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悬空车轮形氮化镓发光二极管

朱刚毅，仇国庆，秦飞飞，刘威，袁佳磊，施政，王永进，徐春祥

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Floating GaN Micro Wheel Light Emitting Diodes

ZHU Gang-yi[1*], QIU Guo-qing[1], QIN Fei-fei[1], LIU Wei[2], YUAN Jia-lei[1], SHI Zheng[1], WANG Yong-jin[1], XU Chun-xiang[2]

(1. *College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing* 210003, *China*;
2. *State Key Laboratory of Bioelectronics, Southeast University, Nanjing* 210096, *China*)
* *Corresponding Author, E-mail: zhugangyi@njupt.edu.cn*

Abstract: Optical loss reducing and brightness improvement are always attractive issues for light emitting diodes. In this paper, GaN based micro wheel light emitting devices (LED) are fabricated on silicon substrate by standard semiconductor technology. Isotropic wet etching process is applied to suspend the device thus optimize the device performance. Electroluminescence (EL) characteristics including the spectral intensity, full width at half maximum (FWHM), turn-on voltage and current induced wavelength shift, communication characteristics such as 3 dB bandwidth of two GaN micro wheels are studied and compared. Due to the reducing of optical loss, cavity effect is more obvious in the floating structure, and the improved EL and communication performance are obtained. The research in this paper is of great significance for the preparation of the electrically pumped light source and the visible light communication.

Key words: light emitting diodes; GaN; micro wheel structures; 3 dB bandwidth
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悬空车轮形氮化镓发光二极管

朱刚毅[1*], 仇国庆[1], 秦飞飞[1], 刘 威[2], 袁佳磊[1],
施 政[1], 王永进[1], 徐春祥[2]

(1. 南京邮电大学 通信与信息工程学院, 江苏 南京 210003; 2. 东南大学 生物电子学国家重点实验室, 江苏 南京 210096)

摘要: 减少器件的界面损耗从而提升其发光性能一直是发光二极管领域一个重要的研究热点。本文采用标准半导体工艺在硅衬底上制备了 GaN 基车轮形发光器件。采用各向同性湿法蚀刻工艺将器件悬空,比较并研究了悬空对器件的性能,包括光强、半高宽、波长漂移、3 dB 带宽等的影响。由于减小了光损耗,在悬空结构中腔效应更加明显,器件的电致发光和通信性能得到了提升。本研究对电驱动光源的制备和可见光通信具有重要意义。

关 键 词: 发光二极管; 氮化镓; 车轮形微腔; 3 dB 带宽

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1　Introduction

GaN-based material system is an ideal material for light emitting devices (LEDs), the band gap of GaN and its alloys covers the range from red to ultraviolet wavelength. GaN has a large band gap and high thermal conductivity, which makes its working temperature high, breakdown voltage high and radiation resistance strong. In addition, GaN-based LED has the characteristics of energy saving, environmental protection, long service life, low power consumption and the like, and is widely applied to various display[1-5], illumination, decoration, communication, imaging and other fields[6-9]. However, the micro-nano structure LED in existence has low luminous efficiency and narrow communication bandwidth, which are all the difficulties faced by LED at present[10-15]. Therefore, improving the luminous efficiency, reducing the FWHM and increasing the communication bandwidth have become urgent problems for micro-nano structure LED to solve. In this paper, a wheel-shaped floating GaN micro cavity LED is proposed. Compared with the ordinary circular micro cavity[16-17], the wheel-shaped micro cavity can eliminate high-order modes and achieve better single mode output[18-21]. The floating micro wheel can reduce the refraction of photons, confine photons in the micro cavity and improve the optical constraint in the vertical direction of the micro cavity. The floating GaN micro wheel LEDs are fabricated by photolithography, inductively coupled plasma (ICP) dry etching GaN and HNF (HF and HNO_3) wet etching silicon. Correspondingly, ordinary micro wheel LEDs are fabricated and the changes of optical, electrical and communication characteristics are compared after the micro wheel LEDs are suspended. Under the same condition, the optical characteristics of two kinds of micro wheel LEDs are studied from the aspects of electroluminescence intensity, FWHM, turn-on voltage and blue shift wavelength. The communication performances of the two type of micro wheel LEDs are measured, and the 3 dB bandwidth at different voltages is obtained.

