Observation of Quantum Interference in a Phase-Coherent Two-Dimensional Superlattice

K.-M. H. Lenssen,* M. E. J. Boonman,† and C. J. P. M. Harmans
Department of Applied Physics, Delft University of Technology, P.O. Box 5046, NL-2600 GA Delft, The Netherlands

C. T. Foxon‡
Philips Research Laboratories, Redhill, Surrey RH1 5HA, United Kingdom
(Received 17 February 1994)

Electron transport in a two-dimensionally periodically modulated potential has been studied by means of gate structures on top of a GaAs/AlGaAs heterostructure. In low magnetic fields ($B < 1$ T) conductance minima are measured due to localization of electron orbits. Superimposed on these minima, Aharonov-Bohm oscillations are observed with periods in B which are submultiples of that corresponding to a single localized orbit. This new phenomenon is attributed to phase-coherent coupling of localized orbits.

PACS numbers: 73.40.–c, 73.20.Dx

Artificial lateral superlattices provide a convenient model system for the research of a number of fundamental effects in electron transport. Employing a grid-shaped metallic surface gate to define the superlattice and by tuning the voltage on this gate, different transport regimes can be obtained: from a weak periodical potential via an artificial two-dimensional crystal to an array of weakly coupled quantum dots. Each of these regimes has typical physical phenomena (theoretically predicted or already measured), ranging from the so-called Weiss oscillations [1], via band structure effects [2], to Coulomb effects. In particular, effects due to two-dimensional coupling of quantum dots are still barely experimentally studied. Here we will discuss measurements in low magnetic fields [3] in the regime of a weak potential, i.e., in a two-dimensional array of strongly coupled quantum dots.

For the samples the two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure is used, because of its high mobility, the large Fermi wavelength, and its excellent gating properties. The 2DEG has a mobility $\mu_e \gtrsim 100\ \mathrm{m^2/V\,s}$ and an electron density $n_s \approx 1.3 \times 10^{15}\ \mathrm{m^{-2}}$, resulting in a Fermi wavelength $\lambda_F \gtrsim 70$ nm and an elastic mean free path $l_e \gtrsim 6\ \mu$m. The material was grown by molecular beam epitaxy and consists of a GaAs substrate with a GaAs/AlGaAs superlattice, a 0.5 μm undoped GaAs layer, a 41 nm undoped $Al_{0.33}Ga_{0.67}As$ spacer, a 38 nm n-doped $Al_{0.33}Ga_{0.67}As$ layer, and a 17 nm undoped GaAs cap layer.

First a wet-etched Hall bar with 12 Ω Ni/AuGe/Ni contacts is made on this material by optical lithography. In the middle of this mesa a grid-shaped gate is fabricated. The grid structure, consisting of 3×3 cells, is defined in a double layer of PMMA (with a total thickness of $\approx$200 nm) by nanolithography with a 100 keV electron beam, to reduce negative influences of the proximity effect between the closely packed wires of the grid. After development the gate metallization is evaporated as 10 nm titanium and 20 nm gold, at a background pressure below 10^{-7} mbar. The result after liftoff in boiling acetone is shown in Fig. 1. A small separation is intentionally left open between the grid and the upper gate to avoid (electrostatic) potential differences across the grid.

The grid is connected by wide leads to bond pads which are situated outside the etched mesa. By applying a negative voltage to the lead, the electron density below the gate can be reduced in a controlled way.

The width of the lines d is less than 50 nm, the size of the unit cell a is 300 nm. In this way a is comparable to the Fermi wavelength of the electrons. Moreover, it is anticipated that phase coherence will be preserved over several cells, since in general the inelastic mean free path l_{in} is much larger than $l_e \gg a$.

