Improvement of Thermal Dissipation of GaN-Based Micro Cavity Light-Emitting Devices

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***Abstract*—Double dielectric DBR based GaN-based micro cavity light emitting devices with two different structures were fabricated, and their thermal characteristics were investigated. To improve thermal dissipation, an AlN current confinement layer with a much higher thermal conductivity than SiO_2 and an electroplated copper heat sink were utilized. The thermal resistance of the device decreased from 923 K/W to 457 K/W, half of that obtained with the typically used SiO_2 current confinement layer and bonded substrate. This is the lowest reported value in GaN-based micro cavity light-emitting devices with double dielectric DBRs. Temperature distribution and heat flux inside of the device was simulated based on a steady state quasi three-dimensional cylindrical model. The results show that heat transport in vertical direction is efficiently bypassing the bottom DBR to the copper plate. This work provides an effective method to improve thermal characteristics of GaN-based micro cavity light-emitting devices with double dielectric DBR structure.**

***Index Terms*—Micro cavity light-emitting devices, thermal dissipation, AlN current confinement layer, electroplated copper plate.**

I. Introduction

GaN based micro cavity (MC) light-emitting devices, including resonant cavity light-emitting diodes (RCLEDs) and vertical cavity surface emitting lasers (VCSELs), have received significant interest in recent years. RCLEDs and VCSELs featured narrow linewidth, high brightness, high spontaneous emission rate, high directionality and good thermal stability [1]. In addition, GaN based VCSELs also have the advantages of low threshold current, circular beam profiles, single longitudinal mode operation, densely-packed two-dimensional arrays, etc. Thus they are promising in applications including visible light communication, high-resolution printing, biomedical, display, data storage, and general lighting [2], [3].

At present, the dual dielectric DBR structure, in which both the top and bottom DBRs are formed by dielectric thin films, is one of the mainstream structures of GaN based MC light emitting devices [4]–[9]. This kind of structure can avoid the difficulties in epitaxial nitride DBRs including the narrow stop band, low reflectivity, and long MOCVD growth time [10]. However, self-heating is more serious in this kind of structure because the thermal conductivity of the dielectric bottom DBR is extremely low (SiO_2-0.15 W/mK, ZrO_2-2.09 W/mK, TiO_2-6.5 W/mK) [11]. Especially, this structure is typically realized by flip chip bonding and p-GaN is on the bottom side of the device. The current confinement layer, which usually is SiO_2 or SiN_x insulation layer, is embedded between p-GaN and the bonded substrate. This dielectric layer locates on the main pathway of thermal transport and impedes the thermal conduction from p-GaN to the heat sink. Serious self-heating is an important issue which reduces the emission efficiency of RCLEDs and impedes GaN-based VCSELs from working under continuous wave operation and at high output power. High temperature within the device will cause degradation in material gain and device properties including threshold current, output power and emission spectrum [12], [13]. Therefore, it is important to properly design the device structure to enable efficient thermal dissipation and to improve the thermal management in GaN-based MC light emitting devices with dual dielectric DBR structure.

Several methods have been investigated to optimize the thermal dissipation in devices with this structure. Charles A. Forman *et al.* from UCSB [14], as well as our previous works [15] reported GaN VCSELs bonded on a copper plate rather than other materials such as Si or Sapphire. The very high thermal conductivity of copper is expected to facilitate the thermal extraction out of the cavity. However, the thick solder materials such as In-Au and Sn have a lower thermal conductivity than that of copper. More seriously, it is found that cracks, air voids or air gaps are easily formed at the bonding interface during the metal bonding process, including Au-Au bonding, In-Au bonding and Sn-Sn bonding [16]–[18]. These air voids or gaps are almost a thermal insulation in the main pathway of thermal transport, impeding heat energy to be conducted to copper heat sink effectively. Besides, the barrier for the heat flux caused by the dielectric confinement layer cannot be eliminated by introducing a substrate with high thermal conductivity. Increasing cavity length is another method to optimize thermal dissipation. According to the theoretically calculated results from our previous work [19] as well as Saadat Mishkat-Ul-Masabih *et al.* [20], Karan Mehta *et al.* [21], and the experiment results from Masaru Kuramoto *et al.* [22], thermal resistance of GaN based VCSELs can be reduced effectively when the cavity length is increased. But increasing cavity

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length has its side effect, that is, the increase of internal losses. The internal losses caused by the absorption in semiconductor layers and lateral optical leakage, which are the main losses in VCSEL cavity, will increase with a longer cavity. So, increasing the cavity length will induce multi-longitudinal mode lasing, increase the threshold current of the device, and may even imped the device from lasing action.