2　Experiments

Fig. 1 illustrates the fabrication process of the suspended GaN micro wheel LED. The micro wheel structures are made from strained GaN layers grown by metal organic vapor phase epitaxy (MOVPE) on silicon substrate. From down to the top of the GaN, apart from Si substrate, the GaN epitaxial structures consist of a 1.2 μm unintentionally doped GaN layer (u-GaN), a 2.8 μm n-GaN layer, a multi-layer 80 nm GaN/InGaN QW and a 0.6 μm p-GaN. The GaN

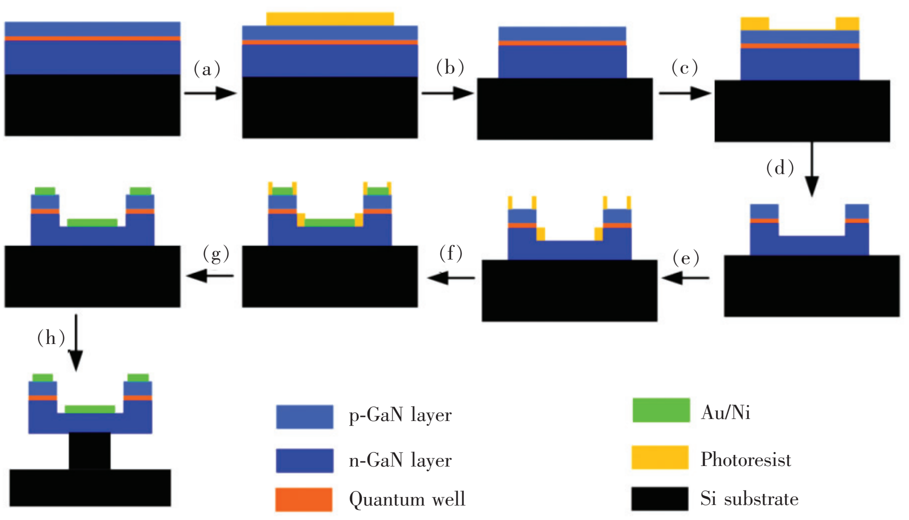

Fig. 1　Flow chart of the fabrication process for floating GaN micro wheel LEDs. (a) Patterning the photoresist layer by photolithography. (b) Etching the GaN layer to the silicon layer by ICP. (c) Patterning the photoresist layer by photolithography again. (d) Etching to the n-GaN layer by ICP. (e) Patterning the photoresist layer by photolithography again. (f) Plating electrode by electron beam evaporation. (g) Removing residual photoresist with acetone solution. (h) Wet isotropic etching of silicon by using HNF solution.

layer is patterned by photolithography, forming micro wheel shapes one by one. Using photoresist as a mask, the wafer can be etched to the silicon layer by ICP. The residual photoresist is then removed with acetone solution. In the same way, ICP is used to etch the wafer into the n-GaN layer from the inside. Then metal gold electrodes are plated on n-GaN and p-GaN layers by electron beam evaporation. Finally, the micro wheel LED is etched with HNF solution isotropic wet etching method to suspend the micro wheel device from the silicon substrate. The final effect is that the silicon substrate under the micro wheel is etched into cone columns to support the micro wheel. The suspended structure will reduce optical loss of the device in the vertical direction and make the emitted light intensity larger. An electron scanning microscope(SEM) is used to capture images of floating GaN micro wheel cavity.

