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III-Nitride Based Cyan Light-Emitting Diodes with GHz Bandwidth for High-Speed Visible Light Communication

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***Abstract*—**A large reduction (from 17 to 5 nm) is made in the thickness of the barrier layers in the multiple-quantum-well (MQW) region of III-nitride based cyan light-emitting diodes (LEDs) grown on patterned sapphire substrates (PSS). This is shown to lead to a simultaneous improvement in the modulation speed, differential quantum efficiency, and maximum output power of the LEDs under both room-temperature and 110 ℃ operation. With our novel device structure we achieve a moderate output power (1.7 mW) with a record-high 3-dB electrical-to-optical (E-O) bandwidth (1GHz). The over two-fold enhancement in the E-O bandwidth (~1 vs. ~0.5 GHz) compared to that previously reported visible LEDs can be attributed to the more uniform distribution of injected carriers within the MQW region and the aggressive downscaling of the thickness of the total active layer, which leads to a shortening of the spontaneous recombination time.

***Keywords* —Light-emitting diodes; Visible light communication**

I. Introduction

Visible light communication (VLC) is considered to be one of the best candidates to meet future demand in ultra-broadband indoor wireless access networks [1,2]. An indoor optical wireless acttocell network can be realized by installing a large number of white-light light-emitting diode (LED) lamps on the ceiling of a building to act as transmitters [1,2]. An optical filter can be installed at the receiver-end of the VLC system to counter problems caused by the slow fluorescent lifetime of the phosphor [1,2] coating on the LED lamps. One of the major factors limiting the bandwidth in the VLC system has been the direct modulation speed of the visible LEDs inside the lamps. Another promising application for high-speed visible LEDs operating at the red [3] or cyan [4-7] wavelengths would be in polymethylmethacrylate (PMMA) based plastic optical fiber (POF) communication systems. Although the red vertical-cavity surface-emitting laser (VCSEL) technology [8] has been demonstrated to work at a much faster speed than that of the red and green (or cyan) LEDs (RCLEDs) [3-7], an LED based solution would have a much lower cost and be advantageous for harsh-environment communication, such as for in-car data

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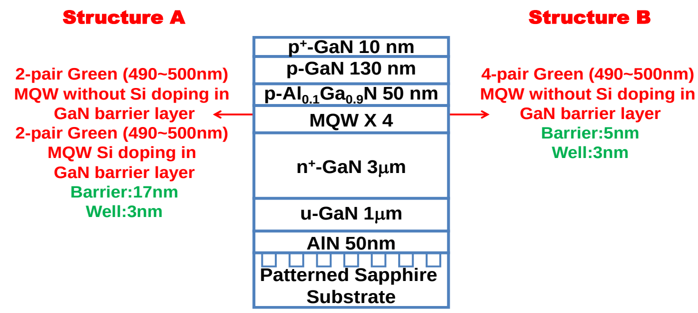

Figure 1. A conceptual cross-sectional view of epitaxial layer structures A and B. For clarity this figure is not drawn according to scale.

transmission [3-6], due to the much lower required driving current density than that of the VCSEL. This characteristic provides the improved device reliability of high-speed LEDs [3,5] and makes the development of visible LEDs with a GHz bandwidth under a lower driving current (density) than that of the laser diode (LD) become the key issue. In most cases, the modulation speed of the LED is limited by the spontaneous recombination time in the active layer. The reported maximum 3-dB electrical-to-optical (E-O) bandwidth is usually less than 500 MHz [9], which corresponds to a carrier recombination time of around 320 ps. It has been demonstrated that this time constant can be further shortened by heavy p+ doping ($>1 \times 10^{19}$ cm^{-3}) of the active layer in GaAs or InP based LEDs, achieving an E-O bandwidth > 1 GHz [9]. However, there is a serious sacrifice of the internal quantum efficiency (output power) arising from the enhancement of the non-radiative recombination process induced by the p-type dopant (defects) [9]. Here, we demonstrate a novel design for the active layers of III-Nitride based cyan LEDs which simultaneously shortens the response time and enhances the internal quantum efficiency. Compared with the traditional design of GaN/$In_xGa_{1-x}N$ MQWs, our proposed device structure has a much thinner GaN barrier layer (17 vs. 5 nm). The central wavelength of the electroluminescence spectra is the same (~480 nm) for both structures. Not only does the thinness of the barrier layer improve the carrier distribution inside the different MQWs but there is also a simultaneous enhancement of both the radiative recombination process and modulation speed of the LED. With the same active diameter (~50 μm) and under the same bias current, the 3-dB E-O bandwidth of our device is higher than that of the reference device (1 vs. 0.9 GHz), with a higher output power (1.7 vs. 1.5 mW). We achieve a record high 3-dB E-O bandwidth (1 GHz) among all the reported visible LEDs [3-7]. The speed performance is superior even to that of the GaN based green (~500 nm) laser diodes (LDs) (1 vs. 0.4 GHz) [10].

