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Wafer bonded 1.55 μm vertical-cavity lasers with continuous-wave operation up to 105 °C

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We report 105 °C continuous-wave, electrically pumped operation of a 1526 nm vertical-cavity surface-emitting laser. An InP/InGaAsP active region was wafer bonded to GaAs/AlGaAs mirrors, with a superlattice barrier to reduce the number of nonradiative recombination centers in the bonded active region. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1368377]

Vertical cavity surface emitting lasers (VCSELs) emitting in the 1.55 μm wavelength region are attractive sources for optical networks. Advantages of VCSELs include low power consumption, efficient fiber coupling, and high volume, low cost manufacturing. Transmission at 1.55 μm allows for long distance transmission over optical fiber with low attenuation and dispersion. The main limitation to realizing commercially viable devices at 1.55 μm has been poor performance at high temperature. Maximum operating temperatures of 70–85 °C are specified for sources in fiber optic networks. The commonly used InP/InGaAsP material system suffers from low characteristic temperatures and poor thermal conductivities that have slowed the rate of long wavelength VCSEL progress compared to that of GaAs/AlGaAs based short wavelength devices. A number of novel approaches have been applied to the development of 1.55 μm VCSELs. High performance devices have been fabricated using buried tunnel junctions,[1] antimonide mirrors,[2] and metamorphic growth.[3] The best high temperature results to date have been achieved using wafer bonded GaAs/AlGaAs distributed Bragg reflectors (DBRs) in both electrically pumped[4] and integrated optically pumped[5] designs. The high thermal conductivity and index contrast of the GaAs based DBRs make them an attractive choice for fabricating long wavelength VCSEL mirrors.

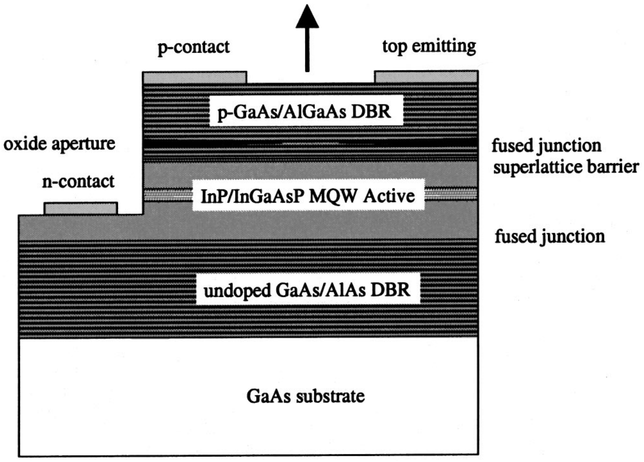

FIG. 1. Wafer bonded, top-emitting 1.55 μm VCSEL structure.

Top-emitting vertical cavity lasers with two wafer bonded GaAs/AlGaAs DBRs were fabricated. The device structure is shown in Fig. 1. The top mirror is a 25.5 period p-type, parabolically graded GaAs/Al$_{0.9}$Ga$_{0.1}$As DBR, with an oxide aperture for mode and current confinement. The $p-i-n$ InP/InGaAsP active region contains 6 strained quantum wells. A four period InP/InGaAsP superlattice was grown on the InP side of the InP/GaAs junction in order to reduce the number of nonradiative recombination centers in the active region.[6] Each layer of the superlattice was 7.5 nm thick and doped p-type. The 31 period GaAs/AlAs bottom mirror is undoped. The p-contact is on top of the p-DBR and the n-contact is on the n-cladding of the active region. The lateral oxidation depth determines the device size. Devices were tested in a p-side up configuration without any special heat sinking.

