Flexible White Light-Emitting Diodes Based on Vertical Nitride Nanowires and micro-size phosphors

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Abstract

White light emitting diodes (LEDs) have received huge worldwide attention in recent years, motivated by their significant role in reducing global energy consumption and practical solid-state lighting (SSL) applications. In addition, flexible light sources are required for a number of applications (e.g. curved surface displays). Nowadays, the key technology for flexible emitters is dominated by white phosphor-converted organic LEDs (OLEDs) [1], [2] and white OLEDs (WOLEDs) by mixing of different colored emitters [3]. Thanks to the efforts of the past decades, WOLEDs have been commercialized thanks to their low cost, compatibility with various flexible substrates and relative ease of processing. However, they still suffer from poor time stability and from a rather low luminance especially for the blue component of the color mixture. On the contrary, nitride semiconductors have excellent performance in the blue spectral range in terms of luminance and external quantum efficiency and have a lifetime of more than 100,000 h. Recently, we have demonstrated blue flexible LEDs based on vertical nitride nanowires (NWs) encapsulated in flexible polymer [4]. Here we report the flexible white phosphor-converted LEDs based on core/shell InGaN/GaN NW blue LEDs grown by MOCVD, which combine the high flexibility of polymers with the high efficiency of the nitride NWs and micro-phosphors.

InGaN/GaN p-n junction core-shell NWs grown by MOCVD on c-sapphire substrate [5] are used for device fabrication as a blue light source (wavelength ~440 nm). A highly n-doped GaN segment (~9 µm) is grown followed by a non-intentionally doped GaN segment (~24 µm), which is surrounded by 7 periods of radial 5 nm/10 nm InGaN/GaN quantum wells (QWs) and is covered with a p-doped 120 nm thick GaN shell. The diameter of the core/shell region varies from 700 nm to 2 µm. Figure 1 shows a scanning electron microscopy (SEM) image of as-grown NWs. Figure 3 illustrates the fabrication steps of flexible white LEDs. First, Ni/Au (3nm/3nm) is sputtered on the InGaN/GaN shell with the protection of lower n^+-GaN part by photo-resist. After the lift-off of photo-resist, Ni/Au is annealed at 400 °C under oxygen. PDMS doped with YAG:Ce phosphor (radium ~2-3 µm) is spin-coated on the NW array to fill the space between the NWs. The PDMS/NW composite film (~30 µm) is peeled off and the shell side of NWs is attached to an arbitrary host substrate. Then Ti/Al/Ti/Au metallization is applied to n^+-GaN side. The membrane is again removed from the substrate and attached to a metal foil which plays a role of an external flexible contact connecting n^+-GaN side. Silver NWs are spin-coated to connect the p-InGaN/GaN side of NWs. Finally, the LED surface is capped with PDMS mixed with YAG:Ce phosphor.

The current density-voltage (J-V) curve of the flexible white LED is shown in Figure 2. The J-V curve shows rectifying diode-like behavior with the threshold voltage around 3 V, above which the current increases exponentially with the bias voltage. Electroluminescence (EL) spectra have been measured at room temperature. The EL spectra at different injection currents shown in the inset of Figure 2 present a broad wavelength distribution from 400 nm to 700 nm covering almost the entire visible spectrum range. Figure 4 shows the photographs of the emitting flexible white LEDs in a flat state and with the bending radii of 5 mm and -5 mm. No significant change of the current or of the EL spectrum has been observed when bending. After several bending cycles, no appreciable change appeared in J-V or EL characteristics compared with the original LED performance.

References

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Figures

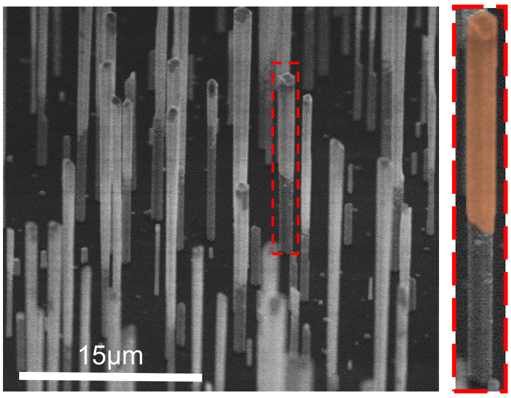

Figure 1. SEM image of a core/shell InGaN/GaN NW array together with a zoomed-in image of an individual NW in which the artificially colored region corresponds to the active core/shell region of the NW.

