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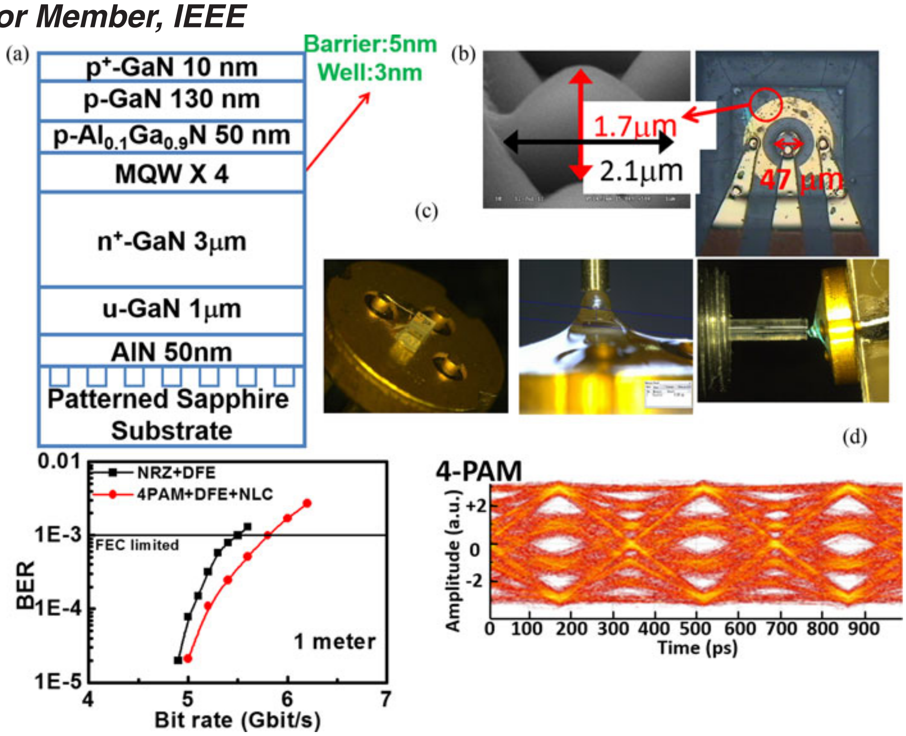

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GaN-Based Cyan Light-Emitting Diode with up to 1-GHz Bandwidth for High-Speed Transmission Over SI-POF

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Abstract: We demonstrate the performance of a novel cyan light-emitting diode (LED) on a patterned sapphire substrate for use as a light source for plastic optical fiber (POF) communications with the central wavelength at 500 nm. By significantly reducing the number of active $In_xGa_{1-x}N$/GaN multiple quantum wells and the thickness of the barrier layers down to 5 nm, such a device with an active diameter of 47 μm demonstrates a record high 3-dB electrical-to-optical bandwidth, as high as 1 and 0.7 GHz, among all the reported high-speed visible LEDs under room temperature and 110 °C operation, respectively. TO-Can packaging with a lens is used to enhance the POF coupling efficiency. Very-high data rates of 5.5 and 5.8 Gbit/s are achieved over step index POF under nonreturn-to-zero and 4-pulse amplitude modulation, respectively. When the POF transmission distance reaches 50 m, there is degradation in the maximum data rate for both modulation schemes to 1.3 Gbit/s due to the dispersion and attenuation of the POF.

Index Terms: Light-emitting diodes (LEDs), fiber optics communications.

1. Introduction

Adding Internet connectivity to cars is attractive to automakers for several reasons, including collection of data from the vehicle, facilitation of preventive maintenance and over-the-air software updates, and improving vehicle safety. However, a great speeding up of the data transmission rate is required for in-car data transmission. An optical cable is preferred to a coaxial cable for in-car data transmission because it is more lightweight, less bulky, and can eliminate interference between the ignition coil and electronic devices that occurs through an electrical cable. Plastic optical fibers (POF) have been introduced for automotive applications which possess greater flexibility and robustness than the commonly used multi-mode glass fibers for data transmission. This becomes an important issue for the sustainability of the in-car network after the occurrence of a traffic accident.

