High-Bandwidth Flexible White Light System for Visible Light Communication

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ABSTRACT

In this study, we propose a flexible white-light system consisting of blue InGaN/GaN single-quantum-well micro-LEDs on a flexible substrate pumping CsPbBr3 perovskite QD (PQD) paper in nanostructure form and CdSe QD paper for high-speed VLC. The micro-LED and PQD paper achieved a maximum bandwidth of 817 MHz and 229 MHz respectively. The white-light system reached a maximum bandwidth of 95.5 MHz and transmission rate of 150 Mbps.

1 Introduction

With the advent of new technology, light emitting diodes (LEDs) have been commercialized and widely used in numerous applications such as large displays, traffic, indoor and outdoor lighting, automobiles, cell phones, liquid-crystal displays, etc. [1]. White-light emitting materials have recently attracted tremendous interest, especially in flexible display devices, for their extensive applications in LEDs, lighting, and communications [2]. Since flexible electronics are the cornerstone of innovative applications in diverse fields such as displays, healthcare, wireless networks, etc., flexible devices need to be developed. This will open up the potential for flexible VLC systems to be incorporated into wearable fabrics and industrial products. Over the last few years, VLC systems have evolved dramatically as white LEDs began to overtake light bulbs because of their higher performance, lower cost, and longer lifetimes.

QDs have been generally used for the realization of the white light system, but the modulation bandwidth of CdSe/ZnS QDs is limited to 3 MHz only. PQDs exhibiting short carrier recombination lifetime and narrow spectral linewidth have received significant interest for the development of white light VLC system with much higher modulation bandwidth than CdSe/ZnS QDs [3]. Semipolar blue micro-LEDs exhibiting high modulation bandwidth owing to smaller size, shorter carrier lifetime and higher current density being preferred to combine with high-bandwidth PQDs to achieve a high-bandwidth white light system. In this work, we proposed a high-performance flexible white LED system with an excellent potential for the application of visible light communication (VLC) by incorporating green emitting PQD paper, red emitting CdSe QDs and semipolar blue micro-LED.

QDs have been generally used for the realization of the white light system for display applications, however the modulation bandwidth of CdSe based QDs is limited to a few MHz only, which limits its applications for visible light communication open up new possibilities for monitoring the modulation characteristics of QDs for future applications. In this study, we propose a flexible white light system comprising of perovskite QDs paper and micro-LED array exhibiting high bandwidth.

2 Experiment

Metal Organic Chemical Vapor Deposition (MOCVD) is used to grow semipolar (20-21) oriented GaN layer on patterned sapphire substrate (PSS). The micro-LED epitaxial structure n-GaN, InGaN/GaN single quantum well (SQW) as the active region, and a p-type GaN layer. The process flow of micro-LED begins with the deposition of indium tin oxide (ITO) layer followed by mesa etching of ITO film using HCl and inductively coupled plasma reactive ion-etching (ICP-RIE) process to form p-type ohmic contact accompanied by thermal annealing in order to provide a better current spreading layer. A passivation layer of Al2O3 and SiO2 was formed to prevent from leakage current due to sidewall defects. The process flow and structure of micro-LED is shown in Fig. 1(a). The flexible white-light system was developed using a flexible blue micro-LED and CsPbBr3 green PQDs with CdSe red QDs. The fabrication process of the white-light system is shown in Fig. 1(b). The flexible micro-LED was fabricated using a polyimide (PI) substrate covered with copper foil shielding tape developed by photolithography and wet etching to establish the electrical conduction. The micro-LED flip-chip was then bonded on the PI substrate using silicone-based electrically conductive anisotropic adhesive to maintain the electrical conductivity between the chip metal contact and the AuSn solder on the substrate; this increased the flexibility of the system. For the color converter, we prepared CsPbBr3 PQD and CdSe QD papers, which were stuck on top of the micro-LED with a flexible substrate using an adhesive, to form the white-light system.

