The Improvement in Modulation Speed of GaN-Based Green Light-Emitting Diode (LED) by Use of n-Type Barrier Doping for Plastic Optical Fiber (POF) Communication

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***Abstract*—We demonstrate a high-speed GaN-based light-emitting diode at a wavelength of around 500 nm for the application to plastic optical fiber communication. By use of the n-type doping in the GaN barrier layers of the $In_xGa_{1-x}N$–GaN-based multiple-quantum-well (MQW), superior performance of modulation-speed (120 versus 40 MHz) and output power to the undoped control under the same bias current has been observed. According to the measured electrical-to-optical bandwidths and extracted *RC*-limited bandwidths of both devices, the superior speed performance can be attributed to higher electron/hole radiative recombination rate in the n-doped MQW than that of undoped MQW.**

***Index Terms*—Light-emitting diode (LED), optical fiber.**

I. Introduction

PLASTIC optical fiber (POF) is very suitable for short-reach optical fiber communication due to its low cost and better tolerance to misalignment of interconnections than glass optical fiber. Recently, POF has become a "killer application" in the auto industry. Groups of automobile manufacturers and suppliers have developed a POF data bus standard for in-car data transmission called Media Oriented Systems Transport (MOST) [1]. When commercial polymethylmethacrylate (PMMA) POF is used, the most popular wavelength for such applications is 650 nm [1], and the high-speed resonant-cavity light-emitting diode (LED) in this wavelength regime are both readily available [2]. However, for such an operation window, the optical bandwidth is narrower and the propagation loss is higher (0.125 versus 0.09 dB/m) than in the high-performance POF system [3], [4] operating under another PMMA loss minimum window, which has a wavelength of around 500 nm [1]. The III-nitride-based green-amber or green-blue LEDs [3]–[7] thus offer a promising choice for such applications. As compared to the performance of diode-pump solid-state green laser, the III-nitride-based LED enjoys the unique advantages of direct current modulation, compactness, and has the potential to serve as a monolithic integrated transceiver module at around 500-nm wavelengths for POF communication [8]. In this letter, we demonstrate an $In_xGa_{1-x}N$–GaN-based high-speed LED at the wavelength around 500 nm and study its dynamic performance in detail. According to the measurement results, the device with n-type barrier-doping in the multiple-quantum-well (MQW) region has superior modulation speed and output optical power to the undoped control under the same bias current. The extracted *RC*-limited bandwidths and measured net electrical-to-optical (E-O) bandwidths of both kinds of devices reveal that the superior speed performance can be attributed to higher electron/hole radiative recombination rate in the n-doped MQW than that of undoped MQW [9], [10].

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II. Device Structure and Fabrication

In order to study the influence of n-type barrier doping on the speed performance of LEDs, two kinds of devices have been fabricated. Devices A and B have similar epi-layer and geometry structures, except for the MQW region. Device A has n-type doping with around 5×10^{17} cm^{-3} doping density in the GaN barrier layers and Device B does not. The epi-layer structures of both devices were grown by metal–organic chemical vapor deposition (MOCVD) on sapphire substrate. The total thicknesses of $In_xGa_{1-x}N$–GaN-based MQW, bottom n-type GaN layer, and topmost p-type GaN layer is around 110, 400, and 400 nm, respectively. Regarding the MQW region, it is composed of GaN barrier with 135-Å thickness and $In_xGa_{1-x}N$ well with 25-Å thickness. Such an epi-layer structure is similar with that of typical GaN-based visible LEDs [5], [6]. Fig. 1 shows a top-view of the demonstrated devices. We fabricated the demonstrated device using standard photolithography, metallization, liftoff, and dry etching processes. We adopted a thick Si_3N_4 film (600 nm), which can reduce the leakage current and parasitic capacitance, to passivate the fabricated devices and integrated them with the coplanar waveguides (CPWs) for on-wafer high-speed measurement. As shown in Fig. 1, one unit LED is integrated with two CPW pads, which have "U-shaped" electrodes on the topmost p-type Ni–Au contact. During on-wafer measurement, these two CPW pads were parallel to uniform the current distribution and reduce the device resistance. The inset in Fig. 2 shows the current–voltage (*I*–*V*) curves of Devices A and B with similar active area ($\sim$14 000 μm^2). The turn-on voltage of Device A was around $\sim$3.7 V and it has