3 Results and Discussion

SEM(FESEM, SU8010) image of the floating GaN micro wheel device is presented in Fig. 2. As can be seen, the device shows well wheel-like structures with standard array in Fig. 2(a). The top view of the non-floating micro-wheel LED is the same as that of the floating micro wheel LED. Individual device presented in Fig. 2(b)-(c) indicates the radius of the floating micro wheel is 75 μm. Yellow region of Fig. 2(b) is the electrode which consists of the circular one connect with n-GaN and the annular one connect with p-GaN. Fig. 2(d) shows the side view of a single floating micro wheel LED. From the top view, it can be seen that the structure produced has a well wheel shape, which helps to produce a low optical loss and high optical conferment cavity structure thus to support high performance light emission. From the side views, it can be clearly seen that the micro wheel LED is in a suspended state. The micro wheel LED in the suspended state can well confine the excited light in the micro cavity. The smooth side walls and surfaces of the micro wheel help to get optical output with lower threshold.

I-V and *C-V* properties of devices are measured using semiconductor device(Agilent Technologies B1500A) and the EL spectra are collected with high-resolution spectrometer(Ocean Optics HR4000) under free space. Fig. 3(a) shows EL spectra from a micro wheel LED excited at different current levels. It can be seen that under low current power, the device exhibits a weak emission band with central wavelength near 445 nm. With the increase of current, the spectral intensity of the micro wheel LED is also gradually increased. Fig. 3(b) shows EL spectra from a floating micro wheel LED excited at different current levels. Comparing with the spectra in Fig. 3(a), the EL spectra of floating devices are sharper and with higher intensity. This will be more obviously in Fig. 4(a), as it presents that, the spectral intensity of both micro wheels increase as a function of the current. And under the same current, the spectral intensity of the floating micro wheel LED is enhanced. The insets in the upper right corner of Fig. 3(a) and Fig. 3(b) display the optical images of the two kinds of micro wheel LEDs under current of 0.3 mA. They show a good wheel shape, and the floating one is brighter. The results indicate that the floating micro wheel devices have better optical properties. The great brightness improvement is caused by the reducing of optical loss. To confirm this, PL of different structure is compared. The inset in the middle of Fig. 3(a) shows the normalized

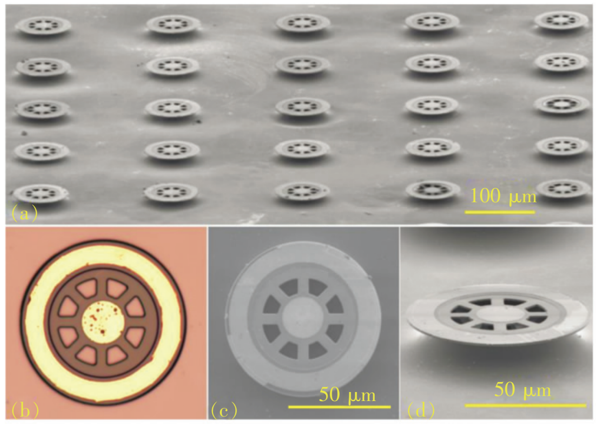

Fig. 2 SEM and optical image(OM) of the floating micro wheels. (a) The side view of the floating micro wheel array. (b) The top view OM of the floating micro wheel. (c) The top view SEM of the floating micro wheel. (d) The side view SEM of a single floating micro wheel.

photoluminescence spectra of the two kinds of micro wheel LEDs. The spectral linewidth of the floating micro wheel is significantly narrower than that of the micro wheel LED. This is because the floating micro wheel LED reduces the optical loss in the vertical direction, confines the light in the micro cavity, which will be benefit the EL properties of floating devices. More interestingly, the increase of current will not only increase the EL intensity, but also cause the shift of wavelength. We observed the blue shift of the

