Performance improvement of blue InGaN light-emitting diodes with a specially designed n-AlGaN hole blocking layer*

Ding Bin-Bin(丁彬彬)[a)b)], Zhao Fang(赵 芳)[a)b)], Song Jing-Jing(宋晶晶)[a)b)], Xiong Jian-Yong(熊建勇)[a)b)], Zheng Shu-Wen(郑树文)[a)b)], Zhang Yun-Yan(张运炎)[a)b)], Xu Yi-Qin(许毅钦)[a)b)], Zhou De-Tao(周德涛)[a)b)], Yu Xiao-Peng(喻晓鹏)[a)b)], Zhang Han-Xiang(张瀚翔)[a)b)], Zhang Tao(张 涛)[a)b)], and Fan Guang-Han(范广涵)[a)b)†]

[a)] *Institute of Opto-Electronic Materials and Technology, South China Normal University, Guangzhou* 510631, *China*
[b)] *Laboratory of Nanophotonic Functional Materials and Device, South China Normal University, Guangzhou* 510631, *China*

(Received 23 October 2012; revised manuscript received 9 January 2013)

Blue InGaN light-emitting diodes (LEDs) with a conventional electron blocking layer (EBL), a common n-AlGaN hole blocking layer (HBL), and an n-AlGaN HBL with gradual Al composition are investigated numerically, which involves analyses of the carrier concentration in the active region, energy band diagram, electrostatic field, and internal quantum efficiency (IQE). The results indicate that LEDs with an n-AlGaN HBL with gradual Al composition exhibit better hole injection efficiency, lower electron leakage, and a smaller electrostatic field in the active region than LEDs with a conventional p-AlGaN EBL or a common n-AlGaN HBL. Meanwhile, the efficiency droop is alleviated when an n-AlGaN HBL with gradual Al composition is used.

Keywords: p-AlGaN electron blocking layer (EBL), n-AlGaN hole blocking layer (HBL), numerical simulation, InGaN light-emitting diode (LED)

PACS: 85.60.Jb, 85.30.–z, 87.15.A–, 78.60.Fi **DOI:** 10.1088/1674-1056/22/8/088503

1. Introduction

InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) are promising for replacing conventional incandescent and fluorescent lamps due to their inherent higher energy efficiencies and other advantages.[1–5] However, these devices suffer from a rapid efficiency droop with increasing injection current,[6,7] which is detrimental to high-brightness applications. Various explanations of the mechanism of the efficiency droop have been proposed, such as carrier leakage from the active region,[8–10] carrier localization,[11,12] Auger recombination,[13,14] poor hole injection,[15] the polarization effect,[16] and so on. However, the origin of the droop is not yet clearly understood. Recently, many approaches to the improvement of optical performance have been reported, such as the use of InGaN barriers,[17] AlInGaN barriers,[18] staggered quantum wells (QWs),[19–21] an AlGaN/GaN superlattice (SL) electron blocking layer (EBL) of gradual Al mole fraction,[22] a staggered AlGaN electron blocking layer,[23] and a graded electron blocking layer (GEBL).[24]

The published simulation results show that the electron leakage may play an important role in the efficiency droop. Therefore, the insertion of an AlGaN layer between the last QW barrier and the p-type hole injection layer has been suggested, with the hope that this wide band gap material layer acts as an EBL to suppress the electrons from escaping from the active region into the p-type hole injection layer. However, recently published studies have indicated that the electron confinement by a typical AlGaN EBL is not sufficiently effective in solving the efficiency droop problem. Furthermore, the use of an AlGaN EBL can cause some undesired effects such as prohibiting the holes from being injected into the active region, which degrades the luminescence characteristics of the blue LED.[25,26] Some scientists have tried to use an InAlN EBL to suppress electron leakage.[27] However, the difficulty of high-quality InAlN material growth is a big challenge. Kuo *et al.*[28] tried to increase the hole injection efficiency and solve the efficiency droop problem using a p-type doped last barrier. However, they paid no attention to the hindrance of hole injection by the AlGaN EBL. Besides, holes are still rather difficult to move between QWs due to the prohibition of the undoped QW barriers in the middle of the active region. Yen *et al.*[29] were aware of the disadvantages of using the traditional p-AlGaN EBL and replaced the EBL with an n-AlGaN HBL below the active region. However, they did not come up with an effective method to reduce the hole leakage at a large injection current density. Thus, in this paper, we propose to remove the p-AlGaN EBL of a conventional InGaN LED and replace it with an n-AlGaN HBL with gradual Al composition between the n-type electron injection layer and the first QW barrier to

*Project supported by the National Natural Science Foundation of China (Grant No. 61176043), the Special Funds for Provincial Strategic and Emerging Industries Projects of Guangdong Province, China (Grant Nos. 2010A081002005, 2011A081301003, and 2012A080304016), and the Youth Foundation of South China Normal University (Grant No. 2012KJ018).

