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Quantum Interference Effect in Selectively Doped GaAs-AlGaAs Submicron Ring

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We have demonstrated magnetoresistance (MR) oscillations due to Aharonov-Bohm effect in MBE grown selectively doped GaAs-AlGaAs submicron ring structures made by electron beam lithography and dry etching techniques. These oscillations arise from quantum interference between electron waves which still reserve its phase coherence inspite of the presence of the elastic scattering. We compare the MR results of three samples (wire, narrow ring and fat ring) and discuss the condition to get larger resistance modulation which is important for device applications.

1. Introduction

Recent development in microfabrication techniques has made it possible to study electronic properties in submicron structures and opened the new field of physics in so called mesoscopic[1)] system together with the possibility of the new device.[2)] New effects have been observed as the conductance fluctuations in a narrow wire[3)] and Aharonov-Bohm magnetoresistance oscillations[4)-6)] in small metallic rings, both of which arises from the quantum interference between electron waves. Experiments[4),5)] in rings have been mainly performed in the highly disordered metalic system ($l \ll L$, where l and L are the elastic mean free path and the sample size, respectively) . Both experiments and theories[7),8)] have confirmed that oscillations have an amplitude of the order of e^2/h independent of the degree of the disorder and the sample size at absolute zero temperature because of the unidentified correlation between each conduction channels.[9)]

To apply this interference effect to the devices so called electron wave transister proposed by S.Datta, the difficulty arises from too small amplitude of oscillations which is universally determined in the disordered system. S.Datta predicts[2)] that a large amplitude of modulation can be achieved in the ballistic transport regime which, in future, may be possible in III-V compound semiconductors using higly sophisticated microfabrication tecniques.[10)]

We fabricated small rings with a diameter of 1 µm and with a different aspect ratio (diameter/width) using selectively doped GaAs-AlGaAs quantum well structure and compared the MR oscillations.

2. Sample Preparation

The starting film was grown by MBE and consisted of a 1 µm thick non doped GaAs conductive layer sandwitched by 600A thick Si doped ($2x10^{18}$ cm^{-3}) AlGaAs barrier layers with 60A thick non doped AlGaAs spacer layers, as shown in Fig.1. The carrier concentration and the mobility of the film sample at 4.2K were $1.6x10^{12}$ cm^{-2} and 17200 cm^2/Vs, respectively. The small Al ring pattern was formed by 50KeV electron beam lithography followed by the lift off process.

The ring structure was made by 1KeV Ar ion beam sputtering using the Al pattern as a etching mask. We made two ring samples with a different aspect ratio and a singly connected broken ring in which one arm of the ring was intentionally cut (ref. inset in Fig.3). The line width and the diameter were determined by the SEM observation, however, the actual width for electrical conduction is smaller than the apparent width because of the existence of the surface depletion layer which is roughly estimated to be 0.1μm.

3. Results and Discussions

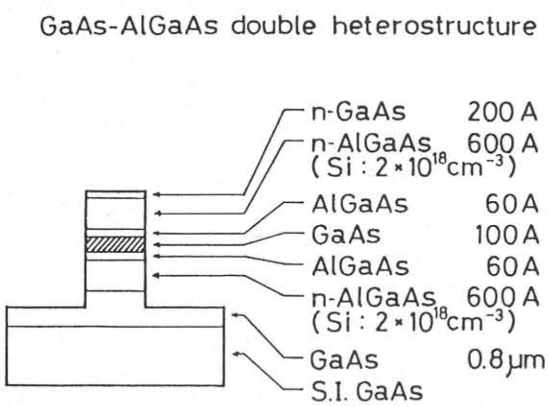
In order to observe the quantum interference effect, the sample size should be less than the inelastic scattering length (l_{in}) and the thermal diffusion length (L_T) which comes from the smearing of the Fermi distribution function at finite temperature. In our sample like Si-MOSFET[11], the latter length is longer than the former one, which indicates that the coherence of the electron wave is determined by the inelastic scattering which is dominated by electron-electron interaction at low temperature.