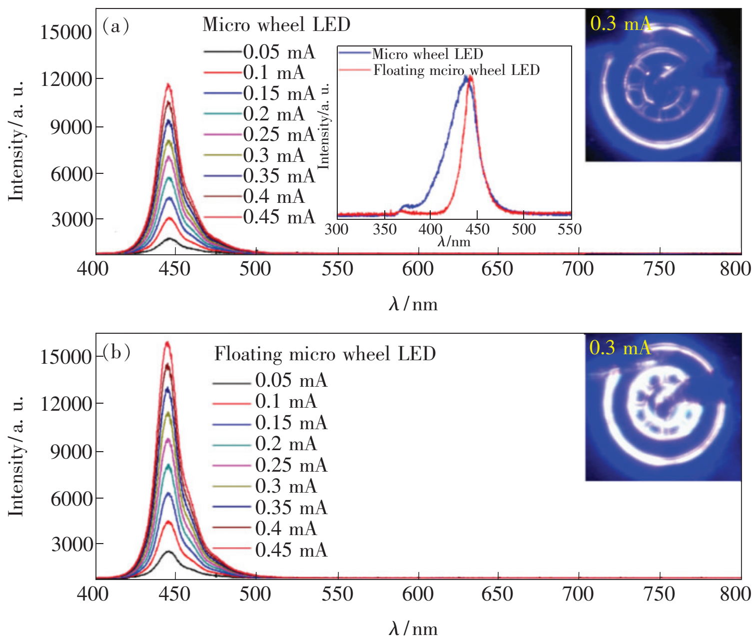

Fig. 3　EL spectra of the two kinds of micro wheels measured at different current. (a) Micro wheel. (b) Floating micro wheel. The inset in the middle of (a) shows the normalized photoluminescence spectra of the two kinds of micro wheel. The inset images in the upper right corner display the optical image with 0.3 mA current separately.

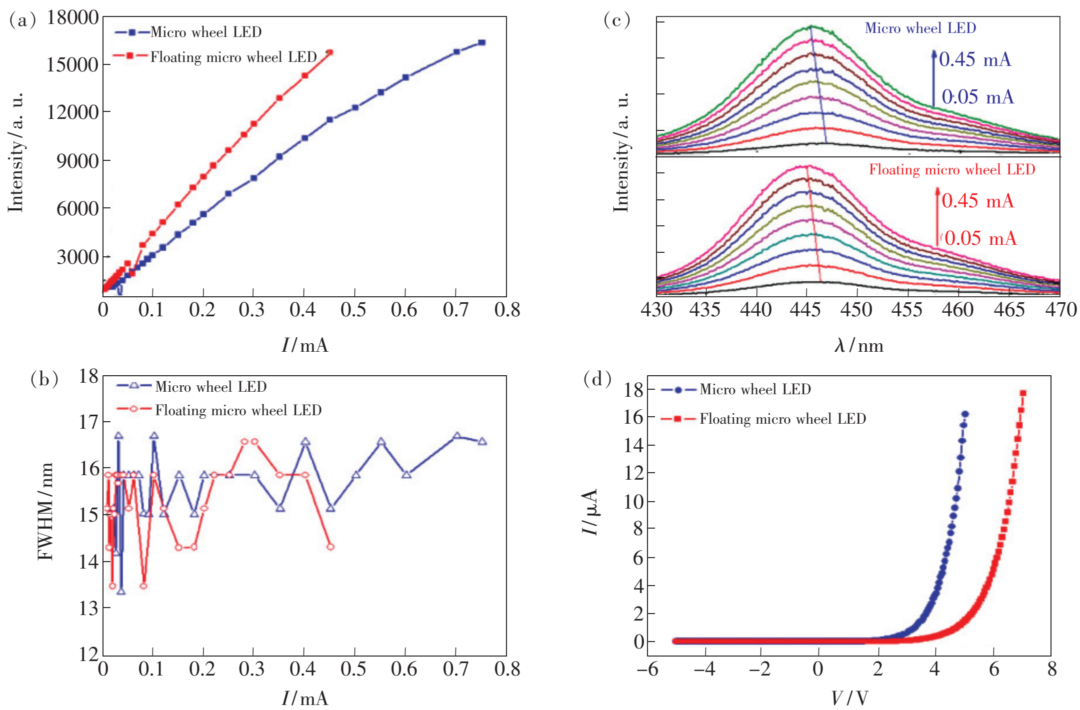

Fig. 4　(a) EL spectral intensity. FWHM (b) and spectral peak centers (c) of the two types of micro wheel at different current strengths. (d) *I-V* curves of the two types of micro wheel LED *versus* the current.

