Long-wavelength, two-dimensional, WDM vertical-cavity surface-emitting laser arrays fabricated by nonplanar wafer bonding

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Abstract. We demonstrate the first long-wavelength, two-dimensional, wavelength division multiplexed vertical-cavity surface-emitting laser array. The eight-channel single-mode array covers the C-band from 1532 nm to 1565 nm. The devices are fabricated using two separate active regions laterally integrated using nonplanar wafer bonding. We achieved single-mode powers up to 0.8 mW, 2-dB output power uniformity across the array, and side-mode suppression ratios in excess of 43 dB. This fabrication technique can be used to maintain the gain-peak and cavity-mode alignment across wideband arrays and, with the use of non-traditional mirrors, can be extended to the fabrication of arrays covering the entire C, S, and L-bands as well as the 1310-nm transmission band.

I. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are of great interest due to their advantages in low-cost manufacturing and packaging. This is made possible by wafer-scale fabrication and testability, low-power dissipation, low-divergence circular-output beams, and the relative ease of fabricating one and two-dimensional VCSEL arrays. These qualities are compatible with the emerging market for coarse wavelength division multiplexing (CWDM) in low-cost, high-performance, optical networks. CWDM networks are being developed as a lower-cost alternative to dense wavelength division multiplexing, and cover the entire low-loss, low-dispersion window from 1470 nm to 1610 nm, typically in 20-nm increments [1]. Integrating all the multiple-wavelength sources required into a single package can achieve great cost savings for this application. Integrating the WDM sources themselves in a wafer-scale fabrication process could attain even further cost reductions. When considering this wide wavelength range for the integrated devices, it is important that the individual devices exhibit uniform device properties, such as threshold, differential efficiency, output power, and other laser emission properties. Any CWDM VCSEL array technology must address these requirements.

Several groups have been working on attaining multi-wavelength VCSEL arrays [2-5]. These techniques, which make use of crystal-growth techniques, have been successful in demonstrating multiple-wavelength VCSEL arrays operating up to 1.2 μm[5] and covering wavelength spans of up to 45 nm [4]. One-dimensional VCSEL arrays operating around 1.55 μm and 1.3 μm have also been demonstrated using superlattice thickness-adjustment etches in wafer-bonded VCSEL structures [6, 7]. All these techniques primarily adjust the cavity-mode wavelength across the surface of the wafer. Though this is sufficient to adjust the lasing wavelength of the devices in the array, the alignment between the gain peak and the cavity mode must also be maintained in order to control the device properties in wideband WDM VCSEL arrays. Thus, it is necessary to have equal control over both composition and thickness laterally across the surface of the wafer to achieve wideband WDM VCSEL arrays. We have previously reported a new technique called nonplanar wafer bonding which is capable of achieving this lateral-composition control [8].

In this paper we have applied nonplanar wafer bonding to demonstrate the first two-dimensional WDM VCSEL array covering the C-band. The array uses eight channels on a 4.5-nm pitch to extend from 1532 nm to 1565 nm. This technique should be extendable to the simultaneous integration of VCSEL active regions covering the C, S, and L bands as well as the 1310-nm transmission band.

2. Array fabrication

The fabrication of this device begins with two strained periodic-gain multi-quantum-well long-wavelength VCSEL active regions grown vertically on an InP wafer and separated by an etch-stop layer. The active regions have optical-cavity lengths of 2.5 wavelengths at 1565 nm and 1547 nm and have photoluminescence peaks at 1530 nm. In addition, the active regions have a two-period superlattice on one side that can be used for additional wavelength control in the second axis of the final two-dimensional array [6].

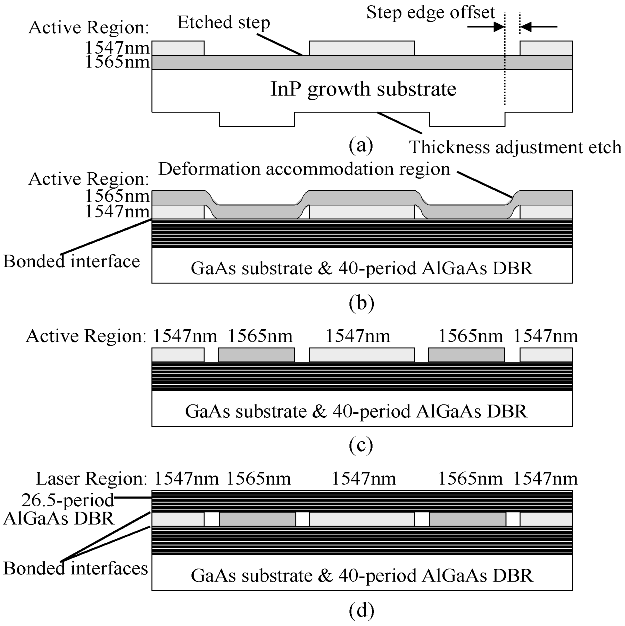

Figure 1. Process-flow cross-section schematics for the fabrication of the eight-channel VCSEL array

