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Air-Hybrid Distributed Bragg Reflector Structure for Improving the Light Output Power in AlGaInP-Based LEDs

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We investigated air gap-induced hybrid distributed Bragg reflectors (AH-DBRs) for use in high brightness and reliable AlGaInP-based light emitting diodes (LEDs). An air gap was inserted into the side of DBRs by selectively etching the $Al_xGa_{1-x}As$ DBR structures. With the AH-DBR structures, the optical output power of LEDs was enhanced by 15% compared to LEDs having conventional DBRs, due to the effective reflection of obliquely incident light by the air gap structures. In addition, the electrical characteristics showed that the AH-DBR LED is a desirable structure for reducing the leakage current, as it suppresses unwanted surface recombinations.

Keywords: Air-Gap, Distributed Bragg Reflector, AlGaInP, Light Emitting Diode.

1. INTRODUCTION

Recently, the performances of LEDs have been drastically improved, and the development of very bright devices that produce red and yellow wavelengths has been enabled by using an AlGaInP material system.[1–5] However, the major drawback of AlGaInP-based LEDs is the absorbing nature of GaAs substrates in the wavelength of interest.[6] Optical losses in the AlGaInP-based LED structure incurred due to the absorption effect in the GaAs substrate are often greater than 50%. Typically, to improve the light extraction efficiency of AlGaInP-based LEDs, a distributed Bragg reflector (DBR) is inserted between the substrate and the n-cladding layer.

The DBR structure is designed to efficiently reflect normally incident light; however, the reflectivity becomes negligible when the incident angle is larger than the critical angle limiting the light output power. To improve the light extraction efficiency in conventional DBR-based LED (DBR LED) structures, it is important to subsequently devise a new DBR structure that efficiently reflects obliquely incident light.

In this paper, we report an air gap-induced hybrid DBR-based LED (AH-DBR LED) structure capable of improving the light extraction efficiency. Then, to verify the influence of AH-DBR structures in 630-nm wavelength LED devices, we compare LED structures having conventional DBRs and air gap-induced hybrid DBRs.

2. EXPERIMENTAL DETAILS

We conducted metal-organic vapor phase epitaxy (MOVPE) on a 2 inch (100) GaAs substrate tilted 10° toward $\langle 011 \rangle$ to grow conventional DBR LED structures emitting at a 630-nm wavelength. After the initial growth of the GaAs buffer layer, 14-period $Al_{0.5}Ga_{0.5}As/AlAs$ Si-doped DBR structures having a quarter-wavelength ($\lambda/4n$) thickness at 630 nm were grown. The 20-period multi-quantum well (MQW) structures consisted of 5 nm $Ga_{0.5}In_{0.5}P$ quantum wells separated by 15 nm $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barrier layers, which were sandwiched between n-type and p-type $Al_{0.5}In_{0.5}P$ cladding layers. Then, a 10 μm-thick GaP window layer was added to

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improve the current spreading and light extraction. To allow for an air gap in the side of DBRs, DBR LED structures were isolated into the GaAs substrate by chip size and selectively etched the DBR materials for 5 minutes using a 10% HF solution in water at room temperature. The DBR materials were selectively etched to 40 um for 5 minutes, laterally. Finally, to compare the device performances, wafers with DBR and AH-DBR LED structures were cut into 500 μm × 500 μm chips having 80 μm-diameter metal contacts on the top p+-contact layer. After dicing, the chips were mounted onto TO-18 headers with no epoxy encapsulation, and all subsequent measurements were carried out using a conventional integration sphere.

3. RESULTS AND DISCUSSION

The conceptual light paths reflected from conventional the DBR and AH-DBR structures are depicted in Figure 1. Conventional DBRs typically reflect the normally incident light within the yellow region, propagating vertically. However, the reflectivity becomes negligible when the incident angle is larger than critical angle (θ_c), and only a small portion of light can be extracted out of the chip through the side facet. To overcome this drawback, an air gap was inserted into the side of the DBR structures. Consequently, incident light larger than θ_c in the AH-DBR structures could be effectively reflected by the air gap, thereby improving the light extraction efficiency through the side facet of the chip.

To evaluate the AH-DBR structure, the angular reflectivity was numerically calculated using the optical transfer-matrix method.[7] In Figure 2, a reflectivity of larger than 90% in the DBR structures was maintained for normally incident light, and the reflectivity became negligible for an incident angle larger than 22.5°. Otherwise, the reflectivity of the air gap structures was negligible for normally incident light, with the reflectivity approaching 100% for an incident angle larger than 17.4°. These simulated data indicate that AH-DBR structures are promising for improving the light extraction efficiency by reflecting normally incident light using DBR structures, and also by reflecting obliquely incident light using air gap structures.

