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Design and comparative study of lateral and vertical LEDs with graphene as current spreading layer

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A B S T R A C T

This study analyzes the current spreading effect of graphene on lateral and vertical light emitting diodes (LEDs). We observe an improvement in uniformity of current distribution, light output power and wall-plug efficiency in lateral LEDs (L-LEDs) with graphene current spreading layer (CSL) as compared to those with indium tin oxide (ITO) CSL. From the results we conclude that graphene CSL may be better alternative to ITO CSL. We further carried out a comparative study of lateral and vertical LEDs with graphene CSL. We observe 17% higher light output power, 16% higher wall-plug efficiency and 62% lower series resistance in the case of V-LEDs with graphene CSL when compared to that of L-LEDs with a graphene CSL. Reasons behind these results have been discussed.

1. Introduction

GaN-based light-emitting diodes (LEDs) have become a potential alternative to conventional light sources due to their high energy-efficiency, high reliability, long life-time, high colour rendering index, good performance even during frequent on–off cycles, environmental friendliness and resistance to thermal and vibrational shocks [1–7]. LEDs are widely being used in various applications like lighting, backlight modules in liquid crystal displays, architecture decoration, traffic signals etc. [8,9]. However, for general illumination applications, the efficiency and light output power of modern LEDs must be further increased [10].

We encounter various problems in conventional L-LEDs, like poor current spreading, reduced heat dissipation, and high forward voltage. These problems can be attributed to the low mobility and high activation energy of the p-GaN layer [11–13]. In recent years, the V-LEDs have gained a lot of consideration by using laser lift-off technique [14,15]. Reasons for this increased attention include better turn-on behaviour and smaller series resistance due to the vertical injection of current. Owing to higher mobility of electrons in the n-GaN layer, current spreading is better and due to the higher conductivity of metal-based substrate heat dissipation is better. Although V-LEDs have small internal resistance, current spreading is still

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a severe problem in high power applications. The small-area top n-contacts and large-backside reflective p-contacts cause current crowding in V-LEDs [13,16,17].

Uniform current distribution in active region is essential for improved LED device performance. Non-uniform current spreading results overheating in the active region, which causes heated junctions. The heating in junctions increases series resistance of LEDs. Currently, several research groups are working on improving current spreading. These methods include the use of transparent conducting layer (TCL) or current spreading layers (CSLs) [18,19], patterned structures, electron blocking layer (EBL) [17], InAlN/InGaN insertion layer between the n-GaN layer and MQWs [20], use of quaternary alloys etc. [21]. Nevertheless, at higher current-level, the current crowding effect is still severe. Overflow mechanism and auger recombination also worsen the performance of LED. Along with non-radiative recombination these affects may also lead to heating, which further deteriorates device performance. In practicality, for a number of applications on high power LEDs, it is therefore necessary to improve the current spreading at higher current injection levels to enhance the efficiency of high power LEDs [22].

ITO CSLs are widely used in various applications like touch sensors, flat panel displays, solar cells and GaN-based LEDs. It has a low sheet resistance (<100 Ω), optical transparency of 85–90%, and unlimited scalability [24]. However, it is criticized for its high cost, poor transparency in the near UV and UV ranges, instability in the presence acid or alkali mediums, and it is vulnerable to ion diffusion into the substrate. It cannot withstand the high temperature procedures, which also limits its application to some extent [24].

In recent years, to overcome these limitations, other CSLs like graphene are being examined. Graphene is a novel two-dimensional carbon material arranged periodically in a honeycomb lattice. A great deal of research is going on graphene. Electrical properties like very high electron mobility (>15,000 $cm^2\ V^{-1}\ s$) [24], optical properties such as 97.7% transmittance for single layer graphene [24], thermal conductivity between $4.84–5.30 \times 10^3\ Wm^{-1}\ K^{-1}$, [24] mechanical and chemical properties of graphene make it quite reliable and ideal for application as CSL [24].

In this paper, we present a comparative study of lateral and vertical LED's performance with respect to *I–V* characteristics, light output power and wall plug efficiency using graphene CSL.

To test the consistency of graphene, we investigated various characteristics of LEDs like current density distribution, light-output power, wall-plug efficiency with graphene as CSL using SimuLED software (from STR Group Inc., Russia) and compared it with results obtained using ITO CSL.

2. Structure and simulation parameters

For the simulation of LED we have used SpeCLED module of STR-SimuLED software, which is used for 3D analysis of current distribution and temperature distribution in the LED using the advanced hybrid approach [23].

Fig. 1(a) and (b) shows simplified structures of L-LED and V-LED used in simulation. For L-LEDs, we have considered an LED having finger-type n- and p-contact electrodes that comprises of 200 nm thick p-GaN layer with doping concentration $1 \times 10^{19}\ cm^{-3}$, multi quantum well region made up of 10 layers, alternately made of $In_{0.2}Ga_{0.8}N$ wells (3 nm) and GaN barriers (5 nm), and a 4000 nm thick n-GaN layer with doping concentration of $5 \times 10^{18}\ cm^{-3}$ layer. We have used sapphire substrate of thickness of 150 μm as bottom substrate.

Similarly, for V-LEDs we have considered an LED having finger-type n-contact electrode that comprises of 4000 nm thick n-GaN layer with doping concentration $5 \times 10^{18}\ cm^{-3}$, multi quantum well region made up of 10 layers, alternately made $In_{0.2}Ga_{0.8}N$ wells (3 nm) and GaN barriers (5 nm), and a 200 nm thick p-GaN layer with doping concentration of $1 \times 10^{19}\ cm^{-3}$. We have considered a copper-based substrate of thickness of 150 μm in contact with p-GaN layer as p-contact electrode as well as reflector. In both the LEDs contact resistances of n and p-electrodes have been assumed to be $10^{-5}\ \Omega\ cm^2$ and $10^{-3}\ \Omega\ cm^2$ respectively.

In both Fig. 1(a) and (b), CSL indicates either graphene or ITO current spreading layer.

3. Simulation results and discussion

By calculating only the minimum and maximum values of the current density we cannot estimate the current spreading [22]. Therefore, to accurately analyze the current spreading in the chip we have selected a reference line in each case to represent the characteristics of entire chip. The reference line has been taken to be a horizontal line at 340 μm away from the bottom edge of the chip. Fig. 2(a) and (b) shows the 2D current density distribution across the active region of hetero-structure along with the reference line considered when ITO and graphene are considered CSL as respectively for an injection current of 350 mA having an average current density of 35 A/cm^2. Fig. 3 shows the variation of current density along the reference line considered when same current is supplied.

Current density distribution in active region can be used to evaluate current spreading in the LED. We can estimate that designs with high current density variation have poor current uniformity. In L-LEDs, current crowding is high because current spreading length is not large enough to spread the current away from electrodes. A non-uniform current distribution leads to local overheating of the active region and increased series resistance [22]. Fig. 2(a) and (b) shows current density distribution for L-LED chips with ITO CSL and graphene CSL having current density variation from $1.1 \times 10^{-5}\ A/cm^2$ to $102.69\ A/cm^2$ and $1.1 \times 10^{-5}\ A/cm^2$ to $58.42\ A/cm^2$ respectively. To get a detailed picture of the current density distribution