Conductance Relaxation in the Electron Glass: Microwave versus Infrared Response

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(Received 3 February 2009; published 19 May 2009)

We study the time-dependent conductance of electron glasses excited by electromagnetic radiation at microwave and infrared frequencies. In either case, the conductance G is enhanced during exposure, but its time dependence after the radiation is turned off is qualitatively different depending on the frequency. For comparison, results of excitation produced by a gate voltage and temperature changes are also shown. The glassy nature of the system allows us to demonstrate that the microwave-enhanced conductance is *not* due to heating. These findings are discussed in terms of an energy E_c that characterizes the equilibrium charge distribution of the electron glass.

DOI: 10.1103/PhysRevLett.102.206601 PACS numbers: 72.40.+w, 72.15.Nj, 72.20.Ee, 73.20.Mf

One of the characteristic properties of the electron glass [1] is a slow relaxation of an out-of-equilibrium conductance. At equilibrium the conductance G is at a local minimum, and any agent that takes the system out of equilibrium gives rise to an excess conductance [2]. In most electron glasses studied to date, the preferred method of exciting the system was a sudden change of the carrier concentration using a gate [2,3]. This usually led to a logarithmic relaxation of the excess conductance, which was theoretically accounted for by several authors [4]. Being an electronic glass, there are many other ways to excite the system and follow its relaxation dynamics.

In this Letter, we study the effects of exposing electron glasses to electromagnetic radiation at microwave (MW) frequencies and compare the results with the response obtained at infrared (IR) frequencies. When either type of irradiation is turned on, G promptly increases. However, the excess conductance ΔG caused by the radiation decays in a different way upon turning it off; ΔG following exposure to IR exhibits sluggish relaxation that may last several hours, while the MW-enhanced G disappears rather quickly. This qualitative difference between the IR and MW excitations is interpreted as evidence for a characteristic energy E_c, presumably the Coulomb interaction associated with the equilibrium distribution of the charge carriers among the (localized) electronic states.

Thirty-two samples were measured in this study. These were thin films of either crystalline or amorphous indium oxide (In_2O_{3-x} and In_xO, respectively) prepared on 110 μm glass substrates with a metallic electrode deposited on their back side to act as a gate. The lateral size of the samples used here was 0.2–1 mm. Their thickness (typically, 30–50 Å for In_2O_{3-x} and 80–200 Å for In_xO) and stoichiometry were chosen such that, at the measurement temperatures (at or close to 4 K), samples had sheet resistance $R_\square$ in the range 3 MΩ–3 GΩ. Fuller details of sample preparation, characterization, and measurement techniques are given elsewhere [5,6].

Several sources were used for MW excitation: Gunn diodes (up to 100 GHz), klystrons (10 and 35 GHz), and a high power synthesizer (HP8360B, 2–20 GHz, and up to ≈ 320 mW $\equiv$ 25 dBm output power). The data shown here are mostly based on output of the latter source being fed to the sample chamber via a coaxial cable. The MW power at the sample stage was measured to be linear with the synthesizer output power. A LED diode (operating at $\approx 2 \times 10^{14}$ sec^{-1}), placed ≈ 2 mm from the sample, was used to generate the IR.

The response of typical In_2O_{3-x} and In_xO samples to MW radiation is compared with the response to IR radiation in Fig. 1. Also shown is the effect of quickly changing the gate voltage V_g which has been the most common method to excite the electron glass [3]. Here we wish to focus on a systematic *qualitative* difference between the effect produced by IR excitation (or changing V_g) and that of the MW illumination, namely, the lack of slow relaxation in $\Delta G(t)$ caused by MW radiation. The absence of a long relaxation tail following excitation by MW was confirmed throughout the range 0.9–100 GHz using different sources. Excitation by visible light sources, on the other hand, led to the same qualitative behavior as observed using the IR excitation.

As the main difference between the IR (and visible) and the MW fields is their frequency ω, the different behavior of $\Delta G(t)$ following excitation by these agents may be a hint at the existence of a characteristic energy E_c such that $E_c \geq \hbar\omega$ for the applied MW and $E_c \leq \hbar\omega$ for the IR illumination. A natural candidate for E_c is the Coulomb energy associated with the interelectron interaction which is of order $e^2 n^{-3}/\kappa$, where n is the carrier concentration and κ is the dielectric constant. It was recently shown that $e^2 n^{-3}/\kappa$ is of the same order as the width of the "memory dip" which is the characteristic signature of the (intrinsic) electron glass [6]. For the indium oxides this energy spans the range 6–80 meV depending on the carrier concentration n. The highest energy of the MW used here (≈ 0.42 meV) and the energy of the IR source (≈ 830 meV) straddle this energy range.

