

Article

Light Output Enhancement of GaN-Based Light-Emitting Diodes Based on AlN/GaN Distributed Bragg Reflectors Grown on Si (111) Substrates

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Abstract: Due to the absorption of opaque Si substrates, the luminous efficiency of GaN-based light-emitting diodes (LEDs) on Si substrates is not high. So, in this work, we insert AlN/GaN distributed Bragg reflectors (DBRs) to improve the light output of GaN-based LEDs on Si (111) substrates grown via metal organic chemical vapor deposition (MOCVD). In order to obtain the highest reflectivity of the AlN/GaN DBR stop band, the growth parameters of AlN/GaN DBRs are optimized, including the growth temperature, the V/III ratio and the growth pressure. As a consequence, the interfaces of the optimal 9-pair AlN/GaN DBRs become abrupt, and the reflectivity of the DBR stop band is as high as 85.2%, near to the calculated value (92.5%). Finally, crack-free GaN-based LEDs with 5-pair AlN/GaN DBRs are grown on Si (111) substrates. The light output of the DBR-based LED is evidently enhanced by 41.8% at the injection current of 350 mA, compared with the conventional DBR-based LED without DBRs. These results pave the way for the luminous efficiency improvement of future green and red GaN-based LEDs grown on Si substrates.

Keywords: light-emitting diodes; AlN/GaN DBRs; growth parameters; light output enhancement

1. Introduction

In the past two decades, III-Nitride DBRs have been applied in LEDs to improve the light output [1–4] or even in vertical-cavity surface-emitting lasers as resonant cavities [5]. Due to the important advantage in that III-Nitride DBRs can be fabricated by in situ epitaxy, many approaches have been adopted such as AlN/GaN [6–10], AlGaIn/GaN [11,12], AlGaIn/AlN [13–16], AlInN/GaN [17–19], AlInN/AlGaIn [20,21] and so on. Among these III-Nitride DBRs, the AlN/GaN DBR structure has attracted most attention, because of the largest refractive index contrast between AlN (2.1) and GaN (2.4). Ives et al. deposited 20.5 periods of AlN/GaN DBRs on SiC substrates, which had a stop band width of 40–50 nm and a maximum measured reflectance of 99% [22]. Cai et al. deposited 25-pair AlN/GaN DBRs on sapphire with the reflectivity exceeding 90%, and the DBR-based LED showed a super-linear increase up to a current density of 135 A/cm² and the relative external quantum efficiency (EQE) kept monotonously increasing with the increase in injection current density [3]. Mastro et al. grew 5-pair AlN/GaN DBRs with the peak reflectivity of 69.8% on Si substrates, while the LED structure was not deposited [23]. Among these substrates (SiC, sapphire and Si) for III-Nitrides heteroepitaxy, it is most difficult to deposit III-Nitride DBRs and GaN-based LEDs on Si, due to the tensile stress caused by the large mismatch of the thermal expansion coefficient between GaN and Si. On the other hand, Si substrates are the lowest cost and they provide opportunities for optoelectronic integration. Thus, it is

very important to insert III-Nitride DBRs in situ between the LED active layer and the Si substrate, since the light emitted downwards would be reflected by the DBR and prevented from being absorbed by the opaque Si substrate [24]. Then, the luminous efficiency of LEDs on Si substrates can be improved. However, there are very few reports about GaN-based LEDs on Si substrates with III-Nitride DBRs. Ishikawa et al. achieved crack-free DBR-based LEDs on Si with only 3-pair AlGaIn/AlN DBR structures, resulting in an improvement of light output power [25]. However, the light output decreased when increasing DBRs to five pairs because of a crack formation.

In this work, in order to obtain the highest reflectivity of DBRs, the AlN/GaN DBRs with the largest refractive index contrast are grown on Si (111) substrates, and the growth parameters of AlN/GaN DBRs are optimized, including the growth temperature, the V/III ratio and the growth pressure. It is found that the optimal growth conditions for AlN/GaN DBRs are growth temperature of 1020 °C, V/III ratio of 2500 and growth pressure of 70 mbar. As a result, the interfaces of the optimized 9-pair AlN/GaN DBRs become abrupt and the maximum reflectivity reaches 85.2%, near to the calculated value (92.5%). Finally, crack-free GaN-based LEDs with 5-pair AlN/GaN DBRs are grown on Si (111) substrates. In comparison with those conventional LEDs without DBRs, the AlN/GaN DBR-based LEDs show a light output enhancement of 41.8%, at the injection current of 350 mA.

