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On an AlGaInP-Based Light Emitting Diode with an Indium-Tin-Oxide (ITO) Direct Ohmic Contact Structure

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Abstract

An interesting AlGaInP multi-quantum-well (MQW) light-emitting diode (LED) with a direct Ohmic contact structure, form by an indium-tin-oxide (ITO) transparent film and AuBe diffused thin layer, is fabricated and studied. The direct Ohmic contact structure is performed by the deposition of an AuBe diffused thin layer and following activation process on the surface of Mg-doped GaP window layer. Experimental results demonstrate that a dynamic resistance of 5.7 Ω and a forward voltage of 1.91 V, under an injection current of 20 mA, are obtained. In addition, the studied LED exhibits a higher external quantum efficiency of 9.7% and a larger maximum light output power of 26.6 mW. The external quantum efficiency is increased by 26% under the injection current of 100 mA, as compared with the conventional LED without this structure. This is mainly attributed to the reduced series resistance resulted from the relatively uniform distribution of AuBe atoms near the GaP layer surface and the effective current spreading ability by the use of ITO film.

The quaternary $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ alloy, grown by low-pressure metal-organic chemical vapor deposition (LP-MOCVD), exhibiting a direct bandgap from 1.9 to 2.25 eV is an attractive material system for light-emitting diodes (LEDs) covering the visible spectrum from the yellow-green to red region. Recently, based on the significant improvement on epitaxial quality of AlGaInP-based material system, the internal quantum efficiency (η_i) of AlGaInP LEDs has reached near 100%. However, the external quantum efficiency (η_{ext}) of AlGaInP LEDs is still lower due to the substantial difference of the reflective index between the quaternary epitaxial layers and air. In order to maximize light extraction from the active layer, it is necessary to incorporate a wide-bandgap material like GaP or AlGaAs with sufficient thickness and electrical conductivity to act as a cap layer and to uniformly spread current from the opaque metal contact. Recently, the indium tin oxide (ITO) layer has been reported to enhance the current spreading effect in AlGaInP-based LEDs. However, it is not possible to make a good and direct Ohmic contact between the ITO and window layer. The high contact resistance degrades the electrical characteristics of AlGaInP-based LEDs. A direct and good p-type Ohmic contact should be developed after ITO deposition. In this work, for the first time, we report a simple and feasible method to directly deposit the ITO film on GaP window layer based on an AuBe diffused thin layer. The low-resistance Ohmic contact characteristics are obtained. By using an AuBe diffused metal thin film through appropriately thermal annealing, i.e., the surface activation process, an AlGaInP-based LED with ITO film is fabricated successfully.

To perform a direct-Ohmic contact, the Au (5 nm)/AuBe (120 nm)/Au (250 nm) metals were thermally evaporated in a sequential layer on the surface of p-GaP window layer. The samples were annealed in N2 ambient for 20 min at 485 ℃. These metal films were subsequently removed by using the P.A.E. (Phosphoric Acid Etchants) and KI solution. The etching process was stopped on the surface of GaP contact layer. Then, the ITO film with a thickness of 300 nm was deposited on the top surface of studied device, denoted as device A, which caused the current injection from p-electrode through ITO spreading layer into the GaP layer. For comparison, different devices, i.e., devices B and C fabricated on the same AlGaInP/GaAs epitaxial layer structure were also included in this work. For device B, the Be diffusion process and ITO film were not employed, whereas only ITO film was used in device C. The chip dimension of 280 × 280 μm^2 was used. The simplified diagrams of studied LEDs are illustrated in insets of Fig. 1(a). Figure 1(a) also shows the I-V characteristics of the contact resistances for the studied LEDs. Clearly, the device B shows the best Ohmic contact behaviors with the resistance of 9.1 Ω. For device C, the interface between the ITO and p-GaP window layer exhibits a significant Schottky-like contact property. This is caused by inherent n-type characteristics of the ITO film. On the other hand, the interface between the ITO and p-GaP layer exhibits an Ohmic contact with the resistance of 24 Ω when the Au/AuBe/Au metal is annealed at 485 ℃ for device A. The relatively higher contact resistance is found for device A. This result could be related to the imperfect or roughening surface of GaP layer attributed to the previous wet etching process which is used to remove the Au/AuBe/Au metal film. This means that the grown wafer is partially damaged. Although the GaP surface is damaged by wet etching process, the studied device A still exhibits good Ohmic contact characteristics. This is mainly attributed to the formation of thin AuBe diffused layer, by thermal annealing, on the surface of p-GaP window layer. Figure 1(b) shows the depth profiles, without ITO layers, analyzed by secondary ion mass spectrum (SIMS), of device A. Clearly, Be atoms exist and distribute in shallow GaP layer surface. The depth of Be diffusion near the GaP window layer is about of 0.1 μm. Here, the presence of this thin AuBe diffused layer yields the Be dominant metallic surface layer.

