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Article *in* Optical and Quantum Electronics · September 2010

DOI: 10.1007/s11082-011-9470-y

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Simulation for light power distribution of 3D InGaN/GaN MQW LED with textured surface

Li-Wen Cheng · Yang Sheng · Chang-Sheng Xia · Wei Lu · Michel Lestrade · Zhan-Ming Li

Received: 27 September 2010 / Accepted: 3 May 2011 / Published online: 15 May 2011

Abstract In this paper, we introduce a full 3D simulation for light power distribution of an InGaN/GaN MQW LED with a textured surface. Device simulation was performed with the APSYS software to get power distribution of light sources inside the LED. Based on this, ray tracing simulation was carried out to get light power distribution outside the LED. During the process of ray tracing, the textured surface was treated as a special material interface whose reflectivity, transmittance and refraction angle are obtained with a Finite-Difference Time-Domain (FDTD) method instead of using the usual Fresnel formulas for normal material interfaces. By comparing the ray tracing results with and without the textured surface, we found that the textured surface yields a smoother transmitted power distribution and greatly improved power extraction efficiency, which are comparable to experiment. These effects may be further improved by optimizing the texture geometry.

Keywords InGaN/GaN · Light-emitting diode (LED) · Light power distribution · Simulation · Textured surface

1 Introduction

High-brightness light emitting diodes (LED) are an active field or research due to their applications in many areas (Shur and Zukauskas 2005). Extraction efficiency and the output

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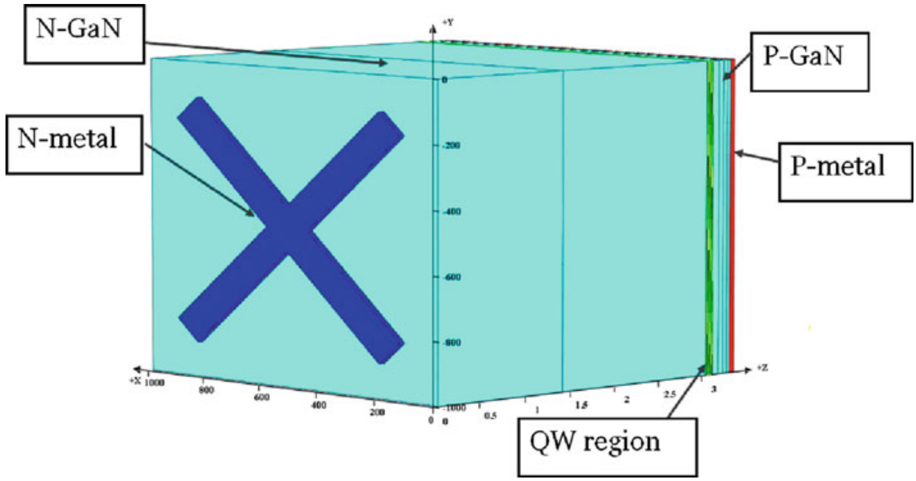

Fig. 1 3D LED with cross-shaped n contact.The N-type GaN surface is textured.

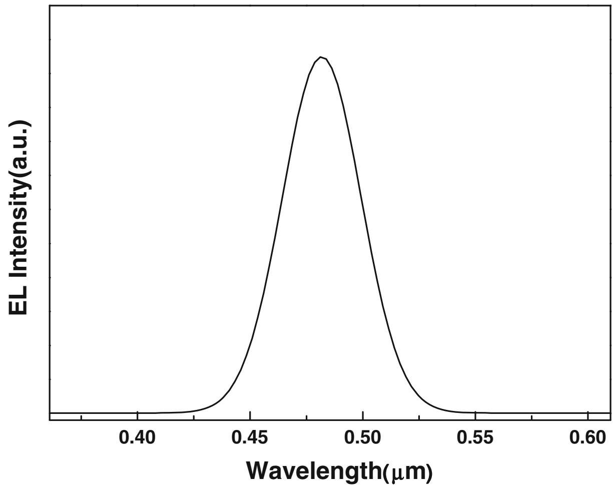

Fig. 2 Normalized electroluminescence (EL) spectrum. Peak is at 480 nm.

distribution of emitted light power are both crucial qualities that LED device developers are trying to improve (Cheng et al. 2008).

