Optical excitation of Electron-Glasses

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Abstract
Electron-glasses can be readily driven far from equilibrium by a variety of means. Several mechanisms to excite the system and their relative merits are reviewed. In this study we focus on the process of exciting electron-glasses by interaction with near infrared radiation. The efficiency of this protocol varies considerably among different electron-glasses, but it only weakly depends on their resistance at liquid helium temperatures. A dramatic enhancement of the excitation efficiency is observed upon doping crystalline indium-oxide with Au. Some enhancement is observed also in samples doped with Pb but this enhancement fades away with time unlike the situation in the Au-doped samples. Several structural and analytical tools are used to characterize the changes in the materials that may be responsible for these effects. Possible routes by which high-frequency electromagnetic fields take the system far from equilibrium are discussed.

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I. INTRODUCTION
Non-equilibrium transport features, expected to occur in electron-glasses [1–5], have been reported in several systems over the last two decades [6–11]. A common way to excite the system to observe these phenomena has been a sudden change of the gate voltage using samples configured as three terminal devices [6–8, 11]. This gating technique is straightforward to apply and may yield very useful information on the nature of the glassy state (such as the memory-dip [12]). However, it may not be possible for technical reasons to configure the sample with a gate, and in a bulk sample this technique is ineffective. It may also give rise to artifacts associated with trapped charge or other defects in the insulating layer that separates the sample from the gate (this appears to be a common problem in some semiconductors). It is therefore desirable to find different ways to take the electron-glass far from equilibrium, and in fact there are several alternatives to achieve that.

A readily available way to excite the electron-glass is to employ a non-ohmic field $F$ along the sample (a longitudinal field) [10, 13]. In this protocol the system is taken from equilibrium to a degree that depends on the applied $F$ as well as on the time the sample is under the stress of the field. Qualitatively similar effect may be obtained by increasing the bath temperature $T$ by $\Delta T$ and maintaining it for a while [13, 14]. The $\Delta T$-protocol is experimentally harder to control and it is usually difficult to quickly change and maintain the bath temperature. This is where the $F$-protocol has a distinct advantage over the $\Delta T$-protocol but the underlying mechanism for excitation seems to be essentially the same; increasing the population of high-energy phonons.

It is natural to expect that the electron-glass could be also excited by exposure to electromagnetic (EM) radiation. It turns out that this depends on the frequency $\omega$ of the EM field. Efficient excitation has been observed in experiments on indium-oxide samples where a brief exposure to an infra-red (IR) radiation led to a slowly relaxing conductance component [15]. Also, it was demonstrated that exposure to IR source effectively erases the memory-dip [15]. Exposing the sample to EM radiation at the microwave frequencies (tested in the range 1-100GHz) on the other hand, was not effective in this regard, in particular, it has no effect on the memory-dip [13, 16]. As long as the microwaves field was on, it did increase the conductance by as much (and even more) as the IR acting on the same sample but once the microwave source was turned off the conductance returned quickly to its equilibrium value.

These empirical results are consistent with the following physical picture. 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. In the electron-glass it is the Coulomb interaction that introduces correlations between states-occupation and their spatial coordinates. Among other things this process leads to a Coulomb gap in the single-particle density of states [17]. Randomizing such a configuration requires an energy investment that exceeds $E_C$, which is of the order of the Coulomb energy [16]. Re-establishing the equilibrium configuration from a state where the sites are randomly distributed is a slow process for reasons discussed elsewhere [16]. Therefore, $\Delta G(t)$ produced by such an excitation agent will decay slowly.

Excitation by the $\Delta T$-protocol (or the $F$-protocol) differs from other protocols in that it usually involves long application-times to be effective. Note that only high-frequency phonons (with energy quantum $> E_C$) can do the job, and such energetic modes are exponentially rare when $\Delta T \ll E_C$. Therefore to achieve a degree of randomization that results in a slowly relaxing $\Delta G$ component in the $\Delta T$-protocol (or the $F$-protocol) requires a long time of applying the excitation agent (depending on $\Delta T$). By contrast, brief exposure to IR is sufficient to effectively randomize the system as will be demonstrated in section III. Given the ease and flexibility of applying the IR-protocol, one wonders why it has been applied so sparingly in the study of electron-glasses [18].