For the measurements the samples are mounted in a dilution refrigerator. The differential resistances are measured by means of a current-biased ac lock-in technique at a temperature of about 40 mK. Always the voltage on the upper gate in Fig. 1 (without grid) is chosen such that the small 2DEG channel between this gate and the grid

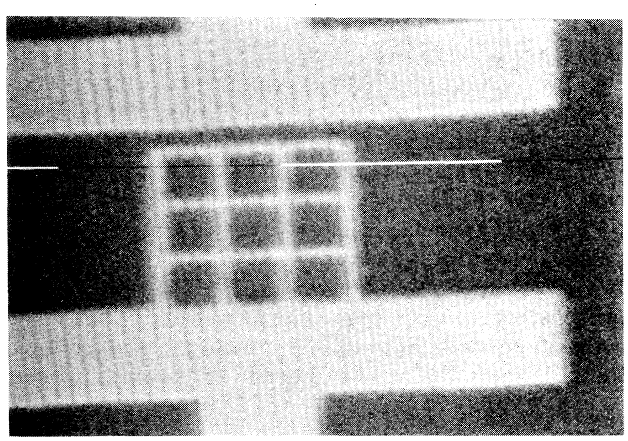

FIG. 1. Micrograph of the metallic gate structure (light area); the white line represents 1 μm.

 0031-9007/95/74(3)/454(4)$06.00

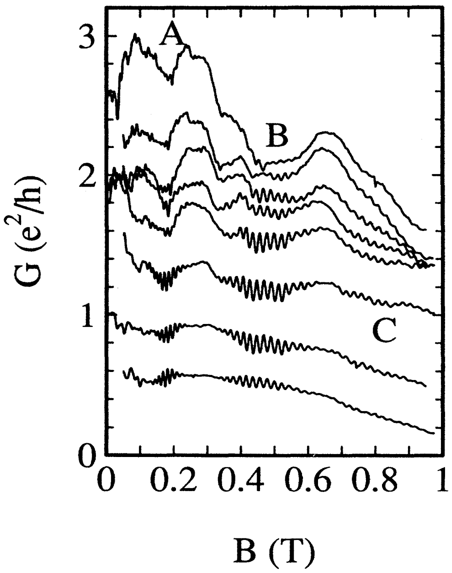

FIG. 2. The differential conductance as a function of the magnetic field for several voltages on the grid ($T = 0.05$ K, $V_{\text{gate}} = -560$ mV; from top to bottom $V_{\text{grid}} = -360, -365, -370, -375, -380, -385, -390$, and -395 mV); the letters A, B, and C refer to the corresponding orbits in Fig. 4.

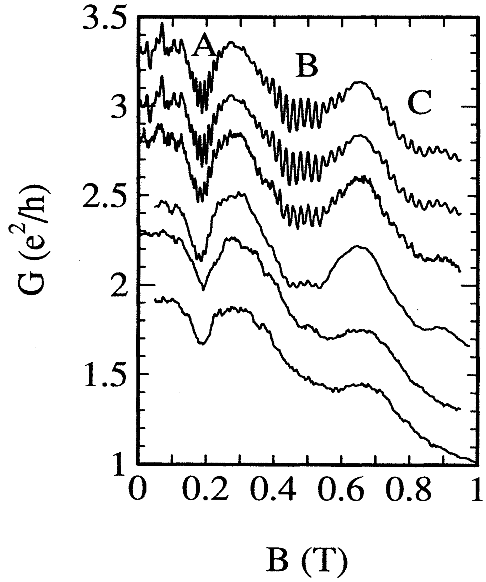

FIG. 3. The differential conductance as a function of the magnetic field at several temperatures ($V_{\text{grid}} = -385$ mV, $V_{\text{gate}} = -560$ mV; from top to bottom $T = 0.05, 0.1, 0.2, 0.5, 1.0$, and 2.0 K); the upper curves have been offset for clarity, and the letters A, B, and C again refer to the orbits in Fig. 4.

is depleted totally ($V_{\text{gate}} = -560$ mV). In this way it is ensured that the electron transport takes place underneath the grid, i.e., through the 2D periodic potential [4].

In Fig. 2 the data of the conductance measurements in low magnetic fields are presented for several voltages V_{grid} on the grid. The applied excitation current is 0.1 nA. Especially for not too negative grid voltages minima in the conductance are observed at $B \approx 0.18$ T (A), $B \approx 0.48$ T (B), and $B \approx 0.80$ T (C). Superimposed on these minima small oscillations can be seen which are periodic in B. The result of increasing the temperature is shown in Fig. 3: While the oscillations are strongly suppressed at a temperature below 1 K, the conductance minima are only weakly affected up to a temperature of 2 K. This suggests that the minima are due to a classical phenomenon, in contrary to the oscillations which have a quantum mechanical origin.