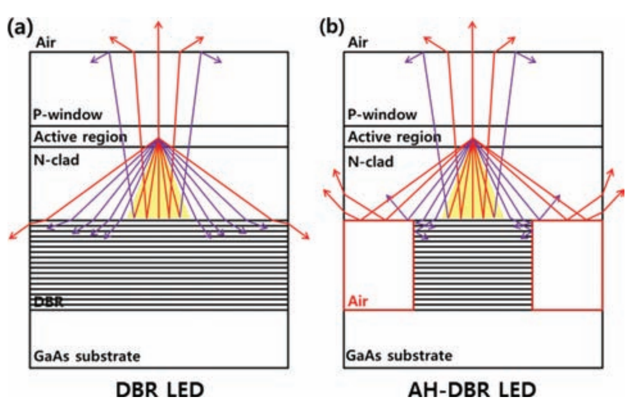

Figure 1. Schematic of layer sequence of LEDs and conceptual path reflected from (a) conventional DBR and (b) AH-DBR structures.

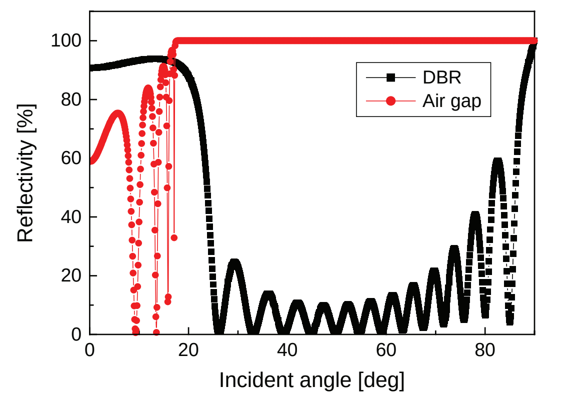

Figure 2. Angle-dependent reflectivity of DBR and air gap structures calculated at a 630-nm wavelength.

To verify the performance of our proposed LED structures, AlGaInP-based LEDs having conventional DBR and AH-DBR structures were prepared. Figure 3 shows the cross-sectional schematics and scanning electron microscopy (SEM) images of the two types of structures. The $Al_xGa_{1-x}As$ DBRs are well etched to 38 μm in depth and the AH-DBR structures relatively well-defined

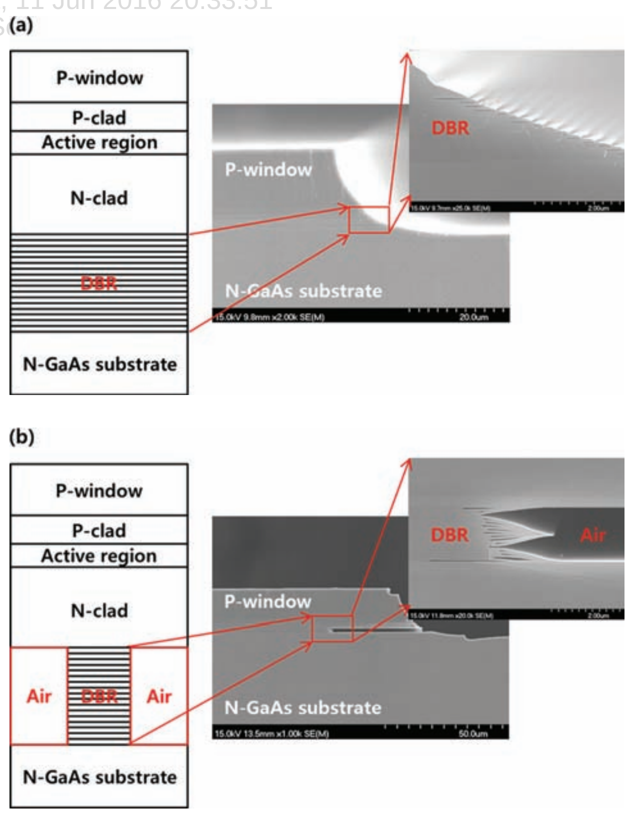

Figure 3. Cross-sectional SEM images of (a) conventional DBR and (b) AH-DBR LED structures.

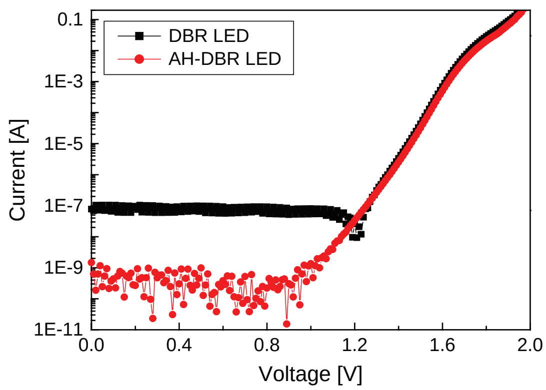

Figure 4. Forward I-V characteristics plotted on a log-log scale of LEDs having conventional DBR and AH-DBR structures.

