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连续工作7.5 W高功率氮化镓基蓝光激光器(特邀)

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摘 要：高功率氮化镓基蓝光激光器在激光显示、激光照明和材料加工等领域具有广泛的应用前景。通过优化GaN基蓝光激光器的封装结构，采用双面封装方式，将热阻降到6.7 K/W，特征温度T_0提高到235 K。脊宽45 μm、腔长1 200 μm双面封装蓝光激光器的阈值电流密度为1.1 kA/cm^2，斜率效率为1.4 W/A，在6 A电流工作下，室温连续工作光输出功率达到了7.5 W。

关键词：激光器；氮化镓；双面封装；热阻；特征温度；光输出功率
中图分类号：TN248.4 **文献标识码**：A **doi**：10.3788/gzxb20225102.0251209

0 引言

氮化镓(Gallium Nitride, GaN)基材料具有大禁带宽度、高电子迁移率、高热导率等特点，且是一种直接带隙发光材料，应用于各种电子器件和光电器件中，受到了广泛关注。相对于GaN基发光二极管(Light Emitting Diode, LED)而言，GaN基激光器(Laser Diode, LD)具有方向性好、亮度高、颜色纯以及在大电流注入下保持高效率的特点，其中高功率GaN基蓝光激光器在激光显示、激光照明、激光通信和金属加工等领域具有重要的应用前景[1-6]。但高功率GaN基蓝光激光器的研制难度极大，主要与外延生长、工艺制备以及封装工艺这三个难点有关：1)激光器外延结构复杂，需保证晶体质量的同时提高量子阱发光效率和减少光吸收损耗[7-9]；2)需减少工艺制备过程中引入的侧壁损耗与腔面损耗[10]；3)需开发与倒装工艺匹配的低热阻封装技术，从而高功率GaN基蓝光激光器能有效散热[11-13]。

近年来，国内外在高功率GaN基蓝光激光器方面都取得了较大的进展。日本日亚公司采用TO90倒装方式，将热阻降至6 K/W，制备了波长为455 nm、连续工作光功率约5.7 W的蓝光激光器[14]；索尼公司报道了连续工作光功率约5 W的蓝光激光器[15]；德国欧司朗公司也采用TO90封装方式，获得了连续工作光功率为5.5 W的蓝光激光器[16]，其热阻为8 K/W；中科院半导体所报道了连续工作光功率为6 W的蓝光激光器[17]。

本文通过优化GaN基蓝光激光器的封装结构，采用双面封装方式以提高蓝光激光器的散热能力，实现蓝光激光器的热阻为6.7 K/W，特征温度T_0为235 K，代表双面封装的蓝光激光器具有好的材料质量、结构和封装。脊宽45 μm、腔长1 200 μm蓝光激光器的阈值电流密度为1.1 kA/cm^2，斜率效率为1.4 W/A，在6 A电流工作下，室温连续工作光输出功率达到了7.5 W。

1 结构

用金属有机化学气相沉积(Metal Organic Chemical Vapor Deposition, MOCVD)外延设备在c面GaN

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自支撑衬底上生长蓝光激光器外延结构。外延结构由硅(Si)掺杂的n-$Al_{0.08}Ga_{0.93}N$下限制层，Si掺杂的n-GaN层，Si掺杂的n-$In_{0.04}Ga_{0.96}N$波导层(Waveguide Layer, WG)，两个周期的$In_{0.16}Ga_{0.84}N$/GaN多量子阱(Multiple Quantum Wells, MQWs)，非故意掺杂的$In_{0.02}Ga_{0.98}N$波导层，镁(Mg)掺杂的p-$Al_{0.2}Ga_{0.8}N$电子阻挡层(Electron Blocking Layer, EBL)，Mg掺杂的$Al_{0.07}Ga_{0.93}N$/GaN (2.5/2.5 nm)超晶格上限制层和重掺杂的p-InGaN接触层组成。蓝光激光器结构如图1所示，首先用磁控溅射设备在蓝光激光器外延结构上沉积金属接触电极p-elecrode，光刻并采用干法刻蚀出激光器45 μm宽的脊形结构，然后在脊形两侧沉积200 nm二氧化硅，起到电学隔离的作用。在顶部沉积p型电极，并将GaN衬底减薄抛光后沉积n型电极。最后沿m面解理成1 200 μm长的巴条，在前后腔面沉积具有不同反射率的多层介质膜形成光学谐振腔。

