J. Phys.: Condens. Matter 4 (1992) L269–L274. Printed in the UK

LETTER TO THE EDITOR

Magnetoresistance oscillations in a two-dimensional electron gas with a periodic array of scatterers

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Received 19 February 1992

Abstract. We have studied the magnetoresistance of a two-dimensional electron gas in an array of antidots with periodicities in the range 0.6–1.3 μm. In weak magnetic fields ($B < 10$ mT) we have observed magnetoresistance oscillations with a period of $hc/2eS$, where S is the area of the cell enclosed by the ballistic trajectories of the electrons. In magnetic fields of $B < 100$ mT, the oscillations originating from the commensurability of the cyclotron radius and the lattice period were studied. The behaviour of some oscillations was found to disagree with the classical model of pinned electron orbits in magnetic fields.

A two-dimensional electron gas in an array of antidots is a new system with periodically arranged scatterers, in contrast to the conventional electron–impurity system. It gives rise to new effects, such as a pinning of electrons due to the commensurability of the cyclotron radius and the period of the lattice [1–3], and the existence of the two groups of carriers in a strong magnetic field [2]. Scattering by periodically arranged antidots could lead to unusual behaviour of the interference effect, which is responsible for electron transport in weak magnetic fields in a system with little disorder, in particular the negative magnetoresistance [4]. In this work the electron transport through a square antidot lattice was studied for different periodicities. The influence of periodically arranged scatterers on the interference effects and classical trajectories in a weak magnetic field was observed.

Our samples were Hall bars fabricated on a basis of GaAs/AlGaAs heterostructures with a high-mobility two-dimensional (2D) electron gas. The distance between potential probes was 500 μm; the width of the sample was 200 μm. The properties of the original heterojunction were: electron density, $n_S = 5.3 \times 10^{11}$ cm^{-2}; mobility, $\mu = (2–5) \times 10^5$ cm^2 V^{-1} s^{-1}. The array of antidots (fabricated by electron-beam lithography and reactive plasma etching) covered the segment of the sample between the potential probes (figure 1). We have measured nine samples with lattice periods $d = 0.6$, 0.7, 0.8, 0.9, 1 and 1.3 μm and hole diameters $2r = 0.15–0.2$ μm. The total number of antidots was $(0.6–3) \times 10^5$. Magnetoresistance was measured by the four-probe method, using an active AC bridge at frequencies of 70–700 Hz at temperatures of 1.3–4.2 K in magnetic fields up to 8 T.

Figure 1 shows the magnetic field dependence of the magnetoresistance before and after the patterning of antidots in the same sample. We can see that the resistance

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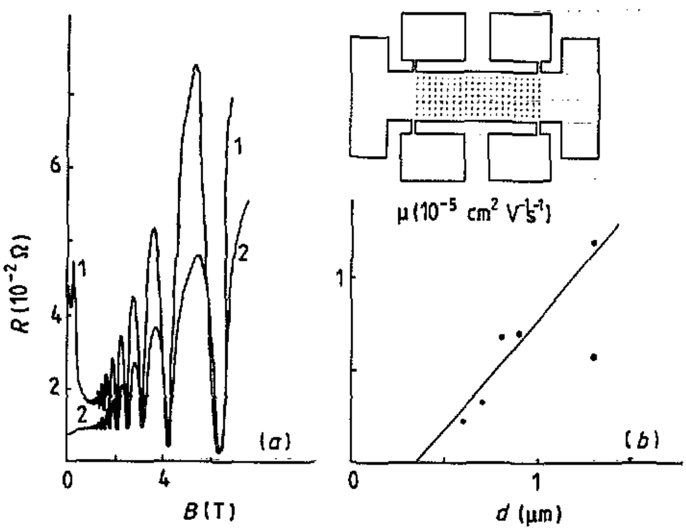

Figure 1. (*a*) Magnetoresistance in patterned (1) and bare samples (2). T = 4.2 K; lattice period (patterned sample) d = 0.9 μm. (*b*) Mobility of the patterned samples as a function of period d (open circle, sample with elliptical shapes of imposed scatterers). Insert—sketch of the sample geometry.

