Transverse-mode & polarization characteristics of double-fused 1.52 μm vertical-cavity lasers

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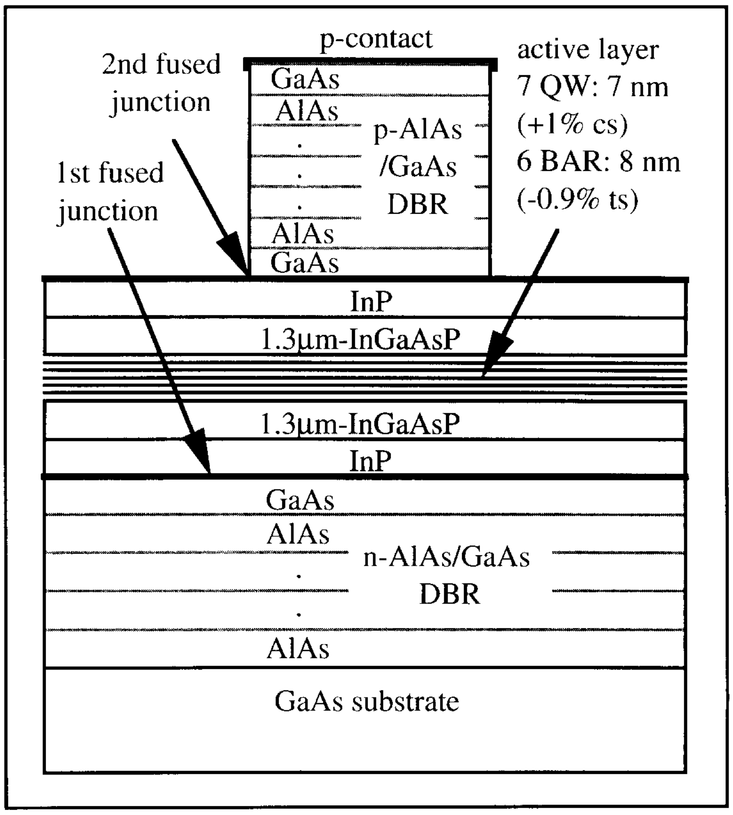
We report on the transverse mode and polarization characteristics of a novel 1.52 μm vertical-cavity laser that utilizes an InGaAsP strain-compensated quantum-well active layer and two AlAs/GaAs quarter-wave mirrors. The 6 and 8 μm diameter devices exhibit room-temperature pulsed threshold currents as low as 4 mA, and a maximum output power of 14 mW was measured on a 60 μm diameter device.

Figure 1. Double-fused vertical-cavity laser structure.



Long-wavelength vertical-cavity lasers are potentially integrable low-cost sources for optical communication systems. The practical choice for 1.3 μm and 1.55 μm emitting/absorbing material is the quaternary InGaAsP alloy lattice matched to InP. The difficulty in using this material system lies in the relatively small refractive index values that can be achieved by varying the InGaAsP composition. A large refractive index ratio is essential for the realization of high reflection coefficients in practical distributed Bragg reflectors. Furthermore, the thermal conductivity of quaternary alloy is an order of magnitude lower than that of InP. To address these issues we have proposed [1] and demonstrated [2] long-wavelength vertical-cavity lasers (VCLs) using AlAs/GaAs mirrors and InGaAsP active layers bonded by wafer fusion [3]. Using this method, substrates of vastly different lattice constants can be bonded to produce an optically transparent junction that is both electrically and thermally conductive [4]. Wafer fusion opens great possibilities for realization of novel optoelectronic devices that utilize InGaAsP and GaAlAs materials in a single structure. Recently, we reported a new long-wavelength VCI structure that uses two AlAs/GaAs quarter-wave mirrors and an InGaAsP strain-compensated quantum-well active region [5]. These devices were fabricated by two wafer fusion steps and exhibited record values for pulsed threshold current at room temperature. In this paper, we report on devices that have similar mirrors and active layer structure but were fabricated using improved reactive ion etching. This process improvement has resulted in a threefold reduction in the lowest threshold current value: 4 mA pulsed al room-temperature. Furthermore, we show that, even though these lasers operate in many transverse modes, the light output is highly linearly polarized with the electric field parallel to the [011] direction. Single mode operation was observed on 6 and 8 μm diameter devices in which the degree of polarization along the [011] axis was as high as 97%.

