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Anomalous field effect in gated Anderson insulators

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Investigation of the field effect in insulating indium oxide films reveals an anomalous feature: The conductance increases for *both* gate-voltage polarities. This feature, as well as the appearance of conductance oscillations, is discussed.

In this paper we report on a low-temperature field effect in gated Anderson insulators. For sufficiently disordered films, the conductance, G, as a function of the gate voltage, V_g, has a positive term which is symmetrical around zero bias. We also observe reproducible conductance oscillations for both gate-voltage polarities. The latter feature was previously reported in several crystalline samples.[1,2] Here we demonstrate that they can be very prominent in amorphous materials as well, a fact that may be useful in understanding their origin.

Our experimental observations were made on both crystalline and amorphous films of indium oxide. Samples were made by thermal evaporation of In_2O_3 onto 100-μm-thick glass substrates as described elsewhere[3] and were 200 Å thick with a typical area of 5×5 mm^2. Two indium contacts (to be referred to as source and drain) were pressed into the sample for two-terminal ac conduction measurements employing current preamplification and lock-in detection. Unless otherwise noted, the source-drain voltages used were of the order of 100 mV rms at 2–10 Hz. Several samples were measured using a four-terminal dc technique with similar results. A copper film evaporated on the back side of the glass substrate was used as a gate. A typical measurement setup is illustrated in the inset of Fig. 1. The bridge circuit was particularly useful for the low resistance samples where the field effect is small. For films with $R_\square < 100$ kΩ, the change of conductance, δG, was essentially proportional to V_g. This linear term should be seen when the relative change in the density of states is small on a scale of the Fermi-level shifting.[4] In terms of $\delta G/G$, we typically measure a linear field effect of 0.1–1% for $V_g = 100$ V in agreement with previous work on mildly disordered indium oxide samples.[5]

At higher resistances, an anomalous feature appears in the field effect as illustrated in Fig. 1. The sample conductance is seen to increase for *both* gate-voltage polarities with a minimum fairly close to $V_g = 0$. The size of this symmetrical component (SC) increases progressively with the sample resistance, and by $R_\square \geq 1$ MΩ it completely overshadows the normal term. The increase of the SC relative magnitude with $R_\square$ is also accompanied by a change of its shape (Figs. 2 and 3). Above a certain resistance, reproducible conductance oscillations clearly establish themselves (Fig. 3).

Figure 4 shows the magnitude of the SC as a function of the sheet resistance. The apparent correlation observed is, we believe, meaningful. However, it should be somewhat qualified: The data in Fig. 4 were all taken in the narrow temperature range 1–4.11 K. At high tempera-

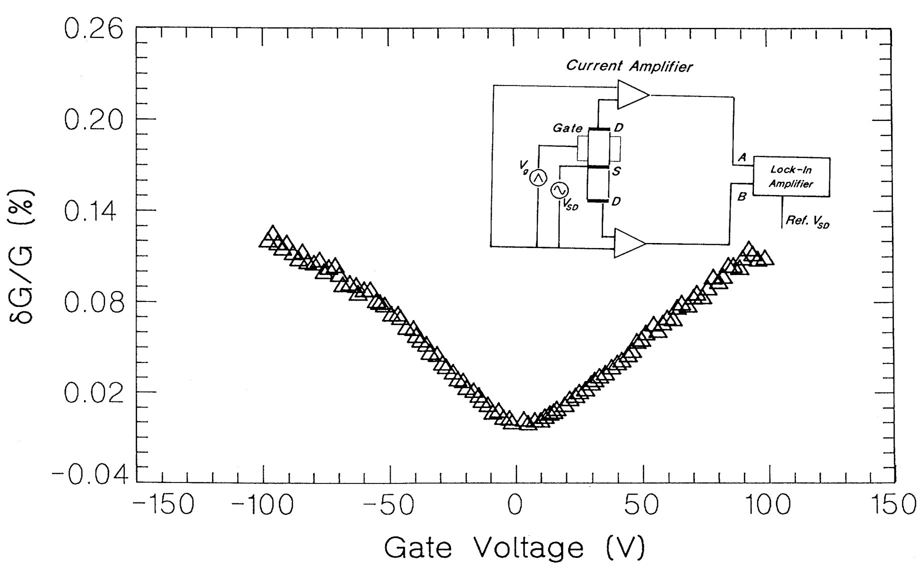

FIG. 1. The anomalous field effect in a 15 M$\Omega/\square$ amorphous indium oxide film at 1.3 K. The inset shows the bridge circuit used in the measurement.