(a) (b)

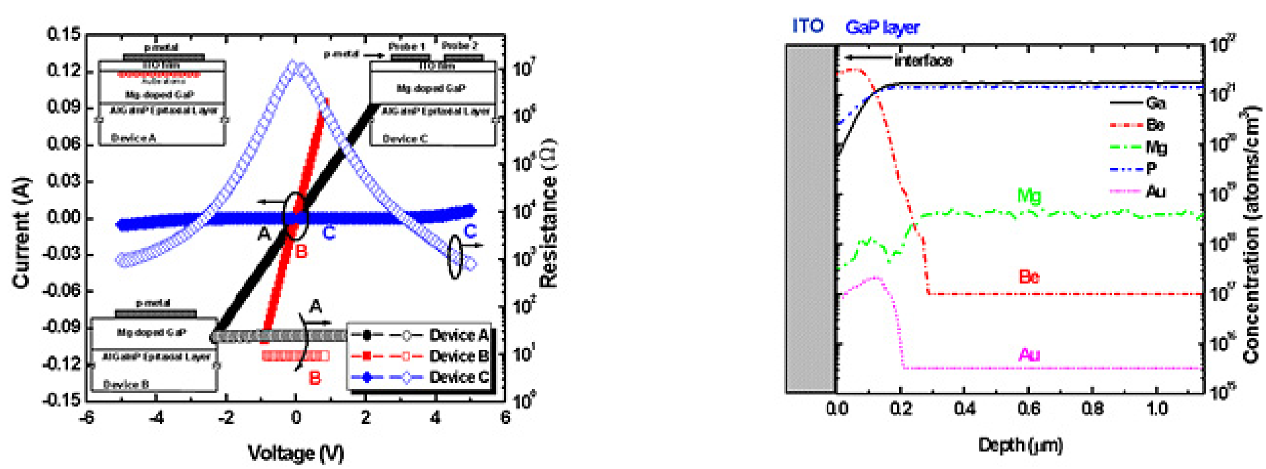

Figure 1 (a) I-V characteristics of contact resistances for the studied LEDs. The inset shows the simplified schematic diagrams for studied devices. (b) The depth profiles, by SIMS measurement, for device A.

Figure 2 illustrates the forward current I_F and dynamic resistance R_d as a function of the applied voltage V_F for studied devices A and B. Experimentally, under a normal DC injection current of 20 mA, the forward voltages of 1.91 and 1.96 V and dynamic resistances of 5.7 and 8.1 Ω are found, respectively, for devices A and B. Although device B has lower contact resistance, the device A exhibits better current spreading effect due to its lower forward turn-on voltage. Hence, for device A, the current injected from p-side electrode is effectively spread through the ITO current spreading layer because the good Ohmic contact is formed. In addition, the lower dynamic resistance of device A can be attributed to the thermal diffusion of Be atoms into the GaP layer. This structure causes better current spreading ability and significantly lower surface series resistance at room temperature. As a result, the good performance of higher conductivity and lower forward voltage can be obtained.

