Efficient InGaN p-Contacts for deep-UV Light Emitting Diodes

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Introduction: Sub-280nm UV-C LEDs are required for applications in water disinfection, gas sensing and photo-chemistry. The external quantum efficiency for these LEDs is usually low (< 20%) [1]. A device challenge is to design an optically transparent p-type layer for hole injection. We have combined Mg-doping and polarization induced p-type doping in graded AlGaN layers for hole generation and injection [2]. To maintain transparency to 280nm photons, the minimum Al-content in the graded AlGaN structure is 65%. Due to the limited availability of large work function metals, forming low-resistance Ohmic contacts to such high Al-content AlGaN layers is not possible. The typical strategy used is to grow heavily Mg-doped GaN on the AlGaN layer for contact formation, and inject holes over the Schottky barrier heterostructure formed by the valence band offset. On the other hand, Mg-doped 18% InGaN layers reach hole densities as high as 3×10^{19} cm^{-3} due to lower activation energy than GaN:Mg (~120meV GaN:Mg, ~60meV 18% InGaN:Mg) [3]. Here, we show that using heavily Mg-doped InGaN as a p-type contact layer for deep UV LEDs leads to a *very large increase* in electroluminescence.

Experimental method: Plasma-assisted molecular beam epitaxy was used to grow deep UV LEDs: one with, and the other without a Mg-doped InGaN p-contact layer on AlN-on-sapphire templates. Layer structures, doping concentrations and p-layer energy band diagram simulations are shown in Fig.1. For electron injection layers, sample A has a 100nm polarization-doped graded up (65-95%) AlGaN:Si, while for Sample B a 350nm of constant 76% AlGaN:Si was used. The n-layers are grown at substrate temperatures ranging from 730 to 750°C to ensure slightly metal rich condition for 2D smooth growth. For the active region, 4 periods of ultra-thin (~2 monolayer) GaN quantum wells embedded in 2.5nm AlN barriers were used. Extreme quantum confinement in the GaN quantum wells produces UV-C emission, demonstrated in our earlier work [4]. For hole injection layers, a Mg-doped graded down 50nm (95-65%) AlGaN layer (Sample A) and the same composition but thicker 100nm layer (Sample B) grown at 730°C was used. A degenerate Mg-doped GaN layer was grown at 650°C for Sample A as the p-contact layer, and for Sample B, Mg-doped 15nm 1% InGaN followed by 5nm of 15% InGaN layers were grown on top of the p-GaN at 650°C. Compositions of AlGaN and InGaN layers were confirmed by high resolution X-ray diffraction. The samples were mesa isolated by ICP/RIE, followed by Ti/Al/Ni/Au (20/100/40/50nm) metal stack deposition as the n-type contact. A semi-transparent current spreading metal stack was deposited (Ni/Au = 5/5 nm) on the p-contact layer, followed by a thick p-contact for probing (Ti/Au = 20/100 nm). Electroluminescence (EL) was collected from the top surface of the device through a monochromator with a PMT detector as shown in inset of Fig.3 (c).

Results: Transmission line measurements (TLM) on both n and p-type layers yielded contact resistance (ρ_c) and sheet resistances (R_{sh}) summarized in Table I. Both samples show comparable sheet and contact resistance for n-layers. P-layers' ρ_c and R_{sh} are also 2 orders larger than n-layers, which means the bottleneck resistance for device performance comes from the p-layers. Sample A (no Mg-doped InGaN) has a p-contact resistance of $3.87\ \Omega \cdot cm^2$, while Sample B (with Mg-doped InGaN) has ~2 orders lower p-contact resistance of $1.28 \times 10^{-2} \Omega \cdot cm^2$ extracted from Fig.2(a). More importantly, as seen in Fig.2(b), the TLM IVs of Sample B show ohmic behavior, instead of the Schottky behavior seen for Sample A. Samples A and B both show deep UV electroluminescence at 243nm and 268nm, respectively (Fig.3(b)) at room temperature. Sample B has a secondary peak around 275nm, due to thickness fluctuations in the ultra-thin GaN/AlN active region. Sample A exhibits degradation in EL emission intensity at current density >30A/cm^2 despite pulsed mode measurement (1s pulse width, 10% duty cycle). In contrast, Sample B was found to operate in CW mode with emission intensity ~100x that of Sample A at similar current density (~50 A/cm^2). Sample B reaches 200A/cm^2 at 10V forward bias, 10x higher than Sample A (from diode JVs; Fig.3(a)).

Conclusion: Using Mg-doped InGaN as the p-contact formation layer has lowered the contact resistance by 2 orders and sheet resistance by 4x in comparison with p-GaN. LEDs with p-InGaN layer operate in CW mode and show 2 orders stronger electroluminescence intensity than standard p-GaN contact layer LEDs. The initial results show p-InGaN incorporation in p-contact layers improves device performance dramatically. A more detailed study on the optimization of doping and transport of p-InGaN will be investigated in the future.

Acknowledgement: This work was supported by Cornell Center for Materials Research (CCMR) with support from the NSF MRSEC program (DMR-1120296), NSF DMREF program (DMREF-1534303) and AFOSR (AFOSR FA9550-17-1-0048).