The radii R_c of the cyclotron orbits [5] which belong to the magnetic fields where the minima occur are respectively 330, 125, and 75 nm. In Fig. 4 these cyclotron orbits are drawn on scale in the grid. It is rather striking that the largest orbit A just encloses four line crossings, that the middle orbit B encircles one crossing, and that the smallest orbit C just fits in one unit cell. The cyclotron orbits cross the grid lines at positions where the potential barrier is expected to be smallest. It is clear that at a certain V_{grid} the electron density under the crossings (where the total gate area in the vicinity is larger) will be lower than that under the lines connecting them [6]. Therefore at not too large values of V_{grid} a kind of antidot array is formed by the line crossings. Conductance minima due to commensurability of cyclotron orbits and an antidot array has earlier been reported in etched samples [7,8], which makes this explanation of the minima in our measurements very plausible. Normally the conduction through such an array is carried by electrons scattering between the antidots. However, at those magnetic field values where the cyclotron orbit "fits" in the array, a fraction of the conduction electrons dwells in these orbits, which will reduce the conductance through the array, yielding a conductance minimum. Clearly, this is only a largely simplified (but appealing) model. In reality the appearance of the cyclotron orbits will deviate from a circle because of the varying two-dimensional potential,

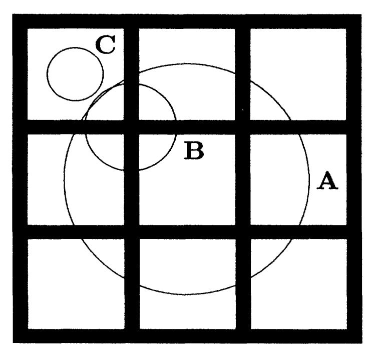

FIG. 4. Schematic view of the grid with the localized electron orbits corresponding to the conductance minima A, B, and C (on scale).

but this will not affect the validity of the basic idea of localized orbits. In fact this phenomenon is the two-dimensional variant of the Weiss oscillations [1] (first found in a one-dimensional periodic potential), which are theoretically described (semiclassically) in [9].

As is evident from Figs. 2 and 3, clear oscillation patterns are found in the minima of the conductance. Nihey and Nakamura [7] also found oscillations in a single conductance minimum. The authors contribute these oscillations to the Aharonov-Bohm effect [10] in one cyclotron orbit. We find for the first time oscillations in three conductance minima. The period of the Aharonov-Bohm oscillations associated with the areas of the localized orbits are 12, 86, and 230 mT. The measured periods are, however, ≈ 12, ≈ 21, and ≈ 24 mT. So, while the period corresponding to the largest localized orbit A is in good agreement with the calculation, there is a discrepancy for the smaller orbits B and C. The difference between the calculated and the measured period is, respectively, about a factor of 4 (B) and a factor of 9 (C). This is exactly the number of localized orbits of kind B or C which is possible within the grid. The largest orbit A can be positioned only in one way in the grid, for the smaller ones there are, however, 4 and 9 possibilities. This leads us to the assumption that the localized orbits are phase-coherently coupled throughout the grid. This is reasonable, since in general the phase coherence length is larger than l_e, and in the plain 2DEG the elastic mean free path $l_e \approx 6$ μm is much larger than the total grid (which is 950 nm). The fourfold, respectively, ninefold degeneracy of the localized states in case B and C is lifted by quantum-mechanical tunneling between these states. This leads to a splitting of the Aharonov-Bohm oscillations and thus to a reduction of the period by a factor of 4, respectively, 9. With this assumption taken into account the theoretically expected periods are 12, 21, and 26 mT, which is in much better agreement with the experimental results.

From four-terminal measurements of the resistance at very low magnetic fields (i.e., below 0.2 T), indications for weak localization effects have been found. Because of the four-terminal configuration these effects cannot be due to the Ohmic contacts (current and voltage probes are much farther apart than the phase coherence length), so they must be attributed to the grid structure [11]. From a measurement for $V_{\mathrm{grid}} = -330$ mV and $V_{\mathrm{gate}} = -560$ mV, which shows a resistance minimum at $B = 0.12$ T, the phase coherence length is roughly estimated to be ≈ 1.6 μm (assuming the pure metallic regime and the width of the relevant constriction being 250 nm) [12]. This confirms that phase coherence is preserved over the total size of the grid, even if localization due to the constriction in the grid is taken into account. That means that we have realized the first phase-coherent two-dimensional superlattices.

