Mesoscopic photovoltaic effect in an electron interferometer

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A photovoltaic effect has been observed in a ring electron interferometer using a AlGaAs/GaAs heterojunction. It is induced at $T \leqslant 4.2$ K by microwave radiation in the form of an emf which oscillates as a function of the magnetic field. The oscillation period is equal to the period of the oscillation in the resistance and corresponds to a change in the magnetic flux across the interferometer by an amount equal to the flux quantum $\Phi_0 = h/e$. The observed effect is shown to be of a mesoscopic nature.

Fal'ko and Khmel'nitskiĭ showed theoretically[1] that the application of microwave radiation to mesoscopic conductors should result in the appearance of a steady-state photocurrent—a photovoltaic effect—because there is no inversion center. A mesoscopic photovoltaic effect was later observed experimentally[2] during the application of a microwave field to microbridges based on δ-doped GaAs. It was found that, in contrast with the universal conductivity fluctuations, for which the mesoscopic contribution is small in comparison with the average conductivity, the microwave voltage is determined entirely by the mesoscopic nature of the system, and it is an effective tool for studying the mesoscopic properties of conductors with small dimensions.[3,4]

In this letter we are reporting the experimental observation of a photovoltaic effect which results from the application of a microwave field to a ring electron interferometer at $T \leqslant 4.2$ K at frequencies from 9 to 145 GHz.

The test samples were prepared by electron lithography and reactive ion etching on the basis of a 2D electron gas at an AlGaAs/GaAs heterojunction. The 2D electron gas had the following properties at $T = 4.2$ K: an electron density $N_s = (7\text{–}9) \times 10^{11}$ cm^{-2}, a mobility $\mu = 10^5$ cm^2/(V · s), and an electron mean free path $l = 1.5$ μm. Figure 1 shows the geometric dimensions of this interferometer. The fabrication technique and the electrical properties of this quasiballistic electron interferometer are described in more detail in Ref. 5.

Experiments were carried out at temperatures of 1.6–4.2 K in magnetic fields up to 7 T. Microwave radiation at a frequency of 9–12 GHz was applied by a cable directly to the ohmic contacts of the interferometer. Radiation with a frequency of 37–145 GHz was applied to the sample by a waveguide. The voltage was measured at the ohmic contacts of the interferometer. The resistance of the interferometer in a zero magnetic field (R_0) was 4–15 kΩ at 4.2 K and varied with the cooling conditions.

Figure 2 shows the voltage (V) and the resistance (R) versus the magnetic field

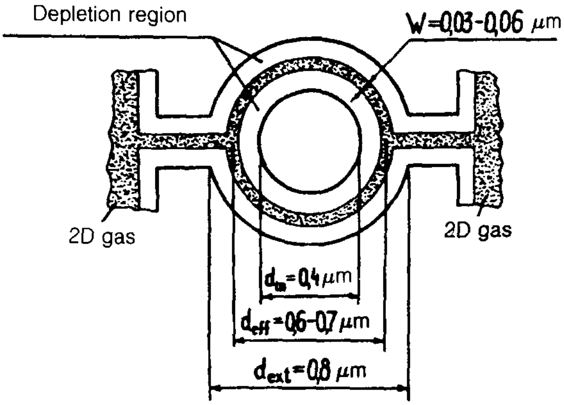

FIG. 1. Schematic diagram and geometric dimensions of the quasiballistic electron interferometer.

for this ring interferometer. There are oscillations in both the magnetoresistance and the voltage; these oscillations are periodic in the magnetic field. The oscillation period corresponds to a change in the magnetic flux linking the interferometer area ($\pi d_{\text{eff}}^2/4$) by an amount equal to the flux quantum $\Phi_0 = h/e$. The amplitude of the periodic oscillations in the magnetoresistance, $\Delta R/R_0$ (R_0 is the resistance in a zero

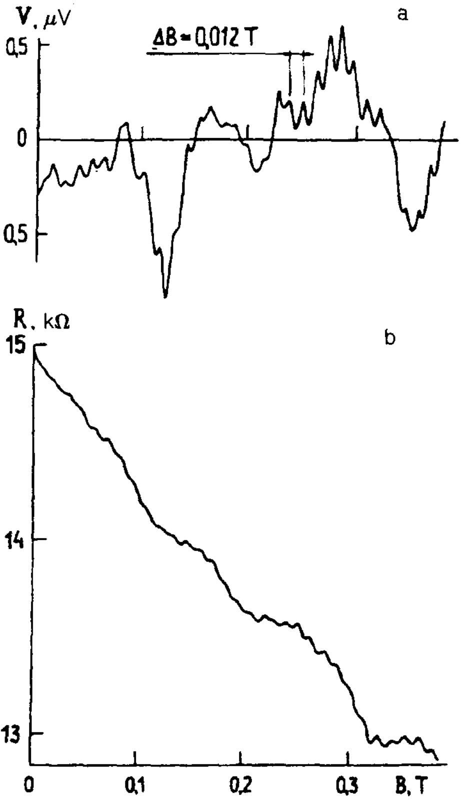

FIG. 2. a—Microwave voltage versus the magnetic field for $f = 9$ GHz, $T = 4.2$ K, sample 1, $R_0 = 15$ kΩ; b—resistance versus the magnetic field for $T = 4.2$ K, sample 1, $R_0 = 15$ kΩ.

magnetic field), at $T=4.2$ K is small, about 5×10^{-3}. The amplitude of the periodic oscillations in the voltage is comparable to the magnitude of the full signal. In addition to the periodic component, there is an aperiodic component in both the voltage and the magnetoresistance. This component is seen most clearly on the plot of the voltage versus the magnetic field.