of the patterned sample at zero magnetic field is six times greater than the resistance of the bare sample. In nine samples with antidots in a magnetic field we observe the new oscillations due to the commensurability of the cyclotron radius and the lattice period d [1–3], and negative magnetoresistance due to the suppression of the electron backscattering by the magnetic field [5]. However, in a strong magnetic field the resistivity of the sample with antidots remains larger than the resistivity of the bare sample. This may be explained by the additional scattering of electrons by impurities induced in the process of reactive ion etching, or the existence of localized electron orbits which appeared in some cases as a second period of the Shubnikov oscillations [2]. Figure 1(*b*) shows the dependence of the electron mobility in the patterned samples in the absence of the magnetic field. We can see that the decrease in the mobility when the periodicity is reduced can be described by the expression $\mu = 1.3e(d-c)/mv_F$, where c = 0.35 μm. It means that the mean free path of the electron is determined by the distance between antidots. The effective diameter c consists of a lithographic hole diameter in the heterostructures and a depletion length around those holes, i.e. $c = 2r + 2t$, where t = 0.07 μm. The open circle in figure 1(*b*) shows the value of mobility for the sample in which imposed scatterers have an elliptical shape of length 0.6 μm along the direction of the current. In this case c = 0.75 μm and we obtain $\mu = 60 \times 10^3$ cm^2 V^{-1} s^{-1} in accordance with experiment. This result shows that in our samples the artificial lattice of antidots is responsible for the electron scattering.

Let us consider the behaviour of the magnetoresistance (MR) of 2D electrons in an antidot array in a weak magnetic field up to 10 mT. Figure 2(*a*) shows the dependence of MR for samples with different periodicities. We see that negative magnetoresistance has some features, the positions of which depend on the periodicity. Two features in the magnetoresistance of samples with d = 0.6 μm are observed which prove the

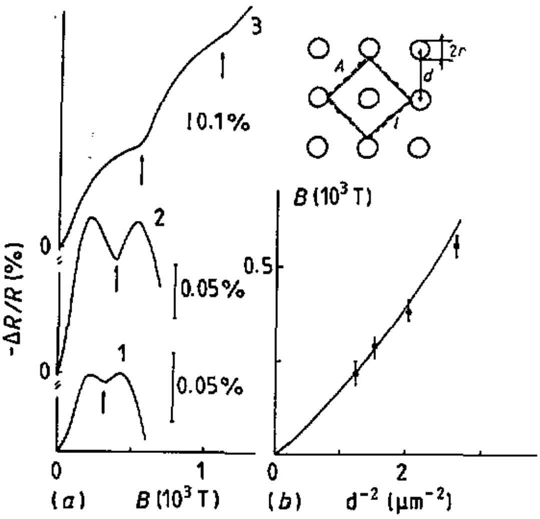

Figure 2. *(a) Low-field dependence of the resistance on B for samples with different* lattice periods d: (1) 0.8 μm, (2) 0.7 μm, (3) 0.6 μm; T = 1.7 K. (*b*) Period of low-field oscillations as a function of d^{-2}. The solid curve is given by $B_0 = hc/el^2$. Insert—sketch of the electron trajectories contributing to Aharonov–Bohm oscillations.

oscillatory character of its behaviour. As the lattice period increases, the value of the negative MR and the amplitude of oscillations decrease; at higher magnetic fields the positive classical magnetoresistance appears. Therefore the second oscillation is not observed for the samples with period d = 0.7 μm and 0.8 μm because of the monotonic component of the classical magnetoresistance. The amplitude of oscillations and the value of the negative MR increase with decreasing temperature. There are no oscillations in the samples with $d > 1\,\mu$m. It should be noted that the dependence of MR on B does not quite agree with the theory for the 2D case [4]. If we use the expression for MR in our case for an estimation and compare with the theory, we obtain $L_\varphi \sim$ 1–2 μm.

