Flexible GaN LED on a Polyimide Substrate for Display Applications

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ABSTRACT

The flexible GaN-based light emitting diode (LED) has been fabricated on a plastic substrate for flexible display applications. The epitaxial structures of the GaN LED arrays are transferred onto a flexible substrate using standard soft lithography technology and connected to a source-meter by metal lines. To verify the mechanically and optically stable characteristics of the GaN LEDs on the flexible substrates, the electrical properties are characterized during 2000 bending cycles at various bending radius. A white light-emitting phosphor-coated GaN LED shows its potential as a next-generation flexible light source.

Keywords: Flexible GaN LED, Flexible display, White LED, Polyimide substrate

1. INTRODUCTION

Light emitting diodes (LEDs) have superior characteristics, such as long-term lifetime, high efficiency, and strong brightness compared to conventional incandescent lamps. With these advantages, LEDs have been developed and explored for consumer electronics such as energy efficient light lamp, back-light unit (BLU), and active matrix organic LED (AMOLED).

The fabrication of LEDs on flexible substrates has attracted a great interest owing to a variety of applications such as flat panel display, electronics paper, and touch panel. Flexible organic LEDs (OLEDs) have been studied actively in the past decades with the feasibility of flexible displays.[1-5] However, OLEDs are limited in terms of their compatibility due to short life time [6], low efficiency, and low brightness compared to inorganic LEDs (ILEDs).[7, 8] These problems can be addressed by standard micro-fabrication and soft lithography techniques in which the thin film on bulk substrate followed by high temperature annealing and then is transferred onto flexible substrates.[9,10] Since the first invention of flexible III-V materials in 2005 [11], Rogers group has presented flexible inorganic LEDs on plastic substrates using micro-structured GaAs/GaN (\(\mu\)-GaAs/GaN).[12-16] Recently in 2011, Lee et al. established the flexible GaN ILED on a liquid crystal polymer substrate for biomedical application by using micro-structure transferring process.[17] Although this work proposed the feasibility for flexible LED biosensor, it was not appropriate for the flexible display applications.

Herein, we report the flexible ILED using a single crystal micro-structured GaN (\(\mu\)-GaAs) on polyimide (PI) substrate. The superb properties of the GaN material in terms of its wide band gap and high efficiency enable the dramatic extension of consumer electronic applications. In this study, we illustrate two substantial enhancements on flexible ILEDs, as follows: (1) establishment of flexible GaN ILED that can be applied to controllable micro-patterned LED arrays [18]; (2) a flexible white LED created through a combination of a blue GaN LED and yellow phosphor, which can be utilized for the promising flexible back-light unit (BLU).[19]

2. RESULTS AND DISCUSSION

Figure 1 illustrates schematic diagrams of the fabrication steps for \(\mu\)-GaN LED arrays settled on a plastic substrate. GaN LED epitaxial layers (n\textsuperscript{+}-(In)GaN/p-(In)GaN/MQW/SLs/n-GaN) were accumulated on a Si (111) substrate by metal organic chemical vapor deposition (MOCVD) (corresponding to Figure 1a). For ohmic contact pad, GaN LED layers were etched by an inductively coupled plasma reactive ion etcher (ICP-RIE) until n-GaN exposed (Figure 1b). Cr/Au

