Direct Multi-Lateral Wafer Bonding for New Functionality in Photonic Integrated Circuits

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Abstract**—This paper demonstrates direct wafer bonding along multiple cleaved facets in a single bonding step. This enables monolithic photonic integrated circuits with new functionality that cannot be realized by traditional integration approaches such as re-growth or selective area growth. We demonstrate the utility of this new technique in fabricating monolithic Coarse Wavelength Division Multiplexed (CWDM) laser arrays and ultra-broadband superluminescent diodes.**

Keywords-Wafer-bonding; CWDM; photonic integrated circuits

I. INTRODUCTION

Direct wafer bonding is a process by which diverse semiconductor materials have been combined into a single monolithic structure through the application of heat and pressure. Since an original wafer bonding paper by Liau and Mull [1], a number of devices have been demonstrated using direct wafer bonding, including commercially available transparent substrate LEDs [2], in which active regions lattice-matched to GaAs are bonded to transparent GaP substrates, and long-wavelength vertical cavity lasers employing GaAs-based mirrors and InP-based active regions [3,4]. Virtually every example of wafer bonding described in the literature employs vertical bonding through stacking of wafers, with the bond interface in the plane of the wafer.

Although *vertical* wafer bonding has created some radically new structures unachievable by epitaxial growth alone, to our knowledge the use of *lateral* wafer bonding has yet to be applied to the production of novel semiconductor devices. Reference [1] did demonstrate such lateral wafer bonding with good mechanical adhesion. That is, bonding was achieved along cleaved facets. The work of [1], however, demonstrated bonding at temperatures too high for preservation of material quality. Thus few, if any, operative devices incorporating lateral bonding have been demonstrated. If this approach could be made practical, it would enable new functionality photonic integrated circuits which could not be realized using traditional approaches such as re-growth or selective area growth.

In this work, we demonstrate lateral bonding at temperatures below 550C, and apply this technique to create two types of devices which are difficult if not impossible to achieve by traditional epitaxial growth-based integration means. The first of these devices is a CWDM array of lasers employing 5 unique gain regions in a single monolithic structure, and the second of these is a broadband superluminescent diode (SLD) structure in which multiple gain regions are integrated axially within a single waveguide. In the CWDM device, we make use of the continuous crystalline nature of the bond interface enabling smooth continuous cleaving across these bonded interfaces. In the SLD device, we make use of the low-loss light propagation *across* the bonded interface. Both types of novel functionality demonstrate that excellent material quality can be preserved through a lateral bonding process.

II. FABRICATION PROCEDURE

Fig. 1 below illustrates the lateral bonding geometry.

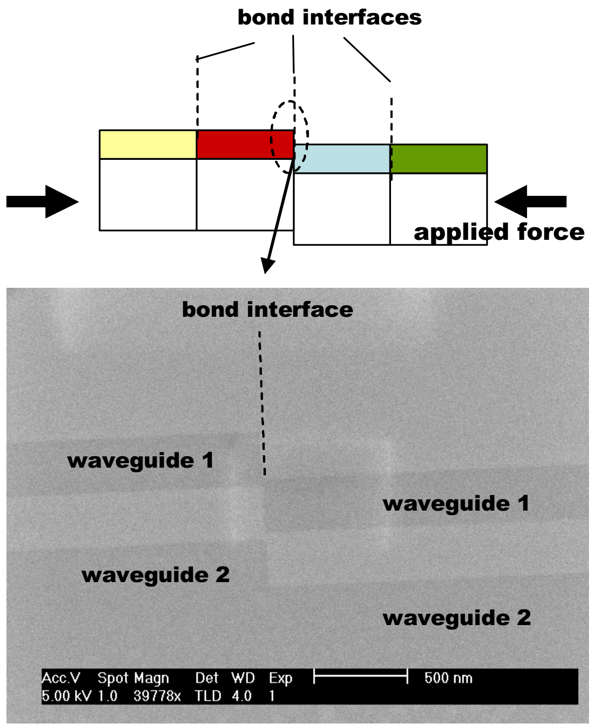

Figure 1: Geometry of multi-lateral wafer bonding. Vertical misalignment highlights the bonded interface.

As shown at the top of the figure, a number of wafer sections, originating from different wafers of different material composition, are arranged laterally adjacent to each other and bonded simultaneously through application of lateral compressive force and a single high temperature bonding step. This technique enables arbitrary material variation from section to section, for materials that can be directly bonded. This in turn enables monolithic photonic integrated circuits in which sections of vastly different materials and even devices can be independently optimized. The technology enables monolithic photonic integrated circuits which span multiple material systems, such as GaAs and InP. Also, in contrast to vertical bonding [1-4], lateral bonding requires no substrate removal after bonding, and less preparation before bonding, making it in many respects a simpler process than ordinary vertical wafer bonding.

