Optical Frequency Response of GaN-based Light-emitting Diodes with Embedded Photonic Crystals

Yu-Feng Yin[1,*], Yen-Hsiang Hsu[1], Liang-Yu Su[1], Yuan-Fu Hsu[1], Li-Cheng Chang[2], Chao-Hsin Wu[2, 3], and JianJang Huang[1, 3, *]

[1]Graduate Institute of Photonics and Optoelectronics, National Taiwan University, No. 1, Roosevelt Road, Taipei, 10617 Taiwan
[2]Graduate Institute of Electronics Engineering, National Taiwan University
[3]Department of Electrical Engineering, National Taiwan University
Phone: (886)-2-3366-3665 *EMAIL: f99941063@ntu.edu.tw, jjhuang@ntu.edu.tw

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Abstract

In this study, sub-GHz modulation of GaN-based photonic crystal light-emitting diodes (PhCLEDs) were demonstrated. The higher operation speed is attributed to faster radiative carrier recombination of extracted guided modes from the PhC microcavity. The optical -3-dB bandwidth up to 240 MHz (an 1.5-fold increase as compared to a conventional LED) is achieved.

INTRODUCTION

In the past few decades, the speed of heterogeneous wireless access network (WAN) has grown rapidly since their inception and progress made in electro-optical (EO) devices and circuit designs. For low-data-rate applications especially, such as home security/automation, sub-GHz radios offer relatively simple wireless solutions that can operate uninterrupted with longer range, reduced power consumption, and lower operating cost [1]. In an indoor wireless communication, visible light communication (VLC) offers another sub-GHz wireless embodiment due to the replacement of incandescent bulbs with high-efficiency Light-emitting Diodes (LEDs) in general illumination [2]. With the continuing advances in III-V alloy system, GaN-based LEDs as VLC sources possess several advantages including stability of the optical output power, resistance to wavelength shift, and good carrier confinement [3]. To this end, both green and blue LEDs have been demonstrated with the optical bandwidth up to 330 MHz and 225.4 MHz [2, 4]. For the photonic crystals (PhCs) embedded light-emitting devices, they exploit not only the photonic band selection but also higher modal quality factor (Q-factor) in the PhC region [5]. Therefore, to achieve a higher optical output, PhCs is often employed in high efficiency photonic components such as LEDs and Lasers. For instance, PhC LEDs (PhCLEDs) exhibits a narrower linewidth, higher output power and better directionality owing to its microcavity structure [5]. A lower-order mode extraction and enhanced Purcell factor also have been characterized and demonstrated in our previous work [6]. In this study, we employ PhCs as an active out-coupler in an effort to allow Bragg scattering and prevent light trapping in the device. With a reduced radiative carrier lifetime and intense photon accumulation in some photonic bands, a higher optical output power and larger modulation bandwidth are obtained in the radio frequency (RF) response analysis.

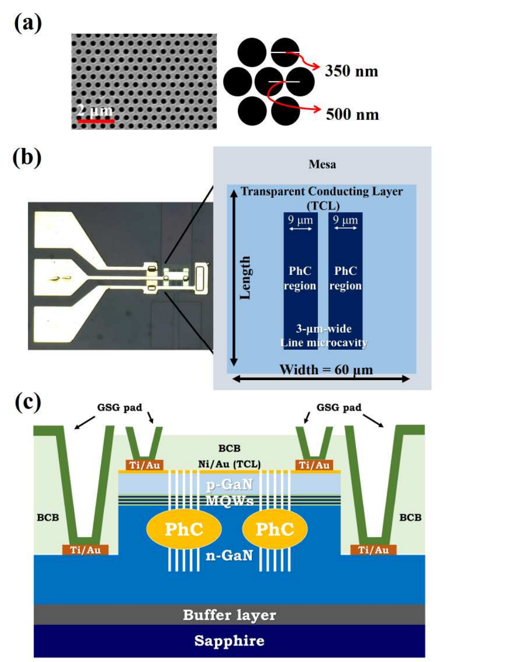

Figure 1: (a) SEM of the design PhCs. (b) Layout of the light-emitting are and PhC region. Left inset is the OM image of PhC54. (c) Cross-sectio structure of PhCLED.

DEVICE FABRICATION

The detailed epi-structures and process flows of the devices were described elsewhere [5]. To increase the interaction between guided modes and PhCs, the PhC nanohole array was fabricated within the light-emitting area with a depth of 700 nm and a transparent conducting

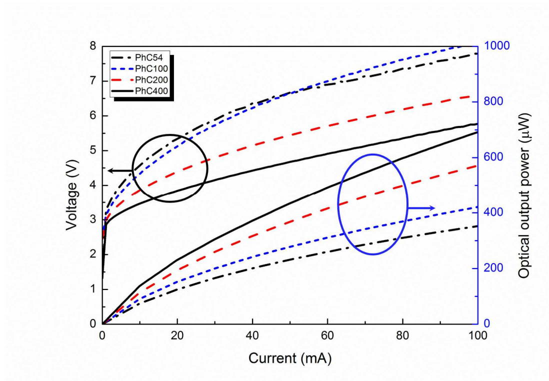

Figure 2: Optical output and electrical property of different PhCLEDs.