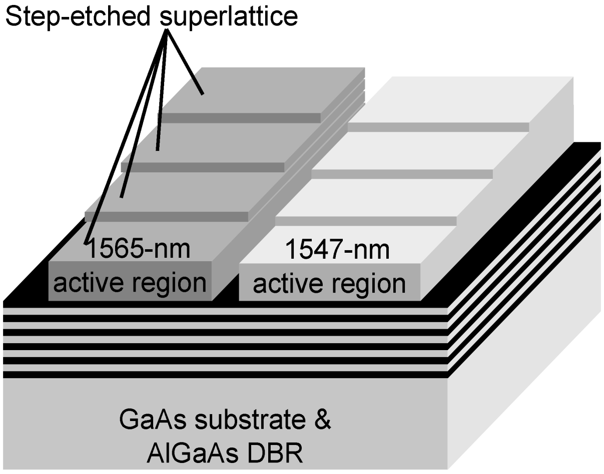

Figure 2. 3-D schematic of the device after the nonplanar bond and the superlattice etch.

The active-region wafer surface is etched with a step-shaped profile to reveal a different active region on each step level. The backside of the wafer is etched to have a profile complimentary to the step-etched active-region side of the wafer, as shown in Fig. 1(a). This thickness-adjustment etch is designed to yield an identical substrate plus epitaxial film thickness at each lateral point on the wafer. The lateral offset between the front-side and back-side step edges provides a region over which the substrate layers can accommodate the deformation. The nonplanar wafer is direct wafer bonded to a 40-period AlGaAs distributed Bragg reflector (DBR) grown on a GaAs substrate. The original InP growth substrate is removed, leaving the active regions attached to the AlGaAs DBR as depicted in Fig. 1(b). The excess active-region material and the deformation accommodation regions are removed, revealing a different active region at each lateral position along the first dimension of the AlGaAs mirror as represented by Fig. 1(c). At this point, the original superlattice that was grown on each active region is etched with a step-shaped profile to trim the cavity resonance of each of the two separate active regions in the second dimension of the wafer surface. Fig. 2 shows a schematic of a small section of the wafer surface after the superlattice etches. Fig. 3 is a photograph of the wafer surface in the same region shown in Fig. 2 and indicates the location of the eight channels in the final VCSEL structure. Each of the separate wavelength regions is about 500 µm wide. A 250-µm region where the deformation accommodation region was removed separates the two active regions from each other. A second, 27-period, AlGaAs DBR is bonded by traditional semiconductor-direct bonding [9] to create the structure shown in Fig. 1(d). One half period of the mirror is used as the etch-stop layer for the substrate removal, leaving a 26.5-period DBR. Fig. 1(d) shows a cross-section schematic of the eight-wavelength VCSEL array structure. Index guiding in the VCSEL structure is accomplished with 30-nm tall, circular post index guides that are etched into the surface of the top DBR prior to the second wafer bond. The index guides are 8 µm in diameter and are located at the bonded interface in the final device structure.

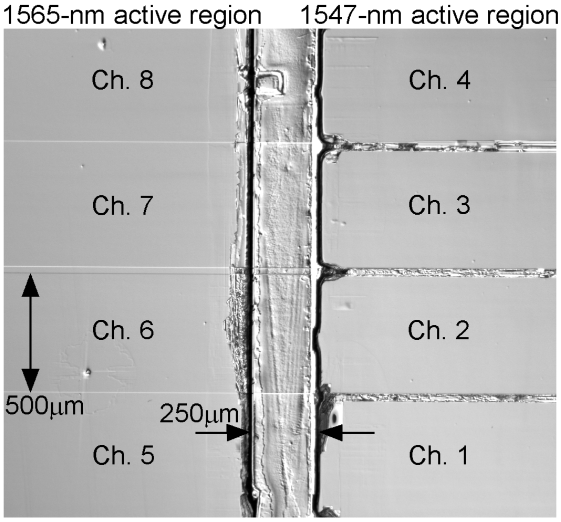

Figure 3. Photograph of the device area after the nonplanar bond and superlattice etch.

