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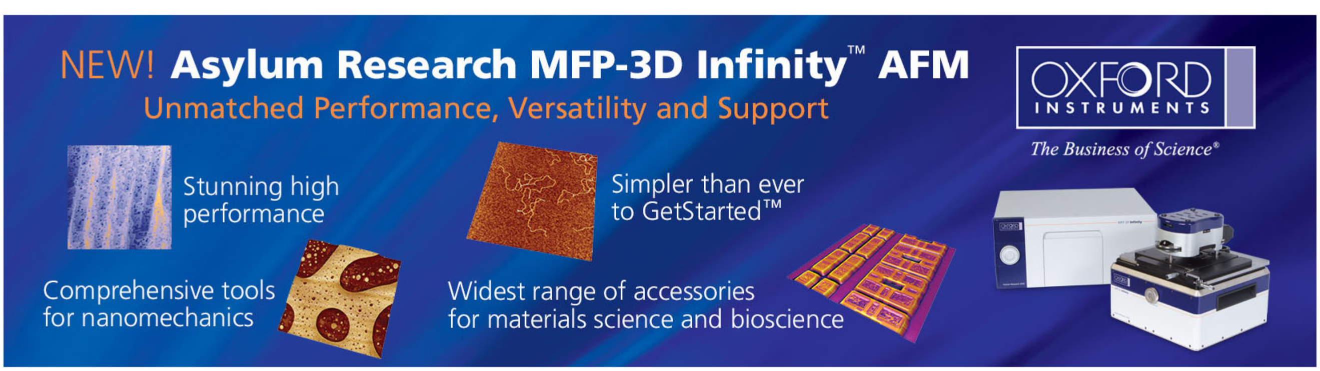

Enhanced *p*-type conduction in GaN and AlGaN by Mg-δ-doping

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Mg-δ-doping in GaN and AlGaN epilayers has been investigated by metalorganic chemical vapor deposition. It was demonstrated through electrical, optical, and structural studies that Mg-δ-doping improves not only *p*-type conduction, but also the overall quality of *p*-type GaN and AlGaN epilayers. A twofold (fivefold) enhancement in lateral (vertical) *p*-type conduction have been achieved for GaN and AlGaN epilayers. It is argued that the observed dislocation density reduction (of about one order of magnitude) is due to the growth interruption in the Mg-δ-doping duration that partially terminates the dislocation propagation in the growth direction. Furthermore, Mg-δ-doping also reduces Mg impurity self-compensation and enhances hole concentrations in Mg-δ-doped GaN or AlGaN. [DOI: 10.1063/1.1559444]

The attainment of highly conductive *p*-type GaN and AlGaN remains one of the biggest obstacles for the III-nitride research. Recently, we have obtained *p*-type $Al_xGa_{1-x}N$ epilayers with x up to 0.27. A hole concentration of about 7×10^{16} cm^{-3} and mobility of 3 $cm^2/V\,s$ at room temperature have been achieved in Mg-doped $Al_{0.27}Ga_{0.73}N$ epilayers.[1] It was observed that Mg activation energy in AlGaN increases almost linearly with Al content. At an AlN fraction of 45%, the activation energy E_A was estimated to be about 0.4 eV, and the estimated resistivity is as high as 2.2×10^4 Ω cm. This deepening of the Mg activation energy with Al content presents a real challenge for obtaining *p*-type AlGaN with high Al content.

In this letter, we report our studies of Mg-δ-doping in GaN and AlGaN epilayers by metalorganic chemical vapor deposition (MOCVD). We have shown that δ-doping enhances lateral and vertical *p*-type conductivities, as well as the material quality, of GaN and AlGaN epilayers.

