Temperature characteristics of InGaAs/GaAs vertical cavity surface emitting laser*

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The temperature characteristics for the different lasing modes at 300 K of intracavity contacted InGaAs/GaAs Vertical Cavity Surface Emitting Lasers(VCSELs) have been investigated experimentally by using the SV-32 cryostat and LD2002C5 test system. In combination with the simulation results of the reflective spectrum and the gain peak at different temperatures, the measurement results have been analyzed. In addition, the dependence of device size on temperature characteristics is discussed. The experimental data can be used to optimally design of VCSEL at high or cryogenic temperature.

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Vertical-cavity surface-emitting lasers (VCSELs) are becoming more and more attractive and popular in many application fields, such as long-haul optical communication systems, short and intersystem, optical computing technology, and laser printing, due to the unique features distinguishing them from conventional edge-emitting lasers. The typical merits of VCSELs include low threshold, high efficiency, high-speed operation, low-divergence circular output beam, single-longitudinal mode operation suitable for monolithic two-dimensional (2-D) integration, and compatibility with on-wafer probe testing. Because these characteristics are strongly affected by the detuning of the gain peak and lasing mode, and sensitive to the temperature change, an understanding of the relationship between the gain spectrum and the lasing mode is important in order to improve temperature characteristics of VCSELs.

The temperature characteristics for different lasing modes at 300 K of intracavity contacted InGaAs/GaAs Vertical Cavity Surface Emitting Laser (VCSEL) have been investigated experimentally by using a SV-32 cryostat and LD2002C5 test system. Some experimental curves of light current, lasing wavelength and threshold current as a function of temperature from 79K to 363K had been measured for different lasing modes. In combination with the simulation results of the reflective spectrum and the gain spectrum at different temperatures, the measurement results were analyzed. In addition, dependence of the device size on temperature characteristics is discussed.

The InGaAs/GaAs intracavity contacted VCSEL structure was grown by the low-pressure metal-organic chemical vapor deposition(LP-MOCVD). It consists of $GaAs/A_{0.9}Ga_{0.1}As$DBRs and an active region of three $In_{0.2}Ga_{0.8}As/GaAs$ strained quantum wells located at the antinode of a 1λ cavity. The bottom n-type DBR and the top intrinsic DBR has 26 and 22 pairs of λ/4 layers, respectively. To reduce optical loss due to free carrier absorption, the doping profile of the bottom DBR is graded with three pairs n-DBRs nearest the optical cavity doped at 1×1017 cm^{-3}, and the pairs further away from the cavity doped at 3×10^{18} cm^{-3}. An 60 nm thickness $Al_{0.98}Ga_{0.02}As$ oxidation layer is inserted above the cavity to confine the current and light. Above the $Al_{0.98}Ga_{0.02}As$ layer, the P+ GaAs ohmic contact layer is used to form the intra-cavity contacted structure. The device fabrication is described in detail[1]. The temperature characteristics have been investigated by using the SV-32 cryostat and LD2002C5 test system under pulse operation (pulse width 30 μs, pulse repeat rate 100 Hz). The precision of temperature can be controlled under 0.1℃.

Fig. 1(a) shows *L-I* characteristics of a 16 μm diameter VCSEL as function of temperature with 930 nm lasing mode at 300 K. The maximum output power decreases monotonically with increasing temperature. The maximum output power of 28.6 mW reduces to 0.7 mW from 79 K to 313 K. The corresponding slope efficiency gradually decreases from 0.77 mW/mA to 0.12 mW/mA. The decrease in slope efficiency is due to the smaller quantum efficiency, a decrease in the internal quantum efficiency and an increase in the internal loss. Comparing to the 930 nm lasing mode, for the 972.6 nm lasing mode at 300 K, when the maximum output

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power also dropped to 0.7 mW, the corresponding temperature is 363 K as shown in Fig. 1(b). For the same oxide aperture device, the larger the detuning degree of the lasing mode shifted to the shorter wavelength of the gain peak at room temperature is, the lower the highest operation temperature is, on the contrary, the superior lasing performance at cryogenic temperature is. The similar behaviors are shown in Fig. 2 (a) and Fig. 2 (b). The maximum output power of 52 mW reduces to 1.5 mW from 83 K to 343 K with 952.2 nm lasing mode at 300 K. Due to the larger oxide aperture, the maximum output power is higher than that of small oxide aperture at cryogenic temperature.

