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InGaN/GaN量子阱悬空微盘发光二极管

朱刚毅[1]，宁波[1]，仇国庆[1]，郭春祥[4]，杨颖[1]，李欣[1]，李炳辉[2]，施政[1]，戴俊[3]，秦飞飞[1]，王永进[1]

（1 南京邮电大学 通信与信息工程学院，南京 210003）
（2 中国科学院长春光学精密机械与物理研究所，长春 130033）
（3 江苏科技大学 理学院，镇江 212003）
（4 江苏鲁汶仪器有限公司，邳州 221300）

摘 要：设计并制备了三种不同结构的电泵浦InGaN/GaN量子阱微盘发光器件，对其光增益和光损耗进行了分析和优化。以p型层的结构为分类标准，器件Ⅰ为圆柱形；器件Ⅱ为器件Ⅰ的悬空结构；器件Ⅲ是悬空的圆环形结构。实验和仿真结果表明，三种器件结构中，器件Ⅱ的结果最好。电极布局为内p外n型的圆柱形器件表面电流分布能够保证发光区和微腔高增益区重合，悬空结构能够降低微盘在垂直方向上的光损耗，有利于更好的光学增益。考虑到共振模式，器件Ⅱ在注入电流大于0.7 mA时，器件Ⅱ实现了峰值波长为408.2 nm、半峰宽为2.62 nm的振荡模式输出。这种电泵浦InGaN/GaN量子阱悬浮微盘二极管器件的设计思路对电泵浦微盘或微环激光器的研制具有重要参考意义。

关键词：GaN微腔；损耗和增益竞争；InGaN/GaN量子阱；片上光源
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0 Introduction

Microcavities can confine light on the sub-wavelength scale resulted in dramatically enhanced light field intensity and prolonged photon lifetime of microdisks and microring as a platform for light and matter interaction, such as laser devices[1-3], active gyroscopes[4-7] and frequency combs[8-10]. As an outstanding representative of 3rd generation semiconductor materials, gallium nitride (GaN) demonstrates superior optical and electrical properties [11-14]. Therefore, GaN microcavity based Light-Emitting Diodes (LED) [15-18] and Laser Diodes (LD) [19-24] offer significant advantages in illumination, laser printing, full-color displays, high-density optical disk storage, and many other fields. The reported electrically pumped lasing devices could be classified as Vertical Cavity Surface-Emitting Lasers (VCSELs) [25-28] and waveguide laser according to the type of structures. The GaN VCSELs are widely reported due to its excellent performance and matured processing technology. Ref.[29] introduced grating into GaN surface-emission structures to realize a laser with a controllable polarization direction. Ref.[30] fabricated an electrically injected GaN-on-Si LD with 'sandwich-like' waveguide architecture, two AlGaN cladding layers were introduced for the optical field confining. Compared with the normal one which usually need to be excited by external light source, light source integrated devices are more convenient. In this case, the electrically pumped microdisk or microring light source, which may have high potential application in active gyroscope and frequency combs, are rarely reported. The reason

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First author: ZHU Gangyi, zhugangyi@njupt.edu.cn
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behinds lie at the limit in material growth and fabrication process. On the other hand, it is also a challenge about reducing optical loss and improving optical gain of the device. The key point to overcome this problem is finding suitable p/n-type electrodes configuration to make the luminescent region as effective microcavity region.

In this study, three well-designed electrically pumped InGaN/GaN microdisk devices were fabricated via photolithography, Inductively Coupled Plasma (ICP) dry etching, and wet isotropic etching technology. Electroluminescence (EL) properties were studied systematically by optimizing the optical loss, the gain region and the position of electrodes. The floating InGaN/GaN quantum well LED based on floating microdisk cavity (Type II) with cylindrical p-type GaN area dramatically reduces the optical loss in the vertical direction of microcavity. The electrode design guarantees that the luminous region and microcavity region can fix together. It is in favor of the microdisk device′s optical gain. Finally, resonant mode appears in the device. Taking the resonant spectra for consideration, the optimized device realizes the EL emission with peak wavelength center of 408.2 nm and Full Width At Half Maximum (FWHM) of 2.62 nm under a small injection current about 0.7 mA. The novel structure design of floating electrically pumped InGaN/GaN QW microdisk device is of key significance for electrically pumped microcavity lasers.

