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Microwave Response of a Ballistic Quantum Dot

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The microwave response (photovoltage and photoconductance) of a lateral ballistic quantum dot made of a high-mobility two-dimensional electron gas in an AlGaAs/GaAs heterojunction has been studied experimentally in the frequency range of 110–170 GHz. It has been found that the asymmetry of the photovoltage with respect to the sign of the magnetic field has mesoscopic character and depends on both the magnetic field and the microwave power. This indicates the violation of the Onsager reciprocity relations regarding the electron–electron interactions in the mesoscopic photovoltaic effect. A strong increase in the conductance of the quantum dot induced by the microwave radiation and unrelated to heating, as well as the microwave-induced magneto-oscillations, has been discovered.

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The microwave response of lateral quantum dots based on a high-mobility two-dimensional electron gas has been a subject of quite intensive investigations in the past 10–15 years. However, the great majority of works in this field deal with single-electron quantum dots [1–3], although studying ballistic quantum dots with a large number of electrons is of undoubted interest [4, 5]. In particular, exactly these quantum dots exhibit violation of the Onsager reciprocity relation in nonlinear transport [4] and suppression of the photovoltaic effect by the magnetic field [5]. In addition, there are interesting theoretical predictions on the possibility of multiphoton excitation of such dots [6].

In this work, we study the microwave response (photovoltage and photoconductance) of a 1 μm^2 open ballistic quantum dot (QD) containing about 10^3 electrons. The quantum dots were fabricated by electron lithography on the basis of an AlGaAs/GaAs heterojunction containing a high-mobility two-dimensional electron gas with a density of (3–4) × 10^{11} cm^{-2} and a mobility of (4–5) × 10^5 cm^2/V s. The respective mean free path of about 4–5 μm was much longer than the quantum dot size. The distance from the structure surface to the two-dimensional electron gas was 105 nm. The samples were Hall bars with a narrow metallic gate sputtered on the central part of each bar. A stadium-like or circular orifice was formed in the gate by electron lithography. The scanning electron microscopy image of the central part of the sample with the stadium-like orifice is shown in Fig. 1a. A quantum dot connected to two-dimensional Fermi seas through the potential barriers is formed in this region by applying a negative bias voltage to the gate. The barrier height can be adjusted by the bias voltage. It should be emphasized that the input and output regions of the described quantum dot are also covered by the gate, in contrast to the standard split-gate design. This technique was chosen to reduce the relative influence of microwave radiation on the potential barriers separating the dot from the Fermi seas. Figure 1b presents the numerical results on the electrostatics of the quantum dot in the Tomas–Fermi approximation, in which only one mode can pass through the contacts to the dot. In this case, the calculated effective area of the dot is approximately 0.7 μm^2 and the dot contains about 2.9 × 10^3 electrons. In this work, we measured the photovoltage V_{ph} and conductance G at temperatures of 1.5–4.2 K in magnetic fields up to 1 T under the action of microwave radiation in the frequency range from 110 to 170 GHz. The dependence of the conductance of the quantum dot on the gate voltage in the absence of microwave radiation is shown in Fig. 1c. As is seen, the QD is in the closed state at the gate voltages below –0.7 V. The open state, in which the conductance is comparable to or more than e^2/h, appears at $V_{\mathrm{g}} > -0.66$ V. Despite the ballistic character of transport, the dependence $G(V_{\mathrm{g}})$ is monotonic. It does not exhibit any plateaus, which would indicate conductance quantization. This can be caused by a large size of the quantum dot and by the fact that, according to the calculations (see Fig. 1b), the quantum wires at the input and output of the quantum dot are extraordinarily short (about 20 nm) owing to the absence of the gate splitting and thereby the

