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Phase-coherent electrons in a finite antidot lattice

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Antidot lattices with a finite number of periods are fabricated such that the size of the total system is smaller than the phase-coherence length of the electrons at low temperatures. The magnetoresistance is dominated by reproducible quantum fluctuations as well as by classical commensurability oscillations. We attribute these fluctuations to electrons that travel phase coherently over the entire system and interfere with each other under the influence of the geometry of the potential landscape. The presence of Aharonov-Bohm oscillations is identified and related to the existence of classically pinned electron orbits.

Lateral superlattices fabricated on semiconductors have revealed a rich variety of physical phenomena in transport experiments as well as in optical spectroscopy.[1] In systems with strong two-dimensional potential modulation a periodic lattice of potential pillars arises, a so-called antidot lattice.[2–5] So far most experiments have been performed on antidot systems whose size is much larger than the electron mean free path λ_l as well as the phase-coherence length λ_ϕ of the electrons. Most experimental observations on lateral superlattices have at least qualitatively been very successfully described by classical theories neglecting the phase of the electrons.[6] Qualitatively, a maximum in the magnetoresistance can be identified with a pinned electron orbit around a group of antidots. A pinned orbit and consequently its corresponding maximum in the magnetoresistance is more likely to occur if the orbit shape and size fit to the fundamental symmetry of the antidot lattice.[5,7]

The Aharonov-Bohm[8] (AB) effect has been observed in single semiconductor[9] rings. Several publications address the question whether and how Aharonov-Bohm oscillations can be observed in large (larger than the phase-coherence length of the system) antidot lattices.[10–12] Since the Aharonov-Bohm effect is intimately related to the phase coherence of the electron[8] it is not clear how this effect should survive self-averaging for systems much larger than the phase-coherence length. Weiss *et al.*[13] presented experimental data similar to Ref. 12. They argue that their observation can be explained by applying Bohr-Sommerfeld quantization to a classically pinned electron orbit. This would require a phase-coherence length λ_ϕ longer than the size of an orbit but not necessarily longer than the size of the whole system.

In order to investigate phase-coherence effects in an antidot lattice it is advantageous that the system size is smaller than the phase-coherence length of the electrons. Here we address this point experimentally by studying the transport properties through an antidot lattice with a finite number of periods. Gusev *et al.*[14] fabricated a finite lattice with 6×7 antidots. They find strong hysteresis effects as a function of magnetic field which they attribute to the change of impurity states in the system and a magnetic-field-tuned transition of AB oscillations from a h/e to $h/2e$ periodicity. In our experiments all observed features are stable and do not depend on the sweep direction of any parameter. The phase-coherence length which is limited by electron-electron scattering is strongly temperature dependent. At low temperatures $T \ll 1$ K the phase-coherence length in high-mobility two-dimensional electron gases (2DEG's) is known to exceed several micrometers in length[9,15] and is thus larger than the size of our system. The lattice period is still considerably larger than the Fermi wavelength. However, since the electrons travel phase coherently through the entire system the magnetoresistance is dominated by fluctuations that arise from the interference of the electrons. We discuss the various physical mechanisms that are responsible for the observed phenomena.

We focus on experimental data that is obtained on a finite square lattice consisting of 9×9 antidots. Figure 1 shows an atomic force microscope image of a typical sample. A square confining geometry surrounds the antidots. The period of the lattice is $a=240$ nm, the size of the total system from side to side is designed to be $10a$. Typical four-terminal measurements are made by passing a current through two contacts (e.g., *i* and *j*) and measuring the voltage drop across the other two contacts (e.g., *k* and *l*).