The double-fused vertical-cavity laser structure, shown in Figure 1, uses two MBE-grown AlAs/GaAs quarter-wave mirrors fused to an MOCVD grown InGaAsP active region. The bottom reflector is a Si-doped 25-period GaAs/AlAs mirror designed for 99.8% reflectivity, while the top is a Be-doped 24-period GaAs/AlAs mirror designed for 99.5% reflectivity. In order to reduce the effects of absorption in p-type GaAs and AlAs at long wavelengths, the p-mirror features a hybrid doping scheme: the 10 periods closest to the cavity are doped $3x10^{17}$ cm^{-3}, while the rest of the mirror is doped $1x10^{18}cm^{-3}$. All the interfaces have been linearly graded over 18 nm and doped approximately live times the bulk doping.

Recent studies have shown that strained quantum wells have higher optical gain and lower transparency than unstrained quantum wells [6], [7]. In order to achieve the high gain needed in InP-based vertical-cavity lasers the number of wells required exceeds the number of strained wells that can be grown coherently. For this reason, strain compensated InGaAs / InGaAsP [8] quantum wells have been investigated for long-wavelength vertical cavity laser applications. In this laser we have used strain-compensated InGaAsP wells and barriers grown under a constant As/P ratio [9]. MOCVD growth under the constant As/P ratio has the advantage of minimizing the Group V element interdiffusion during the growth and the subsequent high temperature processing (wafer fusion). The active layer of our double-fused laser consists of seven strained InGaAsP quantum wells (7 nm and 1 % compressive strain) with strain-compensating InGaAsP barriers (8 nm and 0.9% tensile strain). The fabrication process involves two wafer fusion steps: the first step is the fusion of the n-type mirror to the InP active layer, and then after InP substrate removal, the p-type mirror is fused to the other side of the active layer. In order to minimize Be diffusion, the p-type mirror undergoes the high temperature fusion step only once. Both fusion steps are performed at 630°C for 20 minutes in a hydrogen atmosphere [1-4]. The InP substrate was selectively removed using a mixture of $HCl:H_20$ down to an InGaAsP etch-stop layer, while the GaAs substrate was removed using $NH_40H:H_20_2$ spray etching at pH 8.3 [10]. The devices were defined with circular p-type contacts which were used as a mask in Cl_2 reactive ion etching. An SEM micrograph of finished devices is shown in Figure 2.

