Low-threshold (≤ 92 A/cm²) 1.6 μm strained-layer single quantum well laser diodes optically pumped by a 0.8 μm laser diode

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To explore the ultimate threshold current limit in long-wavelength semiconductor lasers, $In_xGa_{1-x}As/InP$ strained-layer single quantum well laser diodes were studied for the first time by optically pumping with a 0.8 μm laser diode. Low-threshold ($\leqslant 92$ A/cm^2) cw operation was obtained and the lasing wavelength (1.62 μm) corresponding to the transition from the first quantization state of a 25 Å $In_{0.8}Ga_{0.2}As$ well was observed. By taking the carrier collection efficiency ($\leqslant 77\%$) into account, the actual threshold current density could be as low as 70 A/cm^2.

Low-threshold lasers are attractive for parallel optical interconnects with low-power consumption for switching and supercomputer applications. The combination of biaxial strain and quantum confinement has been proposed to reduce the in-plane hole effective mass such that the laser threshold current, Auger recombination, and intervalence-band absorption are reduced.[1,2] Recently, the 1.5 μm strained-layer multiple quantum well (MQW) lasers have been made with high power[3] and low threshold.[4] However, the present threshold current density is still more than one order of magnitude higher than the theoretical value of 10 A/cm^2.[1] In this work, to explore the ultimate threshold current limit, a strained-layer single quantum well active layer was chosen to minimize the current necessary to achieve the transparency and the whole wafer was undoped to minimize the cavity loss. By optically pumping with a 0.8 μm laser diode, low-threshold (143 W/cm^2) cw operation was obtained. The equivalent threshold current density is less than 92 A/cm^2. The lasing wavelength (1.62 μm) corresponds to the transition from the first quantization state of a 25 Å $In_{0.8}Ga_{0.2}As$ well.

As shown in Fig. 1, the step graded-index separate confinement heterostructure (GRINSCH) made of undoped 1.0 μm (145 nm thick)/1.1 μm (145 nm thick)/1.2 μm (10 nm thick) quaternary layers is used to increase the optical confinement in the waveguide region. A single strained-layer $In_xGa_{1-x}As$ well is in the middle of the GRINSCH. The total waveguide thickness is 600 nm with a 2 μm undoped InP layer on the top as the upper cladding layer. The samples were grown by low-pressure organometallic chemical vapor deposition (LP-OMCVD) at 625 °C. The well thickness is estimated to be 25 Å from both the growth rate and the micrograph by a transmission electron microscope (TEM). The amount of strain in the well is about 1.84% in compression corresponding to $x = 0.8$, inferred from x-ray double-crystal diffraction measurements on a 1.3-μm-thick layer grown on InP substrates under identical conditions. The intense room-temperature photoluminescence (PL) peak near 1.6 μm wavelength is in agreement with the calculated value based on the estimated thickness and strain. The wafer was thinned to about 90 μm and cleaved into 500-μm-long bars. The laser bar was soldered on a copper heat sink. To reduce the mirror loss, the facets were high reflection coated with $\lambda/4$ Al_2O_3/Si pairs. The reflectivity is about 99% on the rear facet and 93% on the front facet.

As shown in Fig. 2, the optical pumping was done with a commercial high-power 0.8 μm laser diode. Its emitting area at the output facet is about 400 μm wide. The pump light was focused into a line image of 2.2 mm long and illuminated the laser bar in between two facets. At the output facet, a low-pass optical filter was used to remove 0.8 μm stray light. The lasing region is about 100 μm wide,

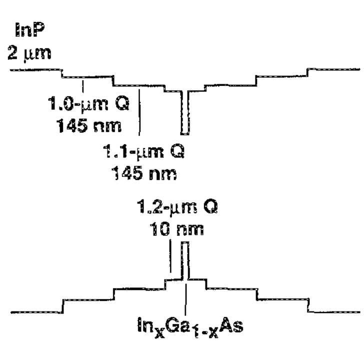

FIG. 1. Schematic band diagram of a GRINSCH strained-layer single quantum well laser.

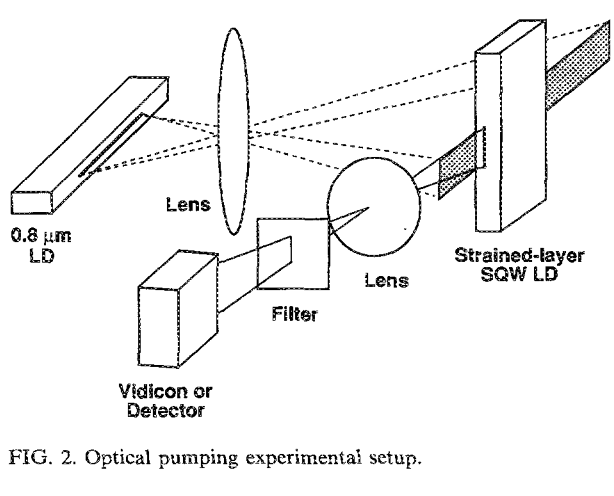

FIG. 2. Optical pumping experimental setup.

