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Hybrid nitride microcavity using crack-free highly reflective AlN/GaN and Ta_2O_5/SiO_2 distributed Bragg mirrors

G. S. Huang[*, 1], **Hou-Guang Chen**[2], **J.-R. Chen**[1], **T. C. Lu**[1], **H. C. Kuo**[1], and **S. C. Wang**[1]

[1] Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, 300 Taiwan
[2] Department of Materials Science and Engineering, I-Shou University, Kaohsiung County, 840 Taiwan

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We report the growth over 2 inch sapphire substrates of hybrid nitride-based microcavities using one crack-free highly reflective AlN/GaN distributed Bragg reflectors (DBRs) incorporated with AlN/GaN superlattice (SL) insertion layers and Ta_2O_5/SiO_2 DBRs. The optical cavity is formed by a 5λ cavity consisting of n-type GaN, 10 pairs multiple quantum wells and p-type GaN sandwiched by AlN/GaN and Ta_2O_5/SiO_2 DBRs. Reflectivity and photoluminescence measurements were carried out on these structures. A 29 periods AlN/GaN DBR incorporated with six AlN/GaN superlattice insertion layers showed no observable cracks and achieved a peak reflectivity of 99.4% and a stopband of 21 nm. Based on these high quality DBRs, the cavity mode is clearly resolved with a linewidth of 2.6 nm. These results demonstrate that the AlN/GaN system is very promising for the achievement of strong light–matter interaction and the fabrication of nitride-based vertical cavity surface emitting lasers.

1 Introduction

The fabrication of high quality nitride microcavities (MC) has recently attracted much attention both for fundamental studies and technological applications. MCs can indeed be used to improve the extraction efficiency of light and to obtain a more directional emission from light emitting diodes [1–4]. Furthermore, MCs with high reflectivity mirrors are required to achieve strong coupling between excitons and cavity photons [5] or to fabricate vertical cavity surface emitting lasers [3, 6, 7]. In addition, the III-nitride semiconductor materials have much larger oscillator strength and binding energy of excitons than other conventional III–V compound semiconductor materials, making them as excellent candidates for observing the strong coupling regime toward room temperature (RT) and understanding of polariton physics. Potential applications of strong coupling in high quality GaN microcavity would be the fabrication of polariton lasers operating at a significantly lower threshold current than conventional nitride lasers as well as nonlinear optical devices like micro-optical parametric amplifiers and ultrafast switches [8–10].

One approach of high-quality nitride-based MCs have previously been reported using at least one dielectric mirror because of the difficulty to grow high reflectivity nitride distributed Bragg reflectors (DBRs) [5–7]. The commonly used DBR material system, $Al_xGa_{1-x}N$/GaN, requires at least 20–60 periods depending on the Al content to achieve reflectivity values exceeding 99%. Another approach has been recently proposed, using lattice-matched $Al_{0.82}In_{0.18}N$/GaN DBRs [11]. With this lattice-matched

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[*] Corresponding author: e-mail: gshuang@mail.nctu.edu.tw, Phone: +886 357 12121#56327, Fax: +886 357 16631

system, a crack-free DBR with a peak reflectivity of 99.4% was demonstrated using 40 periods. Both lower Al composition AlGaN/GaN and $Al_{0.82}In_{0.18}N$/GaN DBRs with lower strain suffer a lower refractive index ($\Delta n/n$), resulting in a large number of pairs required to achieve a high reflectivity. To overcome this problem, we have recently proposed an alternative approach, using AlN/GaN DBR incorporated with AlN/GaN superlattices [12]. With this system, a crack-free 20 pairs DBR with a peak reflectivity of 97% was demonstrated. In this paper, we further report the growth over 2 inch sapphire substrates of hybrid type nitride-based microcavities using one crack-free highly reflective AlN/GaN DBR with superlattice insertion layers and Ta_2O_5/SiO_2 distributed Bragg reflectors. The optical cavity is formed by a 5λ cavity consisting of n-type GaN, 10 pairs multiple quantum wells and p-type GaN sandwiched by AlN/GaN and Ta_2O_5/SiO_2 DBRs.

2 Experiments

These samples were grown in a low pressure EMCORE D75 MOCVD system. Two-inch diameter (0001)-oriented sapphire substrates were used for the growth of samples. Trimethylgallium and trimethylaluminum were used as group III source materials and ammonia as the group V source material. After thermal cleaning of the substrate in hydrogen ambient for 5 min at 1100 °C, a 30 nm-thick GaN nucleation layer was grown at 500 °C. The growth temperature was raised up to 1100 °C for the growth of 2 µm GaN buffer layer. Then AlN/GaN DBR with AlN/GaN SL insertions was grown under the fixed chamber pressure of 100 Torr similar to the previous reported growth conditions [12]. Then n-type GaN and following by a ten pairs InGaN/GaN (2.5 nm/10 nm) multiple quantum wells and p-type GaN were grown to form a 5λ cavity. Finally, an eight pairs of Ta_2O_5/SiO_2 dielectric mirror was deposited by electronic beam evaporation as the top DBR reflector. The reflectivity spectra of the GaN/AlN DBRs and the full microcavity structure were measured by the n&k ultraviolet–visible spectrometer with normal incidence at room temperature. The thicknesses of the individual layers in the DBRs were investigated by transmission electronic microscopy (TEM). The photoluminescence (PL) emission was excited by a 325 nm He–Cd laser of 30 mW and dispersed by a 0.32 m monochromator and detected with a photomultiplier with standard lock-in technique.