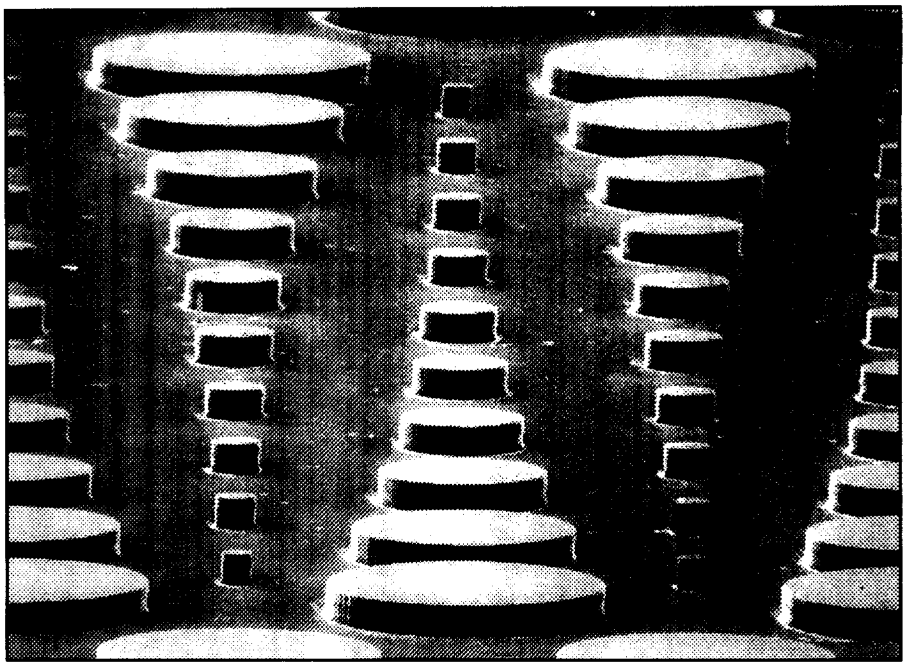


Figure 2. Finished double-fused vertical-cavity lasers. Ten different sizes between 6 and 60 μm inclusive are shown.

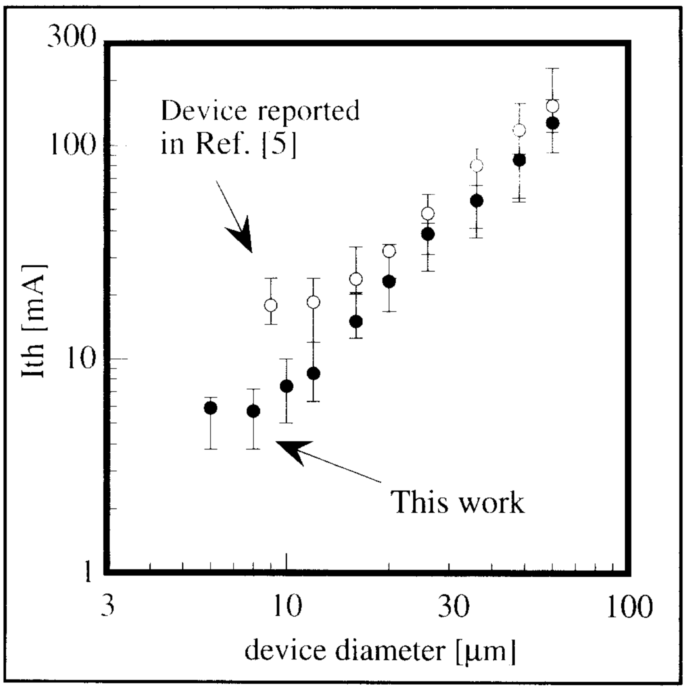


Figure 3: Threshold current as a function of the diameter for devices reported in this work compared to the device reported in Ref. [5]. The error bars indicate the largest and the lowest value measured, while the data point is the median of the measurements.

All ten laser sizes on the mask (6 to 60 μm inclusive) operate at room-temperature under pulsed conditions (50 ns / 25 kHz / 25°C). The lasing

