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Enhanced Hole Generation in Mg-Doped AlGaN/GaN Superlattices due to Piezoelectric Field

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1. Introduction

There is much interest in using GaN and related materials in blue/violet light emitting diodes and laser diodes (LDs). [1-4] In particular, p-type AlGaN with low-resistivity, high carrier concentration and high Al mole fraction is necessary to ensure low-threshold and stable lasing with a shorter wavelength. It has been reported, however, that the hole activation energy in AlGaN is larger than in GaN, [5] which has made it difficult to form the low resistive p-type AlGaN with high carrier concentration. Thicker AlGaN is necessary to obtain sufficient optical confinement but is difficult to grow without cracks due to the lattice mismatch of 3.5% between GaN and AlN. To form high-quality and low-dislocation density GaN and AlGaN, Al(Ga)N/GaN strained-layer superlattices (SLSs) used in LD structures. [6] In addition, Nakamura *et al.* have reported that modulation doping of SLSs can reduce the operating voltage of LDs. [6] In these heterostructures, strain-induced piezoelectric field might be produced. From the theoretical point of view, it has been reported that this piezoelectric field can greatly enhance the transfer of holes from Mg-acceptors in the AlGaN barrier into the GaN well. [7] Therefore, it is vitally important to understand the effect of the piezoelectric fields in the heterostructures for higher hole concentration. In this paper, we report that the use of $Al_xGa_{1-x}N$/GaN SLs results in higher electrical activity of Mg-acceptors.

2. Experimental

GaN and AlGaN layers were grown on c-face (0001) sapphire substrates by a vertical, low-pressure (300 Torr) metalorganic vapor phase epitaxy (MOVPE). Trimethylgallium, trimethylaluminum and ammonia were used as source materials and bis-cyclopentadienyl-magnesium was the p-type dopant source. First we grew a 1-μm-thick undoped GaN layer at 1010°C on an AlN buffer layer deposited at 400°C. Then we grew uniformly Mg-doped $Al_xGa_{1-x}N$/GaN superlattices (SLs) with x values from 0 to 0.4 and with various SL period thicknesses. The thicknesses of the Mg-doped layers were from 0.6 μm to 1.2 μm. The Al mole fraction and the SL period thickness were confirmed by X-ray diffraction measurement. All the Mg-doped samples were annealed at 700°C in nitrogen (N_2) ambient. We used a Ni/Au layer for the ohmic electrodes. The van der Pauw-Hall effect measurement was carried out to establish the hole concentration at room temperature. The Mg concentration (N_{Mg}) was estimated to be about 2×10^{19} cm^{-3} by using secondary ion mass spectroscopy (SIMS).

3. Results and Discussion

Fig. 1 shows the sheet hole concentrations per period as a function of Al mole fraction, x for $Al_xGa_{1-x}N$/GaN SLs with the SL period thicknesses of 360 Å (240 Å/120 Å) and 100 Å (50 Å/50 Å), respectively. For the period thickness of 360 Å, the sheet hole concentration increases as the Al mole fraction increases up to 0.15, and then tends to saturate at about 8×10^{12} cm^{-2} in x range between 0.15 and 0.3, which corresponds to the volume hole concentration of 3×10^{18} cm^{-3}. For the period thickness of 100 Å, the sheet hole concentration increases with increasing Al mole fraction. These tendencies may be ascribed to the strain-induced piezoelectric field, which is produced in the SLs and is large enough to change the slope of valence band edge as schematically shown in Fig. 2. The energy shift (V_p), represented by the product of the piezoelectric field (E_p) and the distance from the interface, depends on the E_p and SL period thickness. This results in lowering the acceptor level below the Fermi-level (E_F) and transferring the holes to the GaN well layers. However, for thin SL period thickness, this piezoelectric field effect becomes weak due to the small V_p as shown in Fig. 2 (b). Therefore, for obtaining the SLs with high sheet hole concentration it is necessary to increase E_p, that is, the Al mole fraction, as shown in Fig. 2 (c). Moreover,

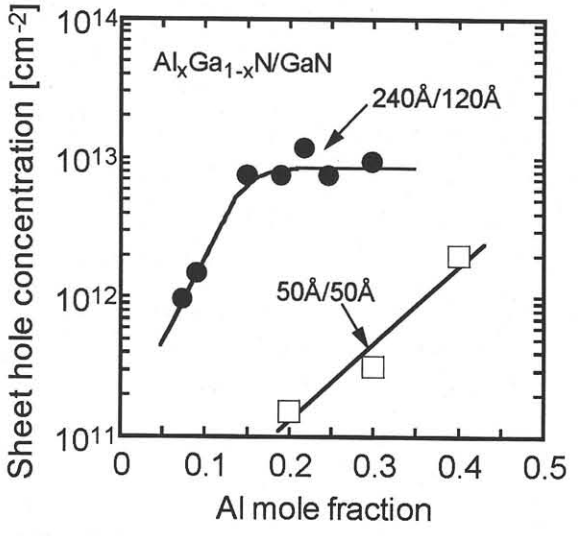

Fig. 1 Sheet hole concentrations as a function of Al mole fraction.

