Sub-100 μA current operation of strained InGaAs quantum well lasers at low temperatures

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Very low threshold currents (<100 μA) have been achieved in InGaAs strained single quantum well lasers at cryogenic temperatures. Threshold currents of 38 and 56 μA and external quantum efficiency ~1 mW/mA have been demonstrated under cw operation condition at temperatures of 6 and 77 K, respectively. The external quantum efficiency increased by about a factor of 2 at low temperatures (<100 K) in comparison to that at room temperature. These results are relevant to the prospect of integration of semiconductor lasers with low temperature electronics for high performance

In short distance optical communication systems, for the same data transmission capability, the total power consumption of using many lasers at low operation currents can be several order of magnitude less than that of using a few lasers at high operation currents.[1,2] In the former configuration, the reduction in threshold currents is important not only because of the tight packing density and low power consumption but also because the reduction in threshold currents will lead to a noticeable increase in modulation bandwidth for a given low operation current. In the continuing push toward ultralow threshold current injection lasers, we have studied the low temperature regime of these lasers. The main interest is to establish the optimal temperature ranges bearing in mind the prospect of combined cryogenic cooling of semiconductor lasers and high performance (high speed and low noise) low temperature electronics. In this letter, we report very low threshold currents in InGaAs quantum well lasers at cryogenic temperatures. Threshold currents of less than 100 μA have been achieved near liquid helium and liquid nitrogen temperatures. The lowest threshold current demonstrated is smaller by about a factor of 3 than the best previous results.[3]

The laser diodes used in the study are graded index separate confinement heterostructure (GRINSCH) strained InGaAs/AlGaAs single quantum well (SQW) lasers. The GRINSCH strained InGaAs/AlGaAs SQW wafer was grown on (100) n-GaAs substrate by molecular beam epitaxy (MBE). The GRINSCH structure consists of a 1 μm GaAs buffer layer, a 1.5 μm n-$Al_{0.5}Ga_{0.5}As$ lower cladding layer, a 2000 Å $Al_xGa_{1-x}As$ graded region (x=0.5–0.2), a 40 Å GaAs space layer, 80 Å $In_{0.3}Ga_{0.7}As$ quantum well (QW), a 40 Å GaAs spacer layer, a 2000 Å $Al_xGa_{1-x}As$ graded region (x=0.2–0.5), a 1.5 μm p-$Al_{0.5}Ga_{0.5}As$ upper cladding layer, and a 2000 Å p^+-GaAs cap layer. After the MBE growth, mesas with an active stripe width ~ 2 μm were (wet) chemically etched. In order to fabricate buried heterostructures (BH) lasers, a p-$Al_{0.4}Ga_{0.6}As$ layer and an n-$Al_{0.4}Ga_{0.6}As$ layer were grown successively to form a blocking junction by a liquid phase epitaxy (LPE) system. After the LPE regrowth, the wafer was processed into BH lasers using other conventional fabrication techniques. High reflectivity (HR) dielectric coatings were applied to some of the laser facets to reduce the mirror losses. Following the above, the laser chips were mounted junction side up on the H mounts. To measure the threshold current of these lasers at low temperatures, the H mounts were attached to a Cu block in a cryogenic system using liquid helium. The ambient temperature at the laser chips in the cryogenic chamber was controlled from room temperature (~300 K) to near liquid helium temperature (~4 K). The optical output of a laser mounted inside the cryogenic chamber emerged through a window and was focused onto a Si detector. Light versus current (L-I) characteristics were measured under cw conditions at different ambient temperatures at the laser chips.

Figures 1 and 2 show the results from the measured L-I curves for three 225-μm-long lasers with different HR coatings. In Table I, we list the corresponding mirror reflectivity of these lasers where R_1 and R_2 represent the front facet reflectivity and the back facet reflectivity, respectively. The corresponding room temperature (RT) cw threshold currents (I_{th}) of these lasers are also listed in Table I. At room tem-

