Microwave photoconductivity in a mesoscopic system

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(Submitted 10 October 1989; resubmitted 26 December 1989)
Zh. Eksp. Teor. Fiz. **97**, 1317–1320 (April 1990)

The effect of microwave radiation on the conductivity of submicron size GaAs samples is studied. The photoconductivity, which depends on the mesoscopic properties of the electron system, is observed and its frequency dependent correlation properties are investigated.

The properties of mesoscopic conductors depend on the specific realization of their random potential. Therefore, they should exhibit many unusual effects.[1] In particular, asymmetries in the potential give rise to a photovoltaic effect,[2] which has been observed recently.[3] Random potentials remove the symmetry between the electrons above the Fermi level and the holes below, which leads, for instance, to anomalously large thermoelectric coefficients.[4] It has been recently shown[5] that the asymmetry of electrons and holes in mesoscopic systems should give rise to an anomalous photoconductivity which varies nonmonotonically with the frequency of electromagnetic radiation in the microwave region.

We have studied experimentally the effect of ultra-high frequency (UHF) fields on the conductivity of a submicron (mesoscopic) GaAs sample. The observed frequency variation of the photoconductivity allows one to determine the electron correlation energy.

Strips of δ-doped layers of GaAs, 0.5–1 μm wide, with potential contacts $L = 2$–$3\ \mu$m apart were studied. The parameters for the initial layers as well as the method of preparation are given in Ref. 3. Measurements were carried out at temperatures of 1.6–4.2 K in magnetic fields up to 3 T. The photoconductivity was measured by the four-probe method, using an active ac bridge at a frequency of 7 kHz. Amplitude-modulated UHF radiation at a frequency of 120 Hz was applied to the sample. Modulation of the current through the sample and of the UHF field amplitude allows one to measure small signals of the photoconductivity when a photovoltaic effect is present. The draw voltage applied to the potential contacts, V_{pp}, was smaller than kT/e. Microwave radiation at a frequency of 6–8 GHz was fed through a cable directly to the current contacts on the sample. Radiation in the range 30–80 GHz was applied by means of a waveguide with a polarizer at the end.

Figure 1a shows the magnetic field dependence of the photoconductivity in the mesoscopic sample for different microwave radiation frequencies. The photoconductivity is mostly positive; it oscillates aperiodically with respect to the positive background and it changes sign at some values of the magnetic field.

Furthermore, the character of the oscillations changes with the frequency of the applied radiation. Figure 1b shows the photoconductivity for higher UHF power and the variation of the conductance (reciprocal resistance) with the magnetic field when there is no radiation. Clearly, even though the photoconductivity and the conductance behave differently with the magnetic field for small levels of UHF power, they have roughly the same form at high power levels.

We next analyze our results. In a strong electric field at high-frequencies, $eE_\omega L/\hbar\omega \gg 1$, mesoscopic fluctuations of the magnetoconductance are suppressed completely, which leads to strong correlations between the oscillations of the photoconductivity and of the magnetoconductance. We observe these correlations in our experiment. Heating of the electron gas provides an alternative interpretation of this effect. Indeed, not only does the average conductivity of electrons depends on temperature (their mobility increases with increasing temperature in the GaAs δ-layers[6]) but the mesoscopic fluctuations contribute $\Delta G \sim T^{-0.5}$ to the conductance.[1] The temperature dependence of the average conductivity leads to a positive photoconductivity, while mesoscopic fluctuations of the conductance produce photoconductivity oscillations, which mimic the observed conductance behavior.