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II. Device Structure and Fabrication

The device structure is designed to enhance the external quantum efficiency and sustain the output optical power. A device suitable for a miniaturized LED for POF communication was grown on a patterned sapphire (PS) substrate [5]. Details of the thicknesses of the four-period $In_xGa_{1-x}N/GaN$ cyan multiple quantum well (MQW) region, bottom n-type GaN layer and topmost p-type GaN layer of both device structures are listed in Figure 1. The reference sample and improved LED structure are labelled A and B, respectively. There are two major differences in the design of the active MQWs of these structures. One is the great reduction in thickness of the GaN barrier layer in the novel device structure from 17 to 5 nm. By thinning down the barrier layer, the total thickness of the active layer can also be reduced from 97 to 37 nm, which leads to an increase in the injected carrier density, radiative recombination rate, and modulation speed of the device. Furthermore, the thinness of the barrier layer should also improve the hole distribution among different wells and enhance the total output power. Figures 2 (a) and (b) show the simulated radiative (spontaneous) recombination rates at different positions in the two proposed epi-layer structures A and B, respectively. Here, the radiative recombination rate given in the two figures has been normalized by the same value for fair comparison. The simulation was realized using the advanced physical models of semiconductor devices (APSYS) simulation program[1] (details can be found in our previous work [11]). We can clearly see that in structure A, there is significant radiative recombination in only one well, which is nearest to the p-side, due to the non-uniform distribution of the injected holes [12]. On the other hand, in structure B, all four wells make a significant contribution to the output light, because of the more uniform distribution of injected holes among the different wells. Thus an enhancement in total output power can be expected.

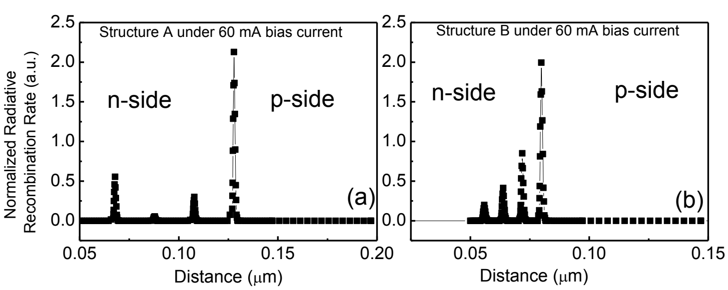

Figure 2. The simulated radiative recombination rate (after normalization) versus different positions in Structure A (a) and B (b).

There is also a difference between the doping profiles of the two MQW structures. A partially n-type doping profile is adopted for the MQWs of the reference device, which can enhance the modulation speed and output power of the LEDs, as demonstrated in previous studies [4,5]. In contrast, in our improved device, the total active layer thickness is less, as little as 37 nm, and none of the layers in this thin active region are doped. This allows concentration of the external applied field in this region and more effective modulation of carrier injection within. Figure 3 (a) shows a top-view of the demonstrated LED chip and an enlargement of the periodic structures on the PS substrate. Each LED has an active diameter of around 50 μm. During device fabrication, each LED is etched down to the insulating PS substrate to minimize the parasitic capacitance of the device. For details of the fabrication processes please refer to our previous work [5].

