# Fabrication of Microcavity Light-Emitting Diodes Using Highly Reflective AlN–GaN and $Ta_2O_5$–$SiO_2$ Distributed Bragg Mirrors

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***Abstract*—We report the fabrication of microcavity light-emitting diodes (MCLEDs) with high reflectivity and crack-free AlN–GaN distributed Bragg reflector (DBR). The $5\lambda$ microcavity structure consists of an n-type GaN, ten pairs InGaN–GaN multiple quantum wells and p-type GaN sandwiched between the hybrid cavity mode of an AlN–GaN and a $Ta_2O_5$–$SiO_2$ DBR. The AlN–GaN DBR has 29 periods with insertion of six AlN–GaN superlattice layers showing a crack-free surface morphology and a high peak reflectivity of 99.4% with a stopband of 21 nm. The output power of MCLED is about 11 $\mu$W at an injection current of 7 mA. The electroluminescence has a polarization property with a degree of polarization of about 51%.**

***Index Terms*—Distributed Bragg reflector (DBR), GaN, microcavity light-emitting diode (MCLED).**

## I. INTRODUCTION

IN RECENT years, the fabrications of planar nitride microcavity (MC) have attracted a lot of attention due to the possibility of enhancing and controlling the interaction between light and excitation in these structures [1]–[6]. For the light-emitting devices, the nitride microcavity has played a key role in the fabrication of microcavity light-emitting diodes (MCLEDs) [7]–[11] and vertical-cavity surface-emitting lasers (VCSELs) [12]–[14]. The circular beam shape, narrower and more directional emission light were demonstrated by these devices. An important requirement for the operation of such devices is the use of high reflectance distributed Bragg reflectors (DBRs). The VCSELs require highly reflective DBR on both sides of the active region to form the resonant cavity, while for the MCLEDs, the high reflectance DBRs can improve the output power and emission spectrum. Several GaN–AlGaN- and AlInN–GaN-based DBR structures have been reported, grown by molecular beam epitaxy and metal–organic chemical vapor deposition (MOCVD) [5], [6], [10]. However, both AlInN–GaN and AlGaN–GaN DBRs required a large number of pairs due to the relatively low refractive index contrast between AlInN (AlGaN) and GaN. All these nitride DBRs were grown on sapphire; there is a high thread dislocation density of $\sim 10^8 - 10^{10}/\mathrm{cm}^2$. The crystal quality becomes worse after a large number of pairs ($\geq$40) are grown. Consequently, the quality of bottom DBRs will affect the microcavity and top DBR. The AlN–GaN DBR has the highest refractive index contrast ($\Delta n/n = 0.20$) that can achieve high reflectivity with relatively less numbers of pairs. Ng *et al.* [15] reported 25.5-pair AlN–GaN DBRs with a peak reflectivity as high as 99% at 467 nm. However, the crack was observed in their samples. Our group has previously reported the 20 pairs of crack-free AlN–GaN DBR with three superlattice (SL) insertion layers achieving a peak reflectivity of 97% at 399 nm with a stopband of 14 nm [16]. In this letter, we report the epitaxy growth, fabrication, and performance of MCLEDs consisting of a $5\lambda$ InGaN–GaN multiple quantum-wells (MQWs) LED cavity between the bottom high reflectivity of AlN–GaN and the top $Ta_2O_5$–$SiO_2$ DBRs.

## II. EXPERIMENT

Our 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-$\mu$m GaN buffer layer. Then AlN–GaN DBRs with AlN–GaN SL insertions were grown under the fixed chamber pressure of 100 Torr similar to the previous reported growth conditions [16], [17]. Then n-type GaN and following by ten pairs InGaN–GaN (2.5 nm/10 nm) MQWs and p-type GaN were grown to form a $5\lambda$ cavity. Finally, The 240-nm-thick indium tin oxide was deposited on the sample for transparent contact layer. Fig. 1(a) shows the cross-sectional view of schematic MCLED structure with a top dimension of $170 \times 120\ \mu\mathrm{m}^2$. The Ti–Al–Ni–Au and Ni–Au were deposited to serve as n-type and p-type electrode by electron beam evaporation, respectively. The diameter of p-contact is 30 $\mu$m and the dimension of n-contact is $100 \times 120\ \mu\mathrm{m}^2$. Then eight pairs of $Ta_2O_5$–$SiO_2$ dielectric mirror were deposited by electronic beam evaporation as the top DBR reflector to fabricate the MCLED. $TiO_2$ has a higher refractive index than $Ta_2O_5$ but

Manuscript received January 15, 2007; revised March 26, 2007. This work was supported by the MOE ATU Program and in part by the National Science Council of Republic of China (R.O.C.) in Taiwan under Contract NSC 95-2120-M-009-008 and Contract NSC 94-2215-E-009-082.