There are three minimum loss windows in the use of polymethylmethacrylate (PMMA) step-index (SI) POFs for data transmission [1], [2]. The most commonly used window relates to the

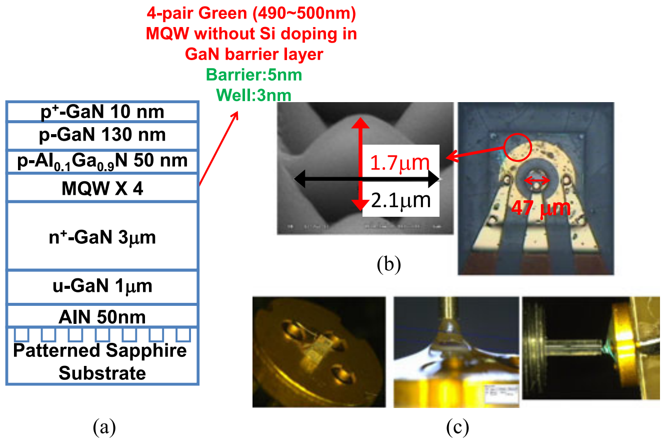

Fig. 1. (a) Conceptual cross-sectional view of the epitaxial layer structure of the demonstrated device. It was not drawn according to scale for clearness. (b) Top-view of the demonstrated LED chip and the magnified picture of the PS substrate. (c) TO-Can packaged LED chips with lens.

wavelength of 650 nm. The commercially available high-speed GaAs resonant cavity light-emitting diodes (RCLEDs) operating at ∼650 nm provide sufficient performance [3], [4]. However, compared with those with a minimum PMMA loss window at the blue-green wavelengths (∼500 nm), the red operating window has a narrower spectral width (∼5 nm vs. ∼20 nm) and a higher propagation loss (8 dB/50m vs. 4 dB/50m) [1], [2]. High-speed III-nitride based green or blue LEDs operating at wavelengths of 400-500 nm have been demonstrated to meet the requirements for such applications [1], [5]–[8]. Compared to the red GaAs RCLEDs, the nitride based LEDs provide greater immunity against ambient temperature variations due to their larger bandgap [5]. In this study, we demonstrate the ability of a novel high-speed cyan nitride-based LED grown on a patterned sapphire (PS) substrate with a miniaturized device area and a thin-barrier active region to further boost its 3-dB electrical-to-optical (E-O) bandwidth performance [6]. Applying a reasonable DC bias current (∼90 mA) to a device with a miniaturized active diameter of ∼47 μm, we can achieve a record high 3-dB E-O bandwidth of 1 GHz, among all those reported for high-speed visible LEDs [8]. During data transmission, a device with a larger active diameter (∼75 μm vs. ∼47 μm) is chosen to allow for a larger power budget, which has a maximum 3-dB E-O bandwidth of around 0.7 GHz measured under room temperature (RT) and a bias current of 100 mA. This novel device is used with a TO-Can lens package at a bias current of 80mA. With the application of off-line signal processing techniques, we can achieve high-speed transmission over the 1 m PMMA SI-POF with data rates of 5.5 Gbit/s and 5.8 Gbit/s obtained using non-return-to-zero (NRZ) and pulse amplitude modulation (4-PAM), respectively. The performance is superior to that of the commercially available red RCLEDs (e.g., Firecomms FC300R-120) under the same test conditions due to the faster modulation speed of our demonstrated cyan LEDs (1 GHz vs. ∼0.1 GHz) [9]. Furthermore, to the best of our knowledge, these data rates are the highest among reported POF transmission results using visible LEDs [9]. However, when the POF transmission distance reaches 50 m, there is degradation of the 4-PAM and NRZ data rate to around 1.3 Gbit/s due to the problems of attenuation and bandwidth limitation of the SI-POF [9], [10].