1 Experimental sections

1.1 Fabrication of GaN LED

Commercially available silicon wafer InGaN/GaN QW epitaxial layer was used to prepare microdisks by using semiconductor micro-nano processing technology. Take the fabrication process of device Ⅱ (Fig. 1) as an example and the others are fabrication via changing the pattern of lithography. Microdisk structures were patterned on the photoresist layer via photolithography (Fig. 1(a)). An epitaxial layer with 2.5 μm thickness is etched onto the n-GaN layer via ICP etching with the photoresist layer as a mask. Then, the residual photoresist was removed by using an acetone solution (Fig. 1(b)). The circular or ring pattern was defined by

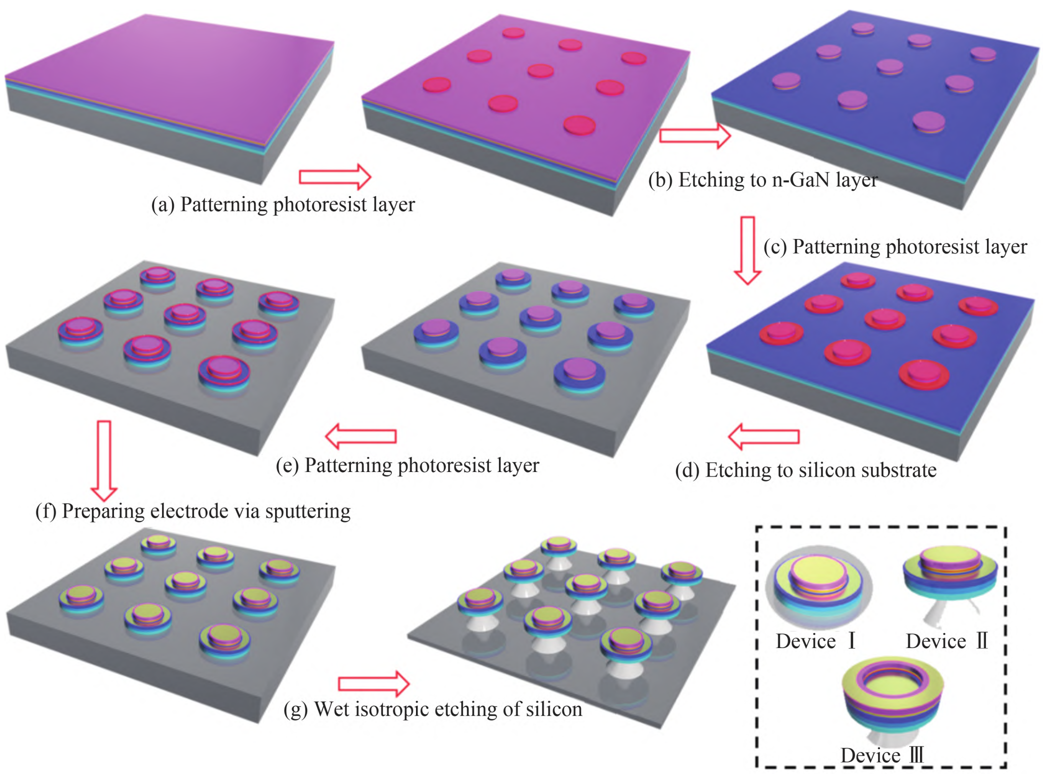


Fig. 1 Fabrication process of floating InGaN/GaN QW microdisk devices, the finally structures of device I, II and III are shown in the box

photolithography (Fig. 1(c)). The sample was etched onto the silicon substrate layer, and the residual photoresist was removed (Fig. 1(d)). The photoresist layer was patterned by photolithography (Fig. 1(e)). The p-electrode and n-electrode were prepared on the p-GaN and n-GaN layers by implementing magnetron sputtering and removing the residual photoresist by using acetone solution. The p/n electrode was composed of nickel (20 nm thick) and gold (100 nm thick) (Fig. 1(f)). Finally, the suspended InGaN/GaN QW microdisk devices were obtained by isotropic wet etching of Si with HF and HNO_3 mixing solution (HF∶HNO_3=1∶1) (Fig. 1(g)). The silicon substrate under InGaN microdisk was etched into the columns to support the InGaN microdisk devices. The structure of fabricated devices Ⅰ-Ⅲ was depicted in box of the right corner of Fig. 1.

