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Physica E 34 (2006) 534–537
PHYSICA E
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Aharonov–Bohm-type effects in different arrays of antidots

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Available online 12 May 2006

Abstract

We have investigated Aharonov–Bohm-type oscillation in the quantum Hall plateau transition region in three types of square arrays of antidots; a large (50 × 160 antidots) array, a small (5 × 10 antidots) array, and the sample with antidots placed only near the side edges. The temperature dependence of the amplitude confirmed that the oscillation originates from the fine structure in the density of single particle states circumnavigating around each antidot. In addition, we have also observed Altshuler–Aronov–Spivak oscillation near zero magnetic field in square arrays of antidots.

PACS: 74.40.Xy; 71.63.Hk

Keywords: AB-type oscillation; Antidot lattice; AAS oscillation; Edge channel

1. Introduction

Antidot array fabricated from two-dimensional electron system (2DES) in GaAs/AlGaAs heterointerface provides an interesting system to explore electron transport in artificial periodic potential. A crucial parameter is the aspect ratio, i.e. ratio between the artificial lattice period and the antidot diameter. Antidot arrays with small aspect ratio can be viewed as 2DES with periodic array of scatterers, while those with large aspect ratio is more like a network of narrow channels formed between the antidots. In the latter systems, several types of oscillatory magnetoresistances periodic in B are known such as Aharonov–Bohm (AB)-type oscillation [1,2] and Altshuler–Aronov–Spivak (AAS) oscillation [3] near zero magnetic field. Recently we investigated these effects at low field and another B-periodic AB-type oscillation in the quantum Hall (QH) regime in a triangular array of antidots [4]. The study raised many questions including, how the AB-type oscillation survives ensemble averaging, what determines the temperature dependence, and whether the phenomenon originates from bulk or edge of the sample. In this work, we extend the measurement to antidot lattices with square symmetry and to different overall array sizes and arrangement in order to shed light on these questions.

We focus on the high-field AB-type oscillations in square antidot arrays and study the effect of the overall array size and array configuration within the Hall bar. We investigate the temperature dependence and evolution with the front gate bias. We also report on the observation of AAS oscillation.

2. Experiment

Samples were fabricated from a GaAs/AlGaAs single-heterojunction wafer with 2DEG (density $n = 3.8 \times 10^{15}\,\mathrm{m}^{-2}$ and mobility $\mu = 60\,\mathrm{m}^2/\mathrm{V\,s}$) residing at a depth 60 nm from the top surface. Samples were shaped in a Hall bar with AuGe ohmic contacts, and antidot arrays were fabricated over the active area of the Hall bar by electron beam lithography and shallow (30 nm) wet chemical etching. Three types of samples were prepared; a large (50 × 160 andidots) array, a small (5 × 10 antidots) array (depicted in Fig. 2(c)), and a sample with linear array of antidots placed along the side edges (Fig. 2(d)). In all cases, the lattice period was $a = 1\,\mu\mathrm{m}$ and the antidot diameter was $d = 600\,\mathrm{nm}$. The effective radius $d^*/2$ of antidots is larger than the lithographical radius $d/2$ typically by $\sim$100 nm. A Au–Ti Schottky front gate enabled to change

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doi:10.1016/j.physe.2006.03.028

the carrier density over the range $n = (1.3-3.8) \times 10^{15}\,\mathrm{m}^{-2}$. The samples were cooled down to 30 mK in a dilution refrigerator. The diagonal and Hall resistances were measured under a perpendicular magnetic field up to 15 T by a standard ac four probe technique.