(Fig. 3(b)). Note that phosphide LED structures are not seriously etched and are well maintained.

To examine the electrical influence of the air gap in the DBR structures, the current–voltage (I–V) characteristics were plotted in log-log scale (Fig. 4). The conventional DBR LED shows a forward bias voltage of 1.95 V at 200 mA. However, the AH-DBR LED shows a slightly higher forward bias voltage of 1.97 V at 200 mA, due to the reduction of the effective junction area. It is interesting to note that the leakage current at a low forward bias could be significantly lowered by inserting an air gap into the side of the DBRs, due to the surface cleaning effect on p–n junction area during wet chemical side-etching of the DBRs. These results indicate that the AH-DBR LED is a desirable structure for reducing the leakage current as it suppresses unwanted surface recombinations.[8]

Figure 5(a) presents the light output power (P_{out}) versus injection current of LEDs having conventional DBR and AH-DBR structures. The P_{out} at 200 mA for the AH-DBR LED was 14.3 mW, brighter than the conventional DBR LED (12.4 mW). To compare the P_{out} characteristics of the AH-DBR LED to the DBR LED according to the current injection, the relative P_{out} enhancement (RPE) is defined as the P_{out} of the AH-DBR LED divided by the P_{out} of the DBR LED. It is interesting to observe that the RPE is larger at a low current. For AlGaInP-based LEDs, the decrease of the internal quantum efficiency due to device heating at a higher current injection results in the reduction of the light output power enhancement.[9] The obliquely incident radiation toward the GaAs substrate passes through the DBRs and is heavily influenced by their absorption. Therefore, the higher RPE at a low current is attributed to the light extraction through the side facet of the chip, due to the effective reflection of the obliquely incident light by the air gap structures. Also, the significantly reduced leakage current of the AH-DBR LED is influenced to the improvement of the RPE particularly at a low current region.

In Figure 5(b), the radiation profile of the two structures is measured at a 200 mA current injection. The width of

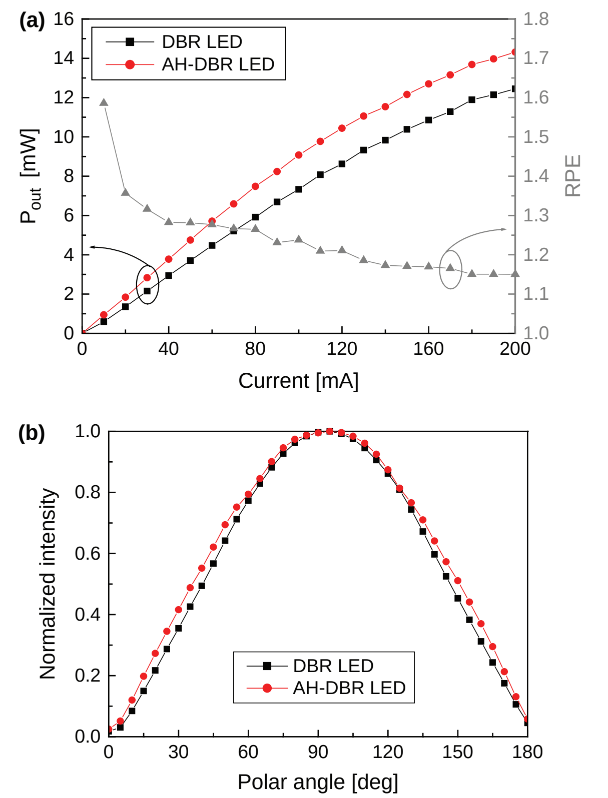

Figure 5. (a) Light output power versus current curve for LEDs having DBR and AH-DBR structures. The RPE versus injected current is also plotted. (b) Measurement of the angular radiation pattern for devices having these structures.

the angular distribution of the AH-DBR LED is seen to be somewhat larger than for the conventional DBR LED. These results also support the fact that light extraction through the side facet of the AH-DBR structures contributes to the total light output power.

4. CONCLUSION

We proposed and demonstrated an air gap-induced hybrid DBR for AlGaInP-based LEDs. By selectively etching the $Al_xGa_{1-x}As$ DBRs, the air gap could be inserted into the sides of DBR structures. With the AH-DBR structures, the P_{out} of LEDs was enhanced by 15% in comparison to LEDs having conventional DBRs due to the effective reflection of obliquely incident light by the air gap structures. In addition, the electrical characteristics revealed that the AH-DBR LED effectively reduces the leakage current by suppressing nonradiative surface recombinations.

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References and Notes

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