Room temperature voltage and continuous-wave (cw) output power characteristics are shown in Fig. 2. The minimum threshold current measured was 0.9 mA for a 6 μm device. The highest output power obtained at 20 °C was 0.65 mW. The room temperature cavity mode was at 1526 nm, and the gain peak was at 1542 nm. Both the lasing wave-

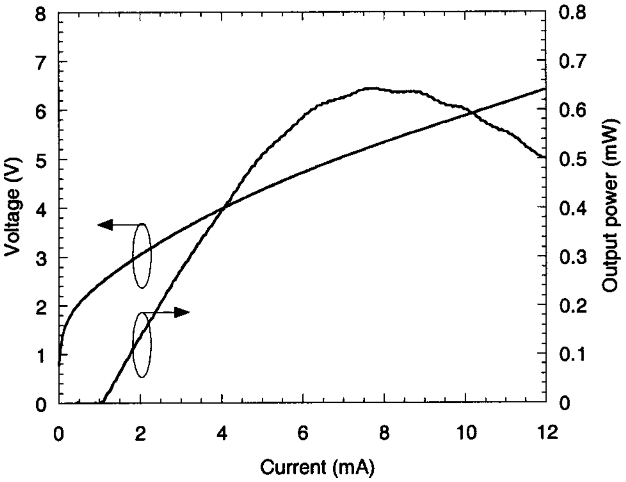

FIG. 2. Room temperature (20 °C) voltage and continuous-wave output power.

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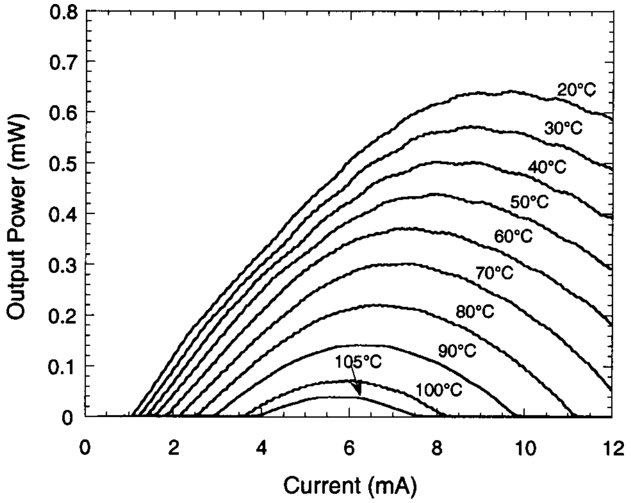

FIG. 3. Continuous-wave light-current characteristics for ambient temperatures of 20–105 °C.

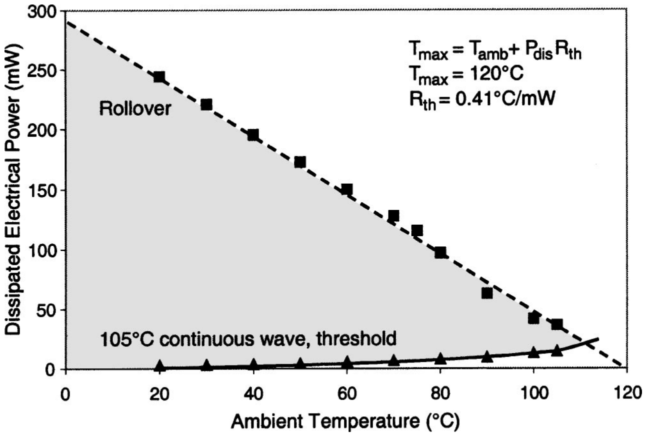

FIG. 4. Thermal resistance and maximum operating temperature.

length and peak gain wavelength increase with temperature. The lasing wavelength shifts at a rate of 0.1 nm/ °C, while the peak gain wavelength increases at a rate of 0.5 nm/ °C.[7] Despite the unfavorable mode-gain offset for these devices, continuous wave operation was achieved at temperatures as high as 105 °C. A family of L–I curves for cw operation from 20–105 °C are shown in Fig. 3.

