Growth and properties of wide spectral white light emitting diodes*

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Wide spectral white light emitting diodes have been designed and grown on a sapphire substrate by using a metal-organic chemical vapor deposition system. Three quantum wells with blue-light-emitting, green-light-emitting and red-light-emitting structures were grown according to the design. The surface morphology of the film was observed by using atomic force microscopy. The films were characterized by their photoluminescence measurements. X-ray diffraction $\theta/2\theta$ scan spectroscopy was carried out on the multi-quantum wells. The secondary fringes of the symmetric $\omega/2\theta$ X-ray diffraction scan peaks indicate that the thicknesses and the alloy compositions of the individual quantum wells are repeatable throughout the active region. The room temperature photoluminescence spectra of the structures indicate that the white light emission of the multi-quantum wells is obtained. The light spectrum covers 400–700 nm, which is almost the whole visible light spectrum.

Keywords: metal-organic chemical vapor deposition, GaN/InGaN multi-quantum wells, group III–V semiconductor, wide spectral white light

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1. Introduction

Great progress has been made on the investigation of group-III nitride alloys since Nakamura *et al.* successfully manufactured the first GaN-based blue light emitting diode (LED). At present, high luminescence efficiency short-wavelength LEDs and laser devices have been successfully manufactured.[1,2] InGaN-based multiple quantum wells (MQWs) are the key structure in those devices. The deep research on the electrical and the optical properties of the InGaN-based multiple quantum wells are beneficial to improving the performance of the devices.[3–5] In the InGaN-based multiple quantum wells, the localization of carriers, which has been investigated extensively, is considered to be a radiation recombination process within a micro region rather than the capture by defects. It has been proved that the high radiation recombination efficiency of short wavelength light emitting devices is related to the localization of carriers.

The method for realizing multi-energy level white light emitting in the III–V semiconductor structures has been rarely reported. The phosphor-free monolithic InGaN-based white-light LED has the advantages of simpler device process and potentially higher efficiency. The earliest report about the method was published by the Nichina Corporation in 2002. Since then, no further report has been published by the Nichina Corporation. The Epitech Technology Corporation reported results about hybrid arranging the quantum wells with different contents in 2006.[6] Another similar research result was also published in June 2006. The luminescence spectra reported in the above literatures all spliced the separate luminescence peaks together due to the narrow band emitting properties. Because the real device can not increase unlimitedly the number of the quantum wells in the active

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region, it is difficult to obtain the high quality multi-energy level white light emitting.

In this paper, we report the research on the growth and the properties of the GaN/InGaN MQW structures wide spectral white light emitting diodes based on GaN materials. The white light without phosphors LEDs are fabricated. The light spectrum covers 400–700 nm wavelength, which is almost the whole visible light spectrum.

2. Experiment

The wide spectral white light emitting diode MQW structure film were grown on a 2-inch diameter (0001) oriented (C-face) sapphire substrate by using the metal-organic chemical vapour deposition (MOCVD) method.[7] Ammonia was used as the group V precursor. Electronic-grade trimethylgallium (TMGa) and trimethylindium (TMIn) were used as the group III precursors. N_2 was used as the carrier gas. The reactor pressure was maintained at 700 Torr. The flow rate of NH_3 was 700 sccm. The ratio of V/III (mole ratio of N and Ga) was 50000.

The wide spectral white light emitting diode structure consisted of a 30-nm-thick GaN low temperature (550°C) buffer layer, a 2-μm-thick high temperature (1050°C) undoped GaN layer and a 500-nm-thick n-type GaN layer with 5×10^{18} cm^{-1} Si doping. Then the blue, green and the red light MQW active layers were grown. The blue light MQW active layer consisted of 2 periods of 3-nm-thick GaN well layers and a 5-nm-thick $In_{0.15}Ga_{0.85}N$ layer. The green light MQW active layer consisted of 2 periods of 3-nm-thick GaN well layers and a 5-nm-thick $In_{0.25}Ga_{0.75}N$ layer. The red light MQW active layer consisted of 2 periods of 3-nm-thick GaN well layers and a 5-nm-thick $In_{0.35}Ga_{0.65}N$ layer. Lastly, a GaN cap with 5×10^{17} cm^{-3} Mg doping was grown on the top of the MQW.

The surface morphology of the MQWs was checked by using a Digital Instruments Nanoscope IIIa atomic force microscope (AFM) at the contact mode in air. The X-ray diffraction (XRD) measurements were performed using a triple-axis diffractometer equipped with a four-crystal Ge(220) monochromator and a three reflection Ge(220) analyzer. The films were characterized by photoluminescence (PL) measurement.

3. Results and discussion

Figure 1 shows the three-dimensional AFM micrograph of the wide spectral white light MQW structures based on the InGaN/GaN quantum wells. We can see that there are a lot of island protuberances, among which the highest is 30.564 nm. The average roughness is 5.68 nm, which shows that the quality of the material is good.