3. Results and discussion

3.1. High-field AB-type oscillation

Fig. 1(a) shows the magnetoresistance in the large array (50×160) of antidots at the base temperature 30 mK in the QH plateau transition region between $\nu = 4$ and 6. The trace contains an oscillatory component which is highlighted in the inset in the form of $\Delta\sigma_{xx}$ after subtraction of smooth background. The oscillation is periodic in B and the period is $\Delta B = 8.0\,\mathrm{mT}$. The corresponding effective diameter calculated from the relation $\Delta B = h/eS$ $(S = \pi(d^*/2)^2)$ is $d^* = 810\,\mathrm{nm}$. The value of d^* is in agreement with the lithographical diameter plus the estimated width of depletion region. The oscillation period is weakly dependent on the gate voltage V_G, as reported earlier [4] for the triangular arrays. The high field AB-type oscillation (HFABO) observed here in square lattice and earlier in triangular lattice originates from quantization of flux enclosed by the edge channels formed around individual antidots. In the QH regime, edge channels are formed around individual antidots. Single particle states are so constructed as to enclose an integer number of flux quanta. As the magnetic field is swept, these single particle states pass through E_F one by one, causing periodic change in the conductivity.

Such a picture is along the same line as has been put forward for the AB oscillation in single antidot systems [5,6]. For the antidot array system, however, we have to consider two factors that could kill the oscillation; i.e. lithographical irregularity and ensemble averaging. Fluctuations in the antidot diameter would smear out the oscillatory effect. From the flux quantization condition, it is estimated that the fluctuation in diameter Δd should not exceeds $2h/(\pi eBd)$. For the present case this condition is $\Delta d < 3\,\mathrm{nm}$, which is well beyond the lithographica precision. This led us to suspect the possibility that only a small portion of the whole array gives rise to the HFABO.

In order to check against the possibility and gain insight into the issue of ensemble averaging, we next measured the small (5×10) array sample. Fig. 1(b) shows the corresponding data. The HFABO is evidently more distinct in the small array sample. The oscillation amplitude in this sample, $\sigma_{xx} \sim 0.05\,e^2/h$, is an order of magnitude larger than the large array sample. The ratio of the oscillation amplitude roughly coincides with the square root of the ratio of the total numbers of antidots between the two samples.

Next we address the issue whether the HFABO arises from bulk or edge of the sample, by comparing two samples illustrated in Figs. 2(c) and (d). Figs. 2(a) and (b) show the gray-scale plot of $\Delta\rho_{xx}$ in the range $6 < \nu < 8$ for the two samples. Fig. 2(e) shows the Fourier power spectra of the trace along the dashed lines shown in the gray-scale plot. The magnetoresistance in the sample with antidots only near the edges is dominated by aperiodic fluctuation and the HFABO component, if any, is small. Hence we suggest that the HFABO arises from the whole sample, which is in accordance with the observation that the HFABO is more conspicuous in the QH plateau transition region where current is spread over the bulk of the sample.

