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## **Electroluminescence enhancement for near-ultraviolet light emitting diodes with graphene/AZO-based current spreading layers**

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**Abstract:** Near-ultraviolet light emitting diodes with different aluminum-doped zinc oxide-based current spreading layers were fabricated and electroluminescence (EL) was compared. A 170% EL enhancement was achieved by using a graphene-based interlayer.

GaN-based near-ultraviolet light emitting diodes (NUV LEDs) have attracted significant research interest due to their intensive applications in various areas where indium tin oxide (ITO) is one of the most widely employed transparent conductive materials for NUV LEDs. Compared to ITO, indium-free aluminum-doped zinc oxide (AZO) has similar electrical and optical properties and is low-cost, nontoxic and more stable at high temperatures, therefore offering an attractive alternative to ITO. Meanwhile, the performance of AZO in NUV applications still needs further improvement. Hence, this work focuses on electroluminescence (EL) enhancement in NUV LEDs with a new type of current spreading layer (CSL) which combines AZO and a single-layer graphene (SLG) as an effective transparent CSL [1].

In the present work, LEDs with solo AZO CSL in Fig.1(a) and SLG/Ni/AZO-based CSL in Fig.1(b) were both fabricated for EL comparison. Standard mesa fabrication including photolithography and an inductively coupled plasma (ICP) GaN etch was applied on a NUV epi-wafer which mainly consists of a 2.5 $\mu$ m n-GaN layer, 9 pairs of 2nm InGaN/ 8nm GaN multiple quantum wells (MQWs) and a 130nm p-GaN layer. Afterwards, two types of CSLs, 250nm AZO and SLG/2nm Ni/250nm AZO, were formed on the mesas, respectively. AZO was deposited through a sputtering process followed by a 5-min annealing at 800°C in N<sub>2</sub> whereas Ni was deposited through an e-beam evaporation process to protect the SLG during the AZO sputtering process followed by a 5-min annealing at 550°C in air. Finally, 30nm Ti/200nm Au layers were e-beam evaporated as p- and n-pads.

Afterwards, EL measurements from the top of the fabricated LEDs in a probe station and spectrometer setup shows that the LED with the SLG/Ni/AZO-CSL has 170% stronger intensity than that of the LED with the AZO-CSL as seen in Fig.2. In addition, the AZO-CSL and the SLG/Ni/AZO-CSL were also fabricated on sapphire for transmittance measurements

by an integrating sphere system. Fig.3(a) shows that AZO-CSL presents a 71% transmittance at 388nm while SLG/Ni/AZO -CSL presents a 66% transmittance, indicating an acceptable sacrifice of around 5%. Furthermore, work function measurements were performed on AZO-CSL and SLG/Ni/AZO -CSL using Bruker's PeakForce Kelvin probe force microscopy. As shown in Fig.3(b), graphene has a higher work function (4.85-4.9 eV) than that of AZO (4.7-4.75 eV).

In summary, a 170% EL enhancement was achieved by the SLG/2nm Ni/250nm AZO CSL in comparison with the 250nm AZO CSL. The enhancement can be attributed to the higher work function of graphene which reduces the potential barrier hence allowing easier carrier injection through the p-GaN layer.

**Acknowledgment**

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[1] Kim, BJ, Mastro, MA, Hite, J., Eddy, CR, and Kim, J: "Transparent conductive graphene electrode in GaN-based ultraviolet light emitting diodes," Optics Express, 18(22), pp. 23030-23034 (2010).

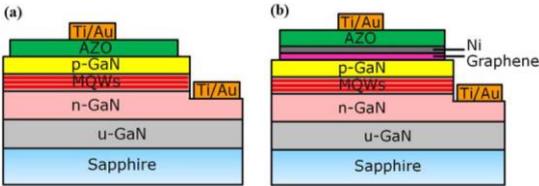


Fig.1 (a): NUV LED with a 250nm AZO CSL;  
 (b): NUV LED with a SLG/2nm Ni/250nm AZO CSL.

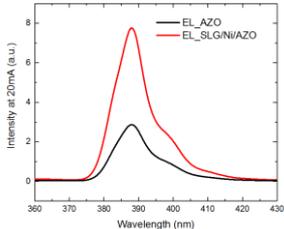


Fig.2 EL spectra of NUV LEDs with different CSLs.

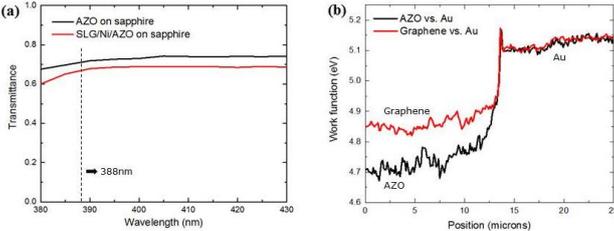


Fig.3 (a): Transmittance of CSLs; (b): Work function of CSLs.