Nonlinear effects in a two-dimensional electron gas with a periodic lattice of scatterers

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The magnetoresistance of two-dimensional (2D) electrons in a periodic lattice of antidots is found to be substantially influenced by an applied electric field. The non-Ohmic behavior of the resistance in the region of commensurability oscillations originates from the electric-field-induced breakdown of the trajectories skipping along the lattice arrays. In the region of magnetic fields where the cyclotron diameter is less than the distance between antidots the breakdown of the orbits skipping around antidots is responsible for the nonlinear behavior of the magnetoresistance. © *1997 American Institute of Physics.*
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The transport of a 2D electron gas in a periodic lattice of antidots has been actively investigated in the last few years. One of the most interesting features of this system is the commensurability oscillations of the magnetoresistance, which have been observed and studied in a number of works.[1–4] In Ref. 2 a ''pinball'' model was proposed, which explained these oscillations as being due to the existence of electron cyclotron orbits which do not collide with antidots at certain magnetic fields. It was later shown[4,5] that this model cannot explain all of the features of the magnetoresistance. In Ref. 3 the diffusion coefficient in a magnetic field was calculated by means of numerical simulations of chaotic dynamics of electron in the lattice of antidots. These calculations were able to account for all the features of the commensurability oscillations of the magnetoresistance. Moreover, it was shown in Ref. 3 that the cause of these oscillations is the appearance of electron trajectories which skip along the lattice arrays. In addition, the model of dynamical chaos predicts some other interesting effects—for example, non-Ohmic behavior of magnetoresistance. In the present work the influence of high electric fields on the electron transport in a periodic lattice of antidots is investigated.

The test samples were Hall bars based on the 2D electron gas in a GaAs/AlGaAs heterojunction ($\mu = 2\cdot 10^5$ cm^2/V$\cdot$s, $n_s = 4.5\cdot 10^{11}$ cm^{-2}). The distance between potential probes was 500 μm, and the width of the device was 200 μm. The part of the sample between the potential probes was covered by a lattice of antidots created by electron beam lithography and reactive ion etching. Samples with different lattice periods, $d = 0.6$, 0.7, 0.8, 0.9 and 1.3 μm, were investigated. The antidot diameter was about $2a = 0.15$–0.2 μm. The magnetoresistance was measured by the four-terminal method using an ac bridge operating at 70–700 Hz in magnetic fields up to 0.8 T at temperatures 1.3–4.2 K. In order to measure nonlinear effects a dc electric field E up to 7 V/cm was

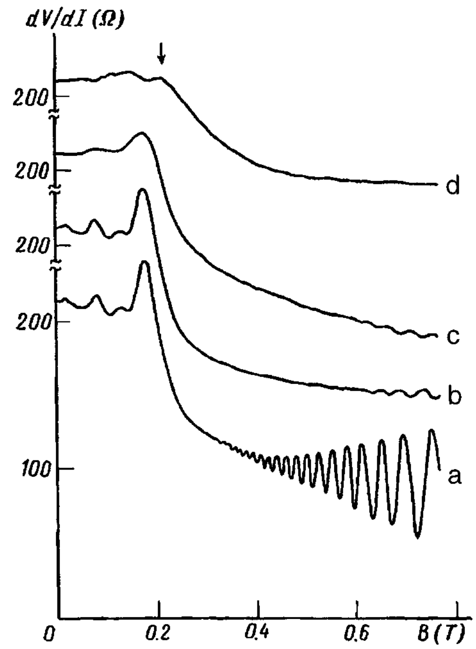

FIG. 1. The magnetoresistance of the sample with $d = 1.3\ \mu$m as a function of magnetic field for different values of applied dc electric field E and lattice temperature T_L: a—$T_L = 1.3$ K, $E = 0$ V/cm; b—$T_L = 4.2$ K, $E = 0$ V/cm; c—$T_L = 1.3$ K, $E = 0.76$ V/cm; d—$T_L = 1.3$ K, $E = 2.4$ V/cm.

applied. The amplitude of the ac electric field on which the signal was measured was less than 0.03 V/cm. Thus, the differential magnetoresistance of the samples was measured experimentally as a function of applied electric field E.