The improved high temperature operation compared to the previously fabricated devices[4] is due to a reduced diode turn-on voltage and lowered differential resistance. A simple thermal model is illustrated in Fig. 4. It is assumed that the device stops lasing once the active region reaches a certain maximum temperature, $T_{\max}$. This maximum active region temperature is constant and independent of the ambient temperature. $T_{\max}$ is equal to the ambient temperature, T_{amb}, plus the thermal resistance, R_{th}, multiplied by the dissipated electrical power, P_{dis}, at rollover. This can be expressed as the equation of a straight line, given by $T_{\max}=T_{\text{amb}}+P_{\text{dis}}R_{\text{th}}$. The data points indicated by squares show the electrical power dissipated at the bias point where the L–I characteristic has rolled over and the device is no longer lasing. The data points indicated by triangles show the electrical power dissipated at threshold by the device with the L–I characteristics shown in Fig. 3. The continuous-wave operating regime, shaded, is bound by the threshold and rollover dissipated power curves. A thermal resistance of 0.41 °C/mW is extracted from the linear fit for a device defined by a 40 μm etched pillar and 6 μm oxide aperture. The maximum active region temperature that will support lasing is determined to be 120 °C. The simple fit used to extract these parameters treats the active region temperature as a one-dimensional distribution. A higher degree of accuracy could be obtained by using a two- or three-dimensional model to determine local heating within the active region. The improved electrical properties reduce the dissipated power and device self-heating. In addition, the superlattice barrier preserves active region luminescence during the bonding process and reduces the number of nonradiative recombination centers. Improved high temperature performance, including higher output powers over the operating temperature range, should be possible with improved mode-gain offset and reduced differential resistance. The high turn-on voltage and resistance are due in part to the electrical characteristics of the p-InP/p-GaAs bonded junction.[8] Optimization of the doping and bonding conditions should result in lower voltage operation.

Electrically pumped, wafer bonded VCSELs with a lasing wavelength of 1526 nm were fabricated. The maximum cw operating temperature achieved was 105 °C. The maximum output power at 20 °C was 0.65 mW. The maximum output power at 80 °C was 0.22 mW. Threshold currents of 0.9 mA were obtained for a 6 μm device. Significant improvements are expected for devices with a more favorable mode-gain offset, lower turn-on voltage, and reduced series resistance.

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[1] M. Ortsiefer, R. Shau, G. Bohm, F. Kohler, and M. C. Amann, Appl. Phys. Lett. **76**, 2179 (2000).

[2] E. Hall, S. Nakagawa, G. Almuneau, J. Kim, D. Buell, and L. A. Coldren, Proceedings of the 26th European Conference on Optical Comm., Munich, Germany, 2000, postdeadline 3.4.

[3] J. Boucart, C. Starck, F. Gaborit, A. Plais, N. Bouche, E. Derouin, L. Goldstein, C. Fortin, D. Carpentier, P. Salet, F. Brillouet, and J. Jacquet, IEEE Photonics Technol. Lett. **11**, 629 (1999).

[4] A. Karim, K. A. Black, P. Abraham, D. Lofgreen, Y. J. Chiu, J. Piprek, and J. E. Bowers, IEEE Photonics Technol. Lett. **12**, 1438 (2000).

[5] V. Jayaraman, J. C. Geske, M. H. MacDougal, T. D. Lowes, F. H. Peters, D. VanDeusen, T. C. Goodnough, S. P. Kilcoyne, and D. Welch, Proceedings of the LEOS Summ. Top. Meet., San Diego, California, 1999, Vol. 3, p. 19.

[6] K. A. Black, P. Abraham, A. Karim, J. E. Bowers, and E. L. Hu, Proceedings Conference IPRM, Davos, Switzerland, 1999, Vol. 1, p. 357.

[7] J. Piprek, Y. A. Akulova, D. I. Babic, L. A. Coldren, and J. E. Bowers, Appl. Phys. Lett. **72**, 1814 (1998).

[8] A. Black, A. R. Hawkins, N. M. Margalit, D. I. Babic, A. L. Holmes, Jr., Y. L. Chang, P. Abraham, J. E. Bowers, and E. L. Hu, IEEE J. Sel. Top. Quantum Electron. **3**, 943 (1997).