The reason for the appearance of a mesoscopic voltage is, as was shown in Ref. 1, that nonequilibrium carriers in mesascopic conductors are scattered coherently by a random potential. For this reason, the fluxes of nonequilibrium electrons to the right and left contacts of the microstructure are unequal; i.e., there is a net steady-state photocurrent: a photovoltaic effect.

The degree of asymmetry (α) of the coherent scattering of the nonequilibrium charge carriers with respect to the ohmic contacts in mesoscopic microbridges is a random function of the magnetic field B and of the excitation energy ($\hbar\omega$) of the nonequilibrium electrons.[1] The random $\alpha(B)$ dependence in the quasiballistic interferometer is manifested as an aperiodic component of the microwave voltage (Fig. 2a).

The aperiodic component of the voltage in the ring interferometer is associated with the asymmetry of the coherent scattering of the nonequilibrium carriers with respect to the ohmic contacts in each individual half-ring; i.e., this component is completely analogous to that which has been studied previously.[3,4] The correlation magnetic field of this component is determined by the area of a half-ring. The average period of the oscillation in the aperiodic component along the magnetic-field scale is about ten times the periodic component. This result agrees with the ratio of the area of a circle with the effective diameter of 0.6–0.7 μm and the area of a half-ring, 0.04 μm wide.

The periodic component of the voltage, which is the result of primary interest, has not been observed previously. It arises because the degree of asymmetry α for a ring interferometer must contain not only a random B dependence but also a periodic one. In other words, a direct interference of electron waves propagating in the different half-rings of the interferometer is manifested in this component. The asymmetry arises in this case because the electron waveguides of the interferometer cannot be perfectly identical, because of scattering impurities at random positions in them. As a result, a steady-state current of nonequilibrium carriers arises with a period corresponding to a change in the magnetic flux by a flux quantum $\Phi_0=h/e$.

As was mentioned above, the degree of asymmetry of the coherent scattering of the nonequilibrium carriers in rectangular mesoscopic conductors is a random function of the electron excitation energy $\hbar\omega$ ($\omega=2\pi f$, where f is the frequency of the microwave radiation).[1] As a result, the photovoltaic effect has a frequency dependence, and one can experimentally determine the correlation energy E_c, which is an important characteristic of a mesoscopic system.[3,4] In a ring interferometer, α should be not only a random function of the frequency but also a periodic function. The periodic function results from a direct interference of the electron waves propagating along different half-rings of the interferometer.

Figure 3 shows experimental results on the voltage versus the magnetic field for

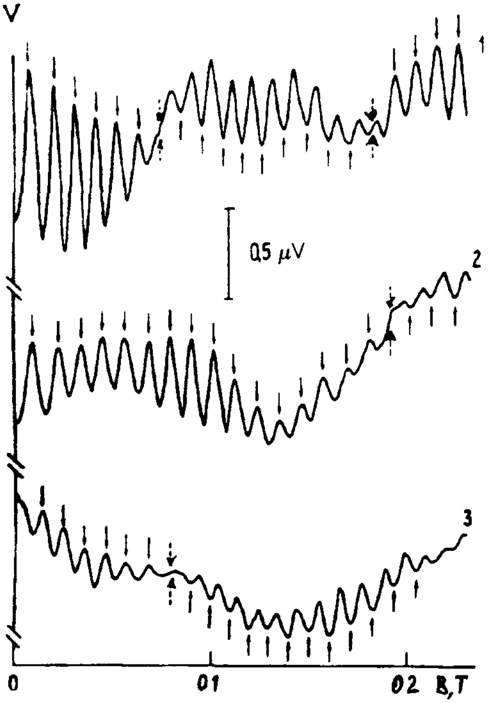

FIG. 3. Microwave voltage versus the magnetic field for various frequencies. 1) $f=9$ GHz; 2) 38; 3) 78 GHz. ($T=4.2$ K, sample 2, $R_0=10$ kΩ).

various microwave frequencies. As the frequency is varied, there is a phase shift of the periodic oscillations in the voltage, and there is a change in the aperiodic component. The existence of two components of the degree of asymmetry—periodic and random—has the consequence that the plot of the voltage versus the magnetic field has points at which the phase of the periodic oscillations is disrupted (as shown by the dashed arrows in Fig. 3). At these points, the oscillation phase changes by π. As the frequency is varied, the positions of these phase-disruption points along the magnetic field scale change. The phase shift of the periodic oscillations in the voltage as the frequency is varied, as a result of the phase disruption points, may differ by π in different regions of the magnetic field. The amplitude of the voltage oscillations also varies with the frequency.

In summary, a mesoscopic photovoltaic effect has been observed experimentally in an electron interferometer. This effect arises from a periodic component of the degree of asymmetry of the coherent scattering of nonequilibrium charge carriers with respect to the ohmic contacts. The photovoltaic effect results from the application of a microwave field with a frequency between 9 and 145 GHz. This effect can be utilized to evaluate the quality of an interferometer at $T=4.2$ K, at which the Aharonov–Bohm oscillations of the conductivity are small. A detailed analysis of the experimental data will require deriving a theory for the photovoltaic effect in an electron interferometer.

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