Modulation Magnesium-Doping in AlGaN/GaN Superlattices

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III nitrides, such as GaN, InN, AlN and their alloys, hold direct wide band gap, stability at high temperature and at hostile environment, are suitable for many applications in blue and near-ultraviolet light-emitting and laser diodes, high-temperature electronics, ultraviolet photodetectors. Although the GaN-based light emitting diodes have been mass-produced, materials issues still dominate. One of the remaining issues is the *p*-type doping of the III nitrides, especially AlGaN with high (>20%) aluminum mole fraction. As far, Magnesium (Mg) is the most widely used *p*-type dopant although its ionization energy is near 150meV. The deep nature of the Mg acceptor and consequent low ionization percentage as well as the low hole mobility induce the conductivity of Mg-doped GaN is limited. The use of AlGaN/GaN heterojunctions has been proposed as a technique to increase the average hole concentration [1,2], and several works [3-5] have provided an experimental demonstration of increased hole concentration through the use of AlGaN/GaN superlattices (SLs). In this letter, we present the modulation Mg-doping of GaN/AlGaN SLs with the motivation of reducing acceptor ionization energy, and we compare this technique to the doping of single AlGaN layer or GaN layer. We expect the improved *p*-type doping through the use of AlGaN/GaN SLs to provide better electrical confinement and to diminish the device resistance.

The III-nitride layers were grown in a home-made horizontal low pressure (100 mbar) metalorganic vapor phase epitaxy. A 25 nm thick, low-temperature (550^{o}C) GaN nucleation layer was deposited on (0001) Al_2O_3 substrate prior to the deposition of AlGaN layer, GaN layer or AlGaN/GaN SLs at 1040 ^{o}C with a total thickness of 0.7 μm. Following the growth, the samples were annealed at 900 ^{o}C in the reactor for 3 minutes to activate the acceptor. Four kinds of uniform-doped and two kinds of modulation-doped samples were prepared. The uniform-doped samples are: series A (GaN:Mg), series B ($Al_{0.2}Ga_{0.8}N$:Mg), series C ($Al_{0.1}Ga_{0.9}N$:Mg), series D ($Al_{0.2}Ga_{0.8}N$/GaN SLs with uniform Mg-doping). The modulation-doped samples are series E and series F, in each case; the Mg doping was applied through only half the SLs, either in region E or in region F, as shown in Fig.1, respectively. In the SLs, the barrier and well thickness (*L*) were kept equal, the SLs period (*2L*) was varied from 2 to 30 nm.

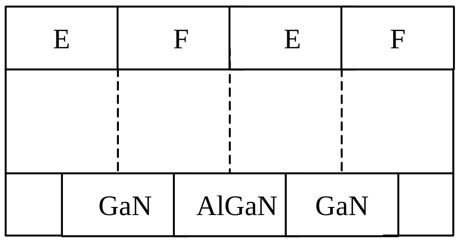

Fig. 1. Schematic diagram of modulation-doped AlGaN/GaN SLs. Region E and F defining each interface are indicated. The substrate is on the right and the free surface of the film is on the left.

X-ray diffraction curve (ω/2θ scan) of a SLs (*2L*=13.6 nm) were obtained (not shown). In addition to the main peak, both the –1 and +1 superlattice peak are visible. The presence of the superlattice peak confirms that there is indeed a superlattice instead of a mixed alloy.

Hall measurements were taken at room temperature or at low temperature. The electrode was In:Zn alloy, but we noticed that it was not a good ohmic contact to the sample from the *I-V* characterization. The measurement electrical current (usually 0.1 mA to 10 mA) was as large as possible, so as to decrease the measurement error induced by the non-ohmic contact between electrode and sample. At room temperature, the resistivity of *p*-GaN:Mg (series A) and *p*-$Al_{0.1}Ga_{0.9}N$:Mg (series C) was usually 1~4 Ω.cm and 6~20 Ω.cm, respectively, but p-$Al_{0.2}Ga_{0.8}N$:Mg (series B) was nearly semi-insulating, usually incapable for measurement. The hole concentration and mobility of p-GaN:Mg was in the range of 1~6x10^{17} cm^{-3} and 7~20 cm^2/V.s, respectively, in comparison, p-$Al_{0.1}Ga_{0.9}N$:Mg was in the range of 1~10x10^{16} cm^{-3} and 4~15 cm^2/V.s. When we doped with Mg in SLs uniformly (series D) and in the region E (series E), these samples always showed p-type conductivity, but the resistivity and hole concentration were dependent on the SLs period, as reported in other works [4,5]. The samples of series D and series E with lowest resistivity and the highest hole concentration were obtained when the period ($2L$) was 13.6 nm. The resistivity and hole concentration of series D was in the range of 0.3~0.6 Ω.cm and 1~4 x 10^{18} cm^{-3}, respectively, in comparison, series E was in the range of 0.2~0.6 Ω.cm and 1~3.9 x 10^{18} cm^{-3}. When we doped SLs with Mg in the region F (series F), the samples showed uncertain type conductivity, different from sample to sample or from area to area in one sample. All of the above-mentioned electrical properties of Mg-doped bulk GaN, bulk AlGaN and AlGaN/GaN SLs are summarized in table 1. Series E and series F owned unambiguously different conductivity indicates that the memory effect, which was reported previously [4-6], was not serious in our reactor.

When the temperature was lowered from room temperature to 150~170 K, the resistivity of both p-GaN:Mg (series A) and p-$Al_{0.1}Ga_{0.9}N$:Mg (series C) increased 3~4 orders, reaching our Hall equipment limit; the resistivity of series D and E samples increased only 1~2 times, however. These results demonstrate that the acceptor ionization energy of series D and E is dramatically reduced, indicate that this technique of Mg-doped AlGaN/GaN SLs can extend the usable temperature range for nitride-based devices requiring p-type conduction. We used Mg-doped AlGaN/GaN SLs as p-type confinement layer instead of GaN:Mg single layer in InGaN/GaN multi-quantum-well light-emitting-diode (LED) fabrication, we observed the LED more brightness and less serial resistor. We are doing the researches on the influence on the characterization of LED in detail.

Table 1. The electrical properties of Mg-doped GaN, AlGaN and AlGaN/GaN superlattices:

Series	Type	Resistivity (Ω.cm)	Hole concentration ($10^{17}cm^{-3}$)	Hole mobility (cm^2/V.s)
A	*P*	1~4	1~6	7~20
B	Semi-Insulating	–	–	–
C	*P*	6~20	0.1~1	4~15
D	*P*	0.3~0.6	10~40	2~15
E	*P*	0.2~0.6	10~39	6~21
F	Uncertain	–	–	–

In summary, we have examined carefully the p-type conductivity of Mg-doped AlGaN/GaN superlattices. Through appropriately Mg-doped AlGaN/GaN superlattices, the resistivity and its temperature coefficient can be lowered dramatically compared with Mg-doped bulk GaN and AlGaN samples. This technique can improve the characterization of light emitting diodes.

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