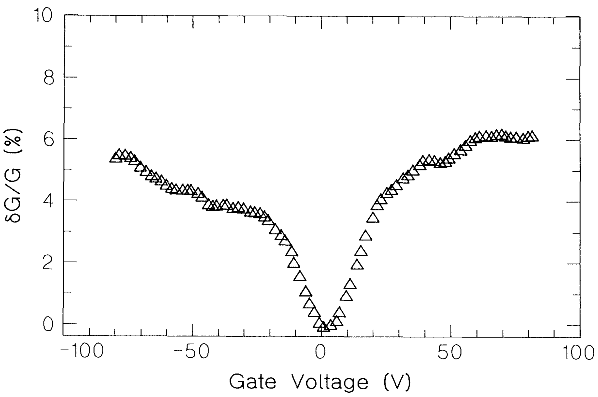

FIG. 2. The field effect for a 50 GΩ/□ amorphous film measured at 1.3 K with a source-drain field of 2 V/cm. Note that the oscillatory structure at high gate voltages is not quite symmetric around $V_g=0$.

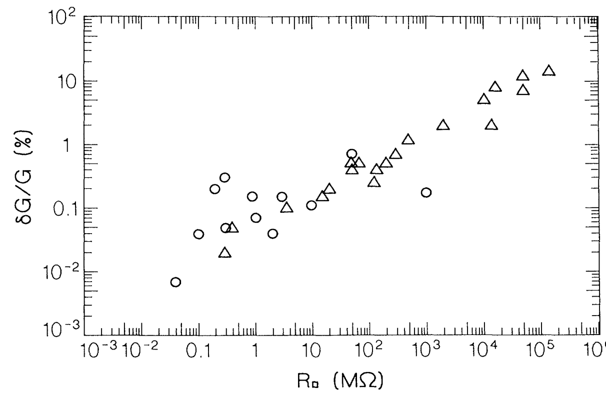

FIG. 4. The relative magnitude of the anomalous field effect vs sheet resistance. $\delta G/G$ is taken to be the average between $\delta G/G_0(V_g=100\text{ V})$ and $\delta G/G_0(V_g=-100\text{ V})$. G_0 is the conductance at $V_g=0$. The circles and triangles refer to crystalline and amorphous samples, respectively.

tures, *regardless* of $R_\square$, the SC does *not* appear. For example, a $\simeq 1$ GΩ/□ amorphous film, measured at 77 K, did not exhibit any SC, while at low temperatures such $R_\square$ typically yield a 1–2% effect (Fig. 4). It is not surprising that the SC is observed only at sufficiently low temperatures, since the gate-voltage scale of the anomaly is equivalent to approximately 10 deg.[6]

The dependence of the SC magnitude on either temperature or source-drain voltage (*provided they are not excessively large*) is, mainly, through their effect on $R_\square$. We also note that within the scatter in the data (Fig. 4), the crystalline and amorphous films are essentially indistinguishable. The relative magnitude of the oscillations in $G(V_g)$ seem to evolve with disorder in a similar way as the SC, except that the oscillations are resolvable at a later stage ($R_\square \gtrsim 100$ MΩ). From the geometrical configuration we estimate that the period or quasiperiod of the oscillations is equivalent to 10^{10} electrons/cm^2 and has this typical order of magnitude within a factor of 5 in all our films regardless of crystallinity, temperature, and $R_\square$.

