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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 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 sidemode suppression ratios in excess of 43 dB. This fabrication technique can be used to maintain the gain-peak and cavity-mode alignment across wide-band arrays and, with the use of nontraditional 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.**

***Index Terms*—Optical fiber communication, optical pumping, semiconductor lasers, surface-emitting lasers, wafer bonding, wafer-scale integration, wavelength-division multiplexing (WDM).**

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 (WDM), and cover the entire low-loss low-dispersion window from 1470 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.

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Several groups have been working on attaining multiwavelength 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 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 wide-band 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 wide-band 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 letter, 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 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.

II. Array Fabrication

The fabrication of this device begins with two strained periodic-gain multiquantum-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 and 1547 nm and have photoluminescence (PL) 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].

The active-region wafer surface is etched with a step-shaped profile to reveal a different active region on each step level. The back side 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

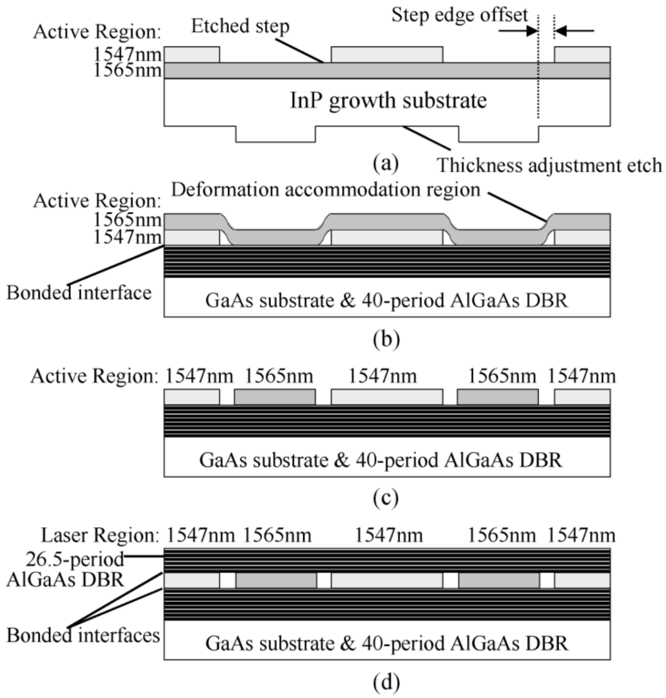

Fig. 1. Process-flow cross-section schematic depicting: (a) the epitaxial-film side and back side of the as-grown wafer etched with a step profile, revealing separate VCSEL active regions at different lateral points on the wafer surface; (b) the VCSEL active regions bonded to the AlGaAs DBR with the InP growth substrate removed; (c) the original vertically grown VCSEL active regions now laterally integrated on the AlGaAs-DBR surface after nonplanar wafer bonding, growth substrate removal, and the etch back of the excess epitaxial layers; (d) the complete VCSEL-array structure after bonding the second AlGaAs DBR and removing the GaAs substrate.

and back side step edges provides a region over which the substrate and epitaxial 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

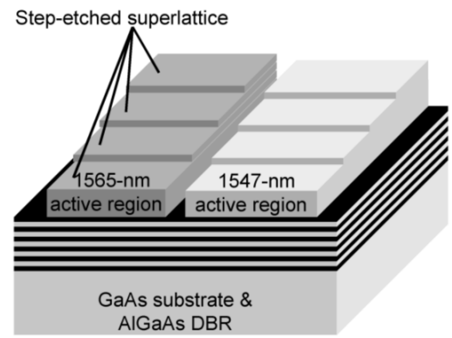

Fig. 2. Three-dimensional schematic of a small section of the wafer surface after the completed nonplanar wafer bonding of the VCSEL active regions in the first dimension and the completion of the superlattice etches in the second dimension.

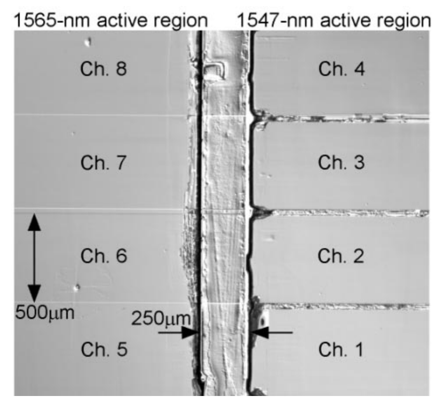

Fig. 3. Photograph of the wafer surface showing the two VCSEL active regions laterally adjacent on the AlGaAs DBR after nonplanar wafer bonding. Four separate wavelength-channel locations per active region are defined by the superlattice etch.

