High-Temperature Stability of 650-nm Resonant-Cavity Light-Emitting Diodes Fabricated Using Wafer-Bonding Technique on Silicon Substrates

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Abstract—AlGaInP-based visible 650-nm GaInP–AlGaInP resonant-cavity light-emitting diodes (RCLEDs) with high-temperature stability were fabricated by wafer-bonding techniques on Si substrates. In this study, the metal-bonding RCLEDs (MBRCLEDs) devices were designed with 84-pm apertures for light output. The MBRCLEDs with a maximum wall-plug efficiency of 13.7% were demonstrated at an injection current of 2.5 mA. In addition, the improved heat sinking of MBRCLEDs led to lower junction temperature, and resulted in a very low power decay of 0.31 dB from room temperature to 100 °C at an injection current of 20 mA.

Index Terms—Metal-bonding resonant-cavity light-emitting diodes (MBRCLEDs), plastic optical fiber, resonant-cavity light-emitting diodes (RCLEDs).

I. INTRODUCTION

VIsIBLE 650-nm AlGaInP-based resonant-cavity light-emitting diodes (RCLEDs) have recently become the most suitable light sources in the applications of low-cost and short-distance network systems based on plastic optical fibers due to a minimum attenuation loss (~0.1 dB/m) at 650 nm [1]. The development of the RCLEDs was focused on achieving high output power, high efficiency, high modulation speed, high coupling efficiency, stable reliability, and low-cost fabrication. From these requirements, the high-performance visible 650-nm RCLEDs have been fabricated [2]–[4]. RCLEDs exhibit several properties which are different from conventional LEDs such as better directionality of the emitted light, narrower spectral bandwidth, higher quantum efficiency, higher output intensity, and higher modulation speed. These properties make RCLEDs an ideal light source for optical communication [5], [6]. Similar to vertical-cavity surface-emitting lasers (VCSELs), RCLEDs have high reflectivity (>98%) bottom n-type distributed Bragg reflectors (DBRs); however, the top p-type DBR has fewer pairs in RCLEDs, compared to VCSELs DBRs. Recently, we demonstrated AlGaInP RCLEDs with different cavity designs which have excellent performances [7]; however, 650-nm-band AlGaInP alloys have several inherent drawbacks, such as the limited barrier height in the GaInP–AlGaInP quantum-well structures and larger thermal resistively due to the large mass difference between gallium and indium [8], [9]. These properties of red visible GaInP–AlGaInP quantum wells will, therefore, affect the temperature sensitivity of GaInP–AlGaInP devices, so the epi-structure needs to be properly designed to control temperature-dependent cavity detuning [7], [10], [11]. Most applications require stability at high-temperature operation; however, wafer-bonding techniques were used in this study to fabricate 650-nm RCLED devices with high-temperature stability. Since the thermal conductivity of Si is 1.31 W/cm·K at room temperature (RT), which is larger than GaAs (0.44 W/cm·K) [12], we replaced the conventional GaAs substrate with a Si substrate to improve the thermal stability of the devices. In this letter, conventional RCLED without the bonding process will be compared to the metal-bonded RCLED (MBRCLED). Furthermore, the current–voltage (I–V) and light–current (I–L) characteristics, wall-plug efficiencies, variations of junction temperature, and eye diagrams will be presented and discussed.

II. EXPERIMENT

The samples were grown on 3-in substrates tilted by 6° toward ⟨111⟩ by a low-pressure (50 torr) metal–organic chemical vapor deposition system. The epitaxial structure consisted of a 1000-Å-thick etching stop layer of n-Ga0.5In0.5P grown on the GaAs buffer layer, 35 pairs of n-type (n = 3 × 10^{18} \text{ cm}^{-3}) Al0.2Ga0.8As–Al0.2Ga0.8As DBRs, which have a reflectivity of 98% and a specific contact resistance of 1 × 10^{-6} \Omega \cdot \text{ cm}^2, a standardized one-wavelength-thick cavity consisting of three pairs of undoped Ga0.5In0.5P quantum wells and (Al0.2Ga0.8)0.1In0.9P barriers, an oxidation layer with higher aluminum composition p-Al0.8Ga0.2As grown upon the active layer, six pairs of C-doped Al0.2Ga0.8As–Al0.2Ga0.8As p-DBR with 1 × 10^{-5} \Omega \cdot \text{ cm}^2 contact resistance, and a 5-nm-thick p+-GaAs contact layer (p = 5 × 10^{-9} \text{ cm}^3) grown on top for improved ohmic contact formation. The schematic diagram of the conventional RCLED device is shown in Fig. 1(a). The Ti–Pt for p-ohmic contact was deposited on the p+-GaAs cap. A 1-μm-thick 130-μm diameter SiN$_x$ hard mask was deposited on the wafer surface for mesa dry etching and for protection from steam during the oxidation process. The 84-μm aperture for light output was then formed using a
wet thermal oxidation processes, and the polyimide was coated on the wafer to form a planarized device structure. Lastly, a p-electrode Ti–Pt–Au pad for wire bonding was deposited and the n-GaAs substrate was thinned to 100 μm. Fig. 1(b) shows that the wafer was bonded on sapphire using wax in vacuum at 120 °C ambient. The GaAs substrate and etching stop layer were removed by chemical etching in solutions of 1NH2OH : 10H2O2 and 1HCl : 10H2O, respectively, as shown in Fig. 1(c). The bonding metals Ti–Pt–Au–In were then deposited on the n-Si substrate, and the AuGe–Au–Ti–Pt–Au metals were deposited on the temporary sapphire with the epi-layer, as shown in Fig. 1(d). The Au and In metals in the bonding layers on the Si substrate and the LED layer were used as eutectic metals in the bonding process. Ti and AuGe metals were used for the Si substrate and n-ohmic contact layers, respectively. The wafer pairs were loaded into graphite jig and an external pressure 0.175 Kg/cm² was applied on the wafers during the wafer bonding process. The jig was then loaded into an oven and annealed at a temperature varying from 180 °C to 230 °C for 120 min in a nitrogen ambient for wafer bonding. After wafer bonding, the fused wafer pairs were immersed in 90 °C organic solution to remove the wax and temporary sapphire substrate. The processed wafer was ground and polished down to 150 μm, and then the Ti–Au ohmic contact was deposited on the backside of the Si substrate. Finally, the wafer was diced to 300 × 350 μm² in this study. The MBRCLED devices were shown in Fig. 1(e). The chips were bonded to TO-46 cans for measurement.