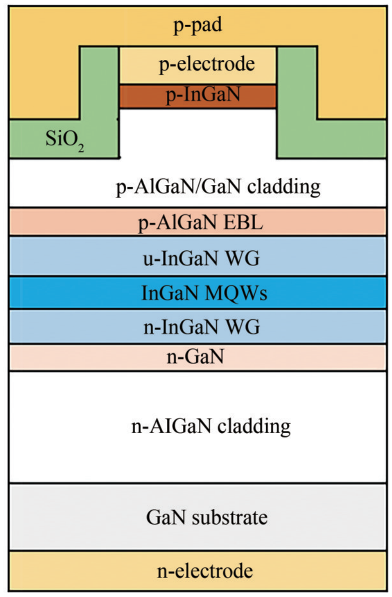


图1　氮化镓基蓝光激光器结构

Fig.1　The structure of GaN-based LD

2　封装

为了获得GaN基蓝光激光器在室温连续条件下的高光功率输出，需要将蓝光激光器单芯片进行封装，GaN激光器的焦耳热主要来自于量子阱的非辐射复合和p型层，采取p-down倒装封装方式才能更好地散热。图2(a)为采取单面封装方式的蓝光激光器示意图，将蓝光激光器倒装封装在AlN过渡热沉上，并共晶在铜块上提供散热通道，AlN过渡热沉与陶瓷基板通过打线串联在一起，作为高功率蓝光激光器的正极，从蓝光激光器的N面打线至陶瓷基板作为负极。与单面封装的蓝光激光器不同，双面封装方式采用铜块2与蓝光激光器N面充分贴合，增加激光器的散热，如图2(b)。