Textured surface technique became popular in order to avoid the problem that external quantum efficiency is limited by the total internal reflection of emitting light at interface of semiconductor and air due to large difference of refractive index (Yang et al. 2005). To form surface texture pattern, several techniques are applied, such as anisotropic photoelectrochemical etching process (Fujii et al. 2004), natural lithography (Yang et al. 2005). These techniques make LED surface roughened in shape of trapezia (Han et al. 2006), pyramid (Fujii et al. 2004) and V-shaped (Tsai et al. 2006), Surface roughness is critical and must be controlled by about one-half wavelength according to (Yang et al. 2005). The dimension of a single texture unit varies near LED peak wavelength (Windisch et al. 1999).

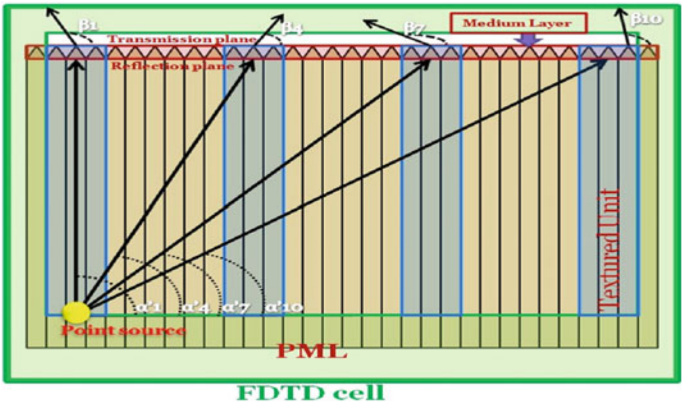

Fig. 3 Schematic diagram of FDTD calculation.

It is important that details of light extraction for these devices be verified and understood so that further improvement or optimization may be achieved. For computational-aided-design(CAD) work, additional complications arise when a LED has a textured surface on a scale similar to the emission wavelength. In that case, the wave nature of the light must be considered and purely geometric approaches such as ray tracing are no longer sufficient.

In this paper, a full solution is proposed to simulate ray transmitting in LED device with a textured surface. Firstly, 3D structure of a MQW LED with cross-shaped contact is built up using CSUPREM. This software is a processing TCAD tool originally intended for silicon devices (CSUPREM 2010) which has lately been extended to conveniently build and mesh complicated 3D structures. Then, the APSYS software (APSYS 2010) performs 3D photoelectric simulations on this LED to yield power distribution of the source light emitted by MQW in this LED. This advanced software simultaneously solves the carrier transport, Poisson and self-heating equations. Various mechanisms critical for LED analysis, such as self-consistent quantum wells, spontaneous emission, non radiative recombination and injection current overflow have been included in the software.

In succession, a 3D ray-tracing (RT) module is applied to simulate how the source rays escape the LED, and counts spatial power distribution of the escaped light. When rays travel in a given medium, light power is gradually absorbed and Fresnel equation is calculated to get power reflectivity and refractivity at material interface. It proves to be especially useful for tracing ray paths (Sheng et al. 2007).

Due to the wave nature of light, the textured surface is treated as a special material interface in 3D RT. Its reflectivity and refractivity are calculated not by the Fresnel equation, but by interpolation from tabulated data extracted from finite-difference time-domain (FDTD) calculation. FDTD is a popular modeling technique to simulate propagation of electromagnetic wave. In this work, MEEP FDTD software (Meep 2010), (Oskooi et al. 2010) is applied. To save computational runtime, a 2D cross-section through the textured surface is picked up and texture unit shape is supposed to be uniform in the FDTD calculation. To get relationship between light incident angle and optical properties, a point source is put under the textured surface in order to make different incident angle at different texture unit. By extracting output of FDTD calculation at each texture unit, reflectivity and refractivity at different incident angle are averaged and normalized for usage of 3D RT simulation.