The magnetoresistance traces for the sample with the lattice period $d = 1.3\ \mu$m at different lattice temperatures and applied electric fields are shown in Fig. 1. Comparison of curves *a* and *b* in Fig. 1 shows that at low values of E the amplitude of the Shubnikov–de Haas (SdH) oscillations decreases with temperature, while the amplitude of the commensurability oscillations remains unchanged. This result is consistent with Ref. 2, where it was shown that the commensurability oscillations do not depend on temperature up to 50 K. As the applied electric field is increased to 0.8 V/cm, the amplitude of the SdH oscillations falls to a value corresponding to a temperature of 4.2 K, and the amplitude of the commensurability oscillations falls by a factor of two (curve c). In a stronger applied electric field the commensurability oscillations disappear, and in the region of magnetic fields where $2R_c < d$ the resistance increases (curve d in Fig. 1), and an additional small maximum (marked by an arrow on the curve) appears, which was not present at lower electric fields.

It should be noted that an applied electric field increases the electron temperature T_e above the lattice temperature T_L (the overheating of the lattice is negligible). The electron temperature can be determined from the SdH oscillations, and for the curve (c) in Fig. 1 it is about $T_e = 4.2$ K, as is seen from a comparison of the SdH oscillations.

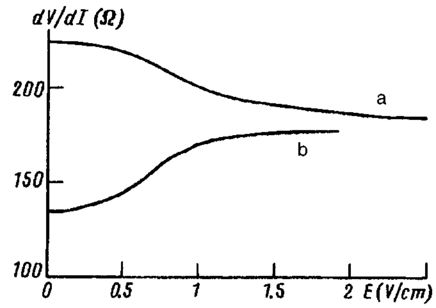

FIG. 2. The resistance of the sample with $d=1.3\ \mu$m as a function of applied electric field E for two different values of the magnetic field B: a—$B=0.17$ T ($2R_c=d$)—commensurability maximum; b—$B=0.27$ T ($2R_c<d-2a$)—corresponds to rosette-like orbits.

However the commensurability oscillations on curve c in Fig. 1 are strongly suppressed in comparison with curve b. This leads to the conclusion that the suppression of commensurability oscillations is not due to heating effects.

The sample resistance as a function of E is presented in Fig. 2 for two different values of the magnetic field. One can see that for magnetic fields satisfying the commensurability condition $2R_c=d$ (curve a) the resistance decreases with E, whereas for stronger magnetic fields it increases with E (curve b). It is also seen that at low and high electric field both curves reach saturation. The same behavior was observed for all of the samples tested. From the dependence of the magnetoresistance on E we determine the electric field $E_{1/2}$ at which the commensurability oscillations are suppressed to half their magnitude. The values of $E_{1/2}$ for the magnetoresistance maximum at $2R_c=d$ are shown in Fig. 3a for the samples with different lattice periods. One can see that $E_{1/2}$ falls off with increasing d roughly according to $E_{1/2}\propto d^{-2}$.

As was mentioned above, there are two models explaining the magnetoresistance maxima in Fig. 1. One of them is based on the presence of ''running trajectories'' that skip along the lattice arrays and which are responsible for the maximum in the diffusion coefficient and, consequently, in the resistance (for the magnetic fields under consideration we have $\sigma_{xy}>\sigma_{xx}$, and the maximum in σ_{xx} therefore corresponds to a maximum in ρ_{xx}). The other explanation involves pinned orbits which do not collide with antidots. It is important that the running trajectories are substantially more sensitive to the initial conditions and to possible distortion of the electron orbit. An applied electric field leads to drift of the cyclotron orbit. For the running trajectories a relatively small drift is sufficient to shift them off the region of stability and therefore break the stable running motion. The critical drift distance l_d during the time between two successive collisions with antidots is in any case considerably smaller than the antidot radius a. Precise estimation of the drift distance l_d necessary for breaking the running trajectories and of the dependence of l_d on the lattice period d requires more-detailed theoretical study of the region of stability of the running trajectories. On the other hand, in order to break the pinned orbit with $2R_c=d$ (corresponding to the main commensurability maximum) the