2. Materials and Methods

Epitaxial layers on 2" Si (111) substrates were deposited in the MOCVD system (Aixtron, Thomas Swan 3x2FT system, Herzogenrath, Germany). In order to eliminate the desorption of AlN or GaN layers during the growth of AlN/GaN DBRs and control their thickness precisely, AlN and GaN of these DBRs were grown at the same condition during each growth and their interval time was as short as 10 s. The thickness of AlN and GaN was 55 and 48 nm, corresponding to the stop band center of 460 nm. The epitaxial structure of these 9-pair AlN/GaN DBRs with a 300-nm GaN cap layer is shown in Figure 1a. There are three series of the 9-pair AlN/GaN DBRs, named series A, B and C. For series A, the growth pressure and the V/III ratio of AlN/GaN DBRs remained at 100 mbar and 2500, while the growth temperature was varied at 1000 °C (sample A1), 1020 °C (sample A2), 1040 °C (sample A3) and 1060 °C (sample A4). For series B, the growth temperature and pressure of AlN/GaN DBRs remained at 1060 °C and 100 mbar, while the V/III ratio was varied at 500 (sample B1), 1000 (sample B2), 1500 (sample B3) and 2500 (sample B4). For series C, the growth temperature and the V/III ratio of AlN/GaN DBRs remained at 1060 °C and 2500, while the growth pressure was varied at 70 mbar (sample C1), 100 mbar (sample C2), 130 mbar (sample C3) and 160 mbar (sample C4). Finally, owing to the stress compensation of the 660-nm compositionally graded AlGaIn buffer layer [26], crack-free GaN-based LEDs with 5-pair AlN/GaN DBRs were grown on Si (111) substrates, consisting of 800 nm n-GaN, 6-pair InGaIn/GaN multiple quantum wells and 240 nm p-GaN, as shown in Figure 1b. As a reference, non DBR-based LEDs on Si were also fabricated, and these two types of LED samples are classified into series D. Reflectivity, SEM images, TEM images and EL spectrum were measured by the spectrophotometer (Shimadzu, UV-3600Plus, Kyoto, Japan), the SEM (Hitachi, SU8220, Tokyo, Japan), the TEM (FEI, Talos F200S, Hillsboro, OR, USA) and the optical spectrum analyzer (Yokogawa, AQ6373, Tokyo, Japan), respectively.

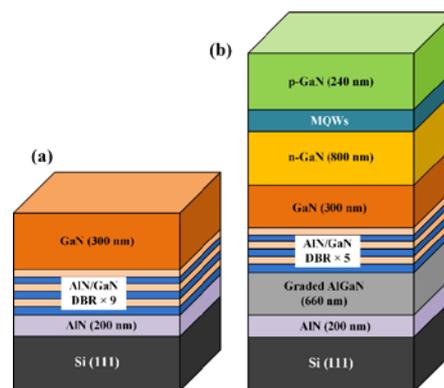


Figure 1. Structures of (a) samples with 9-pair AlN/GaN distributed Bragg reflectors (DBRs) and (b) LEDs with 5-pair AlN/GaN DBRs.

3. Results and Discussion

The temperature-dependent reflectivity of the AlN/GaN DBR stop band of series A is exhibited in Figure 2a. It is clear that the reflectivity is the lowest at the growth temperature of 1000 °C. Then, the reflectivity reaches the highest when the growth temperature rises to 1020 °C. However, when the growth temperature continues to increase to 1040 and 1060 °C, the reflectivity decreases. In order to find the reasons, cross-sectional SEM images of AlN/GaN DBR interfaces are illustrated in Figure 3a. It is found that the AlN/GaN DBR interfaces are very rough and many big V-type defects appear at the growth temperature of 1000 °C. When the growth temperature increases to 1020 °C, the interfaces become much smoother. When further increasing the growth temperature to 1040 and 1060 °C, the smoothness of the interfaces is a little degraded. These SEM results confirm the reflectivity measurement. The reason is that a too low growth temperature would result in the 3D growth of AlN and GaN, which causes rough interfaces [27,28]. On the other hand, a too high growth temperature would lead to the desorption of GaN, which degrades the smoothness of AlN/GaN interfaces [28,29].