†Corresponding author. E-mail: gfan@scnu.edu.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

improve the optical performance.

In this paper, the light output power, internal quantum efficiencies (IQEs), electrostatic fields, radiative recombination rates, energy bands, and carrier concentrations of LEDs with conventional EBL, HBL, and gradual Al composition (GHBL) are investigated numerically with the APSYS (advanced physical model of semiconductor devices) simulation software, which is capable of dealing with the physical properties of LEDs by solving Poisson's equation, the current continuity equation, the carrier transport equation, the quantum mechanical wave equation, and the photon rate equation.

2. Structure and parameters

The original blue InGaN/GaN MQW LED is used in this paper as a reference and is grown on a *c*-plane sapphire substrate, followed by a 4-μm thick n-GaN layer (n-doping = 2×10^{18} cm^{-3}). The active region consists of six 2.5-nm thick $In_{0.15}Ga_{0.85}N$ QWs sandwiched by seven 10-nm thick GaN barriers. On top of the active region are a 20-nm thick p-$Al_{0.15}Ga_{0.85}N$ EBL (p-doping = 5×10^{17} cm^{-3}) and a 0.2-μm thick p-GaN cap layer (p-doping = 5×10^{17}cm^{-3}). The device geometry is designed into a rectangular shape of 300 μm×300 μm. The LED with HBL has a similar layer structure except for the conventional p-AlGaN EBL. The p-AlGaN EBL is removed while the 20-nm thick n-$Al_{0.15}Ga_{0.85}N$ (n-doping = 2×10^{18} cm^{-3}) is placed between the active region and the n-GaN layer. For the LED with GHBL, its structure is identical to that of the HBL, apart from the Al composition of the n-AlGaN layer, which increases gradually from 0% to 15% and then reduces steadily to 0%. These three structures are shown in Fig. 1. The operating temperature is assumed to be 300 K and the internal absorption within the LED device is set to be 500 m^{-1}. The other parameters can be found in Ref. [30].

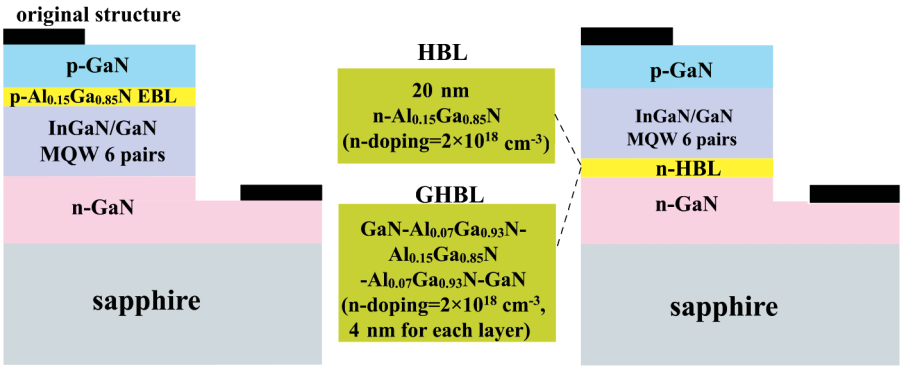


Fig. 1. (color online) The schematics of an original LED with a conventional AlGaN EBL (original structure), an LED with a common n-HBL (HBL), and an LED with an n-AlGaN HBL with gradual Al composition (GHBL).

3. Results and discussion

Figure 2 shows the plots of light output power and IQE versus current for the LEDs with the conventional EBL, HBL, and GHBL. It is evident that the light output power and IQE are significantly enhanced in the LED with an n-AlGaN HBL, compared to those in the LED with the conventional AlGaN EBL. It also shows that the light output power and efficiency droop of the LED with GHBL are improved in comparison to the LED with HBL. Among the structures in Fig. 2(b), the original structure has the smallest IQE and the worst efficiency droop of 23.45%, and the GHBL structure shows the highest IQE and a significantly mitigated efficiency droop of 10.75%.