The image in Fig. 1 illustrates a high resolution field emission SEM (2 nm resolution) of an InP/InP bonded interface formed at 535C. In this figure, a misalignment of about 0.4 microns highlights the bonded interface. As the figure shows, no voids exist at the interface, and the interface would in fact be invisible in the absence of the misalignment. This void-free interface suggests low optical loss and photonic integrated circuits in which light traverses the interface. For purposes other than demonstrating bond quality, the vertical misalignment shown in the figure is avoided using a compressible interlayer to distribute vertical pressure during the bonding process, as illustrated in Figure 2.

Here, the individual wafer sections are pressed against a reference flat with similar thermal expansion properties during application of lateral pressure. The compressible material conforms to the back sides of the various wafer sections in the presence of varying wafer thickness. This ensures low-loss semiconductor waveguide junctions, which after bonding typically have less than 0.1 micron misalignment.

Once the sections have been laterally bonded, the mechanical strength of the assembled structure is sufficiently robust to enable subsequent photolithography and processing as a single structure, finishing with lapping and cleaving of devices. Care is taken to prevent bending of the bonded chip during contact photo-lithography to reduce the risk of inadvertent fracture.

III. MONOLITHIC CWDM ARRAYS

Figs. 3-5 illustrate a photograph, light-current (L-I) curves (uncoated facets), and spectral data of a 5-channel CWDM Fabry-Perot MQW laser array made from laterally bonding 5 distinct wafer sections.

The pitch of the array is 1 millimeter, and is determined by the size of wafer sections used during the bonding process. The minimum size of these sections is dictated by the need for high quality cleaved interfaces for bonding. Using typical InP wafer thicknesses of 350 microns, high-quality cleaving of sections smaller than about 500 microns wide is difficult. The 1 mm pitch used for CWDM arrays gave acceptable yield using crude cleaving tools.

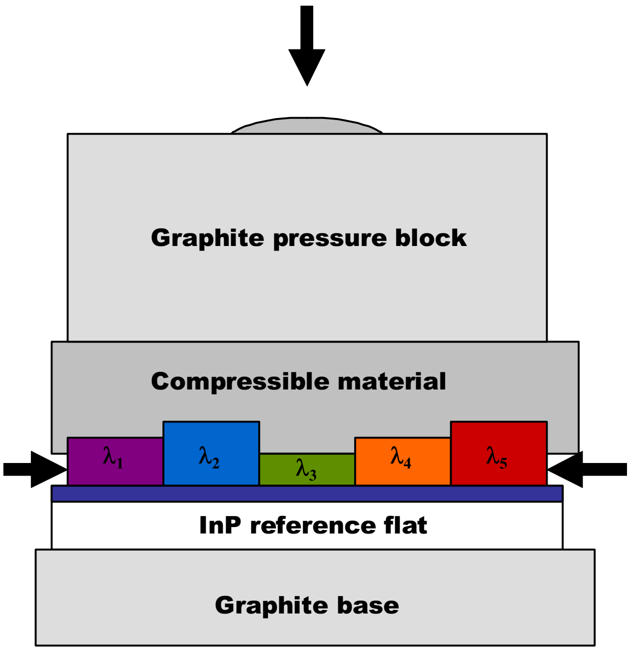

Figure 2: Minimization of vertical misalignments during lateral bonding, enabling low-loss waveguide junctions.

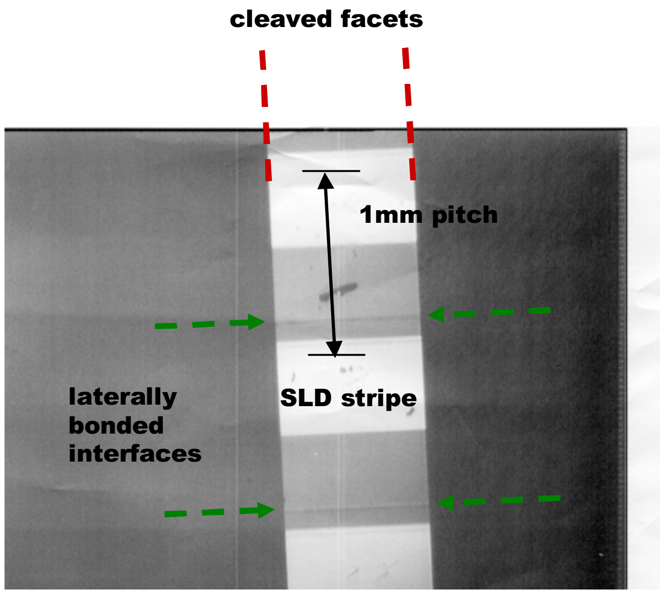

Figure 3: Photograph of laterally bonded coarse wavelength division multiplexer (CWDM) laser array, illustrating smooth continuous cleaved facets across lateral bonds.

