Negative magneto resistance in an Si delta-doped GaAs nano-structure

M Nishikawa*, M Yamaguchi and N Sawaki
Nagoya University, Department of Electronics
Chikusa-ku, Nagoya 464-8603, Japan
E-mail: sawaki@nuee.nagoya-u.ac.jp

Abstract. The negative magneto-resistance has been studied in a small open cavity made by a Si delta doped GaAs. The weak localization (WL) regime has been found and the phase coherence length of the order of 120nm was determined. The deviation from the WL regime was found out if the wire widths connected to the electrodes were nearly equal to or less than the coherence length. The results suggest that we have succeeded in choosing a particular path of the percolation transport in the cavity.

1. Introduction
The negative magneto-resistance (NMR) in semiconductor nano-structures has long been studied for more than twenty years. In a narrow channel made with a two dimensional electron gas (2DEG) in an AlGaAs/GaAs hetero-interface, Thornton et al [1] found an NMR due to quantum interference effect. The NMR was realized if the channel (wire) width was less than the phase coherence length of the carriers[2]. In a wide 2DEG sample, on the other hand, the NMR due to the breakdown of the weak localization (WL) has been found at low temperatures[3]. The magnitude of the WL-NMR as a function of the magnetic field was modified by the boundary scattering[4] or the introduction of an array of strong scattering potential such as anti-dots[5]. The NMR in a narrow wire made of an Si delta doped GaAs has also been investigated[6], where two dimensional model for the WL is adopted and the coherence length of the order of 130nm is determined. As for the origin of the NMR in a delta-doped GaAs layer, a model based on semi-classical transport has been proposed[7], where the authors found an NMR even in a wide sample at high temperatures up to 40K. They accounted for the NMR by using a percolation transport model with narrow channels.

Recently, NMR has also been found in an AlGaAs/GaAs heterostructure[8]. The results in AlGaAs/GaAs and Si delta doped GaAs are similar to each other in several aspects. Firstly, we find the NMR at relatively high temperatures, and secondly the magnetic fields where we find the NMR are more than one order of magnitude higher than those shown in AlGaAs/GaAs hetero-structures. In both cases, the presence of strong random potential in the 2DEG is expected to play the key role. The classical percolation transport under a magnetic field is also apparent in a composite of nanoparticles[9] and a quantum dot net-work[10]. NMR was also found out in an artificial cavity made on a 2DEG of GaAs[11], where the ballistic transport of an electron under a magnetic field plays the key role. Thus the semi-classical transport has still to be studied.

In this paper, the behaviour of the NMR in a small cavity made of an Si delta doped GaAs is studied at 4.2K. We will show that the WL scheme in the NMR is not applicable to a small cavity connected to two narrow wires, the widths of which are less than the phase coherence length.
2. Sample preparation and experimental methods
The Si delta doped GaAs was grown at 500°C by MBE on a semi-insulating (001)GaAs substrate. Following the growth of 500nm thick buffer layer, Si was deposited which was covered by a 150nm thick GaAs top layer. The SIMS analyses showed that the doping density of Si is at 1x10¹³cm⁻² while the Hall measurements showed that the electron density and mobility were 4.4x10¹²cm⁻² and 1,200cm²/Vs at 4.2K, respectively. The low mobility is simply due to presence of Si⁺ donors[7].

The magneto-resistance (MR) was evaluated at 4.2K as a function of the magnetic field applied perpendicular to the sample surface. The MR for the as grown sample exhibited Shubnikov-de Haas (SdH) oscillation. By the FFT analyses, we got two peaks suggesting the presence of parallel conduction with carrier concentrations of 1.5x10¹¹cm⁻² and 5.3x10¹¹cm⁻², due to the third and second subband, respectively[7]. The mobility in the higher subband is estimated to be 4~8,000cm²/Vs[7].

By using a photo- and an electron beam (EB) lithography systems, a Hall bar sample was fabricated to measure the MR. The widths of the current and voltage fingers were 7~10µm wide and a small cavity was fabricated at the centre of the Hall bar as shown in Fig.1. The cavity sample is a rectangle of around 450nm x 500nm connected to the Hall fingers via narrow wires (leads) of 80 ~ 300 nm wide. For the sake of comparative investigation, four types of samples were prepared. Sample A (Fig.1(A)) has two narrow wires, B has only one narrow wire, C consist of only a lead wire portion, and the Sample D has two wires but at different symmetry. In all cases we varied the width of the lead wire to analyze the NMR. Since the width of the wire is more than ten times smaller than the width of the Hall bar, the apparent resistance is determined by the wires.

3. Experimental results and discussions
Figure 2 shows typical MR as a function of the magnetic field. We find strong negative-magneto-resistance (NMR) at low fields. In an un-patterned as-grown sample, the NMR is limited to fields less than 0.5T, but in samples with small structure the NMR persisted up to 7T. At high fields, we can recognize the superposition of the SdH oscillation along with a weak fluctuation due to universal con-
ductance fluctuation (UCF) [12]. The UCF component became strong in wires wider than 150nm and was more enhanced by increasing the wire length. The FFT analyses give a coherence area of the order of 1,000nm².