At low UHF field power, the observed difference between the aperiodic photoconductivity and the conductance oscillations, as well as the frequency variations in photoconductivity (unobserved at high powers), show that there is a nonthermal mesoscopic contribution to the photoconductivity. To estimate this contribution, we calculate, using our experimental data, the following correlation functions:

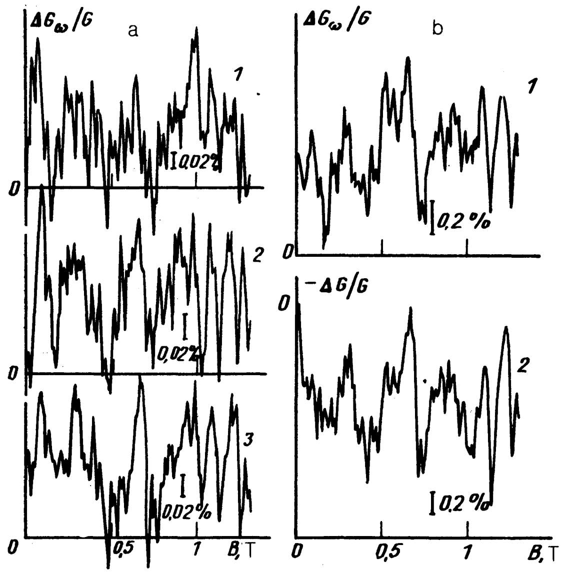

FIG. 1. (a) Variation of the photoconductivity with magnetic field for small UHF radiation power at different frequencies f: 1—6.9 GHz, 2—48 GHz, 3—77 GHz; $T = 1.4$ K. (b) 1—Variation of the photoconductivity with magnetic field for high UHF radiation power [$f = (6.9$–$77)$ GHz] and 2—variation of the conductance with magnetic field without radiation.

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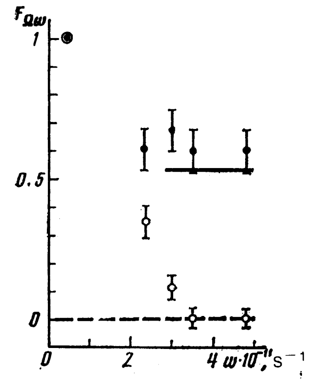

FIG. 2. Correlation functions of the photoconductivity (●) and of the photovoltaic effect (○) for $f = 6.9$ GHz and other frequencies; $T = 1.4$ K, $\Delta B = 0$ T; the dashed line shows the theoretical value of $F_{\Omega\omega}$, from Ref. 5.

$$F_{\Omega\omega} = \langle \delta G_\omega \delta G_\Omega \rangle / (\langle \delta G_\omega^2 \rangle \langle \delta G_\Omega^2 \rangle)^{0,5},$$

$$F_{0\omega} = \langle \delta G_\omega \delta G \rangle / (\langle \delta G_\omega^2 \rangle \langle \delta G^2 \rangle)^{0,5}, \quad (1)$$

where δG_ω are the oscillations of the photoconductivity in a magnetic field B at frequency ω and δG are the magnetoconductance oscillations. Figure 2 shows as a function of magnetic field the photoconductivity correlation function $F_{\Omega\omega}$ for $f = \Omega/2\pi = 6.9$ GHz and for higher frequencies ω. $F_{\Omega\omega}$ first decreases with increasing frequency to a value of ≈ 0.6 and becomes constant further on. We also show, in Fig. 2, the correlation function for the photovoltaic effect in a magnetic field,[3] measured at the same UHF power. The value of the correlation function drops to zero in this case. The value of ω where $F_{\Omega\omega}$ equals one half gives the electron correlation energy, E_c. Note, however, that the number of experimental points is not sufficient for an accurate determination of E. We can only estimate this value as $E_c = (0.1\text{–}0.2)$meV.

We now discuss the observed frequency variations of the photoconductivity and of the photo-emf. It has been shown in Ref. 5 that there are three contributions to the correlation function of the conductance in high-frequency electric fields. These contributions vary differently with frequency and magnetic field. Dynamic suppression of quantum corrections to the conductivity gives the first contribution.[7] It has a monotonic frequency dependence and decreases rapidly with increasing magnetic fields.[8] The second contribution to the photoconductivity is of a mesoscopic nature. It also depends monotonically on frequency, and it shows up as fluctuations of the photoconductivity in the magnetic field. The third contribution is a random function of the energy of excited electrons and of the magnetic field; it is correlated for frequencies $\omega \sim E_c/\hbar$, and is therefore of a mesoscopic nature.