The length l_{in} can be determined by using the following theoretical equation with fitting parameters (A, l_{in})[12].

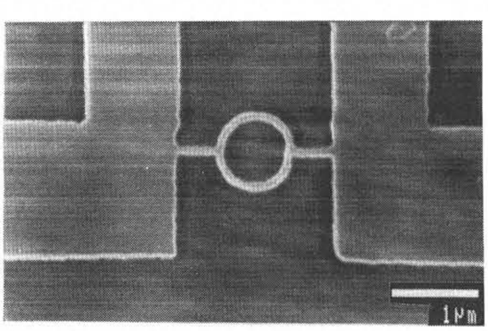
$$G(B)-G(B=0)=\frac{e^2}{2\pi^2\hbar}A\left[\frac{3}{2}\psi\left(\frac{1}{2}+\frac{B_2}{B}\right)-\psi\left(\frac{1}{2}+\frac{B_1}{B}\right)-\frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_{in}}{B}\right)-\ln\left(\frac{B_2^{3/2}}{B_1 B_{in}^{1/2}}\right)\right]$$

$$B_1=B_{el}+B_{so}\ ,\quad B_2=B_{in}+\frac{4}{3}B_{so}$$

where $B_j=\hbar/4el_j^2$ and j represents so (spin-orbit), in (inelastic scattering), and el (elastic scattering), respectively. The



(a)



(b)

Fig.1 (a) Cross-sectionsl view of the sample (b) SEM micrograph

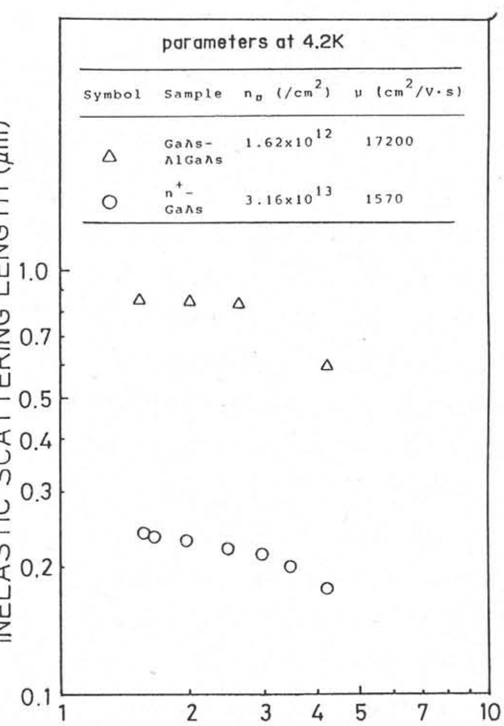
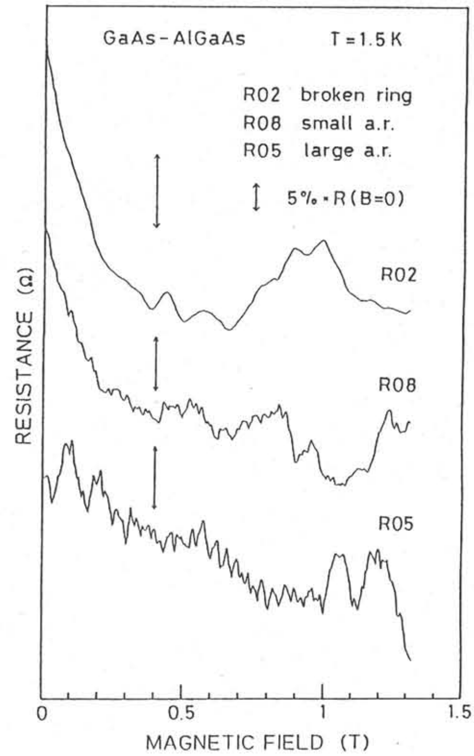


Fig.2 Temperature dependence of the inelastic scattering length (l_{in})

