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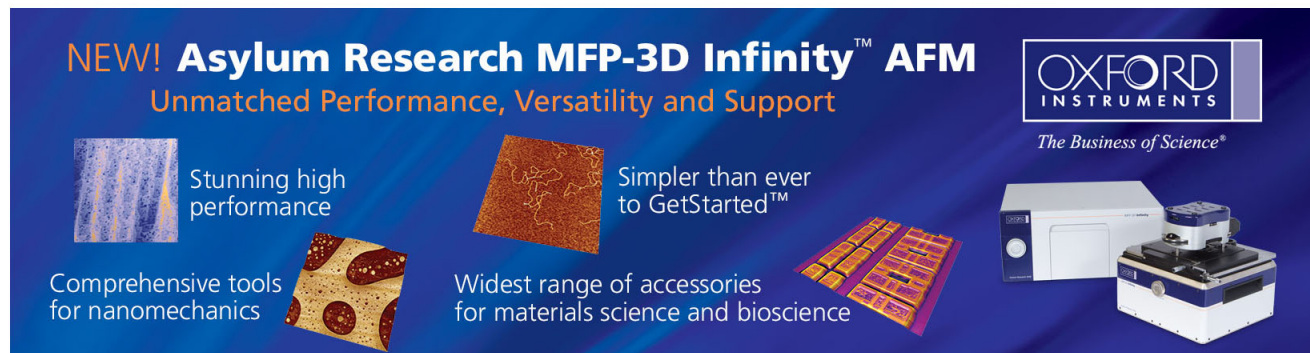
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High-power AlGaInP light-emitting diodes with metal substrates fabricated by wafer bonding

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High-power light-emitting diodes (LEDs) fabricated on Cu substrates were investigated in this study. The AlGaInP LED structure was bonded to a Cu substrate by using indium-tin-oxide as the diffusion barrier layer. It was found that Cu-substrate-bonded LED devices could be operated in a much higher injection forward current, 800 mA, which was eight times higher than that used in traditional GaAs-substrate LEDs. The luminous intensity of the Cu-substrate LEDs could reach as high as 1230 mcd, which was three times higher than that of the GaAs-substrate LEDs. © 2004 American Institute of Physics. [DOI: 10.1063/1.1682696]

The epitaxial growth techniques have significantly improved the brightness and efficiency of light-emitting diodes (LEDs). LEDs operating in the wavelength region ranging from red to green light have been employed by the AlGaInP alloy system grown on GaAs substrates.¹ However, its use in high-efficiency applications has been limited because of the substrate absorption and the internal reflection. Fortunately, the wafer bonding process can solve these problems.²⁻⁷ Nevertheless, despite improving luminous efficiency, LED sources are limited to use in low power applications due to the low thermal conductivity of the substrate. To achieve higher light output performance, it is necessary to drive the LED at a higher current. In this study, AlGaInP LEDs with wafer-bonded metal (Cu) substrates were proposed. The performance of the Cu-substrate LEDs was also been investigated.

The AlGaInP multiple quantum well (MQW) LED structures were grown on GaAs substrates through low-pressure metalorganic chemical vapor deposition. The LED structure consisted of an *n*-GaAs buffer layer, an *n*-InGaP etching stop layer, an *n*-GaAs ohmic contact layer, an AlInP *n*-cladding layer, an undoped $(\text{Al}_{0.15}\text{Ga}_{0.85})_{0.5}\text{In}_{0.5}\text{P}$ MQW active region, an AlInP *p*-cladding layer, and a *p*-GaP window layer. An ITO layer was deposited on the AlGaInP LED to act as a current-spreading layer. On the other hand, the host Cu substrate played the role of a heat sink substrate. These two wafers were cleaned and then placed in contact with each other immediately using a designed fixture⁸ that ensured uniform pressure on each of the wafers. Then, the fixture was loaded into a furnace and annealed at temperatures varying from 400 to 600 °C for 30 min in argon ambient. After the wafers were allowed to cool to room temperature, the GaAs substrate and the InGaP layer were removed by chemical etching in solutions of 1NH₄OH:10H₂O₂ and 1HCl:10H₂O, respectively. The fused epilayer was mesa-etched into isolated devices with 250×250 μm² area. The Au/AuGe dots (with a diameter of 100 μm) were deposited onto the *n*-side (*n*⁺-GaAs contact layer) and then alloyed for

ohmic contact metalizations. It should be noted that the Cu substrate is a conductor, which can act as *p*-side contact; thus it is not necessary to deposit any metal for *p*-side contact. In comparison, the LED samples with the GaAs and Cu substrates were prepared from the same AlGaInP LED epitaxial material, and the samples described here were only cut into chips without encapsulation before electrical and optical measurements.