In this work, we improved the thermal characteristics of GaN based MC light emitting devices with dual dielectric DBR structure by utilizing an electroplated copper plate and an AlN current confinement layer with high thermal conductivity (~200 W/mK) [19]. Instead of the metal bonding process, the copper plate is directly in-situ deposited by electroplating. Thus, problems caused by defects at the bonding interface such as cracks, voids and air gaps could be eliminated, enabling us to maximize the effect of the use of copper substrate. Thermal energy in this device is expected to flow more unhindered from the active layer through the p-GaN to the heat sink. Moreover, according to the calculated results from S. Hang *et al.* [23], the current confinement can be improved by using AlN, because its dielectric constant is 8.5~10, larger than that of SiO_2(3.9). As a control group, devices with SiO_2 current confinement layer and bonded copper substrate were also fabricated. The experimentally measured thermal resistance of the device decreased form 923 K/W to 457 K/W, when the electroplated copper plate and AlN layer were utilized, showing a 50% improvement. The simulation results of the temperature distribution within the devices show that thermal energy can be conducted to the copper plate bypassing the bottom DBR effectively. In line with the thermal improvement, the maximum output thermal roll over current of the device increased from 20 mA to more than 40 mA, and the maximum output power of the devices increased almost three times from 55 μW to 150 μW. This work provides an effective method to improve thermal characteristics of GaN-based resonant-cavity light-emitting devices with dual dielectric DBR structure and is useful in optimizing the structure design and improving the device performance.

II. Material and Methods

The structure of the device with SiO_2 current confinement layer and bonded copper plate (defined as structure A), and the device with AlN confinement layer and electroplated copper plate (defined as structure B) are shown in Figure 1 (a) and (b), respectively. To fabricate devices with structure A, we first deposited a 100-nm-thick SiO_2 current insulation layer with 10-μm diameter current-injection aperture opened on the surface of the epitaxial wafer. Then, a 30-nm-thick indium tin oxide (ITO) layer was deposited in the aperture, followed by the formation of a Cr/Au p-electrode and a 12.5-pair TiO_2/SiO_2 bottom dielectric DBR. After that, the sample was flip-chip bonded on a copper plate through Sn-Sn metal bonding technique, and the sapphire substrate was removed by LLO process. CMP was adopted to remove the undoped GaN layer and thin the n-GaN layer. At last, an n-contact metal and an 11.5-pair TiO_2/SiO_2 top dielectric DBR was deposited. The fabrication processes of devices with structure B are similar. However, a 100 nm thick AlN layer

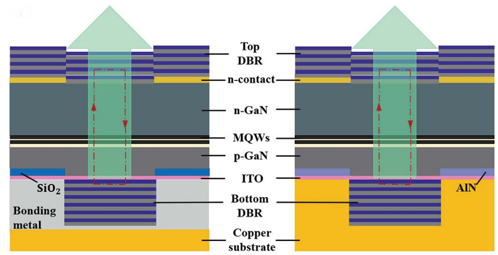

Fig. 1. Structure of GaN base VCESLs of (a) structure A (b) structure B.

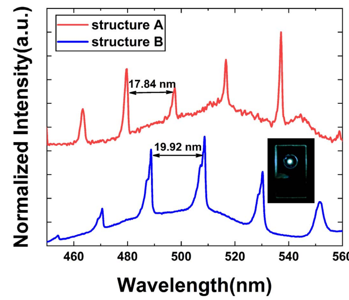

Fig. 2. EL spectra of devices with structure A and B.

with much higher thermal conductivity was used as current confinement layer instead of SiO_2. After the formation of the current confinement layer, ITO and bottom DBR were deposited. Then a copper plate was in-situ electroplated on the sample surface to act as the suspending substrate. Since the copper plate was in-situ formed by atom deposition during the electroplating process, air gaps or voids are hardly formed in the copper layer, which on the other hand, is common in the metal-bonding process. The solder material in structure A, which has a lower thermal conductivity than copper, was also excluded, enabling us to expect a much lower thermal resistance and more effective thermal dissipation.

III. Results and Discussion

A green epitaxial wafer with emission wavelength of about 520 nm was used for device preparation. Figure 2 presents the RT EL spectra measured from the MC light emitters with the two structures. Light emission of the device was collected by an objective lens (10×) and then guided to the spectrometer. Multi-longitudinal mode emission ranging from 460 nm to 550 nm was observed from the spectra. The linewidth of the emission modes turned out to be 0.16 nm under high resolution measurement, corresponding a Q factor of ~3125. The inset of Figure 2 shows the near field emission pattern of the devices with structure B under 1 mA, the bright emission spot locates well in the center of the confined aperture, indicating that AlN layer can realize good current confinement.