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In this work we compare the efficiency of this protocol among different electron-glasses; amorphous and crystalline indium-oxide (In$_2$O and In$_2$O$_3$ respectively), granular-aluminum, and beryllium. The main focus of this work is on the dramatic change of the excitation efficiency of In$_2$O$_3$ samples when doped with Au and Pb. Possible reasons for this enhancement are experimentally tested and the implications to the physics underlying the IR-protocol are discussed.

II. EXPERIMENTAL

A. Sample preparation and measurement techniques

Several materials were used to prepare samples for measurements in this study. These were thin films of crystalline or amorphous indium-oxide (In$_2$O$_3$ and In$_2$O respectively), and granular-aluminum. These three materials were similarly prepared by e-gun evaporation of substrates in partial oxygen pressures of 4-6 mbar and rates of 0.3-1A/second. The In$_2$O$_3$ samples were obtained from the as-deposited amorphous films by crystallization at 525K (unless otherwise mentioned). Also used in this work are films of In$_2$O$_3$-x doped with either Au or Pb. These dopants were deposited from a Knudsen source simultaneously with the indium-oxide, and the composite deposit was then crystallized in the same manner as the In$_2$O$_3$-x. The relative concentration of a dopant was controlled in the deposition process by independently measuring the evaporation rate of each material. Each preparation run produced a batch of samples on a common glass-slide. Each batch included samples for excitation measurements, samples for Hall-effect measurements, and samples for structural and chemical analysis. Carbon coated Cu grids were attached to the substrate for the electron microscopy study.

X-ray photoelectron-spectroscopy (XPS, using Axis Ultra) and transmission-electron-microscopy (TEM, using Tecnai F20 G2) were employed to characterize the films composition and microstructure. Optical studies employed the Cary-1 spectrophotometer and Bruker Equinox-55 FTIR.

Indium contacts were employed in all indium-oxide based samples. To make good quality contacts to the granular-aluminum films gold strips were deposited on the ion-bombarred glass substrates prior to the aluminum deposition. Lateral size of the samples used here were 0.2-1mm. Their thickness (typically, 40-55Å for In$_2$O$_3$-x,In$_2$O$_3$-x:Pb, In$_2$O$_3$-x:Au, 150-600Å for In$_2$O, and 50-60Å for granular-aluminum) and, for In$_2$O$_3$-x based samples, stoichiometry, were chosen such that at the measurement temperatures (at or close to 4K), the samples had sheet resistance $R_{\square}$ in the range 0.2M$\Omega$-3G$\Omega$. This ensured that all these samples are deep enough in the hopping regime to exhibit electron-glass features. All resistance data reported below are per square geometry. We also show for comparison results on beryllium films using a specimen studied in [11].

Optical excitations in this work were accomplished by exposing the sample to an AlGaAs diode (operating at $\approx 0.88 \pm 0.05 \mu$m), placed typically $\approx 10$-25mm from the sample. The diode was energized by a computer-controlled Keithley 220 current-source.

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 4K studies. All measurements reported here were performed with the samples immersed in liquid helium at T$\approx 4.1K$ held by a 100 liters storage-dewar. The ac voltage bias was small enough to ensure near-ohmic conditions (except when it was desirable to simulate higher temperature behavior). Complementary details of sample preparation, characterization, and measurements techniques are given elsewhere [6,10].

III. RESULTS AND DISCUSSION

A. The basic facts

The experimental protocol used for the IR excitation is illustrated in Figure 1 using a rather thick In$_2$O sample. Starting by monitoring G(t) for several minutes to establish a baseline that defines the near-equilibrium conductance $G_0$. The IR source is then turned on for 3 seconds, and then turned off while G(t) continues to be measured. The brief IR burst causes $G$ to promptly increase by $\Delta G$ some of which quickly decays once the source is turned off leaving a slow relaxation tail as shown in figure 1. The inset to the figure demonstrates that the slow component of the induced excess conductance relaxes logarithmically with time, which is a characteristic feature of the electron-glass [21]. It also depicts the way its 'initial' amplitude $\delta G$ is defined in this work (i.e., by extrapolating the logarithmic G(t) to t=1 second, the typical resolution-time in our experiments). The fast component of the relaxation, $\Delta G$-$\delta G$, is essentially a recovery from the thermal shock associated with the IR burst.