Next we discuss our results. More unambiguously, the Aharonov–Bohm effect, due to the intereference of electron waves moving along closed trajectories in opposite directions [6], is responsible for the oscillations in weak magnetic fields. These oscillations in disordered conductors were first observed by Sharvin and Sharvin [7] in the conductance of long cylinders with small diameters. In this case oscillations are due to the interference of pair-electron states diffusing around closed trajectories in opposite directions with a period $\Delta B = hc/2e\pi r^2$, where r is the radius of the cylinder. The conditions for the observation of Aharonov–Bohm oscillations are $l_e \ll L_\varphi \ll L$, where l_e is the elastic mean free path and L is the perimeter of the cylinder. For thin films of gold and copper these oscillations, with period $\Phi_0 = hc/2e$, were observed in the sample for the network geometry [8], i.e. nearly the same as that used in our paper. It should be noted that in all cases $hc/2e$ Aharonov–Bohm oscillations were observed in the 'dirty limit' when $l_e \ll L_\varphi$. Recently Smith *et al* [9] have reported the hc/e Aharonov–Bohm effect in a high-mobility 2D electron gas in a grid-like structure, where the antidot covered almost the whole area of the superlattice unit cell. In this case the interference of the edge states rotating around the antidots was observed in high magnetic fields [10]. Our case differs from that mentioned above: there are a small number of impurities in our samples and electrons are scattered by antidots; also, the magnetic field is too low to influence the classical motion of the electrons. Thus, among all possible trajectories, let us consider the closed paths as shown in the insert of figure 2(*a*). An electron travels ballistically from one antidot to another and has two identical closed trajectories reversed in time. The interference of these trajectories leads to magnetoconductance oscillations with period $hc/2el^2$. We believe that these closed paths are responsible for the observed effect. Oscillations with smaller periods were not found because the corresponding trajectory perimeter is larger than L_φ. Oscillations with a larger period, corresponding to trajectories which lie inside one unit cell, were not observed because of the contribution of the positive magnetoresistance. The circles in figure 2(*b*) show the period of oscillation as a function of d^{-2}; the solid curve shows the results of calculating ΔB from the equation $\Delta B = hc/2el^2$, where $l = 2V(d - c/2)$ (see the insert in figure 2) and $c = 2r + 2t$. To calculate ΔB we take into account the value of the depletion region around the antidots, t, which was obtained from mobility measurements (figure 1(*b*)). We see good agreement between experimental values and our calculations without the use of adjustable parameters. It should be noted that the relative numbers of electron trajectories shown in the insert of figure 2 are negligibly small and for a considerable contribution to the conductivity the electron scattering by antidots must be partially diffuse. However, completely diffuse scattering suppresses Aharonov–Bohm oscillations because of the averaging of the closed trajectories. A more detailed analysis will require further theoretical work for systems with periodic lattices of scatterers. It is possible to explain the observed oscillatory behaviour of the conductivity as being due to the influence on the electron energy spectrum of the magnetic flux penetrating the unit cell of the system [11]. However, in this case the period of the oscillations should be equal to hc/ed^2, which is not consistent with our experiments. Moreover, these oscillations persist in strong magnetic fields, in contrast to our experimental results.

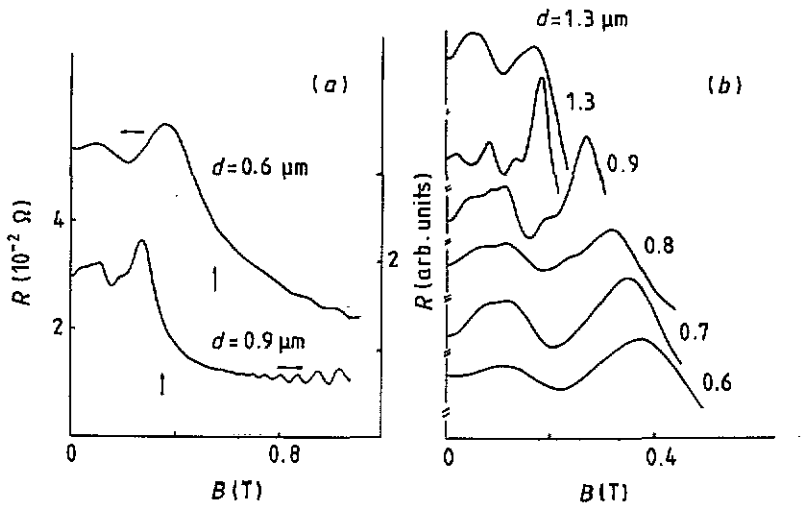

Figure 3. (*a*) Commensurability oscillations and negative magnetoresistance for two samples with different periods *d*. Arrows indicate the features in the negative magnetoresistance curve. (*b*) Magnetoresistance oscillations from samples with different lattice periods. Top curve—sample with elliptical shaped scatterers of length 0.6 μm and width 0.2 μm; other curves—samples with hole-shaped scatterers of diameter $2r = 0.2$ μm.

Let us consider the feature in the magnetoconductance in higher magnetic fields up to 0.5 T. Figure 3(*a*) shows the dependence of MR on B for two samples with different lattice periods. We see oscillations with an amplitude which is much larger than that of the Aharonov–Bohm oscillations and a negative magnetoresistance which begins to saturate in magnetic fields indicated by an arrow. As pointed out earlier, these additional oscillations are due to the commensurability of the cyclotron radius and the lattice period [1,2]. The saturation of the magnetoresistance is a manifestation of the skipping orbit around the antidots [12] when $2R_L = d - c$ [2], where R_L is the cyclotron radius. The commensurability oscillations were investigated for the first time by Weiss *et al* [1], but the dependence of these oscillations on the period of the lattice and the form of scatterers were not studied. In our work we report the detailed study of the magnetoresistance in the samples with different periods of the antidot lattice. Figure 3(*b*) shows the dependence of MR on B in the magnetic field when commensurability oscillations were observed for different values of d. Two samples were studied which had different scatterer shapes, but the same lattice period ($d = 1.3$ μm): in one sample the antidots had the usual hole shapes, and in the other they had ellipse-like shapes of length 0.6 μm and width 0.2 μm (top curve in figure 3(*b*)). As pointed out above, the mobility of the second sample was two times lower than in the sample with hole-shaped scatterers. One can see in figure 3(*b*) that the MR oscillations shift to higher magnetic field with a decrease in the lattice period.