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Digital Object Identifier 10.1109/LPT.2007.898763

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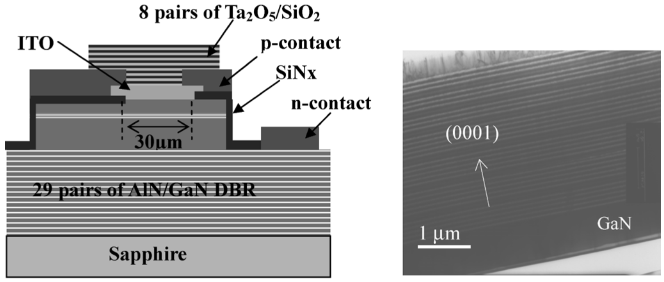

(a) (b)

Fig. 1. (a) Cross-sectional view of the demonstrated MCLEDs. (b) Cross-sectional TEM image of 29 pairs of AlN–GaN DBR incorporated with six SL insertion layers.

$Ta_2O_5$ was selected with low absorption and high transparency in the working wavelength. Meanwhile, one sample of 29 pairs of AlN–GaN DBR with six AlN–GaN SL insertion layers was grown to check reflectivity. 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. Finally, the light output of the MCLEDs was determined using an integrated sphere with a calibrated power meter. Both the PL and the EL data were obtained under continuous-wave conditions.

## III. RESULTS

Fig. 1(b) shows the cross-sectional TEM image of this sample, where the entire DBR structure can be observed. The lighter layers represent AlN while the darker layers represent GaN or AlN–GaN SL insertion layer. From the bottom to the top, the AlN–GaN SL layer was inserted between each of the five pairs of DBR, then each of the three pairs of DBR consequently. Fig. 1(b) shows that no cracks were observed in the TEM image, as checked under optical microscope. It is interesting to note the uniformity of the thickness across the entire structure. The interfaces of AlN–GaN DBRs and the SL insertion layers are well defined and quite flat. It is more important to maintain a coherent periodicity throughout the entire DBR structure. These results suggested that although the total thickness of whole structure is above 4 $\mu$m, the six SL insertion layers seem to be very effective to prevent the formation of cracks.

Fig. 2 shows the room-temperature reflectivity spectrum of crack-free DBR under near normal incidence. It shows the peak reflectivity of 99.4% at 461 nm with flat-topped stopband of 21 nm (the full-width at half-maximum (FWHM) is about 31 nm). The flat topped stopband and the well-defined oscillations, in particular the short wavelength ones most sensitive to internal absorption effects, indicate the high crystal quality of the DBR. Fig. 2 shows typical room-temperature reflectivity spectrum measured on this hybrid microcavity consisting of 29 pairs of AlN–GaN DBRs incorporated with AlN–GaN SL insertion layers and after evaporating eight pairs of $Ta_2O_5$–$SiO_2$ DBRs, respectively. 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 464 nm corresponding to the emission peak. Fig. 2 shows the PL spectrum from the microcavity at room temperature. The cavity resonance mode at 464.18 nm with an FWHM of 0.61 nm is clearly observed as shown in Fig. 2. It indicates the emission peak is well aligned with microcavity formed by the high reflectance of AlN–GaN DBR with SL insertion layers and $Ta_2O_5$–$SiO_2$ DBR. The cavity quality-factor ($Q$-factor) is of the order of 760, which agrees with that was calculated from the reflectivities of both AlN–GaN and $Ta_2O_5$–$SiO_2$ DBRs. Carlin *et al.* [5] 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 larger than that of their sample (180). Furthermore, this epitaxial structure could be fabricated into MCLED and VCSEL devices.

