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Fabrication of High-performance 400 nm Violet Light Emitting Diode

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Abstract: High-performance 400 nm violet InGaN multi-quantum-wells light-emitting diodes (LED) with p-AlGaN electron blocking layer were fabricated on sapphire substrate by metal organic chemical vapor deposition technique. Different kinds of p-AlGaN electron blocking layers were grown in three violet LEDs: bulk p-AlGaN with Al mole fraction of 9%, bulk p-AlGaN with Al mole fraction of 11% and super lattice p-AlGaN/GaN with Al mole fraction of 20%. The output power of violet LED with bulk p-AlGaN(11%) is higher than the LED with bulk p-AlGaN(9%). Typically, the output power of the LED with 10 pairs of p-AlGaN/GaN super lattice electron blocking layer has been greatly improved. A LED with an output power of 21 mW at an injection current of 20 mA is achieved. In additional, the LED also shows an almost linear *I-L* characteristics at high injection current and uniform intensity mapping on LED chip surface.

Key words: metal organic chemical vapor deposition; violet light emitting diodes; GaN light emitting diodes; electron blocking layer; super lattice

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400 nm 高性能紫光LED的制作与表征

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摘要: 利用金属有机物化学气相沉积技术在蓝宝石衬底表面制备了带有 p-AlGaN 电子阻挡层的400 nm 高

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性能紫光 InGaN 多量子阱发光二极管。制作了 3 种紫光 LED,分别带有不同 p-AlGaN 电子阻挡层结构:Al 摩尔分数为 9% 的 p-AlGaN 电子阻挡层;Al 摩尔分数为 11% 的 p-AlGaN 电子阻挡层;Al 摩尔分数为 20% 的 10 对 p-AlGaN/GaN 超晶格电子阻挡层。带有高浓度 Al 电子阻挡层的紫光 LED 的光输出功率高于低浓度 Al 电子阻挡层的紫光 LED。带有 10 对 p-AlGaN/GaN 超晶格电子阻挡层的紫光 LED 的光输出功率获得了极大的提高,在 20 mA 注入电流时测试得到的光输出功率为 21 mW。此外,该 LED 同时显示了在高注入电流下接近线性的 *I-L* 特性曲线和在 LED 芯片表面均匀的发光强度分布。

关 键 词:金属有机物化学气相沉积;紫光发光二极管;GaN 发光二极管;电子阻挡层;超晶格

1 Introduction

Recent years, GaN-based materials have attracted great interest in optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs)[1]. Major developments in the GaN-related fields have led to the commercialization of high-brightness light emitting diodes (LEDs) with the wavelength from ultraviolet to amber spectra regions, and also, to the realization of violet LD with a life time of more than 10 000 h[2-6]. With the increased commercialization of LED, much interest has been focused on the quantum efficiency(QE) and electric properties, all these are related to the crystal quality and LED structure.

In this paper, a systematic study of the structural and optical properties of 400 nm LED with high quality electron blocking layers grown at different conditions was carried out by MOCVD technique. It was found that light-output efficiency at high injection current was seriously influenced by high efficiency p-AlGaN electron blocking layers (EBL). Using 10 pairs of p-AlGaN/GaN super lattice electron blocking layer, the LED shows an output power of 21 mW with peak wavelength of 402 nm under the current of 20 mA.

2 Experiments

2.1 Preparing 400 nm GaN Violet LED on c-plane Sapphire Substrates

The samples were grown on *c*-plane sapphire substrates by Veeco K465i turbo disk MOCVD system. Trimethyl-gallium (TMGa), trimethyl-indium (TMIn), trimethyl-aluminum (TMAl), and ammonia were used as the Ga, In, Al, and N precursors, respectively. Silane and biscyclopentadienyl-magnesium (Cp2Mg) were used as n-type and p-type dopants, respectively. Hydrogen and nitrogen were used as the carrier gas.

Fig. 1 shows a schematic sample structure. The substrates were firstly treated in hydrogen ambient at 1 150 ℃, followed by the growth of about 30 nm thick GaN buffer layer at 530 ℃. Then, the temperature was increased to 1 070 ℃ to grow 2 μm undoped GaN and 1.5 μm Si doped n-GaN. 11 pairs of InGaN multi-quantum wells (MQWs) were grown as active layer and the growth temperature of quantum well was 770 ℃. Finally, active layer was capped 300 nm Mg-doped p-GaN layer at a temperature of 940 ℃. Between the active layer and p-GaN layer, an AlGaN EBL layer was grown in three conditions: (1) with low Al mole fraction (about 9%); (2) with high Al mole fraction (about 11%); (3) with 10 pairs of p-AlGaN/GaN super lattice electron blocking layer (SLEBL, the thickness of p-AlGaN and GaN in the superlattice both are 2.5 nm, the mole fraction of Al is about 20%). The layers were grown at the same temperature of 960 ℃ and same carrier gas atmosphere for the three AlGaN EBL. For simplicity, these samples were denoted as sample A, B, and C, respectively.

