Vol 17 No 9, September 2008
1674-1056/2008/17(09)/3363-04

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

# Influence of patterned $TiO_2/SiO_2$ dielectric multilayers for back and front mirror facets on GaN-based laser diodes*

Chen Wei-Hua(陈伟华)[a], Hu Xiao-Dong(胡晓东)[a]†, Dai Tao(代 涛)[a], Li Rui(李 睿)[a], Ye Xue-Min(叶学敏)[b], Zhao Tai-Ping(赵太平)[b], Du Wei-Min(杜为民)[b], Yang Zhi-Jian(杨志坚)[a], and Zhang Guo-Yi(张国义)[a]

[a] *State Key Laboratory for Mesoscopic Physics and Department of Physics, School of Physics, Peking University, Beijing* 100871, *China*
[b] *Institute of Modern Optics, School of Physics, Peking University, Beijing* 100871, *China*

(Received 31 January 2008; revised manuscript received 14 March 2008)

Ridge InGaN multi-quantum-well-structure (MQW) edge-emitting laser diodes (LDs) were grown on (0001) sapphire substrates by low-pressure metal-organic chemical vapour deposition (MOCVD). The dielectric $TiO_2/SiO_2$ front and back facet coatings as cavity mirror facets of the LDs have been deposited with electron-beam evaporation method. The reflectivity of the designed front coating is about 50% and that of the back high reflective coating is as high as 99.9%. Under pulsed current injection at room temperature, the influences of the dielectric facets were discussed. The threshold current of the ridge GaN-based LDs was decreased after the deposition of the back high reflective dielectric mirrors and decreased again after the front facets were deposited. Above the threshold, the slope efficiency of the LDs with both reflective facets was larger than those with only back facets and without any reflective facets. It is important to design the reflectivity of the front facets for improving the performance of GaN-based LDs.

**Keywords:** dielectric multilayers, GaN-based LD, stimulated emission, threshold current
**PACC:** 4255P, 4260D, 8115H, 7280E

## 1. Introduction

Major developments in wide-gap III–V nitride semiconductors have led to the production of high-brightness light-emitting diodes and to the demonstration of room-temperature (RT) laser light emission in GaN-based heterostructures.[1−4] The electron-beam deposition method to form sub-micrometre scale dielectric coatings for GaN-based laser diodes is fast, flexible and convenient with advantages of masklessness and high resolution. In fabricating of distributed Bragg reflectors (DBR), the method of evaporating dielectric mirrors costs less than focused ion beam (FIB) etching[5,6] and is suitable for large-scale production. The dielectric mirrors can act as the moisture barrier and device overcoats, preventing the degradation of cleaved facets in different atmospheres.[7] The dielectric multilayers have conspicuous characteristics such as high reflectivity and deep cutoff in the background in ultraviolet band. Only a few pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers are sufficient to achieve reflectivity up to 95%. The dielectric coatings have been used as facets in GaAs and InP-based laser diodes to improve the performances of the laser devices.[8,9]

For GaN-based laser diodes there has been made great progress since Nakamura *et al* reported the first InGaN/GaN laser in 1996.[10] But facets with high reflectivity from naturally cleaved mirror are difficult to be achieved. The maximum reflectivity of a perfect smooth GaN mirror is only about 18% due to the low refraction index of GaN. Although the difference in angles between the cleaved face of GaN and the cleaved face of the sapphire substrate often cause the formation of many streaks perpendicular to the substrate on the cleaved facets of GaN,[11] high reflection back facet coatings consisting of dielectric multilayers have been used to reduce the threshold current.[1,12] In Ref.[1] high-reflection facet coatings composed of 4 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilay-

*Project supported by the National High Technology Program of China (Grant No 2007AA03Z403), the National Natural Science Foundation of China (Grant Nos 60776042 and 60477011), and National Basic Research Program of China (Grand No 2006CB921607).
†E-mail: huxd@pku.edu.cn

ers on back facets were used. Both sides of dielectric Bragg reflectors were mostly used in GaN-based vertical-cavity surface emitting lasers (VCSEL) to reduce the loss on the mirror surface.[12,13]

To our best knowledge, the influences of front and back dielectric facet coatings on the performance of GaN-based edge-emitting lasers under current injection have not been reported. In this paper, we report on the demonstration of violet InGaN/GaN MQWs edge-emitting laser diodes under pulsed current operation at RT by using quarter-wave $TiO_2/SiO_2$ dielectric multilayers as front and back cavity mirror facets. The performance of GaN-based edge-emitting lasers is improved by the use of $TiO_2/SiO_2$ multilayers for front and back cavity mirrors.