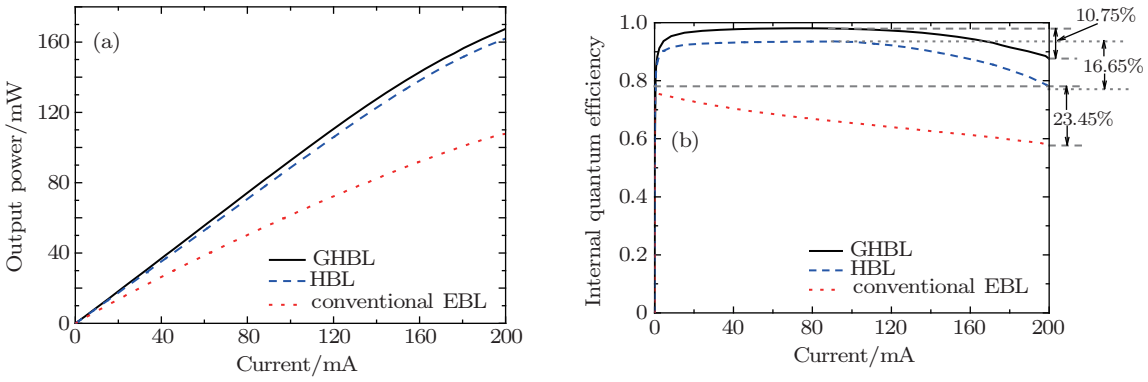


Fig. 2. (color online) Plots of (a) light output power, (b) internal quantum efficiency (IQE) versus current for the LEDs with the conventional EBL, HBL, and GHBL.

Figure 3 shows that the degrees of influence on the electrostatic field and radiative recombination in the active region of the different structures are different. In the figure, a dotted line is marked for better observation. As shown in Figs. 3(a)–3(c), the electrostatic fields in the active region of the LED with the GHBL are the smallest. A comparison between the original structure and HBL structure shows that the electrostatic fields in the active region of the HBL structure are much smaller than the original structure, except for the first QW near the n-GaN layer. The stronger electrostatic fields in the active region will lead to band bending, and poor overlap of the electron and hole wave functions, thereby reducing the radiative recombination rate. Therefore, the GHBL structure has an advantage over the other two structures in radiative recombination due to the smaller electrostatic field in the active region, which can be seen in Figs. 3(d)–3(f).