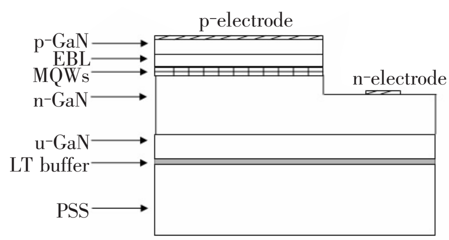

Fig. 1 Schematic drawing of violet LED structure grown on pattern sapphire substrate

2.2 Characterization

The crystalline quality of the GaN films was examined by double crystal X-ray diffraction (DCXRD) rocking curves using Jordan Valley XRD equipment. In each case, the device was in the bare chip geometrical form with a size of 300 μm × 300 μm. Electroluminescence (EL) spectrum of the LEDs was collected by an optical fiber placed near the top of the planar device with emissions by current injection. Similarly, the optical output power was measured by a silicon detector placed in immediate proximity to the top of the LED. Also, the LEDs are encapsulated in ϕ5 lamp package. The nominal inject current is 20 mA, with an electrical input power of 64 mW.

3 Results and Discussion

3.1 DCXRD

Fig. 2 shows the X-ray patterns of the sample A, B and C. The full width at half-maximum (FWHM) of ω scan rocking curve (not shown here) of the three sample in the (0002) and (102) reflections are 280 and 316 arcsec for sample A, 265 and 280 arcsec for sample B, 255 and 275 arcsec for sample C, respectively, indicating a high crystal quality. Furthermore, Fig. 2 shows the ω-2θ scan of sample A, B and C in the (0002) reflection of GaN. The main peak corresponds to GaN diffraction, and the satellite peaks indicate the InGaN and AlGaN diffraction. Four stronger and clear satellite peaks from InGaN layers address a high-quality MQW structure. All these data would prove the quality of violet LED layers in this work.

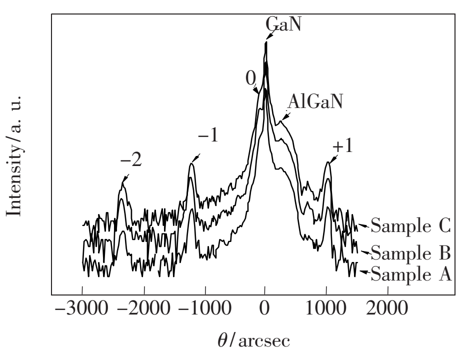

Fig. 2　The ω-2θ scan of sample A, B and C in the (0002) reflection.

3.2 EL Spectra of Violet LED

Fig. 3 shows the EL spectra of violet LED, the peak wavelength is 402 nm and FWHM is 13.4 nm. Fig. 4 shows the peak wavelength *vs.* intensity characteristics of violet LEDs lamp of sample A, B and C with injection current of 20 mA. The intensity of sample B is a little bit higher than sample A, while the intensity of sample C is much higher than the other two samples at the same peak wavelength. The output power of sample C is 21 mW at peak wavelength of 402 nm, with the electrical input power of 64 mW.

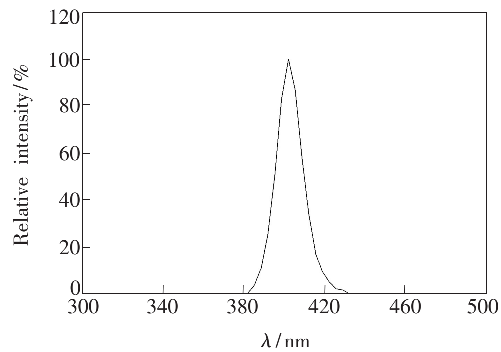

Fig. 3　EL spectra of 402 nm LED, peak wavelength is 402 nm, FWHM is 13.4 nm.

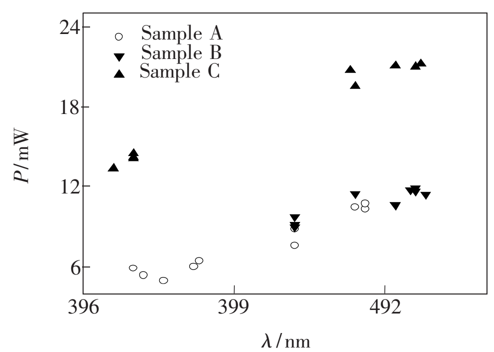

Fig. 4　The peak wavelength *vs.* intensity characteristics of violet LEDs lamp of sample A, B and C.

