

Electrical and optical properties of thick highly doped p-type GaN layers grown by HVPE

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In this paper we report 3–7 μm thick p-GaN growth by hydride vapor phase epitaxy (HVPE) on sapphire substrates. Mg impurity was used for doping. As-grown GaN layers had p-type conductivity with concentration N_A-N_D up to $3 \times 10^{19} \text{ cm}^{-3}$. Mg atom concentration was varied from 10^{17} to 10^{20} cm^{-3} . Hydrogen concentration was about 10 times less than that for Mg, which may explain effective p-type doping for as-grown

GaN layers. Micro-cathodoluminescence revealed a columnar-like structure of the GaN layers with a non-uniform distribution of material regions having dominant 362 nm or 430 nm luminescence. Use of these thick p-GaN layers to grow InGaN-based blue and green LEDs by the HVPE is demonstrated.

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1 Introduction Highly doped p-type GaN-based materials with low electrical resistivity and abrupt doping profiles are of great importance for GaN-based green-blue-violet-UV light emitting devices and electronic bipolar devices. High p-type GaN doping is required to improve (i) carrier injection efficiency in light emitting p-n junctions; (ii) current spreading in light emitting structures, (iii) parameters of ohmic contacts to reduce operating voltage and tolerate higher forward currents needed for the high output power operation of light emitters.

Highly doped p-type GaN layers and AlGaIn/GaN heterostructures with low electrical resistivity will lead to novel device and contact metallization designs for high power high efficiency GaN-based light emitters.

In this work we applied hydride vapor phase epitaxy (HVPE) technology to grow several micron thick p-type GaN layers and report results of the samples characterization.

2 Experimental GaN layers were grown using multi-wafer HVPE growth machines designed and built at TDI. The HVPE growth machines were equipped with an at-

mospheric-pressure horizontal hot-wall quartz reactor and resistively heated furnaces. Samples were grown at about 1050°C using Ga and Al metals as source materials and HCl and NH_3 as gaseous reagents. Mg metal is used for doping. Ar served as a carrier gas. Epitaxial layers and structures were grown on 2-inch single side polished (0001) sapphire substrates. In more details, the HVPE growth procedure was described elsewhere [1, 2]. The grown structures were characterized by X-ray diffraction (XRD), reflection high-energy electron diffraction (RHEED), optical and scanning electron microscopy (SEM), capacitance-voltage (C-V) mercury probe measurements at 1 MHz, Hall-effect measurements, photoluminescence (PL), and micro-cathodoluminescence (CL). Doping profiles in the structures were measured by secondary ion mass spectrometry (SIMS). The micro CL experiments were done using Gatan MonoCL2 system attached to JSM6100 JEOL SEM and containing PMT and grating blazed at 250 nm. Both CL spectra and SEM images were recorded from cross-sections using a 10 kV electron beam with 0.2–1 nA beam currents. The beam raster size was varied from $5.2 \times 8 \mu\text{m}^2$ to collect luminescence

from larger areas to $2.1 \times 1.1 \mu\text{m}^2$ to collect local luminescence spectra. The recorded spectra were corrected for the system response. Monochromatic CL images were obtained by collecting luminescence at the wavelengths selected by the grating.

3 Results and discussion Thickness of p-type GaN layers grown on sapphire substrates ranged from 3 μm to 7 μm . As-grown surface morphology was featureless for p-type GaN layers having N_A-N_D concentration up to $3 \times 10^{19} \text{cm}^{-3}$. This is the highest N_A-N_D concentration reported for as-grown (non-activated) p-GaN materials. RHEED studies indicated high crystalline quality of the near surface region. For 3-4.5 μm thick p-type GaN layers, the FWHM values of X-ray ω -scan rocking curves measured both for the (00.2) symmetric and the (10.2) asymmetric reflections was 350-500 arc sec and 400-600 arc sec, respectively. No clear dependence was observed for the FWHM values of X-ray rocking curves on doping concentrations if concentrations N_A-N_D were in the range from $1 \times 10^{16} \text{cm}^{-3}$ to $3 \times 10^{19} \text{cm}^{-3}$.

A set of p-GaN multi-layer structures was designed to study dependence of Mg on various growth factors. The goal was to develop optimal growth process leading to p-type GaN materials having a maximum Mg concentration (C_{Mg}) and N_A-N_D values. Figure 1 shows SIMS depth profiling of a multi-layer GaN structure. The structure grown on sapphire consisted of 2.2 μm thick undoped GaN layer and five Mg doped GaN layers grown with various growth rates. Other conditions for Mg doping were the same. The data demonstrate ability of the HVPE technology to precise control of p-doping.