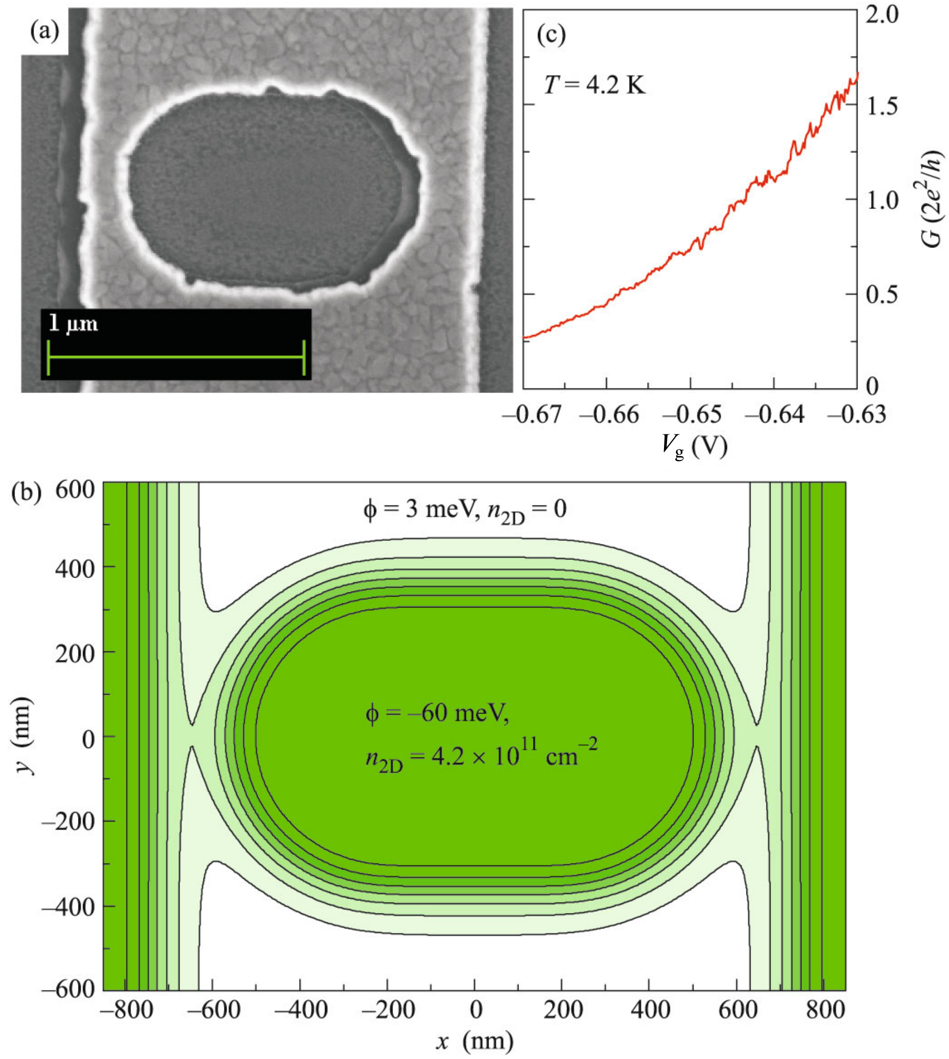

Fig. 1. (Color online) (a) Scanning electron microscopy image of the quantum dot. (b) Distribution of the electrostatic potential at the GaAs/AlGaAs interface inside the dot calculated in the Tomas–Fermi approximation. (c) Conductance G of the quantum dot versus the gate voltage at $T = 4.2$ K.

potential forming the wires is not quite adiabatic. As was shown in [7], this can lead to complete suppression of conductance quantization even at zero temperature. It is noteworthy that the circular quantum dot was also studied in this experiment. Its behavior did not exhibit any qualitative difference from that of the elliptic quantum dot described above.

We first discuss the results of the experiments on the mesoscopic photovoltaic effect. Figure 2a shows a typical magnetic-field dependence of the photovoltage of the quantum dot at a microwave frequency of 169.45 GHz. It exhibits three specific features: (i) the photovoltage decreases drastically (by more than an order of magnitude) in weak magnetic fields (below 0.3 T); (ii) in stronger fields, an oscillating dependence on the magnetic field appears; (iii) the magnetic-field dependence of the photovoltage is essentially asymmetric ($V_{ph}(B) \neq V_{ph}(-B)$), although it was measured in the two-terminal circuit. Below, we discuss all these three features. First, a drastic decrease in the photovoltage of the ballistic quantum dot in the magnetic field was observed in [5] at lower frequencies (10–40 GHz). It was attributed to the magnetic-field suppression of the asymmetry of electron scattering originating from unequal potentials at the input and output of the quantum dot, which can appear owing to both the action of a random potential of individual impurities and fabrication imperfectness of the quantum dot. The oscillating photovoltage is most probably associated already with the fluctuations of the height and shape of the potentials themselves, which appear owing to the fluctuation potential of random impurities. This is indicated by a high value (0.3–0.5 T) of the correlation magnetic field corresponding to the characteristic size of about 100 nm, which is almost an order of magnitude less than the size of the quantum