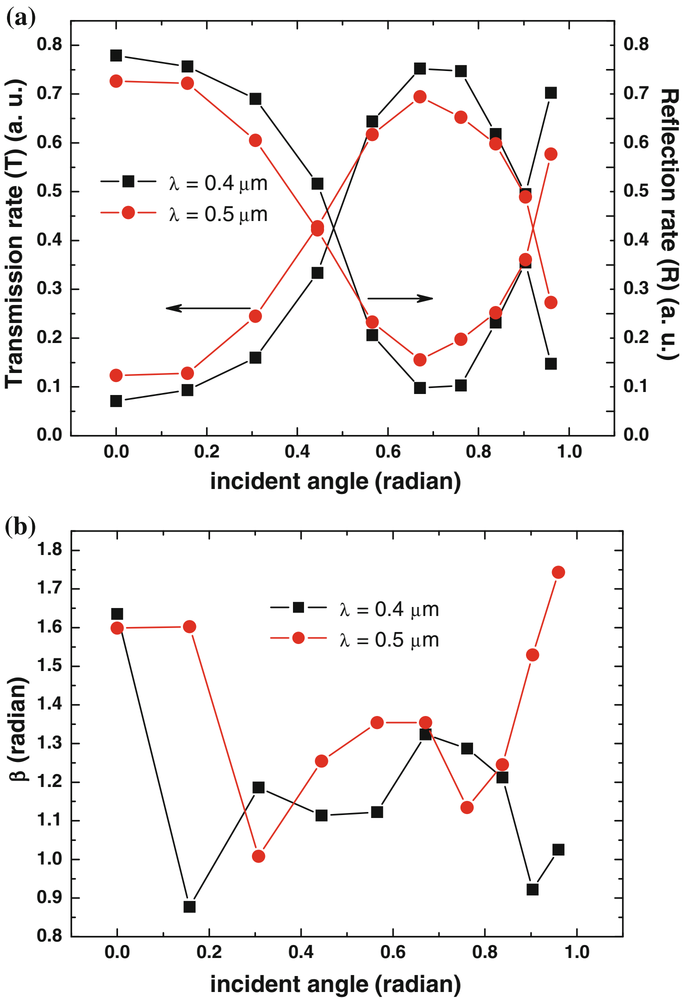

Fig. 4 **a** T, R and **b** β dependent on incident angle for the textured GaN surface at different wavelength

2 LED device structure

The structure of the InGaN/GaN MQW LED under study is shown schematically in Fig. 1, the cross-shaped region shaded in dark blue is the top metal contact. This structure is designed according to conventional LED structural configuration. The material plane (x-y plane) has a size of $1000 \times 1000\ \mu$m. The layer structure consists of 3.0 µm n-doped GaN whose surface is textured, a five-period InGaN/GaN MQW, topped with a 0.25 µm p-doped GaN epi-layer. The indium composition in the wells is 20 percent and the thickness is set to 3 nm in order to produce a peak emission wavelength around 480 nm (Fig. 2).