GaN and $Al_xGa_{1-x}N$ alloys (about 1 μm thick) were grown on sapphire (0001) substrates with GaN buffer layers by MOCVD. The growth temperature and pressure were around 1050 °C and 300 Torr, respectively. The metalorganic sources used were trimethylgallium (TMGa) for Ga and trimethylaluminum (TMAl) for Al. For Mg-doping, bis-cyclopentadienyl-magnesium (Cp_2Mg) was transported into the growth chamber with ammonia during growth. The gas sources used were blue ammonia (NH_3) for N, and H_2 as a carrier gas. Postgrowth annealing at 950 °C in nitrogen gas ambient for 8 s resulted in *p*-type conduction, verified by Hall measurements. The Al content of $Al_xGa_{1-x}N$ alloys were determined by energy dispersive x-ray microanalysis and x-ray diffraction measurement, as well as by the flow rates of TMGa and TMAl. The Al content (x) determined by all three methods agreed within ±0.02. The Mg-dopant concentrations were determined by the flow rate of Cp_2Mg, as well as by the secondary ion mass spectroscopy measurements (performed by Charles and Evan Inc.) for selective samples. Atomic force microscopy (AFM) and scanning electron microscopy (SEM) were employed to examine the etch pit densities. Variable-temperature Hall-effect (standard Van der Pauw) measurements were employed to measure the free hole concentration, mobility, and resistivity of these materials. Photoluminescence (PL) emission spectroscopy was employed to monitor the optical emission properties of the grown epilayers.

Figure 1 is a schematic diagram of a Mg-δ-doped GaN or AlGaN epilayer. A δ-junction-like doping profile is implemented by interrupting the usual crystal-growth mode by closing the Ga (and Al) flow and leaving the N (NH_3) flow continuously. The N-stabilized crystal surface is thus maintained while the Mg impurities are introduced into the growth chamber, so that an impurity-growth mode results. In this mode, the host crystal does not continue to grow. It is hoped that by using this technique, a small fraction of available Ga sites in the δ-doped plane, typically .1 to .0001, will be occupied by Mg impurities.

The enhancement of *n*-type conduction in highly doped GaAs using Si-δ-doping in GaAs has been demonstrated previously for molecular-beam-epitaxy growth.[2,3] An order of magnitude enhancement in electron concentration has been achieved in GaAs by δ-doping over uniform doping. This technique has also been applied to GaAs/AlGaAs heterojunction field-effect transistors (HFETs) for enhanced performance.[4] Delta doping has been proposed to reduce complex-type compensating defects and to increase the *p*-type doping level in II–VI wide-band-gap semiconductors in which *p*-type doping is known to be a difficult issue.[5,6] A

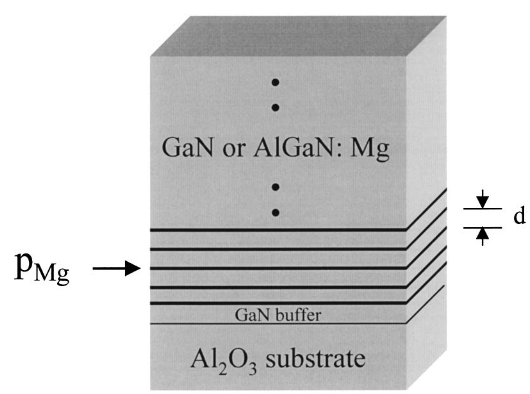

FIG. 1. Schematic diagram of Mg-δ-doped GaN or AlGaN, where d (=15 nm) and P_{Mg} denote, respectively, the distance between two δ-planes and the two-dimensional Mg doping concentration.

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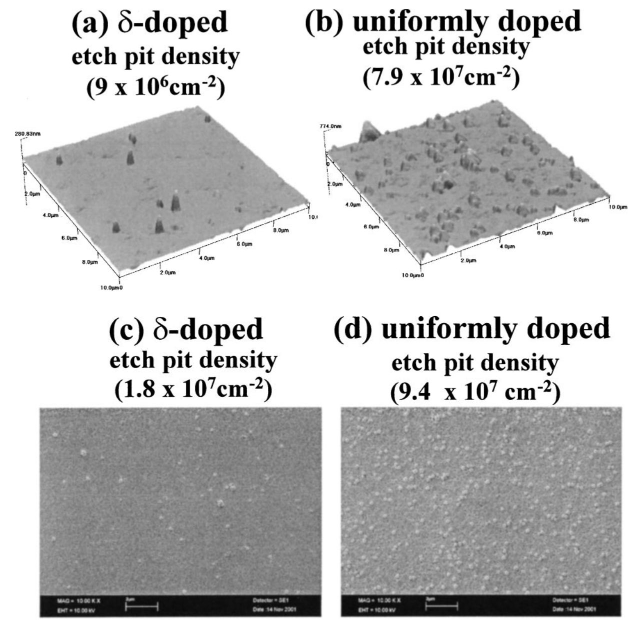