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layers (5 nm/40 nm in thickness) were deposited on both the n-GaN and n+-(In)GaN/p-(In)GaN layers to serve as the n and p ohmic contact pads and annealed at at 600 °C for forming the ohmic contact (Figure 1c). To protect the ohmic contact pads, a PEO (plasma-enhanced chemical vapor deposited-SiO$_2$)/Au/Cr (1 μm/200 nm/10 nm in thickness) layer was additionally deposited onto the contact pads (Figure 1d). PEO/Au layers were patterned using the conventional photolithography and etching techniques (Figure 1e). The GaN LED structures were etched by using chlorine-based ICP-RIE under the PEO/Au/Cr etch mask with a 100 μm x 100 μm narrow-bridge pattern. During the ICP-RIE dry etching process, the PEO mask layer was etched away by high-density plasma. Anisotropic wet etching by potassium hydroxide (KOH, 20.0 wt%, 75 °C, 25 min) removed the underlying Si layer and separates the GaN LED layers (narrow-bridge pattern of 100 μm x 100 μm) from the mother substrate (Figure 1f). A polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning) stamp was uniformly contacted with the Au masked μs-GaN layers. Upon fast removal from the mother substrate, the narrow-bridge-shaped μs-GaN LED was completely transferred onto the PDMS stamp (Figure 1g). Polyurethane (PU, Norland optical adhesive, No. 73) was coated onto PI substrates as a terminus of the GaN LED. The substrate holding the GaN LED was indurated with ultraviolet (UV) light to optically cure the PU. Finally, the GaN LED layers was shown to be attached well to the plastic substrates [polyimide (PI) film, xx μm in thickness] when the PDMS stamp was removed (Figure 1h). A UV-sensitive epoxy (SU8-5) was spin-coated on top of GaN LED/PU/PI substrates. The metal contact area was then opened with standard photolithography, and this was followed by a metallization process that consisted of Au/Cr deposition (150 nm/15 nm in thickness) and the formation of a 2 x 2 array electrode (Figure 1i and 1j). The electrodes were connected to an external source-meter (Keithley 2612A) to turn on the LEDs.

Figure 1. Schematic diagrams of the fabrication steps of μs-GaN LED arrays settled on a plastic substrate.
Figure 2a shows the optical images of our flexible 2 x 2 GaN LED arrays on a PI substrate. The inset of Figure 2a is a magnified image of the active region of the lighted GaN LED. The metal electrodes 1 and 3 are connected in series with 2 and 4, respectively. Figure 2b shows the electroluminescence (EL) spectra of GaN LED measured after transferring onto a PI substrate.

Figure 2. (a) The photograph of the 2 x 2 GaN LED arrays on PI substrate. (b) EL spectra of flexible GaN LED

The I-V curves are measured at various bending cycles and radii, as shown in Figure 3. Figure 3a shows that the electrical property of the flexible GaN LED does not significant change during the bending fatigue test (BFT) at a bending radius of 3.5 mm. No electrical damage is also observed in a harsh cycling condition up to 2000 times on a stage, as shown in the inset of Figure 3a. With the change from flat to about 3.5 mm, degradation does not appear, as shown in Figures 3b and the inset. These results indicate that our flexible GaN LED shows a mechanical stability on the flexible PI substrates and maintains its optical and electrical properties due to good ductility of metal line and thin inorganic material.[20,21]

![Figure 3. I-V curves results of flexible GaN LED measured at various bending cycles and radii.](image)
Figure 4a shows a schematic of a flexible white LED structure composed of a flexible blue GaN LED and yellow YAG:Ce phosphor. YAG:Ce is known to be optically excited by blue light at a wavelength of 460 nm, then emitting at around 550 nm.[22] In the inset of Figure 4b, the flexible white LED is demonstrated; it is activated by a phosphor coating mixed with transparent epoxy resin on the blue LED active region. As shown in Figure 4b, two distinct emission bands from the flexible GaN LED and YAG:Ce phosphor are clearly divided at 440 nm and at approximately 540 nm, respectively. At 440 and 540 nm, the emission intensities increase with an increase in the current from 0.2 to 2.4 mA, as expected. This approach verifies that our GaN-based white LED has the potential to be applied as a flexible white light source for BLU.

3. CONCLUSIONS
In summary, we fabricated the nitride-based flexible LED on a plastic substrate. From the bending test of the radius up to 3.5 mm and a cycling test up to 2000 times, the flexible GaN LED was mechanically and optically stable on flexible...
substrates. The flexible white LEDs demonstrate the feasibility of using a white light source for future flexible BLU devices. These results show that the nitride-based flexible LED can be used as a next-generation flexible light source.

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