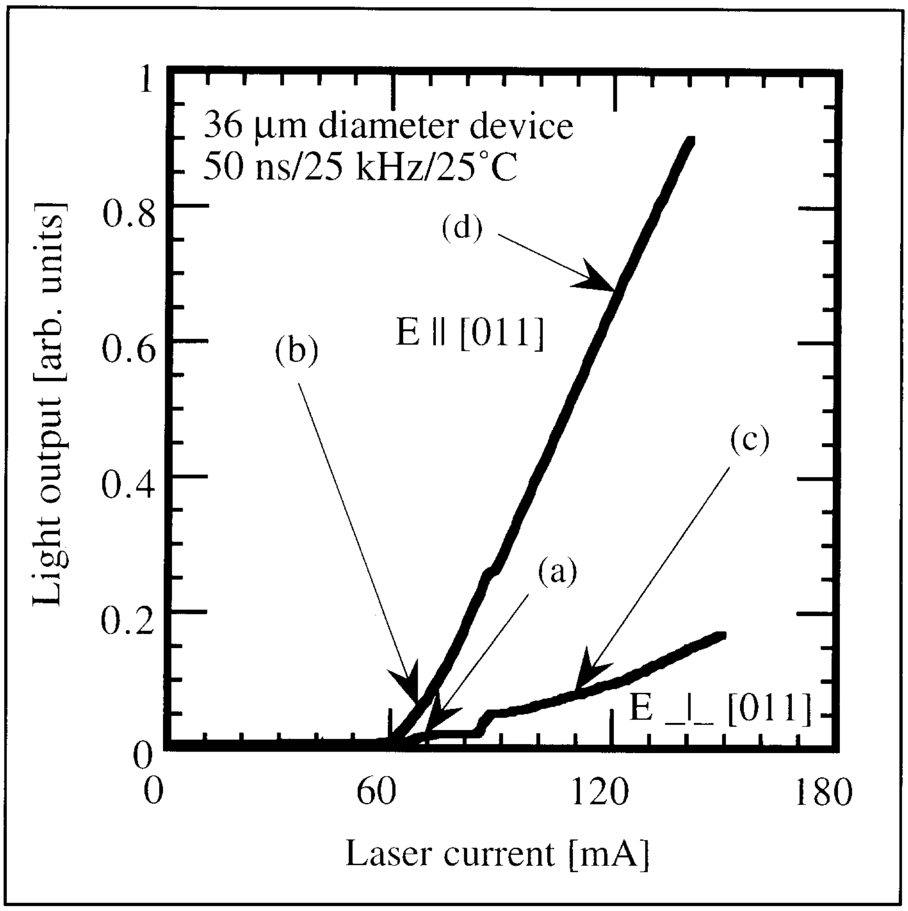


Figure 4. Polarization-resolved light-current characteristics of a 36 μm diameter device. The associated near-field patterns are shown in Figure 5.

wavelength is 1517 nm ± 2 nm, depending on the location on the sample. The lowest threshold current of 4 mA was measured on several 6 and 8 μm devices. The highest pulsed output power of 14 mW was measured on a 60 μm device. The external differential quantum efficiency of devices with diameters larger than 26 μm was approximately 2.5%, while for smaller devices it reduced to below 1%. The temperature dependence of the threshold current shows an exponential behaviour around room temperature with a characteristic temperature of $T_0 \approx$ 28 K. The voltage drop across the devices at threshold ranges from 12 V on the largest to 24 V on the smallest devices and is dominated by the p-AlAs/GaAs mirror heterojunction resistance. This high voltage drop can be significantly reduced with an improved mirror design. The uncertainty of our current and voltage measurements is estimated to be +5%.

Figure 3 shows the threshold current of 120 devices (measured in this work) compared to our previous result [5]. The largest and the lowest value of the threshold current measured are shown with the upper and the lower ends of the error bars. The devices reported in Ref. [5] had corrugated sidewalls resulting trom selective etching of GaAs over AlAs and roughness from interruptions during the etch. In this work, the etching was uninterrupted, the GaAs/AlAs selectivity was reduced by reducing the base pressure before the etch three times (down 17 μPa), and the etched devices were kept in N_2 atmosphere to slow down AlAs oxidation. This improved etching scheme resulted in a threefold reduction in the lowest threshold current as well as the operation of smallest devices on the mask (down to 6 μm). The yield on this run was better than 95%: out of 125 devices of all diameters, 120 were found to laser. The difference between the threshold current data for devices in Ref. [5] and this run clearly indicates

