

Slow conductance relaxations: Distinguishing the electron glass from extrinsic mechanisms

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(Received 18 August 2008; published 20 November 2008)

Slow conductance relaxations are observable in many condensed-matter systems. These are sometimes described as manifestations of a glassy phase. The underlying mechanisms responsible for the slow dynamics are often due to structural changes which modify the potential landscape experienced by the charge carriers and thus are reflected in the conductance. Sluggish conductance dynamics may however originate from the interplay between electron-electron interactions and quenched disorder. Examples for both scenarios and the experimental features that should help to distinguish between them are shown and discussed. In particular, it is suggested that the “memory dip” observable through field-effect measurements is a characteristic signature of the inherent electron glass provided it obeys certain conditions.

DOI: [10.1103/PhysRevB.78.195120](https://doi.org/10.1103/PhysRevB.78.195120)

PACS number(s): 72.80.Ng, 73.61.Jc, 72.20.Ee

I. INTRODUCTION

Many phenomena in solid-state systems involve slow conductance changes. The phenomenon that has been most studied in this context is conductance noise, which often exhibits a $1/f$ power spectrum. In degenerate Fermi systems (metals and heavily doped semiconductors), the prevalent view is that the fluctuations in the conductance G reflect temporal changes in the potential experienced by the charge carriers.¹ Such potential fluctuations may be structural, involving slow dynamics of ions or atoms which, in turn, may be triggered by a modified state of local charge following, for example, electronic rearrangement of valence electrons. These as well as “purely” ionic displacement are referred to in this paper as structural two-level systems. Slow release or trapping of carriers will likewise manifest itself in slow conductance fluctuations. Either mechanism may lead to conductance fluctuations that typically extend to very low frequencies.¹

As a rule, $1/f$ experiments were performed in systems where the average G was time independent, namely, in equilibrium or near-equilibrium situations. There are however many cases where G itself changes slowly with time, which by definition, suggests a nonequilibrium phenomenon. This may occur, for example, due to annealing of defects, neutron irradiation, diffusion of an injected dopant, illumination by light, and many other instances involving changes in the potential landscape, or the density of carriers in the conducting system. It often happens in these cases that the sluggish response observed in G exhibits features that are characteristic of glasses. Experimental results illustrating two mechanisms for such “extrinsic” glassy effects in conductivity will be shown and discussed in Sec. III.

Glassy effects in G may arise from an *intrinsic* mechanism, in which case both the ions’ potential and the carriers’ density may be, in theory, time independent. Glassy behavior of the electronic system in a system with quenched disorder has been anticipated by several authors.^{2–5} This new type of a nonergodic system was first termed electron glass by Davies *et al.*⁴ referring to a system with localized electronic states interacting via an unscreened Coulomb interaction. Glassy effects inherent to the electronic systems that may

arise even in the noninteracting system were also considered.³ However, common to all models of intrinsic electron glass is a sufficiently strong static disorder such that the electronic states are Anderson localized. This is one of the essential differences between the electron glass and the extrinsic mechanisms alluded to above. In the latter, glassy effects may manifest themselves even when the transport mode is diffusive. By contrast, a *prerequisite* for intrinsic electron-glass behavior is that the system is Anderson localized, and thus charge transport must be activated. This condition is necessary but not sufficient; more detailed criteria will be given in the discussion section below.

Nonergodic effects such as slow relaxation, aging, and other memory effects associated with electron-glass behavior were reported in a few systems.^{6–11} Naturally, the question of extrinsic effects dominating or, at least, contributing to the measured effects has been considered in early publications.¹²

There are difficulties in categorically ruling out extrinsic effects. Essentially all glasses, whether mechanical, magnetic, or electronic, show similar dynamical features. While these universal attributes give the impetus to study glasses, the similar effects make it hard to distinguish between different glasses, especially when both types are revealed through the *same* measurable (i.e., conductance). Current theories of the electron glass are not sufficiently detailed to allow this differentiation. The one issue on which theory predicts a qualitative feature that, experimentally, seems to be peculiar to the electron glass is the law of relaxation being logarithmic in time.¹³ This has indeed been verified in several electron glasses,⁸ and in $\text{In}_2\text{O}_{3-x}$ this relaxation law has been observed over almost 6 decades in time.¹⁴ It was also shown in this system that the ions’ or atoms’ dynamics is associated with time scales and spatial scales quite different from the dynamics of the electron glass.¹⁵ Similar results were obtained on granular Al films by Grenet and by Delahaye *et al.*¹⁶ However, the most compelling evidence for an inherent electron glass is the dramatic dependence of the glassy properties on the system carrier concentration.¹⁷ This will be further elucidated in this paper.

In some cases it is possible to identify the origin of the glassy effects in G as arising from an extrinsic mechanism. Two examples that are probably characteristics of a wide range of phenomena will be described in Sec. III. We then

describe, for comparison, the salient features of the electron glass and discuss the differences.

A modest conclusion that one may draw is that there are two types of glassy electronic systems: those that can be unambiguously shown to be extrinsic and those that cannot and for which the only consistent scenario is the electron glass. However, we will argue that, on empirical basis, there is a positive test for the electron glass. This is the memory dip (MD) that on one hand is unequivocally associated with all the glassy features of the system, and on the other hand its characteristic width is determined by the carrier concentration of the material. The special features of the memory dip that are suggestive of an electronic mechanism will be detailed and discussed.

