Supporting information for *Journal of Materials Chemistry*

GaN Light-Emitting Diodes on Glass Substrates with Enhanced Electroluminescence

Jun Hee Choi[1†], *Ho Young Ahn*[1], *Yun Sung Lee*[1], *Kyungwoo Park*[2], *Tae-Ho Kim*[1], *Kyung Sang Cho*[1], *Chan Wook Baik*[1], *Sun Il Kim*[3], *Hyobin Yoo*[4], *Eun Hong Lee*[1], *Byoung Lyong Choi*[1], *Sung-Dae Kim*[4], *Young-Woon Kim*[4], *Miyoung Kim*[4†] ,*Sungwoo Hwang*[1]

[1]Frontier Research Laboratory, Samsung Advanced Institute of Technology, Samsung Electronics, Yongin, Kyunggi-do 446-712, South Korea

[2]Nano Fabrication Group, Samsung Advanced Institute of Technology, Samsung Electronics, Yongin, Kyunggi-do 446-712, South Korea

[3]3D Display Group, Samsung Advanced Institute of Technology, Samsung Electronics, Yongin, Kyunggi-do 446-712, South Korea

[4]Department of Materials Science and Engineering, Seoul National University, Seoul 151-744, South Korea

† Authors to whom correspondence should be addressed.

E-mail: joonie.choi@samsung.com, mkim@snu.ac.kr

I. Electrode pad configuration

We compared our previous and current configurations in Fig. S1. In the previous configuration (Fig. S1 (a)), we directly attached a probe to ITO UE in the active region. This could lead to mechanically induced leakage path in the insulating polymer between ITO UE and Ti LE, giving rise to unstable EL operation (Fig. S1 (b)). Currently, we are using the X-Y configuration (Fig. S1 (c)) designed as a leakage-free structure even in the presence of mechanical damage in the polymer (Fig. S1 (d)), securing stable EL operation.

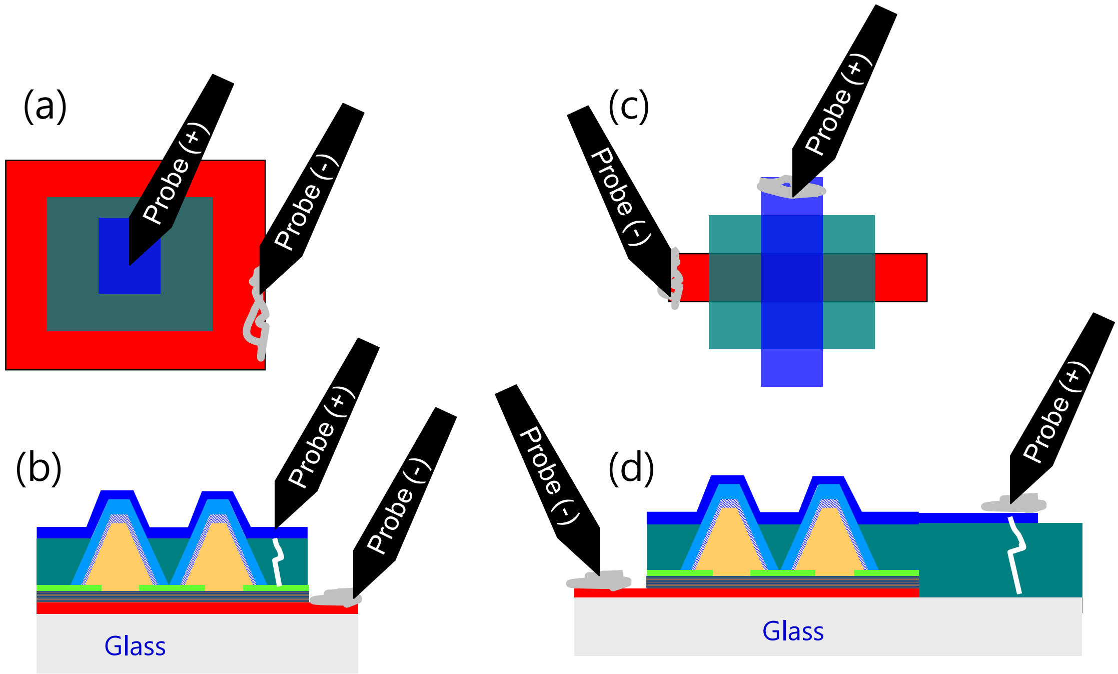

Figure S1. Comparison of electrode pad configurations: (a) and (b) are the plan view and cross-section of the previous configuration, respectively. (c) and (d) are the corresponding parts of the current configuration.