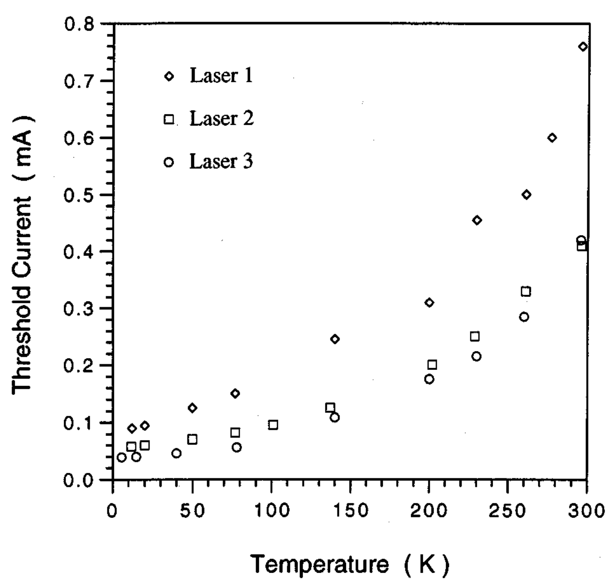

FIG. 1. Measured threshold current as a function of ambient temperature for 225-μm-long InGaAs strained single quantum well buried heterostructure lasers. The lasers have different mirror facet coatings. See Table 1 for the detail.

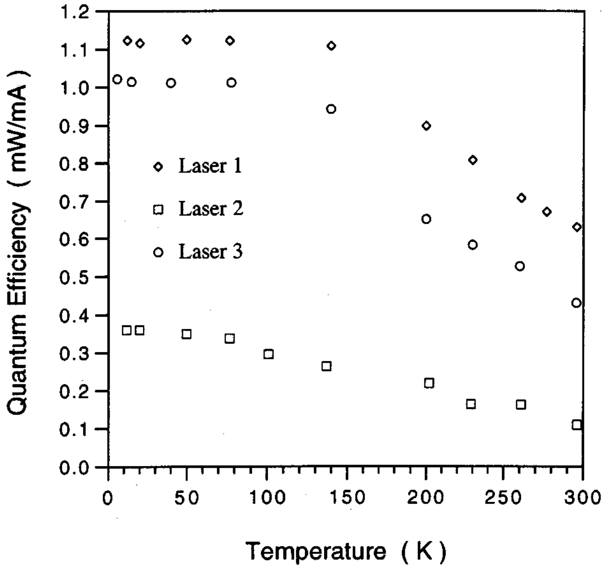

FIG. 2. Measured external quantum efficiency as a function of ambient temperature for 225-μm-long InGaAs strained single quantum well buried hetersotructure lasers. The lasers have different mirror facet coatings. See Table I for the detail.

perature, the typical internal quantum efficiency and internal loss constant of these lasers were estimated to be about 80% and 6 cm^{-1}, respectively. Figure 1 shows the measured threshold current as a function of the laser ambient temperature and Fig. 2 shows the corresponding measured external quantum efficiency. It can be seen from Fig. 1 that the threshold currents of these lasers are reduced by near an order of magnitude in going from about 300 K to about 10 K. Near liquid helium temperature, all these lasers have shown threshold currents of less than 100 μA.

In some low temperature applications where the sensitivity is important, it is necessary to use operation temperature as low as possible to reduce the thermal fluctuation. Sometimes, extremely low temperature is very easy and economic to obtain such as in the space applications. In other applications, low temperature near liquid nitrogen (77 K) might be more favorable due to the dramatic reduction in refrigeration cost. We find, see Fig. 1, that both laser 2 and laser 3 have a threshold current of less than 100 μA at 77 K. In Fig. 3, we show the measured L-I curves for laser 3 at temperatures of 6 and 77 K. The corresponding threshold currents are 38 and 56 μA at 6 and 77 K, respectively. The threshold currents (I_{th}) near liquid helium temperature and at 77 K are listed in Table I for all these lasers for comparison.

Figure 2 indicates that the external quantum efficiency increases as the ambient temperature decreases in these lasers. The increase of external quantum efficiency stems from both the increase in internal quantum efficiency and the decrease in internal loss constant in these lasers as the ambient temperature decreases. Both of these effects tend to saturate below 100 K.

TABLE I. A resume for the strained InGaAs SQW BH lasers under the study. The cavity length is 225 μm. R_1 and R_2 are the front mirror facet reflectivity and the back mirror facet reflectivity, respectively.