layer (TCL) on top of it. For the frequency response characterization, a GSG (ground-signal-ground) RF contact pad were deposited on Benzocyclobutene (BCB) planarization polymer. PhC nanohole arrays were hexagonally arranged with a lattice constant (A) = 500 nm, and an aspect ratio which was radius (R)/A=0.35 as shown in Fig. 1(a). The light-emitting area is defined by the TCL in a rectangular shape with a width of 60 µm and four kinds of length of L (54, 100, 200, and 400 µm). Figure 1(b) shows the detailed layout of the device with a 3-µm-wide line microcavity formed within the PhC region and the left inset is the optical microscope (OM) image of the device with L = 54 µm. PhCLED were named according to the TCL length as PhC54, PhC100, PhC200 and PhC400 respectively. Conventional planar LED (CLED) without PhC region were also fabricated and named as C54, C100, C200, and C400. Figure 1(c) depicts the cross-section view of a PhCLED structure with 700-nm-deep PhCs.

Experimental Results and Discussions

Figure 2 shows L-I and I-V curve of the design PhCLEDs, where the turn-on voltages are between 4 ~ 4.5 V with a leakage current on the order of nA at a -5 V bias condition. The I-V characteristics indicate that the PhCs etched deeply through the active layer don't deteriorate the electrical property much. PhC400 presents a lower resistance and the highest optical output with a 17% enhancement over C400. Figure 3(a) and 3(b) show the emission wavelength of CLEDs and PhCLEDs under different injection currents. Although there is a slightly red shift of the peak wavelength with an increasing current due to the large electric field in the active region, CLED and PhCLED possess a peak light wavelength at 453.2 nm and 454.3 nm at 50-mA injection respectively with electroluminescence linewidth of approximately 23 nm at half maximum (FWHM). In Fig. 2, Fig. 3(a) and 3(b), the light output power varies linearly and emission wavelength stays almost constantly within 40 ~ 60 mA biasing condition. Therefore, in the RF response test, LED is biased under a 50 mA injection current for a linear

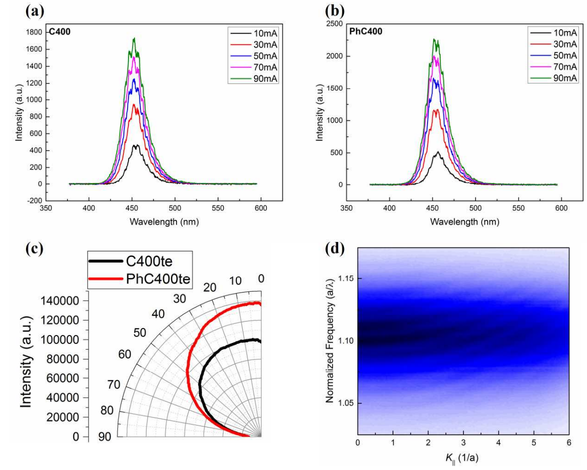

Figure 3: Optical properties of the CLED and the PhCLED. Electroluminescence (EL) spectra of the (a) C400 and (b) PhC400. (c) Angular-resolved profiles of the C400 and PhC400. (d) Measured photonic band of the PhC400.

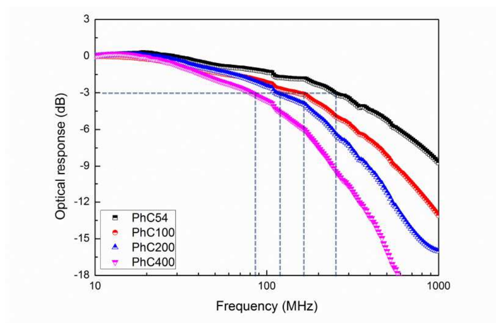

Figure 4: Frequency response of different PhCLEDs at a 50 mA injection current.

operation of the light output. In Fig. 3(c), the radiation profile shows that PhC400 has more light extraction toward the surface-normal direction. After converting the angular spectra into the photonic band in Fig. 3(d), lower-order guided mode extraction is obtained in around small in-plane wavevectors ($K_{\|}$), implying a coherent lower-order mode extraction into the air.

