Improving performances of ITO/GaP contact on AlGaInP light-emitting diodes*

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In this paper AlGaInP light emitting diodes with different types of electrodes: Au/Zn/Au-ITO Au/Ti-ITO Au/Ge/Ni-ITO and Au-ITO are fabricated. The photoelectricity properties of those LEDs are studied. The results show that the Au/Zn/Au electrode greatly improves the performance of LEDs compared with the other electrodes. Because the Au/Zn/Au electrode not only forms a good Ohmic contact with indium tin oxide (ITO), but also reduces the specific contact resistances between ITO and GaP, which are 1.273×10^{-6} $\Omega\cdot$cm^2 and 1.743×10^{-3} $\Omega\cdot$cm^2 between Au/Zn/Au-ITO and ITO-GaP respectively. Furthermore, the textured Zn/Au-ITO/Zn electrode is designed to improve the performances of LEDs, reduce the forward-voltage of the LED from 1.93 to 1.88 V, and increase the luminous intensity of the LEDs from 126 to 134 mcd when driven at 20 mA.

Keywords: Ohmic contact, tunneling, light emitting diode, Zn/Au-ITO/Zn
PACC: 7340C, 7340G, 7360L, 7865K

1. Introduction

High-brightness visible light emitting diodes (LEDs) are of increasing interest because of potential applications such as outdoor displays and digital imaging. $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is an attractive material system for LEDs covering a red-to-green portion of the visible spectrum, and is lattice matched to GaAs.[1] Indium tin oxide (ITO) thin film is widely used in the current spreading layer of optoelectronic devices for its low resistance and high transparency.[2] However, ITO is an n-type semiconductor while its contact layer p-GaP is p-type semiconductor in LED, which will form Schottky contacts. The authors[3,4] found that to reap the benefits of ITO, the contact resistance between the window layer and the ITO layer is necessarily reduced by introducing a thin highly-doped p-type GaAs layer to form a tunneling contact layer. However, the highly-doped p-type GaAs layer will absorb visible light seriously. One could achieve a good Ohmic contact through tunneling when the n^+–p^+ junction was properly reverse biased.[5,6]

In this paper, AlGaInP LEDs with different electrodes are fabricated. In order to evaluate the electrical properties of the LEDs, the specific contact resistances of Au/Zn/Au-ITO, Au/Ti-ITO, Au/Ge/Ni-ITO and Au-ITO are measured. The I–V characteristics of the AlGaInP LEDs with different electrodes are compared, and then we fabricate novel LEDs to achieve better performance.

2. Experiments

First, we performed a contrast experiment to measure the specific contact resistances between ITO and different metals, the process was as follows: ITO-coated glass with a sheet resistance of 9 $\Omega/\Box$ was fabricated by the electron beam evaporation system of the Ultimate in VACunm Technology (ULVAC). The preparation condition was as follows: flux of O_2 25 sccm, substrate temperature 350 °C, deposition rate 4 Å/s (1 Å=0.1 nm), and vacuum pressure: $\sim10^{-3}$ Pa. The transmittance of 300 nm-thick ITO at λ = 630 nm was about 91% measured by a spectrophotometer. Au/Zn/Au(10/10/300 nm), Au/Ti(300/10 nm), Au/Ge/Ni(300/15/10 nm), and

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Au(300 nm) layers were also deposited on the ITO film by the e-beam evaporation, separately and the preparation condition is as follows: vacuum pressure $\sim 10^5$ Pa, and substrate temperature 50 °C. Then circular transmission line model (CTLM) patterns were determined by the standard photolithographic, and then the specific contact resistances between different samples were determined by Agilent 4156C semiconductor parameter analyser. The spacings between CTLM pads were 4 and 8 μm, the radius of the first round was 105 μm and the width of other cirques was 60 μm as shown in the inset of Fig.1.

In order to investigate whether Zn element diffused into the GaP layer as well as the role it played, two samples were prepared. One is Sample A: the ITO film was deposited on the GaP layer, then annealed at 430 °C for 40 s, and CTLM patterns were determined for measuring specific contact resistances of ITO/GaP. The other is Sample B: the Au/Zn/Au film was deposited after ITO film had been deposited on the GaP substrate, then annealed at 430 °C for 40 s, and the Au/Zn/Au film was removed by wet etching. Finally, the same CTLM patterns were determined on the ITO layer for measuring specific contact resistances of ITO/GaP.