II. EXPERIMENTAL

Sample preparation and measurement techniques

Several batches of samples were used in this study. These were thin films of either polycrystalline or amorphous indium oxide (to be referred to as $\text{In}_2\text{O}_{3-x}$ and In_xO , respectively). The films were deposited by an e gun using 99.999% pure In_2O_3 . The amorphous films were typically 80–200 Å thick, while the polycrystalline films had typically a thickness of 30–60 Å. Indium oxide films as deposited onto room-temperature substrates are amorphous. Polycrystalline films were prepared by heating the sample to ≈ 500 K after deposition. The sheet resistance R_{\square} of either structure was adjusted by thermal annealing (for In_xO) or UV treatment (for $\text{In}_2\text{O}_{3-x}$) to be within the range of 2–100 M Ω at 4 K for the electron-glass studies. All samples had lateral dimensions of $\approx 1 \times 1$ mm². Some samples were configured as field-effect devices using either 110 μm cover glass as spacers and a gold film evaporated on the backside as gate, or 0.5 μm thermally grown SiO_2 spacer on heavily doped Si wafer as gate. The 110 μm spacer is used unless otherwise specifically mentioned. This is so as to enable the use of a reasonably high frequency f in the conductance measurements even for samples with very high resistance (note that the sample-gate capacitance is parallel with the ac measurement,⁶ and the RC problem limits the f to low value, thus compromising the temporal resolution and the signal-to-noise ratio). The 0.5 μm spacer is used when it is desirable to cover a wide range of charge variations in the field-effect measurements without using an excessively large voltage. 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 for the 4 K studies, and straightforward resistance measurements was done using HP34401A for the room-temperature measurements. Fuller details of sample preparation, characterization, and measurement techniques are given elsewhere.^{6,11,18} All resistance data reported here are per square geometry [namely, data are specified in terms of the appropriate two-dimensional (2D) resistivity].

III. RESULTS AND DISCUSSION

Glassy features are readily observed in conductivity, and they may be associated with various mechanisms. In this

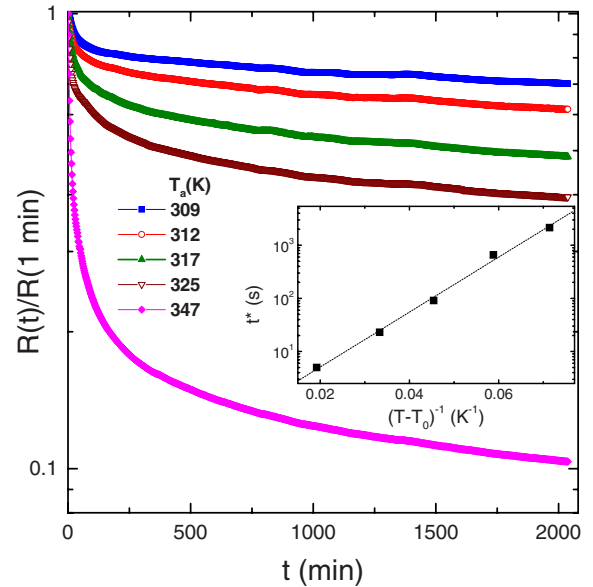


FIG. 1. (Color online) Resistance versus time of annealing (T_a is the hot-stage temperature) for a series of In_xO samples, each with initial sheet resistance of ≈ 2 M Ω . Data are normalized to the R value attained after 1 min (where the hot-stage temperature reached $\approx 95\%$ of its asymptotic value). Inset marks the time t^* for the sample resistance to drop to 70% its value at 1 min.

section we show and discuss some experimental results of two groups of glassy effects revealed in conductance measurements. Examples of glassy effects observable in the conductance that can be shown to be due to extrinsic mechanisms are given in Sec. III A. This is followed by a list of features that should help to distinguish the intrinsic electron glass from the extrinsic glass. In both cases, the data used for illustration were deliberately taken on the same systems, namely, $\text{In}_2\text{O}_{3-x}$ and In_xO . The different glassy mechanisms were achieved by varying the sample parameters (disorder) and the external conditions used in the measurements (in particular, temperature).

A. Glassy effects due to extrinsic mechanisms

The first example we discuss in this category is the process of thermal annealing, commonly used to reduce the resistance of amorphous indium oxide films, In_xO .^{18,19} This involves holding the samples at a constant temperature, typically up to few tens of degrees above room temperature, and monitoring the resistance versus time $R(t)$ as shown in Fig. 1 for a series of samples, all made at the same deposition run. Note that $R(t)$, depicted here on a semilogarithmic scale, exhibits nonexponential relaxation. The observed slow decrease in R is an irreversible process and is due to elimination of microvoids which are common in amorphous materials prepared by quench cooling.²⁰ Naturally, this process also affects the density of the material, namely, the sample volume shrinks, as was directly confirmed by optical measurements.²¹ This leads to a better wave-function overlap and thus enhances the conductance. The slow relaxation of R is then just a reflection of the slow dynamics involved in the

compaction process of the material. The initial resistances of the samples used in Fig. 1 were on the order of 1–2 M Ω , rather deep into the insulating regime, making their conductance very sensitive to even small changes in the landscape potential; this is the only reason for choosing them for the illustration. In fact, slow conductance relaxations were observed even in samples that are well annealed to be on the metallic side of the transition.²¹

Note that at any given time during the process $-\partial R(t)/\partial t$ increases rather fast with annealing temperature T_a , which varies by only $\approx 12\%$ in the series. This presumably means that the annealing process is activated, consistent with thermally assisted atoms' diffusion. A way to characterize the dynamics is to monitor the time t^* it takes for $R(t)$ to decay to a given fraction from its initial value. (This is, admittedly, an arbitrary definition for a relaxation law that does not have a characteristic scale, but any other sensible definition will not change our conclusions.) In the inset of Fig. 1 we plot the dependence of t^* on temperature. As it turns out t^* follows a temperature dependence of the Vogel-Fulcher-Tammann type:²² $t^* \propto \exp[\frac{E}{k_B(T-T_0)}]$, a typical behavior for many classical glasses. The apparent divergence of t^* at $T_0=295$ K (see inset of Fig. 1) has a simple and plausible interpretation: the samples were prepared and handled at or close to room temperature prior to being subjected to the annealing process, and thus they were already well annealed at T_0 . No glassy dynamics of this kind is observed with such samples at or below liquid-nitrogen temperatures.