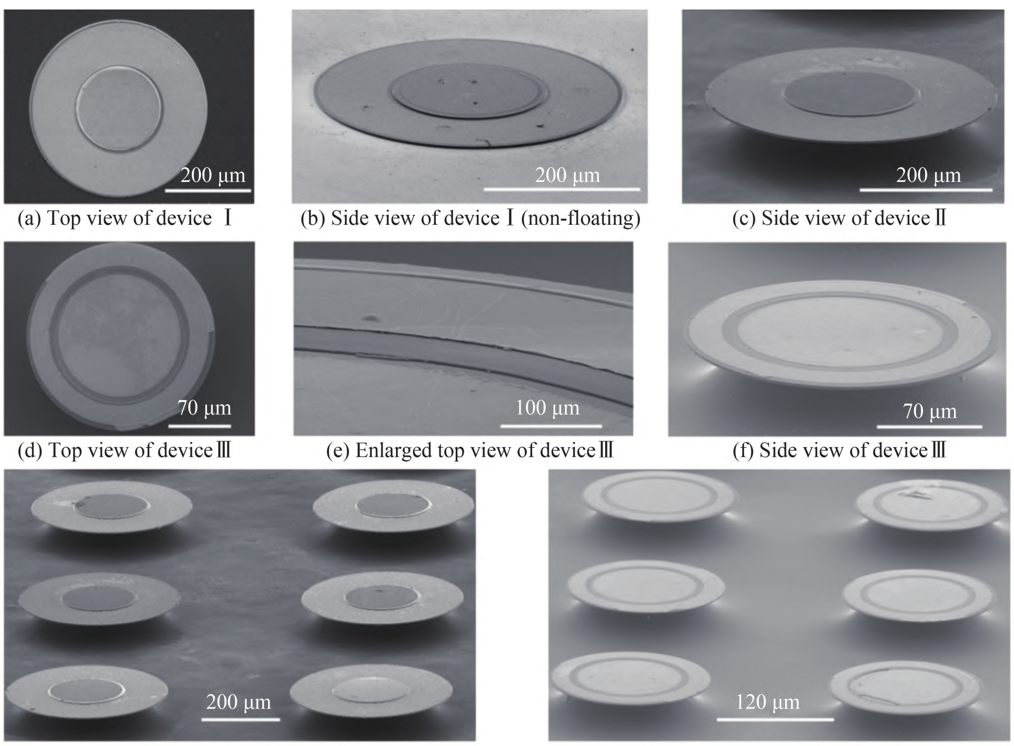
1.2 Sample characterizations

The morphological properties of the samples were characterized by field emission scanning electron microscopy (SEM, Carl Zeiss Ultra-Plus). EL properties and the IV curves of the device were measured by confocal micro photoluminescence (μ-PL) setup (Olympus BX35) with integrated probe system and alternating current source (Keysight B2901) at room temperature.

2 Results and discussion

2.1 Structure and morphology of GaN LED with different structures

The prepared InGaN/GaN QW microdisks have a regular shape and surface with good quality. The inner and out radius is 95 μm and 200 μm for devices Ⅰ and Ⅱ (Fig. 2(a), (b)). The upper and lower electrode layers clearly identify the cylindrical p-type GaN region of these devices. The floating structure of device Ⅱ is identified by the side view SEM picture, in which the microdisk is supported by Si cone pillar (Fig. 2(c)). This design may benefit the reducing of the optical loss from GaN to Si and improve the optical gain. Device Ⅲ is designed with opposite electrode structures to device Ⅱ, thus it presents an annular p-type GaN region on the microdisk (Fig. 2(d)). The inner and out radius of device Ⅲ is 65 μm and 95 μm. The inner n-type circular and outer p-type structures are clearly identified with the lower and upper electrode layers (Fig. 2(e), (f)). With



(a) Top view of device Ⅰ (b) Side view of device Ⅰ (non-floating) (c) Side view of device Ⅱ