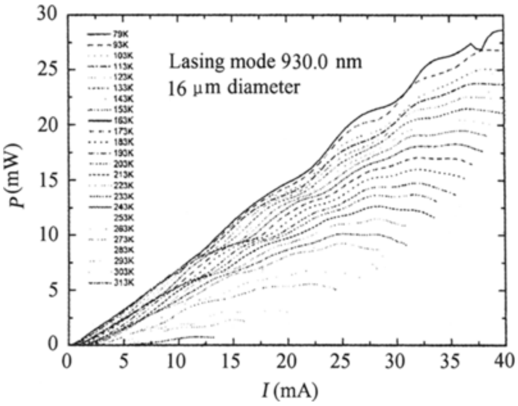

Fig. 1 (a) *P-I* characteristics for different temperature with lasing mode 930 nm at 300 K

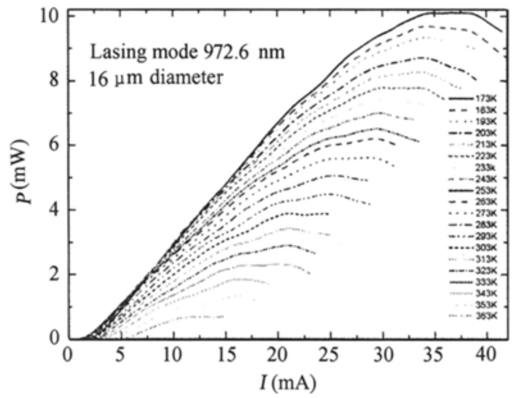

Fig. 1 (b) *P-I* characteristics for different temperature with lasing mode 972.6 nm at 300 K

The temperature dependence of threshold current for the 16 μm and 31 μm oxide-aperture with different lasing mode devices is shown in Fig. 3. Approximate parabolic dependence of threshold current on temperature behavior is shown for all devices. Four VCSELs from different parts of a single wafer are chosen for this study. The different lasing mode is at 972.6 nm, 962.6 nm, 952.2 nm and 930 nm at 300 K, respectively.

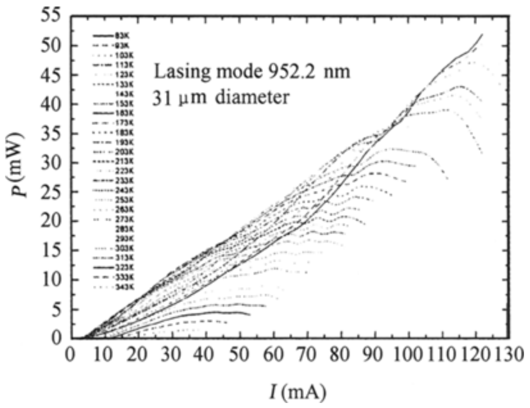

Fig. 2 (a) *P-I* characteristics for different temperature with lasing mode 952.2 nm at 300 K

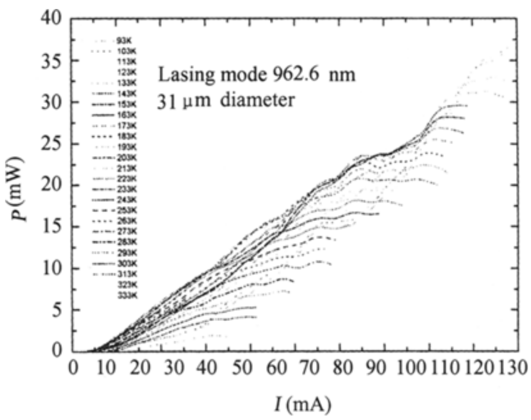

Fig. 2 (b) *P-I* characteristics for different temperature with lasing mode 962.6 nm at 300 K