2. Device Structure and Fabrication

The device structure is grown on a patterned sapphire (PS) substrate and designed in order to enhance the external quantum efficiency and sustain the optical output power of a miniaturized size LED for POF communication [1]. 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 device structures are specified in Fig. 1(a). In comparison to the traditional LED, the GaN barrier layer thickness in the novel device structure has been greatly narrowed from 17 nm to 5 nm.

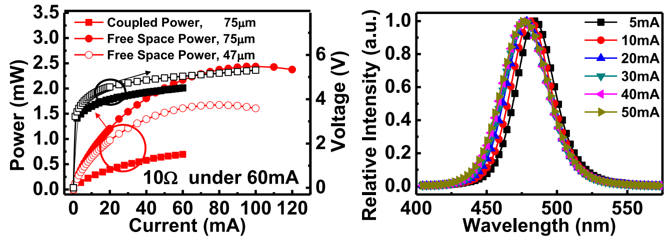

Fig. 2. (a) Measured free-space output power, coupled power into the SI-POF, and voltage vs. bias current of devices with 75 (closed symbols) and 47 (open symbols) μm active diameters. The measured differential resistance of both devices is around 10 Ω under a 60 mA bias current. (b) Measured bias dependent EL spectra of a device with a 75 μm active diameter.

By thinning down the barrier layer, the thickness of the total active layer is greatly reduced to 37 nm, leading to an increase of the injected carrier density, radiative recombination rate, and modulation speed of the device [11]. Furthermore, the thinness of the barrier layer increases the uniformity of the hole distribution among the different wells and enhances the total output power [6]. Fig. 1(b) shows a top-view of the demonstrated LED chip and magnified image of the periodic structures on the PS substrate. Each LED has an active diameter of around 47 μm or 75 μm, respectively. During device fabrication, each LED is etched down to the insulating sapphire substrate to minimize the parasitic capacitance of the device. For data transmission experiments and coupled power measurements, our device is well packaged with a 500 μm half-sphere lens for further improvement of the POF coupling efficiency [1]. Fig. 1(c) shows a photograph of our chip after Transistor-Outline-Can (TO-Can) packaging (TO-56) [1], which is a very popular packaging scheme for optoelectronic devices used in 1.25/2.5 Gbit/sec data communication. In order to obtain good coupling efficiency between the LED output and the POF, a ball lens 500 μm in diameter is adopted in our package and is described in detail in [1].

3. Measurement Results

Fig. 2(a) shows the total free-space output power (P), coupled power into the POF, and the corresponding voltage (V) from the 75 m active diameter device under RT operation, measured with an integrating sphere, versus the bias current (I). The free-space P-I-V curves of a 47 μm device are also given for comparison. Here, the free-space output power is the on-wafer measurement result and the coupled power is measured by use of a diced chip after TO-CAN packaging. As can be seen, the maximum bias current in the coupled power measurement is smaller than that of device used for free-space power measurement (60 vs. 80 mA). This is because the area of the chip becomes smaller after dicing, which usually leads to an increase in the thermal resistance and degradation in the maximum output power (bias current). According to the measured values of the coupled and free-space power of the 75 μm device, the extracted coupling efficiency of our LED after lens integration is approximately 30%. This number is close to the coupling efficiency obtained between the output of the commercially available red RCLED and a POF [3], [4]. In addition, the differential resistance of both devices (47 and 75 μm) measured under a 60 mA bias current is as low as 10 Ω as derived from the V-I curves in Fig. 2(a). Fig. 2(b) shows the measured bias dependent electroluminescence (EL) spectra of the 75 μm device. The measured central wavelength of around 480 nm is close to the minimum loss window of the standard PMMA POF ($<$4 dB/50m) [1]. Compared with the reference device, having an active region of the same design (i.e., same number of MQWs and same well width) but a much thicker barrier layer (17 vs. 5 nm) [6], both devices have very similar central wavelengths and full-width half maximum (FWHM) in their EL spectra. This suggests that our barrier thinning design entails no sacrifice of the POF transmission performance, which will be discussed in greater detail later.