II. The detailed structure of the Structure II and its energy levels regarding dual or multi-colored emission

As shown in Fig. S2 (a), each species is composed of a stack with n-GaN pyramid (inner core)/5-period InGaN/GaN multiple quantum wells (MQWs, outer core)/p-GaN (shell). Therefore, it has basically the same energy band structure as that of typical LEDs. Considering each pyramid was mostly bounded by semipolar (10-11) planes, the band structure of barrier-well-barrier and its energy diagram can be sketched in Fig. S2 (b) and (c) [1].

Various defects including bended threading dislocations [2] and different point defects or their complex are expected to exist in the pyramid stack marked in Fig. S2 (a). These defects would form the defect states in the bandgap. (Fig. S2 (c)) Although the most defect levels in semiconductor materials are known to work as non-radiative recombination centers, those in GaN based materials are exceptionally radiative, emitting yellow light commonly observed during PL or CL measurements. (see Fig. 2 (e) in the manuscript) Nevertheless, it should be noted that the luminescence from such defect states is quite weak especially in electroluminescence (EL) measurements. This is due to absence of strong carrier confinement, resulting in a low recombination rate as estimated by bi-molecular equation. ($R=Bnp$, where R: radiative recombination rate, n and p: electron and hole concentrations.) On the other hand, the carrier confinement is occurring in each well. Therefore, it should be noted that detectable and visible light generated from the pyramid stack originates from InGaN wells, not from the defect states.

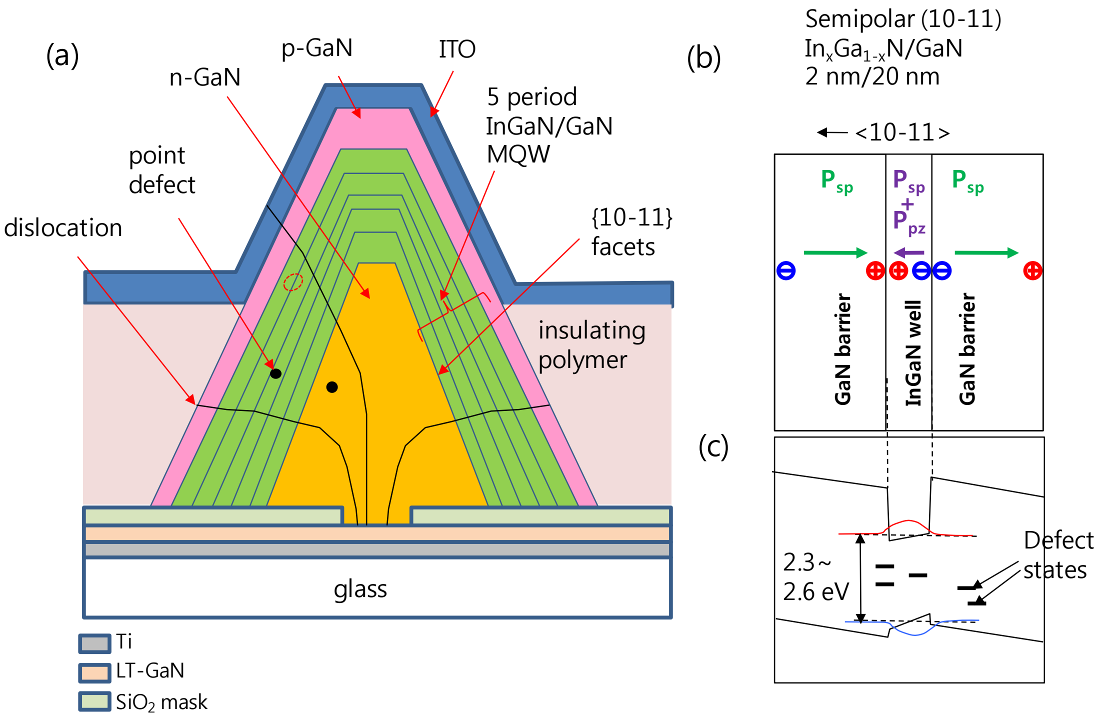

Fig. S2. (a) Schematic representation of a GaN pyramid stack embedded in insulating polymer. (b) (10-11) semi-polar quantum well (QW) structures marked in a dotted ellipse in (a), and (c) corresponding band diagrams [1].

