Photovoltaic effect in a mesoscopic system

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A photovoltaic effect has been observed to occur during exposure of mesoscopic samples of δ-doped GaAs to microwave radiation. The effect stems from the lack of an inversion center in the mesoscopic system.

Al'tshuler and Khmel'nitskiĭ[1] have shown that since the properties of mesoscopic conductors are determined by a specific realization of a random potential, these conductors should exhibit effects which are characteristic of systems which lack an inversion center. Among these effects are the rectification of a low-frequency alternating field, because of a nonohmic current-voltage characteristic,[2] and the generation of a steady-state photocurrent by electromagnetic radiation: a photovoltaic effect.[3] Of these effects, only the nonohmic nature of the current-voltage characteristic has been observed experimentally, in samples with a metallic conductivity[4] and a hopping conductivity.[5]

In the present letter we report the experimental observation of a photovoltaic effect during the application of microwave radiation at a frequency of 6–80 GHz to mesoscopic samples of δ-doped GaAs.

The test samples were strips of δ-doped layers of GaAs, 0.5–2 μm wide, with a distance of 2–3 μm between the potentiometric probes. The strips were fabricated by optical lithography, followed by ion etching. The parameters of the initial δ-doped layers, synthesized by the procedure described in Ref. 6, were (1) an electron density $n_s = 3.5\times 10^{12}$ cm^{-2} and a mobility $\mu = 4200$ cm^2/(V·s) or (2) $n_s = 1.1\times 10^{13}$cm^{-2} and $\mu = 2100$ cm^2/(V·s). Experiments were carried out at temperatures of 1.6–4.2 K in magnetic fields up to 70 kG. Amplitude-modulated microwave radiation at a frequency of 6–8 GHz was applied through a cable directly to the current contacts of the sample. The radiation at 80 GHz was applied to the sample by means of a waveguide. The emf was measured from both the potentiometric contacts and the current contacts on the sample. Figure 1 shows the emf (V) of one of the samples, with parameters of type 2, versus the magnetic field. Shown for comparison is the behavior of the magnetoconductivity $\Delta\sigma(H)/\sigma$. There are aperiodic oscillations in both the magnetoconductivity and the emf. All of the oscillations are reproducible highly accurately. The amplitude of the fluctuations, $\Delta\sigma/\sigma$ is 3×10^{-3}, while the amplitude of the oscillations in the emf is on the order of the signal itself. We also see that the oscillatory emf changes sign several times. Furthermore, we see from the figure that although the maxima and minima of the magnetoconductivity and the emf do coincide somewhat, on the whole there is no overall correlation. We might add that the numbers of oscillations in the magnetoconductivity and the emf are essentially the same, although nearly all of the fluctuations in the emf have an identical amplitude, in contrast with the magnetoconductivity case, where there is a large number of small-amplitude fluctu-

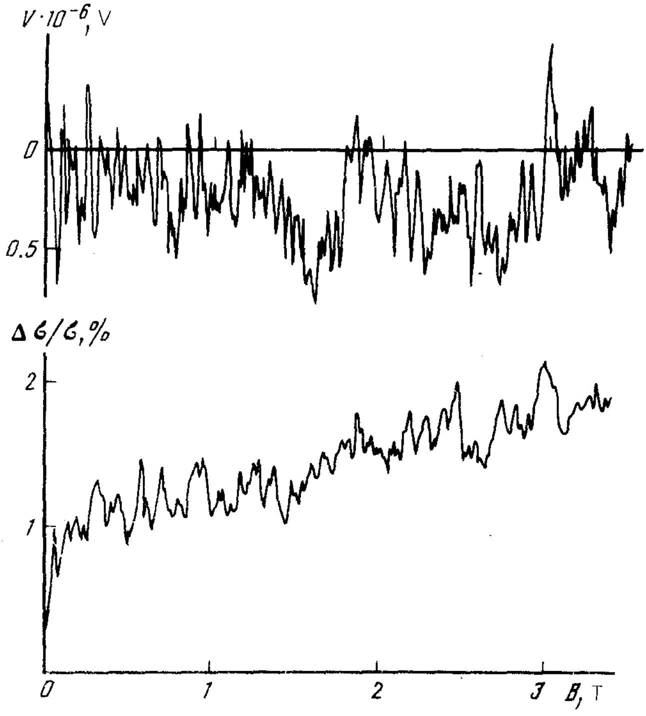

FIG. 1. The emf and the magnetoconductivity versus the magnetic field ($f = 7.4$ GHz, $T = 4.2$ K).

ations. A more accurate examination will require a quantitative analysis of the results, which we intend to carry out in the future.