The qualitative features shown in figure 1 for the In$_2$O sample were obtained on all electron-glass systems studied in this work (six different materials). In terms of the balance between $\delta G$ and $\Delta G$-$\delta G$ however, the results varied considerably among these systems. For example, figure 2 shows IR-excitation results for two of the systems that yielded the smallest slowly-relaxing conductance in response to the IR-protocol; granular-aluminum and beryllium.

The very small $\delta G/\Delta G$ exhibited by the sample in figure 2a was reproduced on all our granular-aluminum samples independent of their resistance (in the range 0.7-150M$\Omega$). In fact, in these samples the slow component was so small as to raise the suspicion that the samples do not exhibit glassy behavior at all! However, applying
FIG. 1: IR excitation protocol applied on a 600Å InO film and $R_\square=50\text{M}\Omega$. The parameters that characterize the results are marked by arrows; $\Delta G$ is the conductance initial jump, $\delta G$ is the initial amplitude for the slowly relaxing part which is defined in this work as the value of the excess conductance at $t=t_S$ which is the time corresponding to $t=1\text{s}$ of the inset plot. The inset illustrates that the asymptotic part of the relaxation follows the logarithmic law.

the F-protocol on the these samples revealed the characteristic electron-glass features as shown in figure 3. Possible reasons for the poor response to the IR-excitation of granular aluminum (in fact, of any granular electron-glass) are discussed in Section III D.

Unless otherwise noted, the IR-protocol shown in this work involved a fixed 3-seconds exposure to the IR source. This is required to allow for a meaningful comparison between different systems; all other things being equal, longer exposures systematically yield larger values of $\delta G/\Delta G$. An example is illustrated in figure 4. Note that during the time the IR is on, and its intensity is held fixed, the conductance keeps going up. This accumulated-over-time excess conductance translates into a larger $\delta G$ when the exposure is terminated. Essentially the same effect results by increasing the bath temperature by $\Delta T$ and holding it (see, e.g., reference [14]) for time $\tau$; the ensuing $\delta G$ is then a monotonic function of $\tau$ (as well as of $\Delta T$). Upon increasing the temperature, the conductance promptly increases by $\Delta G$, but for a short $\tau$, during which $G(T+\Delta T)$ has not significantly changed, $\Delta G$ would decay as quickly as the original bath temperature is re-instated. The 3-seconds protocol is a compromise; it is short enough to minimize the heating contribution to $\delta G$, and long enough with respect to the measurement resolution-time (thus the recorded measurement of $\Delta G$ is reasonably accurate).

Note that samples made of granular-aluminum, beryl-
FIG. 4: Results of IR excitations for a typical film of In$_2$O$_{1-x}$ (42Å thick and R=10.5MΩ), comparing the excess conductance $\Delta G(t)$ ensuing after the source is turned off (after being on for 3s versus 180s).

FIG. 5: Optical transmission as function of wavelength for the materials that were measured by IR-excitation. Transmission through blank substrates were used as baseline in each case. Note the difference in transmission between the 200˚C and 600˚C In$_2$O$_3$ samples indicating that the low transmission is mostly due to absorption (rather than reflection) throughout the entire range of wavelengths. The In$_2$O$_{3-x}$:Au and the In$_2$O$_{3-x}$:Pb samples both with 2 atomic % doping levels relative to the undoped stuff (at least over the range relevant for the IR source employed in these experiments), one might expect that the IR-excitation results on these films should be similar to those of the pure In$_2$O$_{3-x}$. It turns out that, in this case, a small change makes a big difference.

B. The case of In$_2$O$_{3-x}$:Au

The original motivation to add gold to the In$_2$O$_{3-x}$ film was to test the effect of spin-orbit scattering on the microwaves induced excess conductance in the hopping regime. This actually yielded a null result but it led to an intriguing response to IR radiation. Figure 6 shows the results of the IR excitation protocol for a typical In$_2$O$_{3-x}$:Au sample (actually the same film depicted in figure 5 for optical transparency).

