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NONLINEAR EFFECTS IN A TWO-DIMENSIONAL ELECTRON GAS WITH PERIODIC LATTICE OF SCATTERERS

G.M.Gusev, Z.D.Kvon, A.G.Pogosov, M.M.Voronin

Institute of Semiconductor Physics
630090 Novosibirsk, Russia

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The magnetoresistance of two-dimensional (2D) electrons in the periodic lattice of antidots was found to be essentially influenced by an applied electric field. The nonohmic behavior of the resistance in the region of commensurability oscillations originates from the electric field induced break-down 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 break-down of the orbits skipping around antidots is responsible for the nonlinear behavior of magnetoresistance.

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The transport of 2D electron gas in the periodic lattice of antidots is actively investigated in the last few years. One of the most interesting feature of this system is the commesurability magnetoresistance oscillations observed and studied in a set of works [1–4]. In [2] the "pinball" model has been proposed to explain these oscillations by the existance of electron cyclotron orbits not colliding with antidots at certain magnetic fields. Then in [4,5] it was shown that that this model can't explain all of the magnetoresistance features. In [3] the diffusion coefficient in magnetic field has been calculated by means of numerical simulations of chaotic dynamics of electron in the lattice of antidots. These calculations permitted to describe all features of commensurability magnetoresistance oscillations. Moreover as it was shown in [3] the reason of these oscillations is the appearance of electron trajectories skipping along the lattice arrays. Besides, the model of the dynamic chaos predicts some other interesting effects — for example, the nonohmic behavior of magnetoresistance. In the present work the influence of strong electric field on the electron transport in the periodic lattice of antidots is investigated.

The test samples were the Hall bars, fabricated on the basis of a 2D electron gas in GaAs/AlGaAs heterojunction ($\mu = 2\cdot10^5 cm^2/V$ s, $n_s = 4.5\cdot10^{11} cm^{-2}$). The distance between potential probes was 500 μm, and the width of the device — 200 μm. The lattice of antidots, created by electron beam lithography and reactive ion etching, covered the part of the sample between potential probes. The 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 the 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 applied. The amplitude of *ac* electric field on which the signal was measured was less than 0.03 V/cm. Thus, the differential magnetoresistance of the samples was experimentally measured 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 the curves a and b in the figure shows that at low values of E the amplitude of Shubnikov-de Haas (SdH) oscillations decreases with temperature, while amplitude of the commensurability oscillations remains unchanged. This result is consistent with the work [2], where it was shown that the commensurability oscillations do not depend on temperature up to 50 K. With the increase of applied electric field to 0.8 V/cm the amplitude of SdH oscillations falls down to the value, corresponding to the temperature of 4.2 K, and the amplitude of commensurability oscillations becomes two times smaller (curve c). For 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 on Fig. 1) and an additional small maximum (marked by an arrow in the figure) appears, which was not present at lower electric field.

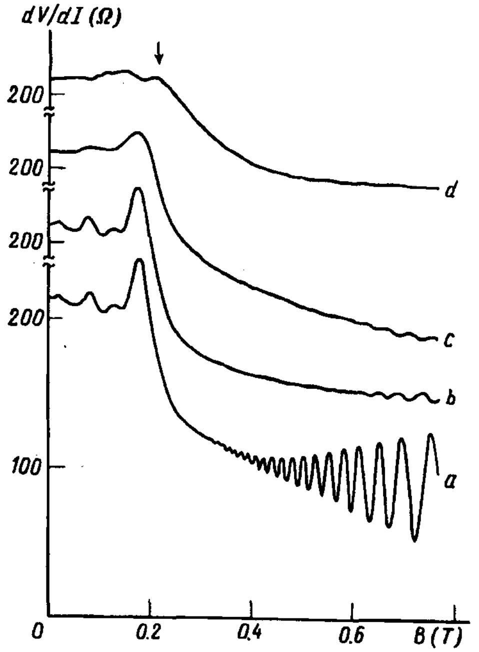

Fig. 1. The magnetoresistance of the sample with $d = 1.3\ \mu m$ as a function of magnetic field for different values of applied dc electric field E and lattice temperature T_L: a - $T_L = 1.3$ K, $E = 0$ V/cm; b - $T_L = 4.2$ K, $E = 0$ V/cm; c - $T_L = 1.3$ K, $E = 0.76$ V/cm; d - $T_L = 1.3$ K, $E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

It should be noted that applied electric field increases electron temperature T_e above lattice temperature T_L (overheating of the lattice is negligible). The electron temperature can be determined from SdH oscillations, and for the curve (c) in Fig. 1 it is about $T_e = 4.2$ K as seen from the comparison of SdH oscillations. However the commensurability oscillations in the Fig. 1c are strongly suppressed with respect to b. It leads to conclusion that suppression of commensurability oscillations is not connected with the heating effects.