The contribution of dynamic quantum corrections falls off at a field B_c (where B_c is the correlation magnetic field) much smaller than the range of fields studied experimentally. Therefore, only the second and third contributions determine the correlation function of the conductance, shown in Fig. 2, in the presence of microwave radiation. These contributions stem from the effect of the UHF field on electron diffusion and the violation of the electron-hole symmetry in a mesoscopic system.

Theory predicts a value of 0.53 for the ratio of random to monotonic frequency contributions to the conductance correlation function for strong magnetic fields $B > B_c$ (Ref. 5). The experimental data in Fig. 2 yield a value of 0.6 ± 0.07, in agreement with theory.

For small UHF radiation power, some correlation between the photoconductivity and the magnetoconductance is exhibited in Fig. 1. A value of 0.9 is obtained from Eq. (1) for the correlation function $F_{0\omega}$ from the data for high UHF radiation power. This value drops to $F_{0\omega} = 0.35 \pm 0.1$ for small power levels after averaging over all frequencies. It is somewhat smaller than the theoretical estimate of $F_{0\omega}$, which equals[5] $(6/17)^{1/2}$ (≈ 0.6). Heating effects can only make the value of the observed correlation of the photoconductivity and the conductance larger, not smaller. The value $F_{0\omega} < 0.5$ found for weak high-frequency electric fields and the good agreement between the theoretical and the experimental dependence of $F_{\Omega\omega}$ on frequency show indirectly that heating does not affect much the photoconductivity of the mesoscopic sample. We note that, because of the small dimensions of the sample, electron gas heating can only take place in its massive contacts and it is difficult to estimate.

Figure 2 shows that the correlation function for the photo-emf becomes zero in the same frequency range $\Delta\omega$ in which the photoconductivity correlation function becomes constant, in agreement with theoretical predictions.[5] Simultaneous measurements of photo-emf and photoconductivity allow the value of the electron correlation energy to be determined independently. For a one dimensional case, which is seemingly realized in our experiment, theory[5] predicts, for $\omega \gg E_c/\hbar$, the following expression for the ratio of the photoconductivity to the photo-emf signal:

$$(\Delta V_\omega / V_{\Phi\Gamma})^2 = 0.2 (e^2 V_{pp}^2 / \hbar\omega E_c). \quad (2)$$

Using our experimental data for $f = 77$ GHz we obtain, from Eq. (2), a value of (0.09 ± 0.3)meV for E_c. This value is in agreement with $E_c = (0.1\text{–}0.2)$ meV obtained from the frequency variation of the photovoltaic effect and of the photoconductivity.

We note that a completely consistent determination of the correlation energy requires $eL_\phi V_{pp}/L \ll E_c$. In our experiment, a draw voltage, V_{pp}, of 0.1 mV was applied between the potential contacts, and L_φ and L were equal to 0.6 μm and 3 μm, respectively. These values satisfy the above condition. Increments of V_{pp} by factors of three or four lead to changes in the pattern of the photoconductivity fluctuations, while the pattern does not vary for $V_{pp} < 0.1$ mV.

In conclusion, we have found a non-heating mechanism underlying the effect of an oscillating high-frequency field on the conductance of a mesoscopic system for the first time. Analysis of frequency and magnetic field dependences shows that the nature of the observed photoconductivity is mesoscopic. A value of the electron correlation energy was obtained by comparing the amplitudes of the photoconductivity and of the photovoltaic effect, which we had measured previously.

We wish to thank V. I. Fal'ko for making the results of Ref. 5 available to us prior to publication, D.I. Lubyshev and V.P. Migal' for providing films with δ-doped layers, and M.R. Baklanov for carring-out the plasma-chemical etching.

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Translated by Jolanta Stankiewicz