The proposed picture is as follows. The system is in equilibrium when the occupation of the electronic states,

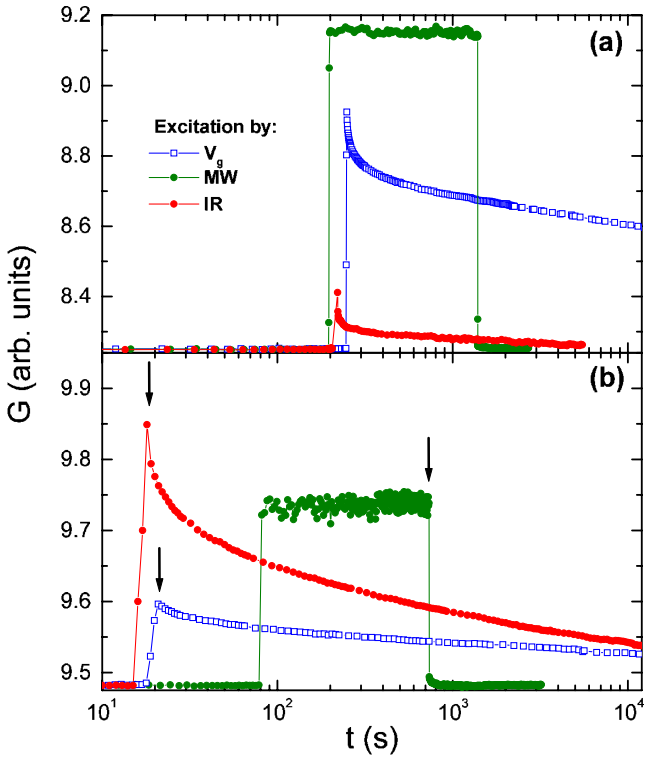

FIG. 1 (color online). Time dependence of the conductance of typical electron glasses under three excitation protocols, each starting from equilibrium; V_g is the gate to sample voltage is swept from 0 to 105 V with rate = 25 V/s; IR denotes the 60 μW source operated for 2 seconds; MW denotes the frequency of 2.633 GHz and source power of 21 dBm held for a few hundred seconds and then turned off. Samples are (a) In_2O_{3-x} thickness 34 Å, $R_\square = 12$ MΩ, and $n = 4.4 \times 10^{19}$ cm^{-3}. (b) In_xO thickness 100 Å, $R_\square = 5$ MΩ, and $n = 9.05 \times 10^{19}$ cm^{-3}. Arrows mark the onset of the respective relaxation process.

under a given potential landscape and temperature, minimizes the free energy. In the interacting system, this leads to a specific organization of the way the localized states are occupied. The Coulomb interaction introduces correlations between state occupation and their spatial coordinates, a process that, among other things, leads to a Coulomb gap in the single-particle density of states [7]. Formation of this configuration from an excited state (where the sites are randomly distributed) is a slow process for several reasons: The lowest energy state of the system cannot be reached without the (inherently slow) many-particle dynamics being involved [8]. Dynamics is further impeded by hierarchical constraints [9] imposed by the Coulomb interactions, and most importantly, quantum friction, which is appreciable in systems with large carrier concentration, is the dominant factor in bringing about sluggish relaxation [6,10]. A substantial change of such a configuration requires an energy investment of $\geq E_c$, which is of the order of the Coulomb energy. Only excitation agents that can impart an energy quantum $\geq E_c$ may randomize this configuration. Since reestablishing an equilibrium configuration is a sluggish process, $\Delta G(t)$ produced by such an excitation agent will decay slowly. This is the case for excitation by IR as well as due to a sudden change in V_g. By contrast, the conductance of the system may be increased without randomizing the equilibrium configuration, e.g., when extra energy is imparted to the hopping process (*from a source with energy quanta smaller than* E_c), in which case the relaxation could be fast. This is presumably the case with the MW excitation (a possible specific scenario is mentioned in the summary below). In general, injecting energy into the system will enhance the conductance rather immediately in any case. Therefore, the excitation-relaxation process will appear asymmetric in $\Delta G(t)$ plots (as in Fig. 1 for the gate and IR excitation) and symmetric (for MW excitation).