The heat dissipation ability of the device can be expressed by thermal resistance, which is defined as [19]:

$$R_{th} = \frac{\Delta T}{\Delta P} = \frac{\Delta\lambda/\Delta P}{\Delta\lambda/\Delta T} = \frac{slope(\lambda, P)}{slope(\lambda, T)}$$

where $\Delta\lambda$, ΔT, ΔP refer to the red shift of cavity mode wavelength, temperature rise within the device, and the increase of consumption of power to produce heat. Therefore, the thermal

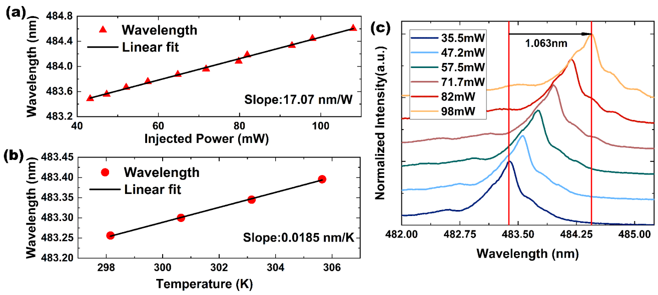

Fig. 3. Wavelength shift of structure A as a function of (a) injected power, and (b) substrate temperature. (c) Normalized emission spectra at different injection power.

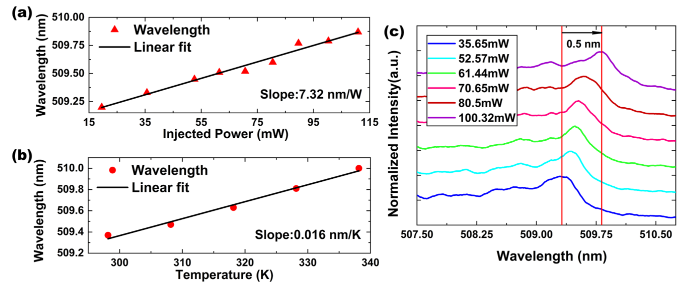

Fig. 4. Wavelength shift of structure B as a function of (a) injected power, and (b) substrate temperature. (c) Normalized emission spectra at different injection power.

resistance of GaN based MC light-emitting devices could be indirectly measured by estimating the dependence of the emission wavelength on injected electrical power and temperature. Because the cavity length has a significant effect on the thermal resistance [19], we controlled the cavity length of the devices with structure A and B to be similar, so that the influence of device structure on thermal resistance can be estimated. The mode wavelengths of the two devices are slightly different in Figure 2, but the mode spacing are similar (mode spacing 17.84 nm at 490 nm for structure A, mode spacing 19.92 nm at 500 nm for structure B). By $\Delta\lambda = \lambda$^2/(2n_{cav} L_{eff}) (where $\Delta\lambda$, λ, n_{cav}, L_{eff} refer to the cavity mode spacing, wavelength, the effective refractive index of the cavity, and the effective cavity length, respectively), the cavity length of devices of structure A and B are calculated to be 3178 nm and 2975 nm, respectively. This small difference has little influence on thermal resistance since the total cavity length is relatively long of around 3 μm.

To estimate the thermal resistance, the wavelength shift of the mode emitting at ~480 nm was studied for a device with structure A. Figure 3 shows the emission wavelength as a function of substrate temperature and injected power. The temperature of the substrate was controlled by a thermoelectric cooler and the injected current was fixed at 1 mA during the temperature dependent measurement. The mode wavelength showed a linear red shift with increasing injected power with a slope of ~17.07 nm/W, as illustrated in Figure 3 (a). Similarly, the mode wavelength also showed a linear red shifted with increasing temperature with a slope of ~0.0185 nm/K, as shown in Figure 3 (b). Figure 3 (c) shows the normalized emission spectra at different injected power. The red shift is ~1.06 nm from 483.38 to 484.44 nm when the injected power increased from 35.5 to 98 mW. The R_{th} of device with structure A is then calculated to be ~923 K/W.