Another set of glassy behaviors observable through conductance measurement is illustrated in Fig. 2. Here we utilize the flexibility of fine-tuning the resistance of In₂O_{3-x} films by UV treatment. Unlike the thermal annealing, this process is reversible, which is useful for many studies. While under pumping and constant UV illumination, the film resistance decreases slowly. Breaking the vacuum by bleeding oxygen into the system reverses the trend. Figure 2 includes several cycles of UV exposure+pumping, alternating with bleeding-air periods resulting in a time sequence of $R(t)$ that obviously retains some “memory” of previous conditions. A fit to a stretched exponential can be easily obtained for each of the relaxations in Fig. 2. In fact, as shown, for example, in the inset, for one of the “recovery” processes (which is cheap to maintain for a long time), one could obtain an impressive fit to a stretched exponential dependence extending over several weeks (more than 5 decades in time).

History dependence and stretched exponential behavior are sometimes taken as a test of a “glass,” so this example might have been considered a bona fide indication of “electronic” glass. Note though that the sample here is actually diffusive, and therefore it cannot be an electron glass, at least not from the point of view of the theories.²⁻⁵ Actually, the reason for these slow conductance changes turns out to be associated with change in stoichiometry in the system. A plausible scenario that accounts for the glasslike dynamics in this case may be understood by studying the structural changes caused by the UV-treatment process.

Indium oxide films, whether amorphous or crystalline, are oxygen-deficient version of the ionic compound In₂O₃, and this nonstoichiometry gives rise to “free”-carrier (electron) density n . The further is x in In₂O_{3-x}, for example, the larger

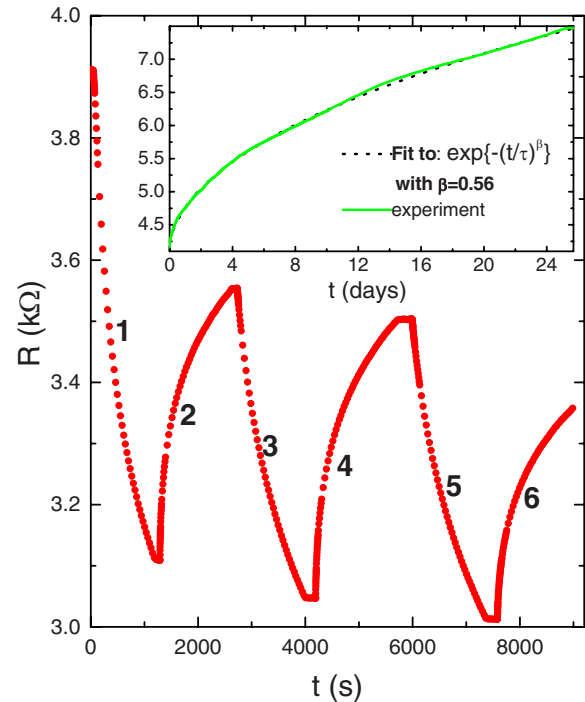


FIG. 2. (Color online) UV-treatment cycles of an In₂O_{3-x} sample as reflected in its sheet resistance R . During stages 1, 3, and 5 the sample is exposed to UV irradiation ($\lambda=280$ nm) while in a vacuum chamber at pressure $p \leq 1$ mTorr. During stages 2, 4, and 6 the chamber is filled with air to $p \approx 10^3$ mTorr. Relatively flat parts occur when UV is turned off (e.g., between stages 5 and 6), or when air is pumped away (e.g., between stages 4 and 5). Inset shows resistance versus time during an extended period of exposure to air.

is n . All other things being equal, larger n yields higher conductivity. This is essentially the same process as when a semiconductor is doped by n -type impurities except that the smallest n feasible in stable In₂O_{3-x} films ($\approx 2 \times 10^{19}$ cm⁻³) is already sufficient to make the system a degenerate Fermi gas. More importantly, the process of “doping” here is easily affected by UV illumination, which breaks the oxygen bonds, and then pumping away the oxygen atoms increases x of the host. Exposing the sample to oxygen-rich atmosphere reverses the process. Naturally, the processes of doping and “undoping” are reflected in the conductivity. The change in n with the UV treatment (and the consequential mobility modification) was studied by a variety of ways including Hall effect and Burstein shifts using optical absorption.²³ Similar effects are observable in other materials such as ZnO and they are sometimes referred to as “persistent photoconductivity,”²⁴ a term originally reserved for electron-hole creation in semiconductors rather than reflecting a change in the system chemistry.²⁵ Another case of an extrinsic effect that manifests itself as slow conductance relaxation is the infamous “DX center” phenomenon. This is now believed to be a structural effect well studied in semiconductors.²⁶

The reason for the sluggish response of the conductance are barriers that the oxygen atoms have to overcome in crossing the film surface, and barriers for the atoms to diffuse into the bulk of the film. The dynamics of these processes in

general depends on a number of factors such as the crystallite size, thickness of the film, and disorder (which makes the relevant barriers a function of space, and thus distributes the diffusion rates over a wide range. The phenomenon is also extremely sensitive to temperature. For example, the hump in the curve between 12 and 16 days (inset of Fig. 2) resulted from the temperature in the room increasing by ≈ 2 K (less than 1% change).

Extrinsic glasses are interesting by their own right; the ease of monitoring the underlying dynamics via the flexible conductance measurement has many advantages for the study of the underlying glassy effects. The conductance in these cases may then reflect all the basic glass features including aging and other memory effects. However, such extrinsic glasses must not be confused with the electron glass. There are some obvious differences between the electron glass and the extrinsic “conductivity glasses” described above (and many others of similar nature) such as temperature and its effect on dynamics and law of relaxation. It is desirable however to have a qualitative test that distinguishes the inherent electron glass from extrinsic mechanisms. Such a test is the existence of a memory dip, a feature that is probed by a field-effect measurement. It has phenomenology which is peculiar to the electron glass as will be detailed in Sec. III C.