The oscillations cannot be explained by the Shubnikov–de Haas effect, because they are periodic in B instead of in $1/B$ and trying, e.g., to extract a carrier density from two adjacent minima around C in Fig. 3 would give unreasonably high values. They are also fundamentally different from the magnetoconductance oscillations observed in single quantum dots in high magnetic fields [13], since our measurements are not in the edge channel regime. In [8,14,15] a rigorous theoretical model for antidot arrays with dimensions large compared to the phase coherence length (quantization of chaotic electron motion) is presented that takes into account the deviations from a hard wall potential. However, the much simpler "pinball" model with free cyclotron radii (described above) seems to be sufficient to give a good description of our measurements. Moreover, it can easily be generalized for phase-coherent arrays.

To make another consistency check we estimate the relevant energy scale of the oscillations. The total magnetic flux enclosed by the coupled orbits in minimum B at $B = 0.48$ T approximately equals 22 flux quanta ϕ_0. With a Fermi energy $E_F = 4.7$ meV, each flux quantum ϕ_0 corresponds to an energy of ≈ 0.21 meV. From this argument one predicts that the oscillations will be suppressed when $4k_BT$ is equal to 0.21 meV, i.e., at $T \approx 0.6$ K. Analogously we estimate that the oscillations in the minima A and C will be suppressed at $T \approx 0.9$ and ≈ 0.5 K. This is in good agreement with Fig. 3. The results of the foregoing are identical to those following from the argument used by Nihey and Nakamura to estimate the typical energy splitting [7].

The conductance minima at magnetic fields corresponding to localized orbits have also been observed in a similar grid with 9×15 unit cells (also with $a = 300$ nm and $d \approx 50$ nm). In this case Aharonov-Bohm oscillations in coupled orbits have not been observed. This may be due to the fact that now the total size of the grid (4.55 μm) is much larger and phase coherence all over the grid is not very likely.

If we look at the effect of variation of V_{grid} in Fig. 2, we see that the position of the conductance minima nearly stays unchanged, but that their amplitude decreases strongly at more negative V_{grid}. This indicates that the height of the potential barriers under the grid lines is increased rather than the width.

That the oscillations stay clearly visible shows again that this phenomenon has a different origin. Not a conductance minimum, but localization and phase coherence are required. When the potential landscape is firmly formed, so that the areas of low barrier height between the antidots are smallest, the cyclotron orbits are best localized, which is optimal for the Aharonov-Bohm oscillations. In fact this requirement is analogous to the condition of small channel width in the usual ring geometry for Aharonov-Bohm measurements.

We believe that Coulomb effects are not important for the description of our measurements. If we measure the magnetoconductance at different values of V_{gate} (varied from -480 to -580 meV), the oscillations in the minima are unchanged. Moreover, when $V_{\rm grid}$ is swept, while the magnetic field is fixed at the value of a conductance minimum, no oscillations are found in the conductance.

In the final stage of preparation of this Letter we became aware of recent related experiments on the subject of phase-coherent electrons in etched antidot lattices [16]. In those measurements indications of localized orbits around 1, respectively, 4 antidots have been found. Moreover, at $T = 30$ mK, reproducible fluctuations have been observed in the magnetoresistance. However, their periods could only be related to the areas of single localized orbits and no evidence was found of phase-coherent coupling of these orbits. This could indicate that in [16] the total size of the antidot lattice is not sufficiently small compared to the phase coherence length of the electrons. In that case their results can be better described in terms of the model of [8,14,15] rather than by the Aharonov-Bohm effect. For that description only phase coherence around a cyclotron orbit is required, but not across the entire superlattice. This theory also explains why oscillatory behavior of the magnetoresistance has been found in large antidot arrays (as in [7]). The much more pronounced shape of our oscillations and the fact that we could not find them in the lattice with 9×15 cells confirm that we have observed a different, new type of oscillations, due to overall phase coherence.

In summary, we have experimentally studied electron transport in a two-dimensional superlattice. Conductance minima due to localized (cyclotron) orbits have been measured. Moreover, for the first time Aharonov-Bohm oscillations superimposed on these minima have been observed that give evidence for phase-coherent, two-dimensional coupling of the localized orbits throughout the grid.