When an applied ac field increases G in a system with a negative temperature coefficient of resistance, it is natural to assume that *heating* is the cause, as was conjectured by Ben-Chorin *et al.* [2]. For strongly localized samples, it takes a rather small change of temperature ΔT to get an appreciable $\Delta G/G$. Figure 2 illustrates this point. The figure shows how $\Delta G/G$ depends on the MW power for several samples, and the inset delineates the temperature change needed to affect such $\Delta G/G$. This plot shows that the required ΔT is less than 8% of the bath temperature even for the two samples with the highest MW sensitivity. However, although some heating accompanies the MW radiation (and, in fact, the IR radiation as well), it turns out to be much less than this estimate, and the bulk of the

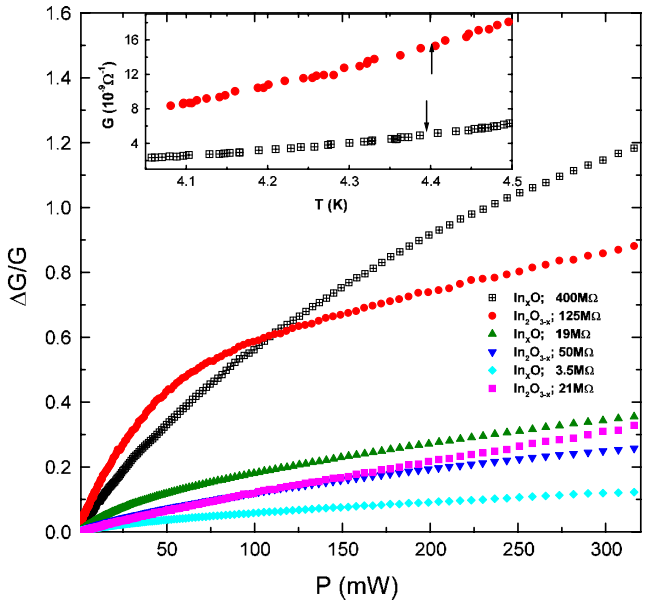

FIG. 2 (color online). Relative conductance change versus MW power for six of the samples that showed the highest sensitivity to MW. Significantly, n in these samples was smaller than 10^{20} cm^{-3}; $\Delta G/G$ for samples with larger n never exceeded 5% at full MW power. The inset shows $G(T)$ for the two samples with the highest sensitivities. The arrows mark the T at which G attains the MW-induced conductance (at full power).

MW-induced ΔG is *not* a result of the sample being heated up by the MW radiation.

That sample heating cannot explain the MW-induced ΔG could have been already deduced from the data in Fig. 2; the sublinear ΔG versus MW power, in a range where both G and the power dissipated to the bath should be linear over ΔT (given $\Delta T/T \ll 1$), is incompatible with a heating mechanism. In the following, we describe experiments that utilize the unique transport features of the electron glass to get a more direct test of this issue.

The first experiment, described in Fig. 3, employs the memory dip (MD) as a thermometer. The MD is the characteristic feature in $G(V_g)$ centered at the gate voltage where the system has equilibrated, and its relative amplitude is extremely sensitive to temperature [5,11]. The figure clearly demonstrates that MW radiation, while increasing the conductance by a certain ΔG, leaves the MD amplitude essentially unchanged [Fig. 3(a)]. To get the same ΔG by raising the bath temperature, one has to use ΔT that produces a distinct change in the magnitude of the MD [Fig. 3(b)]. Obviously, changing G by ΔT yields a different physical situation than the effect of changing it by MW radiation. This can also be seen from another angle as described in the experiment shown in Fig. 4. Here each excitation agent is applied starting from equilibrium and is maintained for ≈ 750 sec. It is then turned off, and the ensuing behavior of $\Delta G(t)$ is recorded. This protocol is illustrated for the ΔT excitation run in Fig. 4(a) (the respective protocol for the MW excitation can be seen, e.g., in Fig. 1). The time dependence of $\Delta G(t)$, after conditions are set at *status-quo ante*, is shown in Fig. 4(b) allowing a comparison between the two protocols. Note that, after the excitations are turned off, at $t = t^*$, $G(t > t^*)$ relaxes back to its equilibrium value for both protocols but in a different way: The amplitude of $\Delta G(t > t^*)$ for the MW protocol is

