Monolithic Integration of GaN-based LEDs

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Abstract. The technology of monolithically integrated GaN-based light-emitting diodes (LEDs) is reported. First, the technology details to realize monolithic integration are described, including the circuit design for high-voltage and alternating current (AC) operation and the technologies for device isolation. The performances of the fabricated monolithic LED arrays are then demonstrated. A monolithic series array with totally 40 LEDs exhibited expected operation function under AC bias. The operation voltage of the array is 72 V when 20 LEDs were connected in series. Some modified circuit designs for high-voltage operation and other monolithic LED arrays are finally reviewed.

1. Introduction

Recently the development and application of GaN-based light-emitting diodes (LEDs) are greatly accelerating in the fields of automotive, liquid crystal display (LCD) television backlighting and solid-state lighting. Especially in the solid-state lighting field, it has been expected that extremely high-brightness illuminating LEDs can significantly replace the current standard incandescent and fluorescent lamps owing to their low energy consumption and enhanced lifetime. Obviously it will be convenient if the LED component can be driven directly by the recent alternating current (AC) high-voltage power source. In this case, the power lose in the rectification circuits can be cut. To realize high-voltage operation, a numbers of LEDs connected in series are necessary to disperse the voltage. Monolithic integration of LEDs can offer not only compact, low-cost and reliable components for high-voltage operation, but also new smart components such as microdisplays and microarray biochips. In this presentation, the fundamental technologies of monolithic integration of GaN-based LEDs will be described. Some application cases, such as a compact monolithic blue LED series array that can operate under high AC voltage will also be reviewed.

2. Circuit design for high-voltage operation

To achieve high-voltage operation, numbers of LEDs should be connected in series according to the operation voltage and the working bias of the LEDs, as shown in Figure 1. Owing to the series connection, the operation voltage will become a multiplication of the forward voltage of a single LED. Figure 2 shows a circuit diagram of a LED array with series and parallel connection to meet AC operation, in which half of the LEDs are connected in series to form one group and then connected reversely with another group in parallel [1]. Shunts between the series LEDs are placed to protect the diodes from reverse bias breakdown, when the breakdown characteristics are not uniform among the

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LEDs. Thanks to this design, a rectification part which converts AC power to DC power can be omitted.

![Figure 1. A circuit diagram of a LED series for DC operation.](image1)

![Figure 2. A circuit diagram of a series LED array for AC operation [1].](image2)

3. Fabrication technologies for monolithic integration

3.1. Device isolation technologies

The GaN LED structure used for monolithic integration is a popular structure which consists of p-type anode layers and n-type cathode layers with an active layer between them. To realize monolithic integration of LEDs, a key technology is device isolation process. If the substrate is a insulator or a semi-insulating substrate, such as sapphire and semi-insulating SiC, the device isolation process can be completed by deeply etching to the substrate forming a trench. For GaN-based materials, dry etching technique is popular in which reactive ion etching (RIE) or inductively coupled plasma (ICP) based on Chlorine-based plasmas is used. Figure 3 is a schematic structure of a monolithically integrated LED array with air-bridge interconnection.

![Figure 3. A schematic structure of a monolithically integrated LED series array.](image3)

Another possible technology for device isolation is heavy metal diffusion. Theoretically if a deep acceptor impurity is introduced, an n-type semiconductor where shallow dopant impurity exists will become semi-insulating. Figure 4 shows the calculation results of electron concentration and resistivity of an n-GaN with dopant impurity concentration of \(2 \times 10^{16} \text{ cm}^{-3}\) and impurity level of 30 meV below the conduction band. When a deep acceptor with concentration of \(2 \times 10^{17} \text{ cm}^{-3}\) and impurity level of 1.0 eV above the valence band is introduced, both the electron density and the hole density become extremely low and the resistivity of the semiconductor film becomes \(9.63 \times 10^{13} \Omega \text{cm}\) while the Fermi level is 1.0 eV above the valence band.