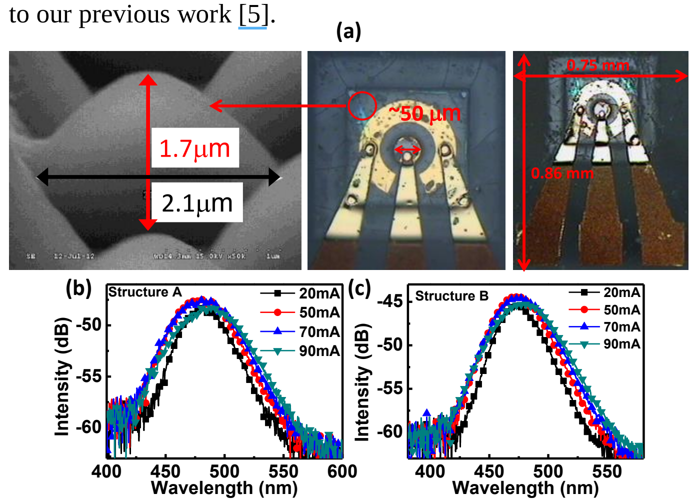

Figure 3. (a) A top-view of the demonstrated LED chip and a zoomed in picture of the light-emitting aperture and PS substrate. (b) and (c) show the measured EL spectra of structure A and B, respectively.

III. Measurement Results

Figures 3 (b) and (c) show the measured bias dependent electroluminescence (EL) spectra of our novel device and the reference device. The central wavelength of both devices is very close, around 480 nm, which is near the minimum loss window of the standard PMMA POF (<4dB/50m) [5]. Figures 4 (a) and (b) show the total free-space light output power (L) and bias voltage (V) versus bias current (I) for structures A and B, respectively. They have the same active diameter (50 μm), as measured by the integrating sphere. The curves in this figure as delineated by the solid and open symbols, represent the measurement results under room temperature (RT) and 110℃ operation, respectively. There are three typical measured L-I-V traces for each structure (Structure A: devices A to C and structure B: devices D to E). It can be seen the I-V characteristics of our demonstrated device are similar to the reference ones. This result indicates that our novel MQW design does not lead to a degradation in the I-V performance of the LED. Furthermore, the output power of structure B really is comparable to or higher than that of structure A (1.7 vs. 1.5 mW) under the same bias current, from RT to 110°C. This occurs because of enhancement of the radiative recombination process in its active region, as illustrated in Figure 2. In addition, the comparable output power of these two structures under 110℃ operation suggests that the thin barrier design does not significantly increase the probability of carriers escaping under high junction temperatures.

Figures 5 (a) and (b) show the electrical-to-optical (E-O) frequency responses of devices A (structure A) and D (structure B) measured under different bias currents and RT operation, respectively. Figures 6 (a) and (b) show the measurement results for the same two devices (A and D) but under an elevated ambient temperature of up to 110°C. Under the same bias current, we can clearly see that the measured 3-dB E-O bandwidths of the demonstrated device (device D) are faster than that of the reference device (device A), and when the bias current reaches 90 mA, the maximum 3-dB E-O bandwidth of

[1]*Crosslight APSYS User's Manuals*, Crosslight Software Inc., Burnaby, BC, Canada, 2013.

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device D can be as high as nearly 1 GHz under RT operation. Here, the measured frequency responses of the microwave reflection coefficients (S_{11}) of these two devices are very similar. This indicates that they have the same RC-limited bandwidth. The observed improvement in E-O bandwidth can thus be attributed to the shortening of the internal response time in device D, as discussed above. The bandwidth performance of device D is over two times faster than that reported for the high-speed red RCLEDs (0.35 GHz [3]) or GaN based green (~500 nm) LEDs and LDs (0.5 GHz [6,10]). In addition, the measured maximum E-O bandwidth (0.89 GHz) of reference device A is also faster than the afore-mentioned best recorded for visible LEDs [3,6]. Compared with LEDs, the LDs intrinsically have a much faster modulation speed. Recently a significant improvement in the modulation speed has been achieved for GaN based LDs in the blue wavelength regime (450 nm) [13,14] and a 3-dB O-E bandwidth as wide as 2.6 GHz has been successfully demonstrated for high-speed wireless linking [13]. However, the required driving current and fabrication cost of GaN LDs are both much higher than would be required for LED based solutions.