Laser ID	R_1/R_2	I_{th} (RT)	I_{th} (77 K)	I_{th} (<15 K)
Laser 1	0.3/0.95	0.76 mA	150 μA	90 μA at 12 K
Laser 2	0.95/0.95	0.41 mA	83 μA	58 μA at 12 K
Laser 3	0.75/0.99	0.42 mA	56 μA	38 μA at 6 K

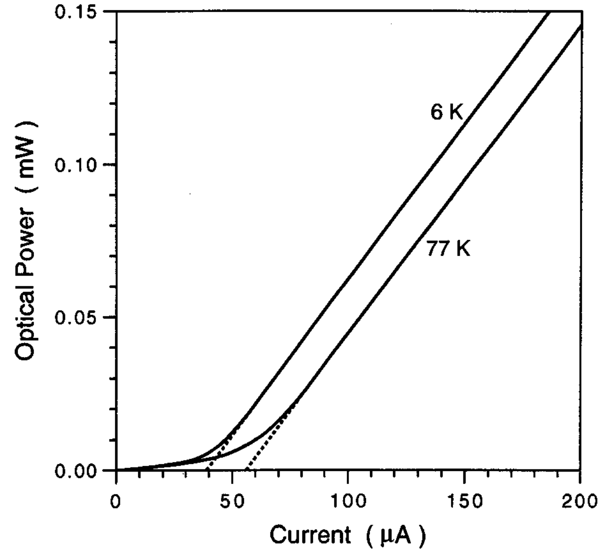

FIG. 3. Light output power as a function of injection current for laser 3 at temperatures of 6 and 77 K. The corresponding threshold currents are 38 and 56 μA at 6 and 77 K, respectively.

The lasing wavelength of these lasers at different low temperatures was also measured and is shown in Fig. 4. As the temperature decreases, the lasing wavelength of these lasers decreases. The solid line in Fig. 4 is a calculated wavelength curve corresponding to the energy band gap of $In_{0.3}Ga_{0.7}As$ at different temperatures. The calculation was

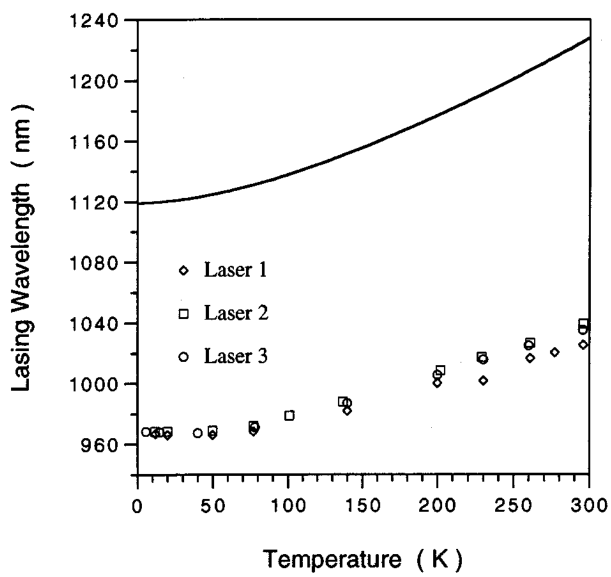

FIG. 4. Measured lasing wavelength as a function of temperature in the strained InGaAs SQW lasers. The solid line is the calculated wavelength corresponding to the $In_{0.3}Ga_{0.7}As$ energy band gap.

made by an empirical relation between the energy band gap and the temperature for $In_{0.3}Ga_{0.7}As$ which is based on the experimental data for the energy band gap of $In_xGa_{1-x}As$ at different temperatures.[4,5] From Fig. 4, we find that the change in lasing wavelength with temperature is due mainly to the change in the energy band gap with temperature in the InGaAs QW. The difference in lasing wavelength and energy band gap wavelength results from the quantum confinement, strain effects and state/band filling of the injected carriers in the InGaAs QW. Note that this difference in InGaAs QW lasers is much larger than that in GaAs QW lasers.[3] The reason is that the InGaAs QW has a deeper QW and the injected holes in InGaAs QW have a smaller effective mass due to the strain effect.

In summary, we have quantified the decrease of threshold current and the saturation in external quantum efficiency with decreasing temperatures in strained InGaAs SQW BH lasers. Sub-100 μA threshold currents have been achieved at cryogenic temperatures under cw conditions. Threshold currents of 38 and 56 μA and external quantum efficiency $\sim$1 mW/mA have been demonstrated at temperatures of 6 and 77 K, respectively. The external quantum efficiency has been enhanced by about a factor of 2 at low temperatures ($<$100 K) in comparison to that at room temperature due to the increase of internal quantum efficiency and the decrease of internal loss constant at low temperatures. These results are encouraging for the prospect of integration of these semiconductor lasers with high performance low temperature electronics.

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