The same measurement was then conducted on device with structure B, as shown in Figure 4. The emission mode at 509 nm was studied, and the red shift of the cavity mode with increasing injected power is much slower with ~7.32 nm/W, less than the half of structure A, as shown in Figure 4 (a). The temperature dependent wavelength shift rate is ~0.016 nm/K, similar to that of structure A, as shown in Figure 4 (b). The thermal resistance of structure B turned out to be 457 W/K. This means that the temperature rise in structure B is much smaller than structure A under the same injected power. To the best of our knowledge, this is the lowest value for GaN based MC light-emitting devices with dual dielectric DBRs. Figure 4 (c) shows the normalized emission spectra at different injected power for structure B. The emission wavelength shows only a 0.5 nm red shift from 509.32 to 509.82 nm when the injected power increased from 35.6 to 100 mW.

The thermal dissipation of GaN based MC light emitting devices with dual dielectric DBRs was greatly improved by optimizing the device structure design. Thermal resistance decreased from 923 to 457 W/K. In devices of structure A, the solder material for metal bonding is around 20 μm-thick Sn with a thermal conductivity of ~67 W/mK, which is much lower than that of copper (400 W/mK). This thick bonding layer will impede thermal energy transfer from p-GaN to the copper heat sink. In addition, cracks and air voids are usually formed at the bonding interface, inducing thermal insulation in the main pathway for thermal transport. Charles A. Forman *et al.* have fabricated GaN based dual dielectric DBR VCSELs by using both Au-Au bonding [16] and Au-In bonding [17]. Air voids and cracks were found in both devices, inducing an inferior thermal performance. The SiO_2 current confinement layer will also affect the thermal transport in the device according to our previous work [19]. The above problems are well solved in structure B, because there is no bonding layer and heat flux can be conducted directly to the copper after being laterally transported out of the cavity. The AlN current confinement layer with high thermal conductivity will not be a barrier for thermal conduction.

In order to validate the experimental results, temperature distribution inside structure B was calculated by a steady-state quasi-3D heat dissipation model, and the detailed information of the model can be found in our previous work [19]. Figure 5 shows the temperature distribution and heat flux inside the device. This figure is zoomed in to present the temperature distribution near the active region more clearly. The temperature rise inside the cavity is 20 K. Since the power used to produce heat was set to be 36 mW, the thermal resistance of the device was calculated to be 555 K/W, agreeing well with the experimental results. The heat energy could by effectively conducted to the copper plate bypassing the bottom DBR, without the barrier of SiO_2 and bonding layer, as shown in the heat flux in Figure 5.

The light-current (L-I) characteristic of the two devices were measured, as given in Figure 6. The optical output power was greatly improved in structure B, in line with the better

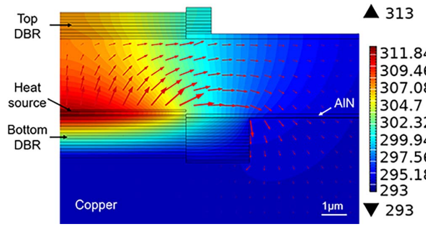

Fig. 5. Temperature distribution and heat flux of GaN based VCSELs of structure B.

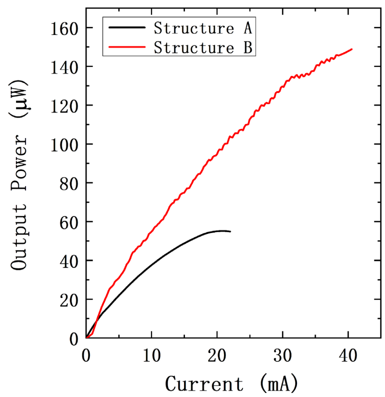

Fig. 6. Light-current characteristics of the devices with structure A and B.

thermal dissipation. The maximum output thermal roll over current increased from 20 mA to more than 40 mA, and the maximum device output power increased almost 3 times from 55 to 150 μW for the thermal optimized device structure. The boosting of output power in structure B confirmed the importance of thermal dissipation in GaN based MC light emitting devices with dual DBR structure. Although lasing action was not realized in these devices, this work is of significance for the improvement of thermal performance in VCSELs, as the thermal dissipation is mainly determined by device structure.

IV. Conclusion

In summary, we improved thermal characteristics of GaN based MC light emitting devices of dual dielectric DBR structure by utilizing electroplated copper and an AlN current confinement layer. The experimentally measured thermal resistance of the device was halved from 923 K/W to 457 K/W compared to the device with SiO_2 current confinement layer and bonded copper plate. The thermal characteristics inside the device was also calculated theoretically, agreeing well with the experimental results. Benefiting from the improvement of thermal dissipation, the maximum output thermal roll over current of the device increased from 20 mA to more than 40 mA, and the maximum output power increased almost 3 times from 55 to 150 μW. This work provides a new design of GaN-based resonant-cavity light emitting devices with dual dielectric DBRs to optimize the thermal dissipation and is useful in improving the device performance.

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