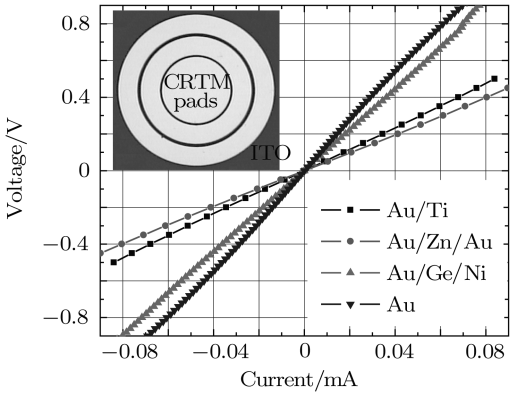


Fig. 1. CRTM pads and the I–V characteristics of Au/Zn/Au, Ti/Au, Au/Ge/Ni/Au, and Au contacts on ITO.

Then we studied the performances of chips with different electrodes. The epitaxial material of AlGaInP LED was grown by metalorganic chemical vapour deposition on temporary n^+-GaAs substrates as shown in Fig. 2. The electrodes of LEDs were deposited under the same condition as that for the CRTM pads.

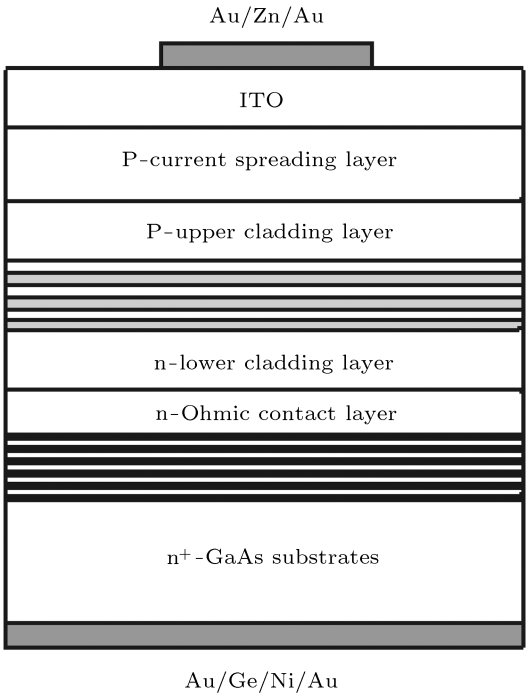


Fig. 2. Schematic of LED structure.

3. Results and discussion

3.1. Mechanism of Zn/Au electrode for reducing forward voltage of LED

All the data are averaged over congener samples after testing repetitiously Figure 1 shows the typical I–V characteristics of the metal-ITO contacts, which were measured between the CTLM pads with a spacing of 4 μm after annealing at 430 °C for 40 s (between the first ring and the second ring). Note that the Au sample reveals a nearly linear behaviour after annealing, while the Au/Zn/Au, Au/Ti and Au/Ge/Ni pads showgood linear behaviours, however, the specific contact resistance of Au/Ge/Ni-ITO is much bigger than those of the others.

Specific contact resistances were determined from a plot of the measured resistances versus the spacing between the CTLM pads.[7] The least square method was used to fit the experimental data to a straight line. Our results suggest that specific contact resistances of the Au/Zn/Au-ITO and the Ti/Au-ITO samples reduce after they have been annealed at 430 °C for 40 s. In Fig. 3, the specific contact resistances of most samples decrease when rapid thermal annealing (RTA) temperature < 430 °C and increase when RTA temperature > 430 °C. This may be attributed to the change of ITO resistivity after

RTA at different temperatures.[8] The trend of changes in carrier concentration of ITO is opposite to that of specific contact resistances at corresponding RTA temperatures.[9] The increase of the ITO resistivity is due to the incorporation of oxygen introduced from the ambient gas.[10] Ti and Zn have the lowest work function of 4.33 eV among these elements, and Zn is also a good doping element for p-GaP.[11] Therefore, they can form the best Ohmic contact with n-type ITO, and the specific contact resistances of Ti/Au-ITO and Au/Zn/Au-ITO are 1.079×10^{-6} $\Omega\cdot$cm^2 and 1.273×10^{-6} $\Omega\cdot$cm^2 respectively. However, the mechanical adhesion between Ti and ITO is not good, especially after being annealed at a high temperature. The electrode will break off after the gold wire ball is bonded as shown in the insert of Fig. 4. The electrode of Ti/Au will break off when the RTA temperature exceeds 360 °C, and the breaking-off proportion is about 60% and 100% when RTA at 360 °C and 430 °C respectively. The Au electrode has the same problem as the Ti/Au electrode.

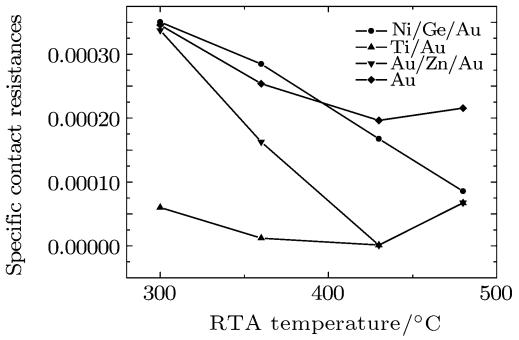


Fig. 3. Specific contact resistances between electrodes and ITO after RTA.

