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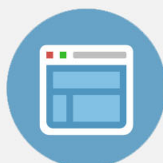

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Wide angle distributed Bragg reflectors for 590 nm amber AlGaInP light-emitting diodes

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A structure for high brightness light-emitting diodes (LEDs) is demonstrated. A distributed Bragg reflector (DBR) is used to enhance the quantum efficiency of the LEDs. This unique DBR uses a composite structure that consists of two DBRs to provide both high reflectivity and wide angle reflection. For 590 nm (amber range) AlGaInP LEDs, the quantum efficiency is increased to 5.05% by using this composite DBR structure. This result is much better than those obtained from conventional DBRs, and is comparable to that of wafer bonded AlGaInP LEDs. © *2000 American Institute of Physics.* [S0021-8979(00)01704-7]

Distributed Bragg reflectors (DBRs) consisting of multiple semiconductor layers have been found to be very effective in increasing the quantum efficiency of light-emitting diodes (LEDs), especially for AlGaInP LEDs which use the absorbing GaAs as substrates.[1–3] The conventional design of DBRs considers only the reflectivity of normal incident light. However, because the light emitted from the active region is isotropic and the reflection angle of DBRs is usually small, a large part of light escapes from the DBRs and gets absorbed by the GaAs substrate. In this article, a wide angle DBR structure, which can greatly enhance the performance of LEDs, is proposed and demonstrated experimentally.

There have been several studies on how to extract the large angle light from the top surface. For example, a thick window layer can help the light escape from the side.[4] But few people have noticed the importance of using DBRs in the wide angle emission.

In our DBR design, we stack two different DBRs together to provide wide angle reflection. Each DBR reflects a different angle of light. This combined configuration results in a wide angle DBR.

For 590 nm amber LEDs, the typical DBRs that one can use to reflect light without absorption are made from $(Al_{0.4}Ga_{0.6})_{0.5}InP/AlInP$. For 15 pairs of such 1/4 λ layers designed for 590 nm, the reflection angle is only about 20°. This is obviously not enough.

We have found in our calculation that a large difference in the refractive index of the two constituent materials in the DBR can increase the reflection angle. However, the refractive index difference is limited by the materials being used. For the LEDs discussed here, $(Al_{0.4}Ga_{0.6})_{0.5}InP/AlInP$ is about the best that one can get without absorbing the emitted light. In the new wide angle design, we add an additional DBR beneath this conventional one. Six pairs of GaAs/AlAs were used for this added DBR. The thickness of the GaAs/AlAs film stack is purposely designed to be 10% thicker to cover a wider light incident angle. The exact thickness of each GaAs and AlInP layer is 413 and 480 Å. The layer difference in the refractive index also helps to improve the reflection angle. The calculated reflectivity of this composite DBR as a function of wavelength and light-emitting angle are shown in Fig. 1. At 590 nm, the reflection angle is larger than 45°. It is more than two times larger than the reflection angle of the conventional DBR. If the wavelength of the emitted light is red or blueshifted, the wide reflection zone can still be maintained.

We have grown our samples on (100) N–GaAs substrates by low-pressure metalorganic chemical vapor deposition (MOCVD). The growth pressure was 50 mbar and the growth temperature was 750 °C.

At first, a wide angle DBR (the combined DBR) alone was grown. The simulated and measured reflection spectra for the DBR are shown in Fig. 2. Very good agreement was observed between the measured and the calculated results. The reflection at the air/semiconductor interface (about 33%) can cause interference between waves traveling in the DBR, and oscillations in the reflection spectrum. This, however, does not affect the real device operation because the DBR is below the LED's *n*-cladding layer and its reflection at the interface in between these two stacks is very small.