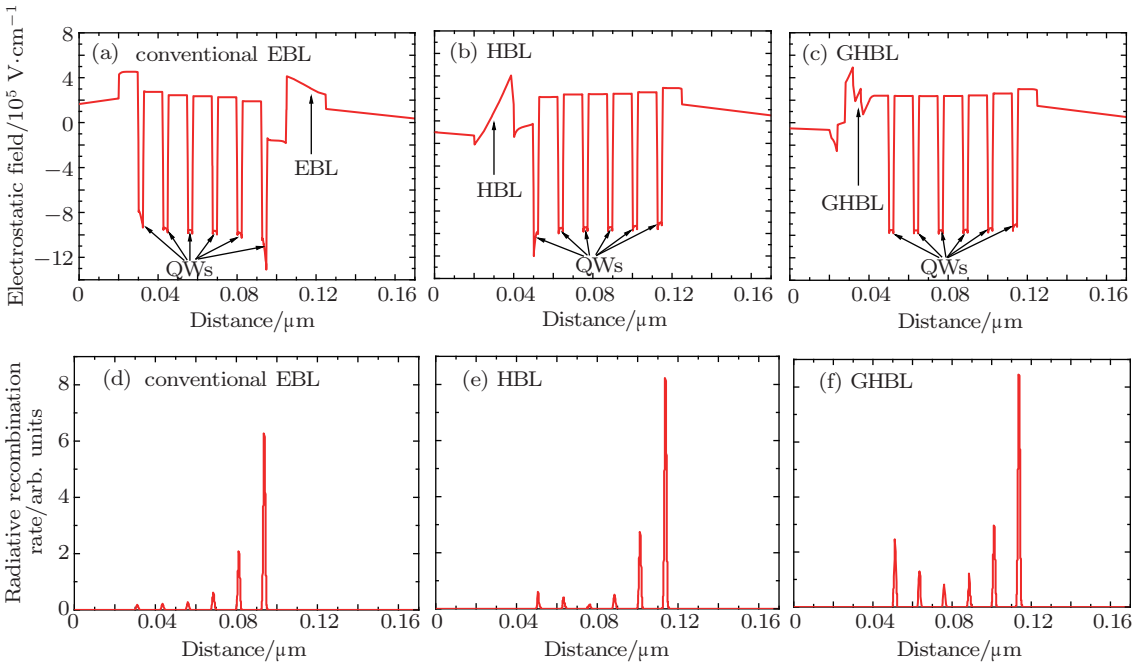


Fig. 3. (color online) (a)–(c) The distance-dependent electrostatic fields, and (d)–(f) the radiative recombination rates of the LEDs with conventional EBL, HBL, and GHBL at 200 mA.

Figure 4 shows the band diagrams and carrier concentrations of the LEDs with the conventional EBL, HBL, and GHBL. As shown in Fig. 4(a), the piezoelectric polarization field together with the spontaneous polarization field pulls down the energy band at the last barrier and AlGaN EBL interface due to the lattice mismatch. It can also be seen in Fig. 3(a) that the lattice mismatch between the last GaN QW barrier and AlGaN EBL can generate a strong strain, and then induce a strong piezoelectric polarization field. As a result, the effective potential barrier height for electrons in the conduction band of the EBL is reduced and the electron leakage cannot be effectively suppressed. Moreover, because of the band bending effect, the EBL also acts as a potential barrier for holes, which may hinder the holes from being injected into the active region. Figures 4(a)–4(c) show the energy band diagrams of the LEDs with the conventional AlGaN EBL, HBL, and GHBL at 200 mA. As shown in the figure, the effective potential heights for holes in the valance band near the last QW barrier and the AlGaN EBL (812 meV) are much greater than those of the LED with HBL (475 meV) and GHBL (474 meV), which implies that the holes are more difficult to inject into the active region than those in the LEDs with HBL and GHBL. According to the figure, the effective potential heights for the holes of the LED with GHBL (734 meV) in the valance band near GHBL and the first QW barrier are much greater than those of the LED with HBL at the same part (485 meV), which shows that it is more difficult for the holes to escape from the active region in the LED with GHBL. As a result, it can be seen in Figs. 4(d)–4(f) that the LED with HBL has the worst hole leakage. It can also be seen from Figs. 4(a)–4(c) that the effective potential heights for electrons in the conduction band near GHBL and the first QW barrier (592 meV) of the LED with GHBL are much greater than those of the LEDs with the conventional EBL (505 meV) and HBL (399 meV). It is apparent in Fig. 4(f) that the LED with GHBL has the lowest electron leakage. Compared with the LED with HBL, the LED with GHBL has small band bendings near the GHBL and the first QW barrier, leading to a large effective potential barrier height for electrons of 592 meV and for holes of 734 meV. In addition, the LED with HBL and the LED with GHBL each have a smaller effective potential barrier height for holes due to the structure without an EBL. As shown in

Fig. 4(f), the LED with GHBL has the largest hole concentration in the QW, the lowest electron leakage and a lower hole leakage, which can be explained as follows. (i) Due to the lack of EBL within the GHBL structure, a lower lattice mismatch between the GHBL and first GaN QW barrier occurs, which brings about a higher hole injection efficiency, thus enhancing the hole blocking effect and radiative recombination in the active region. The GHBL structure therefore has the largest hole concentration in the QW and a lower hole leakage. (ii) The lower lattice mismatch between the GHBL and first GaN QW barrier generates a lower strain, which induces a lower piezoelectric polarization field and then leads to an excellent electron blocking effect and radiative recombination in the active region, resulting in the fact that the GHBL structure has the lowest electron leakage, which can be seen in Fig. 3(c).