E_p becomes small by the lattice relaxation, so it is also necessary to balance the Al mole fraction and the critical thickness. Actually, experimental results in Fig. 1 support the above speculation.

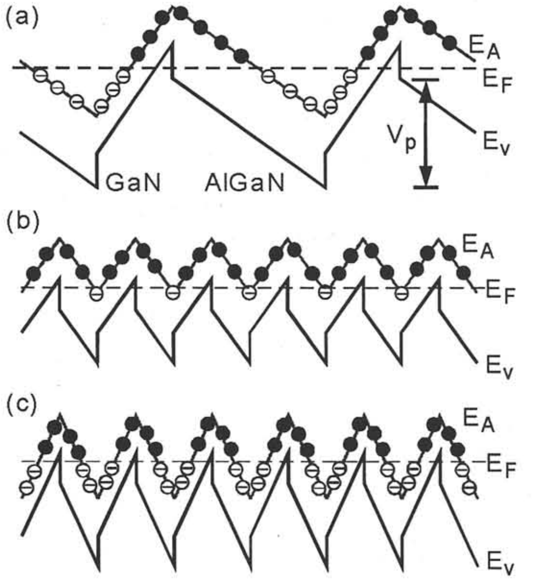

Fig. 2 Schematic illustrations of the valence band edge (a) for long-period SL, (b) for short-period SL with weak strain, and (c) with strong strain.

For the SL period thickness of 360 Å with exceeding the Al mole fraction of 0.15, the constant sheet hole concentration is supposed to be caused by the balance between the increase of E_p due to the Al mole fraction and the decrease of E_p due to the partial lattice relaxation.

Fig. 3 shows the resistivity of Mg-doped GaN and the SLs with various period thickness and Al mole fraction as a function of reciprocal temperature. The measurement temperature range was from 300 K to 400 K. While the resistivity for Mg-doped GaN strongly depends on the temperature, that for SLs changes a little. From Fig. 3, the slope for Mg-doped GaN is calculated to be 164 meV, which is similar to the reported activation energy (157 meV) for Mg-doped GaN. Therefore, the strong temperature dependence of resistivity for Mg-doped GaN is mainly ascribed to the large activation energy of Mg-acceptors. The weak temperature dependence of resistivities for SLs are ascribed to the decrease in the activation energy of Mg-acceptors in SLs and/or the increase the Hall mobility with decrease in temperature. However, the temperature dependence of Hall mobility might not overcome the effect of the large activation energy of Mg-acceptors, since SLs layers were heavily doped with Mg atoms. Therefore, the activation energy of Mg-acceptors might become small in SLs due to the piezoelectric field effect mentioned above.

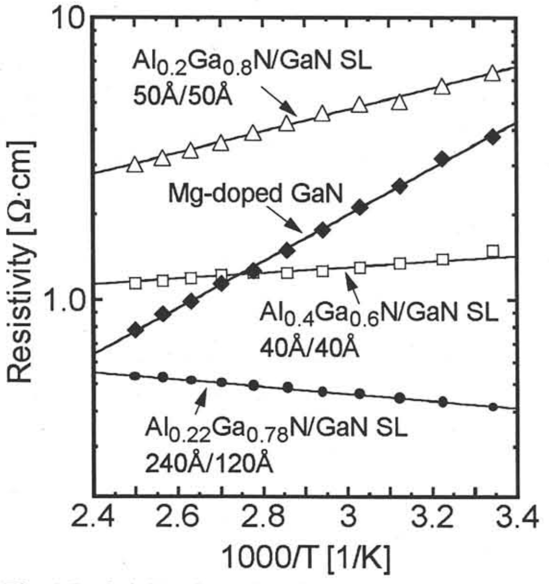

Fig. 3 Resistivity of Mg-doped GaN and SLs as a function of reciprocal temperature.

4. Conclusions

We investigated the electrical properties of uniformly Mg-doped $Al_xGa_{1-x}N$/GaN SLs grown by low-pressure MOVPE. Van der Pauw-Hall effect measurements for $Al_xGa_{1-x}N$/GaN SLs show that the SL period thickness and the Al mole fraction greatly influence sheet hole concentration. We found increased electrical activity of the Mg-acceptors in these SLs due to the piezoelectric field, which greatly modulates band structures. We also found Mg-doped SLs show the weak temperature dependence of resistivity compared with Mg-doped GaN. For obtaining the high sheet hole concentration, it is necessary to balance the SL period thickness, Al mole fraction in SLs and the critical thickness.

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