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Full Length Article

Study on the optical performance of thin-film light-emitting diodes using fractal micro-roughness surface model

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ABSTRACT

Although LEDs have been widely studied using optical simulations, there is no optical model considering the effect of micro-roughness surface (MRS) on the optical performance for packaged LEDs. In this work, we employ the finite-difference time-domain method and the direction-sensitive bidirectional scattering distribution function to characterize the optical properties of the MRS upon the n-GaN layer. The MRS is generated by the Weierstrass–Mandelbrot fractal function. Furthermore, thin-film LEDs (TFLEDs), blue TFLED devices, and white TFLED devices considering the MRS are investigated using the ray-tracing (RT) method. The results show that the MRS has different optical properties when the light propagates out and in the n-GaN layer. In turn, the difference in the scattering ability of various MRS causes a significant effect on the optical performance of packaged TFLEDs, including radiant efficacy, luminous efficacy, intensity pattern and spectrum, as well as the correlated color temperature.

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1. Introduction

Light-emitting diodes (LEDs) have been a promising lighting source due to their advantages in high brightness and long lifetime [1]. Among them, GaN-based thin-film LEDs (TFLEDs) have been regarded as a good candidate for high power and high light quality because of their better light extraction, better heat dissipation, and flexible chip size [2–4]. The optical performance of TFLEDs is mainly determined by the internal quantum efficiency (IQE) and light extraction efficiency (LEE). The former is defined as the ratio of photons generated at the active region to the injected electrons in the active region, whereas the latter is defined as the ratio of photons emitted into free space to the photons generated at the active region. The IQE is generally related to the quality of the epitaxial layers; a high IQE can be gained by decreasing defect density, particularly dislocations [5,6]. However, the LEE is still limited by the total internal reflection and large Fresnel loss occurring at the light extraction surface (LES). The large difference in the refractive index between the n-GaN layer ($n \sim 2.5$) and air ($n = 1$) causes only 4% of the light generated from the active region to be extracted to the air through small radiant angles $\leq \sim 24^\circ$ [7]. Moreover, the light trapped inside also seriously degrades the optical performance of TFLEDs by increasing the internal temperature [8]. Therefore, it is necessary to improve the LEE for TFLEDs with excellent optical performance. Many methods have been employed to improve the LEE for conventional LEDs, such as photonic crystals [9], plasmonic structure [10], texturing LES [11,12], patterned substrates [13], nanoparticles [14], and scattering films [15]. One of them, the LES textured with random structures [11], is significantly appreciated due to the advantages of easy manufacture and high light extraction for TFLEDs [4,16–19].

Most studies have focused on the fabrication method of micro-roughness surface (MRS) for TFLEDs, including wet etching [18,20] and dry etching [21]. From the theoretical side, literature is scarce. Geometric optics [22] has been used to analyze the MRS for conventional LEDs [23,24], but it is not suitable to provide a description of the scattering properties for the MRS with feature size comparable with the emission wavelength of LEDs [25]. To consider the wave properties at MRS, it is promising to solve the Maxwell's equations to obtain the complex angular dependent scattering properties of MRS [26]. Finite-difference time-domain (FDTD) method [27] is considered as a good candidate for solving the electromag-

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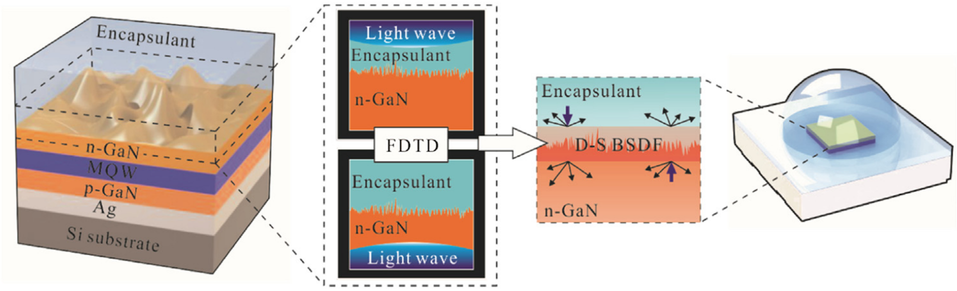

Fig. 1. Method for modeling packaged TFLEDs with micro-roughness surface upon the n-GaN layer.

netic fields on discrete time and space intervals according to the Maxwell's equations. It has been employed to investigate surfaces with micro- and nanostructures for LEDs, such as microsphere array [28,29], hemisphere array [30], and random array [31]. However, as far as we know, all of these studies did not consider LED packages [32] in lighting applications.

