Magnetic Field Tuned Transition of Aharonov-Bohm Oscillations from hc/e to hc/2e Periodicity in the Array of AlGaAs/GaAs Rings

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The variation of Aharonov-Bohm oscillation periodicity and persistent magnetoconductivity have been observed in tlie array of AlGaAs/GaAs rings with diameter of 0.3μm. Magnetic field tuned impurity levels were suggested to be responsible for this behavior. It can be a result of tlie local electron density variation due to the influence of the weak magnetic field on the interference effect. in mesoscopic samples.

I. Introduction

Magnetooscillations in tlie normal metal ring with small diameter due to tlie Aharonov-Bohm effect is one of tlie remarkable phenomena that demonstrated tlie quantum behavior of an electron in solids. These Aharonov-Bohm (AB) oscillations are very sensitive to impurities, because defects introduce tlie additional shift to the electron wave function phase and, consequently, to magnetooscillations of a small single ring at nearly zero msgnetic field[1,2]. Iii small samples, whose size are comparable to tlie phase colierence length L_φ the conductance fluctuations are random because of the interference among all possible trajectories. Tlie results of interference are not averaged, but rather depend on tlie specific arrangement of the scattered centers in the given samples[3]. Tlie change in tlie configuration of the random potential in microstructures gives rise to variation of tlie mesoscopic fluctuation pattern in a specific sample. This configuration can be changed as a result of spontaneous switching[4,5], under the interband irradiation[6,7] and after application of a strong electric field pulse[5,6]. Magnetic field also can influence the impurity level, ancl change in the switching time of a single impurity with magnetic field was observed[8]. However, it is difficult to see the influence of magnetic field on tlie conductance fluctuations because of their random pattern. Another situation exists in the single submicron ring. In this case AB oscillations with the periodicity given by the flux quantum $\Phi_0 = hc/e$ are dominant. Introduction of an additional shift in the magnetic field can change an apparent periodicity of AB oscillations.

In this paper we report the variation from hc/e to $hc/2e$ AB oscillation periodicity in the array of rings tuned by magnetic field. We suggested that the impurities are responsible for this behavior. We indirectly observed also nonmonotonic behavior of the impurity energy which can be connected to a mechanism based

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on the influence of the electron local density on the defect[9].

The test samples were Hall bridges based on AlGaAs/GaAs heterostructures with 2D electron gas. In tlie initial heterostructures tlie electron density was $n_s = 4 \times 10^{11}\text{cm}^{-2}$ and electron mobility $\mu = 2 \times 10^5 \text{cm}^2/\text{Vs}$. The samples witli area 500 x 200μm^2 were split off, and in the middle part between tlie potentiometric probes tlie square bridge was formed witli size $2 \times 2\mu\text{m}^2$. In this bridge a periodic lattice of holes (antidots) was patterned using electron lithography. The lattice periocl d was 0.3 μm, lithography antidot size c = 0.15 μm. Next, tlie lithography samples were etclied using reactive plasma etching, which was stopped before the AlGaAs spacer. The antidot size was larger than the geometric diameter because of tlie depletion region around the antidots, therefore we have a = c + t, where t is tlie width of this depletion region. Thus, our system is different from other antidot lattices which have been studied previously and for whicli $d/a >> 1$[10]. Also our samples have a small size L = 1, where 1- mean free patli in tlie initial heterostructures, therefore the electron transport was quasi ballistic. The geometry of our array is closer to tlie geometry of tlie connected rings with diameter 0.3μm. Tlie magnetoresistance was measured by the four probe method at frequencies 70- 700 Hz in a magnetic field up to 0.5 T at temperature 1.7-4.2 K. We measured two samples with identical parameters.

We found tlie magnetoresistance oscillations which can be connected most clearly witli AB effect, however their beliavior was unusual. Tlie typical curves of this magnetoresistance are shown in Fig.1a. Fig.1b shows the periodicity of AB oscillations. The periodicity is varied from Φ_0/S to $\Phi_0/2S$, where $S = \pi d^2/4$ is the ring area with diameter d. Tlie envelope of the magnetoresistance curve, correlated witli periodicity variation is observed. After several sweepings of B the oscillation picture is slightly changed, in particular, tlie second minimum of the resistivity moves to the higher magnetic field (curve 3), and oscillations with periodicity hc/e move to the higher B too. We swept B 10-20 times and found that the sample begins to reveal hysteresis