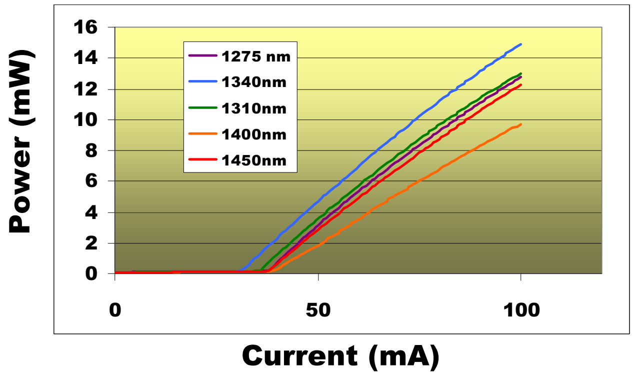

Figure 4: L-I curves associated with each of 5 laser channels, with wavelengths shown in legend.

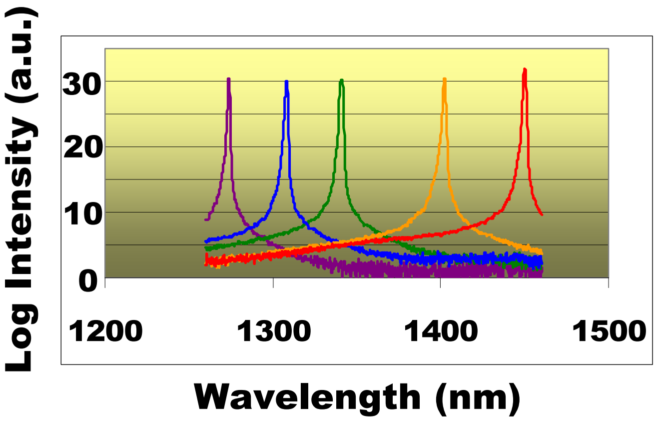

Figure 5: Laser Spectra of coarse wavelength division multiplexer (CWDM) array with 180 nm span.

From the initial device results of Figs. 3-5, it is clear that the quality of the original materials can be preserved during lateral bonding. The second significant observation is that cleaving monolithic arrays across the bonded interface can be accomplished without fracture at the bond, which indicates crystal continuity or near continuity at the bond interfaces. This smooth cleave ensures that the arrays can be coupled to fiber ribbon, or other devices which require the array to have a planar facet for interconnection.

The spectral data of Fig. 5 illustrate an array span of 180 nm using 5 different material gain regions. This array span would be impractical with epitaxial regrowth, where 4 regrowth steps would be required to achieve 5 gain regions. Additionally, selective area growth, which enables variation of quantum well thickness during growth, is typically limited to about 100 nm variation at wavelengths of near 1.3 microns. Finally it is important to note that nothing of the original device design or geometry needed to be changed to employ lateral bonding, so that no additional limits are placed on the performance of the individual laser diodes.

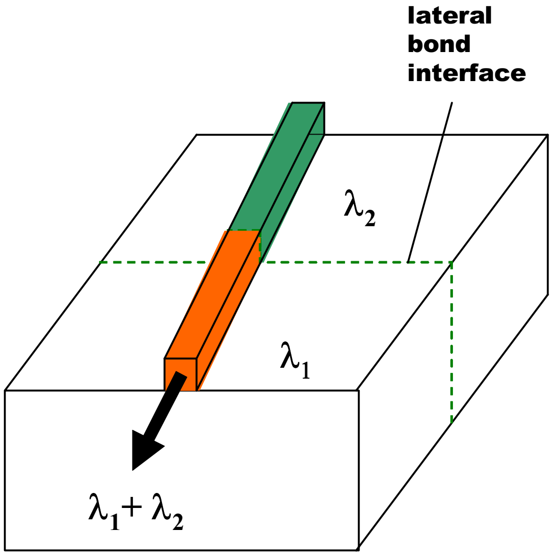

Figure 6: Two section superluminescent diode (SLD) in which the waveguide straddles the bonded interface. Spectral bands from two different gain regions (λ_1 and λ_2) are generated within a common waveguide, and the output represents, to first order, a superposition of the two spectra.