Note that the slowly relaxing part of the excess conductance is not only much larger than that of the pure material, it is also considerably larger than the 600˚C In$_2$O$_3$ film despite its IR absorption being stronger (compare figures 1 and 6). To check on the possibility that there is some unusual absorption outside the range probed by the spectrometer (figure 5), we tested the In$_2$O$_{3-x}$:Au sample in a FTIR extending the measurement to 1.3μm and compiled the results for this particular sample in figure 7. No sign of an outstanding absorption feature could be found over the range relevant for the used EM source.
FIG. 6: The 3-second IR-protocol using a $\text{In}_2\text{O}_3-x:\text{Au}$ sample (2 atomic % Au doping, same sample as depicted in figure 5 for optical transmission), thickness is 55Å and $R_{\square}=11\text{M}\Omega$. $\delta G$ and $t_S$ are as defined in figure 1. The inset illustrates the logarithmic relaxation law.

FIG. 7: Optical transmission for one of the measured $\text{In}_2\text{O}_3-x:\text{Au}$ (with 2 atomic % Au) extended further into the infra-red regime by stitching data from a UV-visible spectrophotometer and FTIR. Both spectra were normalized by the measured transmission of the same blank substrate used for the sample deposition. The dashed lines delineate the spectral region where the IR source may have an appreciable intensity.

Large values of $\delta G/\Delta G$ (in the range 70-90%) were found in each and every Au doped $\text{In}_2\text{O}_3-x$ studied in this work. These included samples with $R_{\square}$ ranging between 250k$\Omega$ to 1.5G$\Omega$, and with doping levels of either 2 atomic % (12 samples) or 4 atomic % (5 samples). The latter group showed only slight advantage over the 2% group in terms of $\delta G/\Delta G$, which makes it interesting to measure the dependence of $\delta G/\Delta G$ on smaller doping levels. Unfortunately, our current preparation and analysis methods are not yet accurate enough to attempt such a study.

$\delta G/\Delta G$ in a given sample depends to some degree on the IR-excitation level as shown in figure 8. The decrease of $\delta G/\Delta G$ with IR intensity shown in the figure presumably reflects the saturation in $\delta G$ at these temperatures; the typical saturation value for $\delta G$ by gate excitation for a sample with the same $R_{\square}$ and measured under similar conditions is $\approx 10\%$ (see, e.g., [11]) and probably also due to the growing weight of the ‘heating’ effect that accompanies the illumination. At any rate, it is clear that the Au-doping has a dramatic influence on the efficiency of IR-excitation process in the $\text{In}_2\text{O}_3-x$ samples. The question is why does the addition of gold increase $\delta G/G_0$, or in other words, why does it enhance the system randomization?

As argued above, randomizing the system entails an energy cost. We must therefore accept that the addition of gold somehow enhances the absorption of energy in the $\approx 0.88 \pm 0.5\mu\text{m}$ wavelength, and given that the optical gap of $\text{In}_2\text{O}_3-x$ is at much higher energy (of order 3.7eV), this must be an intra-band absorption [22]. In a clean metal this process has an extremely small oscillator-strength due to momentum-conservation constraints. Absorption becomes more likely when defects or impurities are present. Therefore, it is natural to look for changes in the microstructure of the $\text{In}_2\text{O}_3-x:\text{Au}$ films relative to the undoped material. Such changes are indeed observed in high resolution TEM micrographs (figure 9). The micrograph for the $\text{In}_2\text{O}_3-x:\text{Au}$ exposes a much higher density of grain-boundaries and various structural defects than
C. Not all that’s heavy is (good as) Gold

Three batches of In$_2$O$_{3-x}$:Pb films with doping levels of 2 atomic % were made and measured in this study with $R_\parallel$ (at $T\approx$4K) ranging from 0.7MΩ to 250MΩ. In terms of general transport properties, such as current-voltage characteristics, the Pb-doped films behave similarly to the Au-doped samples (for comparable resistance, sample-size, etc.). The 2%-doped Au and Pb systems also had similar carrier-concentration, $n=(1-2.2)\cdot10^{20}$cm$^{-3}$ (measured via Hall effect at room temperature), a somewhat higher value than that of the undoped indium-oxide, which is usually in the range (4-8)$\cdot10^{19}$cm$^{-3}$. Finally, just like the Au-doped samples, all In$_2$O$_{3-x}$:Pb samples that were in the hopping regime showed electron-glass effects and exhibited slow relaxation following IR-excitation. However, unlike the Au-doped samples, their IR randomization efficiency turned out to be lower, and moreover, it was a function of the sample age.