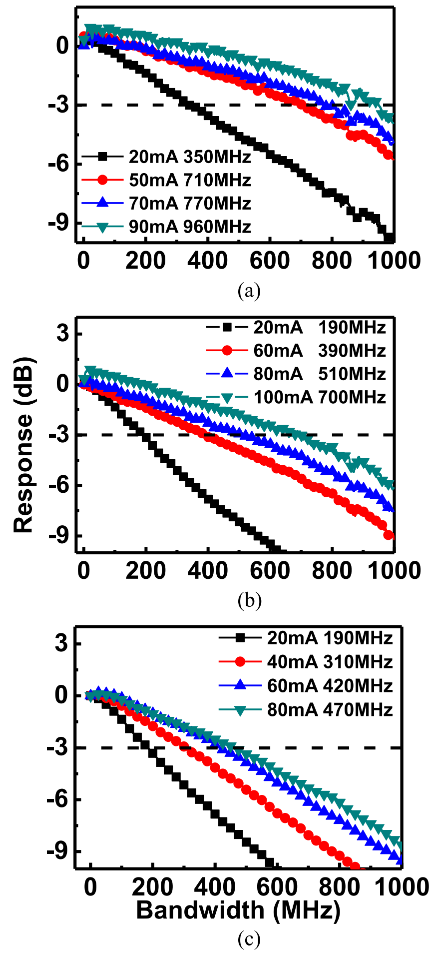

Fig. 3. (a) Measured bias dependent E-O frequency responses of the (a) 47 μm device, (b) 75 μm device, and (c) 75 μm device after TO-Can packaging under RT operation.

Fig. 3(a) to (b) show the on-wafer measured E-O frequency responses of our devices with 47 μm and 75 μm active diameters, respectively, under different bias currents and RT operation. Just like the dynamic behavior of typical LEDs, there is an increase in the measured O-E bandwidths with the bias current with both devices, which is due to the enhancement in spontaneous recombination rate with the increase of the injected current (carrier) density into the active volume [11]. Furthermore, when the bias current reaches 90 mA, the maximum 3-dB E-O bandwidth of our small device almost reaches 1 GHz. To the best of our knowledge, this speed performance is the highest ever reported for any visible LED [1]–[8]. However, as shown in Fig. 3(b), there is a slight degradation of the measured maximum 3-dB E-O bandwidth with the 75 μm device, to 0.7 GHz, when the driving current is 100 mA. Fig. 3(c) shows the measured E-O responses for the same 75 μm device after TO-Can packaging with a lens, as shown in Fig. 1(c). We can clearly see that the maximum E-O bandwidth is reduced from 510 MHz to 470 MHz under the same bias current of 80 mA. This implies that the TO-56 packaging causes only a slight degradation in the speed performance. This degradation in speed performance can be attributed to the extra parasitic capacitance and inductance induced by the pins of the TO-Can, which must be mounted on a printed-circuit (PC) board for high-speed measurement. Compared to the GaAs based red RCLEDs, one of the major advantages of III-nitride based LEDs is their superior performance in harsh environments due to the larger bandgap of the active layers [5].

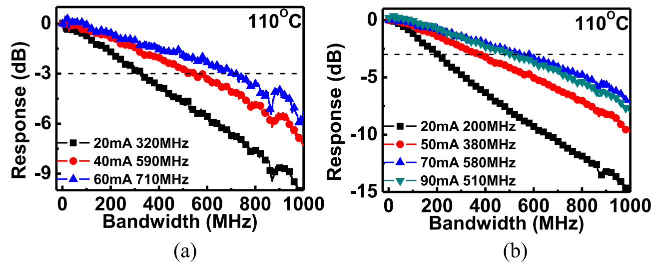

Fig. 4. (a) Measured bias dependent E-O frequency responses of (a) 47 μm device and (b) 75 μm device under 110 °C operations.