B. Intrinsic electron-glassy effects

In theory, glassy effects in the conductance may originate from the interplay between disorder and interactions while the ions are stationary. In fact, sufficiently strong spatial disorder, such that the electronic states are localized, is claimed to lead to a glassy state even in the noninteracting system³ (Fermi glass). The presence of disorder however, has other consequences; in the first place it gives rise to two-level systems that, in turn, manifest themselves in a wide spectrum of $1/f$ noise extending to very low frequencies.¹ This means that, even near equilibrium, ion or atom dynamics occurs on time scales that, partially, overlap with typical relaxation times of the electron glass, as already remarked elsewhere.¹² Measurements on mesoscopic samples of $\text{In}_2\text{O}_{3-x}$ showed that the electron-glass dynamics occurs on a *much* shorter time scale (and different spatial scale) than the dynamics associated with structural two-level-systems, suggesting that the two phenomena are of different origins.¹⁵ It seems plausible that the two phenomena should influence one another, but there is yet no evidence for such an effect. In particular, we failed to detect any specific contribution to the $1/f$ noise due to the glassy state. For example, no measurable change in noise could be detected when the sample was kept out of equilibrium by a continuous excitation (created by continuously sweeping the gate voltage).

The other issue that the localization brings about is the impaired screening, which makes the notion of a Fermi glass (noninteracting) of somewhat academic scenario. Indeed, electron-electron interactions are believed to be essential for the existence of the glassy phase.^{4,5} Experimentally, the relevance of interactions in real systems is evidenced by the observation that, all other things being equal, the typical re-

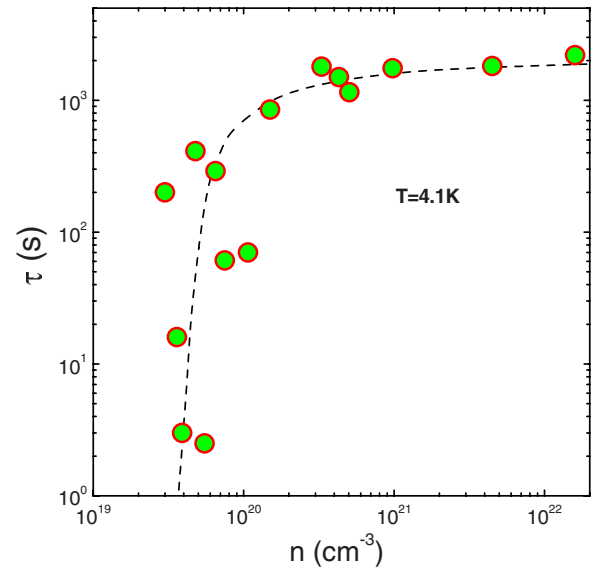


FIG. 3. (Color online) Typical relaxation time τ , as a function of the carrier concentration n for a series of In_xO samples (data are based on the two-dip experiment; see Refs. 17 and 28 for fuller details and interpretation). Note the sharp drop in τ for $n \lesssim 10^{20} \text{ cm}^{-3}$.

laxation time τ of the electron glass is controlled by the carrier concentration n of the system.¹⁷ Using a series of In_xO films of similar resistance, it was shown that τ varies by 3 orders of magnitude for a change of a mere factor of 4 in n . This is illustrated in Fig. 3 (based on data from Ref. 17 and newer data added recently using similar techniques). Other sample parameters such as resistance, magnetic field, and temperature have a much smaller effect on τ .^{12,27,28} Finally, τ has been essentially unchanged when the sample spatial extent has been varied from ≈ 1 cm down to $2 \mu\text{m}$,¹⁵ and is also independent of thickness within the range studied. Vaknin *et al.*¹⁷ argued that these results imply the importance of electron-electron interactions. Note that the change in n in this series of samples amounts to changing the In/O ratio in the preparation stage by a few percent. This hardly influences any structural aspects and therefore it is hard to reconcile this observation with any extrinsic mechanism. It should be emphasized that the results in Fig. 3 are not an artifact of the specific measurement technique; other methods of measuring the dynamics reflect the same systematic dependence on n . These methods and their caveats are fully described in Refs. 27 and 28. The physics of this dramatic dependence on n shown in Fig. 3, which empirically accounts for the absence of inherent slow relaxation in low-density systems (e.g., lightly doped semiconductors as will be further discussed below), was interpreted as a quantum friction effect in Ref. 28.

Other systems that show electron-glassy effects (i.e., $\text{In}_2\text{O}_{3-x}$ and granular metals) lack the flexibility of varying n over a substantial range. (n may be easily varied in semiconductors but their τ appears to be quite short due to reasons explained elsewhere.^{17,28}) There is however, one feature that is common to all (inherent) electron glasses—this is the MD. The MD appears in field-effect measurements as a minimum

of the conductance versus gate voltage $G(V_g)$ centered around V_g^0 —the gate voltage where the system was allowed to equilibrate.^{9,11,12} It was initially termed “anomalous field effect” by Ben-Chorin *et al.* in Ref. 6, where it was realized only in the note added in proof that it is a nonequilibrium effect. As more elaborate experiments became available, the intimate connection between this “anomaly” and the electron-glass properties became evident. In fact, every single aspect of the electron glass, such as slow relaxation, memory effects, and aging, is reflected in the temporal behavior of the MD.¹¹ For example, it was shown that history dependence, such as aging, is wiped out when the MD is destroyed by either exposure to infrared source or non-Ohmic field.²⁹ Also, for a given system, the electron-glass dynamics, as well as its temperature dependence, is uniquely characterized by the MD width.²⁸

C. MD properties

The physics underlying the function $G(V_g)$ we refer to as MD is not yet well understood. Several authors have conjectured that the MD is a reflection of the Coulomb gap.^{30–33} Adopting this view indeed helps to understand some of the nontrivial features exhibited by $G(V_g)$ of electron glasses, such as the two-dip experiment.^{10,12} On the other hand, some difficulties with this interpretation were also pointed out.^{9,17} In the following, these reservations will be re-examined in view of recent experiments.