Typical results of the 3-second IR-excitation protocol are shown in figure 10. These are results of measurements on the same In$_2$O$_{3-x}$:Pb sample but taken at different times; the data in figure 10a were taken a day after preparation while those in figure 10b were taken after the sample was at room temperatures for eleven months. The latter shows significantly smaller $\delta G/\Delta G$. This complication was found when a sample that has been previously measured was re-inserted into the cryostat for further measurements after spending a couple of weeks at room temperatures. It then yielded $\delta G/\Delta G\approx$17%, already a smaller value than the one-day-old $\delta G/\Delta G\approx$30% result. It is remarkable that the changes with time in the In$_2$O$_{3-x}$:Pb samples so well reflected in $\delta G/\Delta G$ seem to be so subtle as to have escaped our structural and analytical characterization. These included TEM, optical spectroscopy and XPS analysis.

The surprising In$_2$O$_{3-x}$:Pb results, prompted us to test the In$_2$O$_{3-x}$:Au samples over a similar period of time. However, unlike the In$_2$O$_{3-x}$:Pb samples, the results of $\delta G/\Delta G$ for In$_2$O$_{3-x}$:Au samples were independent of their age. In addition to the difference between the two systems with regard to sample age, the maximum value of $\delta G/\Delta G$ we obtained to date with ‘young’ In$_2$O$_{3-x}$:Pb was of the order of 35%, still considerably less than in the gold-doped system. The source of these differences appears to be related to chemistry which dictates the way the Au and Pb are incorporated into the In$_2$O$_{3-x}$ lattice. Indeed, XPS studies showed a clear difference between In$_2$O$_{3-x}$:Au and In$_2$O$_{3-x}$:Pb.

Figure 11 compares some of the characteristic binding energies for Au and Pb obtained from XPS scans of the respective samples where these elements were incorporated. The binding energies of the Pb 4f levels are consistent with Pb$_3$O$_4$ suggesting that the Pb resides in the In$_2$O$_{3-x}$ matrix by forming Pb$_3$O and PbO, (i.e., with oxidation state of either +2 or +4). Gold, on the other hand, retains its neutral valency. There is a small upward
shift of the binding energies of the Au:4f electrons by \( \approx 0.1 \text{eV} \), presumably due to the reduced screening associated with the In$_2$O$_{3-x}$ matrix relative to the reference (metallic) Au film. Electron diffraction patterns taken of samples with level doping smaller than 6.8\% reveal just the bcc rings of In$_2$O$_3$. No evidence for Au clusters is detected by either the diffraction patterns or in high resolution imaging of these films. This is consistent with previous studies \cite{23,24} of In$_2$O$_{3-x}$:Au where it was concluded that the Au atoms reside in oxygen vacancies (or possibly di-vacancies).

Being chemically bonded with oxygen the Pb atoms reside in the In$_2$O$_{3-x}$ as either, interstitials, or they replace indium atoms in the In$_2$O$_{3-x}$ lattice. In the later case they play a similar role as Sn, which is a common dopant in indium-oxide. This is presumably the cause of the higher carrier-concentration in In$_2$O$_{3-x}$:Pb samples relative to the undoped material.