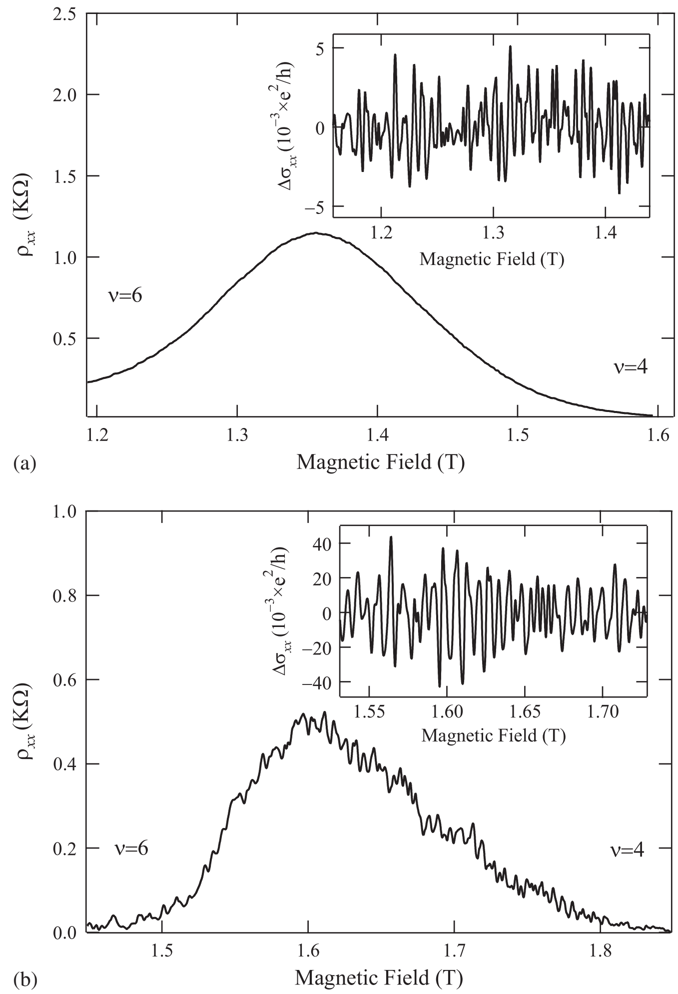

Fig. 1. (a) Magnetoresistance in the QH plateau transition region between $\nu = 4$ and 6 in the large (50×160) array sample at $V_G = -160\,\mathrm{mV}$. The inset shows the oscillatory component of σ_{xx} after subtraction of smooth background. The mean oscillation amplitude is $\Delta\sigma_{xx} \sim 0.005\,e^2/h$. (b) Similar data for the small (5×10) array sample at $V_G = -152\,\mathrm{mV}$. The mean oscillation amplitude, $\Delta\sigma_{xx} \sim 0.05\,e^2/h$, about an order of magnitude larger than the large array sample.

Fig. 3 shows the temperature dependence of the HFABO amplitude in the small array sample. The dashed curve is a fit to the formula

$$A \propto \frac{aT}{\sinh aT}, \quad a = \frac{2\pi^2 k_B}{\Delta E} \tag{1}$$

similar to the temperature dependence of Shubnikov–de Hass effect. This suggests that the B-periodic HFABO