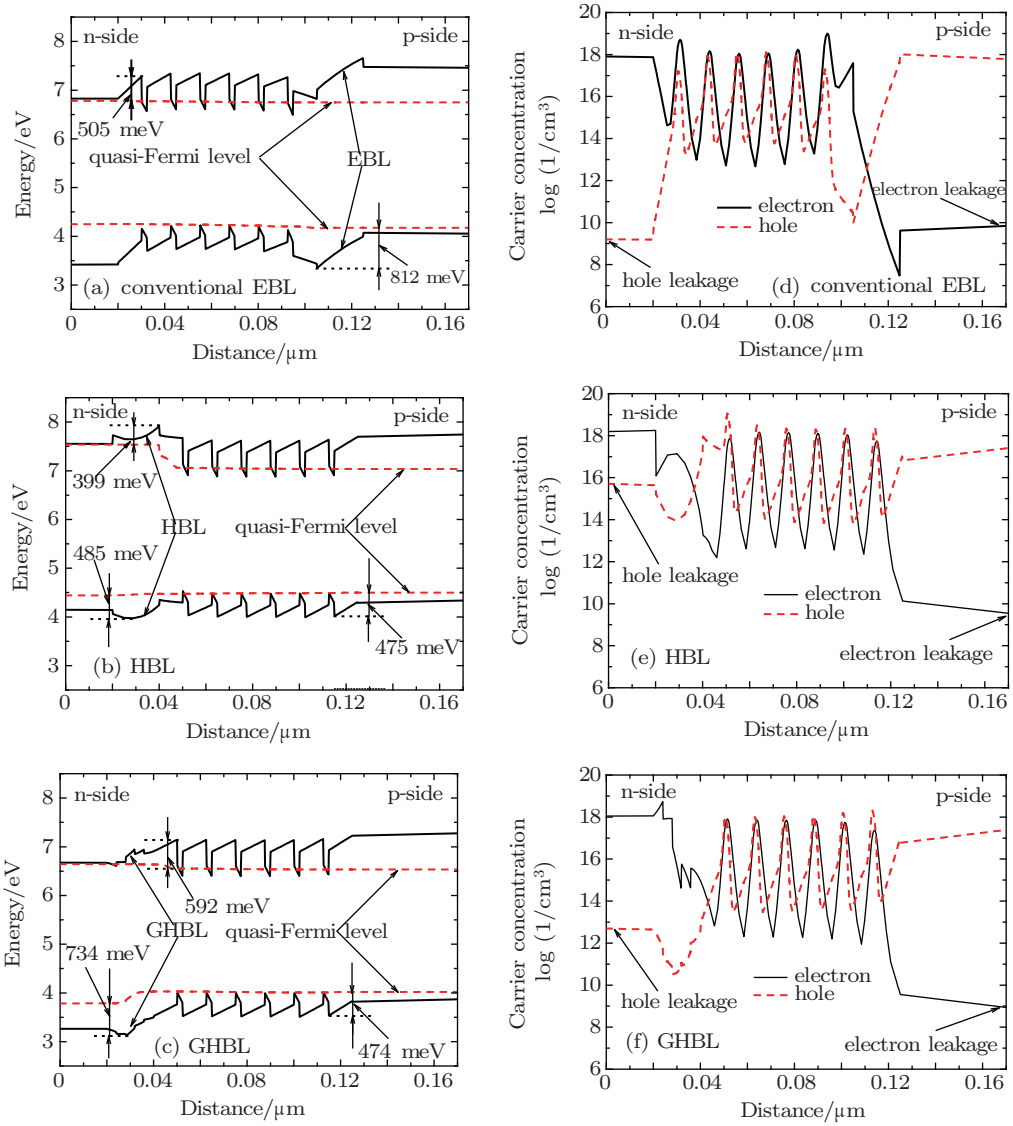


Fig. 4. (color online) (a)–(c) The distance-dependent energy band diagrams, and (d)–(f) the carrier concentrations of the LEDs with conventional EBL, HBL, and GHBL at 200 mA.

4. Conclusions

In this paper, blue InGaN LEDs with conventional EBL, HBL, and GHBL are investigated numerically. When the GHBL structure is used, the hole injection efficiency into the active region can be greatly increased, the electron leakage can be reduced, and the electrostatic fields in the active region can be considerably relieved. The InGaN LED with an n-AlGaN HBL with gradual Al composition can considerably improve the optical performance, such as a much larger recombination rate and higher IQE. Moreover, the efficiency droop of this structure is markedly alleviated.