Fig. 5 shows the *I-L* characteristics of violet LEDs on wafer of sample C, which have the 10 pairs of p-AlGaN/GaN super lattice electron blocking layer. The output power addresses an almost linear *I-L* characteristics while the injection current was increased from 0 to 270 mA.

As mentioned above, the EL power of sample B is a little higher than sample A, while the intensity of sample C is much higher than the other two samples at the same peak wavelength. The possibilities

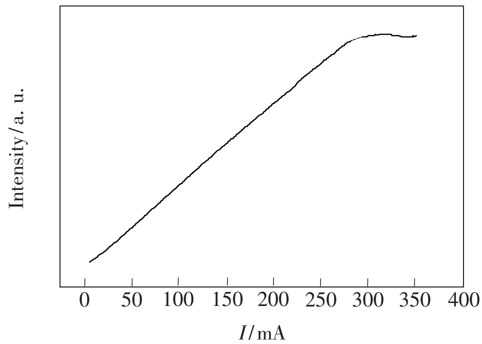

Fig. 5 The *I-L* characteristics of violet LEDs on wafer of sample C

are that the self-heating by the current crowding and the nonradiative recombination[7]. When the LED wavelength becomes shorter than 450 nm, compared with that grown on the lateral over growth GaN layer, external quantum efficiency (EQE) of LED grown on sapphire substrate would be decreased since alloy composition fluctuations in the InGaN well layer becomes smaller and that the carriers would be more easily overflow to the nonradiative center[8]. This means more and more electrons and holes recombine with nonradiation and lead to the increase of temperature at the nonradiative center area, resulting in the self-heating in the local area. Additionally, since the carrier localizations in the InGaN QW layers due to the band-gap-potential inhomogeneity of InGaN materials[9], and the current crowding effect in the InGaN lateral current transport LED system[10-11], the carrier localizations would be much more significant.

In order to decrease the self-heating in LED, *i. e.* the current crowding, there are several way, such as improving the metal contact layer, introducing Si or indium in the InGaN MQW layers[9,12], improving current spreading state, and *etc.* This work will concentrate on the investigation of current spreading state improvement.

In sample A, the Al mole fraction (9%) of the electron blocking layer (EBL) is a lower than the sample B (Al mole fraction is 11%). The band gap of EBL is not high enough for blocking the electron, the electron may overflow to the nonradiative center[8] in p-GaN layer, which means that more electrons and holes recombine at the non-radiative center area of p-GaN layer, resulting in the self-heating in the local area. While the EBL band-gap of sample B is higher than that of sample A, more electrons were limited in the active layer region, leading to the radiative recombination. So the intensity of sample B is higher than sample A at the same peak wavelength.

In sample C, the intensity is the highest among three samples at same peak wavelength. The electron blocking layer (EBL) is formed by high Al mole fraction (20%) 10 pairs of Mg-doped AlGaN/GaN super lattice structure. The band gap of the 10 pairs of AlGaN/GaN super lattice layers is suitable for the electron blocking from the MQW to the p-GaN layer since the Al mole fraction (20%) is high enough. Meanwhile the holes move from the p-side to the p-AlGaN/GaN super lattice layers, well spread at the super lattice layers, decrease the current crowding. So the intensity of sample C is the highest at the same peak wavelength due to the electron blocking effect and holes spreading effect.

Meanwhile the output power of sample C addresses an almost linear *I-L* characteristics while the injection current was increased from 0 to 270 mA. The violet LED works at so high current density may due to the current spreading, when the holes move at the p-AlGaN/GaN. There are less self-heating in the LED and more radiactive recombination.

Fig. 6 shows the EL intensity mapping on violet LEDs chip of sample B and C. For sample B in Fig. 6, the uniformity of normalized intensity mapping is not good. More light comes out from the region near the p-electrode, while less light comes out from the region far from the p-electrode. The holes go through

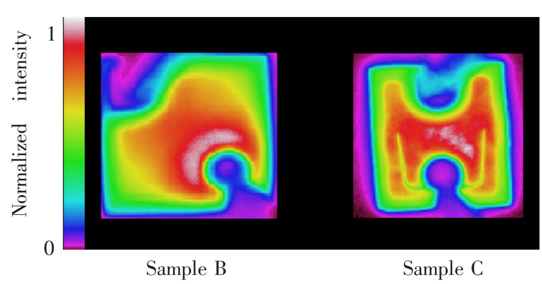

Fig. 6 Normalized intensity mapping of violet LED on chips (300 μm × 300 μm) at the injection of 20 mA

the p-AlGaN layer to the active layer, not well spread at the p-AlGaN. The recombination of electron and holes was limited at active layer region near the p-electrode. So, the intensity uniformity of sample B chip surface is not good.