## 2. Experiment

III–V nitride films used in our work were grown by MOCVD method on c-plane sapphire substrate. The ridge InGaN MQW LD consisted of a GaN buffer layer grown at a low temperature of 550°C, a layer of n-type GaN:Si, an n-type 160 pairs of $Al_{0.2}Ga_{0.8}N/GaN$ superlattice for lower cladding layer, an n-type GaN lower optical guiding layer, an active layer of five InGaN/GaN multiple-quantum wells, a p-type GaN upper optical guiding layer, a p-type 100 pairs of $Al_{0.2}Ga_{0.8}N/GaN$ superlattice for upper cladding layer, and a p-type GaN contact layer. The diodes were cut into individual cavities with length of 800 $\mu$m. The area of the ridge LDs was 10 $\mu$m × 800 $\mu$m. Transfer matrix method was employed to design the parameters of dielectric multilayers. High-reflection facet coatings composed of 9 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers were patterned on the back facet, then 2 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers were patterned on the front facet using electron-beam evaporation method by DMDE 450. In order to obtain data from the same LD chip convenient for comparing, the LDs were detected before every deposition step. The structure morphologies of the resulting cavities were observed by scanning electron microscopy (SEM). Emitting spectra were measured by $x - y$ triple-grating Raman spectrometer (Dilor Co.) with a resolution of 0.02 nm. The operated current source was AC-107D-8 (AVTECH Co.). The samples were operated at a current of 300 ns pulse width and 500 Hz repeat frequency.

## 3. Results and discussion

The centre wavelength used in the controlling process in deposition was 400 nm. The width of every layer was designed to be $\lambda/4n$, with $\lambda = 400$ nm, and $n$ being the refractive index of corresponding dielectric layer. With $n_{SiO_2} = 1.5$, $n_{TiO_2} = 2.254$, the designed width of $TiO_2$ layer should be approximately 44 nm, and the width of $SiO_2$ layer should be approximately 67 nm. Most significance is the crystalline quality of material grown epitaxially above the mirrors and the limited bandwidth of the dielectric mirrors. The typical SEM image (Fig.1.) of the back cavity facet with 9 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers shows good quality of the dielectric mirrors and the consistent width of every layer compared to the theoretical calculations.

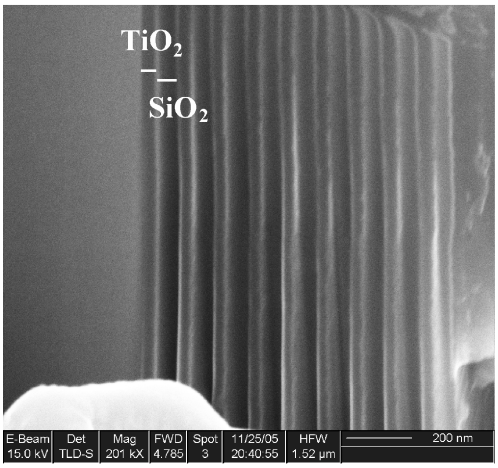



**Fig.1.** Cross-sectional SEM image of the $TiO_2/SiO_2$ dielectric multilayers on the back facet of an InGaN/GaN MQW LD.

Assuming that the dielectric multilayers were infinite in two dimensions without absorption and losses, we calculated the dependence of reflectivity on wavelength using transfer matrix method. Calculated reflectance spectra for back facet with 9 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers and for front facet with 2 pairs as function of wavelength are shown in Fig.2. The reflectivity of back facet gives a peak of 99.9% and a 140 nm high-reflectivity bandwidth. The bandwidth of the dielectric mirrors is comparable to the nitride/air DBR mirror facets.[5,6] Considering both the output power of the laser diodes and the demand of reduction of the threshold current, the reflectivity of the front facet was designed to be approximately 50%.

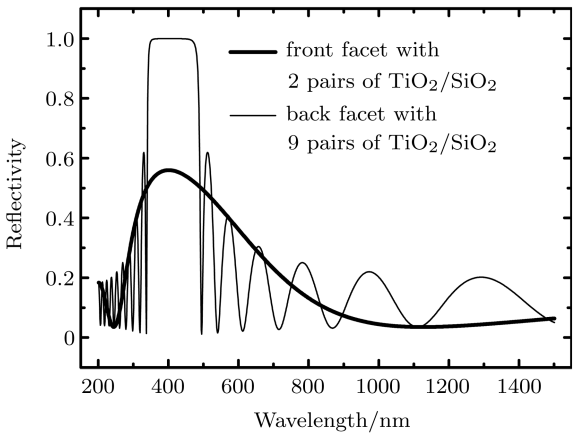



**Fig.2.** Calculated reflectance spectra for the back facet with 9 pairs of quarter-wave $TiO_2/SiO_2$ dielectric multilayers and for front facet with 2 pairs as functions of wavelength.