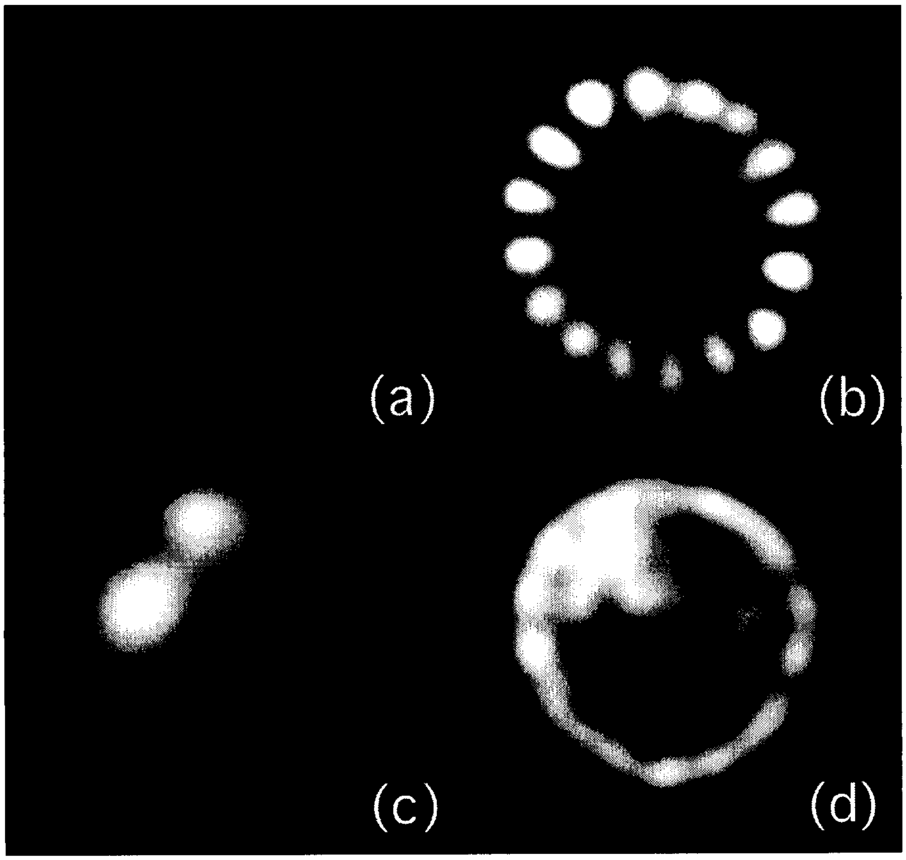


Figure 5. Polarization-resolved near-field pattern for the device with light-current characteristic shown in Figure 4. (a) $I \approx I_{th}$, E_|_ [011], (b) $I \approx I_{th}$, E|| [011], (c) $I \approx 1.8\, I_{th}$.E_|_ [011]. (d) $I \approx 1.81\, I_{th}$. E || [011].

that the rough sidewalls have a significant impact on the cavity loss for small diameters, while for large devices both samples show that the best broad-area threshold current density possible with this cavity is in the range 3-4 kA/cm.^{2} Further improvement of these values is expected with a better *p*-type AlAs/GaAs mirror design.

Multiple transverse-mode operation was observed in the near-field patterns and the spectra of devices of all sizes. Most of the 6 and 8 μm diameter devices lased in a single transverse mode up to 3 or 4 times the threshold current. The output from all devices was highly polarized, even when many transverse modes were lasing. In all of the devices tested, the maximum intensity was polarized along the [011] direction (electric field parallel to the [011]).

Figures 4 and 5 show the polarization resolved light-current characteristics and the associated near-field patterns of a 36 μm diameter device at $I \approx I_{th}$ and at $I \approx 1.8\ I_{th}$ The existence of a field pattern with 16-fold radial symmetry at $I \approx I_{th}$ (Figure 5b) attests the quality of the etched sidewalls and the absence of damage to the active layer from wafer fusion. The absence of emission from the center may be a result of current crowding at the edges and indicates that a large number of transverse modes are already present at threshold. The near-field pattern with the 16-fold radial symmetry clearly exists only with the electric field polarized along the [011] direction. The central region of the laser starts to emit at higher currents (Figure 5d), while the light intensity along the orthogonal direction (Figures 5a and 5c) is much weaker on all device sizes. The cause for this highly polarized behaviour is not well understood. We speculate that polarization anisotropy has been introduced by uniaxial strain locally introduced and relaxed by the dislocations at the fused interface. We have performed polarization resolved measurements of the photoluminescence from the active layer of this device and were not able to observe such anisotropy (note that the InP epilayers are exposed in the completed device to make such measurements possible). An example of a highly polarized output from a 6 μm device is shown in Figure 6, where at 15 mA the degree of polarization $V = (I_{max} - min)/(I_{max} + I_{min})$ was 97%. The threshold current of this laser was below 4 mA, and the line width was limited to 0.5 nm by chirping during the pump pulse. The multiple-mode operation of a 10 μm diameter device at two times threshold is illustrated in the polarization-resolved near-field pattern shown in Figure 7.