3 Results

Fig. 2(a) shows the EL spectrum of the white light generated from the white-light system with the micro-LED drive current increasing from 7.2 to 72 mA. The spectrum also shows the result of the emission of green light from the nanostructured PQD paper with a peak wavelength of 528 nm and the emission of red light from the CdSe QD paper with a peak wavelength of 625 nm, confirming the generation of white light. The inset image shows a flexible white-light system with high illumination of white light. The time-resolved photoluminescence (TRPL) was employed to investigate the lifetime of the carriers of both the semipolar micro-LED and PQD paper, as shown in Fig. 2(b). The calculated average PL lifetimes for the semipolar device, PQD, and CdSe QD papers were 0.64, 5.92, and 12.88 ns respectively. The semipolar device had a shorter lifetime because of the weak polarization-related electric field and huge overlap of the electron-hole wave function, which led to a faster carrier recombination lifetime [4]. The shorter carrier lifetime of PQD is attributable to the quantum-confinement effect, which results in faster radiative recombination and a subsequent increase in the photoluminescence quantum yield.

The semipolar blue micro-LED had a maximum 3-dB bandwidth of 817 MHz, corresponding to an injection current of 113 mA, as shown in Fig. 3(a), which is promising for VLC application. The short average carrier lifetime of the semipolar micro-LED was consistent with the measured frequency bandwidth. The eye diagram of the semipolar micro-LED is shown in the inset of Fig. 3(a); a maximum data rate of 1.5 Gbps was achieved owing to the sufficiently high 3-dB bandwidth. The measured 3-dB bandwidth of the green-emitting PQD paper was 229 MHz under an injection current of 113 mA, as shown in Fig. 3(b), which is the highest bandwidth reported for PQDs thus far. The inset of Fig. 3(b) shows the eye diagram of the PQD paper with a data transmission rate of 400 Mbps, which is also the highest reported value thus far. In addition, the BER value for the blue micro-LED at 1.5 Gbps data rate is 2.1×10^{-4} while that for the PQD paper at 400 Mbps is 1.5×10^{-4}. These BER values is much lower than the forward error correction (FEC) limit of 3.8×10^{-3} required for free-error data transmission. The high bandwidth and high data transmission rate were attributed to the short carrier recombination lifetime of the nanostructured PQD paper. The bandwidth of the PQD paper prepared with cellulose was compared with that of a typical PQD film by casting as a film; the bandwidth of the nanostructured PQD paper was much higher than that of the PQD film, as shown in Fig. 3(b). The PQDs-based white light system displays a frequency bandwidth of 95.5 MHz and a data transmission rate of 150 Mbps corresponding to an injection current of 113 mA as shown in Fig. 3(c). The high-bandwidth of the white-light system is also attributed to high bandwidth of the semipolar micro-LED and well as that of PQD paper.

4 Conclusions

A white-light system has been proposed with the incorporation of PQD paper, CdSe paper and micro-LED. The PQD paper used in this study has the highest modulation bandwidth of 229 MHz with a data transmission rate of 400 Mbps, and the semipolar micro-LED has a modulation bandwidth of 817 MHz with a data rate of 1.5 Gbps. The white light system exhibits a maximum bandwidth of 95.5 MHz and data transmission rate of 150 Mbps, which can be used for high speed VLC applications.

References

[1] J. Cho, J. H. Park, J. K. Kim, and E. F. Schubert, Laser Photon. Rev. 11, 1600147 (2017).

[2] S. Mei, X. Liu, W. Zhang, R. Liu, L. Zheng, R. Guo, and P. Tian, ACS Appl. Mater. Interfaces 10, 5641–5648 (2018).

[3] I. Dursun, C. Shen, et al., ACS Photon. 3, 1150–1156 (2016).

[4] M. Monavarian, A. Rashidi, A. Aragon, S. Oh, M. Nami, S. DenBaars,and D. Feezell, Opt. Express 25, 19343–19353 (2017).

