Percolation transport in an AlGaN/GaN heterostructure

N. Sawaki¹²³, XX. Han², Y. Honda², and M. Yamaguchi²
¹ Dept. Electrical Engg., Aichi Inst. of Technology, Yakusa, Toyota, 470-0392 Japan
² Dept. Electronics, Nagoya University, Chikusa-ku, Nagoya 464-8603 Japan
³ Nagoya Industrial Science Research Institute, Chikusa-ku, Nagoya 464-0819 Japan

Abstract. Magneto-transport in an AlGaN/GaN heterostructure has been studied at 4.2K and it was found that the magneto-resistance is negative at low fields. The negative components disappeared by inserting a thin AlN film between the AlGaN barrier layer and the GaN layer. The negative component is attributed to the presence of alloy disorder at the hetero-interface. It increases linearly followed by saturation, which is characteristic to the percolation transport in random potential.

1. Introduction
AlGaN/GaN hetero-structure attracts much attention in the progress of high frequency/high power transistors. Since the III-nitrides have large energy band gaps, hetero-structures made of III-nitrides shows large band offsets. As the results, we might achieve an electron device with superior performances. But, an alloy such as AlGaN or GaInN has large potential fluctuations due to random distribution of the elements, which in turn affects the transport properties at hetero-interfaces. This fact is in contrast to the case of AlGaAs/GaAs heterostructure where the alloy scattering has rather a fractional role in the electron mobility [1]. In spite of a long history in the studies of AlGaN/GaN, only a few studies have been reported to the magneto-transport phenomena.

In this study, we have investigated the magneto-resistance in an AlGaN/GaN heterostructure and found that the magneto-resistance at low fields is negative, while it is positive in an AlN/GaN heterostructure. And the appearance of the negative components is attributed to the presence of percolation transport in the random distribution of scattering potential.

2. Samples
The samples were made by metal-organic vapour phase epitaxy (MOVPE) on a (0001) sapphire substrate [2]. Following the deposition of a 30nm thick low temperature GaN buffer layer, a 1.0µm thick nominally non-doped GaN layer followed by a 20 ~25 nm thick AlxGa1-xN (x=0.15~0.30)

Table 1. 2DEG density and mobility in AlxGa1-xN/AlN/GaN hetero-structure at 17K

| Sample | AlN thickness (nm) | Al composition (x) | 2DEG density ($10^{11}$cm$^{-2}$) | Mobility (cm$^2$/Vs) |
|--------|-------------------|--------------------|-------------------------------|-------------------|
| #01    | 0                 | 0.15               | 5.5                           | 6,640             |
| #02    | 0                 | 0.20               | 8.4                           | 5,690             |
| #03    | 0                 | 0.30               | 12.3                          | 3,810             |
| #11    | 0                 | 0.24               | 10.0                          | 6,680             |
| #12    | 1                 | 0.24               | 9.6                           | 26,100            |
| #13    | 2                 | 0.24               | 11.1                          | 13,400            |
barrier layer was grown at 1080 °C. In some samples, a thin AlN layer was grown between the GaN layer and the AlGaN barrier layer. In order to characterize the electronic properties, the 2DEG density and mobility were investigated with van der Pauw configuration at low temperatures. Typical results are summarized in Table 1. The electron density was $5 \sim 12 \times 10^{12} \text{ cm}^{-2}$ depending on the Al composition in the barrier layer, that is attributed to different confinement efficiency due to different strength of the piezo-electric field induced at the hetero-interface. The electron mobility was investigated as a function of the temperature. We found that the mobility is determined by alloy disorder at the hetero-interface [2].

3. Magneto-transport measurements
Magneto-transport at 4.2K was analyzed under magnetic field applied normal to the hetero-interface up to 7 Tesla. Typical results for samples #01~#03 are depicted in Fig.1(a). It is obvious that the magneto-resistance shows Shubnikov-de Haas (SdH) oscillations at high magnetic fields. In a sample with high Al composition exhibits weak SdH oscillation reflecting the low electron mobility in the sample. In all samples under study, we have negative magneto-resistance components at low fields. This is the main interest of the present study.

![Fig.1. Normalized resistance R as a function of the magnetic field in AlGaN/GaN heterostructure with (a)different Al composition (Sample #01~#03) and (b)different AlN thickness (Sample #11~#13).](image)

Similar measurements were performed for a series of samples with an AlN intermediate layer (sample #11~#13) and the results are displayed in Fig.1(b). We can see that the negative magneto-resistance component at low fields disappears by the insertion of a thin AlN layer. In case of the sample with a 2nm thick AlN layer, the AlN layer would act as an actual potential barrier to the 2DEG at the hetero-interface. Thus we might conclude that the negative component is attributed to the AlGaN alloy used as the barrier layer or the presence of alloy disorder at the hetero-interface.