The sample resistance as a function of E is presented in Fig. 2 for two different values of magnetic field. One can see that for the magnetic field 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 the saturation. The same behavior was observed for all of the tested samples. From the dependencies of magnetoresistance on E we determine the electric field $E_{1/2}$ at which the commensurability oscillations are suppressed to half a 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 down with the increase of d roughly according to $E_{1/2} \propto d^{-2}$.

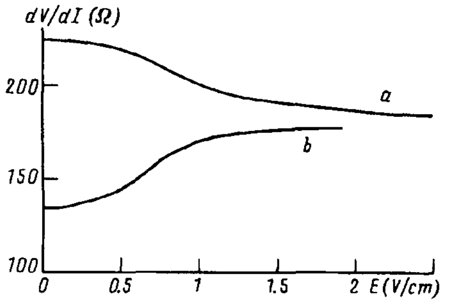

Fig. 2. The resistance of the sample with $d = 1.3$ μm as a function of applied electric field E for two different values of magnetic field B: a – $B = 0.17$ T ($2R_c = d$) – commensurability maximum; b – $B = 0.27$ T ($2R_c < d - 2a$) – corresponds to rosette like orbits

As it was mentioned above there are two models explaining the magnetoresistance maxima in Fig. 1. One of them is based on the running trajectories skipping along the lattice arrays which are responsible for the maximum in diffusion coefficient and, consequently, in the resistance (for the considered magnetic fields $\sigma_{xy} > \sigma_{xx}$ and therefor maximum in σ_{xx} corresponds to maximum in ρ_{xx}). The other one is connected with the pinned orbits not colliding with antidots. It is important that running trajectories are essentially more sensitive to the initial conditions and possible distortion of the electron orbit. Applied electric field leads to the drift of the cyclotron orbit. For the running trajectory the respectively small drift is enough 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 at least essentially less than the antidot radius a. The exact estimation of l_d breaking the running trajectories as well as the dependence of l_d on the lattice period d requires more detailed theoretical study of the region of stability of running trajectories. On the other hand, in order to break the pinned orbit with $2R_c = d$ (corresponding to the main commensurability maximum) the average drift distance during 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). For the lattice period $d = 1.3\mu$m 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 reverse sign with respect to one in the region of commensurability oscillations described

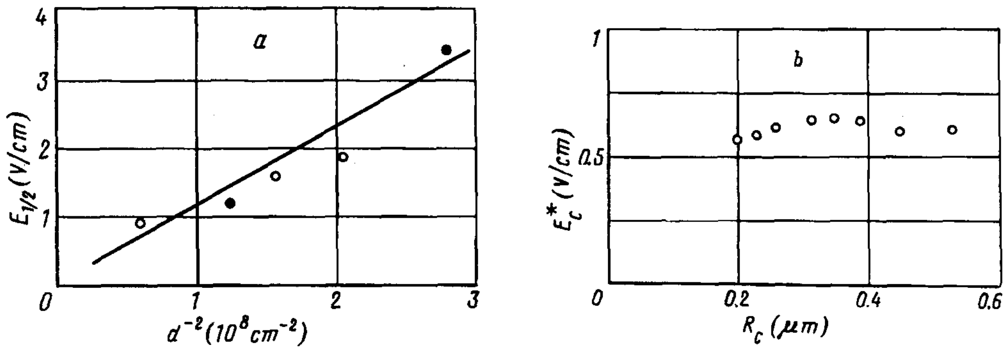

Fig. 3. *a*) The electric field $E_{1/2}$ resulting in the suppression of the main commensurability oscillation (in the magnetic field satisfying the condition $2R_c = d$) to half a value measured for the samples with different d as a function of d^{-2}. The solid line is drawn as an eye guide. *b*)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

above. This behavior of magnetoresistance can be explained if we suggest that in this region of magnetic fields the electrons perform rosette-like orbits skipping around antidots. These electrons are localized and do not contribute to the conductivity. But the high electric field (more than some critical E_c^*) results in the break-down of the localized motion due to the drift of the cyclotron orbit by analogy with the skipping-along-arrays trajectories. It leads to the increase of conductivity and resistance of samples which affects the experimental dependence of magnetoresistance on the electric field (Fig. 1).

The experimental dependence of E_c^* on R_c is shown in Fig. 3*b*. 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 numeric 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 the delocalization of electrons due to electric field is observed, but for lower B electron trajectories becomes diffusive. Thus a new maximum in resistance at high electric field is observed as indicated above (Fig. 1). The corresponding value of antidots radius a is consistent with the measurement of a by other methods [5].

Thus, in the present work the magnetoresistance of the 2D periodic lattices of antidots with large variety of periods was found to exhibit nonlinear behavior in the applied electric field. The analysis of the obtained results within the frames of the dynamic 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 tested samples. In higher magnetic field the nonlinear effects are connected with breaking of the localized rosette motion. More detailed comparison of some of the obtained results (such as the values of the critical electric fields breaking the regular motion and their dependence on the lattice period) with the theory requires further theoretical study of the region of stability of runaway and rosette-like orbits.

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