We start by reviewing the basic properties of the phenomenon at a given temperature, as the great majority of experiments were performed at or around ≈ 4 K. The MD revealed in the $G(V_g)$ scans is characterized by its relative amplitude $\Delta G/G$ and by its shape (functional form). There are several variables that may affect appreciably $\Delta G/G$; however, the functional form of the MD is *independent* of *any* of these variables. For example, increasing the sweep rate of the gate voltage V_g increases $\Delta G/G$ [logarithmically; see Figs. 4(a) and 4(c)]; yet upon rescaling *just the y axis*, the MD of two scans with quite different $\partial V_g / \partial t$ would perfectly overlap one another [Fig. 4(b)]. The dependence on V_g sweep rate (that in this work has been extended to cover more than 3 decades) also illustrates that the MD is a nonequilibrium phenomenon as well as the basic $\log(t)$ dynamics.

Another factor that affects the amplitude but not the shape of the MD is the time during which the system equilibrates after the initial cooldown to the measurement temperature (Fig. 5). The evolution of $-\Delta G$ with time at $V_g=0$ is just the $\log(t)$ law of the electron glass that one observes in $G(t)$, say after a quench from high temperature (even without configuring the sample with a gate). The interesting thing here is that while this conductance “equilibration point” is slowly going down, it “drags” with it some region around $V_g=0$ in such a manner to keep the shape of the symmetric field effect (i.e., the MD) constant (cf. inset of Fig. 5). Note that this region extends over a rather large range of V_g , a point to which we shall return below.

Finally, two other factors that do not affect the MD shape are disorder and magnetic field. By higher disorder we refer to samples that are deeper into the insulating phase. This is

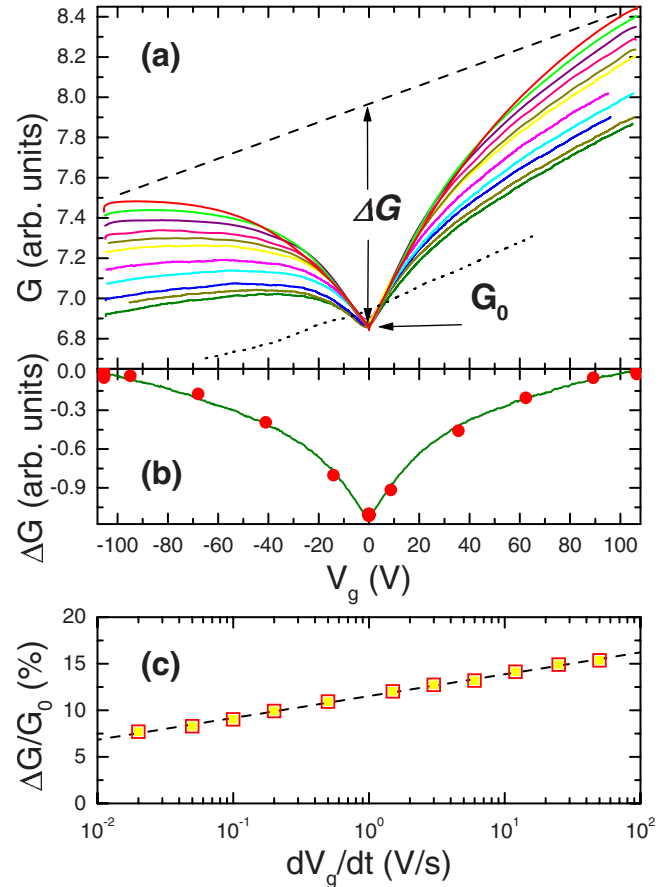


FIG. 4. (Color online) (a) Field effect as a function of the gate-voltage sweep rate, showing 11 different rates [with values depicted in (c)]. Sample is $\text{In}_2\text{O}_{3-x}$ with $R=26$ M Ω at 4 K. Dashed line indicates linear approximation to the equilibrium field effect for the fastest rate. Dotted line is an actual result of a sweep rate during 2 days over the range shown. (b) The collapse of the MD data for the slowest and fastest sweep rates in (a) after subtracting the linear part of the field effect and normalizing the amplitude. (c) The MD normalized amplitude $\Delta G/G_0$ as function of sweep rate illustrating the basic $\log(t)$ dependence.

manifested by a larger R at a given T . Both, the slope of asymmetric field effect and $\Delta G/G$ of the MD increase with the sample resistance. However, disorder has no effect on the shape of the MD.¹¹ A magnetic field as high as 30 T, while changing G by as much as a factor³⁴ of 4, which naturally affects the equilibrium (asymmetric) part of the field effect, does not change the MD shape (Fig. 6). Interestingly, the magnetic field changes both ΔG and G in such a way that $\Delta G/G$ is constant. Other agents that modify G also change $\Delta G/G$. The reason for that is not currently understood.

The only factor that, at a fixed temperature, does affect the MD shape is the carrier concentration n of the system. The characteristic width of the MD (to be defined below) increases monotonically with n , and *that seems to be a “universal” feature, common to all electron glasses studied to date, $\text{In}_2\text{O}_{3-x}$, In_xO , and granular metals.*¹⁵ Note that this observation clearly implicates an electronic mechanism, and qualitatively it is in line with the Efros-Shklovskii Coulomb gap,^{35,36} which increases monotonically with the density of