Fig. 4(a) and (b) show the on-wafer measured bias dependent E-O frequency responses of our 47 μm and 75 μm active diameter devices, respectively, at 110 °C operation. As can be seen, there is only a slight degradation in the maximum speed for both devices (~30% degradation; 1 GHz to 0.7 GHz) when the temperature reaches 110 °C. Furthermore, even under such a high ambient temperature, neither of these two devices show serious (around 20%) degradation in the maximum output power [6]. The dynamic/static measurement results indicate that the demonstrated GaN LED can sustain excellent transmission performance under high-temperature (T) operation. The observed E-O bandwidth degradation under high bias currents observed at an ambient temperature (T) of 110 °C conflicts with the behavior reported for GaAs based high-speed LED [3], which usually exhibit an enhancement of the bandwidth under high-T operation due to an increase of the carrier leakage and non-radiative recombination rate. Nevertheless, such an improvement in speed under high-T operation of GaAs LEDs would usually be accompanied by a dramatic reduction in the output power which would limit its transmission performance [3].

The distinct bias/temperature dependent dynamic performance of our GaN based LEDs can be attributed to the fact that, under an extremely high bias current density ($>$1 kA/cm^2), the piezoelectric field inside the active regions can be screened, which thus increases the effective barrier height and minimizes the carrier leakage from MQWs [12] that occurs under high-T operation. On the other hand, under a moderate bias current density, the screening effect is not pronounced and an improvement in the E-O bandwidth with the increase of ambient T can thus be observed for the 75 μm device when the bias current is below 80 mA, as shown in Fig. 3(b) and 4(b).

For the data transmission experiments, the TO-Can packaged 75 μm LED is used with a lens at the transmitter side for a larger power budget, compared to that of the 47 μm device, as shown in Fig. 2(a). The LED was modulated over Bias-T by NRZ and 4-PAM signals based on a pseudo-random binary sequence (PRBS 2^7–1). The bias current of the LED under testing was 80 mA. For the arbitrarily selected waveform generator (Tektronix 7102) to provide a modulating signal of the proper level, an additional preamplifier MERA-556+ (Mini Curcuits) was required. A commercially available optical receiver Graviton SPD-2 with a 400 μm Si PIN photodiode was used on the receiver side. The output signal from the receiver was captured by a real time oscilloscope (Tektronix DSA 71604) for further offline signal processing and direct error counting. The offline processing included signal resampling at twice the bit rate, synchronization and T/2 fractionally spaced decision feedback equalization (DFE) with 24 feedforward and 10 feedback taps. A 1-mm core-diameter PMMA SI-POF (POF class A4a.2, according IEC 60793-240) with lengths of 1, 20, or 50 m was used to connect the transmitter and receiver ends. Fig. 5(a) shows the measured BER values versus different bit rates for the case of 1 meter POF transmission. For the case of 4-PAM transmission, we implemented an additional Volterra-based nonlinearity compensation (NLC) algorithm to improve the BER performance [9], [10]. We can clearly see that the forward error correction (FEC) limited data rate (BER$<10^{-3}$) for NRZ and 4-PAM transmission is 5.5 Gbit/s and 5.8 Gbit/s, respectively. Fig. 5(b) and (c) show the corresponding measured eye-patterns for these two data rates and modulation schemes. This data rate is higher than the value reported in our previous work (5.8 Gbit/s vs. 5.5 Gbit/s) [9] which was obtained using a 4-PAM with the same test conditions and setup. This improvement can be attributed to the improvement in the modulation speed of our LED.

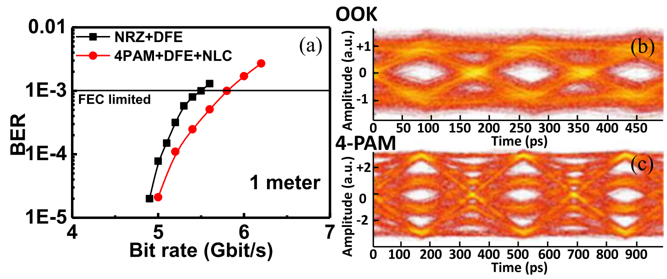

Fig. 5. (a) Measured BER values versus bit rates of an LED under NRZ and with a 4-PAM modulation format over 1 m SI-POF. (b) NRZ and (c) 4-PAM eye patterns at 5.5 and 5.8 Gbit/s, respectively.