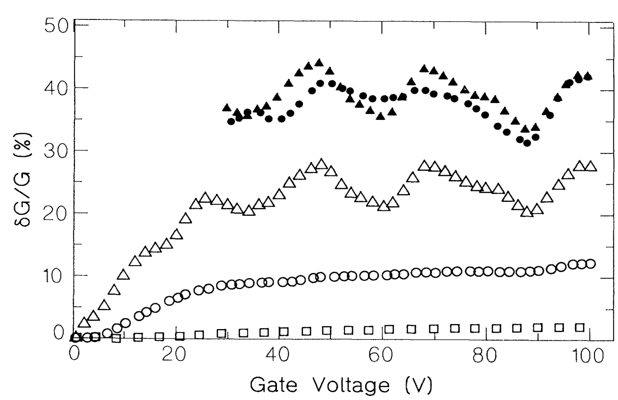

FIG. 3. The field effect of a highly disordered amorphous film measured at 1.3 K for various source-drain voltages. Open triangles: $V_{sd}\leq 0.1$ V, $R_\square=140$ GΩ. Open circles: $V_{sd}=1$ V, $R_\square=50$ GΩ. Open squares: $V_{sd}=10$ V, $R_\square=2$ GΩ. The solid triangles and circles are obtained from the open triangles and circles data sets by subtracting off the "background" $G(V_g)$ and multiplying by 1 and 10, respectively (the data is shifted in the Y axis). This is done just to illustrate the insensitivity of the quasiperiod to the effective electron temperature.

We have carefully considered several experimental artifacts as possible causes for this zero-bias anomaly. The fact that *no* SC is found at 77 K even for high resistance films eliminates many artifacts related to circuit considerations (e.g., preamp nonlinearities). More importantly, the SC is observed both with a two-wire ac technique and by four-probe dc measurements with no discernible difference in magnitude. It is emphasized that the actual increase of G with $|V_g|$ around $V_g=0$ is also observed in the dc technique. This excludes from consideration problems such as field-dependent leakage or voltage-dependent capacitance (note that the gate-sample capacitance appears in parallel with the sample and thus may influence the ac measurement). In an ac measurement such effects might contribute to the SC but they should not be bothersome in the dc technique. It is obvious that, in a dc measurement, changing the gate-voltage polarity should cause the contributions to $\delta G/G$ from such problems to change their sign. In particular, such effects cannot possibly cause a positive δG for both polarities of V_g. For the same reason, one can also exclude the possibility that part of the gate voltage induces an electric-field component along the film, thereby enhancing its conductance.

A typical field of 10^6 V/m, which is used in our experiments, produces a pressure of $\simeq 10$ N/m^2. Such mechanical pressures exist, of course, for *both* gate polarities and thus are a potential candidate for a symmetrical effect (assuming that pressure can affect the conductance). It is, however, difficult to believe that amorphous and crystalline indium oxide films should show similar behavior and it is even more difficult to account for the saturation of the SC at such low pressures. Nevertheless, in order to assess the severity of this physical source of the SC we have subjected a $\simeq 1$ GΩ film to tensile strains and stresses of up to 10^4 N/m^2 and to hydrostatic pressures of up to 10^3 N/m^2. We have also applied strain and hydrostatic pressures simultaneously. No change in the resistance (to an accuracy of 0.5%) was observed in either case. It is, therefore, concluded that the SC does not arise from electromechanical strains or from common measurement problems.

When interpreting field effect measurements it is common to view the conductance change as reflecting the variation in the density of states with energy. We have considered the possibility that the SC represents a density-of-states modulation due to the underlying disorder. One mechanism that should perhaps be considered in this regard is the Coulomb gap. The zero-bias anomaly in the density of states predicted by several authors,[7] may indeed account both for the special role of zero field and for the fact that the SC occurs only in highly disordered samples. However, while the field effect probes the thermodynamic density of states, the Coulomb gap is a nonequilibrium, dynamical phenomenon. Thus, if the SC is related to it, one expects its magnitude to be time dependent.[8] We then expect an explicit dependence of $\delta G/G$ on, say, the scan rate of the gate voltage. Using the data in Fig. 5 one can place a lower bound of $\simeq 10^3$ s at $T \simeq 4$ K on the time scale that must be involved.[9] The existence of such long time scales cannot be ruled out. Actually, evidence for such "glassy" behavior has been observed. Cooling the sample with an applied gate voltage, V_{gc}, causes the minimum in $G(V_g)$ to be centered nearer V_{gc} (instead of at $V_g=0$). This behavior will be discussed in a future paper. Therefore the negative result implied by the data in Fig. 5 is not conclusive in eliminating the Coulomb gap as a possibility. On the other hand, it is not clear whether the oscillations and the dependence of the characteristic width of the SC with the disorder can be explained along these lines. Interestingly, the characteristic width of the SC seems to be of the same size as the quasiperiod of the oscillation, which tempts one to look for a common origin.