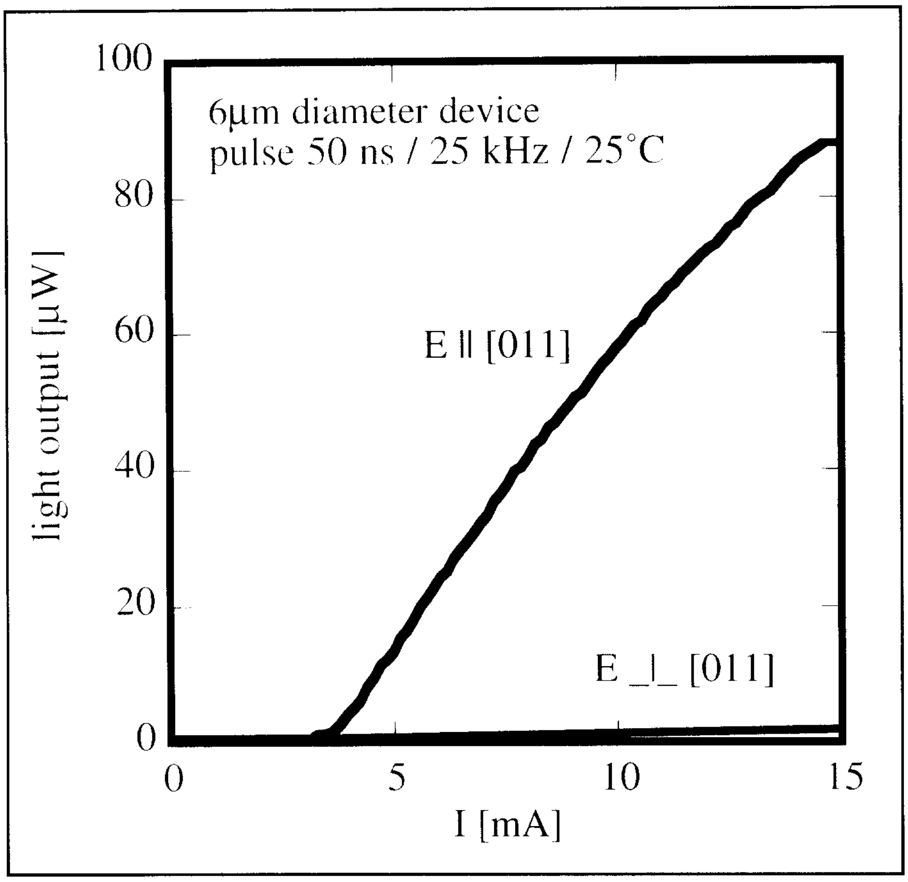


Figure 6. Polarization-resolved light-current characteristic of a 6 -μm diameter device. At 15 mA the degree of polarization was 97 %.