IV. IN-LINE INTEGRATION FOR BROADBAND SUPERLUMINESCENT DIODES

The CWDM arrays of Figs 3-5, though novel and illustrative of material quality and mechanical robustness of the bonds, did not require propagation of light across the bonded interface. The low loss suggested by the void-free interface of Fig. 1 was not exploited in these devices. Fig. 6, however, illustrates another new device which does make use of this feature.

Fig. 6 represents an approach to creating extremely high bandwidth SLDs for high resolution in-vivo-imaging of biological specimens. Here, two spectral bands are integrated with a single lateral bond, and a superluminescent diode ridge-waveguide incorporates both gain regions axially along a single waveguide. Figure 7 illustrates the spectra of SLDs fabricated using the individual gain regions which are combined in the structure of Fig. 6. As shown, one is centered near 1320 nm, and the other is centered near 1450nm. Each SLD incorporates multiple state quantum wells to broaden the emission to more than 100 nm per section. The goal of the combined structure of Fig. 6 is to create SLDs with a spectral (3dB) bandwidth greater than 200nm. Coherent light sources with this highly broadband emission will translate directly into improved resolution of Optical Coherence Tomography (OCT) systems.

Figure 8 illustrates the combined spectrum achieved after lateral bonding the two SLDs. Output power is approximately 1.6 mW, and the spectrum extends over a range greater than 200nm. The 3-dB bandwidth of these devices is substantially less, due to a lack of spectral crossover between the two emissions. This is can be eliminated by simply shifting the

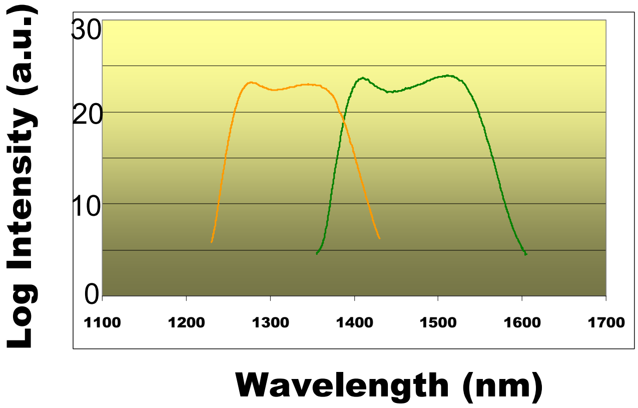

Figure 7: Two superluminescent diode (SLD) gain regions and associated spectra before combining in device of Fig. 6. Each SLD has approximately 100 nm bandwidth.

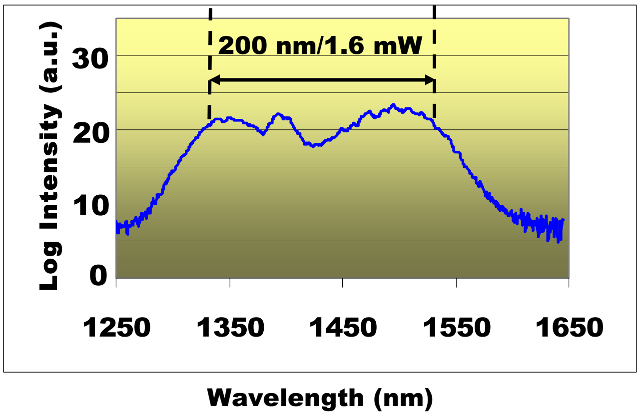

Figure 8: Combined spectrum when SLDs of Fig. 7 are combined through device of Fig. 6. The possibility of still wider bandwidth remains, if the full width of the individual SLDs can be realized. The low intensity in the center of the spectrum could be eliminated by better centering of the two spectra, and this should allow future devices with >200nm 3dB bandwidth.

design of one of the two emissions. Regardless, the spectrum illustrates the nearly equivalent contributions from both gain regions, and the spectral breadth achievable using lateral bonding within waveguide regions. Fig. 8 represents a promising first experiment in axial SLD integration, with considerable room for improvement.

V. Conclusions

Lateral bonding offers a new approach to creating monolithic photonic integrated circuits with new functionality and increased performance. This work has demonstrated two initial types of laterally bonded devices: monolithic CWDM arrays and axially integrated broadband SLDs.

The scalability of lateral bonding to larger circuits with large numbers of cleaved facet bonds may be difficult initially, due to the lack of handling equipment designed for such die geometries, and dimensional tolerances that have not yet been determined. Nevertheless, even at lower rates of manufacture, numerous new future device possibilities present themselves. Some examples are laser/modulator pairs in which the two devices can be independently optimized, integrated optically-pumped devices in which one laser is aligned to pump another undoped longer wavelength laser, and other new active/passive device configurations.

Acknowledgment

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