The reflectivity versus V/III ratio of series B is depicted in Figure 2b. It is obvious that the reflectivity increases with the increase in the V/III ratio of AlN/GaN DBRs, while it tends to be saturated at the value of 2500. Figure 3b displays the corresponding cross-sectional SEM images of the AlN/GaN DBR interfaces of series B. It can be seen that the interfaces are very rough at the V/III ratio of 500 while they become quite flat at the V/III ratio of 2500, which indicates that the smoothness of AlN/GaN interfaces is improved with the increase in V/III ratio. These results agree with the measurement of reflectivity. This is because the higher V/III ratio improves the surface mobility of Ga (Al) atoms, which promotes the two-dimensional (2D) growth of GaN (AlN) films [30–32], whereas the lower V/III ratio reduces the surface mobility of Ga (Al) atoms, which results in the three-dimensional (3D) growth of GaN (AlN) films and rough interfaces of AlN/GaN DBRs.

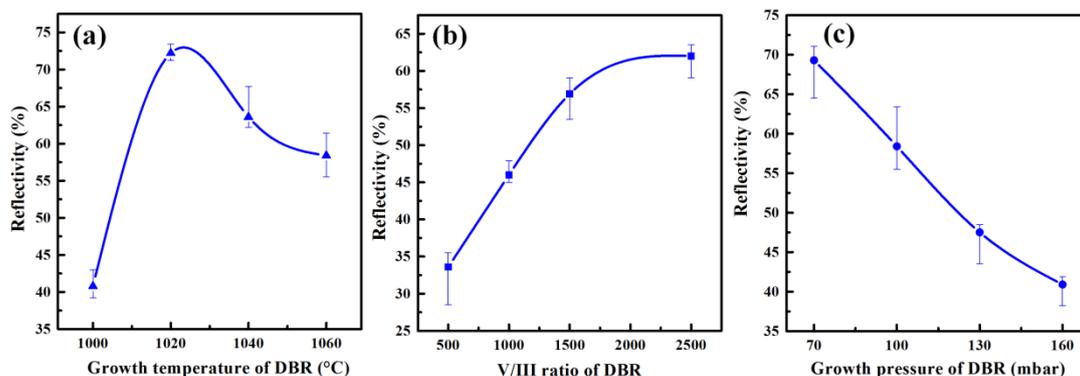


Figure 2. The reflectivity of the AlN/GaN DBR stop band of (a) series A, (b) series B and (c) series C.

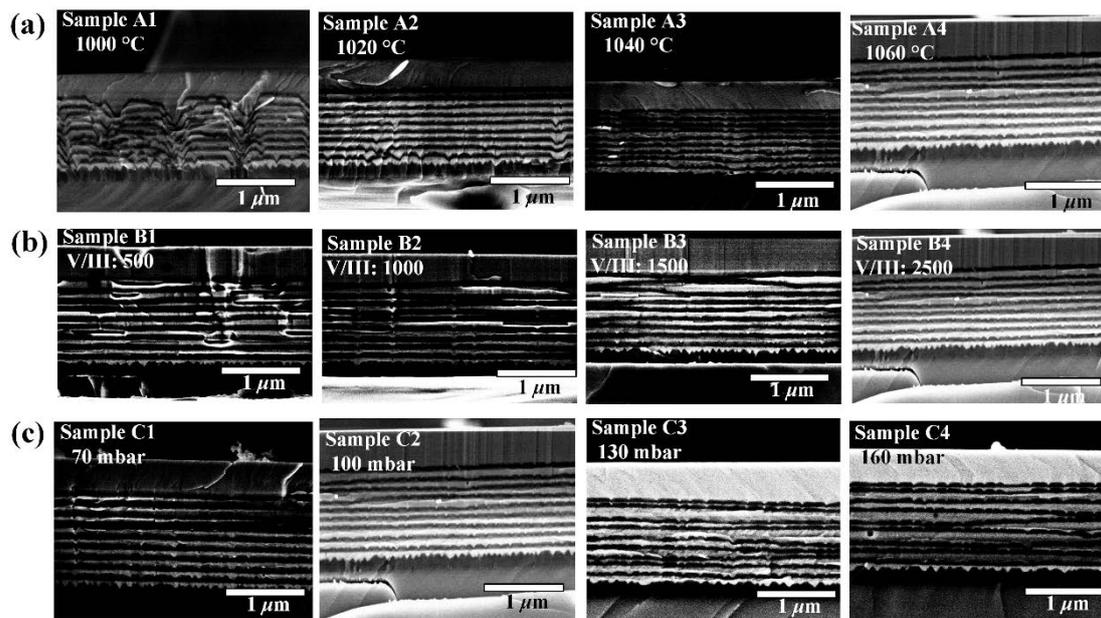


Figure 3. Cross-sectional SEM images of (a) series A, (b) series B and (c) series C.