That the Pb and Au atoms occupy different sites in the indium-oxide lattice is consistent with the quite different spin-orbit scattering contributed by these dopants in indium-oxides. Gold-doped samples were used in several past experiments in both the hopping \cite{23} and the diffusive \cite{24} regimes, and in both cases the incorporation of Au was shown to enhance spin-orbit scattering. Lead-doping on the other hand, did not seem to be effective in this regard, which may seem surprising considering that Pb is a heavy impurity. The reason for that is that the main source of elastic scattering in In$_2$O$_{3-x}$ is oxygen vacancies, not the heavy In atoms (or the Pb residing on In sites). Effective spin-orbit scattering occurs only when a heavy atom like Au resides on an oxygen site. A similar situation occurs in n-type GaAs; spin orbit scattering is weak despite the presence of the heavy Ga. In both cases it is the large affinity of electrons to (the light) anion that determines the relative importance of spin-orbit scattering \cite{25}.

Note that the weak spin-orbit scattering of In$_2$O$_{3-x}$ and In$_2$O$_{3-x}$:Pb is also a property of beryllium and aluminum, being light elements. It is intriguing that these materials also share a much smaller IR excitation efficiency relative to In$_2$O$_{3-x}$:Au where spin-orbit scattering is strong. Spin-orbit scattering has been known to alter optical transitions probabilities e.g., by lifting-off selection rules \cite{25}. However, attempts to find an explanation for the enhancement effect of the Au doping along this line have not produced anything conclusive.

The different positions where the Au and Pb dopants reside in the In$_2$O$_{3-x}$ lattice should also have consequences for the band structure of the material. Band structure calculations suggest that the bottom of the conduction band of indium-oxide is mainly formed from indium 5s-states hybridized with oxygen 2s-states \cite{25}. This could be the reason for the modified carrier-concentration due to the Au inclusion. More generally, for doping levels of few percents there is probably an impurity band associated with the foreign element, and the only question is at what energy range it forms; if it overlaps with any of the host relevant bands, a profound change in the material properties may take place.

Modifications in the nature of the conduction-band states is of vital importance to the oscillator-strength for the intraband transitions, which in turn, determine the
efficiency of the IR excitation. Such changes are actually observable in the optical spectra of the In$_2$O$_{3-x}$:Au and In$_2$O$_{3-x}$:Pb systems. These may have been easy to ignore in figure 5 because they are relatively weak (especially at the energy range where the IR absorption may occur). To resolve better the more subtle details we compare in figure 12 the ratio between the transmission versus wavelength of the undoped In$_2$O$_{3-x}$ relative to the two systems under consideration. Note that the spectra is now extended somewhat further into the near UV where the relative changes in the transmission stand out more clearly.

Focusing first on the In$_2$O$_{3-x}$:Pb spectrum one notes that over most of the range relevant for the IR-excitation there is no evidence for absorption over that of the pure In$_2$O$_{3-x}$ and therefore no reason why this sample should exhibit different excitation behavior. There seems however to be a higher threshold for the interband absorption in the Pb-doped sample. This is due to the Burstein shift associated with the higher carrier-concentration n. A similar effect has been observed in undoped In$_2$O$_{3-x}$ where n was increased by UV-treatment [28], as well as in many studies of indium-oxides doped with Sn [29].

The spectrum for the In$_2$O$_{3-x}$:Au sample does indicate excess absorption throughout the entire studied range, with a broad ≈4% peak around λ ≈400nm. A similarly shaped feature, at a lower energy, was reported in quantum dots and ascribed to an intraband absorption [30]. The spectroscopic features at wavelengths ≲800nm are not directly relevant for the excitation process (as the IR source has negligible contribution at this range) but they may be indicative of changes in the band structure. The nature of the modifications in the electronic states that give rise to the enhanced intraband absorption are yet to be determined.

D. The routes for system randomization

Once intraband transitions are turned on, system randomization becomes possible (the $\hbar \omega > E_C$ condition is easily fulfilled as $E_C$ in In$_2$O$_{3-x}$ is ≤10meV) and may proceed along two main routes. Either route will drive the system far from equilibrium, achieving a long-lived, enhanced conductance state. The first is a direct transition from an equilibrium site at $r_i$ to another localized state at $r_j$, where a photon is absorbed to make up for the difference in energy. Alternatively, excitation occurs by a two-stage process where a vertical on-site excitation decays via phonon emission, which in turn supply the energy for the $r_i \rightarrow r_j$ transition.