This latter feature led us to consider another possible explanation for the SC. Oscillations in $G(V_g)$ have been previously reported by a number of authors in GaAs (Refs. 1 and 10) and Si metal-oxide-semiconductor field-effect transistors.[1] Poole, Pepper, and Myron[2] examined the systematics of such oscillations in several systems including commercially manufactured field-effect transistors. These authors claimed that the oscillations are usually resolvable only below a threshold conductance and most of them had a typical period of $10^{10}-10^{11}$ electrons/cm^2. It is noted that the quasiperiod of the oscillations in the present study and the correlation of their appearance with low G are both in agreement with the observations by Poole, Pepper, and Myron. Recently, large conductance oscillations were reported for mesoscopic, insulating wires of Si, GaAs, and indium oxide.[11] The oscillations were periodic in gate voltage and this periodicity was similar for all these samples (*when the period in the electric field is taken for comparison*). Furthermore, the period of the oscillations was of the same order of magnitude as the quasiperiod observed in the present study.

The qualitative difference between the findings in indium oxide (both for our samples and for the mesoscopic wires) and those reported for the semiconductors is that in indium oxide, oscillations are observable for *negative* as well as positive gate polarities. This, in turn, is probably due to the large disparity in carrier concentration (*Fermi energies*) between the two systems. The Fermi energy in crystalline indium oxide is $\simeq 0.3$ eV and can be as high as a few electron volts in the amorphous films[3] as compared to millivolts in the semiconductors. Although this is only a quantitative difference, it could well be the reason for the fact that the SC is not observable in semiconductors.

If our samples can be viewed as randomly connected ensembles of such mesoscopic structures, it seems possible to explain the quasiperiodic oscillations as resulting from an incomplete averaging process. It is implicitly assumed that the period of oscillation of the individual components is similar (though not necessarily identical). Given the close similarity in the magnitude of the field quasiperiod even in *different* systems, this assumption is quite plausible. This scenario may account for the dependence of the relative size of the oscillations on disorder: Ensemble averaging is believed to be less effective in highly disordered samples due to the highly rarefied current-carrying network and the peculiar statistical properties characterizing their transport.[12] Also, the assumption of independent, mesoscopic constituents is more natural in a strongly localized system.

To account for the appearance of the SC with this line of reasoning, an additional conjecture regarding the uniqueness of zero bias has to be invoked;[13] an example for such an assumption is that $G(V_g=0)$ of an ensemble member is more likely to be near a local minimum. This would bring about a relatively large dip in the conductance of the sample as a whole at zero bias, whereas at higher gate voltages the oscillations would tend to be smeared out by any disparity in the periods of individual ensemble members. Although this conjecture is somewhat speculative, it is not at variance with currently proposed models for the periodic oscillations in mesoscopic systems.

In summary, we have shown the existence of anomalous

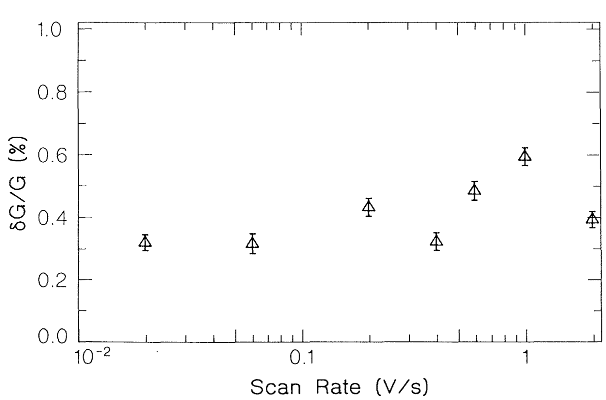

FIG. 5. The dependence of the symmetrical field effect magnitude (calculated as for Fig. 4) on the gate-voltage scan rate. The measurements were taken on a 200 MΩ/□ amorphous sample at 4.11 K. The nominal scan rate for most measurements was 0.2 V/s.

field effects in insulating crystalline and amorphous indium oxide films. The physical origin of these effects is not understood at present. Further progress in this problem must await a better understanding of the origin of periodic oscillations in such systems, which is still an open question.

Note added in proof. Professor M. Pollak has brought to our attention that the glassy behavior associated with the SC may be related to a long-lived excited state of the electron system. The ground state in this picture is alleged to have minimum conductivity. This conjecture is now under investigation.

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[13]The special role of zero bias is at least partially related to the fact that the sample is cooled down with zero gate voltage, as mentioned above.