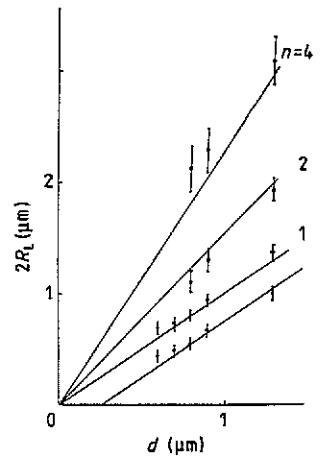

Figure 4. Cyclotron diameter in the peaks of oscillations as a function of d. The solid line is given by: (1) $2R_L = d$, (2) $2R_L = 1.6d$, (4) $2R_L = 2.28d$, where n is the number of antidots corresponding to a pinned orbit. Bottom line—$2R_L = d - c$.

Figure 4 shows the dependence of the position of the last oscillation for all periods and the position of two neighbouring oscillations for samples with periods $d = 1.3$, 0.9 and 0.8 μm. We see that the positions of these oscillations are in agreement with those calculated from the commensurability conditions (solid lines in figure 4): $2R_L = d - c$, $2R_L = d$, $2R_L = 1.6d$, $2R_L = 2.28d$ [1,2]. However, for oscillations at lower magnetic field this classical picture does not describe the experiment. We see that, for the sample with period $d = 1.3$ μm (figure 3(*b*), second curve from the top), the first magnetoconductance oscillation at low magnetic field appears when $2R_L = 14.8$ μm, i.e. the cyclotron diameter is 11 times larger than the period of the lattice. Calculation of all possible trajectories for this value of cyclotron diameter gives a very small number of commensurable pinned electron orbits with a negligibly small contribution to the conductivity [1,13]. For the sample with lattice period $d = 0.9$ μm, the first oscillation has a maximum when $2R_L = 6.2$ μm, which is also not in agreement with the classical description of commensurability oscillations. Decreasing the period to 0.6 μm (figure 3(*b*)), only two oscillations are observed: the oscillation at higher magnetic fields has a maximum when $2R_L = d$ and the second when $-2R_L = 3.8d$. It should be noted that with decreasing electron density and increasing antidot diameter the second anomalous oscillation shifts to higher fields and disappears [2]. We also see this in figure 3(*b*) for the samples with period $d =$ 1.3 μm. For the sample with elliptical shaped scatterers we see only two oscillations: the oscillation at higher magnetic fields has a maximum when $2R_L = d$, and the second when $2R_L = 3.4d$. However, for the sample with hole-shaped scatterers, as pointed out above, anomalous oscillation was observed when $2R_L = 11.4d$. Thus, the position of the anomalous oscillation depends on the diameter or the size of the antidots. Also the dependence of the maximum of the anomalous oscillation on the period (for a constant diameter of antidots) is given by $B^{\max} \sim d^{2.5}$, not by $B^{\max} \sim d$, as for commensurability oscillations. Thus these anomalous oscillations provide proof in favour of the electrons being trapped by the periodic lattice not only for commensurability conditions. It should be noted that ballistic transport through a periodic lattice of antidots could be chaotic. As has been shown in two-dimensional cross-junctions electrons have long dwell times [14]. The chaotic nature of transport in antidot lattices can be responsible for anomalous oscillations in the magnetic field. Further theoretical work on systems with periodic arrays of scatterers is required.

In conclusion, we have studied two types of magneto-oscillations: quantum oscillations due to the influence of the magnetic field on the phase of the electron wavefunction (Aharonov–Bohm oscillations); and the classical oscillations due to the commensurability of the cyclotron diameter and the lattice period. We have found anomalous oscillations, the behaviour of which is not in agreement with classical description.

We thank H Raith for the 'ELPHY' system used in the electron beam lithography, M V Entin for valuable discussion and V G Plyuchin for carrying out the plasma etching.

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