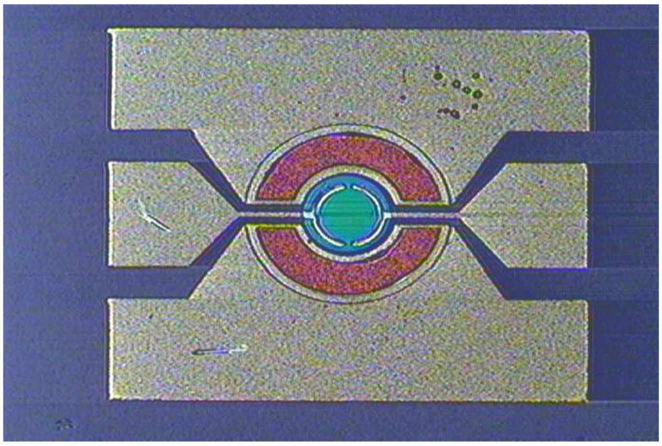

Fig. 1. Top-view of the demonstrated LED. The active area of the device shown in this figure is about 14 000 μm ^{2}. (Color version available online at: http://ieeexplore.ieee.org.)

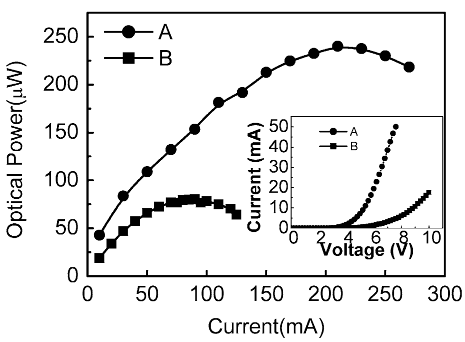

Fig. 2. Measured output optical power (*P*) versus the bias current (*I*) of Devices A (closed circles) and B (closed squares). The inset shows the measured *I–V* curves of Devices A (closed circles) and B (closed squares) under forward bias.

much lower differential resistance than that of Device B due to that the n-type doping in the barriers can improve the quality of interfaces between $In_xGa_{1-x}N$ wells and GaN barriers during MOCVD growth [11].

III. Measurement Results and Discussion

During dc and ac measurement, we used a POF to serve as the optical probe and collect the output power from LED directly without using any lens. The measured electroluminescence spectra of Devices A and B under the same bias current (100 mA) are given in the insets of Fig. 3(a) and (b), respectively. As compared to the center wavelength of Device B ($\sim$518 nm), the center wavelength of Device A ($\sim$496 nm) is slightly blue-shift, which can be attributed to the screening of piezoelectric field in the n-type doping $In_xGa_{1-x}N$–GaN-based MQW and the renormalization of quantized states in the well region [12]. Fig. 2 shows the collected optical power (*P*) versus injected current (*I*) of Devices A and B. Both devices have similar active areas ($\sim$14 000 μm ^{2}). We can clearly see that Device A has much higher output optical power than Device B under the same bias currents. Furthermore, the value of collected optical power ($\sim$100 μW under 50 mA) in POF of Device A is large enough for data transmission [3]. The superior *P–I* performance of Device A to Device B is possibly due to that the superior interface quality of n-doped MQW to undoped

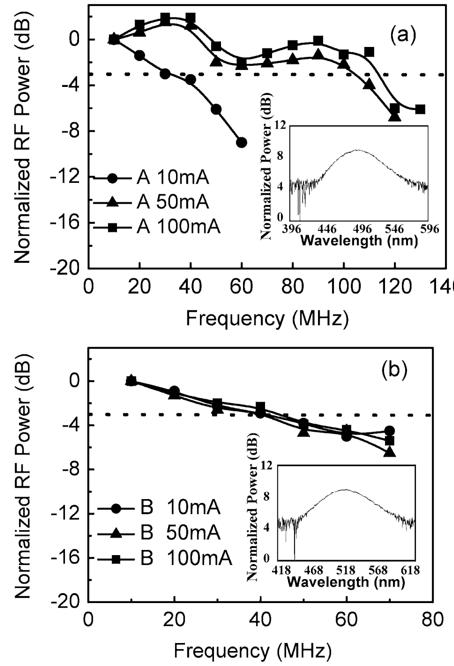

Fig. 3. Measured frequency responses under different bias current (10, 50, and 100 mA) of (a) Device A and (b) Device B. The insets in (a) and (b) show the measured electroluminescence (EL) spectra under 100-mA bias current of Devices A and B, respectively.