AlGaInP LEDs were then fabricated with the wide angle DBRs. The proposed LED consists of a wide angle DBR, a Si-doped *n*-AlInP cladding layer, seven AlGaInP quantum wells, a Mg-doped *p*-AlInP cladding layer, and an 8 μm *p*-GaP window layer. Although the 8 μm GaP window layer is thinner than the optimum 50 μm reported by Huang *et al.*[4] it does allow approximately the same amount of light emission from the side and the top. Since in this study, our emphasis is on the DBR design, we used a window layer thickness easily grown by MOCVD. The *p*-and *n*-ohmic contacts were AuBe/Au and AuGe/Ni/Au, respectively. The scribed chip (400 μm×400 μm) was then mounted and molded in resin.

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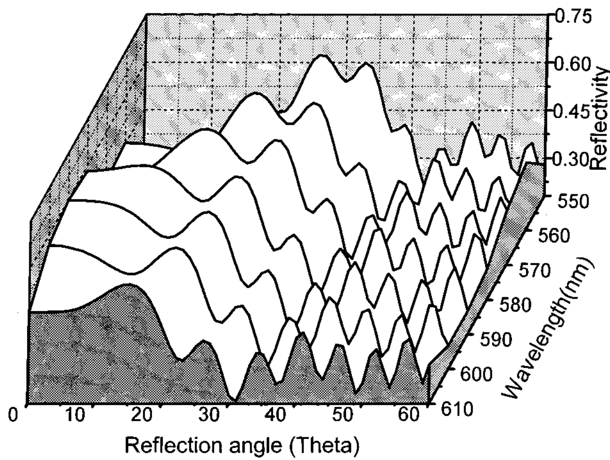

FIG. 1. The calculated reflectivity as functions of light-emitting angle and wavelength for wide angle DBR with 15 pairs of $(Al_{0.4}Ga_{0.6})_{0.5}InP/AlInP$ DBR and six pairs of GaAs/AlAs DBR.

The internal resistance of the DBR is also important in this application. The resistance of a DBR usually increases in response to both the increasing band gap differences within two constituent materials and the number of pairs of DBRs. However, in view of the fact that the DBR used here is *n* type, the internal resistance is inherently small. Experimentally, we have seen nearly identically series resistance for devices with and without this DBR.

Figure 3 shows the emission spectra of an AlGaInP LED with the wide angle DBR at an injection current of 20 mA. The spectra of a LED without DBR and a LED with conventional DBR are also shown in the same figure for comparison. The emitted light intensity is significantly higher for the LED with a wide angle DBR. The spectra for three LEDs are almost identical with respect to their shapes.

The LED improvement factor, defined as the ratio of the total light-emitting power of LEDs with DBRs and the light

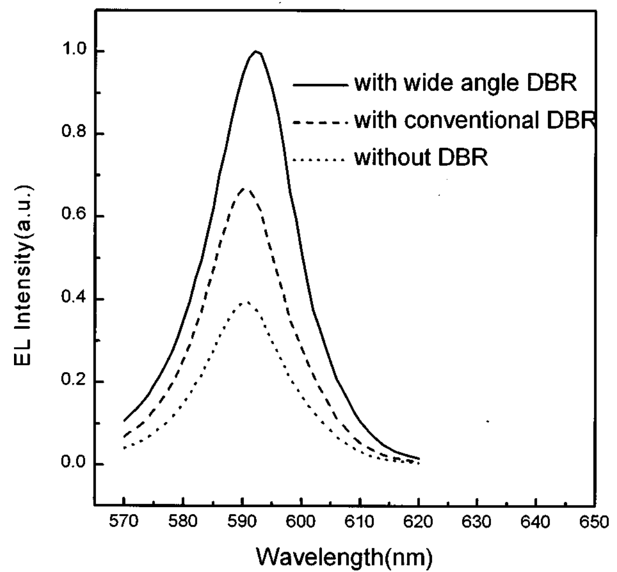

FIG. 3. The emission spectra of AlGaInP LEDs without DBR, with conventional DBR and with the wide angle DBR.