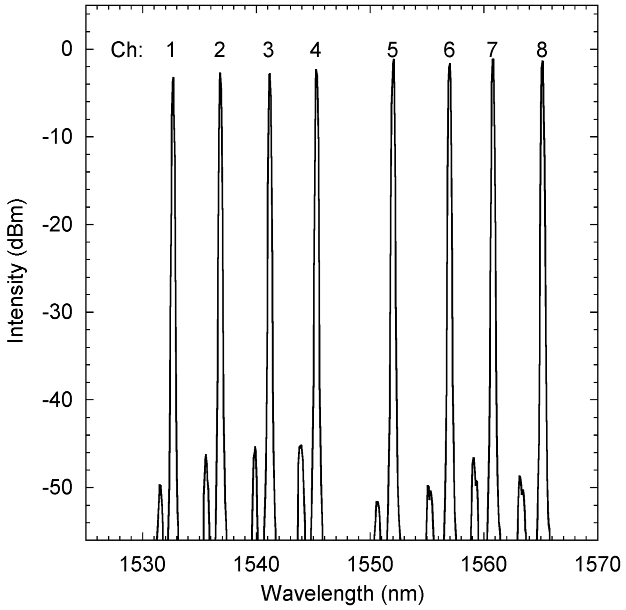

Figure 4. Superimposed lasing spectra of the eight-channel VCSEL chip

3. Results

The final structure is an eight-channel, two-dimensional, WDM VCSEL array. The array is optically pumped with a 980-nm pump laser. The periodic-gain active regions utilize about 680 nm of 1.35-µm InGaAsP barrier material and have a single-pass absorption of about 80%. Fig. 4 shows the room-temperature lasing spectra at a constant absorbed pump power of 10.5 mW for each device. There is a 2-dB variation in the output power at this constant pump power. The devices all exhibit single-mode operation with the worst-case side-mode suppression ratio of 43 dB occurring in the fourth channel. The excess wavelength separation between the fourth and the fifth channel is a result of a growth-rate error during the growth of the 1565-nm active region.

4. Conclusion

Nonplanar wafer bonding has been used to generate the first long-wavelength, two-dimensional, WDM VCSEL array. These devices exhibit high-quality single-mode emission over the range of 1532 nm to 1565 nm. By using two separate active regions laterally integrated on the surface of the wafer we have demonstrated that nonplanar wafer bonding can be used as a lateral-heterogeneous-integration technique in the fabrication of VCSEL arrays. This technique can be extended to combine VCSEL active regions with optimised gain-peak and cavity-mode alignment over a wide wavelength range, allowing for the future fabrication of uniform wideband WDM VCSEL arrays suitable for CWDM optical-network applications.

References

[1] B. E. Lemoff, OSA Optics and Photonics News, vol. 13, no. 3, pp. S8-S14, Mar. 2002.

[2] C. J. Chang-Hasnain, J. P. Harbinson, C. Zah, M. W. Maeda, L. T. Florez, N. G. Stoffel, and T. Lee, IEEE J. Quantum Electron., vol. 27, no. 6, pp. 1368-1376, June 1991.

[3] L. E. Eng, C. J. Chang-Hasnain, K. Bacher, M. Larson, G. Ding, and J. S. Harris, Proc. LEOS'94, 1994, pp. 261-262.

[4] F. Koyama, T. Mukaihara, Y. Hayashi, N. Ohnoki, N. Hatori, and K. Iga, Electron. Lett., vol. 30, no. 23, pp. 1947-1948, Nov. 1994.

[5] M. Arai, T. Kondo, M. Azuchi, T. Uchida, A. Matsutani, T. Miyamoto, and F. Koyama, 14th IPRM, 2002, pp. 303-306.

[6] A. Karim, P. Abraham, D. Lofgreen, Y. J. Chiu, J. Piprek, and J. E. Bowers, Electron. Lett., vol. 37, no. 7, pp. 431-432, Mar. 2001.

[7] V. Jayaraman, M. Soler, T. Goodwin, M. J. Culik, T. C. Goodnough, M. H. MacDougal, F. H. Peters, D. VanDeusen, D. Welch, Proc. 2000 CLEO, 2000, pp. 344.

[8] J. Geske, V. Jayaraman, Y. L. Okuno, and J. E. Bowers, Appl. Phys. Lett., vol. 79, no. 12, pp. 1760-1762, Sept. 2001.

[9] A. Black, A. R. Hawkins, N. M. Margalit, D. I. Babic, A. L. Holmes, Jr., Y. Chang, P. Abraham, J. E. Bowers, and E. L. Hu, IEEE J. Select. Topics Quantum Electron., vol. 3, no. 3, pp. 943-951, June 1997.