Conductance relaxation in the Electron-Glass; Microwaves versus infra-red response

Z. Ovadyahu

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

Abstract

We study the time-dependent conductance of electron-glasses excited by electromagnetic radiation at microwaves (MW) and infra-red 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 MW-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.

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 [1]. Being an electronic glass, there are many other ways to excite the system and follow its relaxation dynamics.

In this note we study the effects of exposing electron-glasses to electromagnetic radiation at microwaves (MW) frequencies and compare the results with the response obtained at infra-red (IR) frequencies. When either type of irradiation is turned on $G$ promptly increases. However, the excess conductance $\Delta G$ caused by the radiation decays in a different way upon turning it off; $\Delta G$ 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$_2$O$_{3-x}$ and In$_x$O respectively) prepared on 110$\mu$m glass substrates with a metallic electrode deposited on their backside to act as gate. Lateral size of the samples used here were 0.2-1mm. Their thickness (typically, 30-50A for In$_2$O$_{3-x}$ and 80-200A for In$_x$O) and stoichiometry were chosen such that at measurement temperatures (at or close to 4K), samples had sheet resistance $R_{\square}$ in the range 3M$\Omega$-3G$\Omega$. Fuller details of sample preparation, characterization, and measurements techniques are given elsewhere [5, 6].

Several sources were used for MW excitation: Gunn diodes (up to 100GHz), Klystrons (10 and 35GHz), and a high power synthesizer (HP8360B, 2-20GHz, and up to $\approx$320mW=25dBm 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 $\approx 2 \cdot 10^{14}$ sec$^{-1}$), placed $\approx$2mm from the sample, was used to generate the IR.

The response of typical In$_2$O$_{3-x}$ and In$_x$O 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 $V_g$, 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 0.9-100GHz 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 $\omega$, the different behavior of $\Delta G(t)$ following excitation by these agents may be a hint on 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 inter-electron interaction which is of order $e^2n^{-3}/\kappa$ where $n$ is the carrier concentration and $\kappa$ is the dielectric constant. It was recently shown that $e^2n^{-3}/\kappa$ is of the same order as the width of the "memory dip" which is the characteristic signature of the (intrinsic) electron-glass [4]. For the indium-oxides this energy spans the range 6-80meV depending on the carrier-concentration $n$. The highest energy of the MW used here ($\approx$0.42meV) and the energy of the IR source (830meV), straddle this energy range.

The proposed picture is as follows. The system is in equilibrium when the occupation of the electronic states, 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 states occupation and their spatial coordinates, a process that, among other things, leads to a Coulomb gap in the single-particle density of states. 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 environmental energy investment of $E_c$. A substantial change of such a configuration requires an antifactor in bringing about sluggish relaxation, which is appreciable in strongly-localized states. F or strongly-localized systems, the relaxation time is of the order of the Coulomb interaction time, i.e., $\tau \approx 10^{-15}$ s. That sample heating cannot explain the MW induced $\Delta G$ could have been already deduced from the data in Fig. 2; The sublinear $\Delta G$ versus MW-power, in a range where both G and the power dissipated to the bath leaves the MD amplitude essentially unchanged (Fig. 3a). Obviously, changing G by $\Delta T$ yields a different physical situation than 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 changes. The figure clearly demonstrates that MW radiation, while increasing the conductance by a certain $\Delta G$, it leaves the MD amplitude essentially unchanged (Fig. 3a). To get the same $\Delta G$ by raising the bath temperature one has to use $\Delta T$ that produces a distinct change in the magnitude of the MD (Fig. 3b). Obviously, changing G by $\Delta T$ 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 experiments shown in Fig. 4. Here, each excitation agent is applied starting from equilibrium, and is maintained for several samples, and the inset delineates the temperature change needed to affect such $\Delta G$. This plot shows that the required $\Delta T$ 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 MW-induced $\Delta G$ is not a result of the sample being heated-up by the MW radiation.
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 4b 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 relatively small, and it relaxes rather fast while a glassy (logarithmic) relaxation is observed in the $\Delta T$ 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 $\Delta T$ that would increase the MW-induced conductance (at full power).

These experiments tell us also what is the difference between exposing the system to MW radiation and raising its temperature by $\Delta T$. 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 exponentially diminished probability. Letting $\Delta T$ 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. 3a (see also [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 paths with the accompanying re-organization 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 opti-
FIG. 4: Comparison between the temporal dependence of G subjected to ∆T and MW protocols (see text). Sample is a In$_2$O$_{1-x}$ (thickness 34Å R$_G$ =28MΩ n =4.27·10$^{19}$ cm$^{-3}$). (a) Illustrating the protocol for ∆T=60mK chosen to match the $\Delta G/G \approx 30\%$ produced by exposing the sample to MW (power of 25dBm at f=2.416GHz) in the MW protocol. (b) The time dependence of the excess conductance of the two protocols.

cal excitation experiments, in particular, over the energy range 6-80meV 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 $\omega$ that scales with the MD width (that, in turn, is determined by the carrier-concentration $n$). Electron-glasses with low n might have offered a more convenient frequency range: A crossover frequency $\omega_c$ of 0.4-0.7THz was reported in $G(\omega)$ measurements on Si:P samples with n in the range 1.6-10$^{18}-3\cdot10^{18}$cm$^{-3}$, smaller by 1-3 orders of magnitude than the carrier-concentration in the glassy-oxides. Unfortunately, conductance relaxation in low n systems appears to be rather fast (see [3] 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 US Israel Binational Science Foundation and by the Israeli Foundation for Sciences and Humanities.

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