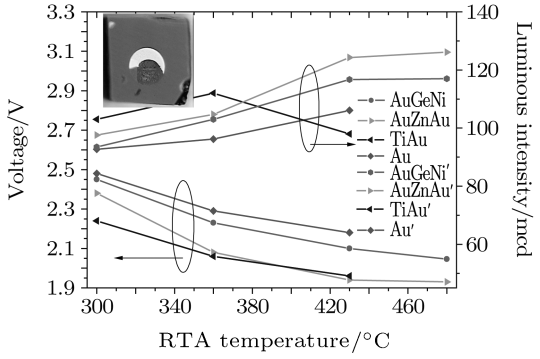


Fig. 4. Forward voltage and luminous intensity of LEDs driven at 20 mA.

In this paper, all chips have the same dominant emission wavelength of 630 nm. The forward voltages of LEDs were measured by using the HP-4156C semiconductor parameter analyser and the luminous intensities of LEDs at 20 mA were then measured by an integrated sphere detector. The LED with Au/Zn/Au electrode indicates the best performance as shown in Fig. 4. The forward voltage of all the chips descends observably with the rise of RTA temperature. There are two reasons: first, the alloy of n-type Au/Ge/Ni electrode forms a good Ohmic contact with GaAs;[12] second, the contact resistances between metal electrode and ITO or between ITO and p-GaP decrease after RTA. It can be explained in Fig 3 directly. Figure 5 helps us investigate whether the element of electrode diffuses into GaP and its influence. The comparative experiment as mentioned in Section 2 was made. It is obvious that Au/Zn/Au electrode affects the specific contact resistance between ITO and GaP after RTA. The Results show that the specific contact resistances of samples A and B are $5.63\times10^{-3}\Omega\cdot$cm^2 and 1.743×10^{-3} $\Omega\cdot$cm^2 respectively when they were annealed at 430 °C for 40 s as shown in Fig. 5.

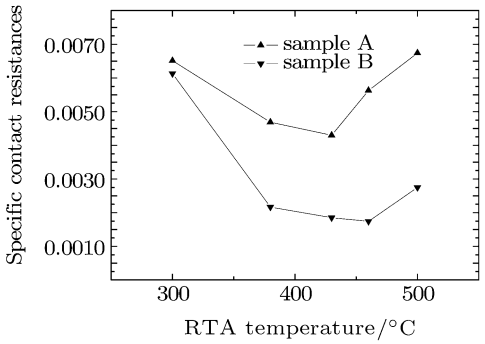


Fig. 5. Specific contact resistances between ITO/GaP in different process after RTA.

Although the Au/Ti-ITO contact has a better performance than the Au/Zn/Au-ITO contact after RTA at 430 °C, the voltage of LED with Au/Zn/Au electrode is lower. It can be explained with Figs. 3, 4 and 5. This may be due to the fact that the Au/Zn/Au electrode not only forms a good Ohmic contact with ITO, but also reduces the specific contact resistance between ITO and GaP. The diffusion of Zn element into p-GaP results in the narrowing of the potential barrier width of the contact interface and by the tunneling effect, a good Ohmic contact forms.[13,14] Figure 6 shows the diffusion abilities of Au and Zn elements. The first layer is Au/Zn/Au electrode, the second layer is ITO and the third layer is GaP. The EDS shows that Zn element has already passed though the

ITO layer and diffused into the surface of GaP layer.

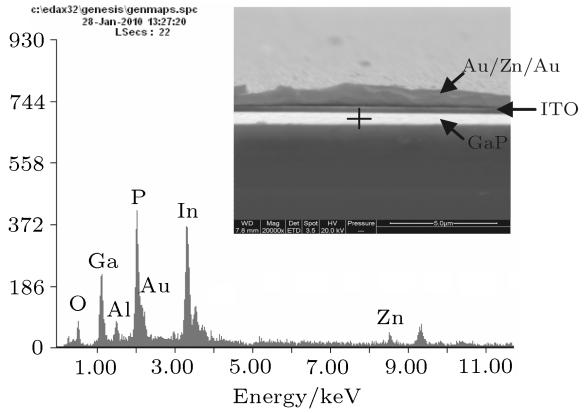


Fig. 6. Cross section images of LED, observed by SEM and EDS.