Figure 3 shows the optical spectra of a ridge InGaN MQW LD under pulsed current injection with a 300 ns pulse width and 500 Hz repeat frequency at room temperature. In Fig.3, with an injection current $I = 650$ mA, the LDs without dielectric mirrors and with only back facet coating are both below their thresholds. After the front dielectric facet was deposited, despite of the lowest spontaneous emission, a sharp stimulated emission of the LD appears. The deposition of front reflective coating reduces the threshold current of the GaN-based LD. This peak position of the stimulated emission shows a blue shift in comparison with the peak value of the spontaneous emission similar to the results of other groups.[1,14] The corresponding mechanisms in detail need further investigation at present.

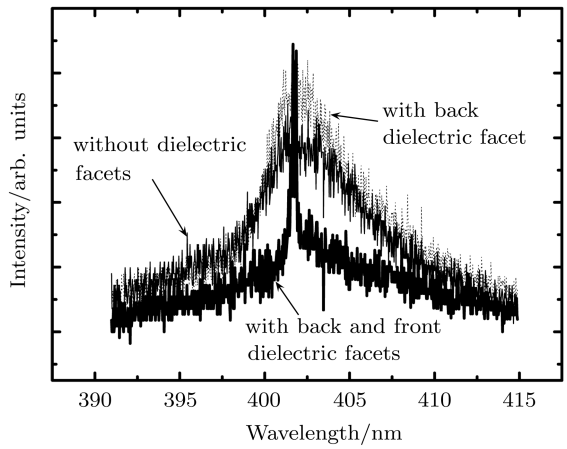



**Fig.3.** Emission spectra of an InGaN MQW LD chip with dielectric $TiO_2/SiO_2$ front and back facet coatings at a pulsed current of $I = 650$ mA.

Figure 4 shows the lasing optical spectra of the ridge InGaN MQW LD under pulsed current injection $I = 700$ mA, with a 300 ns pulse width and 500 Hz repeat frequency at RT. Sharp and strong laser emissions are observed for the GaN-based LD with back facet and both facets, while the LD without any reflective facet shows an unorderly and far lower optical spectrum. Obviously, the light intensity is getting larger after the dielectric mirrors formation. The reflectivity improvement should be caused by the dielectric facets. Because of the reflectivity improvement, the designed dielectric mirrors can discriminate and select laser modes efficiently and a stable single-frequency laser is obtained after the deposition of the dielectric mirrors. In our experiment, due to the reflectivity improvement, the optical intensity inside the LD increases and results in the red shift of the stimulated emission peak after the deposition process for both back and front facets, as shown in Fig.4.

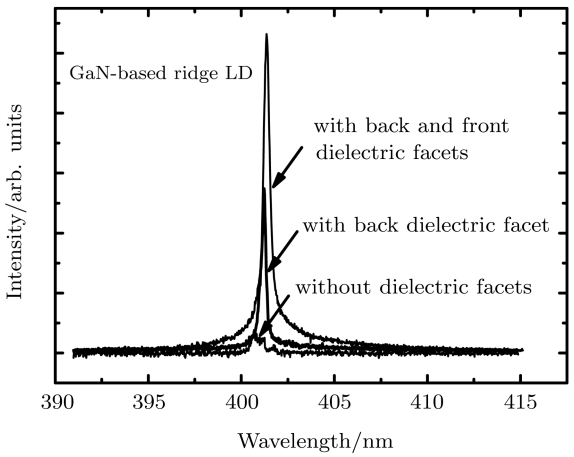



**Fig.4.** Stimulated emission spectra of an InGaN MQW LD chip with dielectric $TiO_2/SiO_2$ front and back facet coatings at a pulsed current of $I = 700$ mA.

Figure 5 shows the light output power per coated facet of the ridge LD as a function of the pulsed forward current $(L - I)$. The differential slope efficiency of per-facet emission obtained above the threshold current indicates the reduction of the loss in mirror facets after the dielectric multilayers were deposited. Although the front reflective facet keeps off a portion of output optical power (this is obvious especially in the spontaneous emission region), above the threshold, the slope efficiency of the LD with both reflective facets is larger than those with only back facet and without facets. Then the output power of the LD with back and front facets becomes the largest

when the injection current is 850 mA in this experiment. The disadvantage is that the output power of the LD with front and back facets is lower than that with only back high reflective facet until the injection current increases to a certain value. On the other hand, the threshold current of the ridge GaN-based LD is decreased after the deposition of the back dielectric mirrors and decreased again after the front facet is deposited as shown in the $L-I$ characteristics in Fig.5. In our work, the reduction of the threshold current was about 30–100 mA which was about 10% of the threshold current of the virgin lasers. Therefore, it is important to design a suitable reflectivity of the front facets of the GaN-based LDs.