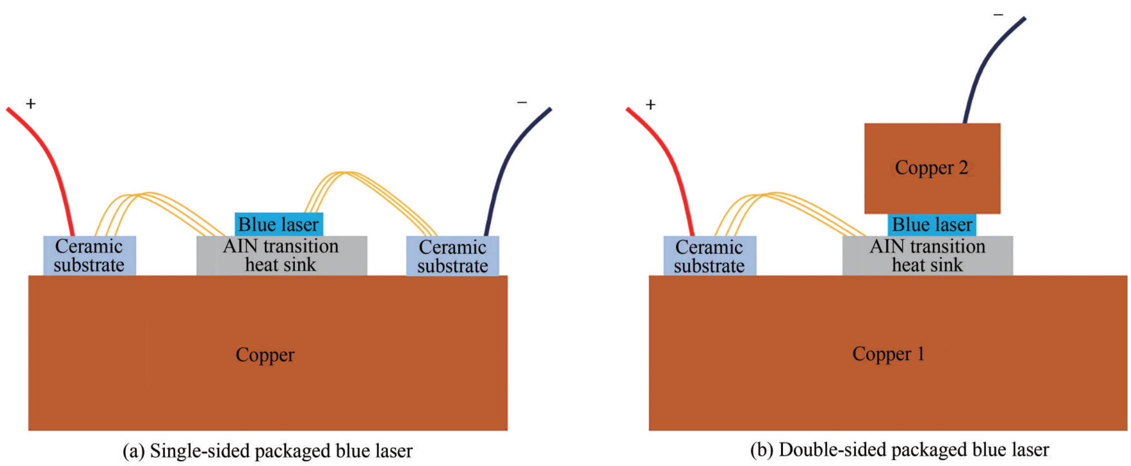


图2　高功率GaN基蓝光激光器的两种封装方式

Fig.2　Two packaging methods for high-power GaN-based blue laser diode

2.1　热阻

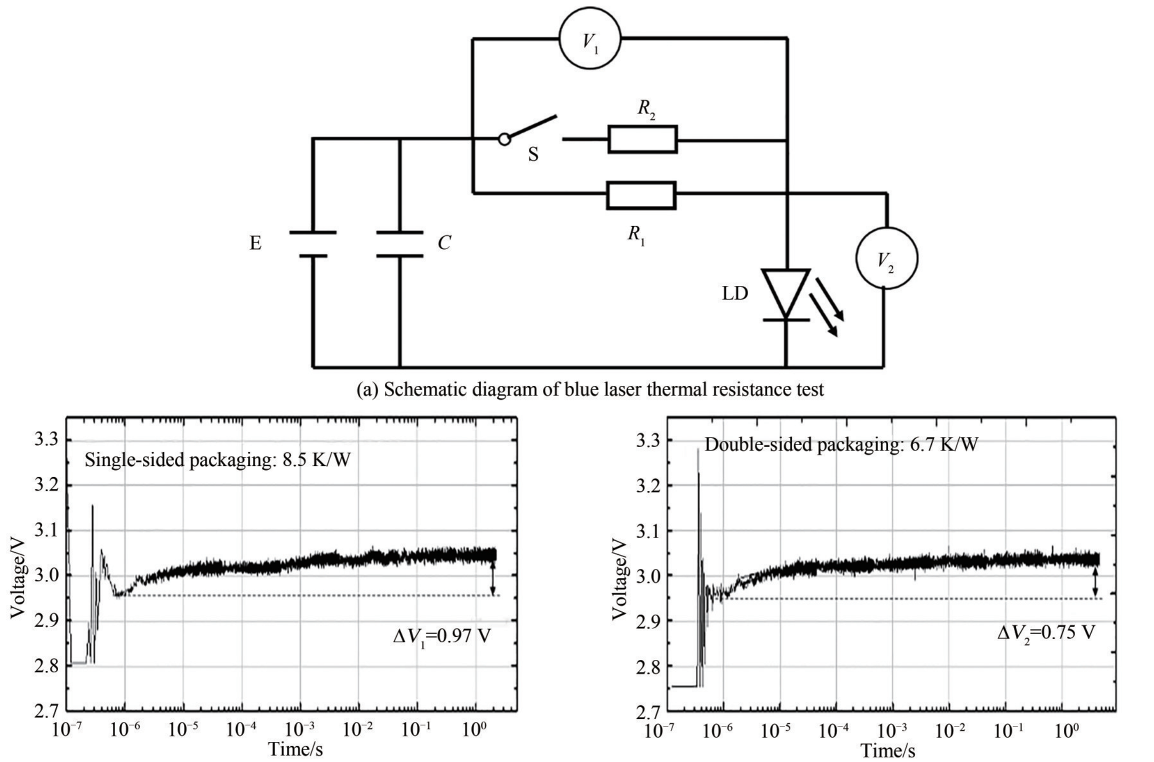
通过激光器的热阻大小可以判断封装的好坏，测量激光器正向电压随温度变化关系，获得激光器的电压温度系数，从而计算出热阻[18-19]。图3(a)为热阻测试电路示意图，其中E是一个小的直流电源，并联电容C用以吸收电源的噪声波动，电路中并联了两个电阻$R1$和$R2$，其中$R1$的阻值远大于$R2$，待测试的蓝光激光器串联在电路内，示波器测量电阻两端以及激光器两端电压变化情况。测试开始前，先闭合开关S，由于并联电阻较小，激光器在大电流、高结温下工作；随后断开开关S，激光器转换成小电流工作，结温慢慢下降，正向电压发

生变化，此正向电压差即为结温变化引起的正向电压变化值，根据式(1)和(2)可计算出蓝光激光器的热阻[20-21]

$$\Delta T=\left(V_{\mathrm{FB}}-V_{\mathrm{FA}}\right)/T_{\mathrm{C}} \tag{1}$$

$$R_{\mathrm{th}}=\Delta T/\left(I_{\mathrm{H}}V_{\mathrm{H}}-P_{\mathrm{out}}\right) \tag{2}$$

式中，V_{FB}是小电流平衡状态稳定的电压，V_{FA}是断开开关后一定延时时间后的小电流电压，T_{c}为电压温度系数，R_{th}是热阻，I_{H}是激光器大电流工作时电流，V_{H}是激光器大电流工作时电压，P_{out}是大电流工作时的光功率。单面封装和双面封装方式的蓝光激光器的电压随时间变化曲线分别如图3(b)和图3(c)所示。根据电压差求得单面封装的蓝光激光器的热阻为8.5 K/W，而双面封装的蓝光激光器的热阻为6.7 K/W。可以发现采取双面封装方式的GaN基蓝光激光器的热阻较小，能更有效散热，有利于高功率蓝光激光器室温连续条件下工作。



(a) Schematic diagram of blue laser thermal resistance test

(b) The voltage-time curve of the single-sided packaged blue laser

(c) The voltage-time curve of the double-sided packaged blue laser

图3　不同封装方式的蓝光激光器热阻测试曲线

Fig.3　Thermal resistance test curves of blue lasers with different packaging methods

2.2　特征温度

激光器的阈值电流密度J_{th}随温度变化而变化，阈值电流密度与温度之间的关系满足[22]

$$J_{\mathrm{th}}\left(T_{\mathrm{r}}+\Delta T\right)=J_{\mathrm{th}}\left(T_{\mathrm{r}}\right)\exp\left(\frac{T-T_{\mathrm{r}}}{T_0}\right) \tag{3}$$