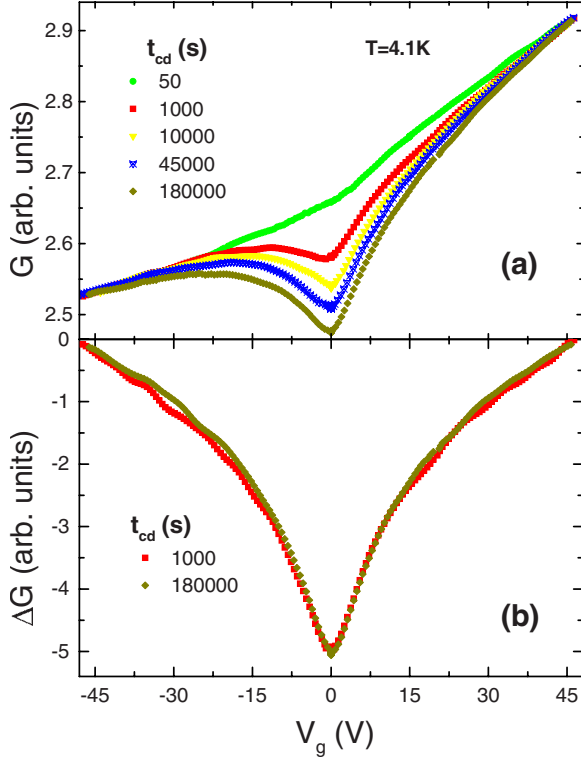


FIG. 5. (Color online) (a) Field-effect sweeps taken at several times since cooldown t_{cd} showing the MD slow evolution. Sample is $\text{In}_2\text{O}_{3-x}$ film with $R=49$ M Ω . (b) The collapse of the MD shape for the data for the sweeps taken at $t_{cd}=10^3$ s and $t_{cd}=180\,000$ s (after subtracting the equilibrium field effect and expanding the $t_{cd}=10^3$ s MD data by a constant factor).

states (DOS).³⁶ As mentioned in Sec. I, the possibility that a Coulomb gap (or, more generally, an interaction gap) is the underlying physics of the MD was considered, but several reservations were raised against it. A serious concern is the relevance of a single-particle DOS to conductance. In addition, a severe problem was a factor of ≈ 10 discrepancy¹⁷ between the experimental results for the width of the MD and the value expected for the strength of the Coulomb interaction (Ref. 17 used $\approx \frac{e^2}{\kappa r}$, with a dielectric constant $\kappa \approx 10$ and $r \approx n^{-1/3}$ as a measure of this energy). It is this discrepancy that we wish to re-examine here and show that it was based on a definition of width that, though natural, may have underestimated its value.

The definition of the MD width adopted by Vaknin *et al.*¹⁷ is based on measuring the width (in volts) of the MD at half height from the $G(V_g)$ scan. Using the gate-sample capacitance, the width in terms of the associated charge ΔQ is obtained. Note that it is this charge range ΔQ rather than the voltage span ΔV_g which is the relevant variable for characterizing the width of the MD. This has been demonstrated by comparing field-effect transistor (FET) samples with different spacers and spacer thicknesses for a given electron glass.¹¹ Then, the width in energy units is derived with the ΔQ associated with the half height and the calculated density of states using the measured n and free-electron formulas.

Since the half height of the MD (to be referred to as $\Gamma_{1/2}$) is experimentally well defined, this procedure of assigning a

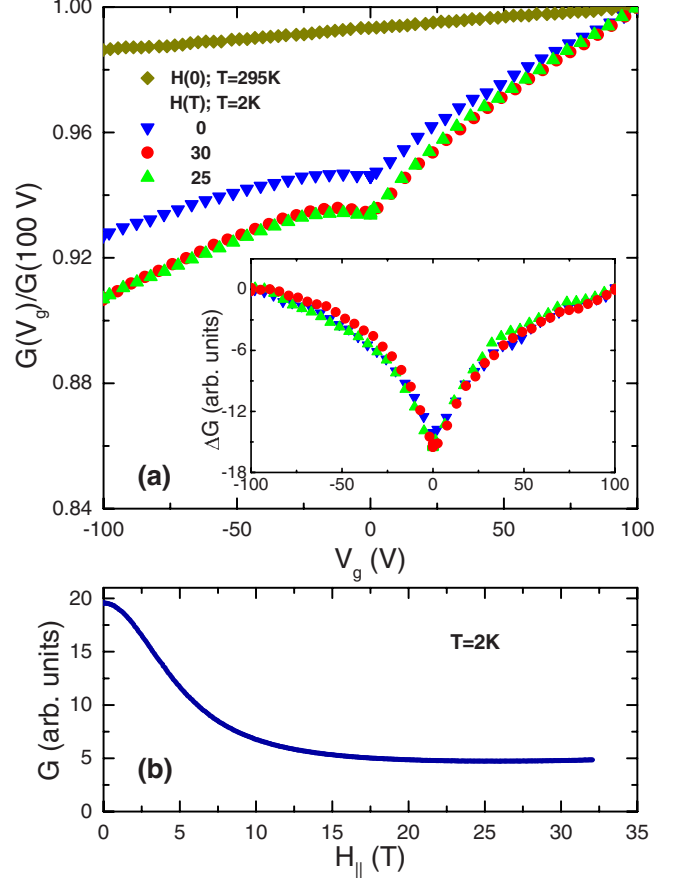


FIG. 6. (Color online) (a) Field-effect sweeps taken for different values of a magnetic field (parallel to an $\text{In}_2\text{O}_{3-x}$ film plane). The sample is 32 Å thick and has sheet resistances of 500 k Ω at 4.2 K and 2.11 M Ω at 2 K. For comparison, the field effect of this sample at room temperature is also shown. Note the change in the equilibrium field effect with either temperature or magnetic field (the sample resistance increases with magnetic field; see lower graph). Inset shows the preservation of the MD shape and magnitude [in this case just the linear field effect has been subtracted from the $G(V_g)$ data]. (b) The magnetoconductance of the film. For larger fields, quantum interference effects (which exhibit positive magnetoconductance) start to take over the spin effects. This creates the minimum in $G(H)$ at 25 T.