output of LEDs without DBRs, is plotted against the DBR's peak reflectivity as shown in Fig. 4. The line is the calculated result without considering the angle effect. The experimental results measured from LEDs with three different DBRs are shown by: ● (GaAs/AlAs DBR), ▲ ($(Al_{0.4}Ga_{0.6})_{0.5}InP/AlInP$ DBR), ▼ (the wide angle DBR). Using the wide angle DBR, we have obtained an improvement factor of 2.55 with respect to those without DBRs. The reason that this value is higher than the calculated result is due to the wide angle reflection. This result is also much better than those obtained with conventional DBRs. With this wide angle DBR, the output power at 20 mA is about 2.1 mW and its quantum efficiency can reach 5.05%, comparable with wafer bonded AlGaInP LEDs with a very thick window layer.[5] We should point out that the process of mak-

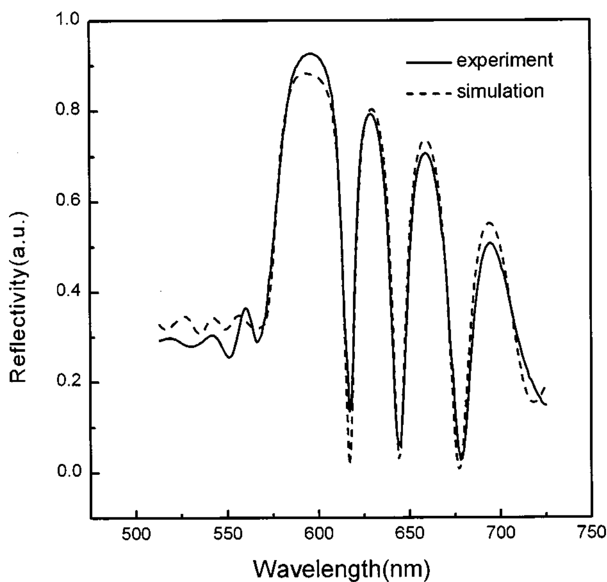

FIG. 2. The simulated and measured reflection spectra for the wide angle DBR.

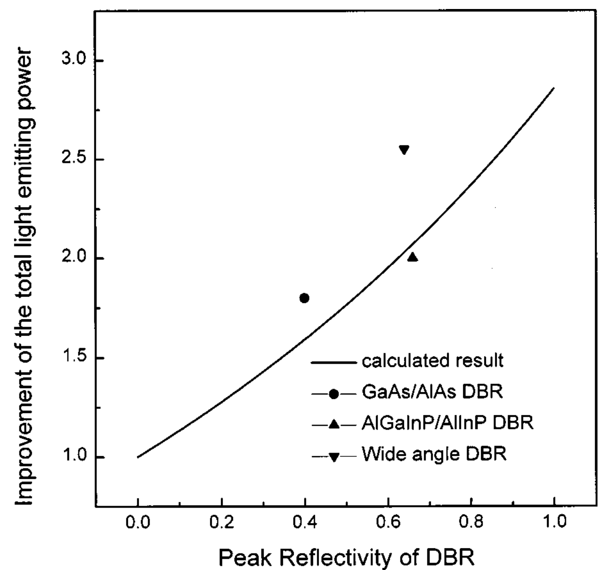

FIG. 4. The improvement on the total light-emitting power as a function of the DBR's peak reflectivity.

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ing the proposed LEDs is the same as for conventional LEDs and it is much easier than making wafer bonded LEDs. Our result would be even better if a thicker window were used.

In conclusion, a wide angle DBR has been designed and implemented in conjunction with high brightness amber LEDs. In this design both the reflectivity and reflection angle of DBRs were considered. The light intensity of LEDs with the wide angle DBRs is about 2.55 times higher than that of the LEDs without DBRs. The output power at 20 mA is 2.1 mW and its quantum efficiency is 5.05%, which are comparable to those of wafer bonded LEDs with similar emitting wavelength.

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