MQW [11] and lower device turn-on resistance with less device heating, as shown in the inset of Fig. 2. In order to further improve the optical coupling efficiency between POF and both devices and achieve better *P–I* performance, the light-emitting areas and shape of apertures of our demonstrated LEDs should be optimized [3]. During ac (modulation-speed) measurement, we injected the RF signal into both LEDs and the modulated optical power was collected by POF and then fed into a low noise Si-based photoreceiver with a 125-MHz electrical bandwidth, which was connected with an RF spectrum analyzer. The influence of used RF cables, photoreceiver, and bias tee, on the measured frequency responses was de-embedded carefully. Fig. 3(a) and (b) shows the measured frequency responses of Devices A and B with similar active areas ($\sim$14 000 μm ^{2}) under different bias currents, respectively. We can clearly see that when the bias current is over 50 mA, Device A exhibits much higher 3-dB electrical bandwidth than that of Device B ($\sim$120 versus $\sim$45 MHz). There are two major modulation-speed-limiting factors of LED; one is *RC* time constant and the other is spontaneous recombination time. In order to clarify which one results in the observed significant bandwidth enhancement of Device A, we have performed the capacitance–voltage (*C–V*) and *I–V* measurement on both devices to obtain their *RC*-limited bandwidths. Both devices with similar active areas exhibited similar values of capacitance under forward bias and Device A has around two times smaller differential resistance than that of Device B under the same bias current. However, even the calculated *RC*-limited bandwidth of Device B with $\sim$14 000 μm^2 active area is around $\sim$200 MHz, which is much larger than the obtained net E-O bandwidth ($\sim$45 MHz). Fig. 4 shows the measured frequency responses of Device B with different active area ($\sim$14 000 versus $\sim$123 000 μm^2) under

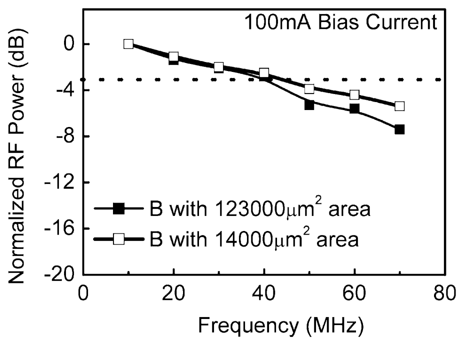

Fig. 4. Measured frequency responses of Device B with different active area. Closed squares: device with around 123 000 μm^2 active area; open squares: device with around 14 000 μm^2 active area.

the same bias current (100 mA). We can clearly see that even with a much larger active area and more serious *RC*-limited bandwidth, these two devices have similar 3-dB electrical bandwidth. Such measurement results indicate that the dominant bandwidth limiting factor of Device B is the spontaneous recombination time in the undoped $In_xGa_{1-x}N$–GaN-based MQW instead of its *RC* delay time and the improvement in speed performance of Device A is due to the enhancement of radiative recombination rate in n-type doped MQW layers [9], [10]. The significant enhancement of radiative recombination rate in n-type-doped $In_xGa_{1-x}N$–GaN-based MQW as compared to undoped control has also been reported and studied by the time-resolved photoluminescence technique [10]. The space charge field, which is induced by the n-type doping in the GaN barrier layer, can screen the piezoelectric field and result in higher degree of electron/hole wave function overlapping [9]–[12] and higher spontaneous emission rate [9]–[12] in the MQW region. According to our dc and ac measurement results, as shown in Figs. 2–4, we can conclude that the n-type doping in the $In_xGa_{1-x}N$–GaN-based MQW can improve the speed and power performance of green LED very effectively. Such a useful result is possibly originated from the fact that n-type barrier doping can improve the interface quality [11], screen the piezoelectric field, which plays an important role in the nitride-based laser or LED even under forward-bias [13], and increase the radiative recombination rate, in the MQW region. On the other hand, the improvement in both speed and output power of our device is contrary to the normal behavior of traditional red LED for POF communication [14], which usually has a tradeoff in its speed and power performance due to the incorporation of defects in its active MQW layers and the increase of nonradiative recombination rate [14].

IV. Conclusion

We demonstrate the high-speed performance of GaN-based LED at green wavelength regime. By utilizing the n-type doping in the barrier layers of $In_xGa_{1-x}N$–GaN-based MQW layers, significant enhancement of speed and output optical power has been observed. Such improvement can be attributed to the enhancement of spontaneous recombination rate in the MQW active region. The promising E-O measurement results ensure its application to 150-Mb/s POF data transmission.

References

[1] Information Gatekeepers, Inc., "Present state-of-the-art of plastic optical fiber (POF) components and systems," presented at the Plastic Optical Fiber Trade Organization (POFTO) Brighton, MA, 2004, unpublished.