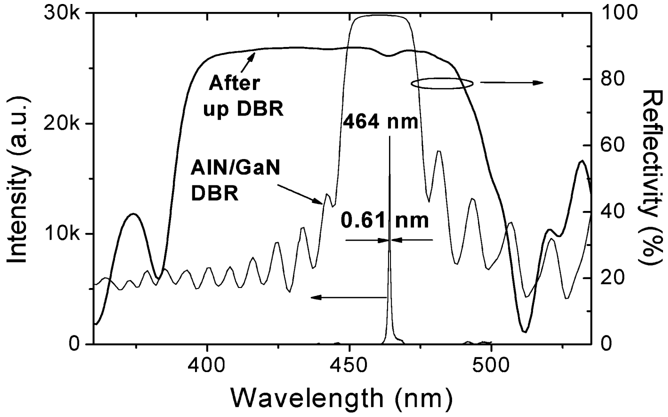

Fig. 2. Reflectivity spectrum of the bottom AlN–GaN DBRs at room temperature. Reflectivity spectrum after evaporating up DBR and PL spectrum of microcavity at room temperature.

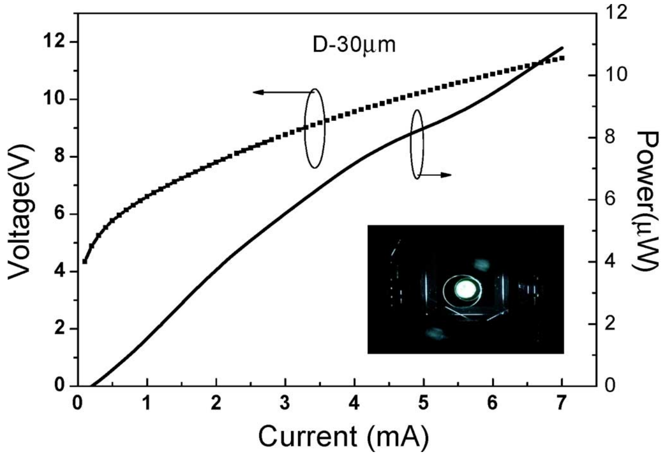

Fig. 3. Operation voltage and $L$–$I$ as a function of the current at room temperature of MCLED. The inset is the top view photograph of MCLED at an injection current of 6 mA at room temperature.

Fig. 3 shows the measurement results of room-temperature light–output power [($L$–$I$) curve] and current–voltage ($I$–$V$) curve characteristic of MCLED. The effective current aperture

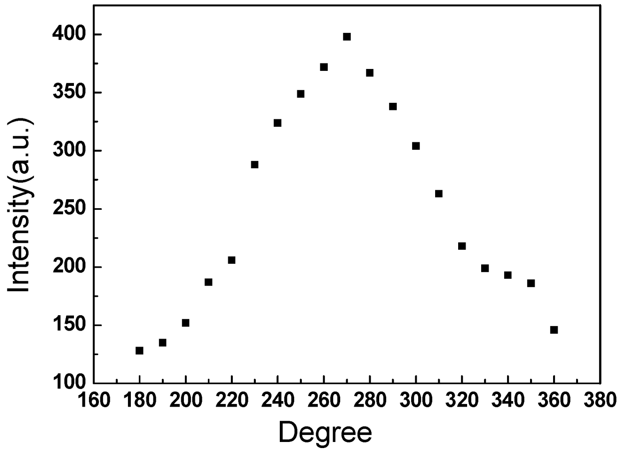

Fig. 4. Polarization characteristic of electroluminescence of MCLED.

was about 30 $\mu$m. The turn on voltage and resistance of the MCLED was about 4 V and 740 $\Omega$, respectively. The results show that the high resistance is due to the lateral current of $5\lambda$ intracavity. The $L$–$I$ is about 11 $\mu$W at 7 mA. The inset shows the top view photograph of MCLED at an injection current of 6 mA. However, the $L$–$I$ does not increase linearly with current increasing above 2 mA due to the thermal degradation. Fig. 4 shows the electroluminescence intensity as a function of the angle of the polarizer. The variation of the EL intensity with the angle of the polarizer shows nearly a sine variation. The specific orientation of the emission polarization did not exist. The degree of polarization is defined as $P = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensity of the nearly sine variation, respectively. The result shows that the emission beam has a degree of polarization of about 51%, suggesting a polarization property of the light emission.

## IV. CONCLUSION

We have shown that the SL insertion layers should be very effective to avoid the formation of cracks in the DBRs. Using the AlN–GaN system incorporated with SL 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. In particular, the $Q$-factor of 760 could be promising for the demonstration of strong light-matter interaction in hybrid MCs at room temperature. The output power of MCLED is about 11 $\mu$W at an injection current of 7 mA. The electroluminescence has a polarization property with a degree of polarization of about 51%.This should be a good approach to the fabrication of optoelectronics devices like VCSELs and polariton-based lasers.

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