FIG. 2. AFM and SEM morphologies of etched surfaces of p-type AlGaN epilayers after a 0.5-μm removal by inductively coupled plasma (ICP) etching. AFM images of (a) Mg-δ-doped and (b) uniformly Mg-doped p-type AlGaN epilayers. SEM images of (c) Mg-δ-doped and (d) uniformly Mg-doped p-type AlGaN epilayers. AFM and SEM images reveal that the etch pit density was significantly reduced in Mg-δ-doped p-type AlGaN compared with uniformly Mg-doped p-type AlGaN.

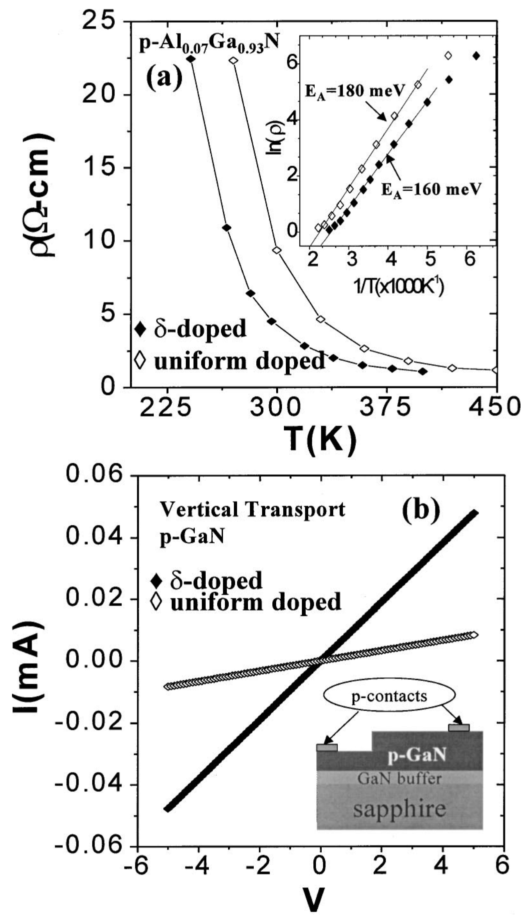

FIG. 3. (a) Resistivity (ρ) of representative uniformly Mg-doped and Mg-δ-doped p-AlGaN epilayers as functions of temperature. The inset shows the Arrhenius plots of the resistivity, which indicate that δ-doping reduces the activation energy of Mg acceptors in AlGaN. (b) Comparison of "quasi" vertical transport properties of uniformly Mg-doped and Mg-δ-doped p-type GaN. Etching depth (0.5 μm) and p-type ohmic-contact geometry were nominally identical for the two samples, as accomplished by ICP etching and photolithography patterning.

high p-type doping level of 1.5×10^{18} cm^{-3} was achieved in ZnBeSe epilayers by δ-doping.[7]

Recently, by employing Si-δ-doping in the barrier region of AlGaN/GaN HFET structures, we have observed improved dc performance, that is, enhanced maximum current, reduced leakage current, and increased breakdown voltage in Si-δ-doped structures over those of uniformly doped ones.[8]