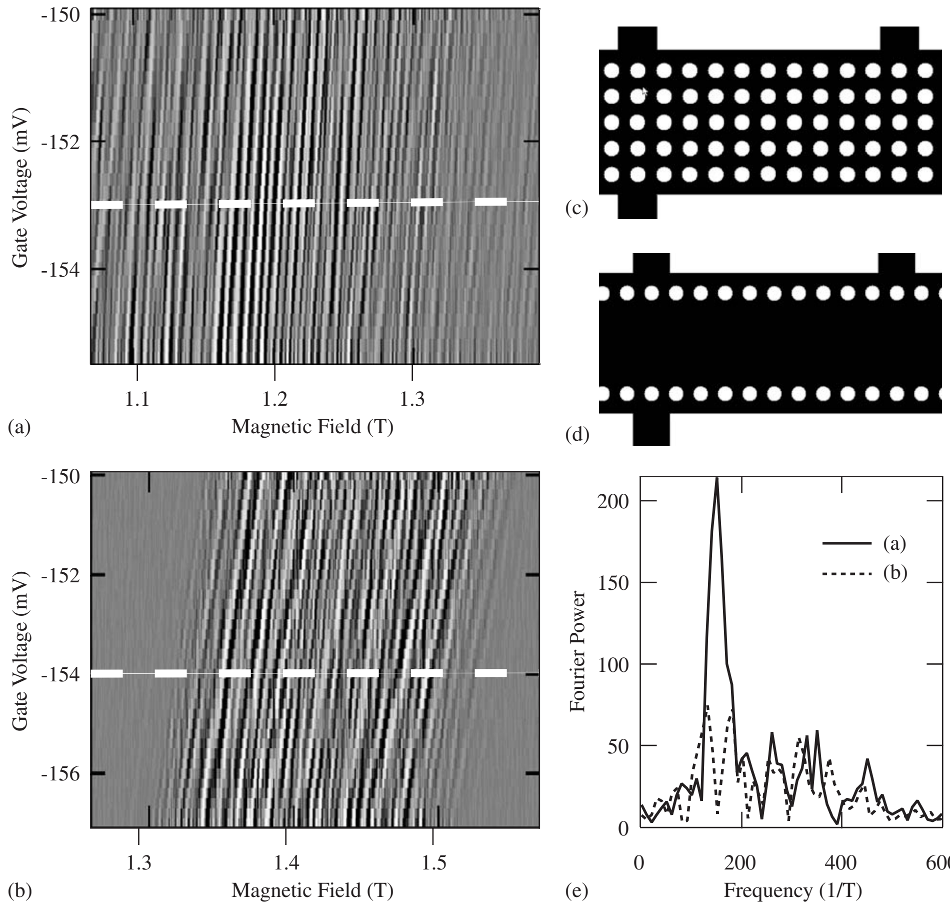

Fig. 2. (a) Gray-scale plot of $\Delta\rho_{xx}$ in the range $6<\nu<8$ as a function of B and gate voltage for the small array sample (depicted in (c)). Periodic oscillation is observed, with the periods $\Delta B = 6.7\,\mathrm{mT}$ and $\Delta V_G = 2.3\,\mathrm{mV}$. (b) Corresponding data for the sample with antidots placed only near the side edges (depicted in (d)). No clear periodicity is observed for this sample. (e) Fourier power spectra obtained from the data in the field range (a) $1.14 \leqslant B \leqslant 1.24\,\mathrm{T}$ and (b) $1.4 \leqslant B \leqslant 1.5\,\mathrm{T}$ along the dashed lines shown in gray-scale plot. The oscillation with clear periodicity is observed for (a), while little periodic component for (b).

reflects the oscillatory fine structure in the density of states which has a characteristic energy separation ΔE. To estimate the value of ΔE we obtained the period ΔV_G of the HFABO with respect to the gate voltage. The oscillation as a function of V_G presented in Fig. 2(a) is caused by periodic crossing of single particle states through E_F induced by sweeping V_G. To derive the energy separation from ΔV_G we used the equation $\Delta E_G = \alpha \Delta V_G$, where $\alpha = \mathrm{d}E_F/\mathrm{d}V_G$ is a conversion factor obtained from the Fermi energy versus V_G relation shown in Ref. [4].

The experimental data are summarized in Table 1. As shown in Table 1, the values of the characteristic energy scale for the oscillatory fine structure in the density of states estimated by two different methods agree with each other.

3.2. AAS oscillation in square array

The inset of Fig. 4 shows low-field magnetroresistance at the base temperature (30 mK) for $V_G = -140$ and 60 mV. The main panel shows the oscillatory part of magnetoresistance near 0 T for different gate voltages, which exhibits the AAS ($\Delta B = h/2eS$) oscillation with the period consistent with the unit cell area ($S = a^2$). To date, the AAS oscillation has been primarily studied in triangular antidot lattices [3,4]. The AAS oscillation in square lattice is reported [7], but the effect is not so clear because of the high measurement temperature. The reason why the AAS oscillation is less likely to occur in square antidot lattices is because the number of ballistic electron trajectories that return to the original position is much smaller than in triangular lattice [8]. The AAS oscillation in the present system is observed when relatively strong negative gate bias is applied. Under such conditions, the electron mean free path is $\sim 1.5-3.0\,\mu\mathrm{m}$, so that there are enough scattering events other than at the antidot boundaries to make the electron trajectory return to the original position.

4. Conclusion

We have investigated the AB-type oscillations in square lattices of antidots with different overall array size in the QH plateau transition regime. The oscillation originates from the fine structure in the density of states created by