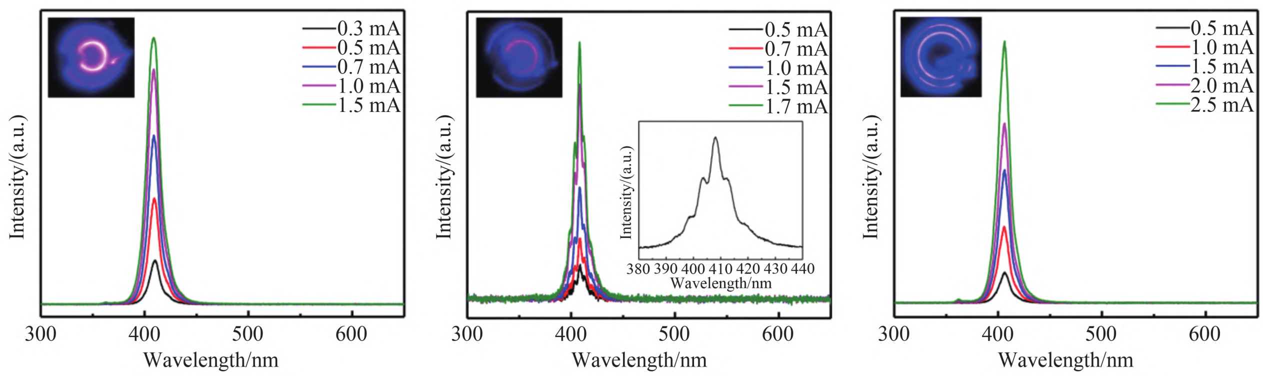
(d) Top view of device Ⅲ (e) Enlarged top view of device Ⅲ (f) Side view of device Ⅲ

(g) Array structure of device Ⅱ (h) Array structure of device Ⅲ

Fig. 2 SEM images of InGaN/GaN QW devices similar methods, GaN LED array can be obtained (Fig. 2(g), (h)).

2.2 Electrical properties of GaN LED with different structures

To evaluate the light emission of the fabricated devices, the EL spectra of devices Ⅰ, Ⅱ, and Ⅲ were obtained under different injection currents as depicted in Fig. 3. Peak wavelength are located at about 408.5 nm, 408.2 nm and 406.3 nm respectively. The EL intensity of the microdisk device gradually increases with the increase of injection currents. The inset images in Fig. 3(a)~(c) show the corresponding luminous images of three types of devices. The luminous regions of devices Ⅰ and Ⅱ are the inner p-type electrode circle edge on the microdisk, and the luminous region of device Ⅲ is the outer p-type electrode edge on the microdisk. The different electrode positions and shapes determine the devices' position and luminous shape area. For device Ⅱ, interestingly, the EL spectrum appears clear resonant mode. Taking the resonant spectra for consideration, spectra with peak wavelength near 408.2 nm sharp FWHM can be seen.



(a) EL of device Ⅰ (b) EL of device Ⅱ (c) EL of device Ⅲ

Fig. 3 EL spectra under the different injection currents, inset shows the enlarged spectra under 2 mA and luminous images of three types of devices

Ⅰ-Ⅴ curves of devices Ⅰ-Ⅲ are also measured and shown in Fig. 4. Since the Ni/Au electrode is used both in the p-GaN and n-GaN, it is hard to form an ohmic contact in n-GaN side. Turn-on current of plenary device I is about 18 V and increases the turn-on voltage for suspanded devices. The turn-on voltage of device Ⅲ is higher than 21 V. The increasing of turn-on voltage is due to that the wet etching process will cause some damage to the surface electron of the device. Leak current of different devices is low. The EL intensity rapidly increases in Fig 4(b). With the increasing of current, FWHM of device I and device Ⅲ are in the region of 12~14 nm. This value is in the similar level of commercial LED. However, due to the cavity effect, the resonant mode appears in device Ⅱ. Two different phenomenon can be obtained in Fig.4(c), for the spectra under low driven current, the resonant peaks are unclear, and FWHM in this case is near 12 nm, and for the higher driven current, considering the resonant peaks of each EL spectra and we re-calculated the FWHM of spectra at resonant position, the FWHM decreased to values below 3 nm for device Ⅱ when the injection current was more than 0.7 mA.

The narrow of FWHM and nonlinearly increasing of EL intensity confirm the well EL properties of the devices. It is also related to the electron and photon coupling in spatial. As demonstrated in the inset of Fig. 3, the luminescence region mainly concentrated in the core of the microdisk in device Ⅰ, Ⅱ and the inner and outer sides of the microring in device Ⅲ. In this case, compare with device Ⅲ, the special electrode structure design of inner p and outer n region in device Ⅰ, Ⅱ are more efficient. To make it clear, the simulation result of surface current distribution is performed by CST (CST Studio Suite). The surface current distribution of device Ⅰ, Ⅱ is concentrated at the p-type column edge located in the inner region of the microdisk determined by n-type and p-type semiconductor electrical potential difference (Fig. 5(a)). Thus the current distribution of