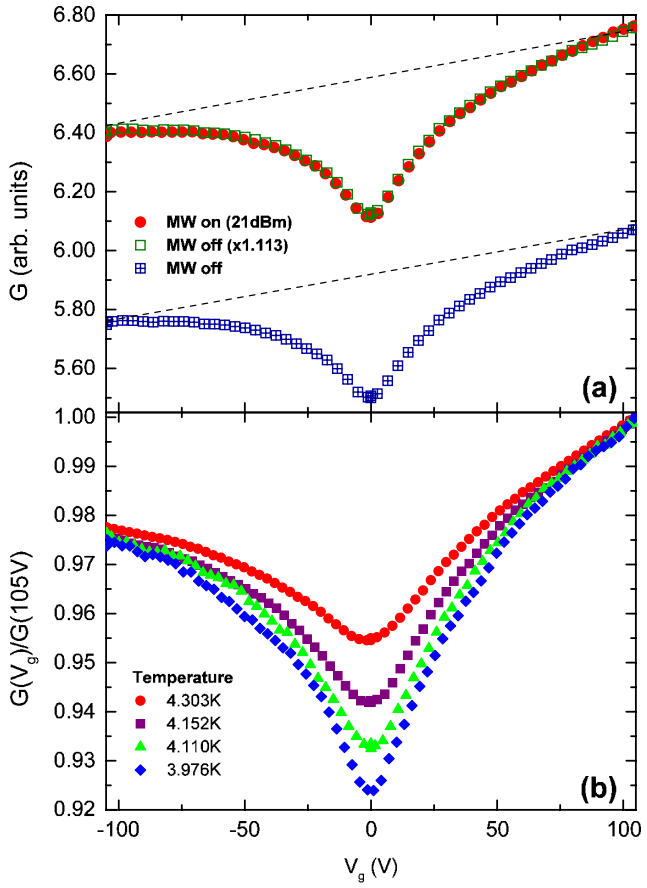

FIG. 3 (color online). $G(V_g)$ traces taken under various conditions for a typical In_2O_{3-x} sample (thickness 34 Å, $R_\square = 28$ MΩ, $n = 4.3 \times 10^{19}$ cm^{-3}). Note the memory dip centered at $V_g = 0$ where the sample was first equilibrated for 46 hours. (a) With and without MW radiation (at $f = 5.487$ GHz) at a bath temperature $T = 4.11$ K. (b) At different temperatures (with MW off and an equilibration period of 2 hours at each T). Note that the slopes of the antisymmetric field effect (see [10] and references therein), depicted by dashed lines, are essentially unaffected by the MW. This suggests that the enhanced G is not due to an increase in carrier concentration.