wavelengths of the two types of micro wheel devices. As presented in Fig. 4(c), When the current increases from 0.05 mA to 0.45 mA, the central wavelength of the micro wheel LED moves from 445.7 nm to 444.27 nm and shifts by 1.43 nm, and the central wavelength of the floating micro wheel moves from 445.7 nm to 444.6 nm and shifts by 1.1 nm. Due to the polarization in quantum well, energy band will be bended thus redshift the emission and the phenomenon is called quantum confinement Stark effect (QCSE). Under electrically driven, the electric field will reduce the QCSE and realize blue shift of the emission. Comparing with the LED without suspending, the blueshift is smaller. This makes it convince that the light emission of the floating micro wheel LED is relatively stable and the fluctuation is small, and it will not shift greatly with the increase of current, so it has a broad application prospect.

Fig. 4(b) shows the FWHM shift *versus* the current. FWHM of floating device is in the region of 13 – 17 nm while the normal device shows a FWHM in the region of 15 – 17 nm. Different from the photoluminescence spectrum, not all FWHM of the floating micro wheel is significantly smaller than that of the normal devices. The electrical characteristics of the floating micro wheels are affected in the process of wet etching of the Si substrate. Therefore, the FWHM of the floating micro wheels is not less than that of the micro wheels as expected. As shown in Fig. 4(d), the effect of improving the optical characteristics of floating micro wheel devices is the increase of the turn-on voltage. The turn-on voltage of floating micro wheel devices is about 2 V higher than that of non-floating micro wheel LEDs. Due to the suspension, the metal contact of micro wheel LEDs is affected, and the turn-on voltage becomes higher. Therefore, we can draw a conclusion that the floating micro wheel LEDs improve optical characteristics by reducing the electrical characteristics.

One important issue for optical communication is to get a stable and high performance light source. To further demonstrate the advantage of floating devices, we use our device to conduct a 3 dB measurement. Fig. 5(a) and 5(b) show the relationship between the amplitudes and frequencies of the two kinds of micro wheel LEDs at different voltages. From Fig. 5(a), it can be seen that the signal amplitude of the micro wheel attenuates rapidly with increasing frequency at a voltage of 9 V to 13 V. Among them, the signal attenuates fastest at 9 V, and the amplitude attenuates 20 dB when the frequency is 16 MHz. This phenomenon shows that the communication characteristics of micro wheel LEDs are not particularly ideal and are not suitable for transmission between wide frequency bands. The attenuation of floating micro wheel is much better than that of micro wheel. As shown in Fig. 5(b), when the frequency is within 14 MHz, the amplitude attenuation of the floating micro wheel LED is small, and the amplitude attenuation speed is greatly accelerated as the frequency continues to increase. Finally, we got the relationship between 3 dB bandwidth and voltage of two kinds of micro wheels as shown in the illustration in Fig. 5(b). When the voltage increases from 9 V to 13 V, the 3 dB bandwidth of the micro wheel LED is below 4 MHz. When the voltage increases from 14 V to 17 V, the 3 dB bandwidth of the floating micro wheel LED increases and then decreases, reach maximum 3 dB bandwidth of 15 MHz at 16 V. Therefore, it is obviously that the floating micro wheel has a better 3 dB bandwidth and better communication characteristics. In addition, Fig. 5(d) shows the variation of the capacitance of the two kinds of micro wheel LEDs with voltage at a frequency of 100 kHz, and Fig. 5(c) is a partial enlarged view. From negative bias to small positive bias, the capacitance of both micro wheels slowly increases with the increase of voltage. When the voltage reaches 0.2 V, the capacitance of the micro wheel rapidly decreases to negative value. When the voltage reaches 1.5 V, the capacitance of the floating micro wheel LED also rapidly decreases to negative value, and the decrease amplitude is larger. When the direct voltage is applied, the capacitance of the device is mainly diffusion capacitance generated by carrier diffusion. With the increase of the applied voltage, the capacitance will also increase continuously. After reaching a certain voltage value, the main source of capacitance is the injection electronics instead of the electronics generated by carrier diffusion. A large number of carriers will compound in the active region. The compound carrier concentration exceeds the diffusion concentration, and the capacitance will decrease rapidly to negative value. As can be seen from the Fig. 5(d), due to the high efficiency of the floating micro wheel LED, the floating micro wheel LED has a very obvious negative capacitance phenomenon.