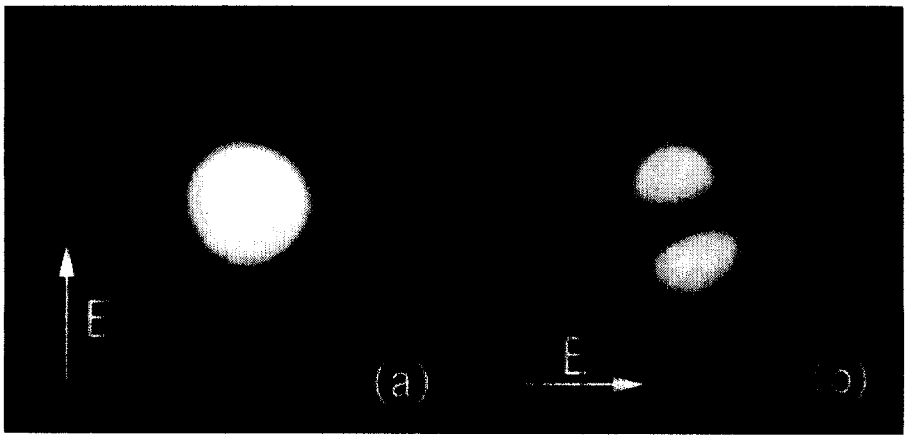


Figure 7. Polarization-resolved near-field patterns of a 10 mm diameter device at two times the threshold current. (a) E 11 [011] (maximum intensity), and (b) E .1 [011] (minimum intensity).

Very strong polarization anisotropy has been observed in multi-mode double-fused vertical-cavity lasers. The maximum intensity for all devices occurs with the electric field parallel to the [011] direction. Further investigation of this polarization anisotropy may open possibilities for realization of vertical cavity lasers with stable and controlled polarization characteristics. Finally, the improved fabrication of double-fused 1.52 μm vertical-cavity lasers resulted in record low values of pulsed threshold current and threshold current densities at room-temperature. With improved p-type Al(Ga)As/GaAs mirrors and a suitable surface passivation continuous-wave room temperature operating long-wavelength vertical cavity lasers should be possible.

Acknowledgement

This paper is reproduced by kind permission. It was the recipient of the Michael Lunn Memorial Award for Best Presentation at the IPRM95 Conference. A slightly shorter version of this paper is published in Electronics Letters Vol. 31 no. 8 pp. 653-654, 13 April 1995. The work was supported by ARPA and Rome laboratories.

Biography

Dubravko I. Babic was born in Zagreb, Croatia in 1959. He received the Dipl. Ing. degree from University of Zagreb, Croatia in 1982 and his M. S. degree from University of California, Santa Barbara in 1984. From 1985 to 1989 he was working on the design, fabrication and characterization of high-speed silicon and GaAs microwave diodes in the Advanced Bipolar Devices research and development department of Avantek, Inc. in Santa Clara, California. From 1989 to 1995 he has been working on his Ph. D. degree at the University of California, Santa Barbara. As a part of his doctoral project, he fabricated the first room-temperature continuous-wave operating 1.54 μm vertical-cavity laser. His research interests include the physics of semiconductor micro-resonators, vertical-cavity lasers, and the fabrication of optoelectronic by fusion bonding.

References

[l] J. J. Dudley, M. Ishikawa, D. 1. Babic, B. I. Miller, R. P. Mirin, W. B. Jiang, J. E. Bowers, E. L. Hu *Appl. Phys. Lett.* 61, 3095 (1992).

[2] J. J. Dudley, D. I. Babic, R. Mirin, L. Yang, B. I. Miller, R. J. Ram, T. E. Reynolds, E. L. Hu, J. E. Bowers, *Appl. Phys. Lett.* 64, 1463 (1994).

[3] Z. L. Liau, D. E. Mull, *Appl. Phys. Lett.* 56, 737 (1990).

[4] R. J. Ram, E. Yang, K. Nauka, Y. M. Huong, M. Budowise, D. E. Mars, J.J. Dudley, S. Y. Wang, *Appl. Phys. Lett.* 62, 2474 (1993).

[5] D.I. Babic, J.J. Dudley, K. Streubel, R.P. Mirin, J.E. Bowers, E.L. Hu, *Appl. Phys. Lett.* 667 1032 (1995).

[6] E. Yablonovitch and E.O. Kane, *J. Lightwave Technol. 6, 1292 (1988).*

[7] S. W. Corzine, R.H. Yan, L,. A. Coldren, *Appl. Phys. Lett.* 57, 2835 (1990).

[8] C.H. Lin, C.D. Chua, Z.H. Zhu, F. E. Ejeckam, T.C. Wu, Y. H. Lo, *Appl. Phys. Bett.* 64, 3395(1994).

[9] K. Streubel, J. Wallin, G. Landren, U. Ohlander, S. Lourdudoss, O. Kjebon, *J. of Crystal Growth.* 143, 7 (1994).