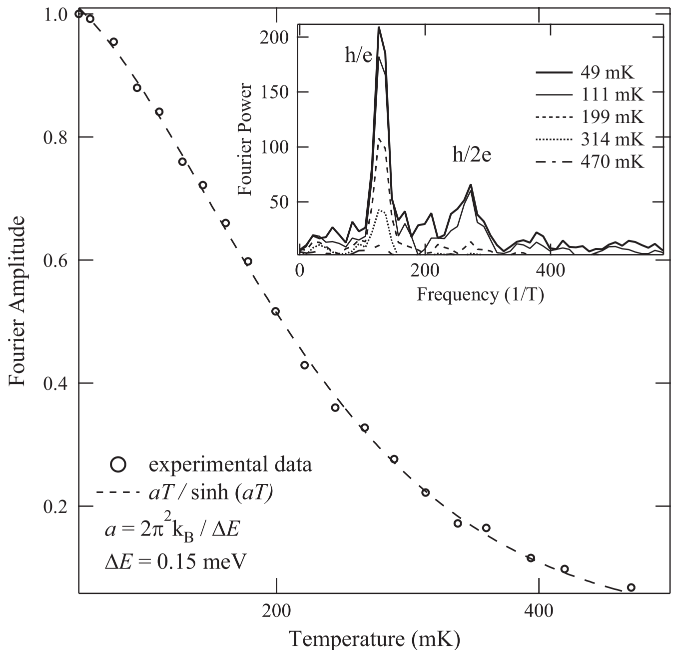

Fig. 3. Inset: the Fourier power spectra of the high-field AB-type oscillation in the small array at $\nu = 4-6$ and -100 mV for different temperatures. Main panel: temperature dependence of the amplitudes of the h/e-peak in the inset and fit to $aT/\sinh(aT)$.

Table 1
Summary of the experimental data: ΔE is estimated from the temperature dependence and ΔE_F from the gate voltage dependence

V_G (mV)	n (10^{15} m^{-2})	ν	ΔV_G (mV)	α	ΔE_F (meV)	ΔE (meV)
−152	2.15	3–4	1.8	0.05	0.09	0.14
		4–6	2.3		0.12	0.12
		6–8	2.8		0.14	0.14
−100	2.55	4–6	2.7	0.04	0.11	0.15
		6–8	3.2		0.13	0.16
−45	3.09	4–6	3.2	0.03	0.10	0.14
		6–8	3.5		0.11	0.14

the quantization of edge states circumnavigating each antidot. This picture is supported by the fact that the characteristic energy scales obtained from the temperature dependence of the oscillation amplitude and from the gate bias dependence agree with each other. Comparison of the three samples suggests that the HFABO arise from the bulk of the sample, although there still remains a puzzling issue why the AB-type oscillation can be observed in a large array of antidots in spite of lithographical irregularity and ensemble averaging.

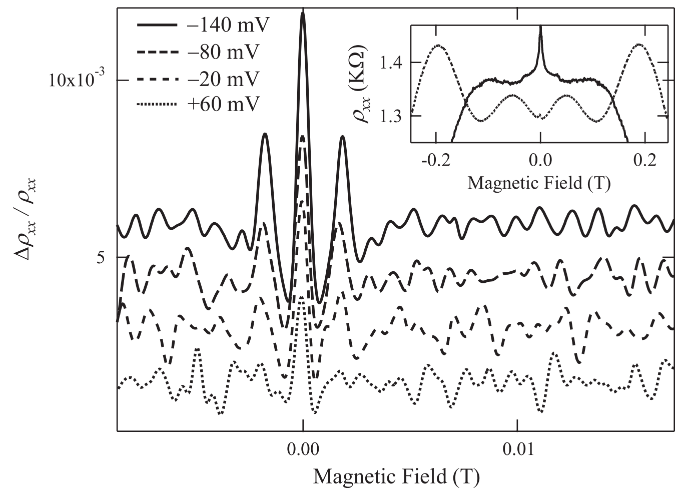

Fig. 4. Inset: low field magnetoresistance in the large array sample at $V_G = -140$ mV (upper curve) and $+60$ mV (lower curve, offset by 0.84 kΩ). Main panel: the AAS ($h/2e$) oscillation with period 1.9 mT. Each trace is offset vertically by 2.0×10^{-3} for clarity. The amplitude decreases with increasing electron mean free path.

Acknowledgements

This work has been supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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