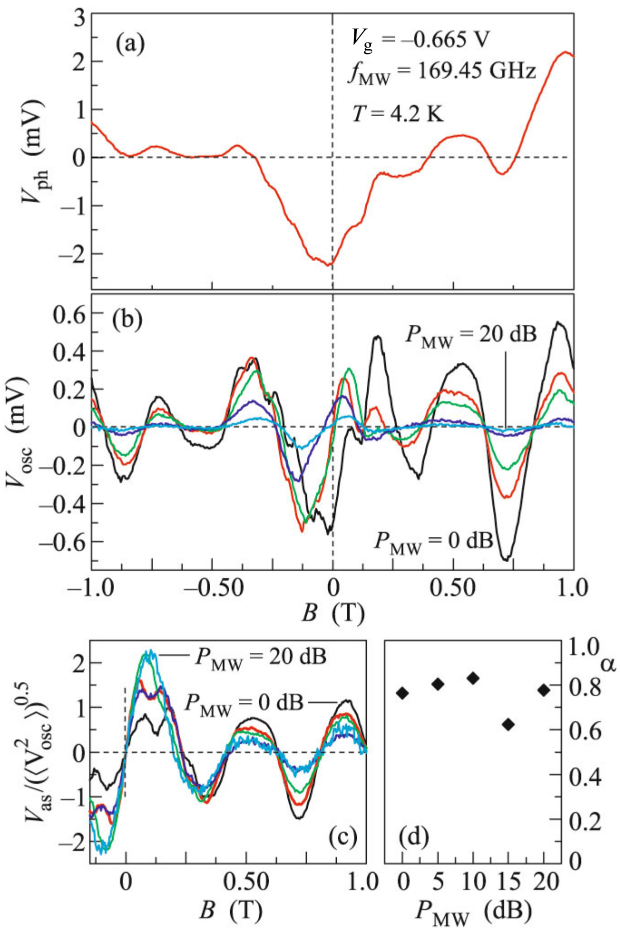

Fig. 2. (Color online) (a) Magnetic-field dependence of the photovoltage V_{ph} at an incident radiation frequency of 169.45 GHz, the gate voltage $V_g = -0.665$ V, and the temperature $T = 4.2$ K. (b) Fluctuating part V_{osc} of the photovoltage under the same conditions at a microwave power attenuation of 0 to 20 dB with a step of 5 dB; (c) the antisymmetric (with respect to the direction of the magnetic field) component of the fluctuating part V_{as} of the photovoltage normalized to the rms oscillation amplitude $\sqrt{\langle V_{osc}^2 \rangle}$; (d) the photovoltage asymmetry $\alpha = \sqrt{\langle V_{as}^2 \rangle} / \sqrt{\langle V_{osc}^2 \rangle}$ versus the microwave power P_{MW}.

dot. The asymmetry of the photovoltage with respect to a sign change of the magnetic field can be caused by its nonequilibrium nature. It is noteworthy that the symmetry breaking of the photovoltaic effect with respect to a sign change of the magnetic field (the violation of the Onsager reciprocity relation) was first observed in [8]. However, only the very fact of symmetry breaking was reported without its comprehensive investigation (in particular, without the investigation of the power dependence). As was shown almost a decade later [9–12], the violation of the Onsager reciprocity relation can appear in mesoscopic effects exactly under nonequilibrium conditions owing to the

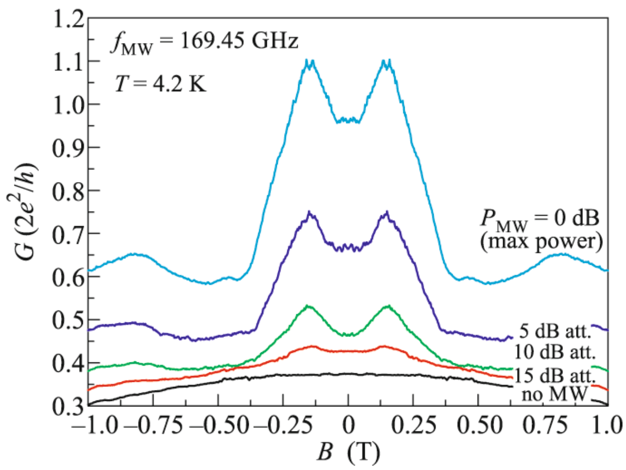

Fig. 3. (Color online) Magnetic-field dependence of the conductance of the ballistic quantum dot at different microwave powers ($V_g = -0.67$ V).