The fabrication process starts from a GaAs-$Al_xGa_{1-x}As$ heterostructure ($x=0.3$) that is grown by molecular-beam epitaxy and contains a high-mobility two-dimensional electron gas situated 65 nm below the surface. At liquid-He temperatures the carrier density is $N_s=3\times10^{11}$ cm^{-2} and the mobility is $\mu=8\times10^5$ cm^2/V s resulting in a mean free path of the carriers of $\lambda_l=7$ μm. A Hall bar is defined by wet etching and provided with Ohmic contacts (AuGe/Ni). The sample is then patterned using electron beam lithography. The resist pattern is transferred onto the electron gas by a carefully tuned wet etching step (about 30 nm in

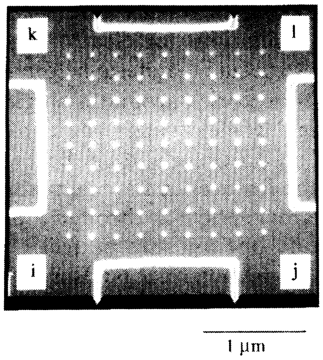

FIG. 1. Image taken with an atomic force microscope of the wet-etched pattern on the surface of a $Al_xGa_{1-x}As/GaAs$ heterostructure. The dots in the center mark the antidots, the wide lines the square circumference of the geometry. Ohmic contacts are made to the corners of the square indicated with *i*, *j*, *k*, and *l*.

depth).[16] We like to note here that the antidot pattern as well as its confining square geometry are transferred in the same etching step which provides inherently good alignment of the structures. Figure 1 presents an image that is taken after the resist has been removed from the sample surface. Each antidot is well developed and the variations of the antidot sizes are remarkably small. After the resist is removed a gate metal is evaporated on top of the sample. The sample is cooled in a dilution refrigerator down to temperatures of 30 mK. Low current levels (10 nA) are chosen to avoid heating of the electron gas.

Figure 2 presents the magnetoresistance of a typical sample for two temperatures. At $T=4.2$ K the magnetoresistance (dashed line) displays well-known maxima that are related to classical electron trajectories being pinned around groups of antidots. For low temperatures, $T=30$ mK, new structure appears (solid line) and strong reproducible fluctuations occur around the classical commensurability oscillations.

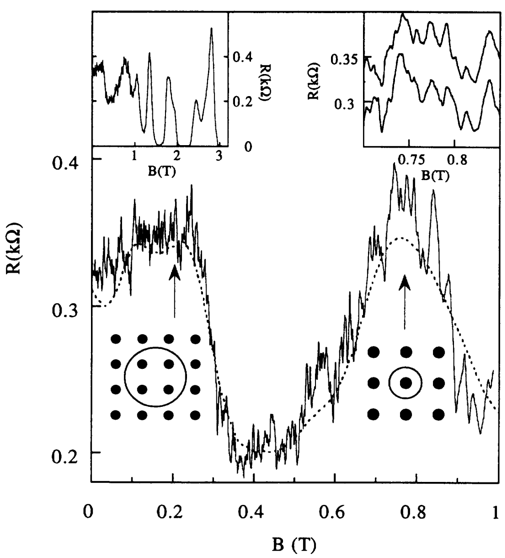

FIG. 2. Magnetoresistance trace at $V_g=0$ for $T=4.2$ K (dashed line) and $T=30$ mK (solid line). The schematic antidot patterns with the circles indicate the classically pinned electron orbits that correspond to the maxima in the magnetoresistance as marked by the arrows. The right inset in the top part of the figure presents two magnetoresistance traces for $V_g=0$ (upper curve) and $V_g=2$ mV (lower curve, offset by 50 Ω for clarity). The main features are very similar while the details in these traces are different. The left inset shows R up to 3.2 T.

We have fabricated a sample with 6×6 antidots and a lattice constant $a=360$ nm. In addition a sample was fabricated where the finite antidot lattice was transferred to the electron gas in a purely electrostatic manner. We find that the experimental observations as discussed below do not depend critically on the fabrication process nor on the specific lattice parameters.

Taking the geometric factor of the van der Pauw geometry into consideration the resistance can be expressed in terms of a conductance. We find a mean amplitude of the fluctuations of the order of e^2/h. At higher magnetic fields $B>1.2$ T the fluctuations rapidly decay in amplitude and the Shubnikov–de Haas (SdH) oscillations dominate the magnetotransport resembling those of an unpatterned 2DEG (Fig. 2, left inset). By a thorough analysis we have made sure that the minima in the magnetoresistance observed at low B do not correspond to the filling factors extrapolated from the SdH oscillations at high B.