式中，T_{r}是室温，T_0是特征温度。

特征温度T_0是衡量半导体激光器温度稳定性的参数，它与激光器芯片的材料质量和结构有关，可判断激光器能否在室温下连续工作，用两个不同温度下阈值电流的比值来衡量激光器的热稳定性，比值越小代表这个器件具有更好的温度特性[22-24]。图4(a)为单面封装的蓝光激光器从室温加到65 ℃时的连续工作下功率-电流(P-I)曲线，可以发现随着温度增加，蓝光激光器的阈值电流增加，斜率效率略微下降，图4(b)为其特征温度的拟合曲线，根据式(3)拟合的单面封装蓝光激光器的特征温度为132 K。根据双面封装的蓝光激光器从室温加到65 ℃时的连续工作下的P-I曲线，如图4(c)，阈值电流增加更为缓慢，拟合获得双面封装的蓝光激光器的特征温度为235 K，如图4(d)所示，对比发现双面封装的蓝光激光器的特征温度更高，表明这种封装方式具有更好的温度稳定性。

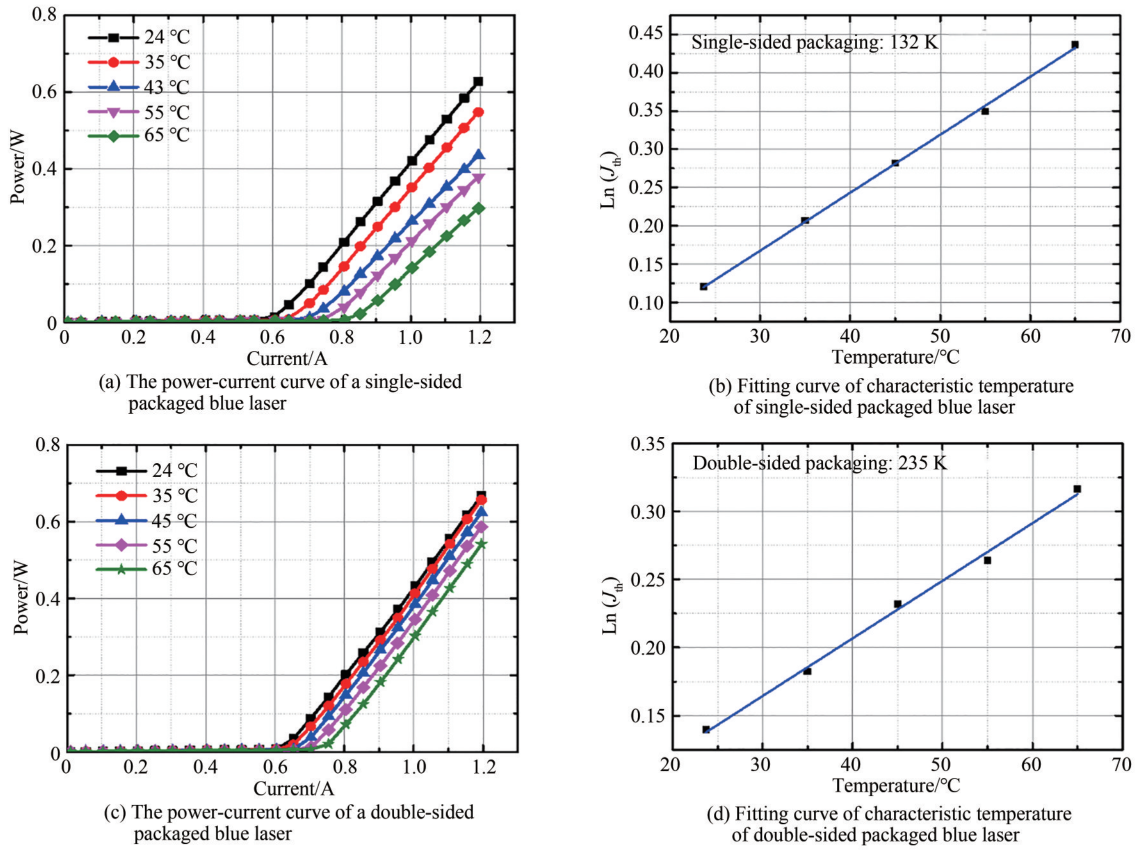


图4　不同封装方式的蓝光激光器的特征温度测试曲线

Fig.4　Characteristic temperature curves of blue lasers with different packaging methods