electron–electron interactions. Further experiments on the measurement of the transport response under the conditions of weak [4, 13, 14] and strong [15, 16] deviation from equilibrium confirmed the theoretical conclusions. Thus, the Onsager relation should break down in the mesoscopic photovoltaic effect owing to its nonequilibrium nature as such. The magnetic-field dependence of the fluctuating part V_{osc} of the photovoltage is shown in Fig. 2b for several values of the microwave power. As is clearly seen, the asymmetry of the signal with respect to the sign of the magnetic field and the amplitude of the fluctuating photovoltage increase with the power. The magnetic-field dependence of the asymmetric fluctuating component $V_{as}(B) = [V_{osc}(B) - V_{osc}(-B)]/\sqrt{\langle V_{osc}^2 \rangle}$ of the photovoltage normalized to the magnitude of the photovoltage fluctuations is shown in Fig. 2c for the same values of the power as in Fig. 2b. The mesoscopic character of the asymmetric part can be clearly traced with an increase in power: this part decreases with an increase in power in weak fields and increases in stronger fields. Thereby, the magnitude of the asymmetric part is comparable with the total signal and exhibits a weak nonmonotonic power dependence (Fig. 2d). Thus, the violation of the Onsager relation is pronounced even at the lowest powers used in this experiment. This is not a surprise, since the photovoltaic effect, as was mentioned above, is a fundamentally nonequilibrium phenomenon.

We now discuss the behavior of the conductance of our quantum dot under the action of microwave radiation. Figure 3 shows the magnetic-field dependence of the conductance at different microwave powers and the gate voltage $V_g = -0.67$ V, when the conductance of the quantum dot is $0.37 \times (2e^2/h)$, i.e., corresponding to a half-closed quantum dot. In the absence of the radiation, the quantum dot exhibits a small positive magnetoresistance indicating partial reflection of the edge current state that appears in the magnetic field. Applying the microwave radiation leads to two effects. First, the conductance of the quantum dot in zero field increases, reaching approximately $2e^2/h$ at the maximum power, which already corresponds to the open dot. Second, most interestingly, the radiation induces oscillating behavior of the conductance.

We start the discussion of the above results with the behavior of the conductance in zero magnetic field. Figure 3 clearly shows that the microwave radiation leads to a strong (by a factor of three) increase in the conductance, actually rendering the quantum dot from a half-closed to an open state. Such a strong effect cannot be explained by heating, since simultaneous measurements of Shubnikov–de Haas oscillations in the macroscopic part of the sample indicate a sample overheating by no more than 1–2 K, whereas the conductance tripling requires heating to liquid-nitrogen temperature. A possible mechanism of such a strong increase in the conductance of the quantum dot under the action of the microwave field could be its multiphoton excitation predicted in [6]. However, an unambiguous explanation needs further experiments. The appearance of the microwave-induced oscillating magnetic-field dependence $G(B)$ of the conductance of the quantum dot resembles another phenomenon, microwave-induced resistance oscillations of a high-mobility two-dimensional electron gas [17]. However, there are principal differences between the observed oscillations and microwave-induced resistance oscillations. First, the former ones are irregular. Second, they do not correspond to any harmonics of the cyclotron resonance and their characteristic magnetic-field period is an order of magnitude greater than the period of microwave-induced resistance oscillations. Thus, the finite motion of electrons is crucial for the existence of the oscillations observed in this work and their nature is hardly related to microwave-induced resistance oscillations. A more realistic assumption seems to be the relation of the observed oscillations to the harmonics of magnetoplasma resonances emerging inside the quantum dot. However, the estimate of the frequency of the magnetoplasma mode yields 700 GHz for a size of 1 μm, which is too high to speak of the harmonics at a frequency of 169 GHz. Clarification of the nature of the discovered oscillations requires further experiments.

Thus, investigation of the microwave response of a ballistic quantum dot carried out in this work indicates that the photovoltage and photoconductance of the quantum dot exhibit a number of new properties, further investigation of which is of undoubted interest.

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