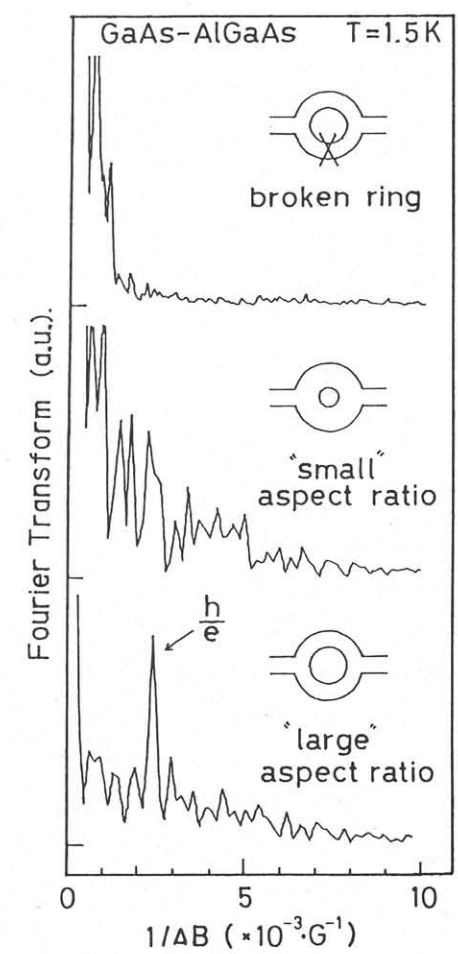
results observed in doped GaAs film[13] is also shown for comparison. As seen from the figure, l_{in} is about 0.8μm at about 4.2K which is much longer than that of doped GaAs. Actually, we made the ring sample with a same size in which MR oscillations could not be observed because of its much shorter l_{in} than the diameter.

Figure 3 shows (a) the magnetoresistance and (b) its Fourier transform with respect to the magnetic field. Three different samples were measured. They are (R02) the singly connected broken ring in which the one arm is intentionally cut, (R08) the ring with the smaller aspect ratio and (R05) the ring with the larger aspect ratio. Fine structures can be observed in the ring sample superimposed on the background MR due to the weak localization effect, while only aperiodic conductance fluctuations with the larger field scale are observed in the singly connected broken ring. The Fourier transform (FT) shows the clear peak only for R05, the sample which has the larger aspect ratio. The FT of R08, the sample which has the smaller aspect ratio, shows the complicated structure around the expected position of h/e oscillation, while no evidence of the peak can be identified for the broken ring, R02. The reason why a clearer peak can be observed in R05 than in R08 is that the transverse mode increases with increasing the width, which reduces the coherence of electron waves.

The corresponding diameter to the period



(a)



(b)

Fig.3 (a) Magnetoresistance and (b) Fourier transform of three samples. R02:broken ring, R05:ring with d_{out}=0.9μm and d_{in}=0.3μm, R08:ring with d_{out}=1μm, d_{in}=0.2μm of h/e peak is rather close to the innerside diameter. This suggests that the surface depletion layer exists on the side wall of the ring. The diameter should be the average of the innermost and outermost diameter if the depletion layer of the equal thickness exists at inner and outer side surface. The actual width may not be uniform along the side wall though the reason is not clear.

The amplitude of the oscillation is about 2 % in a relative value of the resistance or 0.1 e^2/h in the absolute value of the conductance. This value is smaller than the theoretical predictions for two different cases. (the one for the disorderd system and one for the ballistic regime). The possible reason is as follows. (1) At first the present device is not in the ballistic transport regime. (2) The inelastic scattering length is comparable to or shorter than the diameter of the ring. The amplitude is predicted to decrease in proportion to $\exp(-\pi d/l_{in})$.[5] (3) Many transverse mode exist because of the condition $\lambda_F \ll W$, where λ_F and W are the Fermi wave length and the width, respectively. (4) The present structures is not optimum to observe the maximum modulation. The structure should be designed to induce the minimum electron wave scattering.

4. Conclusion

We have fabricated submicron rings in MBE grown selectively doped GaAs-AlGaAs double heterostructures by electron beam lithography and dry etching techniques. It was shown that a large aspect ratio is important to observe large MR oscillations which is necessary for device applications. It is also important to reduce a ring diameter and to guide single mode.

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