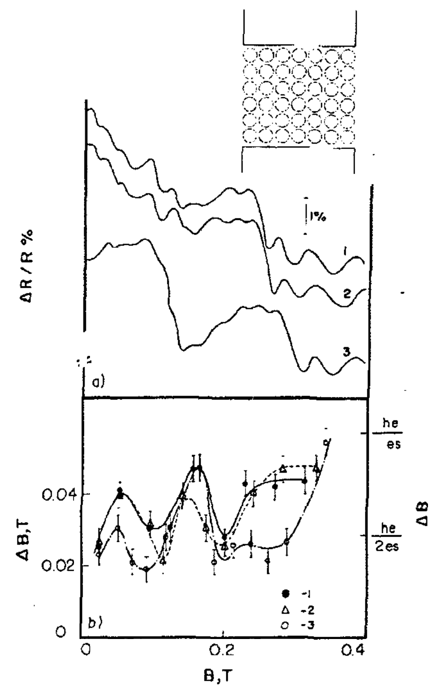


Figure 1: a) Magnetoresistance as a function of magnetic field, T=4.2 K; Insert: Schernatic view of the sample. b) Periodicity of oscillations for the different rnagnetoresistance curves.

behavior. The same situation was observed when we swept B up with low velocity (0.3 T/min) and switched off B after the approach of B_{max} with high velocity (2T/min). Fig. 2 shows some typical magnetooscillation curves when the magnetic field was swept up and down. We observe two features differences from AB oscillations in a single AlGaAs/GaAs ring: decrease of tlie periodicity and hysteresis of the magnetoresistance oscillations. For curves 1,2 the resistivity did not return to the initial state when B was turned off. The sample resistivity was relaxed to this state during 30 s. The magnetic fielcl B was swept up and down 10 times, and magnetooscillations were slightly transformed into the curves 3,4 wliich also reveal liysteresis. For these curves after 30-40 s at zero magnetic field the sample returned to the first state. This behavior was repeated several times. Oscillation periodicity for curves 3,4 is changed from hc/eS to $hc/2eS$ (fig.2). Maximum amplitude of the conductance oscillation was found to be 0.8e^2/h.

We believe that the impurities are responsible for tliis behavior. For the dynamic study of this effect we measured the resistance as a function of time during a smeeping of the magnetic field. Fig. 3 shows four

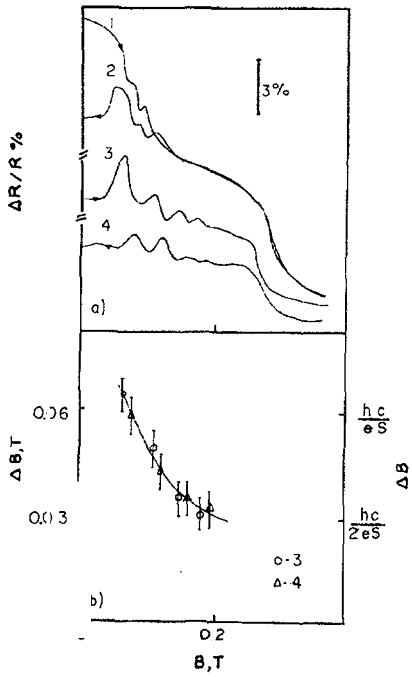
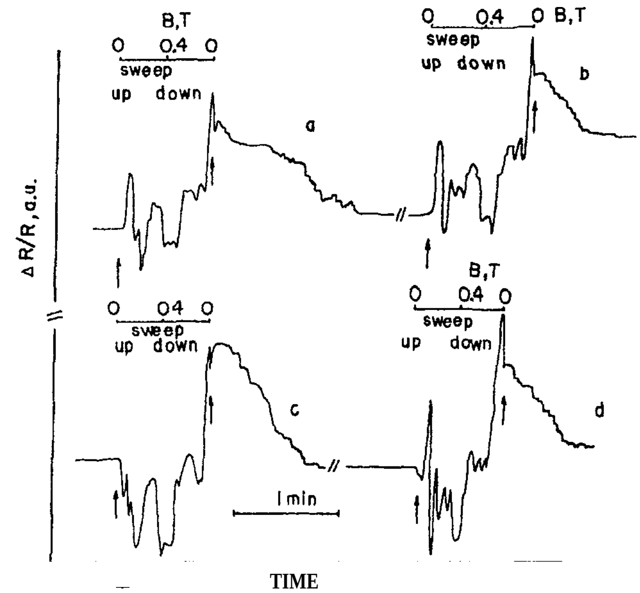


Figure 2: Magnetoresistance with hysteresis as a, function of B: 1,3 - B sweep up, 2,4 - B sweep down; b) Periodicity of AB oscillations for curves 3,4.



Figiire 3: Resistivity as a function of time during a magnetic field sweeping and following relaxation.