Reference:

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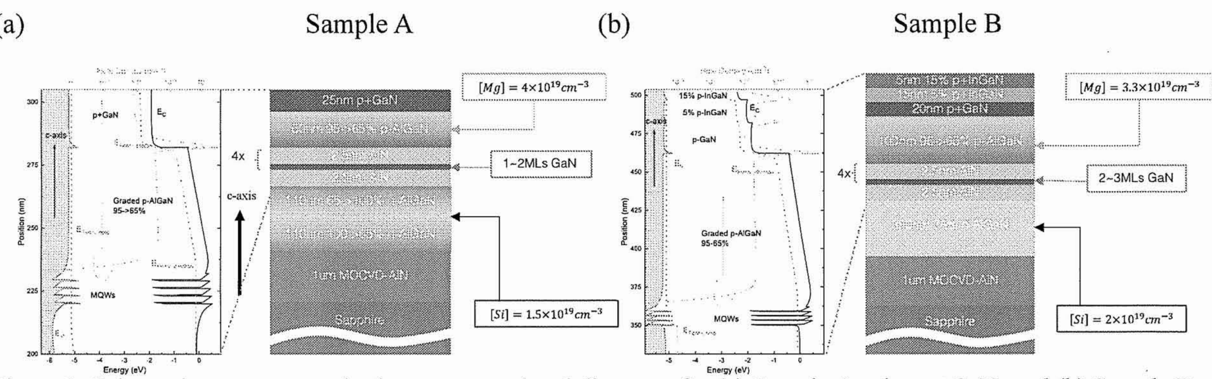

Figure 1. Schematic structures and p-layers energy band diagrams for (a) Sample A using p+GaN, and (b) Sample B using a novel 1% p-InGaN and 15% p-InGaN p-contact layer.

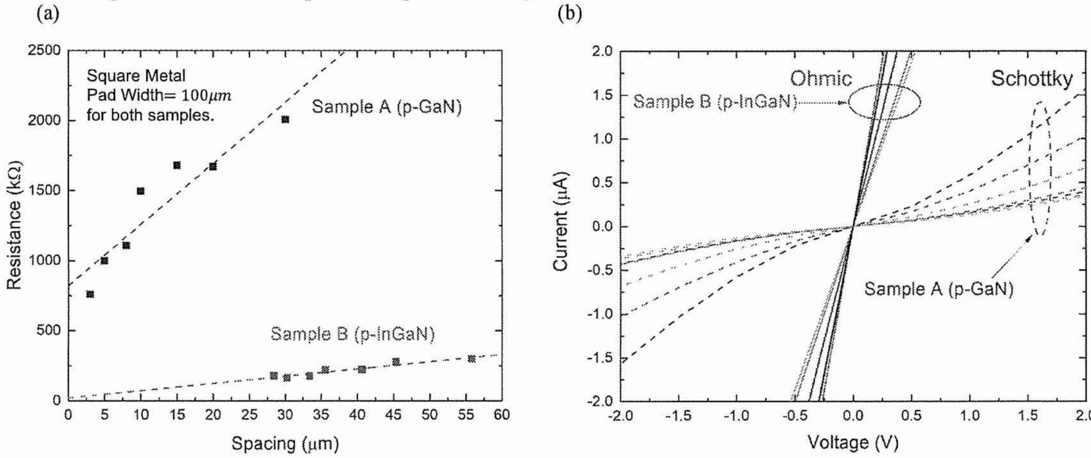

Figure 2. (a) Transmission line measurements of the Sample A (without p-InGaN) and Sample B (with p-InGaN) p-type layers. (b) IV curves from the TLM.

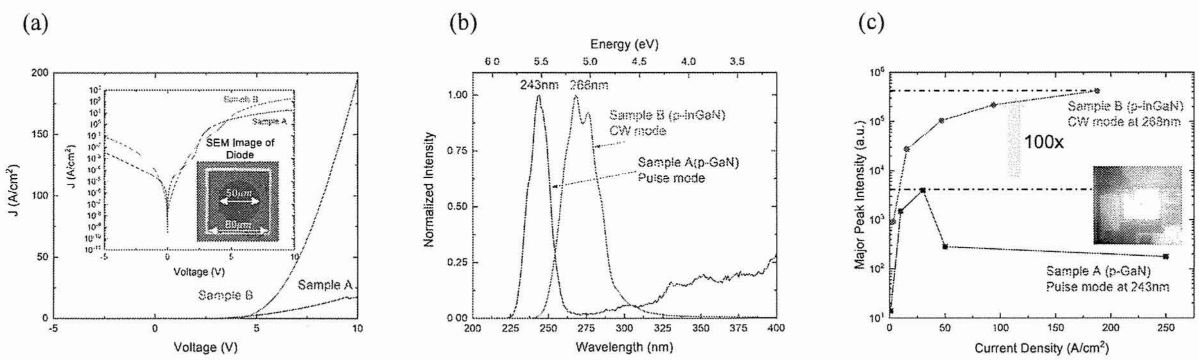

Figure 3. (a) Diode JV characteristics (inset is plotted in log scale), (b) room temperature electroluminescence of Sample A (B) showing major peak at 243nm (268nm), and (c) major peak intensity vs injection current density: Sample B shows ~100x stronger emission than the highest intensity of Sample A. Sample A shows degradation in emission intensity at high current injection level.

Table. I. Summary of contact resistance and sheet resistance.

TLM	$p - R_{sh}(k\Omega/\mathrm{sq})$	$p - \rho_C(\Omega \cdot cm^2)$	$n - R_{sh}(k\Omega/\mathrm{sq})$	$n - \rho_C(\Omega \cdot cm^2)$
Sample A (w/o p-InGaN)	2181	3.87	4.34	3×10^{-3}
Sample B (w p-InGaN)	528	1.28×10^{-2}	2.35	4.7×10^{-4}