We are grateful to C. W. J. Beenakker, J. R. Kraayeveld, and J. E. Mooij for helpful discussions and to the Delft Institute of Micro-Electronics and Submicron technology (DIMES) for the use of their facilities. This research was financially supported by the Dutch Foundation for Fundamental Research on Matter (Stichting F.O.M.).

*Present address: Philips Research Laboratories, Prof. Holstlaan 4, NL-5656 AA Eindhoven, The Netherlands.

†Present address: High Field Magnet Laboratory, Nijmegen University, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands.

‡Present address: Department of Physics, Nottingham University, Nottingham NG7 2RD, United Kingdom.

[1] D. Weiss, K. von Klitzing, K. Ploog, and G. Weimann, Europhys. Lett. **8**, 179 (1989).

[2] See, for example, L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1970); D.R. Hofstadter, Phys. Rev. B **14**, 2239 (1976); G. Kirczenow, Surf. Sci. **263**, 330 (1991).

[3] Measurements in the (high field) quantum Hall regime are described elsewhere: K.-M.H. Lenssen, M.E.J. Boonman, J.R. Kraayeveld, C.J.P.M. Harmans, and C.T. Foxon (to be published).

[4] The 2DEG under the wide connecting leads is already depleted at a voltage of -320 mV.

[5] R_c is defined as the free cyclotron radius in the absence of a periodic potential, so $R_c = m^* v_F / eB$ with v_F the Fermi velocity and m^* the effective mass of the electrons.

[6] The line crossings were intentionally doubly exposed by the electron beam to avoid diagonal connections between the cells. The resulting broadening of the crossings even reinforces this effect.

[7] F. Nihey and K. Nakamura, Physica (Amsterdam) **184B**, 398 (1993).

[8] D. Weiss, K. Richter, E. Vasiliadou, and G. Lütjering, Surf. Sci. **305**, 408 (1994), and references therein.

[9] C.W.J. Beenakker, Phys. Rev. Lett. **62**, 2020 (1989).

[10] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).

[11] This is confirmed by the observation that the minimum in the differential resistance, as a function of the magnetic, field is dependent on $V_{\rm grid}$ but not on $V_{\rm gate}$.

[12] C.W.J. Beenakker and H. van Houten, Solid State Phys. **44**, 1 (1991).

[13] B.J. van Wees, L.P. Kouwenhoven, C.J.P.M. Harmans, J.G. Williamson, C.E. Timmering, M.E.I. Broekaart, C.T. Foxon, and J.J. Harris, Phys. Rev. Lett. **62**, 2523 (1989).

[14] R. Fleischmann, T. Geisel, and R. Ketzmerick, Phys. Rev. Lett. **68**, 1367 (1992).

[15] D. Weiss, K. Richter, A. Menschig, R. Bergmann, H. Schweizer, K. von Klitzing, and G. Weimann, Phys. Rev. Lett. **70**, 4118 (1993).

[16] R. Schuster, K. Ensslin, D. Wharam, S. Kühn, J.P. Kotthaus, G. Böhm, W. Klein, G. Tränkle, and G. Weimann, Phys. Rev. B **49**, 8510 (1994).

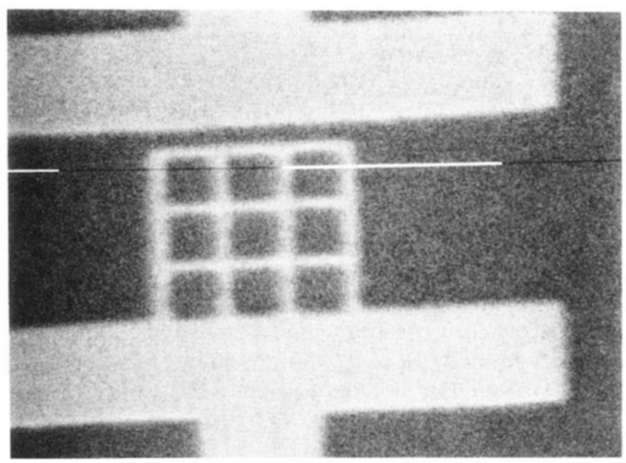

FIG. 1. Micrograph of the metallic gate structure (light area); the white line represents 1 μm.