width to a particular sample is convenient and unambiguous. However, if the modulation in $G(V_g)$, or more precisely $G(Q)$, reflects a DOS versus energy structure, then the shape of the MD would depend on temperature due to the thermal occupation of states. This indeed seems to be the case; the MD gets broader as T increases.³⁷ The price for the experimentally convenient definition is a spurious temperature-dependent energy scale. In simple words, the temperature dependence of $\Gamma_{1/2}$ is an artifact that arises from the nonlinear mapping between added charge and the associated energy change. This point was elaborated on by Lebanon and Mueller,³³ who, using a model, showed that the MD shape becomes more “cusplike” as the temperature is reduced in a way that qualitatively resembles the experiments (however, the specific relation between the assumed DOS and G is still to be justified). Using the “half height” $\Gamma_{1/2}$ criterion for

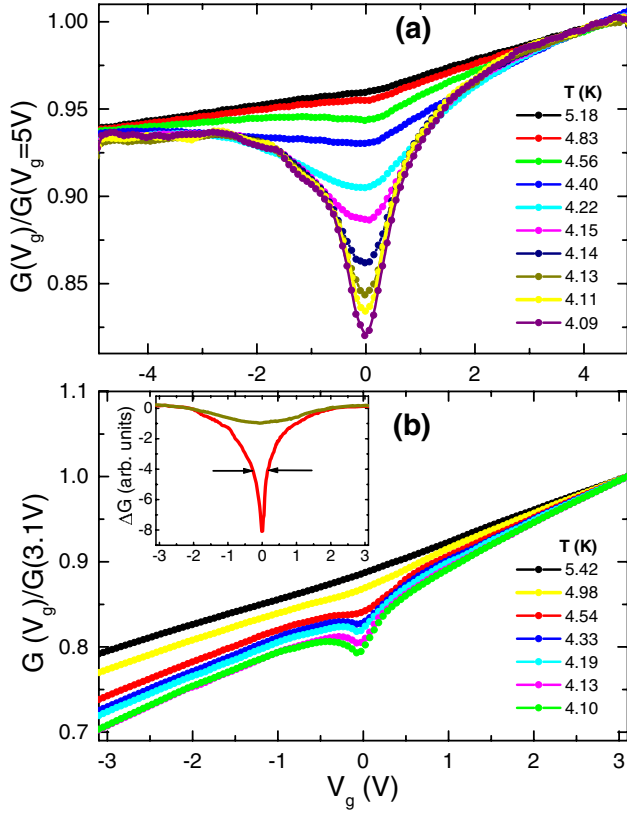


FIG. 7. (Color online) Dependences of the field effect on temperature for (a) In_xO sample with $R=25.2 \text{ M}\Omega$ at 4 K and (b) $\text{In}_2\text{O}_{3-x}$ sample with $R=17.6 \text{ M}\Omega$ at 4 K. In both cases the spacer is $0.5 \mu\text{m}$ of thermally grown SiO_2 on heavily doped Si wafer. Inset of (b) is the MDs at 4.1 and 5.42 K [after a linear part of the equilibrium field effect has been subtracted from the $G(V_g)$ data].

comparison with the Coulomb energy is therefore problematic, which, in hindsight, being temperature dependent was not relevant for the comparison to start with.

An alternative way to define the energy scale associated with the MD suggests itself when one studies the temporal evolution of $G(V_g)$ after a quench-cool from high temperature as shown in Fig. 5. Note that the $G(V_g)$ scans of this sample show time dependence throughout the interval (-50 to $+50 \text{ V}$), while outside it G tend to approach a time-independent regime. The precise boundaries of this region may be ill defined, yet, obviously, the “active” energy band extends over a wide range that does not depend on time nor on $\Delta G/G$. It makes sense then to use this active region as the relevant V_g scale and derive the MD width (henceforth labeled Γ) from it. Indeed, this definition for the MD width turns out also to be temperature independent. This is illustrated in Fig. 7(a) for an In_xO sample and in Fig. 7(b) for $\text{In}_2\text{O}_{3-x}$. Note that in these experiments, the equilibrium (asymmetric) part of the field effect changes with temperature. This results from the higher sensitivity of $\Delta G/\Delta Q$ as the temperature is lowered and R increases (compare with Fig. 5, where T is fixed). Note incidentally that the slope of the equilibrium field effect in In_xO is considerably smaller than that of the $\text{In}_2\text{O}_{3-x}$ sample (Fig. 7). This is a result of the shallower slope of the thermodynamic DOS versus energy in the amorphous material.

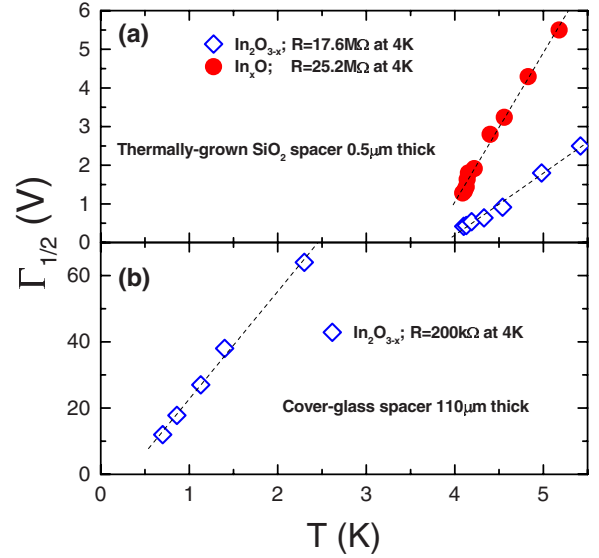


FIG. 8. (Color online) The dependences of the half-height width $\Gamma_{1/2}$ on temperature (a) for the sample in Fig. 7 and (b) for an $\text{In}_2\text{O}_{3-x}$ sample configured with $110 \mu\text{m}$ of SiO_2 .

The pronounced temperature dependences of $\Gamma_{1/2}$ of these samples are shown in Fig. 8(a). For comparison, the dependence of the half-height width on temperature for an $\text{In}_2\text{O}_{3-x}$ FET sample with a much thicker spacer is shown in Fig. 8(b), which shows that $\Gamma_{1/2}(\text{V})$ at a given T does scale with the thickness of the spacer (which affects the sample-gate capacitance) as mentioned above.