For an effective randomization process, many such transitions should take place during the excitation and, in addition to energy conservation, this requires reasonably good overlap of the wavefunctions involved in the transitions. It is here that the Anderson insulator has a distinct advantage over a granular system. The determining factor in the granular system is the grain-size which has a fixed value set by the system microstructure. The equivalent of a "grain" in the Anderson insulator is the localization length $\xi$ which is determined by multiple scattering off the disorder potential, and importantly, it is a function of energy. Realistic low temperature studies of Anderson insulators rarely if ever involve samples where the Fermi energy $E_F$ is far from the mobility edge (or, in the two-dimensional case, an energy region where $\xi$ is not the limiting factor for the overlap). Optical excitation energy may be large enough to probe states with essentially extended states. The Fermi energy of In$_2$O$_{3-x}$ for example, is of order 0.1eV, and $\hbar \omega \simeq 1$eV should be sufficiently large to secure significant overlap of most $r_i \rightarrow r_j$ transitions. In a granular system only special pairs of initial-final states (possibly related by Mahan exciton conditions [31]) might be available for favorable $r_i \rightarrow r_j$ transitions. Moreover, when the grains are made of the pure element (as is the case of granular aluminum), the probability of intraband absorption is very small to start with even though the spatial overlap for on-site transitions may be excellent.

It should still be possible to drive a granular system far from equilibrium if the EM frequency is high enough to cause photoemission. Electrons ejected from the sample will be replaced by the neutralizing charge that will flow into the system from the contacts, which in turn should effectively randomize the system in a similar way that changing a gate voltage would have [32]. The photon energy required to achieve these conditions for a typical granular system is probably in the vacuum-UV range, which may be large enough to induce structural changes in the sample. This complication could how-
ever be monitored, and taken into account if use is made of mesoscopic samples where effects associated with the potential-landscape set by the ions were shown to be separable from the electron-glass dynamics [23].

E. Summary

We have studied in this work several aspects of electron-glass excitation by near IR radiation. Six different materials were used in this study, all showing similar electron-glass features when driven far from equilibrium. In terms of their response to the IR excitation however, they exhibit widely different efficiency defined by \( \frac{\delta G}{\Delta G} \). In gold doped indium-oxide this measure of efficiency could be as large as 90% while the best figure we obtained on granular-aluminum samples never exceeded 2%. In general, the efficiency of taking the system far from equilibrium by IR radiation appears to be low, the case of \( \text{In}_2\text{O}_3-x : \text{Au} \) being an exception (and to a degree, also \( \text{In}_x\text{O} \)). Based on the phenomenology presented here it seems obvious that the main reason for the poor response of most systems is not energy conservation but rather some selection-rules that suppress optical transitions. In the case of \( \text{In}_2\text{O}_3-x \) the relevant transitions for the \( h\omega \) used here involve the conduction band electronic states (intraband transitions). The addition of Au atoms to the lattice apparently relaxes these selection-rules leading to real absorption that in turn randomizes the system. A weaker effect occurs when Pb atoms are incorporated into the structure, and moreover, the enhanced \( \frac{\delta G}{\Delta G} \) fades away with time. Chemical analysis indicate that the Pb atoms occupy different sites in the \( \text{In}_2\text{O}_3-x \) lattice than the Au atoms, which may provide the clue for the difference in their effects on the IR-excitation efficiency. Microscopic band structure calculations are needed to elucidate these issues.

It is remarkable that the enhancement of \( \frac{\delta G}{\Delta G} \) produced by the Au doping (and to some degree, by the Pb doping as well), is much more conspicuous than the respective effects observable in any of the spectroscopic and analytical tools used here. This sensitivity of the electron-glass may prove useful in studies of basic condensed matter phenomena.

Driving electron-glasses far from equilibrium by high-frequency EM radiation has the advantages and flexibility of modern light-sources. Having an efficient system like the \( \text{In}_2\text{O}_3-x : \text{Au} \) opens possibilities of performing experiments that hitherto were not feasible. An examples for such an experiment is spatially localized excitation, which could yield unique information pertaining to the nature of the relaxation in electron-glasses. Also, excitation studies using sources with different photon energies should help to identify the energy scales relevant to the studied phenomena.

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