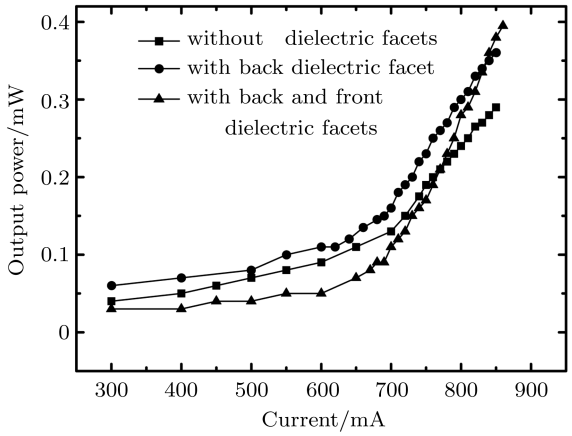



**Fig.5.** $L-I$ characteristics of an InGaN MQW LD chip measured under pulsed operation at RT. The samples are operated at a current of 200 ns pulse width and 500 Hz repeat frequency.

However, the relatively low reduction of threshold current indicates that maybe the dielectric mirrors were not perfect enough in these devices. This might be caused by the limitation of the electron-beam deposition method. In addition, another reason may be that many streak lines perpendicular to the substrate on the cleaved facets might affect the quality of the deposited dielectric multilayers.

## 4. Conclusions

High-reflection dielectric facet coatings of quarter-wave $TiO_2/SiO_2$ dielectric multilayers have been successfully patterned onto the mirrors of the GaN-based edge-emitting laser diodes using electron-beam evaporation method. Using the same GaN laser chip, GaN-based LDs without $TiO_2/SiO_2$ dielectric facets, with back dielectric facet and with both sides of dielectric facets are investigated under pulsed current operation. In our work, the threshold current of the ridge GaN-based LD is decreased after the deposition of the back dielectric mirrors and decreased again after the front dielectric facet was deposited. The total reduction of the threshold current is about 30–100 mA. Above the threshold, the slope efficiency of the LDs with both reflective dielectric facets is larger than those with only back dielectric facets and without any reflective dielectric facets.

## References

[1] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Sugimoto Y and Kiyoku H 1996 *Appl. Phys. Lett.* **69** 1477

[2] Kuramata A, Domen K, Soejima R, Horino K, Kubota S and Tanahashi T 1997 *Jpn. J. Appl. Phys.* **36** L1130

[3] Zhang J M, Zou D S, Xu C, Zhu Y X, Liang T, Da X L and Shen G D 2007 *Chin. Phys.* **16** 1135

[4] Liu Z, Wang X L, Wang J X, Hu G X, Guo L C and Li J M 2007 *Chin. Phys.* **16** 1467

[5] Kotani T, Hatada Y, Funato M, Narukawa Y, Mukai T, Kawakami Y and Fujita S 2005 *Phys. Stat. Sol.* (c) **2** 2895

[6] Dai T, Zhang B, Zhang Z S, Xu J, Chen W H, Li R, Bao K, Wei Q Y, Xu K, Hu X D, Yang Z J, Kang X N, Pan Y B, Lu M, Zhang G Y and Gan Z Z 2007 *Phys. Stat. Sol.* (c) **4** 196

[7] Schoedl T, Schwarz U, Kümmler V, Furitsch M, Leber A, Miler A, Lell A and Härle V 2005 *J. Appl. Phys.* **97** 123102

[8] Liu S N, Shen G D, Xu C, Zhang J M and Zou D S 2007 *Acta Phys. Sin.* **56** 2905 (in Chinese)

[9] Zhang J M, Zou D S, Xu Chen, Guo W L, Zhu Y X, Liang T, Da X L, Li J J and Shen G D 2007 *Chin. Phys.* **16** 3498

[10] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Jpn. J. Appl. Phys.* **35** L74

[11] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Jpn. J. Appl. Phys.* **35** L217

[12] Kim T, Martin R W, Watson I M, Dawson M D, Krauss T F, Marsh J H and de La Rue R M 2001 *Mater. Sci. Eng.* B **82** 245

[13] Kao C C, Peng Y C, Yao H H, Tsai J Y, Chang Y H, Chu J T, Huang H W, Kao T T, Lu T C, Kuo H C, Wang S C and Lin C F 2005 *Appl. Phys. Lett.* **87** 081105

[14] Schmidt T J, Yang X H, Shan W, Song J J, Salvador A, Kim W, Aktas O, Botchkarev A and Morkoc H 1996 *Appl. Phys. Lett.* **68** 1820