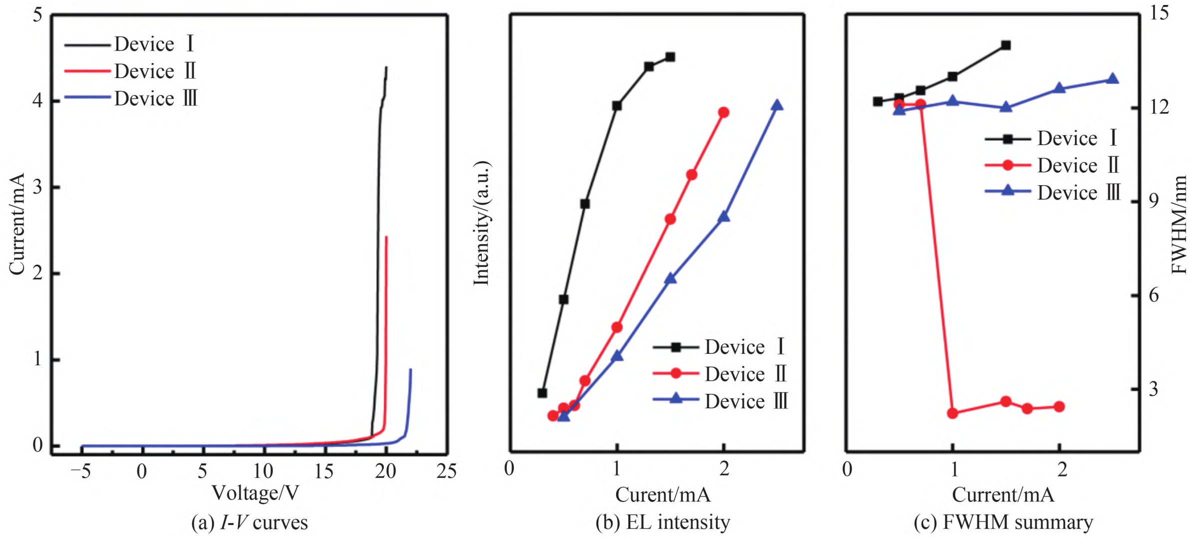


Fig. 4 Electrical and spectral detail characteristics of different devices

device Ⅰ and device Ⅱ resulted in a luminous region mainly on the p-type column edge (Fig. 3 (a), (b)). The surface current distribution of device Ⅲ is mainly concentrated at the inner edge of the p-type located on the outer zone of the microdisk (Fig. 5(b)). Thus the current distribution results in a luminous region mainly in the inner part of the microring (Fig. 3(c)). The overlap of the luminous region and the current region in device Ⅰ, Ⅱ is conducive to the efficient drive of the device. The above simulations analysis of surface current distribution strongly supports the experimental results of EL spectra. Comparing the date in Fig. 3(b) and Fig. 3(c) we can see that the electrode design of the device is significant for the overlap of the luminous region and light confirm region, the realization of an electrically pumped resonant mode.

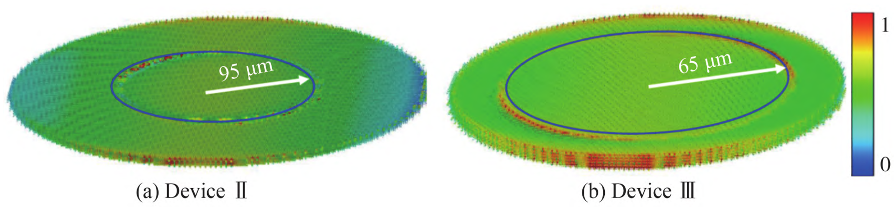


Fig. 5 The surface current distribution simulation of two types of microdisks

3 Conclusion

In summary, the floating InGaN/GaN QW microdisk LED with different kinds of p-type GaN regions is fabricated based on the above analysis. The floating microdisk device has better light confinement owing to the reduction of optical loss in the vertical direction. The structure design with cylinder p-type GaN region on the microdisk can ensure that the microcavity resonance region and luminous region overlap owing to the surface current distribution determined by n-type and p-type semiconductor electric potential difference. Thus, high quality LED with FWHM of 2.62 nm and peak wavelength at 408.2 nm is realized. The novel structure design of an electrically pumped InGaN/GaN QW floating microdisk LED is crucial for electrically pumped lasers.