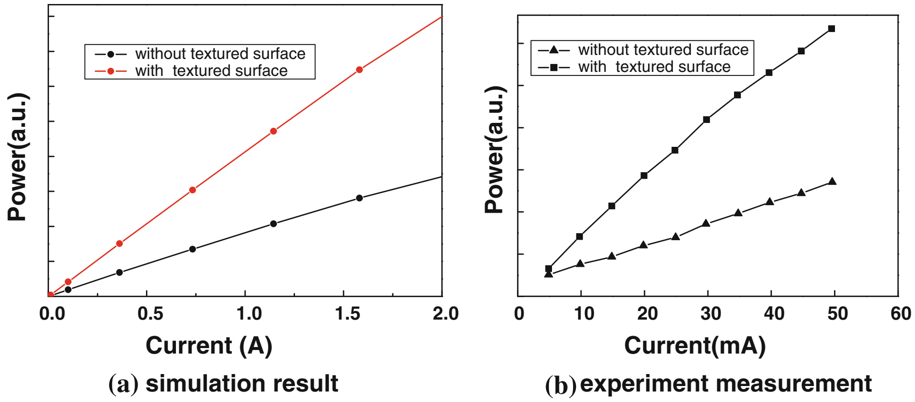

Fig. 5 Transmitted light power versus current

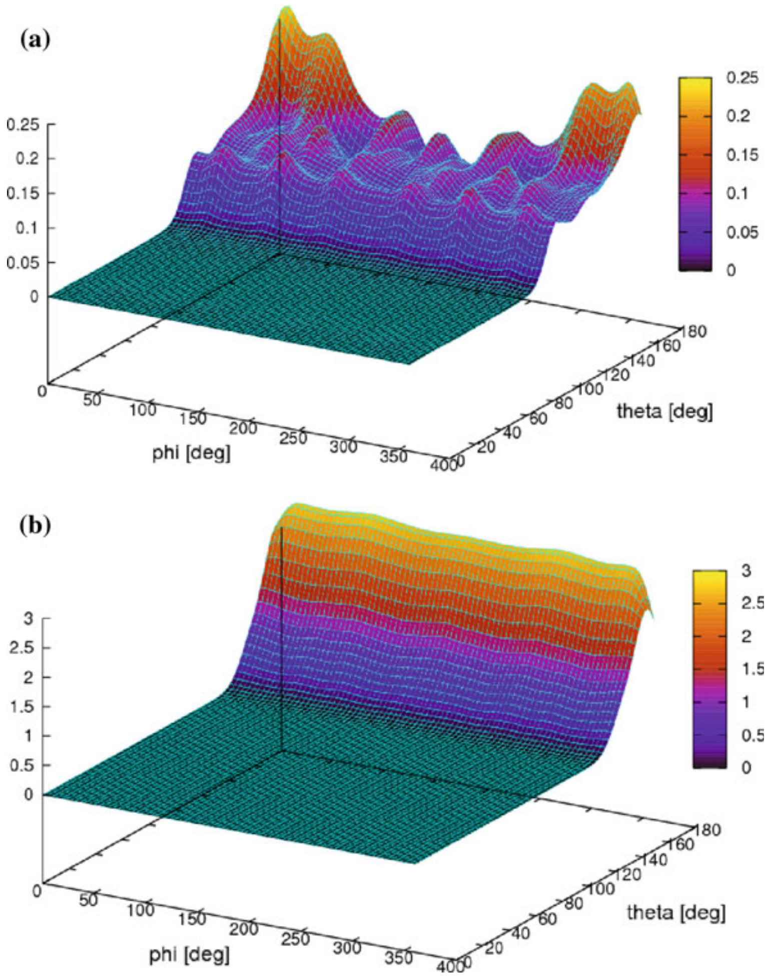

Fig. 6 Transmitted light power distribution. **a** without textured surface; **b** with textured surface

3 Results and discussions

Firstly, we carry out FDTD calculation for the texture which has a 2D profile and is formed by a set of equilateral triangles, each of which has height of 0.5 μm and bottom edge length of 1 μm.

Figure 3 shows how the FDTD calculation for the texture is set up. A point source is put at the corner so that incident angle is different at each textured unit which includes three triangles. The reflection coefficient is calculated using the power flow through a place at the bottom of the triangles. The transmission coefficient is defined in the same way using a plane at the top.

By extracting data after FDTD calculation, reflection (R) and transmission (T) rate at different incident angles ($\pi - \alpha$) are obtained. By averaging the transmitted optical energy, the exit angle β for each unit is also obtained. Since FDTD is based on time-dependent Maxwell's equations and its runtime increases approximately by 4 orders of magnitude when simulation region size increases, after some tentative simulations, we finally applied 10 textured units which are suitable for not only gathering enough data but also saving on simulation time. Each set of FDTD calculation produces T, R and β values for the textured n-GaN surface for a given source wavelength and angle of incidence. Data sets for 10 different wavelengths ranging from 0.3 to 1.3 μm and for 10 values of α are tabulated and used for the 3D RT. Runtime of FDTD calculation is less than half hours in Intel I7 920 platform with 8 CPU threads at 2.66 GHz and 12 GB memory. Figure 4 shows two of these data sets.

Finally, a batch of 3D ray-tracing simulation is applied for the 3D LED structure with textured surface at different current bias(different light source profile). A similar batch simulation is also run except for that normal Fresnel rules are used at n-GaN surface. Simulation results in Fig. 5a show that the textured surface increases the transmitted power about 2.35 times, which is accordant with the measurement results (Fujii et al. 2004) in Fig. 5b.

We also plot the angular dependence of the emitted power as a function of two spherical coordinate variables phi and theta in Fig. 6. We can see that power is mainly transmitted through the -z direction (theta = 180^{o}) where the n contact is located. Figure 6a indicates that n contact has strong influence on power distribution if there is no textured surface while Fig. 6b shows that textured surface strongly smoothes the in-plane angular dispersion of the transmitted light power.

Through Fig. 4a, we can get that at wavelength of 480 nm the LED emitted, peak rate of power transmission is only about 0.7, which means that if we change geometry of the texture unit, there is ample opportunity to improve the power transmission rate in the future.

4 Conclusion

For the first time we have conducted a 3D simulation for light power distribution of a InGaN/GaN MQW LED with textured surface. By comparing ray-tracing results with and without textured surface, we observe notable improvements of the extraction efficiency and power distribution. Simulation results are comparable to experimental measurements. In future work, texture geometry may be optimized to get higher LED extraction efficiency.

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