Since the current probes and the potentiometric probes are equivalent for the cases of steady-state emf's generated in the sample, the emf's measured in the two cases should be completely the same. We might also note that although the resistance measurements were carried out by the four-probe method, the magnetoresistance, like the emf, was symmetric under reversal of the magnetic field, in contrast with the results of Ref. 7. The apparent reason for this symmetry is that in our case the relation $L_\varphi < L$ holds, where L_φ is the phase coherence length, and L is the distance between the potentiometric probes. As was shown in Ref. 8, the antisymmetric part of the magnetoresistance is small in comparison with the symmetric part.

Films of δ-doped GaAs constitute a quasi-two-dimensional electronic system with several filled quantum-size-effect levels.[9] Correspondingly, universal fluctuations of the magnetoresistance are sensitive to only that component of the magnetic field which is directed perpendicular to the layer of two-dimensional electrons. Figure 2a shows that emf fluctuations are also determined exclusively by that component of the magnetic field which is perpendicular to the surface of the sample, and in a magnetic field parallel to the δ layer there are no oscillations in the emf.

Figure 2b shows the emf as a function of the magnetic field for two microwave frequencies, 7.1 and 77 GHz. We see that the emf's for the two frequencies behave in a

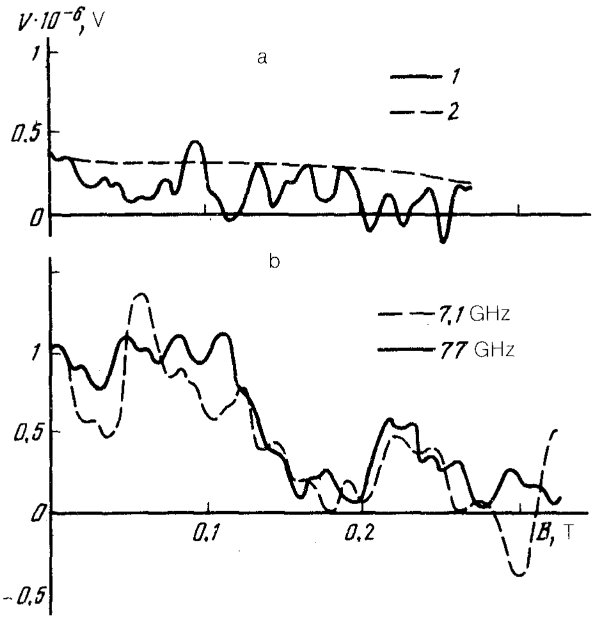

FIG. 2. a: The emf versus the magnetic field. 1—$B \perp$ the surface; 2—$B \parallel$ the surface of the sample. b: The emf versus the magnetic field for two microwave frequencies ($T = 4.2$ K). (The results shown in Figs. 1, 2a, and 2b were measured at different times and at different microwave power levels.)

similar way. Although the maxima do coincide to some extent, there is essentially no overall correlation. However, an unambiguous comparison of the behavior of V at different frequencies, with the goal of establishing a frequency dispersion of the emf, is hindered by the uncertainty regarding the polarization of the radiation leaving the waveguide.

Measurements of the negative magnetoresistance for the macroscopic structures which were studied show that the coherence length L_φ is 0.45 μm at $T = 4.2$, and we have a time $\tau_\varphi = 1.5 \times 10^{-11}$ s. In this case the frequency range selected for these experiments is the best choice for a study of the photovoltaic effect[3] at amplitudes of the microwave field which do not cause a heating.

With increasing microwave power, we observed an increase, approximately linear in the emf, followed by the onset of saturation at an emf $\sim 10\,\mu$V. This saturation may have been caused by a heating of the sample. At high temperatures the theory yields the following estimate of the effect[3]:

$$I \sim \frac{e}{\tau_\varphi} \left(\frac{eEL_\varphi}{\hbar\pi^2\tau_f^{-1}}\right)^2 .$$

With $E = 3$ V/cm we find $V \sim 3.5\,\mu$V, in accordance with the observed values of the emf.

In summary, we have observed a photovoltaic effect in a mesoscopic system for the first time. In contrast with the universal conductivity fluctuations, for which the mesoscopic component is small in comparison with the average conductivity, the effect observed here is determined exclusively by the mesoscopic nature of the system. One can accordingly hope that the photovoltaic effect will prove to be an effective new tool for studying the mesoscopic properties of conductors with small dimensions.

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