3 Results and discussion

Room temperature reflectivity spectra of crack free DBR measured near normal incidence are presented in Fig. 1. We have previously reported the 20 pairs of crack free AlN/GaN DBR with three superlattices

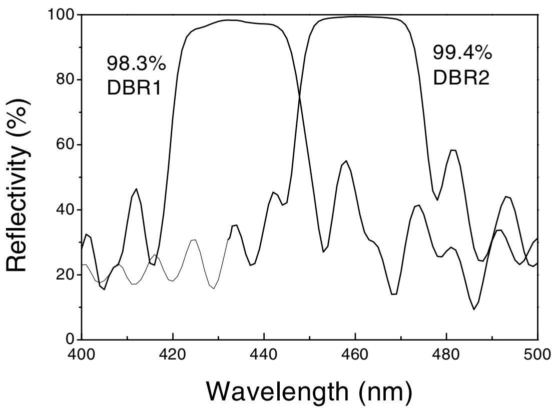

Fig. 1 Reflectivity spectra of two AlN/GaN DBRs with peak reflectance of 98.3% and 99.4% at centre wavelengths of 434 and 461 nm, respectively.

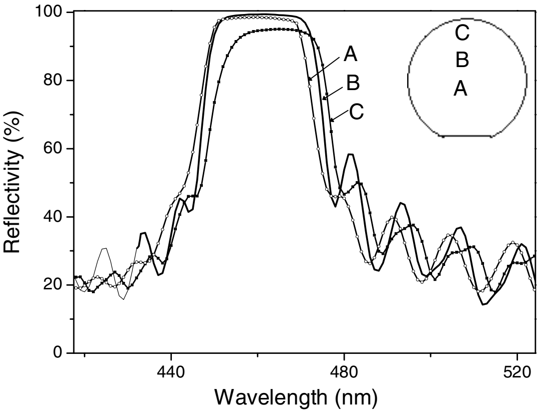

Fig. 2 Reflectivity spectra of the DBR 2 taken across the 2 inch wafer, which are located in order from the center of the wafer to the edge along the radius.

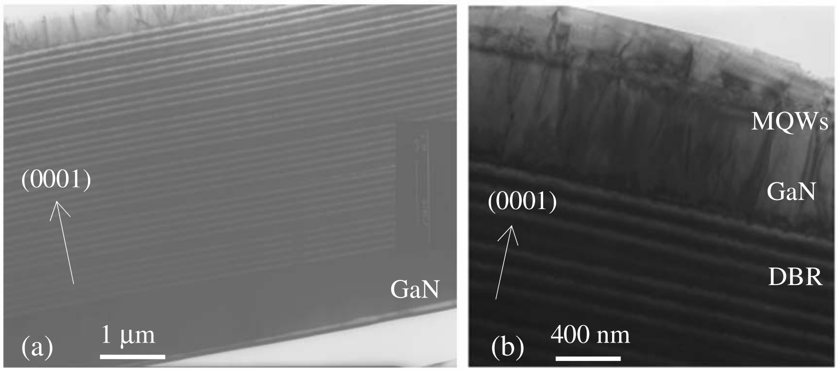

Fig. 3 (a) TEM cross-sectional images of 29 pairs AlN/GaN DBRs incorporated with 6 pairs insertion layers, (b) 5λ cavity and DBRs.

insertion layers achieving peak reflectivity of 97% at 399 nm with stopband of 14 nm [12]. The sample labeled DBR 1 was 25 pairs of crack free AlN/GaN DBR with four superlattice insertion layers. One pair of AlN/GaN superlattice insertion layers, which was the same as our previous report [12], was inserted between each five pairs of AlN/GaN DBRs. Here we define the stopband between the reflectivity more than 97%. The peak reflectivity of 98.3% at 434 nm with stopband of 19 nm was shown in Fig. 1. In order to achieve crack free and the higher reflectivity DBR, the sample was 29 pairs of AlN/GaN DBRs with six insertion layers. We chose to insert one superlattices layer in the first four sets of five pairs of DBR and second three sets of three pairs of DBR. The sample labeled DBR 2 shows the peak reflectivity of 99.4% at 461 nm with stopband of 21 nm. The flat topped stopband and the well-defined oscillations in particular the short wavelength ones most sensitive to internal absorption effects are indicative of the high sample quality. Figure 2 shows the reflectance spectra of DBR 2 at three areas A, B and C, which are located in order from the center of the wafer to the edge along the radius. At area A, the peak reflectivity of 98% was obtained at wavelength of 460 nm, at area B, 99.4% at 461 nm, and at area C, 95% at 465 nm, respectively. The difference of peak wavelength was 5 nm across the wafer.