We have observed that δ-doping significantly suppresses the dislocation density in GaN and AlGaN epilayers. This is illustrated in Fig. 2, where AFM and SEM morphologies of etched layers of Mg-δ-doped and uniformly Mg-doped $Al_{0.07}Ga_{0.93}N$ epilayers are shown. The results clearly demonstrate a significant reduction of dislocation density (or etch pit density) in δ-doped p-type $Al_{0.07}Ga_{0.93}N$. The AFM images shown in Figs. 2(a) and 2(b) indicate that the etch pit density decreased by almost one order of magnitude from 7.9×10^{7} cm^{-2} in the uniformly Mg-doped layer to 0.9 $\times10^{7}$ cm^{-2} in the Mg-δ-doped layer. The SEM images in Figs. 2(c) and 2(d) reveal a reduction of etch pit density from 9.4×10^{7} cm^{-2} in the uniformly Mg-doped to 1.8 $\times10^{7}$ cm^{-2} in the Mg-δ-doped p-type $Al_{0.07}Ga_{0.93}N$ layer. The results thus strongly suggest that δ-doping can reduce dislocation density and hence improve the overall material quality of III-nitrides in general, which will be extremely beneficial to the fabrication of optoelectronics and photonics devices, especially UV emitters. We believe that the observed reduction in dislocation density is due to the growth interruption in the Mg-δ-doping duration. Ga or Al atoms are halted during δ-doping, which stops the growth of GaN or AlGaN. It is known that growth interruption generally reduces the dislocation densities due to the partial termination of dislocation propagation in the growth direction.

Additionally, Mg-δ-doped GaN and AlGaN epilayers exhibit much improved electrical properties over uniformly doped layers. For GaN, we have achieved a room temperature p-type resistivity of Mg-δ-doped p-GaN epilayers as low as 0.6 Ω cm (free hole concentration around 2 $\times10^{18}$ cm^{-3} and mobility around 5 cm^2/V s), while uniformly Mg-doped GaN epilayers typically exhibit a p-type resistivity >1 Ω cm. It was observed that the Mg-δ-doping enhances only the hole concentration and induces no changes in the hole mobility. Similar results have been obtained for p-type AlGaN alloys. The typical mobility of the p-type AlGaN alloys studied here is around 5 cm^2/V s and is only weakly dependent on temperature; hence, the temperature variation of the p-type resistivity is attributed predominantly to the temperature dependence of the hole concentration. We thus plot the comparison results of the temperature-dependent resistivity of uniformly Mg-doped and Mg-δ-doped p-type $Al_{0.07}Ga_{0.93}N$ epilayers in Fig. 3, which demonstrates a twofold reduction of resistivity at room temperature by employing Mg-δ-doping. Furthermore, the measured Mg acceptor activation energy (E_A) was also reduced from 180 meV in uniformly Mg-doped p-type $Al_{0.07}Ga_{0.93}N$ to 160 meV in Mg-δ-doped p-type $Al_{0.07}Ga_{0.93}N$, which may be attributed to the enhanced free hole concentrations in Mg-δ-doped p-type $Al_{0.07}Ga_{0.93}N$. We have also carried out preliminary studies of the vertical trans-

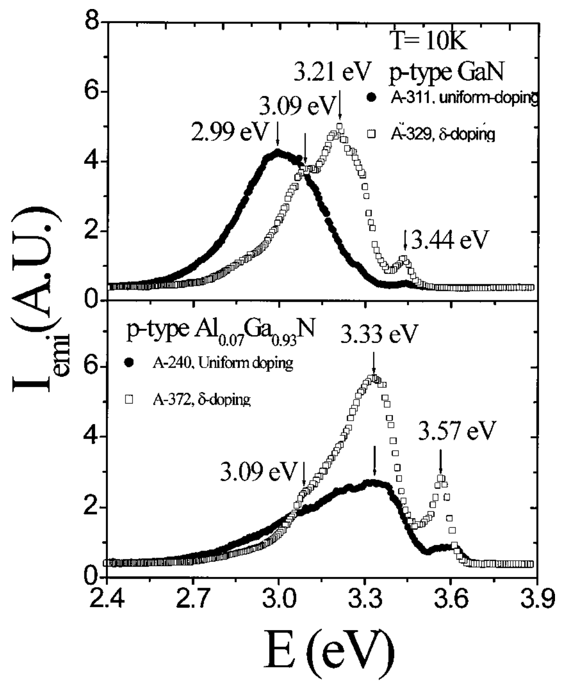

FIG. 4. Comparison of low-temperature (10 K) PL emission spectra of uniformly Mg-doped and Mg-δ-doped GaN and AlGaN epilayers.