Figure 2c exhibits the reflectivity as a function of growth pressure of series B. It is obviously seen that the reflectivity decreases distinctly when increasing the growth pressure of AlN/GaN DBRs from 70 to 160 mbar. The reason can be found in the cross-sectional SEM images of AlN/GaN interfaces, as shown in Figure 3c. When the growth pressure is 70 mbar, the thickness of GaN (AlN) films is uniform and the interfaces are very sharp. However, when the growth pressure is 130 or 160 mbar, the thickness of GaN (AlN) films fluctuates visibly, which leads to the roughness of AlN/GaN interfaces and the low reflectivity. Therefore, this indicates that the lower growth pressure facilitates the 2D growth of GaN (AlN) films and thereby results in sharp interfaces of AlN/GaN DBRs and higher reflectivity, and vice versa [27].

Therefore, the optimized growth parameters of AlN/GaN DBRs are a growth temperature of 1020 °C, V/III ratio of 2500 and growth pressure of 70 mbar. The experimental and calculated reflectivity of the optimized 9-pair AlN/GaN DBRs are exhibited in Figure 4a. It can be seen that the experimental curve fits the calculated one quite well. The reflectivity of the DBR stop band is 85.2%, which is close to the calculated value (92.5%). Cross-sectional TEM images of AlN/GaN DBRs are shown in Figure 4b. It is observed that the interface occurs abruptly when GaN is grown on AlN, but gradually in reverse order. This is caused by the compositional pulling effect when AlN is grown on compressed GaN [33]. Ga atoms move into AlN during the growth, which results in a graded AlGaN layer. Meanwhile, it can be seen that V-type pits occur in the AlN layer, which may result from the lower mobility of Al atoms or microcracks of AlN caused by tensile stress. All these factors would degrade the interfaces of AlN/GaN DBRs and reduce the reflectivity.

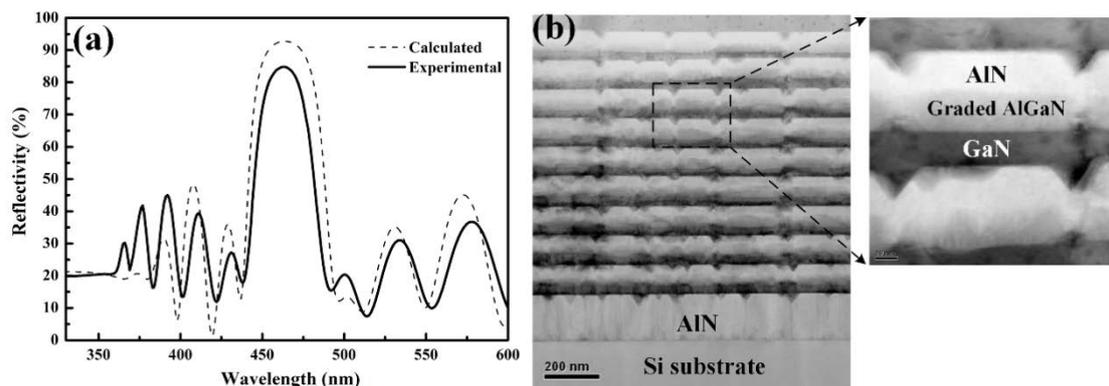


Figure 4. (a) The experimental and calculated reflectivity and (b) cross-sectional TEM images of the optimized 9-pair AlN/GaN DBRs.

Figure 5 shows the calculated and experimental reflectivity of 9-pair AlN/GaN DBRs under different incident angles. The experimental results are in good agreement with the calculated results. With the increase in incident angles, the DBR stop band shows a blue shift and the reflectivity has a slight decrease, which is due to the reduction of the optical path. On the other hand, the critical angle of GaN-based LEDs is $\arcsin(1/n_{\text{GaN}}) = 24.6^\circ$, where n_{GaN} is the refractive index of GaN (2.4). Since the critical angle is quite small, the DBRs still have the ability to significantly improve the light output of LEDs in the light output direction.