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.

III. Results and Discussion

The final structure is an eight-channel two-dimensional WDM VCSEL array. The array is optically pumped with a 980-nm pump laser, a technique that has been commercially implemented in a wafer-scale process [10]. 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 sidemode 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.

Fig. 5 shows the room-temperature output of the devices verses the absorbed pump power over the range of single-mode operation of all channels. Because all eight channels utilize the same DBR output mirror, variation exists in the overlap of the VCSEL standing wave and the etched index guides. This

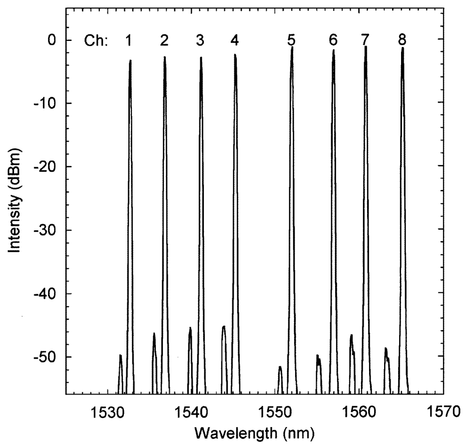

Fig. 4. Superimposed room-temperature VCSEL emission spectra from the eight-channel WDM VCSEL array measured at a constant absorbed pump power of 10.5 mW.

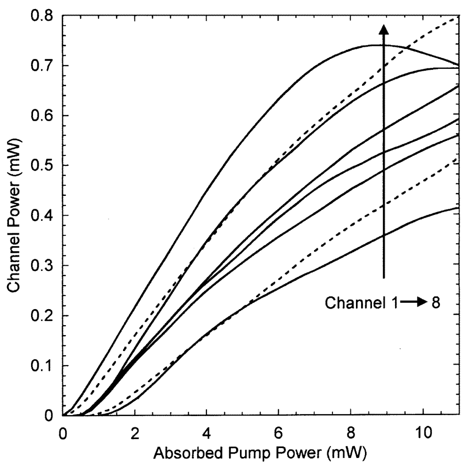

Fig. 5. Plot of VCSEL channel power versus absorbed pump power for the eight-channel WDM VCSEL array. The devices operate single mode over the range shown. Channels 2 and 7 are shown with dashed lines for clarity.

variation gives rise to a variation in the strength of the index guide for each device. The simulated V-parameter for the first channel is 1.12 and this parameter varies in an approximately linear manner to reach a final value of 2.43 for the eighth channel. In all devices, thermal lensing occurred at higher absorbed pump powers, with the problem most prominent in devices with weaker etched index guides. The strength of the index guide effects the overlap between the lasing mode and the gain provided by the focused pump light. Thus, the stronger index guide present in the longer wavelength channels is believed to contribute to the lower thresholds in these devices. Nonuniformities in the operation of the devices can also be attributed to difficulties in properly aligning the pump beam with the device, and maintaining the alignment over time. Additional difficulties occurred during the growth of the active-region stack. These difficulties resulted in both active regions having the same PL peak, a characteristic detrimental in achieving uniform device properties over all channels of the two-dimensional WDM array. The top DBR, which is centered at 1542 nm, provides nearly uniform reflectivity for channels 1 through 5. However, the longer channels are 15 to 23 nm off of the DBR center and experience an increase in mirror loss that contributes to an increase in their differential efficiency.

Several steps can be taken to improve the device uniformity. The differential efficiency can be controlled by removing mirror periods off the array surface at different lateral locations on the sample surface to achieve a uniform output DBR reflectivity across the array. Controlling the active-region growth more precisely to achieve a 20-nm difference between the two gain peaks will improve the threshold uniformity of the array, as well as the uniformity of the position of thermal rollover. Controlling the strength of the index guide for each device will improve the threshold uniformity, as well as reduce the problem of thermal lensing in the devices, thereby allowing for higher single-mode powers.

IV. 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 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 optimized gain-peak and cavity-mode alignment over a wide wavelength range, allowing for the future fabrication of uniform wide-band WDM VCSEL arrays suitable for CWDM optical-network applications.

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