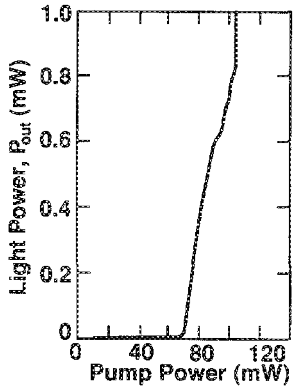

FIG. 3. cw light output vs pump power at 18 °C heat sink temperature.

measured from the near-field image on the vidicon camera. Figure 3 shows the light output versus pump power under cw operation at 18 °C heat sink temperature. The pump power is the power absorbed by the InP cladding layer of the laser, which only takes account of the area and the reflection at the air-InP interface. For a 100-μm-wide and 500-μm-long laser, the threshold pump power is about 71 mW. Since 0.8 μm light is highly absorbed in the InP layer ($\alpha \sim 3\times10^4$/cm),[5] most carriers are generated near the top surface and have to diffuse into the quantum well about 2 μm away. The threshold current density can be accurately determined if the carrier collection efficiency into the well is known. The current density is conservatively estimated to be 92 A/cm^2 based on a 100% carrier collection efficiency. It is the lowest value ever reported in the long-wavelength region. For a 100-μm-wide stripe laser, being able to operate in cw mode is another indication of extremely low threshold current density. Figure 4 shows the cw lasing spectrum at 1.2 times of the threshold pump power. It lases near 1.62 μm corresponding to the transition from the first quantization state. Furthermore, the lasing wavelength is on the longer wavelength side of the PL peak wavelength. The main reason is the low loss due to the undoped waveguide and high reflection facets. For comparison, electrically pumped 1.5 μm lasers with a single $In_{0.53}Ga_{0.47}As$ quantum well previously reported[6] lased on the second quantization transition with a threshold current density of 750 A/cm^2.

To take account of the carrier loss due to surface and bulk recombinations, the carrier collection efficiency is calculated by the use of the continuity equation.[7] The diffusion process is mainly controlled by the slow moving carrier (hole). The ambipolar diffusion coefficient is estimated to be 7.5 cm^2/s from the diffusion coefficients of electron and hole.[8] The GRINSCH region containing a quantum well is assumed to be a perfect carrier sink. Figure 5 shows the calculated carrier collection efficiency of a quantum well as a function of ambipolar diffusion length for different surface recombination velocity S. The carrier collection efficiency is also experimentally estimated to be no more than 77% from the increased PL intensity after removing the InP upper cladding layer. Therefore, the actual threshold current density could be as low as 70 A/cm^2. From Fig. 5, the ambipolar diffusion length and the surface recombination velocity of the InP cladding layer are estimated to be on the order of 4 μm and 10^4 cm/s respectively, in reasonable agreement with measured values.[9]

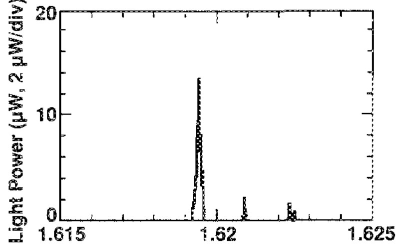

FIG. 4. cw lasing spectrum at 1.2 times of the threshold pump power.

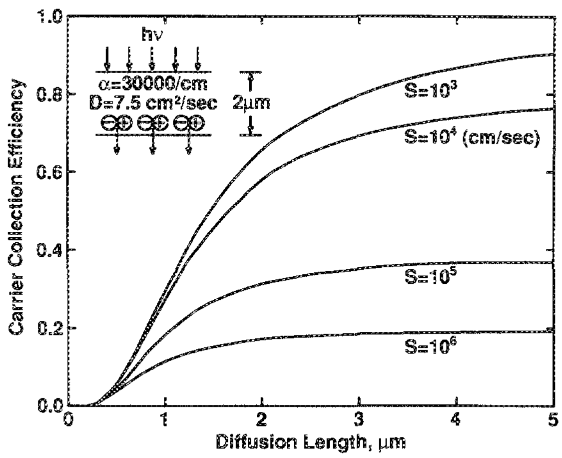

FIG. 5. Calculated carrier collection efficiency of a quantum well under optical pumping as a function of ambipolar diffusion length for different surface recombination velocity S.

In conclusion, we have demonstrated the low-threshold potential of the strained-layer single quantum well laser in the long-wavelength region. The actual threshold current density could be as low as 70 A/cm^2. In spite of the small optical confinement ($\sim$0.35%) of the single, thin strained-layer quantum well (8–9 monolayers), the lasing wavelength (1.62 μm) corresponding to the transition from the first quantization state was obtained by minimizing the cavity loss and the mirror loss.

[1] E. Yablonovitch and E. O. Kane, J. Lightwave Technol. **6**, 1292 (1988).
[2] A. R. Adams, Electron. Lett. **22**, 249 (1986).
[3] P. J. A. Thijs and T. Van Dongen, Electron. Lett. **25**, 1735 (1989).
[4] U. Koren, M. Oron, M. G. Young, B. I. Miller, J. L. De Miguel, G. Raybon, and M. Chien, Electron. Lett. **26**, 467 (1990).
[5] H. Burkhand, H. W. Dinges, and E. Kuphal, J. Appl. Phys. **53**, 655 (1982).
[6] T. Tanbun-Ek, R. A. Logan, H. Temkin, K. Berthold, A. F. J. Levi, and S. N. G. Chu, Appl. Phys. Lett. **55**, 2283 (1989).
[7] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981).
[8] T. P. Pearsall, *GaInAsP Alloy Semiconductors* (Wiley, New York, 1982).
[9] E. Yablonovitch and T. J. Gmitter, in *Proceedings of Symposium on Diagnostic Techniques for Semiconductor Materials and Devices*, edited by T. J. Shaffner and D. K. Schroder (Electrochemical Society, Pennington, New Jersey, 1988), Proc. Vol. 88.20, p. 207.