### III. RESULTS AND DISCUSSION

Fig. 2 shows the $I–J$ curves of MBRCLEDs and conventional RCLEDs operated at RT, at 60 °C and at 100 °C ambiance. It can be clearly seen that the output power of MBRCLEDs decays less than that of conventional RCLEDs over the temperature range from RT to 100 °C, which is less than conventional RCLEDs. From RT to 100 °C ambient, the output power drop of MBRCLEDs was −0.31, −1.78, and −2.5 dB for current injection of 20, 50, and 70 mA and the output power drop of conventional RCLEDs was −1.75, −3.03, and −5.47 dB for current injection of 20, 50, and 70 mA, respectively. The wall-plug efficiency is shown as a function of injection current for conventional RCLEDs and for MBRCLEDs at RT in Fig. 3. The maximum wall-plug efficiency of MBRCLEDs was 13.7% at an injected current of 2.5 mA, while the wall-plug efficiency of MBRCLEDs and conventional RCLEDs at injection current of 20 mA is 10.75% and 8.55%, respectively. It could be observed that the difference of the wall-plug efficiency between MBRCLEDs and conventional RCLEDs increased when the injection current was increased. Since the thermal conductivity of GaAs is smaller than that of Si, the self-heating effect is relatively obvious in the conventional RCLEDs due to the poor heat dissipation at high current injection. As the injection current increases from 2.5 to 70 mA, the wall-plug efficiency values of MBRCLEDs and conventional RCLEDs decrease from 13.7% to 4.72% and from 13.7% to 2.87%, respectively.

The increase in junction temperature ($\Delta T_J$) and the forward voltage ($V_F$) as a function of the injection current are shown in Fig. 4 for MBRCLEDs and conventional RCLEDs at a fixed ambient temperature of 25 °C. The increase in junction temperature was obtained by observing the change in ($V_F$) as a function of injection current. It is note worthy that the $I–V$ characteristic of MBRCLEDs is almost the same as that
of conventional RCLEDs, indicating that no metal diffusion occurred at the bonding interface. On the other hand, the junction temperature of the conventional RCLEDs increased dramatically with increased injection current due to the lower thermal conductivity of GaAs, and the higher thermal resistance compared to the metal-bonded Si substrate. Under these circumstances, the performance of the RCLEDs will drop with elevated temperature due to increased leakage current and nonradiative recombination. The serious leakage current in visible red devices is mainly attributed to the relatively low conduction band offset value compared to InGaN–GaN and AlGaAs–GaAs quantum-well structures [13], [14]. The MBRLED’s fabrication process includes both wax bonding and metal bonding, which could damage the thin epi-layers. The above results clearly demonstrate, however, that the double metal bonding, which could damage the thin epi-layers.

Fig. 4. Junction temperature increase \((\Delta T_J)\) and forward voltage \((V_F)\) as a function of the injection current for MBRLEDs and conventional RCLEDs at RT.

IV. CONCLUSION

In summary, visible GaInP–AlGaInP MBRLEDs with high-temperature stability were fabricated on Si substrates by wafer-bonding techniques. Since the thermal conductivity of Si is larger than that of GaAs, the variation of junction temperature of MBRLEDs is relatively small compared with that of conventional RCLEDs. MBRLEDs with 84-\(\mu\)m apertures provide high wall-plug efficiency of 13.7\% and 10.7\% at injected current of 2.5 and 20 mA, respectively, and a smaller power drop of 0.31 dB from RT to 100 \(^\circ\)C due to improved heat dissipation. The excellent performance of these devices indicates that they should be suitable for high-temperature, high current injection, and high data communication applications.

REFERENCES