The ratios $\frac{\Gamma}{\Gamma_{1/2}}$ (where $\Gamma_{1/2}$ is taken at $T \approx 4 \text{ K}$) are ≈ 8 for the In_xO in Fig. 7(a), and ≈ 10 for the $\text{In}_2\text{O}_{3-x}$ sample in Fig. 7(b). A ratio of 7–10 was found for the series of In_xO samples with n in the range of $6 \times 10^{19} - 8 \times 10^{21} \text{ cm}^{-3}$. In terms of energy, this range amounts to 10–80 meV, respectively, a range that compares favorably with the associated electronic energy $\approx \frac{e^2}{\kappa} n^{1/3}$. These values for the MD width are not too far from the values expected for the Efros-Shklovskii Coulomb gap, leading us to reconsider the possible connection between the two.

The main difficulty in trying to compare the MD with the Coulomb gap is related to the different prescriptions for measuring them. The Coulomb gap is a single-particle DOS which, by definition, is associated with adding charge to the system while all other particles are frozen (such as, e.g., in tunneling or photoemission experiment). It is also an equilibrium entity. This is not the situation in the field-effect measurements where, for any feasible sweep rate, some relaxation takes place, and when carried out under equilibrium conditions no MD is observed [cf. the dotted line in Fig. 4(a)]. Nevertheless the two phenomena seem to be linked to a similar energy scale. Clarifying the possible relation between the Coulomb gap and the MD is a challenge to theory.

A related issue is how the “interaction band” associated with the MD affects the equilibrium conductance G . Experimentally, the conductance versus temperature $G(T)$ in all electron glasses is always activated, as it must be for a system with localized states. However, no characteristic $G(T)$ law can be identified. For example, $\text{In}_2\text{O}_{3-x}$ films usually

exhibit $G(T) \propto \exp[-(T_0/T)^\alpha]$ with $\alpha \approx 1/3$ when deeply insulating (namely, Mott-type behavior in a 2D system) and $\alpha \approx 1$ when closer to the diffusive regime. Granular metals and In_xO films often show stretched exponential $G(T)$ with $\alpha \approx 1/2$, while in granular Al films $\alpha \approx 0.8$ has been reported.⁸ It appears that there is more diversity in the $G(T)$ laws of the electron glasses than in their nonequilibrium properties, which are remarkably similar. Therefore, slow conductance relaxation due to the electron-glass scenario may be positively identified by the behavior of the associated MD but not by $G(T)$.

D. Discussion

The experimental observations detailed above raise this question: What about those systems that do show hopping conductivity yet do not show MD in field-effect measurements—are they not electron glasses? This is quite a pertinent question; there are many such systems, notably semiconductors. To our best knowledge, a memory dip has not been reported in any semiconductor even at temperatures lower than 1 K.

Theoretically, the electron glass is generic to a degenerate Fermi system with localized states and Coulomb interactions. The theory conjectures that all such systems are electron glasses (and, by our proposed test, should exhibit MD in field-effect measurements). Theory however does not specify the typical relaxation time of a given system, so here again we have to rely on experiment. All experiments performed to date suggest that the relaxation time τ , and thus the time for the MD to “form” and “decay,” is a monotonous function of n and relaxation times that are appreciably larger than few seconds are found only in systems with $n \gtrsim 10^{20} \text{ cm}^{-3}$.

As shown in Fig. 3, below a certain carrier concentration n , τ drops down *extremely* fast. Such a “critical” concentration may vary to some degree between different systems, yet it is hard to see what else except n (and to a considerably lesser degree R) may have an appreciable effect on τ for a generic effect that hinges on just localized states and Coulomb interactions.³⁸ A possible reason for the dramatic n dependence based on quantum friction scenario was offered in Ref. 28, but here we shall treat this finding on purely empirical grounds. Since semiconductors that are in the hopping regime have typically $n \ll 10^{19} \text{ cm}^{-3}$, it is quite conceivable that their typical τ (defined by the two-dip experiment) will

be much smaller than 1 s, as suggested by Fig. 3. That will make it very hard to see the MD in a field-effect experiment, which is an inherently slow process due to the gate-sample capacitance and sample resistance. Simply stated, a consistent answer is that *all* hopping systems are in principle electron glasses provided their resistance is large enough, and they are measured at low enough temperature. However, if no MD is observed it might mean that their “slow” relaxation is too short to be observed in the field effect. In this situation, observing conductance relaxation for larger time than that which would allow MD detection should be a warning sign of an extrinsic mechanism.

In summary, we discussed the differences between extrinsic and intrinsic glassy effects observed in conductance measurements. A simple test for an intrinsic electron glass has been proposed based on a field-effect measurement performed on the system after allowing it to equilibrate. The appearance of a dip with dynamics that precisely coincides with the relaxation of the excess conductance caused by, e.g., a quench from high temperatures, is a primary signature of the electron glass. In addition, the dip should have a characteristic shape that does not depend on disorder, magnetic field, or gate-voltage sweep rates, and width that is on the order of a relevant electronic energy. Moreover, the shape of the dip should depend on temperature even for $T \ll \Gamma$, an attribute that is peculiar to the electron glass, quite distinct from thermal smearing.

It would be of great interest to extend the study of the electron glass to include more materials and, in particular, to further test the empirical connection between carrier concentration and relaxation time. Systems that are may be promising in this regard include high- T_c compounds, and transition-metal semiconductor alloys provided that they are sufficiently deep into the hopping regime. On the theoretical side, there is the challenge of dealing with the nonequilibrium DOS that is associated with the memory dip, which seems to be the essence of the electron-glass physics.

ACKNOWLEDGMENTS

The author acknowledges with gratitude the hospitality and use of facilities at the NHMFL at Tallahassee, and illuminating discussions with A. L. Efros. This research was supported by a grant administered by the U.S.-Israel Binational Science Foundation and by the Israeli Foundation for Sciences and Humanities.

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