To confirm the effect of heavy metal diffusion for GaN device isolation, Ni was adopted to diffuse into a n-GaN layer with doping concentration of \(1 \times 10^{17} \text{ cm}^{-3}\) and thickness of 5 \(\mu\)m. The measurement pattern is a ring-type resistor with two Ohmic contacts in both sides and a space of 20 \(\mu\)m. When Ni was introduced into the space area, we found that the current between the two Ohmic pads decreased
according to the diffusion condition, as shown in Figure 5. Compared with that of the as-grown sample, the current decreased if Ni was diffused under diffusion temperature of 1000 °C and time of 30 minutes. If the diffusion temperature and time were raised to 1050 °C and 180 minutes, respectively, the current decreased further by three orders. The diffusion depth of the latter condition was estimated to be 4 μm. This indicates that heavy metal diffusion is also a possible method for GaN device deep isolation. Further work is still necessary to investigate the reproducibility and estimate the energy level of Ni in GaN.

3.2. Fabrication of monolithically integrated LED array
After the device isolation process, the next step was a second dry etching by which the n-GaN layer was exposed for preparing the cathode Ohmic contact. Transparent anode electrode was then formed utilizing Ni/Au. Ti/Al/Ti/Au multi-player metal was adopted as the cathode electrode. The cathode contact metal also worked as the first local layer for interconnection. Finally, a gold electroplating process was utilized to form air-bridges, second layer interconnection lines and pads. Figure 6 shows a photography of a fabricated monolithic LED array with 5 LEDs in series.
3.3. Evaluation of monolithically integrated LED arrays

Figure 7 shows the forward current-voltage characteristics of 4 LED arrays with 1, 3, 7 and 20 LEDs in series. The forward voltages were almost proportional to the LED number connected in series. A monolithic series array with totally 40 LEDs exhibited expected operation function under AC bias. The operation voltage of the above array is 72 V when 20 LEDs were connected in series [1]. The output powers were also proportional to the LED number connected in series. This work also demonstrated a new method to achieve high output power. Based on this technology, a series of commercial products with operating voltage from 100 to 230 V has been developed [2].

4. Modified Circuit designs for High-Voltage Operation

In the above design, actually only 50% of the LEDs emit simultaneously, resulting low active layer utility ratio. Thermal burden might also be high due to the compact layout design. In order to improve the active layer utility ratio and to improve the thermal burden, there is still much space to optimize the circuit and layout design. A modified circuit configuration was reported in which a part of LEDs were designed in series at branch sides acting as Wheatstone bridge for rectification [3]. In this design, 10×4 LEDs are used for rectification and 15 LEDs are placed in the center of the bridge. Under operation, 35 LEDs will emit among totally 55 LEDs, resulting emitting ratio of 63.6%. Another circuit design with ladder type was also investigated to improve the uniformity and reliability [4]. In this design, 39×2 LEDs are used in both sides connected back-to-back and 36 LEDs are placed in the center. Under operation, 75 LEDs will emit among totally 114 LEDs, resulting emitting ratio of 65.8%. Operation up to AC voltage of 220 V was demonstrated.

5. Other Integrated GaN LEDs Arrays

Monolithic integration technology can be also used to improve the emission efficiency of GaN LEDs. It was reported that when hundreds of LEDs were connected in parallel, the overall emission efficiency increased over the conventional LEDs for the same device area [5, 6]. Monolithic integration technology can be also expanded to realize GaN LED-based self-emission micro-displays [7] and GaN LED-based micro-array biochips [8].

6. Conclusion

To achieve high-voltage operation, numbers of LEDs can be monolithically integrated in series if the substrate is insulating or semi-insulating. A monolithic series array with totally 40 LEDs exhibited expected operation function under AC bias. The operation voltage of the above array is 72 V when 20 LEDs were connected in series. The active layer utility ratio and the thermal burden can be improved by carefully optimizing the circuit and layout design. Monolithic integration technology can be also used to improve the emission efficiency of GaN LEDs, to realize GaN LED-based self-emission micro-displays and GaN LED-based micro-array biochips. In conclusion, monolithic integration is a smart method to realize various functional integrated arrays by using

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