III. Correlation between light output power and luminance

The most common method for evaluating LED performance is measuring light output power (P_{out}) emitting to all the direction using integration sphere. P_{out} has the unit of watt (radiometry) or lumen (photometry).

In our case, due to difficulties in making a LED chip required for integration-sphere measurement, we measured luminance (or brightness) of our samples using a tool called calorimeter. Luminance (L) has the unit of cd/m^2, meaning optical power per unit area and per unit solid angle (steradian). This unit is commonly used for surface light-emitting sources such as displays. We used the CS2000 (Konica-Minolta Inc.) calorimeter for measuring luminance.

P_{out} can be calculated from L by approximating our LEDs as a Lambertian light source (an ideal diffuse surface) with emitting area (A).

$$P_{optical, photomtry} = \pi LA \qquad (1)$$

By putting L=2700 cd/m^2 and A =2.9 mm^2, P_{out} is 24 x 10^{-3} lumen. P_{out} in lumen can be converted to P_{out} in watt using the following equation and the eye sensitivity function vs. wavelength [3].

$$P_{out}(lumen) = [683\frac{lm}{W}\int_{\lambda} V(\lambda)P(\lambda)d\lambda]/[\int_{\lambda} P(\lambda, watt)d\lambda] \qquad (2)$$

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IV. Analysis for efficient GaN LEDs on glass

I-V curve of the GaN LEDs on glass is shown in Fig. S3. Although we accomplished enhancement of microscopic uniformity and luminance values in this work, the I-V curve still exhibits non-ideal diode characteristics. From the figure, the calculated values of parallel resistance (R_p) and series resistance (R_s) were 14.8 kΩ and 310 Ω, respectively. (R_s and R_s were *dV/dI* values at V_f=0.1 and 11.5 volts.) To make our EL devices more efficient, both R_p and R_s effects should be greatly reduced (The ideal values of R_p and R_s should be infinity and zero, respectively.).

To increase R_p, insulation between upper and lower electrodes should be optimized. First, we need to focus on the pyramid stack itself. Although we obtained conformal p-GaN coating by controlling Mg concentration [4] across the pyramid surface to eliminate shorts as written in the manuscript, there is still a possibility of leakage through dislocations. Considering the band diagram (Fig. S2 (c)), leakage by tunneling issue would not seem to be critical. Second, we also assume that leakage might occur through the interface between polymer and p-GaN. Some passivation of the pyramid defect or interface might be required. We are developing “SiO_2 coated insulation process” to solve out the raised issues. Third, as we wrote in the manuscript, we found that minimum polymer thickness was required for stable EL operation.

To reduce R_s, we need to optimize an imperfect interface between the GaN rod and the Ti layer generated by the thermal mismatch between Ti and LT-GaN during cooling down after the GaN rod growth. A p-GaN shell of moderate p-type conductivity, uniform thickness distribution around the MQWs/n-GaN pyramid, and its good ohmic contact to ITO might solve the problem.

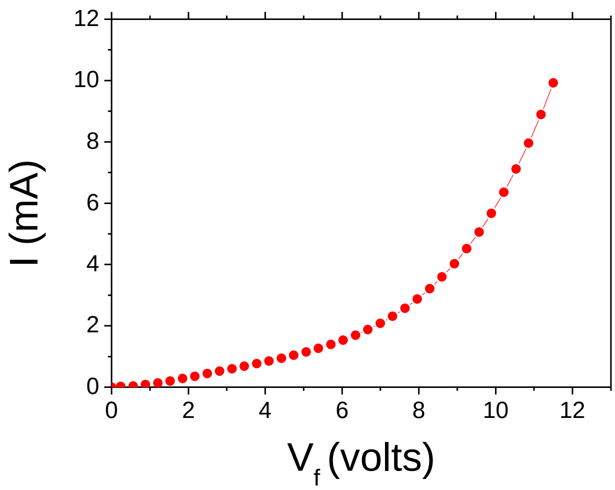

Fig. S3. I-V curve of GaN LEDs on glass.

Reference

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