The spontaneous optical frequency responses for four different layouts under an injection current 50 mA are shown in Fig. 4. When the magnitude of optical output power approach to half of its DC value, a -3-dB frequency, f_{3dB}, a RF characteristic of the intrinsic LED can be defined. The highest f_{3dB} bandwidth of 240 MHz is obtained from PhC54, an 1.5-fold increase compared to a conventional CLED. Table I concludes the optical bandwidth with different mesa sizes of CLED and PhCLED. The *RC*-limited bandwidths is observed in the CLED, but in PhCLEDs, the PhC can effectively enhance the operation speed. In order to clarify the *RC*-limited factor in our devices, the intrinsic components of the LED after de-embedding the extrinsic parasitic *RC* are obtained by the vector network analyzer (VNA). Based on the

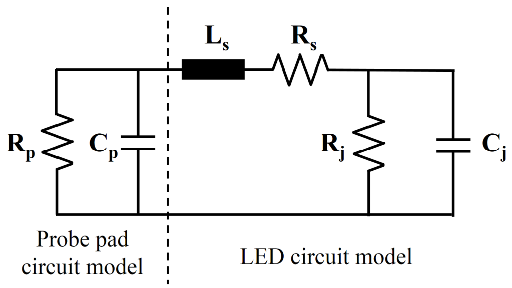

Figure 5: Small-signal equivalent model of the LEDs with RF probe pads.

TABLE II
PARAMETERS FOR THE SMALL-SIGNAL MODAL OF LEDS

	C54	C100	C200	C400
R_j (Ω)	18	13	9	8
C_j (pF)	8	16	23	45
R_s (Ω)	21	21	16	7
	PhC54	**PhC100**	**PhC200**	**PhC400**
R_j (Ω)	13	12	10	9
C_j (pF)	11	20	26	43
R_s (Ω)	18	17	15	10

equivalent small signal model in Fig. 5 [7, 8], the intrinsic component such as junction resistance (R_j), junction capacitance (C_j), contact resistance (R_s), and contact inductance (L_s) can be fitted by the S_{11} of 2×2 scattering parameters (s-parameters) from the experimental data. Although the resistance of a smaller mesa slightly increases, the capacitance of the L=54 μm is reduced to one fifth of the one of L=400 μm. Both CLED and PhCLED have similar *RC* time constant. Therefore, the enhanced optical bandwidth in PhCLED is owing to a shorter spontaneous radiative lifetime. The relations between radiative lifetime and bandwidth are described as follows:

$$\tau_r = \frac{[(n_0+p_0)^2+4J/Bew]^{1/2}-(n_0+p_0)}{2J/ew} \quad (1)$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_r} + \frac{2s}{w} \quad (2)$$

$$f_{3dB} = \frac{1}{2\pi\tau_{eff}} \propto (J)^{1/2} \quad (3)$$

where τ_r is radiative lifetime, (n_0+p_0) are electron and hole concentration at the thermal equilibrium, J is biasing current density, B is recombination probability, w is thickness of active layer (MQW), s is surface recombination velocity, and τ_{eff} is effective carrier lifetime. Based on equation (3), under high biasing current density, the bandwidth increases approximately as $(J)^{1/2}$. However, Fig. 6 concludes the relation of the obtained bandwidth of PhCLEDs at a various injection condition. It can be seen that the bandwidth of PhCLEDs increase approximately as $(J)^{0.28}$ which is slower than the ones of CLEDs according to the relation of the power bandwidth product and the injection carrier density [9]. It suggests some additional recombination occurs within the PhC structure, because the PhCs provide good lower-mode extraction efficiency with reduced carrier radiative lifetime [6]. Therefore,

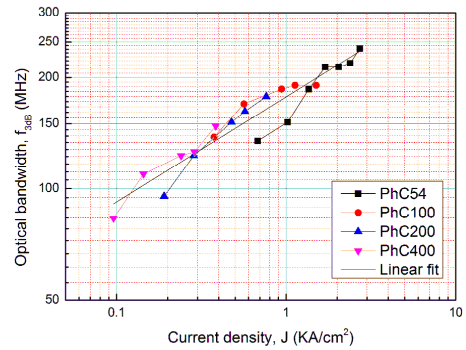

Figure 6: The modulation bandwidth as a function of the injected curren density of PhCLEDs.

PhCLEDs show a better high-speed performance than CLEDs. Also, a 50% bandwidth enhancement is obtained in the PhCLEDs as compared to the result of a CLEDs. A planar LED may have an even smaller capacitance with a 54×3 μm^2 light-emitting area, but the current density around the line microcavity is so high that it would degrade the device performance. For PhCLEDs, the PhC regions not only mitigate the current crowding in the small light-emitting area but provides a better photon confinement by the PhCs. Therefore, the shortened photon lifetime in a PhC-embedded LED pushes the modulation toward higher speed under the same injection current density.

CONCLUSIONS

In summary, we report a 50% high-speed performance improvement of GaN-based LED by using a photonic crystals embedded structure in the light-emitting area. The PhCs not offer only a better light extraction but reduce the possibility of device degradation in a small light-emitting area. The proposed PhCLED structure enables a stable operation of a small LED with a smaller device capacitance, higher photon accumulation on specific photonic bands, and a shorter photon lifetime, leading to a larger modulation bandwidth.

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ACRONYMS

PhCs: Photonic crystals
LED: Light-emitting diode
VLC: Visible light communication
EO: Electro-optical
RF: Radio frequency
TCL: Transparent conducting layer
BVB: Benzocyclobutene