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InGaN/GaN Quantum Well LED Based on Floating Microdisk Cavity

ZHU Gangyi[1], NING Bo[1], QIU Guoqing[1], GUO Chunxiang[4], YANG Ying[1], LI Xin[1], LI Binghui[2], SHI Zheng[1], DAI Jun[3], QIN Feifei[1], WANG Yongjin[1]

(1 *College of Telecommunications and Information Engineering*, *Nanjing University of Posts and Telecommunications*, *Nanjing* 210003, *China*)

(2 *Changchun Institute of Optics*, *Fine Mechanics and Physics*, *Chinese Academy of Sciences*, *Changchun* 130033, *China*)

(3 *College of Science*, *Jiangsu University of Science and Technology*, *Zhenjiang* 212003, *China*)

(4 *Jiangsu Leuven Instruments Co.*, *Ltd.*, *Pizhou* 221300, *China*)

Abstract: Although microcavity lasers with different structures have been proposed, the on-chip laser is still a critical bottleneck restricting the development of integrated optoelectronic systems. Ⅲ-Ⅴ semiconductors Light Emitting Diodes (LEDs) and Laser Diodes (LDs) on Si substrates, featured with suitable for large-scale and large-wafer-size manufacturing, are a convenient option for on-chip light sources. With the development of material fabrication, the quality of GaN wafers is high enough, optically pumped lasing has been realized in Si-based GaN microcavity, and more effort has been put into studying electrically pumped lasers. The reported electrically pumped lasing devices could be classified as Vertical-Cavity Surface-Emitting Lasers (VCSELs) and waveguide lasers according to the type of structures. Until now, the electrically pumped GaN lasing has also been realized in the Fabry-Perot (F-P) cavity and Whispering Gallery Modes (WGM) cavity. Many issues, such as the optical loss between the gain materials and the substrate, the improvement of the cavity quality, and the photon-electron coupling in the cavity region, can highly influence the optical performance of the device. In general, the floating process of the device will reduce the optical loss significantly, and improving the cavity quality is a critical issue in realizing high-quality lasing. Hence, the structure design will be essential in achieving a high-quality GaN laser.

In this paper, we designed and fabricated three types of electrically pumped InGaN/GaN Quantum Well (QW) microdisk devices to analyze and optimize their optical gain and loss and balance the coupling of the gain region and optical resonant region. The samples are fabricated using a standard microfabrication process, including photolithography, ICP etching, and wet etching based on 1nGaN/GaN epitaxial wafer on Si substrate. All the devices show well-circular structures. The device Ⅰ, with a planar structure, was designed with a cylindrical p-type GaN region on the inner side of the microdisk. The inner and outer radius is 95 μm and 200 μm for Device Ⅰ. Device Ⅱ is a floating device with the same planar structure as that of device Ⅰ. Device Ⅲ was designed with a ring-shaped p-GaN region on the outside of the microdisk, and it is also designed as a floating structure. Device Ⅲ has an inner and out radius of 65 μm and 95 μm. We define a gap between the n-GaN and p-GaN area to avoid device short circuits. For Devices Ⅱ and Ⅲ, through the isotropic wet etching of Si substrate, the whole LED is suspended for several micrometers. This strategy can ensure the reduction of optical loss of the cavity. The Ⅳ curves, EL spectra, and luminous images are recorded during the experiment. Ⅳ curves indicate that the turn-on voltage of device Ⅰ is about 18 V, and the wetting etching process will increase the turn-on voltage of the device; the turn-on voltage of device Ⅲ is over 21 V. Driven current-dependent EL spectra of different devices indicates that peak wavelength are located at about 408.5 nm, 408.2 nm, and 406.3 nm for device Ⅰ, Ⅱ and Ⅲ, respectively. The EL intensity of the microdisk device gradually increases with the increase of injection currents. FWHM of device Ⅰ, and device Ⅲ is in the region of 12～14 nm. What struck us was that the EL spectra are also related to the electrode region. CCD images of samples under fixed driven current indicate that the light emission mainly occurs near the electrode, but the light will be transmitted in the microcavity. Compared with others, device Ⅱ can ensure that the luminous and resonance microcavity regions overlap owing to the better surface current distribution. In addition, the floating structure of the microdisk reduces the optical loss of the microdisk laser in the vertical direction and favors better light confinement. Finally, device Ⅱ realizes EL emission with resonant mode under an injection current of about 0.7 mA. Considering the resonant spectra, the spectra show resonant mode at a peak wavelength of 408.2 nm and a Full Width at Half Maximum (FWHM) of 2.62 nm. The novel design of floating electrically pumped InGaN/GaN QW microdisk is significant for electrically pumped microdisk or microring laser.

Key words: GaN microcavity; Loss and gain competition; InGaN quantum well; On-chip light source
OCIS Codes: 020.2649; 060.3510; 140.3380; 140.3570