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Invited Paper

Analysis of extraction routes in surface textured thin-film optical emitters with transparent substrates

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ABSTRACT

We propose a systematic strategy that enables analysis of the outcoupling efficiency through each extraction route for two-dimensional (2D) patterned thin-film optical emitters with transparent substrates. Full-vectorial simulations combined with the near-to-far-field transformations are applied to quantitatively analyze the extraction routes of blue-emitting InGaN/GaN light-emitting diodes (LEDs) on 2D patterned sapphire substrate, from which the main extraction routes are through the top and side surfaces of the substrate. For patterned sapphire substrates, the ratio of top to side emission is calculated for various lattice constants (a) of the pattern; for example, the efficiencies through the top and side routes are nearly equal at $a = 3000$ nm. We find that the top extraction of light is dramatically improved by increasing the index contrast in patterned substrates, suggesting high-index-contrast patterned substrates containing hollow cavities. The dramatic enhancement in top emission is verified by measuring the far-field distribution of InGaN/GaN LED devices fabricated on sapphire substrate containing hollow cavities and reference patterned sapphire substrate. The simulation algorithm studied herein will provide valuable design freedom for thin-film optical emitters such as GaN-based LEDs and organic LEDs.

1. Introduction

The development of high-efficiency and wide-color-gamut optical emitters is a key point in current lighting applications, including backlights and general illumination units [1]. GaN-based light-emitting diodes (LEDs) and organic LEDs are representative optical emitters that fulfill the necessary requirements and witnessing their distinctive applications. For example, organic LEDs fabricated on polyethylene terephthalate (PET) substrates are essential for flexible displays [2,3]. For both inorganic and organic LED devices, the introduction of internal [4–6] or external [7,8] grating patterns is indispensable to outcouple the light that would otherwise be confined by total internal reflections. To achieve more efficient light extraction, patterns of diverse morphologies have been studied: periodic vs. random [9], dielectric vs. metal [10], nanoscale vs. microscale [11,12], and so on. However, no effort has been made to identify the available routes of light extraction for patterned optical emitters.

Both GaN-based LEDs and organic LEDs are fabricated on thick and transparent substrates. Therefore, generated light can escape through the top surface (i.e., top leaky mode) or through the four substrate sides (i.e., substrate mode; Fig. 1A) [13–15]. In addition, the use of waveguide modes can provide a channel for light extraction. Fig. 1B shows ray tracing simulation results of the extraction efficiencies of unpatterned flip-chip GaN LEDs for various levels of total GaN absorption [13]. These results show that the light extracted by means of the top and substrate-side routes is substantial, whereas the extracted light coupled to waveguide modes is marginal for non-zero internal absorption levels [13]. However, this simulation method cannot be used for practical LED devices with diffraction gratings.

Herein we propose a finite-difference time-domain (FDTD) method combined with near-to-far-field transformation to separate the individual extraction efficiencies for patterned LED devices having transparent substrates. We applied the developed simulation method to quantitatively analyze the extraction routes in flip-chip blue GaN-based LEDs on a patterned sapphire substrate (PSS). The individual extraction efficiencies were calculated for various lattice constants (a) and refractive index contrasts in the pattern. These numerical findings will be particularly important in designing chip-scale package (CSP) schemes for white light sources [16]. In CSP schemes, it is a nontrivial issue to conformally cover the top and side surfaces of LED chips with a color-conversion phosphor layer [17], because this inevitably degrades the color uniformity