port properties of Mg-δ-doped p-type layers, which are more critical to the performance of UV emitters. Our preliminary results obtained on p-type GaN shown in Fig. 3(b) have shown that we could obtain a fivefold reduction in vertical resistivity in Mg-δ-doped p-type layers compared with uniformly Mg-doped p-type layers.

Furthermore, comparison measurements for the PL emission spectra of Mg-δ-doped and uniformly Mg-doped GaN and AlGaN epilayers have also been carried out, and the results are presented in Fig. 4. Based on a previous study,[9] we attribute the 3.2-eV (3.33-eV) emission line seen in Mg-δ-doped GaN ($Al_{0.07}Ga_{0.93}N$) to the recombination between the conduction-band-to-impurity transition involving shallow Mg impurities. It is interesting to note the 3.21 eV emission line is absent in uniformly Mg-doped GaN in which the dominant emission line at 2.99 eV may be associated with the conduction-band-to-impurity transition involving doping induced deep-level centers.[9] Moreover, Fig. 4 shows that the PL emission intensities associated with the band-to-impurity transition line, as well as with the exciton bound to acceptor transition line (I_1 around 3.44 eV for GaN and 3.57 eV for AlGaN),[9,10] are enhanced in Mg-δ-doped layers, pointing to a reduction of nonradiative recombination centers. This corroborates the results shown in Fig. 2: dislocation density is reduced in Mg-δ-doped epilayers. Thus, all of our experimental data, including electrical, optical, and structural data, imply that Mg-δ-doping improves not only p-type conduction, but also the overall quality of III-nitride films.

In addition to the reduction of dislocation density giving rise to a more efficient doping, we believe that autocompensation of Mg impurities is also reduced in Mg-δ-doped layers. Due to the relatively large Mg ionization energy in p-type GaN of about 160 mV, only about 1% of the Mg impurities are ionized at room temperature. Therefore, high doping incorporation of Mg impurities around 10^{20} cm^{-3} is a routine practice in nitride optoelectronic and electronic device structures. Self-compensation is more likely under the condition of high Mg doping levels. During the δ-doping process, however, the Mg impurity incorporation process is modified compared with that of uniform doping. Since the Ga (and Al) atoms supply is halted, Mg impurities are more likely to replace the Ga or Al atoms during the δ-doping process. This would reduce Mg impurity self-compensation and enhance hole concentrations in Mg-δ-doped GaN and AlGaN.

It has been demonstrated recently by several groups that incorporating Mg-doped AlGaN/GaN superlattice structure into devices could enhance the hole conduction in the lateral direction.[11–13] However, the enhancement of hole conduction in the vertical direction by employing a superlattice structure is limited because a superlattice structure simultaneously introduces potential barriers for hole conduction in the vertical direction due to the presence of higher-band-gap materials. On the contrary, δ-doping does not introduce any potential barriers in the vertical direction and is expected to enhance the vertical transport as well as the lateral transport of holes.

In summary, we have demonstrated that Mg-δ-doping enhances the lateral and vertical p-type conductivities, as well as the material quality, of GaN and AlGaN epilayers. We have achieved twofold and fivefold enhancements in p-type lateral and vertical conductivities, respectively, in GaN and AlGaN epilayers by employing Mg-δ-doping. It is expected that Mg-δ-doped layers have higher vertical conductance compared with those of superlattice structures due to the absence of potential barriers introduced by higher-band-gap material. The δ-doping technique represents the ultimate control of dopant profiles and is expected to play an increasingly important role in III-nitride electronic and photonic devices.

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