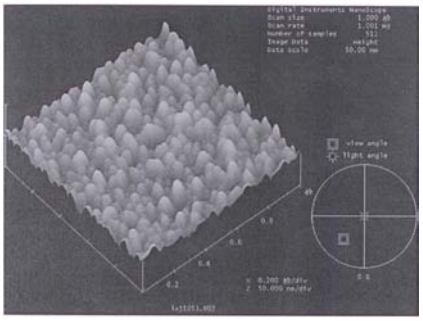


Fig. 1. The AFM micrograph of the wide spectral white light MQW structures.

Figure 2 shows the (0002) $\omega/2\theta$ XRD scan and the fitting figure of the wide spectral white light InGaN/GaN MQW structures obtained from the double crystal high resolution XRD. We can see that the position of the peak for the (002) plane lies in 17.25°. Its right satellite peak arrives at minus four levels, which shows the good quality of the interface of the InGaN/GaN sample. The three different secondary fringes indicate that three different quantum wells are obtained, and the thicknesses and the alloy compositions of the individual quantum wells are repeatable throughout the active region. The fitting results show that the well thickness is 4.855 nm and the average In composition is 17.695%.[4−7]

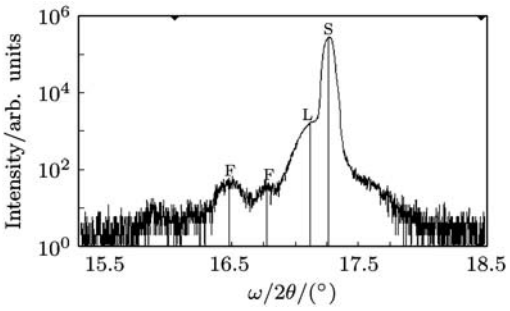


Fig. 2. The (0002) $\omega/2\theta$ XRD scan and the fitting figure of the wide spectral white light InGaN/GaN MQW structures.

Figure 3 shows the room temperature PL spectra of the wide spectral white light LED structure. The insert shows a photograph of the PL. We can see

clearly that the light spectrum covers 400–700 nm, which almost covers the whole visible light spectrum. These indicate that the white light LEDs are obtained. The current versus voltage characteristics of the LEDs obtained by using a Hewlett Packard 4156C semiconductor parameter analyzer at room temperature are shown in Fig. 4. The insert shows a photograph of the electroluminescence (EL) of the white light LED. The turn on voltage is about 2.9 V at 300 K. and the drive current is about 1.6 mA.

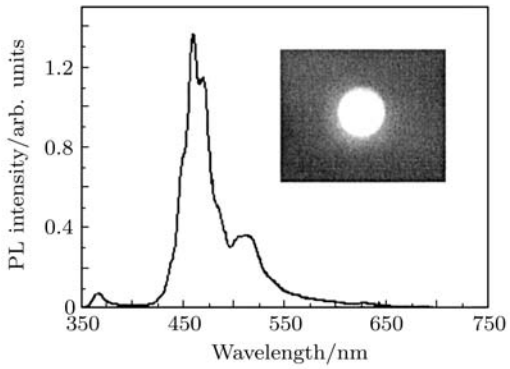


Fig. 3. The PL spectra of the wide spectral white light LED structures. The insert shows a photograph of the PL.

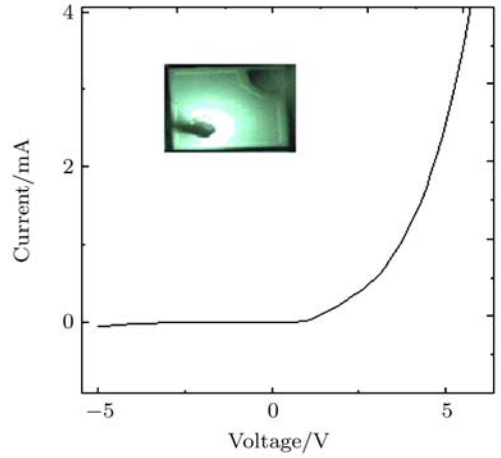


Fig. 4. (colour online) The current versus voltage characteristics of the white light LED. The insert shows a photograph of the EL.

4. Conclusion

Wide spectral white light emitting diodes have been designed and grown on a sapphire substrate by using a metal-organic chemical vapor deposition system. Three quantum wells with blue-light-emitting, green-light-emitting and red-light-emitting structures were grown according to the design. The surface morphology of the film was observed using the AFM. The X-ray diffraction $\theta/2\theta$ scan spectroscopy was carried out on the MQWs. The secondary fringes of the symmetric $\omega/2\theta$ XRD scan peaks indicate that the thicknesses and the alloy compositions of the individual quantum wells are repeatable throughout the active region. The room temperature PL spectra of the structures indicate that the white light emission of the MQWs is obtained. The white light without phosphors LED was fabricated. The light spectrum covers 400–700 nm wavelength, which is almost the whole visible light spectrum. The turn on voltage is about 2.9 V at 300 K. and the drive current is about 1.6 mA.

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