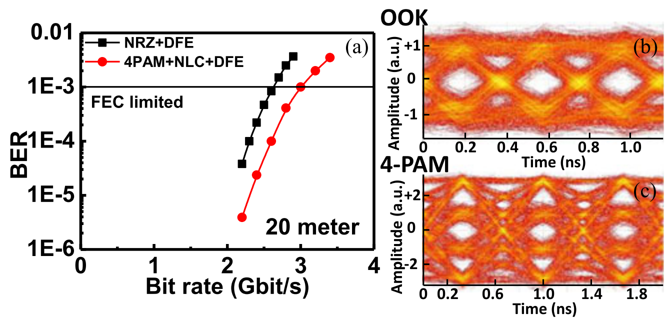

Fig. 6. (a) Measured BER values versus bit rates of an LED under NRZ and 4-PAM modulation format over 20 m SI-POF. (b) NRZ and (c) 4-PAM eye patterns at 2.6 and 3 Gbit/s, respectively.

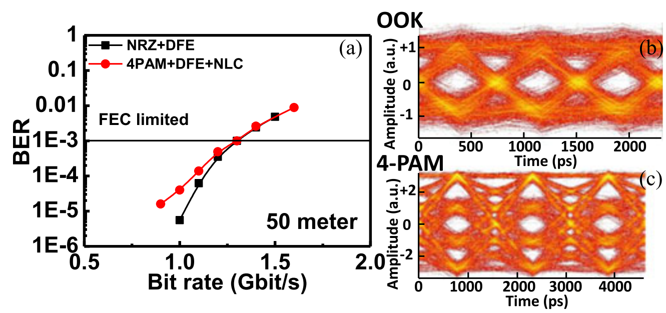

Fig. 7. (a) Measured BER values versus bit rates of an LED under NRZ and 4-PAM modulation format over 50 m SI-POF. (b) NRZ and (c) 4-PAM eye patterns at the same data rate as 1.3 Gbit/sec.

To the best of the authors' knowledge, the demonstrated data rate is the highest for POF transmission using visible LEDs. Figs. 6 and 7 show the measured BER versus different bit rates obtained using the same test setup and modulation formats as shown in Fig. 5, but with POFs over 20 m and 50 m in length. We can clearly see that there is significant degradation in the maximum FEC limited data rates for both modulation schemes with an increase in the POF length. This can be attributed to the dispersion and attenuation within the SI-POF [9], [10]. Nevertheless, for the 20 m long POF case, the transmission performance of our proposed device is still superior to that of the commercial red RCLED (3 Gbit/s vs. 2.7 Gbit/s) under the same test setup and with the same POF length [9]. The 20 m POF length should meet the requirements for linking distance for most in-car data communication networks. In order to further improve the maximum data rate over an SI-POF, LEDs with a narrower spectral-width and higher optical power are desired. As shown in Fig. 2(b), the full width at half maximum (FWHM) of the EL spectra broadens from 30 nm to 40 nm when the bias current increase from 5 to 50 mA. These numbers are larger than for the GaAs red RCLED ($\sim$40 nm vs. 18 nm), which implies a more serious chromatic dispersion through POF transmission by use of our demonstrated device [9].

4. Conclusion

We demonstrate the functioning of a miniaturized GaN based cyan LED on a patterned sapphire substrate. By thinning the barrier layer thickness in the active region, shrinking the device active area, and using TO-Can packaging with a lens, we fabricate an LED with a 75 μm active diameter which can provide a reasonable optical power of 0.7 mW coupled into the POF, a high E-O bandwidth of 470 MHz at a bias current of 80mA, and data rates of 5.5 Gbit/s and 5.8 Gbit/s at BER of 10^{-3} over 1 m of SI-POF under NRZ and 4-PAM modulation schemes, respectively. When the POF transmission distance reaches 50 m, there is degradation of the maximum data rate to 1.3 Gbit/s due to dispersion and attenuation in the SI-POF. An improved transmission performance can be expected by further narrowing down the spectral width of the proposed device.

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