[2] M. Saarinen, V. Vilokkinen, M. Dumitrescu, and M. Pessa, "Resonant-cavity light-emitting diodes operating at 655 nm with a high external quantum efficiency and light power," *IEEE Photon. Technol. Lett.*, vol. 13, no. 1, pp. 10–12, Jan. 2001.

[3] M. Akhter, P. Maaskant, B. Roycroft, B. Corbett, P. de Mierry, B. Beaumont, and K. Panzer, "200 Mbit/s data transmission through 100 m of plastic fiber with nitride LEDs," *Electron. Lett.*, vol. 38, pp. 1457–1458, Nov. 2002.

[4] T. Matsuoka, T. Ito, and T. Kaino, "First plastic optical fiber transmission experiment using 520 nm LEDs with intensity modulation/direct detection," *Electron. Lett.*, vol. 36, pp. 1836–1837, Oct. 2000.

[5] J. K. Sheu, J. M. Tsai, S. C. Shei, W. C. Lai, T. C. Wen, C. H. Kou, Y. K. Su, S. J. Chang, and G. C. Chi, "Low-operation voltage of InGaN/GaN light-emitting-diodes with Si-doped $In_{0.3}Ga_{0.7}N$/GaN short-period superlattice tunneling contact layer," *IEEE Electron Device Lett.*, vol. 22, no. 10, pp. 460–462, Oct. 2001.

[6] S. J. Chang, W. C. Lai, Y. K. Su, J. F. Chen, C. H. Liu, and U. H. Liaw, "InGaN/GaN multiquantum well blue and green light emitting diodes," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 2, pp. 278–283, Mar./Apr. 2002.

[7] A. J. Shaw, A. L. Bradley, J. F. Donegan, and J. G. Lunney, "GaN resonant cavity light-emitting diodes for plastic optical fiber applications," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2006–2008, Sep. 2004.

[8] J.-W. Shi, H.-Y. Huang, J.-K. Sheu, S.-H. Hsieh, Y.-S. Wu, J.-Y. Lu, F.-H. Huang, and W.-C. Lai, "Nitride-based photodiode at 510-nm wavelength for plastic optical fiber communication," *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 283–285, Jan. 1, 2006.

[9] Y.-C. Cheng, S.-W. Feng, E.-C. Lin, C. C. Yang, C.-H. Tseng, C. Hsu, and K.-J. Ma, "Quantum dot formation in InGaN/GaN quantum well structures with silicon doping and its implication in the mechanisms of radiative efficiency improvement," *Physica Status Solidi (c)*, vol. 4, pp. 1093–1096, 2003.

[10] M. S. Minsky, S. Chichibu, S. B. Fleischer, A. C. Abare, J. E. Bowers, E. L. Hu, S. Keller, U. K. Mishra, and S. P. Denbaars, "Optical properties of InGaN/GaN quantum wells with Si doped barriers," *Jpn. J. Appl. Phys.*, vol. 37, pt. 2, pp. L 1362–L 1364, Nov. 1998.

[11] L. W. Wu, S. J. Chang, T. C. Wen, Y. K. Su, J. F. Chen, W. C. Lai, C. H. Kuo, C. H. Chen, and J. K. Sheu, "Influence of Si-doping on the characteristics of InGaN-GaN multiple quantum-well blue light-emitting diodes," *IEEE J. Quantum Electron.*, vol. 38, no. 5, pp. 446–450, May 2002.

[12] H. Haratizadeh, B. Monemar, P. P. Paskov, J. P. Bergman, B. E. Sernelius, P. O. Holtz, M. Iwaya, S. Kamiyama, H. Amano, and I. Akasaki, "Photoluminescence study of Si-doped GaN/$Al_{0.07}Ga_{0.93}N$ multiple quantum wells with different dopant positions," *Appl. Phys. Lett.*, vol. 84, pp. 5071–5073, Jun. 2004.

[13] J. Piprek, R. Farrell, S. P. Denbaars, and S. Nakamura, "Effects of built-in polarization on InGaN-GaN vertical-cavity surface-emitting lasers," *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 7–9, Jan. 1, 2006.

[14] L. B. Chang, D. H. Yeh, L. Z. Hsieh, and S. H. Zeng, "Enhanced modulation rate in platinum-diffused resonant-cavity light-emitting diodes," *J. Appl. Phys.*, vol. 98, p. 093504, Nov. 2005.