Figure 1(a) shows a successful LED wafer bonded on a Cu substrate at 500 °C for 30 min. After removing the GaAs

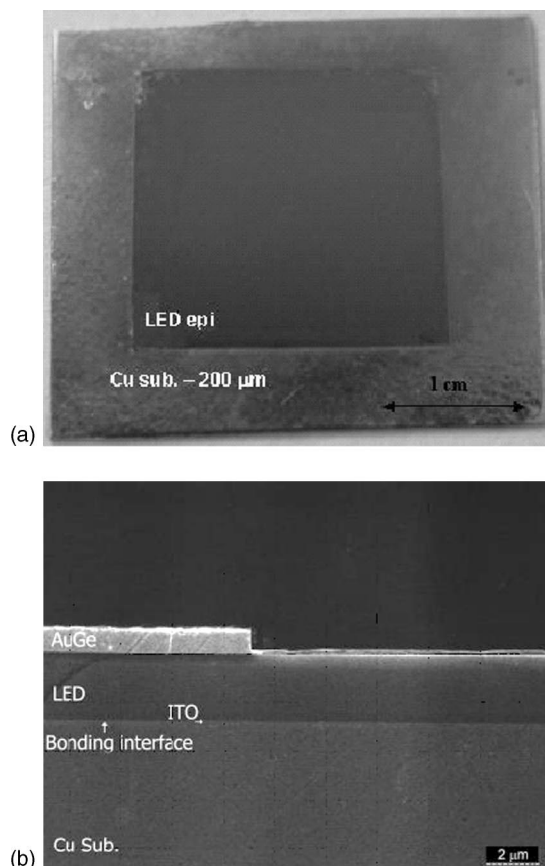


FIG. 1. (a) A successful Cu-substrate-bonded LED sample and (b) a scanning electron micrograph of the cross section of the LED structure.

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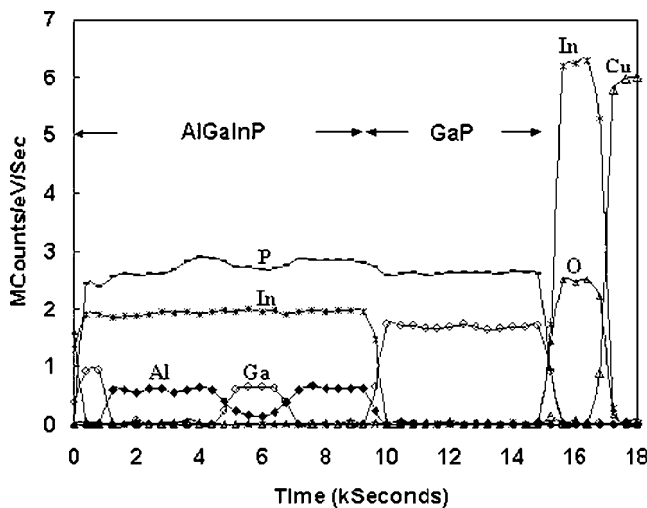


FIG. 2. Auger depth profiles of AlGaInP LED/ITO-Cu sample bonded at 500 °C for 30 min.

substrate, no peeling or cracks were observed on the mirror-like surface despite the large difference between the thermal expansion coefficients of GaAs ($6.86 \times 10^{-6}/^{\circ}\text{C}$) and Cu ($16.8 \times 10^{-6}/^{\circ}\text{C}$). The fused epilayer then was mesa-etched into isolated devices, deposited with contact dots, and then alloyed for ohmic contact metalizations.

Figure 1(b) shows the cross-section image of this bonded LED structure. Neither cavity nor unbonded area was found on the bonded interface. The Auger depth profiles of AlGaInP LED/ITO/Cu substrate are shown in Fig. 2. It revealed no Cu element diffused into the AlGaInP active layer of LEDs structure. For the purpose of comparison, an indium-tin-oxide (ITO)-free AlGaInP LED substrate was also bonded to Cu substrate at the same condition. The Cu element was found to diffuse into the AlGaInP LED structure and destroy the LED structure. The results indicated that the ITO layer employed here not only acted as a current spreading layer but also a barrier layer.

When ITO film was used as the bonding layer, it was also found that the bonding temperature would affect the yield of the Cu-substrate LEDs. The sample did not bond at temperatures below 400 °C. At temperatures greater than 400 °C, the bonded area increased when temperature increased as a result of both the reaction and diffusion rates increasing with temperature. However, when bonding temperature reached 600 °C, the Cu element could penetrate through the ITO layer and destroy the LED structure.