In fact, the TFLEDs need to be packaged with other optical elements such as lens [33], reflectors [34], and color-converted elements [35] before being utilized for lighting applications. The light emitted from the active region can interact with phosphor particles, lead-frame, and the encapsulant in packaged TFLEDs [33–35]. Moreover, the backscattered and converted light caused by phosphor, as well as the reflection light, are unavoidably affected by the MRS on the n-GaN layer [36]. Especially, the conformal phosphor layer (CPL) [37] that directly contacts the LES of TFLEDs can lead to a great amount of backscattered light influenced by the MRS. This makes it difficult to obtain the optical performance of packaged TFLEDs with MRS fabricated on the n-GaN layer; a suitable MRS for TFLEDs may not play the same role on packaged TFLEDs. Therefore, it is highly expected to take the packages into consideration when studying the MRS for TFLEDs, as it can provide a better understanding on the MRS for LEDs lighting applications.

In this paper, we have theoretically investigated the effect of MRS on the optical performance of packaged TFLEDs. First, we proposed the method for modeling packaged TFLEDs considering the MRS upon the n-GaN layer; then the optical properties of the MRS were presented and discussed. Finally, the optical properties of the MRS were applied to the packaged TFLEDs according to the proposed method and their optical performance was investigated in detail.

2. Method

In this part, the FDTD and ray-tracing (RT) method are combined to establish the model of TFLED devices by introducing the direction-sensitive bidirectional scattering distribution function (D-S BSDF) for MRS. The optical properties of MRS with feature size comparable with wavelength are solved by the FDTD method while the optical properties of TFLED devices with feature size far larger than wavelength are solved by the RT method, the wave properties can be considered in TFLED devices without limitation of feature size. In order to study the effect of MRS on the optical performance of packaged TFLEDs, it is necessary to characterize the optical properties of the MRS in the packaged TFLED model. The detailed process is shown in Fig. 1 and Fig. S1 in the online version at DOI: 10.1016/j.apsusc.2017.03.041. First, the MRS was built using the 3D Weierstrass–Mandelbrot (W–M) fractal function [38]. Then, it was applied to the FDTD 3D simulation region to solve the electromagnetic fields for the planar wave source (PWS). The electromagnetic data was used to calculate the D-S BSDF for the MRS upon the n-GaN layer. Finally, the D-S BSDF was combined with the RT model used to study the TFLEDs and devices with MRS.

2.1. *Mathematical model of MRS*

The mathematical model of MRS is based on the use of fractals [39]. As shown in Fig. 2, the morphology of MRS for TFLEDs from Cree® EZ900™ appears multi-scale, random, and distorted. The fractal properties are satisfied as its structure function [40] can be fitted linearly.

From the fractal geometry point of view, such profiles are continuous, nondifferentiable, and self-affine. These mathematical properties are satisfied by the W–M fractal function [41,42], which is a superposition of sinusoid with spaced frequencies and amplitudes that follows a power law. Therefore, the profile of rough surfaces $Z(x)$ can be calculated with the W–M function given by

$$Z(x) = \sum_{n=-\infty}^{+\infty} \gamma^{(D-2)n}\left[\cos\phi_{\mathrm{n}} - \cos\left(\gamma^{n}x + \phi_{\mathrm{n}}\right)\right], \tag{1}$$

where $\gamma(>1)$ is a scaling parameter that determines the density of frequencies and self-property in the surface profile, which is chosen to be 1.5 based on considerations of surface flatness and density of frequency in the roughness investigation [43]. D is the self-affine fractal dimension $(1<D<2)$ that characterizes the irregularities of the profile, which is independent of the resolution of the instruments. n is the frequency index and ϕ_{n} is the random phase $(0<\phi_{\mathrm{n}}<2\pi)$.

To obtain the optical parameter of a rough surface in the 3D-FDTD calculations, it is necessary to extend the W–M function to two dimensions using [38]:

$$Z(x,y) = L_{\mathrm{s}}\left(\frac{L_{\mathrm{s}}}{G}\right)^{D-2}\left(\frac{\ln\gamma}{M}\right)^{\frac{1}{2}} \times \sum_{m=1}^{M}\sum_{n=0}^{n_{\max}}\gamma^{(D-3)n} \times\left[\cos\phi_{\mathrm{m,n}} - \cos\left(\frac{2\pi\gamma^{n}\left(x^{2}+y^{2}\right)^{\frac{1}{2}}}{L_{\mathrm{s}}}\times\cos\left(\tan^{-1}\left(\frac{y}{x}\right)-\frac{\pi m}{M}\right)+\phi_{\mathrm{m,n}}\right)\right], \tag{2}$$

noindent where L_{s} is the sample length; G is the vertical height scaling parameter independent of frequency, which is termed the fractal roughness; M is the number of ridges used to construct the surface, the random surfaces are obtained with $M>3$; γ, $\phi_{\mathrm{m,n}}$, and D have the same meaning as in (1), while it should be noted that D herein was 2.7 obtained according to the atomic force microscopy picture shown in Fig. 2, based on the structure function method [40]; $n_{\max}$ is the upper limit of the frequency index, which denotes the number of cosine shapes added for the surface. When $n_{\max}\to+\infty$, it means that the cut-off length L_{c} tends to be zero, and (2) becomes the mathematical representation of the real

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