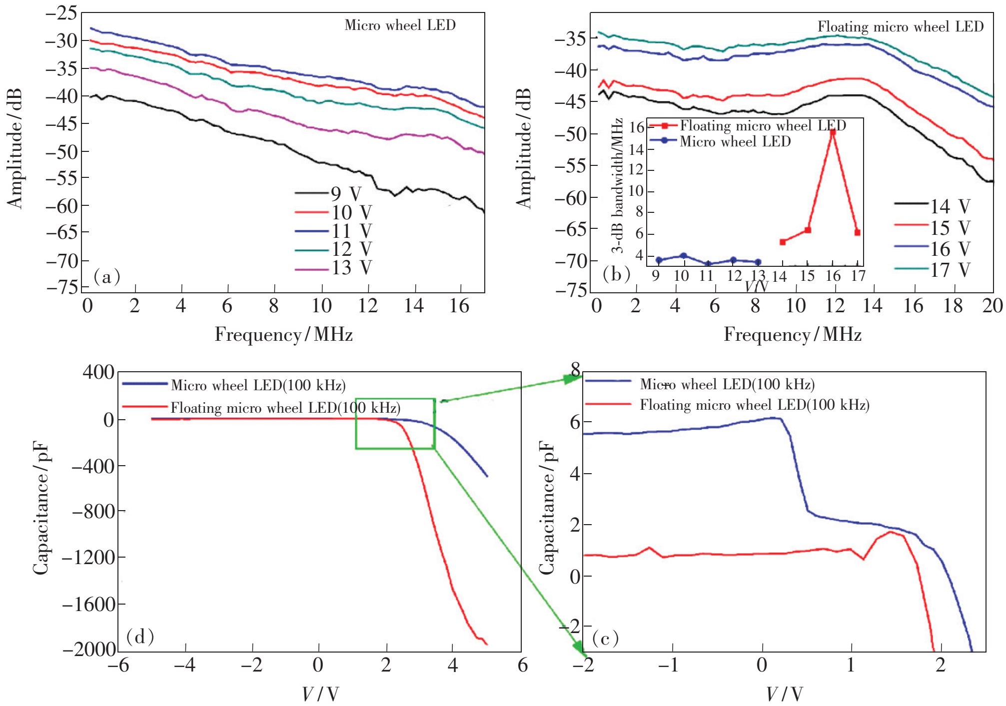

Fig. 5　Correspondence between amplitude and frequency of the two kinds of micro wheel at different voltages. (a) Micro wheel. (b) Floating micro wheel. The inset in (b) shows the relationship between 3 dB bandwidth and voltage of the two kinds of micro wheel. (c) Local enlargement of variation curve of two kinds of micro wheels capacitance with voltage at 100 kHz frequency. (d) Variation curve of capacitance of two kinds of micro wheels with voltage at 100 kHz frequency.

4　Conclusion

In summary, we prepared the floating micro wheel LED by photolithography and ICP etching. Under the same conditions, a series of experiments are carried out to compare GaN micro wheel LED. In the room temperature EL test, the floating micro wheel LED emits strong fluorescence, and the luminous intensity is much higher than that of micro wheel LED. The characteristics of EL, including the full width at half maximum, turn-on voltage and blue shift wavelength are analyzed. The results show that the optical properties of the floating micro wheel LED are better than those of the micro wheel LED, but the electrical properties are exactly the opposite. This illustrates that the floating micro wheel LED improves the optical properties by reducing the electrical properties. At the same time, the communication characteristics of the two kinds of micro wheel LEDs are studied. The floating micro wheel LED has longer 3 dB bandwidth and better communication characteristics. This work is necessary to improve the stimulated emission characteristics and optical gain of the optical micro cavity.

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朱刚毅(1980-),男,河南洛阳人,博士,副教授,硕士研究生导师,2013年于东南大学获得博士学位,主要从事宽禁带半导体微腔光电特性的研究。
E-mail: zhugangyi@njupt.edu.cn