Figure 3 presents the current versus voltage (I - V) of the Cu-substrate LEDs bonded at 500 °C for 30 min. The device exhibited normal p - n diode behavior with a forward voltage of 1.96 V at 20 mA, which was similar to that of GaAs-substrate LEDs. This indicated that the wafer-bonding process did not degrade the performance of LEDs. It is worthy to note that the series resistance of Cu-substrate LED (1–2 Ω) is lower than that of GaAs-substrate LED (5–7 Ω).⁹

The effects of heat sink observed in high power LEDs are very important with regard to the removal of heat from LED devices. The performance of the LEDs would otherwise degrade when the operation temperature increased. Figure 4 shows the peak spectral wavelength as a function of the dc drive current. During the test conditions, these two LED

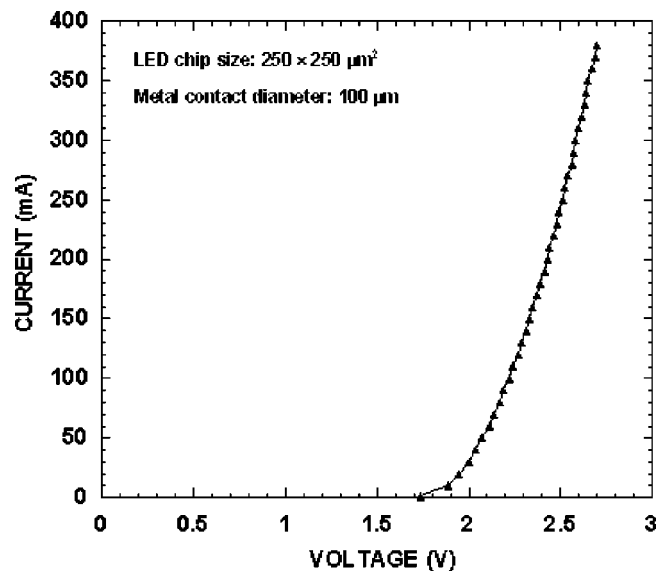


FIG. 3. Current–voltage characteristic of the Cu-substrate-bonded LED devices fabricated by wafer bonding technology.

samples, which had been cut into chips without encapsulating, were put on a metal chunk. The data show that the emission peak wavelengths shift toward longer wavelengths with increasing dc drive current, which is caused by the joule heating. Unlike the 4 nm redshift exhibited at 170 mA in GaAs-substrate LEDs, the Cu-substrate LED devices exhibits a more favorable 2 nm redshift. The redshift of the emission wavelength occurred as the temperature increased. From the shift in emission wavelength and a wavelength shift with temperature of 0.096 nm/°C for 620 nm AlGaInP LEDs,¹⁰ it could be estimated that the thermal resistance of the Cu-substrate LEDs was approximately 60 °C/W smaller than that of GaAs-substrate LEDs. Thus the temperature of GaAs-substrate LEDs was about 20 °C higher than that of the Cu-substrate LEDs at 170 mA.

Figure 5 shows the effects of injection current on the luminous intensity of the LEDs. When the injection current was less than 100 mA, the luminous intensities of two samples were the same, meaning that the wafer-bonding pro-

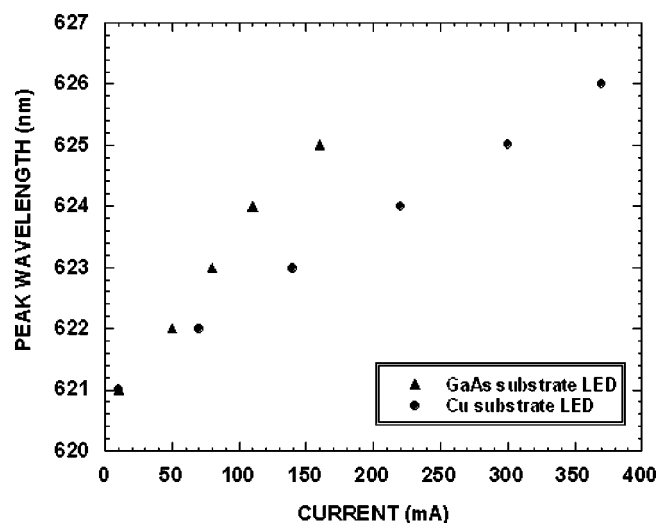


FIG. 4. Peak spectral wavelength against dc injection current for the LEDs with a GaAs substrate and a Cu substrate.