[10] H. Tanobe, T. Tamanuki, T. Uchida, F. Koyama, K. Iga, *Jpn. J. Appl. Phys.* 31 pt. 1, 949 (1992).

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Update on long-wavelength vertical-cavity laser development

by Dubravko Babic

The double-fused vertical-cavity lasers reported in [1] demonstrated record low threshold currents and current densities under pulsed operation. However, their continuous-wave operation at room-temperature was limited by high power dissipation in the device. For this reason, two issues were addressed in the later development of these devices: the reduction of the resistance of the p-AlAs/GaAs mirror and better high-temperature operation of the active layer. Using similar laser structure (as in [1]), and improved active layer and p-mirror designs, we have recently demonstrated the first room-temperature continuous-wave operation double-fused vertical-cavity lasers [2]. The active layer of these devices contains seven 6 nm compressively strained InGaAsP quantum-wells and six 7 nm strain-compensating barriers, embedded in an InP cladding on both sides. The quaternary separate confinement region, used in previous devices [1], was omitted in order to reduce carrier leakage and improve high temperature performance. The p-mirror has 30 periods of Be-doped $A_{l0.67}Ga_{0.33}As$/GaAs with bulk doping of 4×10^{17} cm^{-3} and parabolically graded interfaces.

Five lasers with diameters between 8 μm and 20 μm operated continuously, while all other sizes operated pulsed at room temperature (23 C). (The mask pattern is identical to that shown in Fig. 2 of Ref. [1]). The lasing wavelength was 1542+/-1 2 nm. The narrowest linewidth -easured was 0.32 nm limited by the presence of multiple transverse modes within this linewidth. The lowest CW and pulsed threshold currents were 2.3 mA and 1.8 mA (8 μm device), while the lowest CW and pulsed threshold current densities are 2.5 kA/cm^2 (20 μm device) and 1.4 kA/cm^2 (60 μm). The continuous-wave characteristic temperature T_o dT/dlnI_{th}(T) at room-temperature varies between 28 and 37 K, while the pulsed T_o value is in the neighborhood of 37 K. Highest CW and pulsed operation temperatures were 34°C and 50°C, respectively.

Future developments of this structure involve the reduction of the thermal resistance by flip-chip mounting, the reduction of the device electrical resistance by engineering lower resistance mirrors, and finally the reduction of optical scattering on the sidewalls by the use of lateral AlGaAs oxidation. Our group at UC Santa Barbara has recently demonstrated the first laterally- oxidized long-wavelength vertical-cavity laser (1.56 mm) with a record-low continuous-wave threshold current of 1.5 mA at room temperature [3]. The highest continuous-wave and pulsed operation temperatures for these devices were 39°C and 70°C indicating that a wide range of temperatures and very low threshold currents will be possible in long-wavelength vertical-cavity lasers obtained by wafer fusion, making these devices a promising choice for low-cost communication optical sources.

References

[1] D. I. Babic, J. J. Dudley, K. Streubel, R.P. Mirin, N. M. Margalit, J. E. Bowers, E. L. Hu, "Transverse-mode and polarization characteristics of double-fused 1.52 um vertical-cavity lasers", 1995 Indium Phosphide and Related Materials Conference, Sapporo, Hokkaido, Japan, paper SB1.2, May 9-13 (1995).

[2] D. I. Babic , K. Streubel, R. P. Mirin, N. M. Margalit, J. E. Bowers, E. L. Hu, D. E. Mars, L. Yang, K. W. Carey, "Continuous-wave room-temperature operation of 1.54 um vertical-cavity lasers", IEEE Phot. Technol. Lett., Vol. 7, No. 11, pp. 1225-1227 (1995).

[3] N. M. Margalit, D. I. Babic, K. Streubel, R. P. Mirin, S. Zhang, D. E. Mars, J. E. Bowers, E. L. Hu, "Laterally oxidized long-wavelength CW vertical-cavity lasers", Proc. 1996 Opt. Fib. Conf., paper PD10, San Jose, 1996.