Electronic Supplementary Material (ESI) for Nanoscale

Supplementary Information

Light Extraction Enhancement with Radiation Pattern Shaping of LEDs By Waveguiding Nanorods with Impedance-Matching Tips

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FDTD Simulation

The FDTD analysis was carried out using a commercial software package (RSoft CAD) to simulate the interaction of electromagnetic waves and LED devices for gaining insight into the light propagation across the syringe-like ZnO nanorod layers, through which the light extraction effect and the syringe-like ZnO nanorods can be correlated. More details about simulated structures and optical parameters are depicted in Fig. S1. The calculation of the propagation of electromagnetic waves in the nanostructure is based on Maxwell's equations. The polarization of the starting electric field can be specified. In the report, the results of using transverse electric (TE) field are shown. Although in practice the polarization of light emitted from an LED is randomly distributed, the simplified result is convincing since the as-fabricated nanostructure is also randomly distributed at the 2-D surface as well as the encountering electromagnetic wave. In addition, in the simulation schemes we have applied periodic nanorods for simplicity, while in the practical case the nanorods are randomly arranged. This might also affect the light extraction effect. As a short summary, the FDTD simulations qualitatively demonstrate the superior extraction capability of our syringe-like ZnO nanorods, and the enhancements from the simulation are consistent with results acquired from the experiments.

Three types of LEDs are compared in the 2-D simulation scheme based on FDTD method: the bare LED, the LEDs with flat-end NRs and syringe-like NRs. As shown in Fig. S1, the bare LED is constructed by GaN and ITO, denoted by Part A. The LED with flat-end nanorods is formed by adding Part B on Part A, and the LED with syringe-like nanorods is the superposition of Part A, B, and C.

The monochromatic excitation source is positioned 0.22 μm below the interface of GaN and ITO layer, corresponding to the QW region in practical LED scheme. The emitting wavelength is chosen to be at 528.5 nm, matching with the peak emission wavelength of the EL spectra at 20 mA injection current. The refractive index (n) of the materials are listed in the table, whose values are subjected to the wavelength of the excitation source.

The widths of the GaN and ITO layers are 8 µm, and the thicknesses are 2.88 and 0.25 µm, respectively. The combination of these two layers are denoted by Part A, and are taken as the bare LED scheme. The diameter and length of the flat-end nanorod (*i.e.* Part B) are 0.13 and 1.5 µm, respectively. The width at the bottom of the tapered tip (*i.e.* Part C) is 50 nm, and the height of the tapered part is 300 nm. The morphology of the ZnO nanostructure is revealed in Fig. S1. The detectors were placed at 3.77 µm above the ITO surface to monitor the time-averaged optical power of the LEDs. The calculated power is normalized with respect to the excitation source.

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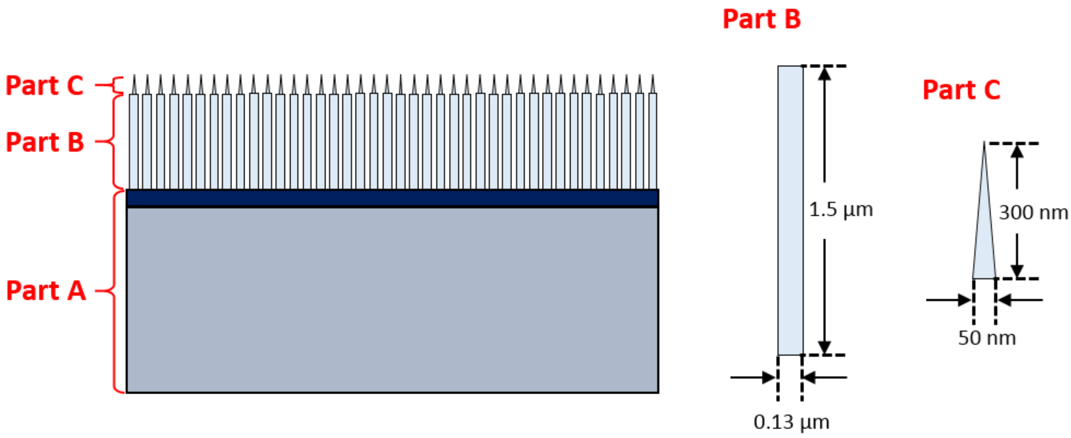

Part	Material	Thickness / Height (µm)	Width (µm)	n at 528.5 nm
A	GaN / ITO	2.88 / 0.25	8	2.43 / 2.1
B	ZnO nanorod	1.5	0.13	2.03
C	ZnO nanotip	0.3	0.05	2.03

Figure S1. Schematic of the LED with syringe-like ZnO nanorods for FDTD simulations.