3　器件性能

图5为单面封装和双面封装的GaN基蓝光激光器的室温连续电注入时的功率-电流-电压（P-I-V）曲线，脊宽45 μm、腔长1 200 μm的两种封装方式的蓝光激光器的激射波长均为442 nm，阈值电流密度均为1.1 kA/cm^2，双面封装的蓝光激光器的斜率效率为1.4 W/A，单面封装的蓝光激光器的斜率效率更高为1.5 W/A。当电流增加至3 A，单面封装的蓝光激光器的斜率效率开始明显下降，当电流继续增加至4 A时，功率出现了饱和，这是单面封装的蓝光激光器散热不佳、结温升高所导致，同时，我们发现单面封装的蓝光激光器的电压小于双面封装的蓝光激光器，也表明单面封装的蓝光激光器散热不佳，热量囤积导致电压下降。最终获得的双面封装的蓝光激光器在6 A电流工作下，工作电压为5.9 V，输出功率达到了7.5 W，表明低的热阻和高的特征温度有助于获得高功率蓝光激光器。

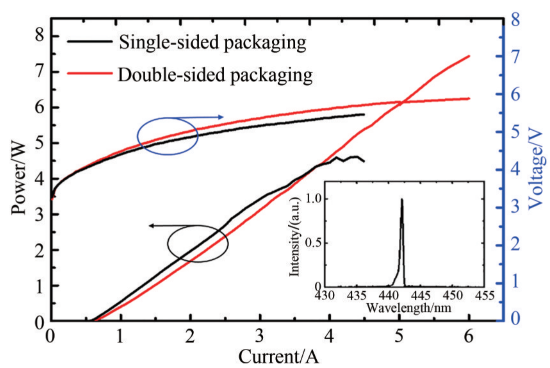


图5　不同封装方式的蓝光激光器的室温连续工作时的P-I-V曲线

Fig.5　P-I-V curves of blue laser with different packaging methods under continuous-wave operation at room temperature

4 结论

采用双面封装方式，优化GaN基蓝光激光器的封装结构，优化后双面封装GaN基蓝光激光器热阻降到6.7 K/W，特征温度T_0提高到为235 K，表明双面封装的蓝光激光器具有良好的材料质量、结构和封装。脊宽45 μm、腔长1 200 μm双面封装的蓝光激光器的阈值电流密度为1.1 kA/cm²，斜率效率为1.4 W/A，在6 A电流工作下，室温连续工作光输出功率达到了7.5 W。

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High-power GaN-based Blue Laser Diodes with 7.5 W of Light Output Power Under Continuous-wave Operation (Invited)

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Abstract: Gallium Nitride (GaN)-based materials have the characteristics of large band gap, high electron mobility, high thermal conductivity, etc., which are used in various electronic devices and optoelectronic devices, and have received extensive attention. High power GaN-based blue laser diodes (LDs) have great prospects in laser display, laser lighting, metal processing and other fields. However, the development of high-power GaN-based blue lasers is extremely difficult, mainly related to the difficulties of epitaxial growth, processing and packaging technology. Firstly, the epitaxial structure of blue laser is complicated, and the crystal quality needs to be ensured while improving the luminous efficiency of the quantum well and reducing the light absorption loss. Secondly, the sidewall loss and cavity surface loss need to be reduced during the manufacturing process. Last but not least, a low thermal resistance packaging technology needs to be developed, so that high-power GaN-based blue lasers can effectively dissipate heat. In this work, by adopting the double-sided packaging method for GaN-based blue lasers, which use the copper fully attached to the N-side of the blue laser to increase the heat dissipation. According to the change in the forward voltage caused by the junction temperature change, the thermal resistance of the single-sided packaged blue laser is 8.5 K/W, while the double-sided packaged blue laser has a thermal resistance of 6.7 K/W. It can be found that the GaN-based blue laser with double-sided packaging has lower thermal resistance and can dissipate heat more effectively, which is beneficial for the high-power blue laser to work under continuous room temperature conditions. According to the power-current curves of the blue laser from room temperature to 65 ℃, the characteristic temperature of the single-sided packaged blue laser is 132 K, and the characteristic temperature of the double-sided packaged blue laser is 235 K, it is found that the characteristic temperature of the double-sided packaged blue laser is higher, which means that has better temperature stability. Finally, we demonstrate the double-sided packaged blue lasers with a ridge width of 45 μm and a cavity length of 1 200 μm which have a threshold current density of 1.1 kA/cm^2 and a slope efficiency of 1.4 W/A. The light output power reaches 7.5 W at 6 A under continuous-wave operation at room temperature, it means that the double-sided packaged blue laser has good material quality, structure and packaging.

Key words: Laser diode; Gallium Nitride; Double-sided packaging; Thermal resistance; Characteristic temperature; Light output power

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