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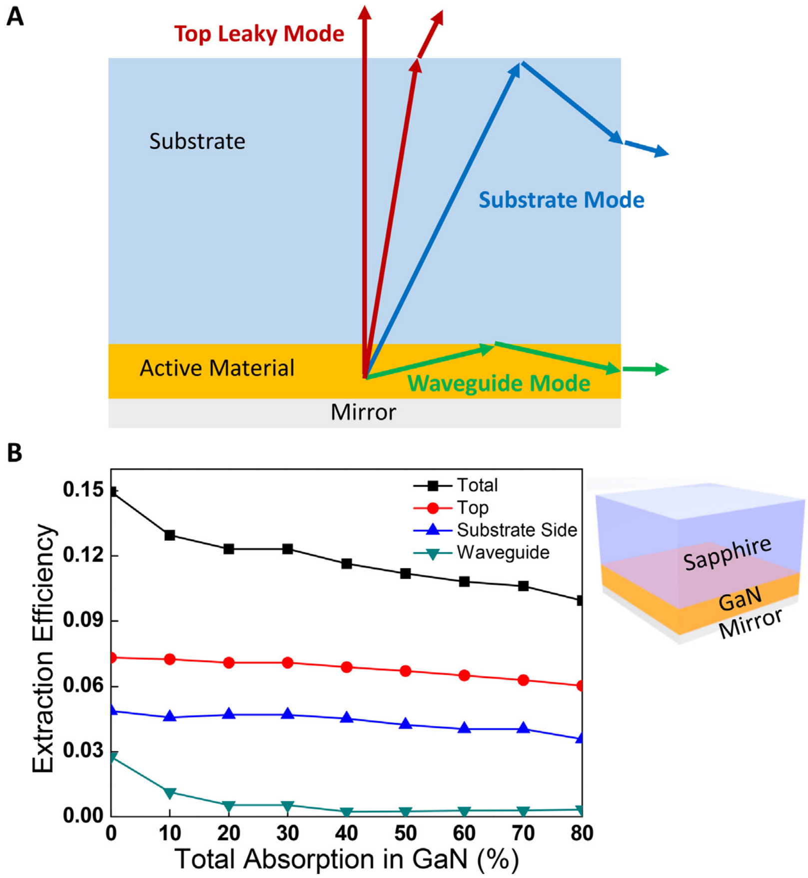

Fig. 1. Light extraction routes for optical emitters with thick transparent substrate. (A) Schematic illustration of a flip-chip GaN-based LEDs and its available light extraction routes: top leaky mode, substrate mode, and waveguide mode. (B) Simulated extraction efficiencies of flip-chip GaN-based LEDs for each light extraction route as a function of GaN absorption, performed by means of ray tracing simulations. Insets: schematic of the simulated structure (top) and snapshot image representing randomly directed rays (bottom).

over various viewing angles. Moreover, simulations accounting all of the individual extraction routes provide more reliable total extraction efficiency and far-field distribution from patterned LED devices. Thus, one needs to predict the extraction efficiencies of LED devices for each available escape route. This numerical strategy can be extended to organic LEDs as well as other GaN-based LEDs (e.g., ultraviolet AlGaN LEDs [18]) with different bandgaps and internal absorptions.

2. Extraction efficiencies per escape routes for patterned LED devices

The upper panel in Fig. 2A schematically illustrates a simulated flip-chip GaN-based LED with a PSS. To simulate the PSS, a square-lattice packing scheme of hemispherical objects was employed. A monochromatic (e.g., $\lambda = 450$ nm) dipole source with transverse-electric (TE) or transverse-magnetic (TM) polarization was excited in the GaN medium. To represent internal absorption in devices (e.g., free carrier absorption in an n-type GaN layer [19], material absorption in a bottom mirror, etc.), two 50-nm-thick absorption layers (absorption coefficient, $k = 0.01$) were introduced. Note that this absorption condition is somewhat arbitrary and should be adjusted based upon absorption measurements from the LED devices under consideration [20,21]. To calculate the extraction efficiencies through the top and sapphire-side routes, all electric and magnetic fields were acquired at a certain plane in the semi-infinite sapphire space after all the incident and scattered fields became completely stabilized in the simulation.

Then, the angular distribution of outgoing energy per unit solid angle was obtained by using the near-to-far-field transformation based on the reciprocity theorem [22,23]. According to the reciprocity theorem, the electric- and magnetic fields at distant points are calculated from equivalent electric and magnetic currents induced by buried scattering elements [22]. Therefore, the developed algorithm is valid when patterned LED devices include sufficiently-thick (>100 μm) transparent substrates; both practical inorganic and organic LEDs have such thick substrates. Finally, the energy extracted from the top surface was recorded by integrating the far-field distribution over all solid angles within $\pm 45.4^\circ$ from the normal direction; this angle is a critical angle for the sapphire–air interface. For the energy extracted from the four substrate sides, the integration was performed over the same angular span but with respect to the in-plane directions. To consider possible optical cavity effects, the same simulations were iterated while the position of the excited dipole source was scanned horizontally within a projected unit cell (bottom, Fig. 2A).

Fig. 2B exhibits source-position dependent far-field distributions of a patterned GaN-based LED with $(a, D) = (500\,\text{nm}, 250\,\text{nm})$ for TE and TM polarizations. The far-field distributions constructed in a sapphire space changed slightly with variations in the source position. The different polarizations yielded greater difference in the resulting distributions; in the TM (electric dipole oscillation parallel to the normal direction) cases, there was no apparent power around the normal direction, which can be explained by dipole radiation theory [24]. For specific wavelengths and polarizations, integrated far-field distributions were acquired by averaging the data from various individual source positions. Fig. 2C shows the