Therefore we will discuss our experimental observations within the framework of phase-coherent electron transport. The Aharonov-Bohm effect is likely to occur in an antidot lattice in the present geometry. Generally, the electrons traveling on various trajectories through the antidot lattice may interfere with each other after having encircled groups of antidots. We thus expect that the geometry of the antidot lattice will have a significant influence on the interfering trajectories. Moreover, electrons will interfere due to random potential fluctuations that arise from the modulation doping as well as from imperfections of the fabrication process of the antidots. For samples that are smaller than the phase-coherence length but larger than the elastic mean free path this phenomenon is known to cause so-called universal conductance fluctuations. In the present case, however, where the electrons travel ballistically through the entire system, the electron motion is rather dominated by quantum ballistic transport.

A calculation employing scattering matrix theory[17] on finite and ideal antidot lattices reveals very similar resistance spectra as those observed experimentally. In another approach the quantum-mechanical band structure of an antidot lattice was calculated[18] and the conductivity computed with the Kubo formula. Again structure appears in the conductivity similar to the experimental data. This is a further indication that the interference of phase-coherent electrons is the basic physical mechanism leading to the experimental observations.

For comparison we fabricated a sample that contains no antidots but only the square confining geometry. A few reproducible resistance fluctuations occur that are negligible compared to the rich structure that is observed in the antidot lattice. We conclude that potential fluctuations that arise from the random arrangement of the doping atoms have a minor influence on the magnetoresistance.

Next we address the question of how details of the potential landscape arising from imperfections of the fabrication process influence the features in the resistance traces. The right inset of Fig. 2 presents magnetoresistance traces that are obtained for two very similar gate voltages. The Fermi energy for the two experiments differs by only about 0.5%. The two curves are vertically offset for clarity. The mean periodicity as well as the main features are very little affected by the change in gate voltage while the details of the experimental traces are modified. A small change in gate voltage has a strong influence on the random features of the potential configuration and the corresponding correlation of the electron trajectories. The overall shape of the antidot landscape will, however, depend very little on such small changes of the gate voltages. We thus argue that indeed most of the experimentally observed resistance fluctuations and in particular the most pronounced features are caused by the regular geometry of the antidot lattice.

A closer look at Fig. 2 reveals that for a small magnetic-field interval $\Delta B \sim 0.2$ T around $B \sim 0.7$ T there is a rather regular structure. The mean periodicity obviously decreases for decreasing magnetic field, i.e., the features become denser. In order to get a clearer understanding of the situation we calculated a Fourier power spectrum (FPS) for several ΔB intervals. In Fig. 3 we present three FPS that are calculated on the same resistance trace but for different magnetic-field intervals. For intervals that cover the resistance maximum corresponding to classical electron trajectories around a single antidot, i.e., $0.4 < B < 0.8$ T, a pronounced peak in the FPS occurs at a frequency of about 14 1/T. The expected AB frequency $f_{AB} = ea^2/h$ based on the area of a unit cell of the lattice is marked by a vertical line. We conclude that we observe AB oscillations for electrons going around a single antidot in a specific magnetic-field regime.

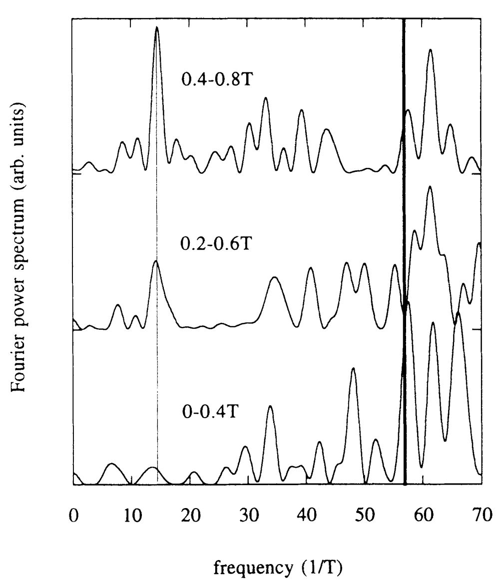

FIG. 3. Fourier power spectrum calculated for different ΔB intervals on the experimentally obtained magnetoresistance trace. The curves are vertically offset for clarity. The two straight lines indicate the position of the Aharonov-Bohm frequency for an area corresponding to one unit cell (thin line) and four unit cells (thick line) of the antidot lattice, respectively.