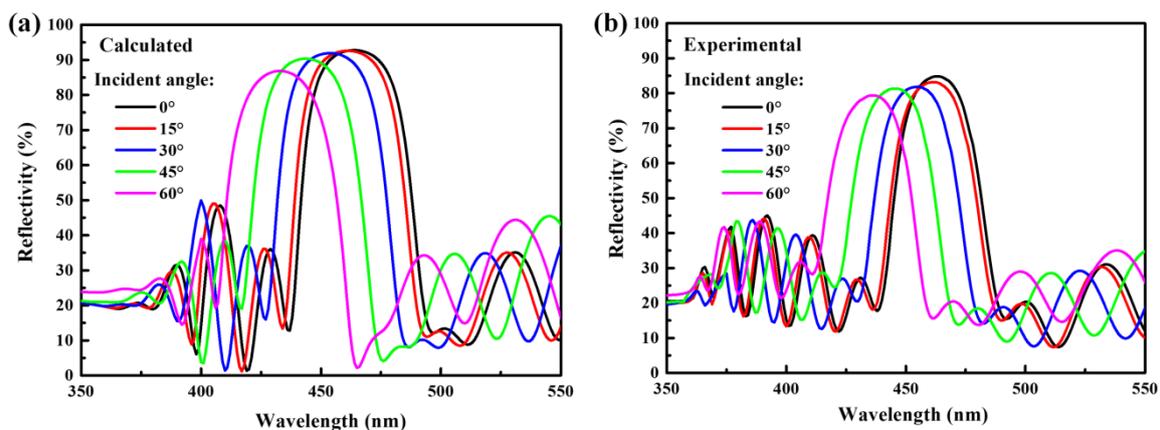


Figure 5. (a) The calculated and (b) experimental reflectivity of 9-pair AlN/GaN DBRs under different incident angles.

Finally, LED samples in series D are fabricated, with the LED chip size of $1 \text{ mm} \times 1 \text{ mm}$. Figure 6a,b illustrate the electroluminescence (EL) spectrum of the non-DBR-based and the DBR-based LEDs at different injection currents, which is measured by an optical spectrum analyzer through an optical fiber at the near-top of the LED chip. This indicates that the EL intensity of the DBR-based LED is evidently improved at each injection current, compared with the non-DBR-based LED. To further quantify the enhancement of the light output, the integrated EL intensity is carried out, as shown in Figure 6c. The light output (integrated EL intensity) of the DBR-based LED is enhanced by 41.8% at the injection current of 350 mA (operating current).

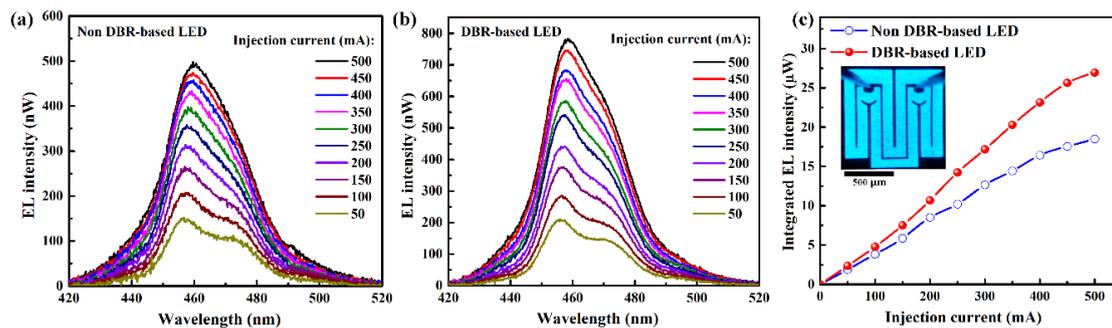


Figure 6. Electroluminescence (EL) spectrum of (a) the non-DBR-based and (b) the DBR-based LEDs at different injection currents. (c) Integrated EL intensity (light output) of the DBR-based and the non-DBR-based LEDs, with an insert of a DBR-based LED chip with the size of 1 mm × 1 mm.

4. Conclusions

In summary, we insert AlN/GaN DBRs to enhance the light output of GaN-based LEDs on Si (111) substrates by MOCVD. The growth parameters of AlN/GaN DBRs are optimized, including the growth temperature, the V/III ratio and the growth pressure. As a consequence, the reflectivity of the DBR stop band of the optimal 9-pair AlN/GaN DBRs is as high as 85.2%, near to the calculated value (92.5%). Finally, crack-free GaN-based LEDs with 5-pair AlN/GaN DBRs are grown on Si (111) substrates. The light output of the DBR-based LED is evidently improved, and it is enhanced by 41.8% at the injection current of 350 mA, in comparison with the conventional non-DBR-based LED. These results pave the way for the luminous efficiency improvement of future green and red GaN-based LEDs grown on Si substrates.

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