The increase of LED luminous intensity in Fig. 4 is mostly attributed to the rise of ITO transmittance after RTA and shown in Fig. 7. Moreover, the decrease of ITO square resistance under an appropriate RTA temperature, which is good for current spreading, will also improve luminous intensity.[15]

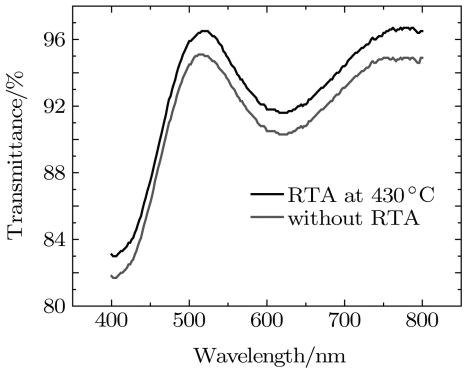


Fig. 7. Transmittance of ITO film vs wavelength after RTA.

3.2. Improved electrode for LEDs

From the experimental results and the known fact that the extraction efficiency of LEDs can be increased by surface texture,[16] we fabricated LED with a new type of electrode. After the growth of the LED wafer, the regular hole-pattern was determined on the GaP layer by using the inductively coupled plasma reactive ion (ICP-RIE) system. The periodic distances of hole-pattern on GaP were 4 μm and 8 μm as shown in Fig. 8. Then, we deposited a 20 Å-thick Zn layer as a contact layer, ITO film with a thickness of 3000 Å was evaporated as a current spreading layer. Finally, the Au/Ge/Ni/Au and Au/Zn/Au were deposited as n- and p-electrodes, respectively. The wafer was then cut into chips with a size of 200 μm×200 μm. And a conventional LED chip without Zn contact layer and textured surface was also fabricated by using the same LED wafer for a fair comparison.

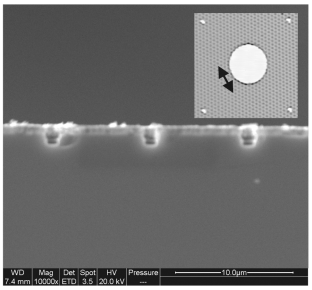


Fig. 8. Cross section image by SEM and the top view of LEDs.

The I–V characteristics of the conventional LED chip and the chip with improved electrode are shown in Fig. 9. The forward voltages of the LEDs with different structures are 1.93 and 1.88 V at 20 mA, separately, which are in agreement with the previous results that the diffusion of Zn element could reduce the specific contact resistance between ITO and GaP and thus reduce the forward voltage. In addition, the increase of contact area by surface texture will also reduce the contact resistance and the forward voltage. The light output powers of LEDs are shown in the inset of Fig. 9. The luminous intensity of the LED with an improved electrode was increased by 6.3% as compared with that of conventional LED at 20 mA. Moreover, Zn layer can reduce the forward voltage without reducing the luminous intensity, this may be due to the high transmittance of 20 Å-thick Zn film as shown in Fig. 10.

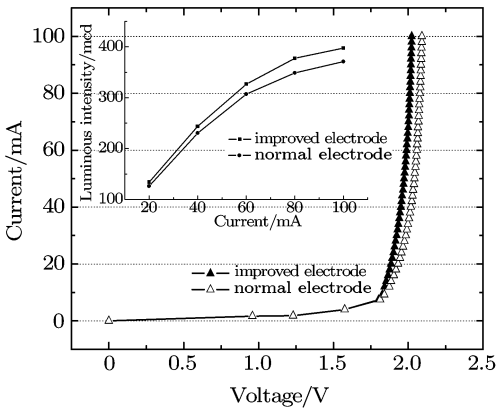


Fig. 9. I–V characteristics and luminous intensities of LEDs with and without improved electrodes.

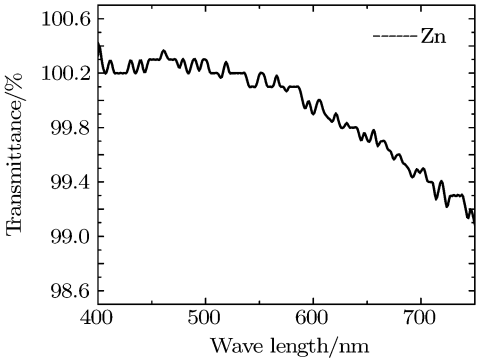


Fig. 10. Transmittance of Zn film with a thickness of 20Å.

4. Conclusion

In this paper studied are the specific contact resistances of metal electrode/ITO and ITO/GaP to investigate the mechanism of the electrode for reducing the forward voltage of LEDs. After the samples are annealed at 430 °C for 40 s the specific contact resistance between An/Zn/Au and ITO is 1.273×10^{-6} $\Omega\cdot\mathrm{cm}^2$, and the specific contact resistance between ITO and GaP is 1.743×10^{-3} $\Omega\cdot\mathrm{cm}^2$. In addition, the forward voltage of the LED with improved electrode is 1.88 V at a current injection of 20 mA. The external quantum efficiency and the power efficiency are raised by 6.3% and 2.7%, respectively.

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