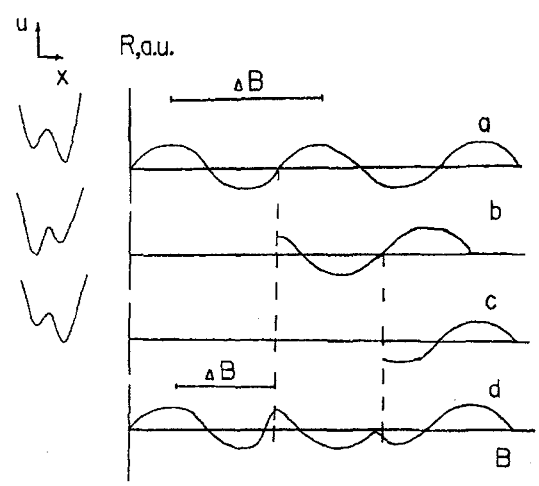


Figure 4: Schematic illustration of the AB periodicity variation due to tlie changing in the impurity state. Insert left: impurity potential at different magnetic field.

curves, measured after each the other. We see, that when magnet c field was swept down, hysteresis of tlie magnetooscillations was observed, and the sample resistaiice was found to be higher than for tlie initial states. When tlie magnetic field is turned of, tlie resistivity hops to tlie initial state. The long tail of tliis relaxation was found. We sce that this tail consist of tlie several steps, wliich correspoiids to the change in tlie state of a single impurity. From the calculation of the steps nuinhcr we can determine that 10-20 impurities were tuned by magnetic field and after hops to tlie initial states. Fig. 3 also shows tliat for curves b and d tlie final resistance is not exactly equal to the initial state. It means tliat the some part of impurities were staying iii tlic new metastable state. The oscillations patterii for each curves are different which is caused by tlie little variation in tlie configuration of the scattering potential due to these long switch time impurities. However, the correlatioii between magnetooscillations curves is high: only oscillations amplitudes are smeared and distinguished more clearly.

In mesoscopic samples, telegraph noise connected to switching of the two-level impurity state lias been observed[4,5]. This switching is related to tunneling iii a double well energy potential with slight assymmetry or activation over this internal barrier[11], and thus, with tlie motion of tlie scatterer from one place to anotlier. In this case tlie interference electron pattern can be affected by this motion[3]. If defect hopping is activated by tlie teinperature (we believe that this mechanism is dominant in our case), activation energy is responsible for the switching time. When the activation energy is larger than the therinal energy, the impurity spends all time in the lower state. The proposed mechanism of the impurity switching influence on the AB oscillations is illustrated in Fig. 4. When the magnetic field increases, impurities hop to tlie other state (Fig. 4b). Configuration of the random potential is changed, therefore the new phase shift to AB oscillations is introduced. In our case magnetic field changes the state of many impurities (a long relaxation time tail was found). Therefore the AB oscillation phase is not changed abruptly, but a smooth transition is observed (Fig. 4d). As the magnetic field increases further, impurities can hop back to the initial state (Fig. 4c), or defects with higher hopping barrier height switch to tlic second state. As a result of the change ill the configuration of the random potential the apparent AB oscillations periodicity is slightly randomized: it is varied between hc/e and $hc/2e$. We also believe that the envelope of magnetoresistance oscillations on Fig. 1 can be connected with impurity hops to the other state. In this case it is a new kind of magnetoresistance due to the changing in the configuration of the random potential. We sec also this magnetoresistance for curve 1 (Fig. 2), however because the oscillations are smeared, analysis of their periodicity is difficult.

For the two-level system the living time t_u and t_d spent in up and down states can be introduced. For tlie system with a barrier when tlie activation mechanism is dominant $t_d/t_u = \exp(E_a/kT)$, where E_a is the activation energy. In our case at $B = 0$, $t_d >> t_u$ and $E_a > kT$; in a magnetic field this situation is reversed, $t_d << t_u$, i.e. E_a decreases and changes the sign. The magnetic field influence on the telegraph noise in a mesoscopic sample was observed in Ref.[8], however tlie mechanism of this effect was not clear. It is well known that the activation energy increases with B for tlie conduction band Γ-valley. Also it is necessary to apply high magnetic field ($> 3T$) to shift the impurity energy to tlie value kT due to the Zeeman splitting, if g-factor is equal 2, and magnetic momentum is different for these two levels in a double well defect. Another mechanism has been proposed by Al'tshuler and Spivak[9]. Interference of the electron waves is responsible for tlie local electron density. Magnetic field influences the interferente due to AB effect and thus electron local density is changed, therefore the energy of the nearly located impurity is varied too. The Al'tshuler-Spivak mechanism should lead to a random fluctuation of the local impurity energy, because of the random pattern of tlie electron density in the disordered scattering potential. The autocorrelation function of the impurity energy is equal[9]:

$$< E(B)E(O) > \approx (h\omega_c)^2 l/L \approx (h\omega_c)^2 \qquad (1)$$

for L N I. ω_c-cyclotron frequency. In tlie array of rings the electron interference is determined by the ring geometry and not by the specific impurity configuration as in mesoscopic samples. Therefore tlie impurity energy should oscillate with periodicity Φ_0, and the amplitude of this oscillation should increase linearly with magnetic field. As can be seen from Figs. 1, 2 transition of AB periodicity is observed at R $\approx$ 0.2 T, therefore $E_a \approx h\omega_c$ N 0.35meV. This energy is comparable to thermal energy, therefore t_u N t_d. As we mentioned above, when the magnetic field was swept down with high velocity, the sample resistance hopped to tlic other state. A similar effect. exists in heavy doped GaAs and AlGaAs alloy system after illumination of the sample by light at low temperature- persistent photoconductivity[12]. In our case irnpurity switching time lies in tlie interval 1-50 s, therefore when the magnetic field is turned off at a higher rate, some defects were staying in the metastable state due to the barrier. The sample was switched to the state with another resistivity in a zero magnetic field, and we observed persistent magnetoconductivity and hysteresis behavior (Figs. 1-3). This persistent magnetoconductivity can be positive (Fig. 2) or negative (Fig. 3). We also see the long tail of the impurity relaxation arising from the different switching time in the ensemble of impurities. Some defects have a longer relaxation time, therefore the picture of the magnetooscillations differs from the initial. However, after irradiation by light or heating of the sample up to room temperature, we turned off the device to tlie initial state. These experiments were carried out during two months, and during all the time we ohserved the impurity switching induced by tlie weak magnetic field.

It should be noted that. recently new magnetooscillations with periodicity hc/ea^2 have been observed in samples which contain 10^5 antidots[13,14]. As was suggested in Ref. [14], it is not due to AB effect, and quantization of the periodic orbits (QPO) is responsible for these oscillations. The next difference in our experiments can be emphasized: QPO oscillations appear only at $B > 0.5T$ and $T < 1.5K$ in contrast to AB oscillations which are seen at smaller magnetic field and at $T = 4.2K$. The thermal broadening of energy levels, which depends on the magnetic field value, is responsible for the behavior of QPO oscillations.

In summary, we have observed the influence of the weak magnetic field on the impurity state in the system with an array of submicron rings. Novel magnetoresistance appeared because of the changing in the configuration of the random potential by magnetic field. Metastability of these states is responsible for the hysteresis of the magnetoresistance and persistent magnetoconductivity. A more delicate effect connected with sensitivity of the AB oscillation periodicity to the impurity state has been found: variation of the apparent periodicity between hc/eS to $hc/2eS$. The Al'tshuler-Spivak mechanism, because of the change in the local electron density which leads to the impurity energy shift, is responsible for this behavior.

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References

1. S. Washburn and R. A. Webb, Rep. Prog Phys. 55. 1311 (1992).
2. A. D. Benoit, S. Washburn, C. P. Umbach, R. B. Laibowitch and R. A. Webb, Phys. Rev. Lett. **57,** 1765 (1986).
3. B. L. Al'tshuler and R. Z. Spivak, JETP Lett. **42,** 447 (1985).
4. M. J. Kirton and M. 3. Uren, Adv. Phys. 38, 367 (1989); K. S. Ralls, R. A. Buhrman, Phys. Rev. Lett. 60, 2434 (1988): D. E. Beutler, T. L. Meisenheimer and N. Giordano, Phys. Rev. Lett. **58**, 1240 (1987).
5. G. M. Gusev, Z. D. Kvon, E. B. Ol'shanetskii, V. Sh. Aliev, V. M. Kudryashov and S. V. Palesskyi, J. Phys.: Cond. Matter **36**, 6507 (1939).
6. G. M. Gusev, Z. D. Kvon and E. B. Ol'shanetskii, Sov. Phys. JETP **74,** 735 (1992).
7. S. J. Klepper, O. Millo, M. W. Keller, D. E. Prober and R. N. Sacks, Phys. Rev. **B** 44, 8380 (1991).
8. N. M. Zimmerman, B. Golding and W. H. Haemmelle, Phys. Rev. Lett. **67,** 1322 (1991).
9. 13. L. Al'tshuler and B. Z. Spival, JETP Lett. 49, 671 (1989).
10. K. Ensslin and P. Petroff, Phys. Rev. **B41,** 12307 (1990); G. M. Gusev, V. T. Dolgopolov, Z. D. Kvon, A. A. Shashkin, V. M. Kudryashov, L. V. Litvin and Yu. V. Nastaushev, JETP Lett. **54,** 364 (1991); A. Lorke, J. P. Kotthaus and K. Ploog, Phys. Rev. B **44,** 3447 (1991).
11. C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. 55, 859 (1985).
12. D. V. Lang and R. A. Logan, Phys. Rev. Lett. **39,** 635 (1977).
13. F. Nihey and K. Nakamura, Pliysica B**184**, 398 (1993).
14. D. Weiss, K. Richter, E. Vasiliadou and G. Lutjering, Proc. 10th Int. Conf. on EP2DS (Newport, USA, 1093).