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Enhancement of light extraction efficiency by evanescent wave coupling effect in AlGaInP light-emitting diodes

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Although the internal quantum efficiency of AlGaInP LEDs has reached near 100%, the light-extraction efficiency (η_{ext}) is still seriously limited to a relatively lower value of about 50% even when sophisticated light extraction techniques have been employed. The low η_{ext} is caused by the high refractive index of the AlGaInP material (>3), and thus a strong total internal reflection at the interface. In a conventional flat-surface LED, only the light inside the narrow escape cone can be extracted to air, which accounts only for a few percent of the total light. We have proposed a novel light extraction technique based on an evanescent wave coupling effect in a sub-wavelength -sized ridge structure (Fig. 1). Using this technique, the light outside the escape cones can be directly extracted to air through a unique evanescent-to-propagating light transformation effect. Significant enhancement of light extraction efficiency has been demonstrated by photoluminescence studies. Here, we report on the first successful application of this technique to the AlGaInP LEDs and the observation of a significant improvement of η_{ext} over the conventional techniques.

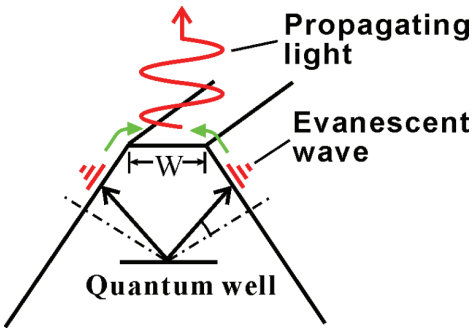

Fig. 1 Schematic illustration of the evanescent wave coupling effect in a fine ridge structure.

The original epitaxial structure, grown by MOVPE, is composed of a 0.7 μm Si-doped $Al_{0.7}Ga_{0.3}As$ layer for current spreading and ridge structure formation, a 0.1 μm Si-doped AlInP cladding layer, a 3-period $(Al_{0.7}Ga_{0.7})_{0.5}In_{0.5}P/Ga_{0.5}In_{0.5}P$ quantum well (QW) active layer, a 1.9 μm Zn-doped $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layer, and a 20 nm Zn-doped GaAs Ohmic contact layer. After the formation of an Ohmic contact on the Zn-doped GaAs (Ti/Pt/Au circles, 1% surface occupation), an Ag mirror was evaporated on the wafer surface. The LED wafer was flipped and attached to a GaAs submount by AuSn eutectic bonding. Fine ridge structures were then fabricated by photolithography and wet chemical etching on the exposed $Al_{0.7}Ga_{0.3}As$ surface after removal of the original GaAs substrate. As shown in the scanning electron microscopy (SEM) image of Fig. 2, the lateral width of the top-flat facet and the depth of the ridge were about 500 and 600 nm, respectively. These dimensions are small enough for the realization of a strong evanescent wave coupling effect as confirmed by a finite-difference time-domain simulation.

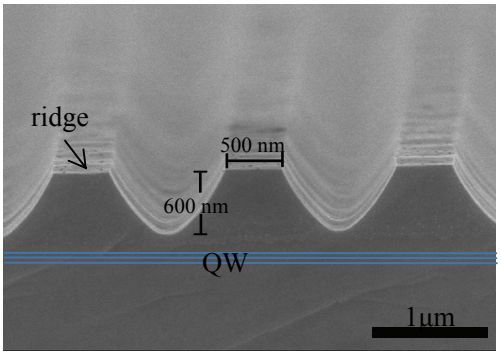

Fig. 2 SEM image of the ridge structure formed on the surface of the LED.

The wafer was isolated into 1×1 mm^2 LED chips by wet chemical etching, and the light output power was measured by a Si photodiode from the top of the device in a probe measurement system. The device with ridge structures on the surface showed an electroluminescence intensity of about 4.4 times stronger than that of a reference planar-surface device at a driving current of 20 mA. The intensity difference of these two samples can also be clearly distinguished by naked eye and the CCD photograph shown in Fig.3. Being taken from the same 12×13mm^2 wafer, these two samples should have similar internal quantum efficiency. Thus, the above results clearly indicate a 4.4-times enhancement in η_{ext} of the ridge sample as compared with the planar one. For AlGaInP LEDs, the light-extraction enhancement by the conventional techniques, such as random roughening and photonic crystals, is typically lower than 2 times over a planar surface sample. Therefore, the evanescent wave coupling effect is indeed much more effective than the conventional techniques. We think that our technique represents a significant step in the development of ultrahigh-efficiency LEDs.

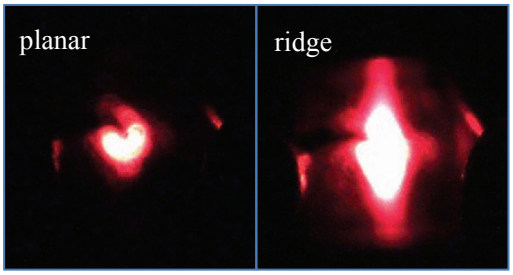

Fig.3 CCD photographs of LEDs with a planar and ridged top surface.