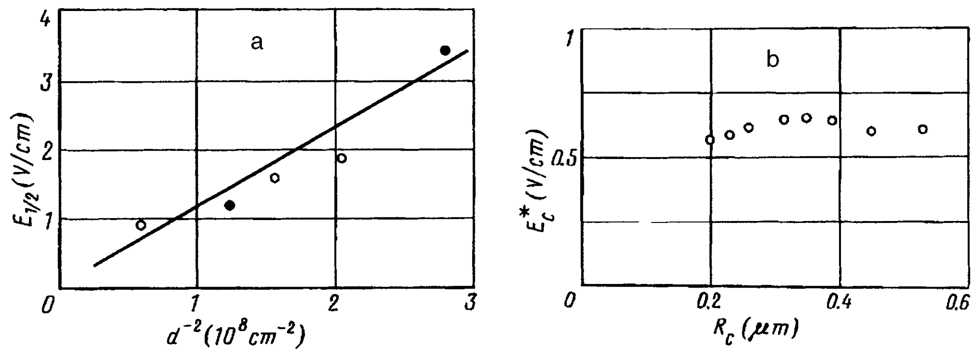

FIG. 3. a: The electric field $E_{1/2}$ resulting in the suppression of the main commensurability oscillation (in a magnetic field satisfying the condition $2R_c = d$) to half its value, measured for the samples with different d as a function of d^{-2}. The solid line is drawn as a guide to the eye. b: The experimental dependence of the critical field E_c^* corresponding to breakdown of the trajectories skipping around antidots on the cyclotron radius R_c for the sample with lattice period $d = 1.3$ μm.

average drift over the time $\tau \sim 2\pi/\omega_c$ ($\omega_c = eH/mc$) should be of the order $l_d \sim d/2 - a$.

One can estimate l_d from the experimentally measured value of the critical field $E_{1/2}$: $l_d = \pi v_d/\omega_c$ ($v_d = cE_{1/2}/H$ is the drift velocity). At a lattice period $d = 1.3$ μm, l_d is 0.003 μm. This value is significantly smaller than the radius of an antidot. Therefore, taking into account the above discussion, one can conclude that the model based on the running trajectories more likely explains the main commensurability maximum at $2R_c \approx d$, and the breaking of these trajectories by an applied electric field leads to the experimentally observed suppression of the commensurability oscillations.

At higher magnetic field when $2R_c < d - 2a$ the magnetoresistance also exhibits nonlinear dependence on the electric field. This dependence has the opposite sign from that in the region of commensurability oscillations described above. This behavior of the magnetoresistance can be explained on the assumption that in this region of magnetic fields the electrons move on rosette-like orbits skipping around antidots. These electrons are localized and do not contribute to the conductivity. But a high electric field (above a certain critical value E_c^*) results in breakdown of the localized motion due to the drift of the cyclotron orbit by analogy with the trajectories that skip along the arrays. It leads to an increase in the conductivity and resistance of the samples and thus affects the experimental dependence of the magnetoresistance on the electric field (Fig. 1).

The experimental dependence of E_c^* on R_c is shown in Fig. 3b. One can see that the critical field E_c^* does not depend on the cyclotron radius. Theoretical support for this fact as well as the numerical estimation of E_c^* requires further theoretical consideration.

It should be noted that the electron orbits corresponding to the condition $2R_c = d - 2a$ show a threshold behavior for the applied electric field. For higher B a delocalization of the electrons by the electric field is observed, but for lower B the electron trajectories become diffusive. Thus a new maximum in the resistance at high electric fields is observed, as indicated above (Fig. 1). The corresponding value of the antidot radius a is consistent with the measurement of a by other methods.[5]

Thus in the present work the magnetoresistance of 2D periodic lattices of antidots with a wide variety of periods has been found to exhibit nonlinear behavior in the applied electric field. Analysis of the results within the framework of dynamical chaos theory shows that the model of runaway electron trajectories can explain the suppression of the main commensurability maximum by the applied electric field for all of the samples tested. In higher magnetic fields the nonlinear effects are connected with breaking of the localized rosette motion. More-detailed comparison of some of our findings (such as the values of the critical electric fields for breaking of the regular motion and their dependence on the lattice period) with the theory requires further theoretical study of the region of stability of the runaway and rosette-like orbits.

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