References

[1] Muramoto Y, Kimura M, Dempo A, Nouda S, Fukawa Y and Sakai S 2011 *J. Soc. Inf. Disp.* **19** 907
[2] Pimputkar S, Speck J, DenBaars S P and Nakamura S 2009 *Nat. Photon.* **3** 180
[3] Horiuchi N 2010 *Nat. Photon.* **4** 738

[4] Chen Y X, Shen G D, Guo W L, Xu C and Li J J 2011 *Chin. Phys. B* **20** 017204
[5] Wang Z J, Li P L, Yang Z P, Guo Q L and Li X 2010 *Chin. Phys. B* **19** 017801
[6] Mukai T, Yamada M and Nakamura S 1999 *Jpn. J. Appl. Phys. Part* **38** 3976
[7] Sun W, Shatalov M, Deng J, Hu X, Yang J, Lunev A, Bilenko Y, Shur M and Gaska R 2010 *Appl. Phys. Lett.* **96** 061102
[8] Kim M H, Schubert M F, Dai Q, Kim J K, Schubert E F, Piprek J and Park Y 2007 *Appl. Phys. Lett.* **91** 183507
[9] Schubert M F, Chhajed S, Kim J K, Schubert E F, Koleske D D, Crawford M H, Lee S R, Fischer A J, Thaler G and Banas M A 2007 *Appl. Phys. Lett.* **91** 231114
[10] Rozhansky I V and Zakheim D A 2006 *Phys. Status Solidi C* **3** 2160
[11] Wang J X, Wang L, Zhao W, Hao Z B and Luo Y 2010 *Appl. Phys. Lett.* **97** 201112
[12] Wang J X, Wang L, Wang L, Hao Z B, Luo Y, Dempewolf A, Muller M, Bertram F and Christen J 2012 *J. Appl. Phys.* **112** 023107
[13] Delaney K T, Rinke P and Van de Walle C G 2009 *Appl. Phys. Lett.* **94** 191109
[14] Shen Y C, Mueller G O, Watanabe S, Gardner N F, Munkholm A and Krames M R 2007 *Appl. Phys. Lett.* **91** 141101
[15] Rozhansky I V and Zakheim D A 2006 *Semiconductors* **40** 839
[16] Ghazai A J, Thahab S M, Hassan H A and Hassan Z 2011 *Opt. Express* **19** 9245
[17] Kuo Y K, Chang J Y, Tsai M C and Yen S H 2009 *Appl. Phys. Lett.* **95** 011116
[18] Fu Y K, Jiang R H, Lu Y H, Chen B C, Xuan R, Fang Y H, Lin C F, Su Y K and Chen J F 2011 *Appl. Phys. Lett.* **98** 121115
[19] Zhao H, Liu G, Zhang J, Poplawsky J D, Dierolf V and Tansu N 2011 *Opt. Express* **19** A991
[20] Liao C T, Tsai M C, Liou B T, Yen S H and Kuo Y K 2010 *J. Appl. Phys.* **108** 063107
[21] Zhao H and Tansu N 2010 *J. Appl. Phys.* **107** 113110
[22] Zhang Y Y and Yin Y A 2011 *Appl. Phys. Lett.* **99** 221103
[23] Chen J, Fan G H and Zhang Y Y 2013 *Chin. Phys. B* **22** 018504
[24] Kuo Y K, Chang J Y and Tsai M C 2010 *Opt. Lett.* **35** 3285
[25] Chichibu S F, Abare A C, Minsky M S, Keller S, Fleisher S B, Bowers J E, Hu E, Mishra U K, Coldren L A, Denbaurs S P and Sota T 1998 *Appl. Phys. Lett.* **73** 2006
[26] Kuokstis E, Yang J W, Simin G, Khan M A, Gaska R and Shur M S 2002 *Appl. Phys. Lett.* **80** 977
[27] Choi S, Kim H J, Kim S S, Liu J, Kim J, Ryou J H, Dupuis R D, Fischer A M and Ponce F A 2010 *Appl. Phys. Lett.* **96** 221105
[28] Kuo Y K, Tsai M C, Yen S H, Hsu T C and Shen Y J 2010 *IEEE J. Quantum Electron.* **46** 1214
[29] Yen S H, Tsai M C, Shen Y J, Hsu T C and Kuo Y K 2009 *IEEE Photon. Technol. Lett.* **21** 975
[30] Wang C H, Ke C C, Lee C Y, Chang S P, Chang W T, Li J C, Li Z Y, Yang H C, Kuo H C, Lu T C and Wang S C 2010 *Appl. Phys. Lett.* **97** 261103