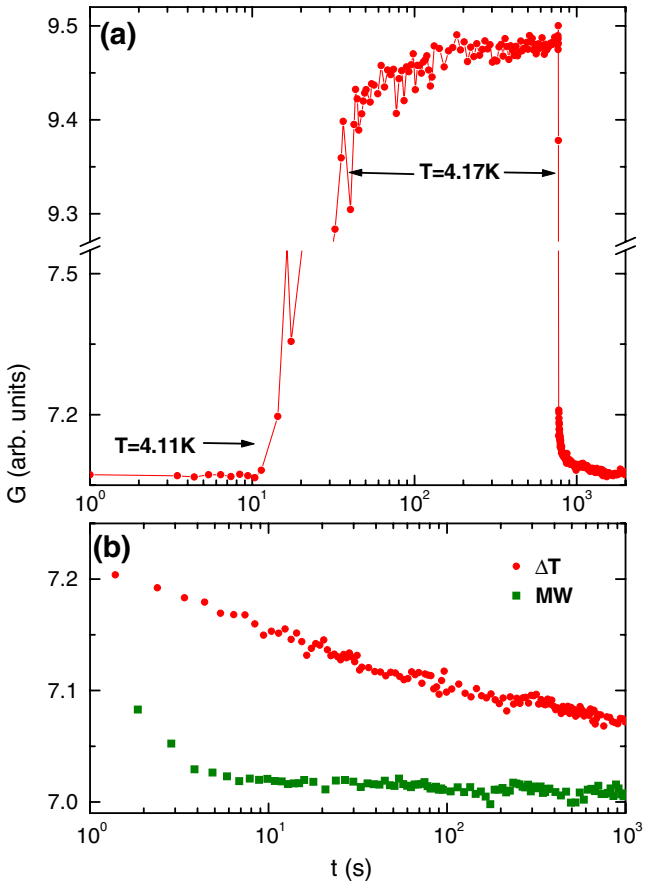

FIG. 4 (color online). Comparison between the temporal dependence of G subjected to ΔT and MW protocols (see text). Sample is a In_2O_{3-x} (thickness 34 Å, $R_\square = 28$ MΩ, $n = 4.27 \times 10^{19}$ cm^{-3}). (a) Illustrating the protocol for $\Delta T = 60$ mK chosen to match the $\Delta G/G \approx 30\%$ produced by exposing the sample to MW (power of 25 dBm at $f = 2.416$ GHz) in the MW protocol. (b) The time dependence of the excess conductance of the two protocols.

relatively small, and it relaxes rather fast while a glassy (logarithmic) relaxation is observed in the ΔT protocol and a measurable $\Delta G(t > t^*)$ persists for a much longer time. On the basis of these experiments we estimate that the temperature increment the samples gain from the radiation is smaller by 30–50 than the ΔT that would increase G by the MW-induced value.

These experiments tell us also what *is* the difference between exposing the system to MW radiation and raising its temperature by ΔT; the latter presumably affects the equilibrium configuration, while the MW does not.

A question arises here: As $\Delta T \ll \frac{E_c}{k_B}$, how does one reconcile the respective $\Delta G(t)$ behavior with our conjecture that it takes an energy quantum $\geq E_c$ to modify the equilibrium configuration to get glassy relaxation? The answer is that, in contrast with MW radiation that has a high frequency cutoff, at a temperature T the system still experiences phonons with $\hbar\omega \gg k_B T$, albeit with an exponentially diminished probability. Letting ΔT operate on the system for a finite time affects the equilibrium configuration through the presence of thermal phonons with energies $\geq E_c$. The exponential sensitivity of the MD amplitude to temperature apparent, e.g., in Fig. 3(a) (see also [6,11]), is one manifestation of this effect.

Applying a non-Ohmic longitudinal field seems to have a similar effect as raising the temperature [12] in that it leads to slow relaxation. This may be partly due to real heating [13] or to a field-created new current path with the accompanying reorganization of the equilibrium configuration of the occupied states.

In summary, we investigated the behavior of the excess conductance created by electromagnetic radiation applied to several electron glasses. A systematic qualitative difference is found between sources depending on the quantum energy of the associated photon. This is argued to be consistent with a characteristic Coulomb energy relevant for the electron glass. Our conjecture is amenable to a more refined test by carrying out optical excitation experiments, in particular, over the energy range 6–80 meV, which is the range of energies associated with the glassy phase of the indium oxides. This should be possible using synchrotron radiation with a series of samples having different carrier concentration n. We expect a crossover from MW-like to IR-like response around a frequency ω that scales with the MD width (that, in turn, is determined by the carrier concentration [10,14]). Electron glasses with low n might have offered a more convenient frequency range; a crossover frequency ω_c of 0.4–0.7 THz was reported in $G(\omega)$ measurements on Si:P samples [15] with n in the range 1.6×10^{18}–3×10^{18} cm^{-3}, smaller by 1–3 orders of magnitude than the carrier concentration in the indium oxides. Unfortunately, conductance relaxation in low n systems appears to be rather fast (see [6,10] for a discussion of this issue), in which case the qualitative change of behavior in $\Delta G(t)$ excited by low vs high frequencies may be hard to observe.

The phenomenology associated with the MW-induced excess conductivity, in particular, the lack of slow relaxation and the sublinear dependence on power, puts constraints on the underlying mechanism. Detailed examination of the glassy features in the presence of MW radiation rules out heating as the reason of the effect. A promising direction is a mechanism based on a model recently proposed by Müller and Ioffe [16]. In this scenario, the MW drives collective electronic modes that act as an extra energy source thus enhancing hopping processes. This scenario is currently being explored.

Discussions with A. Amir, A. Efros, Y. Imry, and M. Pollak are gratefully acknowledged. 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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