t_w = 600$ s. (b) The same data as in (a) plotted after $\Delta G(t, T_m)$ for each T_m curve is multiplied by an appropriate constant $h(T_m)$. The sample in this case has $R = 200$ MΩ at $T = 4.11$ K.

the spin glass is quite temperature dependent [3,15]. The need for corrections to the t/t_w scaling in spin glasses has been attributed to possible ergodic relaxation of spins in some regions of the system [16].

There are, of course, many differences between the detailed nature of the spin glass and of the electron glass. We mention those that may be responsible for the above differences in the observations: (i) The interaction in the electron glass is of longer range than it is in the spin glass. This makes it less likely that an electron move freely in the electron glass than a spin flip freely in the spin glass. (ii) Spin and spin direction in the (Ising) spin system are analogous, respectively, to a site and site occupation in the hopping system. In the spin glass, a single spin flip is allowed. Such flips of weakly coupled spins might well be responsible for the fast processes in the spin glass. Analogous processes to these do not occur in the hopping system because a single hop changes the occupation of *two* sites. Both points work in the direction of making the microscopic ergodic processes in the electron glass less probable. In addition, different properties are used to measure the dynamics of the two systems. Magnetization, used in the spin glass, is a sum over local properties (individual spin orientations) while the current used in the electron glass cannot be decomposed into a sum of local properties. Thus, local regions with the fastest dynamics do contribute to the observed magnetization in spin glasses, whereas local regions with fast dynamics (associated with small local resistances) do not affect the global current.

Finally, we wish to comment on the temperature dependence of the relaxation. The data presented in Fig. 4 suggest that the dynamics associated with aging in our system is fairly insensitive to temperature. Temperature independent dynamics was reported [17] for dispersive transport in films of polyvinylcarbazole measured between 280–380 K. Our results (that were reproduced on three samples) are in keeping with this observation over a considerably larger range of temperatures. In fact, with a less disordered sample, we were able to extend the measurements down to 0.67 K without noticing any slowdown in the relaxation dynamics. It appears then that it should be feasible to study the nonergodic properties of electron glasses at arbitrarily low temperatures by reducing the sample disorder. This will open the exciting possibility to probe the quantum effects predicted [18] for glasses in the limit $T \rightarrow 0$, which is not readily accessible in ordinary systems.

In summary, we have shown that physical aging, hitherto studied in structural glasses and spin glasses, is also observable in an electron glass thus attesting to the ubiquitous nature of the phenomenon. The apparent lack of temperature dependence seems to suggest that relaxation dynamics in the electron glass is fairly insensitive to energetic considerations. This intriguing observation clearly deserves further study.

This research was supported by a grant administered by the U.S.-Israel Binational Science Foundation.

[1] L. C. E. Struik, *Physical Aging in Amorphous Polymers and Other Materials* (Elsevier, Amsterdam, 1978); L. M. Hodge, Science **267**, 1945 (1995).
[2] L. Lundgren, P. Svedlindh, P. Nordblad, and O. Beckman, Phys. Rev. Lett. **51**, 911 (1983).
[3] E. Vincent, J. Hammann, M. Ocio, J.-P. Bouchaud, and L. F. Cugliandolo, in *Complex Behavior of Glassy Systems*, Lecture Notes in Physics, edited by Miguel Rubi and Conrado Perez-Vicente (Springer, Barcelona, Spain, 1996).
[4] M. Ben-Chorin *et al.,* Phys. Rev. B **44**, 3420 (1991); M. Ben-Chorin *et al.,* Phys. Rev. B **48**, 15 025 (1993); G. Martinez-Arizala *et al.,* Phys. Rev. Lett. **78**, 1130 (1997); G. Martinez-Arizala *et al.,* Phys. Rev. B **57**, R670 (1998).
[5] Z. Ovadyahu and M. Pollak, Phys. Rev. Lett. **79**, 459 (1997).
[6] A. Vaknin *et al.,* Phys. Rev. Lett. **81**, 669 (1998).
[7] J. H. Davies, P. A. Lee, and T. M. Rice, Phys. Rev. Lett. **49**, 758 (1982); M. Pollak, Philos. Mag. B **50**, 265 (1984); M. Pollak and M. Ortuño, Sol. Energy Mater. **8**, 81 (1982).
[8] The conductivity, which is measured in our experiments, is not stationary after quenching the sample (like the susceptibility of spin glasses); on the other hand, ac conductivity under the application of a gate voltage is problematic due to experimental complications. The experimental procedure used here seems to be more suitable to the electron glass system, and in our view still qualifies as aging. Whether this difference in the experimental procedure is responsible for the differences in the aging behavior between the electron glass and spin glass is not clear.
[9] K. L. Ngai, A. K. Rajagopal, and C. Y. Huang, J. Appl. Phys. **55**, 1714 (1984); R. V. Chamberlin, G. Mozurkewich, and R. Orbach, Phys. Rev. Lett. **52**, 867 (1984).
[10] R. G. Palmer, D. L. Stein, E. Abrahams, and P. W. Anderson, Phys. Rev. Lett. **53**, 958 (1984).
[11] After a reference run was made with some known t_w.
[12] M. Lederman *et al.,* Phys. Rev. B **44**, 7403 (1991).
[13] The barriers in this context are in phase space, as is customary in other glasses. The effective barriers in the electron glass case are represented by *correlated* transitions of electrons. The barrier height then depends on the number of electrons involved. See also Ref. [7].
[14] A. Vaknin *et al.,* Europhys. Lett. **42**, 307 (1998).
[15] R. Hoogerbeets, Wei-Li Luo, and R. Orbach, Phys. Rev. Lett. **55**, 111 (1985); M. Alba, J. Hammann, M. Ocio, Ph. Refregier, and H. Bouchiat, J. Appl. Phys. **61**, 3863 (1987); J.-P. Bouchaud *et al.,* J. Phys. I (France) **4**, 139 (1994).
[16] Alternatively, it might be due to different dynamics in the two types of systems—the dynamics of the spin glass is believed to be determined by activation factors alone while the dynamics of the electron glass is determined by activation factors as well as tunneling factors.
[17] F. C. Bos and D. M. Burland, Phys. Rev. Lett. **58**, 152 (1987). It should be pointed out that, unlike our work, this dispersive-transport study is believed not to involve interactions.
[18] L. F. Cugliandolo and C. Lozano, Phys. Rev. B **59**, 915 (1999).