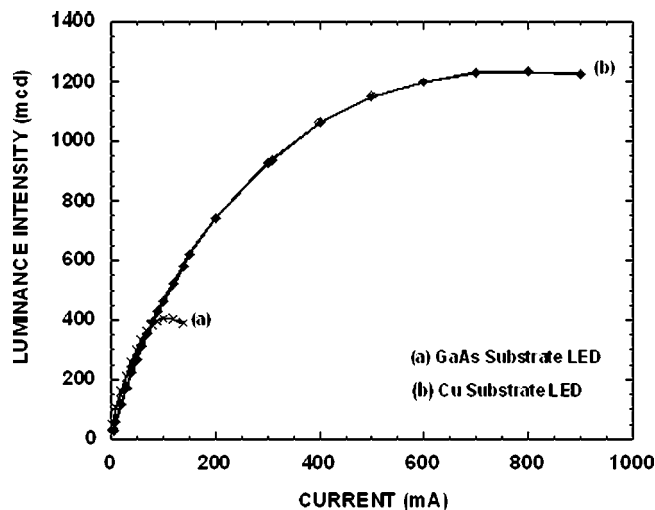


FIG. 5. L - I curves for conventional GaAs-substrate LED and Cu-substrate LED.

cess did not degrade the performance of Cu-substrate LEDs. When the injection current reached 100 mA, the GaAs-substrate LEDs were saturated. However, the intensity of the Cu-substrate LEDs did not saturate at 100 mA. The maximum luminous intensity of Cu-substrate LEDs could reach as high as about 1230 mcd at 800 mA, which was three times higher than the saturation intensity of the GaAs-substrate LEDs at 100 mA.

These results were due to a much smaller series resistance of the Cu-substrate LEDs as compared with GaAs-substrate LEDs, thereby reducing the total amount of joule heating. Since the reduction of the joule heating would increase the quantum efficiency of the LEDs, the Cu-substrate LEDs had a smaller redshift, and could be driven at a higher current and therefore obtain a higher luminous intensity. This difference might also be a result of the disparity between their respective thermal conductivities; the thermal conductivity of Cu ($401 \text{ W m}^{-1} \text{ K}^{-1}$) is nine times higher than that of GaAs ($46 \text{ W m}^{-1} \text{ K}^{-1}$). Therefore, by using these wafer bonding techniques, the joule-heating problem in conventional LEDs can be significantly reduced.

The other important issue of the Cu-substrate LEDs is the reliability. Copper is an impurity long known to cause strong degradation in LEDs.¹¹ The efficiency of Cu-contaminated LEDs would significantly decrease after life test. In this study, the life test of Cu-substrate LEDs was performed at forward current of 20 mA in room temperature, corresponding to 32 A/cm^2 . As shown in Fig. 6, the degradation of the luminescence-output intensity was less than 5% after 500 h of life test.

In summary, high-power Cu-substrate LEDs fabricated by bonding AlGaInP LED structure to Cu substrate were investigated in this study. An ITO film was used as an intermediate layer to bond wafers. It was found that the sample did not bond at temperatures below 400°C . When bonding temperature reached 600°C , the Cu element diffused through the ITO layer and destroyed the LED structure. Fortunately,

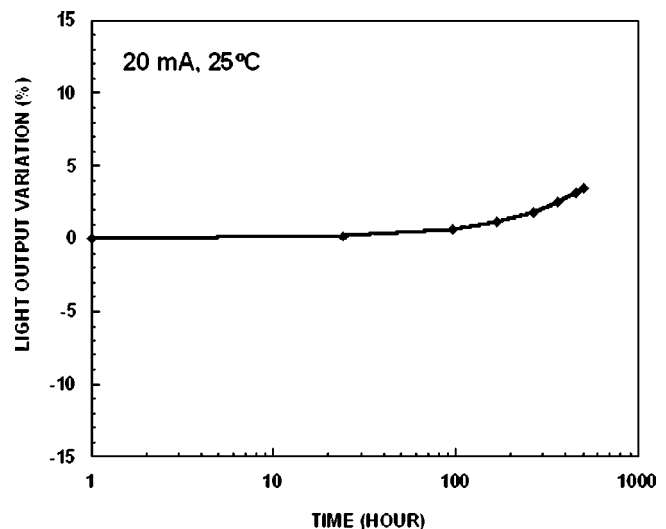


FIG. 6. Luminescence-output intensity variation as functions of time. During this life test measurement, a 20 mA current was injected into the Cu-substrate LED at room temperature.

Cu did not penetrate the ITO layer when samples were bonded at 500°C for 30 min, and the high-power Cu-substrate LEDs were successfully fabricated. In Cu-substrate LEDs, the joule heating exhibited in conventional GaAs-substrate LEDs was significantly reduced because the Cu substrate has larger thermal conductivity and lower thermal resistance as compared with GaAs substrate. It was found that Cu-substrate LEDs could be operated in a much higher injection forward current, 800 mA, which was eight times higher than that used in GaAs-substrate LEDs. The luminous intensity of the Cu-substrate LEDs could reach as high as 1230 mcd, which was three times higher than that of the GaAs-substrate LEDs.

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