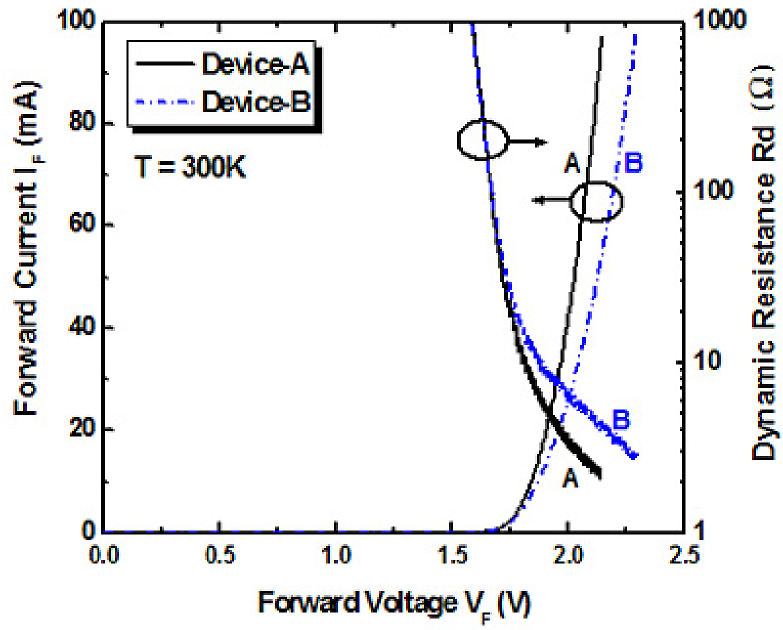

Figure 2 Forward I-V and dynamic resistance characteristics of the studied LEDs.

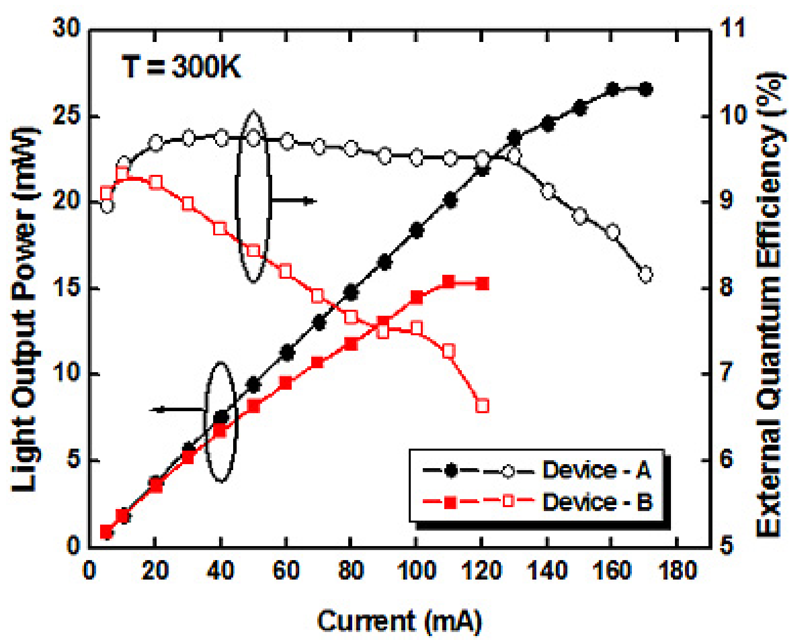

Figure 3 Light output power and external quantum efficiency as a function of DC injection current.

Figure 3 shows the light output power and external quantum efficiency as a function of DC operation current at room temperature. Both of the studied LEDs exhibit linear relations between the light output power and injection current. It is worth to mention that the LED with an ITO conducting film (device A) achieves a stable light output power at high injection current condition due to the reduction of current crowding effect near the opaque metal. Experimentally, an output power of 26.6 mW is obtained for the device A under a current of 160 mA. However, the light output power of the device without ITO film (device B) is saturated at 110 mA and gradually degraded with further increasing the injection current. Clearly, the device B suffers from current crowding effect whereby the injection current is mainly confined around the metal contact region. This certainly gives the increase of joule heating. The external quantum efficiencies of the device A are 9.7 and 9.5% at 50 and 100 mA, respectively. Obviously, these values are significantly higher than those of device B. For instance, the device B shows lower external quantum efficiency value of 7.5% at 100 mA.