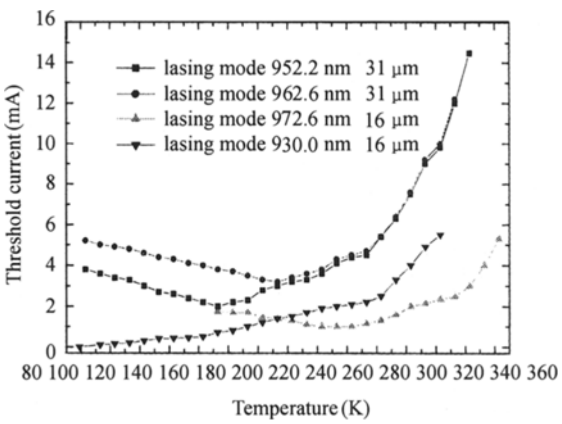

Fig. 3 The threshold currents as a function of temperature with different lasing modes

The corresponding minimum threshold current is observed at 263 K, 213 K, 173 K and 79 K respectively, where the gain peak and the lasing mode are optimally aligned (as discussed below). For the same oxide aperture device, the larger the detuning degree of the lasing mode shifted to the shorter wavelength of the gain peak at room temperature is, the lower the minimum threshold current is. The threshold current for the device of the lasing mode of 930 nm is 0. 1 mA (threshold current density 124 A/cm^2) at 79 K.

As described above, the performance of VCSEL device depends strongly on the degree of overlap between the gain spectrum and the lasing mode. The minimum threshold current occurs at the temperature at which the gain peak and the lasing mode are optimally aligned. The lasing wavelength for VCSEL is determined by the optical properties of the mirrors and the cavity. To determine the temperature dependence of the cavity resonance, the thermal dependence of the refractive index of $Al_xGa_{1-x}As$ is used as the liner insert value of 2.67×10^{-4}/K(GaAs) and 1.43×10^{-4}/K(AlAs) [2], and the thermal expansion coefficient was taken as a typical value of 5.5×10^{-6}/℃[3]. The reflectivity spectrum using the transmission matrix method at the different temperatures are simulated as shown in Fig. 4. In calculations, the absorption and the refractive index dispersion are taken into account. The 0. 065 nm/K red-shift rate of cavity resonance was calculated.

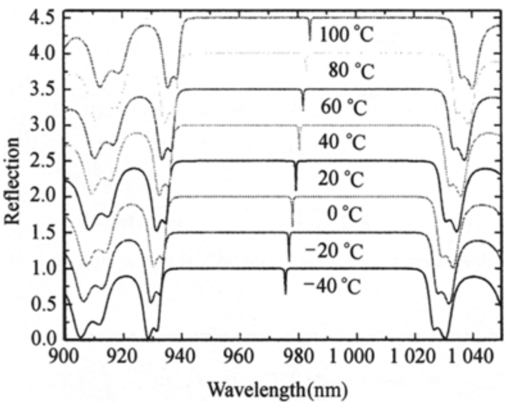

Fig. 4 The reflection spectra as function of wavelength for different temperatures

The wavelength of lasing mode and gain peak shift with temperature at different rates. The wavelength of gain peak is determined by fabricated an edge-emitting laser. Because the top intrinsic DBR is etched to expose the ohmic contacted layer during fabrication an edge-emitting laser, the threshold current is very large, plotted in Fig. 5.