The cross-sectional TEM image of DBR 2 is shown in Fig. 3(a), where the entire DBR 2 structure can be observed. The lighter layers represent AlN while the darker layers represent GaN or AlN/GaN superlattice insertion layer. From the bottom to the up, the AlN/GaN superlattice layer was inserted between each five pairs of DBR, then each three pairs of DBR consequently. It is interesting to note the uniformity of the thickness across the entire structure. In Fig. 3(a), no cracks can be observed in the TEM image. However, some V-shaped defects (dark spots) were still observed on the interfaces of GaN or AlN layers in Fig. 3(a). These V-shaped defects have been reported earlier to be due to various origins such as stack-

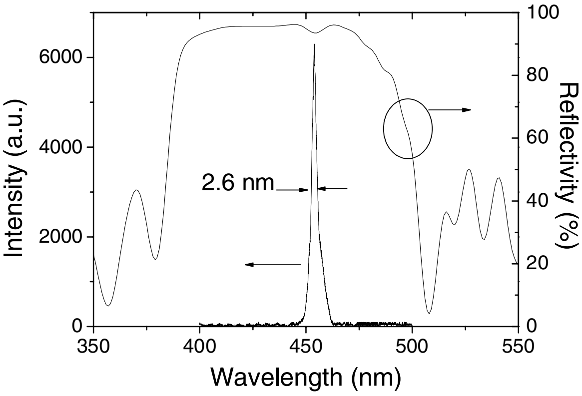

Fig. 4 Room temperature reflectivity and PL spectra of 5λ cavity mode.

ing mismatch boundaries and surface undulation [13, 14]. It is important to point out that the observed roughness in the this case did not affect the peak reflectivity because the wavelength of the light being reflected was much longer (~460 nm) compared to the degree of roughening (~ 10 nm). It is more important to maintain a coherent periodicity throughout the entire DBR structure. The 5λ cavity consisting of n-type GaN, 10 pairs multiple quantum wells and p-type GaN was also shown in Fig. 3(b).

Typical room temperature reflectivity spectrum measured on this hybrid microcavity consisting of 29 pairs of AlN/GaN DBRs incorporated with AlN/GaN superlattices insertion layers and 8 pairs of Ta_2O_5/SiO_2 DBRs is presented in Fig. 4. The large stopband (70 nm) results from the significant refractive index contrast between Ta_2O_5 and SiO_2 layers. The cavity dip mode is measured at 454 nm corresponding to the emission peak. However, the full width at half maximum (FWHM) of the dip is 8 nm due to the bad resolution of spectrum. Figure 4 shows the PL spectrum from the microcavity at room temperature. The cavity resonance mode at 454 nm with a FWHM of 2.6 nm is clearly observed as shown in Fig. 4. It indicates the emission peak is well aligned with vertical cavity formed by the high reflectance of AlN/GaN DBR with superlattices insertion layers and Ta_2O_5/SiO_2 DBR. The cavity quality factor is of the order of 175. This value is lower than the theoretical value of 1050 that calculated from the reflectivities of both AlN/GaN and Ta_2O_5/SiO_2 DBRs. The lower Q-factor is partly due to the absorption of InGaN/GaN quantum wells and p-type GaN inside the cavity. Carlin et al. [4] reported an empty $3\lambda/2$ GaN cavity surrounded by AlInN/GaN DBRs with reflectivities close to 99%. The Q-factor of our sample is nearly same as that of their sample (180). Furthermore, we inserted a 5λ cavity consisting of n-type GaN, 10 pairs multiple quantum wells and p-type GaN instead of their no light emitter inside GaN cavity.

4 Conclusions

In summary, using the AlN/GaN system incorporated with superlattice insertion layers, Bragg mirrors with reflectivity higher than 99.4% were obtained. The fabrication of hybrid nitride-based microcavities made of crack-free highly reflective AlN/GaN DBRs and dielectric mirror was demonstrated. Their characteristic linewidth of the cavity mode of 2.6 nm and stopband width of 21 nm corresponding to the state-of-the-art for nitride MCs are comparable to those achieved in nitride based MCs. In particular, the Q-factor of 175 could be promising for the demonstration of strong light−matter interaction in hybrid MCs at room temperature. This should pave the way toward the fabrication of optoelectronics devices like VCSELs and polariton based lasers.

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