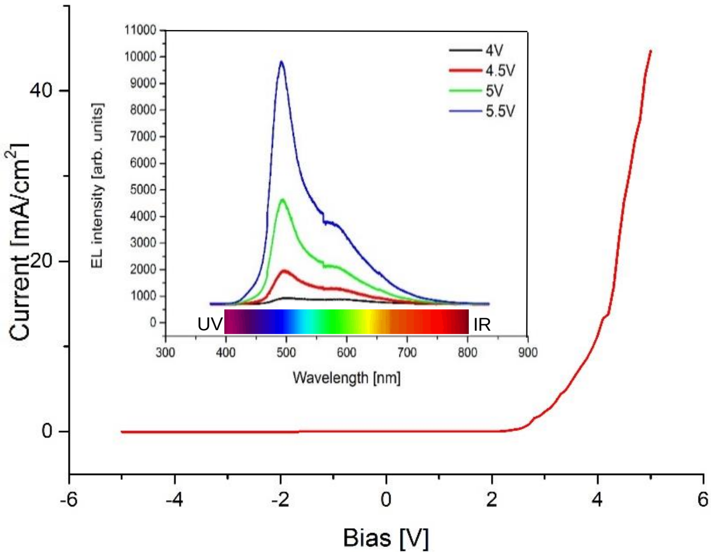

Figure 2. J-V curve of a flexible white LED (normalized to the device total surface). Inset shows the EL spectra at room temperature under biases from 4 V to 5.5 V.

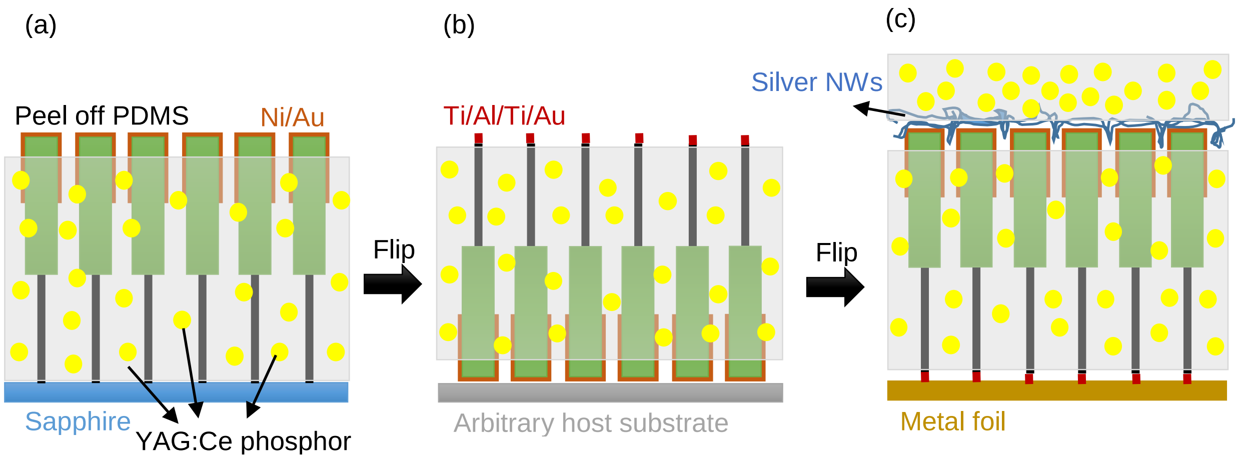

Figure 3. Fabrication process flow of flexible white LEDs based on free-standing polymer-embedded NWs.

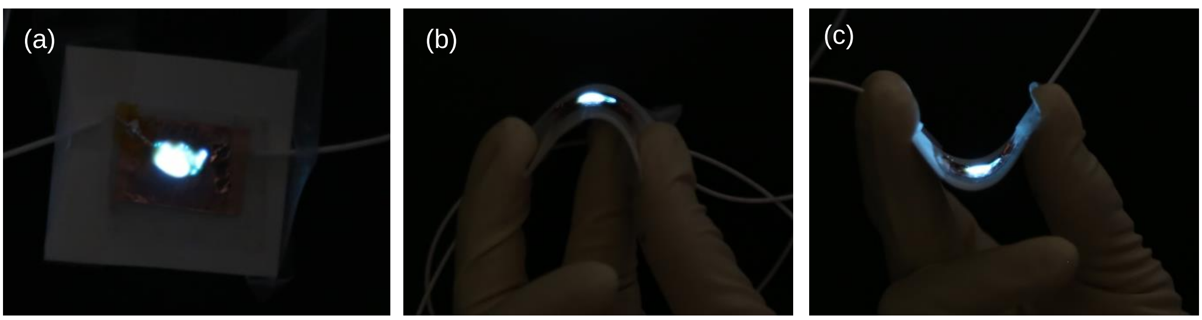

Figure 4. Morphological characteristics of flexible LEDs emitting white light with bending radii of (a) infinity (b) 5 mm (c) -5 mm.