The inset shows the optical spectrum, the emission wavelength is located at 981 nm under 500 mA. The common gain peak was appreciatively considered 981 nm due to the same epi-wafer. The simulated result of the temperature dependence of gain peak is summed up as following: above 160 K, the rate shift of the gain peak for InGaAs/GaAs (MQW) is 0. 323 nm/K, which is close to the measured value (0. 33 nm/K[4]). The temperature dependences of the lasing mode (measured results) and gain peak (simulated result) are shown in Fig. 6. The saturation of the gain peak at lower temperature range (T<160 K) is due to the nonlinearity of the lattice thermal expansion coefficient, which can also be observed in[5]. The lasing mode as a function of temperature was also measured under the injection current of 25 mA. The curves intersections of the gain peak and the different lasing mode with temperature, which is at 972. 6 nm, 962. 6 nm, 952. 2 nm and 930 nm (from at 25 mA) at 300 K, are observed at 263 K, 223 K, 183 K and 79 K respectively. The larger oxide aperture device suffers from relatively low thermal resistance due to the inversely linear decrease of thermal resistance with active diameter[6]. So the calculated optimal temperature of the minimum threshold current for 31 μm diameter devices is a little different from the measured value.

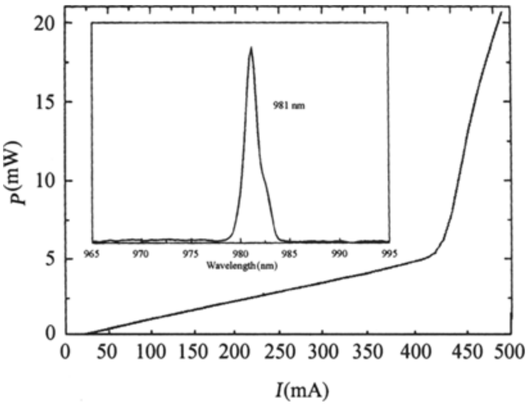

Fig. 5 P-I characteristics of edge-emitting laser

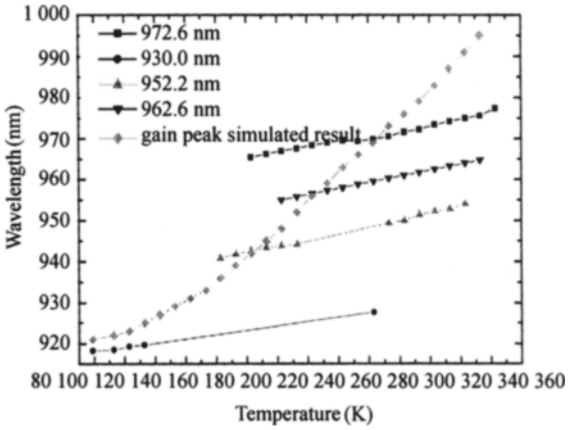

Fig. 6 The lasing wavelength (measured results) and gain peak wavelength (simulated result) as a function of temperature

This similar behavior can be observed[7]. The calculated optimal temperatures of the minimum threshold current for 16 μm diameter devices agree with the experimental results well. However, the detuning of gain peak and lasing mode is the key factor that determine temperature of the minimum threshold current. For the same detuning degree of the gain peak and lasing mode, the wavelength of the gain peak and lasing mode is $\pm N \times 10$ nm detuning at 300 K. Temperature of the minimum threshold current is changed about $\pm N \times 40$ K. (N is real number)

In conclusion, for the same oxide aperture device, the larger the detuning degree of the lasing mode shifted to the shorter wavelength of the gain peak at room temperature is, the lower the highest operation temperature is, the lower the minimum threshold current is. The threshold current for the 16 μm diameter device of the lasing mode of 930 nm is 0. 1 mA (threshold current density 124 A/cm^2) at 79 K. The wavelength of the lasing mode and gain peak is $\pm N \times 10$ nm detuning at 300 K. Temperature of the minimum threshold current is changed about $\pm N \times 40$ K. (N is real number). The data are applied to optimizing the characteristics of VCSEL at high or cryogenic temperatures.

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