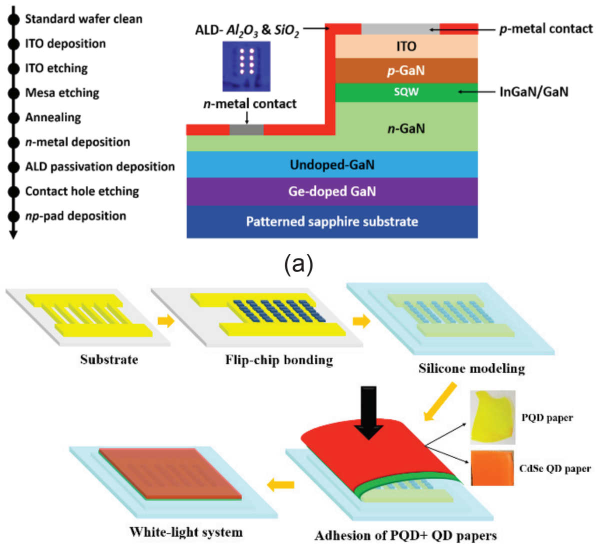
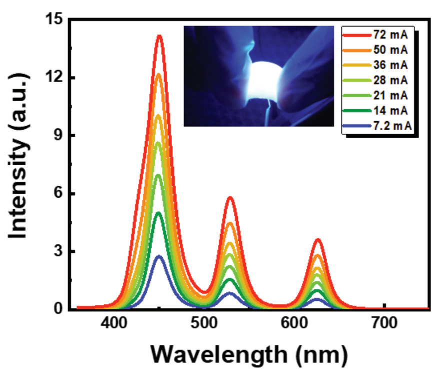


Fig. 1 (a) Process flow and structure of micro-LED. (b) White light system process flow.



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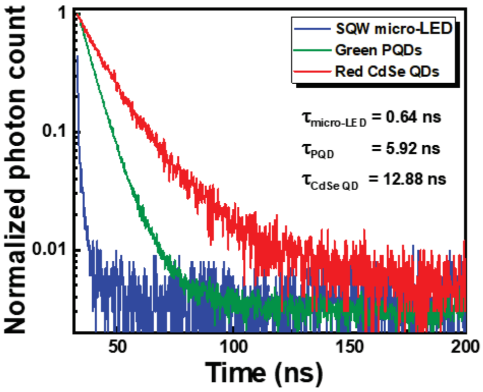
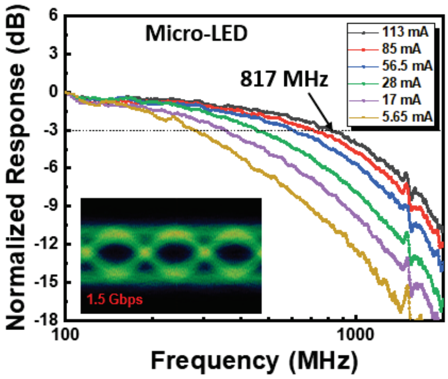


(b)

Fig. 2 (a) Spectrum of white light generated using the semipolar micro-LED and PQD paper and CdSe QDs. Inset: Photograph of the flexible white-light system. (b) TRPL curves for semipolar micro-LED, PQD and CdSe QD papers.



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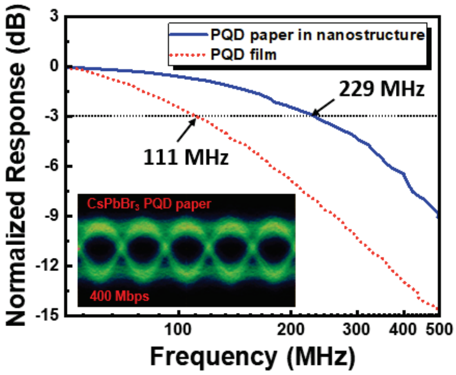

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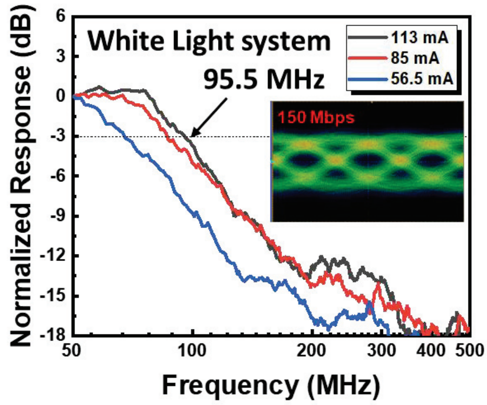

(c)

Fig. 3 Modulation bandwidth and eye diagrams for (a) Semipolar micro-LED (b) PQD paper and PQD film (d) White light system.