Figure 2 shows C_{Mg} depending on GaN growth rate. Under other growth conditions being equal, lower growth rate resulted in higher C_{Mg} value. The atomic concentration of Mg up to $3 \times 10^{19} \text{cm}^{-3}$ was measured for this sample. Lower growth rate in our experiments was obtained by de-

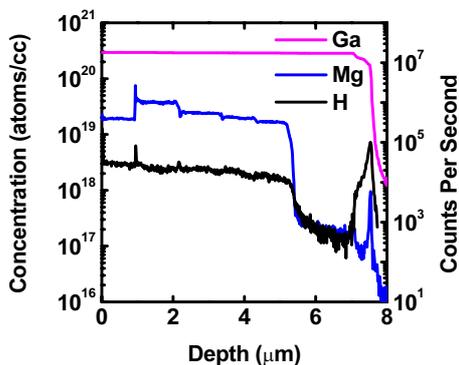


Figure 1 SIMS depth profiles for p-type GaN multi-layer structure grown by HVPE. The structure total thickness is about 7.6 μm . The gallium (Ga) counts axis is to the right and the concentration axis for other elements (Mg, H) is to the left. The sample surface is to the left.

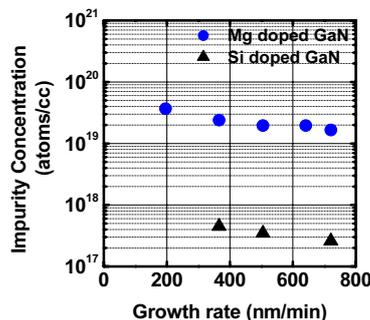


Figure 2 Dependence of impurity concentration on GaN layer growth rate. The data are taken from the SIMS analysis. Dependence for Si-doping of GaN is given for comparison.

creasing HCl active gas flow over Ga metallic source that means effectively decreasing partial pressure of gallium chlorides in vapour phase. Due to preservation of the total pressure in the reactor at the atmospheric level, the vapour ratio $[\text{Mg}]/[\text{Ga}]$ is effectively increased causing the rise of Mg incorporation in the growing layer. The similar tendency was observed for Si-doping GaN layers given for comparison in Fig. 2.

Hydrogen concentration in Mg-doped GaN is about one order of magnitude less than that of Mg as shown in Fig. 1. The developed HVPE process is almost hydrogen free. Argon used as a carrier gas and the only sources of hydrogen are ammonia and hydrogen chloride.

The results of SIMS analysis showed that hydrogen background concentration follows the Mg concentration trend. Hydrogen is known to form H:Mg complex in GaN and post-growth thermal treatment is required to obtain p-type conductivity for MOCVD process, which typically use hydrogen as a carrier gas. As-grown Mg-doped GaN layers grown by HVPE showed p-type conductivity without any activation of the grown layers. Figure 3 shows relationship between Mg and H concentration in Mg-doped

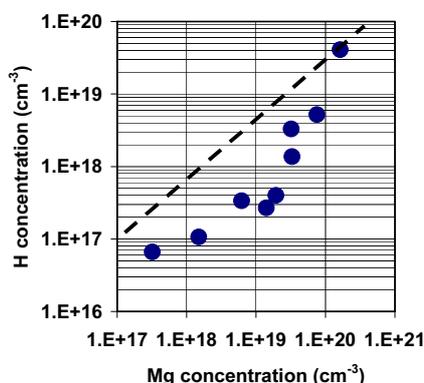


Figure 3 Relationship between Mg doping concentration and H background concentration in Mg-doped p-type GaN layers grown by HVPE on sapphire substrates. Dashed line corresponds to equal atomic concentration of Mg and H. The data are taken from the SIMS analysis.

p-type GaN within the wide range of Mg concentrations from $3 \times 10^{17} \text{ cm}^{-3}$ to $1.6 \times 10^{20} \text{ cm}^{-3}$ according to SIMS data. The H background concentration remains lower than that of Mg in this concentration range in HVPE grown p-type GaN layers.