Since pinned trajectories around a single antidot exist over a finite magnetic-field range the enclosed area will not be independent on the magnetic field. We thus cannot expect that the features in the magnetoresistance that arise because the magnetic flux through a pinned electron orbit is changed by one unit are perfectly periodic in B. Since the details of the potential landscape in our samples are unknown it is difficult to predict the magnetic-field dependence of the electron orbit size. Even if the Fourier transform procedure does not account for all the effects in our samples we still use it because it is mathematically well defined and has a forthright interpretation.

The FPS around $B \approx 0.2$ T, i.e., in the magnetic-field regime where the electrons classically encircle groups of four antidots, reveals a peak at a different frequency. The expected AB frequency based on the area corresponding to four unit cells is again marked by a vertical line and falls well within the range of the FPS maximum.

Of course more peaks in the FPS occur that are related to the aperiodic resistance fluctuations. Often closely neighbored maxima occur in the FPS as, e.g., in the bottom trace around 60 1/T. Furthermore another maximum shows up around 32 1/T in some of the FPS. This frequency is close to what one expects for the AB oscillation for an electron orbiting around two antidots. We do not understand the details of these observations and expect that more refined experiments will enlighten this situation.

For single rings the criterion for the observation of AB oscillations is based on geometrical considerations.[9] In quantum dots AB oscillations have been observed at high magnetic fields where the electrons are confined to edge states close to the perimeter of the dot.[19] Here we argue that in an antidot lattice for a specific magnetic field where the pinned electron orbits around groups of antidots the electrons preferably travel around an area that is roughly given by the group of antidots. The role of the quantum-mechanical edge states in a quantum dot at high magnetic fields is taken over by the classically pinned trajectories around groups of antidots. Of course in the antidot lattice the trajectories and their respective geometry are not as well defined. This might be the reason why the AB oscillations in an antidot lattice are not as pronounced. In addition, with changing magnetic field there is a crossover from one typical kind of classical pinned trajectory to another which changes the average area and therefore the amount of flux quanta per magnetic-field interval.

In a 2DEG without antidots the appearance of SdH oscillations is related to the formation of Landau levels. In the presence of a lateral superlattice the Landau levels transform into Landau bands. Even at low magnetic fields, $B \approx 0.2$ T, Landau quantization is not completely negligible. Many edge states are populated and extend throughout the antidot lattice. The equipotential lines representing the edge states resemble, however, very closely the regular classical trajectories. We thus argue that the picture we give of AB oscillations arising from electrons traveling phase coherently along classical electron trajectories should persist into the regime where Landau quantization becomes important.

The presented interpretation of the AB effect gives further confirmation on the validity of the concept of classically pinned electron trajectories. For further refined sample geometries one might expect that experiments as our complement the emerging understanding of the crossover from classically chaotic trajectories to quantum-mechanical wave functions.[20]

In conclusion we have presented a detailed investigation of reproducible oscillations and fluctuations in the magnetoresistance of a finite antidot lattice. The oscillations are most likely associated with phase-coherent electrons that interfere with each other under the influence of the antidot potential landscape. Aharonov-Bohm oscillations arising from the interference of electrons which encircle groups of antidots can be identified.

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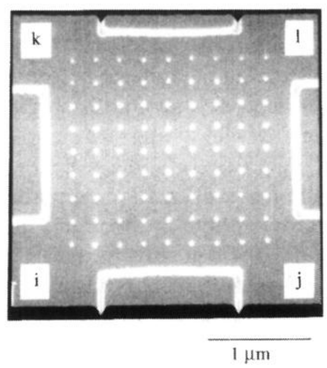

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