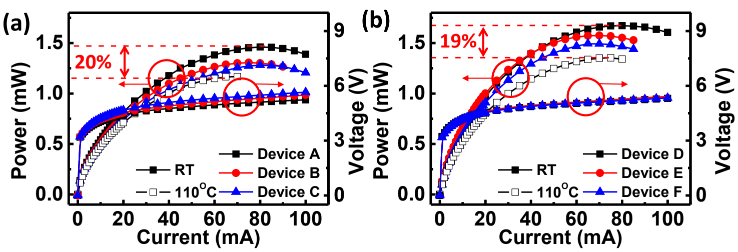

Figure 4. L-I-V curves (solid symbols; square, circle, triangle) measured under RT operation for (a) structure A (devices A to C) and (b) structure B (devices D to F). L-I curves (open symbols) measured under 110℃ operations of devices A and D are also specified.

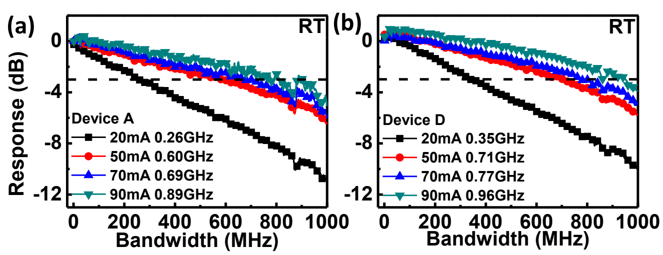

Figure 5. Bias dependent E-O frequency responses for (a) device A and (b) device D measured under RT operation.

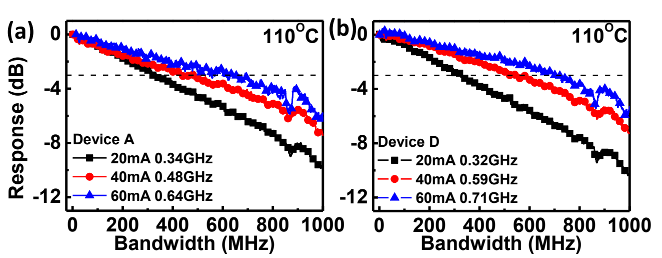

Figure 6. Bias dependent E-O frequency responses for (a) device A and (b) device D measured under 110℃ operation.

Both device structures (A and B) achieve record speed performance for any visible LEDs [1-7]. This achievement can be attributed to the aggressive reduction of the thickness of the total active layer (barrier + well) as illustrated in Figure 2 and the minimization of the RC-limited bandwidth achieved by depositing the metal pads on insulating PS substrates. This design results in a much smaller parasitic capacitance compared to that of high-speed LEDs with metal pads deposited on a thin (~1 μm) insulating dielectric layer on the n+ GaN contact layer [3,6,7]. Furthermore, as can be seen in Figures 4 and 6, there is no serious degradation in the maximum bandwidth (1 to 0.7 GHz) or power (1.7 to 1.4 mW) even when the temperature rises to 110℃. This is quite different from the behavior of the high-speed red RCLED [3], which shows bandwidth enhancement (110 to 130 MHz) and serious degradation in the output power (~40%) when the temperature increases from 10 to 70℃ [3]. The large bandgap offset in the active layer and the activation of the p-type dopant (Mg) in our III-nitride LED under high ambient temperatures [15] act to suppress electron leakage and produce superior high-temperature performance over that of the GaAs based high-speed red LED [5].

IV. CONCLUSION

A significant reduction in both the thickness of the GaN barrier layer and total active region of III-nitride based cyan LEDs can simultaneously enhance both the output optical power and modulation speed. The results are experimentally verified. Using this device structure, we successfully produced cyan LEDs which demonstrated a record 3-dB E-O bandwidth (1 GHz). High-speed visible LEDs usually have an E-O bandwidth of less than 0.5 GHz. This novel structure for high-speed LEDs is expected to greatly boost the data rate for visible-light and POF communications without significantly increasing the cost of the light source or the energy consumption.

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