In order to confirm the fact, the nature of the scattering events was investigated. By analyzing the amplitude of the SdH oscillation as a function of the magnetic field (Dingle plots)[2], the quantum scattering time in each sample was determined as summarized in Table 2, where the transport scattering times were also depicted, determined by the corresponding electron mobility at 17K. As shown in Table 2, by inserting a thin AlN intermediate layer, the transport scattering time or the electron mobility was increased by a factor. The scattering time deduced from the SdH measurements (quantum scattering time), on the other hand, was not changed much. As the result, the ratio of the transport scattering time against the quantum scattering time became as large as 13~14 in a sample with 1~2 nm thick AlN intermediate layer. This fact suggests that short range scattering events such as interface roughness and/or alloy disorder predominates the scattering events in samples without an AlN intermediate layer, while a long range scattering (presumably non-uniform polarization fields) predominates in a sample with AlN layer. In conclusion, the negative magneto-resistance is associated with the short range scattering centres due to interface roughness and/or alloy disorder.
Table 2. Transport and quantum scattering time and their ratio

| Sample | Transport Scattering Time (ps) | Quantum Scattering Time (ps) | Ratio |
|--------|--------------------------------|-----------------------------|-------|
| #11    | 0.84                           | 0.22                        | 3.8   |
| #12    | 3.26                           | 0.23                        | 14.2  |
| #13    | 1.68                           | 0.13                        | 13.0  |

In Fig.1, the magneto-resistance at high fields is modified by the SdH effect which oscillates along a base line. As was shown by Katsuno et al [3], the base line is well expressed by $\alpha B^2$ at low fields ($\alpha$ is an adjustable parameter). Adopting the method, the behaviour of the positive/negative components at low fields were extracted and the results are depicted in Fig.2. The plots shown in Fig.2 suggest that the positive/negative component increases at low field followed by saturation. Careful investigation of the positive components for samples #12 and #13 suggests that we have a normal magneto-resistance components expressed by $\delta R(B) \sim 1/(\sigma + \beta B^2)$, where $\sigma$ is the conductivity at zero magnetic field and $\beta$ is a parameter representing the magneto-resistance [4]. This normal component should show quadratic increase as $B^2$ followed by saturation in agreement with the experimental observation. While, in samples without an AlN interlayer (Sample #01~#03, and #11) the negative component increase linearly followed by saturation. This is the point of the present investigation.

4. Origin of the negative magneto-resistance: Percolation transport in random potentials

In the present samples, the SdH effect appears at fields higher than 3 T. This suggests that the negative/positive components at low fields as shown in Fig.2 should be accounted for neglecting the formation of Landau levels. According to the semi-classical theory for the magneto-transport, the magneto-resistance is positive irrespective to the nature of scattering events and we may expect the component described as $\delta R(B) \sim 1/(\sigma + \beta B^2)$, as described earlier [4]. This is just the case observed for samples with a thin AlN layer. The negative components found in samples without AlN layer, on the other hand, must be attributed to a different mechanism.

Almost three decades ago, negative magneto-resistance was found in various materials/structures, which was attributed to quantum interference effect [5] or weak localization [6]. But the interference effect may not be applicable to the present case, because the electron mobility/transport scattering time is not so long at 4.2K. The positive magneto-conductance (or the negative magneto-resistance) due to weak localization is represented by [7]

$$\delta G = \{We^2/\pi hL\}[\Psi(1/2 + z) - \ln(z)]$$

(1)

where
In equations (1) and (2), \( W \) and \( L \) are the width and the length of the sample, respectively, \( \psi(z) \) the digamma function, \( L_\phi \) is the coherence length. Equation (1) shows that the \( \delta G/G \) should be proportional to \( B^2 \) at low magnetic fields, which is not the present case. Therefore the WL should be omitted in our observation.

Recent studies on the transport in random networks often find negative magneto-resistance at low fields [8,9]. Similar phenomenon was found in a delta-doped GaAs sample [3] or an antidote lattice [10], where the 2DEG transport is violated by random distribution of scattering potentials. The characteristic behaviour of the negative component is such that it increases linearly at low fields followed by saturation, which is just the case observed in Fig.2. Katsuno et al [3] studied the case in an Si delta doped GaAs, where the transport is due to the 2DEG in the delta doped layer. Because of the random distribution of the Si donors, the 2DEG is subject to non-uniform potential distribution or the non-uniform Fermi energy in the 2DEG plane. According to Katsuno et al, the negative component is attributed to the random nature of the transport in 2DEG, or the transport is due to percolation like network. More recently, a numerical simulation on the random lattice has been performed to support the phenomenon [11].

Recently, negative magnetoresistance was found in an AlGaNR GaN hetero-structure[12], where the negative component persisted up to 15 Tesla along with a weak SdH oscillation. They tried to express the results with a model formula for a percolation transport. But the analytical results depends strongly on parameters used and discussion is rather ambiguous. Thus, the negative-magnetoresistance at high fields is the subject of further studies. They did not find clear evidence of the negative components as shown in our present work.

In conclusion, the magneto-transport in AlGaNR GaN heterostructure has been investigated as a function of the alloy composition in the barrier layer and the thickness of the AlN thin layer. Negative magnetoresistance component was found in low magnetic fields in samples without a thin AlN layer. This showed that the negative component is attributed to the presence of alloy disorder in the heterostructure. Comparing the negative component found in a 2DEG transport in an Si delta doped GaAs sample, the phenomenon is attributed to the percolation transport in random media.

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