It was also observed for Mg-doped p-GaN layers that lower hydrogen concentration resulted in higher $N_A - N_D$ values for the same C_{Mg} . Two samples (A and B) having the same C_{Mg} of $(1-3) \times 10^{19} \text{ cm}^{-3}$ were grown. Sample A had H atomic concentration of $1.3 \times 10^{18} \text{ cm}^{-3}$ and possessed $N_A - N_D$ concentration of $1.3 \times 10^{18} \text{ cm}^{-3}$. Sample B had H atomic concentration of $4 \times 10^{17} \text{ cm}^{-3}$ and possessed $N_A - N_D$ concentration of $1.2 \times 10^{19} \text{ cm}^{-3}$.

Hall-effect measurements at 300 K for as-grown p-GaN layer revealed hole mobility and carrier concentration of $15-40 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $4 \times 10^{17} - 1.5 \times 10^{18} \text{ cm}^{-3}$, respectively.

It is known that for p-type GaN doped with Mg either blue luminescence band at 2.7-2.9 eV (430-460 nm) or ultraviolet luminescence band at 3.0-3.2 eV (370-380 nm) dominate the PL spectrum [3].

In this work, CL spectra acquired from the surface of heavily doped p-type GaN layer having concentration $N_A - N_D$ of about $1 \times 10^{19} \text{ cm}^{-3}$ consisted of dominated peak at 430 nm and a weak peak at 363 nm. To clarify the origin of the peaks, micro-CL measurements were performed on the sample cleaved edge. The sample was a 5.4 μm thick GaN layer doped with Mg grown on sapphire. Fig. 4 shows micro-CL spectrum acquired from sample surface by scanning e-beam over the area of $4 \times 6 \mu\text{m}^2$. Micro-CL measurements showed the same emission peaks at 362 nm and at 430 nm. Micro-CL studies performed on cleaved edge of the sample revealed a columnar-like structure of the GaN material with a non-uniform distribution of material regions having dominant 360 nm or 430 nm luminescence as shown in Fig. 5 and Fig. 6. C-V profiling of samples confirmed that thick Mg-doped HVPE GaN layers possess p-type conductivity through the whole layers.

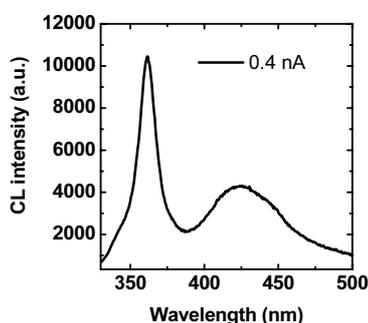


Figure 4 Micro-CL spectrum detected on cleaved edge of a 5.4 μm thick p-GaN sample. The peak at 363 nm is coming from p-GaN/sapphire interface as seen in Fig. 5. The peak at 430 nm is observed across the whole thickness of the p-GaN layer as shown in Fig. 6.

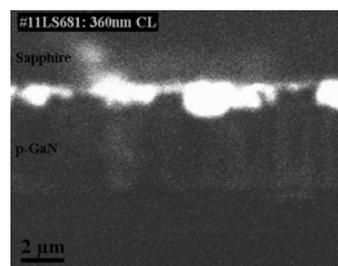


Figure 5 Monochromatic CL micrographs of cross sectional p-type GaN layer corresponding to the emission at 360 nm. The emission mainly originates at the p-GaN/sapphire interface.

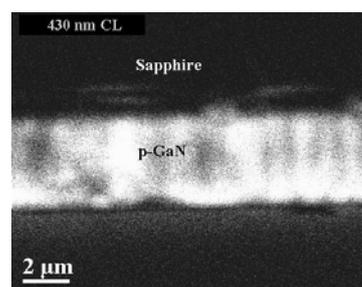


Figure 6 Monochromatic CL micrographs of cross sectional p-type GaN layer corresponding to the emission at 430 nm. The emission is mainly observed across the whole thickness of the p-GaN layer.

Grown p-GaN/sapphire samples were used as the template substrates for InGaN-based light emitting diode structures emitting in the blue-green spectral region (450-510 nm). Latter results will be published elsewhere.

4 Conclusions P-GaN layers were grown by HVPE using Mg doping. For as-grown Mg doped GaN layers concentration $N_A - N_D$ up to $3 \times 10^{19} \text{ cm}^{-3}$ was obtained. Hole mobility of $15-40 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at hole concentration of $4 \times 10^{17} - 1.5 \times 10^{18} \text{ cm}^{-3}$ were measured at 300 K. Micro-CL studies revealed non-uniform distribution of 360 nm and 420 nm emissions in as-grown p-GaN layers. The p-GaN/sapphire templates are proposed as substrates for blue-green light emitters.

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