The main interest in the present paper is the strong NMR around the zero-magnetic field, which is depicted in Fig.2(b). We can see that the strong NMR component is associated with a weak oscillatory component. The behaviour of the NMR peak at zero-magnetic field is very similar to those found in a cavity samples made of a GaAs/AlGaAs hetero-structure[11]. But we should note that the range of the magnetic field is more than ten times higher in the present case. We found that the period of the oscillatory component depends on the size of the wire, i.e., the narrower the wire is, the shorter the period becomes. This was more evident in samples C. Thus the origin is attributed to some kind of interference not in the cavity but in the wire. The exact analyses will be due for further studies.

Since the resistance minimum (conductance peak) could not be fit to a Lorentzian[11], we examine the data with the WL model[6]. In this model, the conductance peak for the 2DEG sample is expressed by:

$$\delta G = \left\{ \frac{W e^2}{\pi h L} \right\} [\psi(1/2 + z) \cdot \ln(z) ]$$

where

$$\frac{1}{z} = \frac{8 \pi e B L}{\hbar}$$

In equations (1) and (2), $W$ and $L$ are the width and the length of the wire, respectively, $\psi(z)$ the digamma function, $L_\phi$ is the coherence length. By fitting the experimental results to equation (1), we can determine the coherence length. On the other hand, equation (1) shows that the $\delta G/G$ should be proportional to $B^2$ at low magnetic fields.

In Fig. 3 the normalized magneto-conductance $\delta G/G$ were plotted for various samples. We found the behaviour was well described by equation (1) in most samples and we determined the coherence length. The results for typical samples are summarized in Table 1. The coherence length for sample B and C were of the order of 70nm and 120nm, respectively, irrespective to the wire width. These values are nearly equal to that reported earlier[6]. It is notable that we got the coherence length of 117nm even in sample C-100 where the wire is 100nm wide. This fact suggests that the WL in sample C is

![Graph](image)

**Figure 3.** $\delta G/G$ as a function of the magnetic field. The straight broken line represents the slope of $B^2$.

| Sample | W(nm) | $\alpha$ at low fields | $L_\phi$ (nm) |
|--------|-------|------------------------|---------------|
| A-23   | 135   | 1.3                    | --            |
| A-46   | 260   | 2.0                    | 90            |
| B-26   | 140   | 2.0                    | 73            |
| C-100  | 100   | 2.0                    | 117           |
| D-47   | 100   | 1.5                    | --            |
organized not only within the wire but also in the Hall bar near the wire. In sample A and D we could not fit the experimental curve to equation (1) if the wire width was less than 150nm (In Fig.3, the $\delta G/G$ does not obey the $B^2$ dependence for samples A-23 and D-47). Therefore, we might conclude that the WL model does not hold for a small cavity connecting with two narrow wires.

The apparent coherence length of 120nm in sample C is nearly equal to the estimated mean free path of the 2DEG. Moreover the UCF for samples with wide wires showed same order of the coherence length. Therefore the coherence length in the rectangle cavity of Sample A or D should be of the same order, which is less than the size of the cavity under study. That is, the formation of a ballistic trajectory reflected on the potential wall of the cavity will be ruled out. Alternatively, semiclassical percolation transport should be applied. In the present samples, the percolation network should be modified by the localized coherent trajectories organized by the potential fluctuations in small area[7]. Incidentally, the shape of the WL peak is determined by the statistical average of the localized trajectories of various sizes. So, if the size of the cavity is large enough, we should have the same WL peak. But in the present case, the cavity is not large and the number of the localized trajectories which could commit to the sample conductance is very limited. As the result, we should find different behaviour of the WL peak.

If the wire width is less than the coherence length, all the localized coherent trajectories in the cavity will be independent from those outside the cavity. So we could find out one of the trajectories nearby through the narrow wire which is functioning as the probe. In order to limit the independent trajectories to a small number, the size of the cavity must be small enough. And to find a specific (not statistical) network, two or multiple terminal configuration will be essential in agreement with the experimental observation. The manner of the probing should be determined by the relative position of the local potential near the terminal wires. Actually, the behaviour of the conductance peak varied from sample to sample in case of the type A or D.

In conclusion, we have found the WL regime is not hold in a small cavity connected to electrodes through narrow cannels. The breakdown of the WL regime suggests that we could have picked up a particular localized trajectory through a narrow channel (wire) out of a few (several) trajectories near the electrode. If the cavity is equipped with multiple wires, each wire (probe) should give a different result which is determined by the potential distribution nearby. This might works as a kind of multiple-ports signal processor.

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*present address; Fujitsu Ltd., Tokyo 197-0833, Japan
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