For sample C in Fig. 6, the uniformity of normalized intensity mapping on chip surface is better than sample B, light comes out from the surface of the whole LED uniformly. It is much easier for the holes transfer through the p-AlGaN layer than the un-doped GaN in the 10 pairs of p-AlGaN/GaN super lattice layers, so the holes will transfer to horizontal direction at the un-doped GaN region, leading the holes will spread at horizontal direction at the whole super lattice region. Then the electrons and holes recombine at the whole active region. There are less non-radiactive recombination region and less self-heating. So the intensity uniformity of sample C chip surface is good, and the intensity of sample C is much higher than sample B.

4 Conclusion

In this paper, a high-performance violet LED with an emission wavelength of 400 nm has been successfully fabricated. Our data indicate that the LED with low Al mole fraction of AlGaN electron blocking layers shows lower output power due to the electron over flow to p-doped GaN layer and self-heating phenomena. By inserting high Al mole fraction p-AlGaN electron blocking layers between the active layer and p-GaN layer, the output power would be improved. In additional, the LED with 10 pairs of p-AlGaN/GaN super lattice electron blocking layer shows higher performance than the LED with bulk AlGaN electron blocking layers. Consequently, an LED with higher performance at high injection current has been developed, which presents an output power of 21 mW with an electrical input power of 64 mW, at the peak wavelength of 402 nm.

References:

[1] Nakamura S. The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes [J]. *Science*, 1998, 281(5379):956-961.

[2] Nakamura S, Senoh M, Iwasa N, *et al.* Superbright Green InGaN single-quantum-well-structure light-emitting diodes [J]. *J. Appl. Phys.*, 1995, 34(10B):1332-1335.

[3] Mukai T, Morita D, Nakamura S. High-power UV InGaN/AlGaN double-heterostructure LEDs [J]. *J. Crystal Growth*, 1998, 189/190(1/2):778-781.

[4] Mukai T, Yamada M, Nakamura S. Current and temperature dependences of electroluminescence of InGaN-based UV/blue/green light-emitting diodes [J]. *Jpn. J. Appl. Phys.*, 1998, 37(11B):1358-1361.

[5] Nakamura S, Senoh M, Nagahama S, *et al.* InGaN/GaN/AlGaN-based laser diodes with modulation-doped strained-layer superlattices [J]. *Jpn. J. Appl. Phys.*, 1997, 36(2):1568-1571.

[6] Wang H X, Li H D, Lee Y B, *et al.* Fabrication of high-performance 370 nm ultraviolet light-emitting diodes [J]. *J. Crystal Growth*, 2004, 264(1/2/3):48-52.

[7] Wierer J J, Fischer A J, Koleske D D. The impact of piezoelectric polarization and nonradiative recombination on the performance of (0001) face GaN/InGaN photovoltaic devices [J]. *Appl. Phys. Lett.*, 2010, 96(5):051107-1-3

[8] Mukai T, Nakamura S. Ultraviolet InGaN and GaN single-quantum-well-structure light-emitting diodes grown on epitaxially laterally overgrown GaN substrates [J]. *Jpn. J. Appl. Lett.*, 1999, 38(10):5735-5739.

[9] Uchida K, Tang T, Goto S, *et al.* Spiral growth of InGaN/InGaN quantum wells due to Si doping in the barrier layers [J]. *Appl. Phys. Lett.*, 1999, 74(8):1153-1155.

[10] Guo X, Schubert E F. Current crowding and optical saturation effects in GaInN/GaN light-emitting diodes grown on insulating substrates [J]. *Appl. Phys. Lett.*, 2001, 78(21):3337-3339.

[11] Kim H, Park S J, Hwang H, *et al.* Lateral current transport path, a model for GaN-based light-emitting diodes: Applications to practical device designs [J]. *Appl. Phys. Lett.*, 2002, 81(7):1326-1328.

[12] Cho Y H, Song J J, Keller S, *et al.* Influence of Si doping on characteristics of InGaN/GaN multiple quantum wells [J]. *Appl. Phys. Lett.*, 1998, 73(8):1128-1130.