Vertical and lateral heterogeneous integration

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(Received 12 June 2001; accepted for publication 30 July 2001)

A technique for achieving large-scale monolithic integration of lattice-mismatched materials in the vertical direction and the lateral integration of dissimilar lattice-matched structures has been developed. The technique uses a single nonplanar direct-wafer-bond step to transform vertically integrated epitaxial structures into lateral epitaxial variation across the surface of a wafer. Nonplanar wafer bonding is demonstrated by integrating four different unstrained multi-quantum-well active regions lattice matched to InP on a GaAs wafer surface. Microscopy is used to verify the quality of the bonded interface, and photoluminescence is used to verify that the bonding process does not degrade the optical quality of the laterally integrated wells. The authors propose this technique as a means to achieve greater levels of wafer-scale integration in optical, electrical, and micromechanical devices. [DOI: 10.1063/1.1404399]

The wafer-scale integration of different types of advanced optical, electrical, and micromechanical semiconductor devices on a single chip requires techniques for combining differing semiconductor structures in the lateral plane of the wafer. Present techniques for such wafer-scale monolithic integration include regrowth, repeated selective area wafer bonding,[1] and selective area growth[2,3] (SAG). Regrowth restricts the designer to lattice-matched layers and the number of regrowth steps scales with the number of differing epitaxial regions desired. Selective area bonding overcomes the lattice-matching limitation but the number of selective area bond steps scales with the level of heterogeneous integration desired, exposing the structures to repeated high temperature and high pressure processing. SAG has achieved multiple regions of varying epitaxial layer thickness, but the layer ordering in each region is identical and the designer is again faced with the lattice-matching limitation.

We propose the use of nonplanar wafer bonding as a means to achieve a wafer with multiple epitaxial regions in a single wafer bond step. Nonplanar wafer bonding can achieve lateral heterogeneous integration by means of a vertical to lateral transformation of epitaxially grown structures. This technique allows for large-scale monolithic integration of lattice-mismatched materials in the vertical direction and the lateral integration of dissimilar lattice-matched structures.

Nonplanar wafer bonding begins with multiple epitaxial regions grown vertically on a wafer as shown for the case of four different regions in Fig. 1. The surface is then etched with a step shaped profile to reveal a different epitaxial region on each step level. The backside of the wafer is etched to have a profile complimentary to the step etched epitaxial film side of the wafer, as shown in Fig. 2(a). This substrate thickness adjustment etch is designed to yield an identical substrate plus epitaxial film thickness at each lateral point on the wafer. The wafer is then direct wafer bonded[4] to a transfer substrate that may have a differing lattice constant. We can remove the original growth substrate leaving the epitaxial layers attached to the transfer substrate as depicted by Fig. 2(b). At this point the excess epitaxial layers are etched back, leaving a different epitaxial region at each lateral position on the transfer substrate as represented by Fig. 2(c).

The technique described here relies on the ability of the wafer to deform slightly under pressure. This deformation has been shown previously for very small step heights on the order of hundreds of angstroms.[5] The present technique can accommodate greater step heights by using a backside thickness adjustment etch to promote deformation of the wafer and by using a lateral offset between the step edges on the epitaxial film side of the wafer and the step edges of the backside etch. When pressure is applied during direct wafer bonding, pressure on the backside of the wafer will be concentrated on the step edges and that pressure will be transferred through the substrate and promote the flattening of the step-etched epitaxial layers against the transfer substrate. The lateral offset between the front side and backside step edges determines the distance over which the substrate and epitaxial layers must accommodate the deformation. These defor-

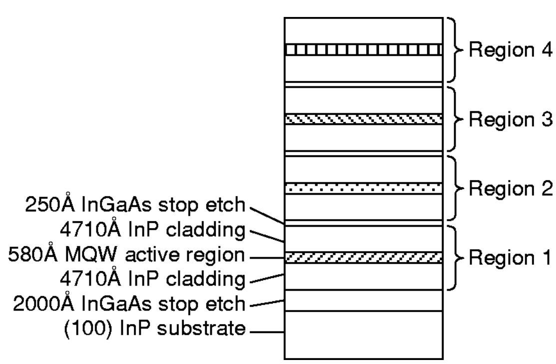

FIG. 1. Schematic of an example structure with four regions epitaxially grown on a substrate.

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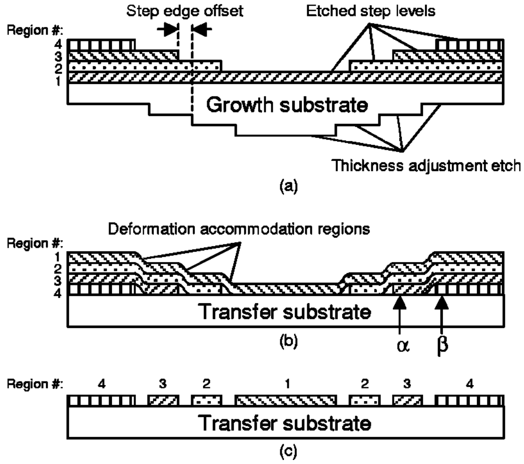

FIG. 2. Cross-section schematics depicting: (a) the epitaxial film side and backside of the as-grown wafer etched with a step profile, (b) the epitaxial layers bonded to the transfer substrate with the growth substrate removed (α and β denote the observation points for Fig. 5), (c) the original vertically grown epitaxial regions now laterally integrated on the transfer substrate after nonplanar bonding, growth substrate removal, and the etch back of the excess epitaxial layers.

mation accommodation regions are etched away after the substrate removal, during the etch-back step. The laterally varying epitaxial regions remaining on the transfer substrate after the etch-back step have not been deformed and retain their material qualities after bonding, as we will show next.

To test the nonplanar wafer bonding technique, four different unstrained multi-quantum-well (MQW) active regions were grown on (100) InP by metalorganic chemical vapor deposition (Fig. 1). The MQW active regions consisted of three 60 Å InGaAsP quaternary (Q) quantum wells with 100 Å 1.1 μm Q barriers. Each of the four regions was separated by a 250 Å InGaAs stop etch layer for ease of processing and substrate removal. The photoluminescence (PL) peaks of the four regions were intentionally made different to ultimately achieve different PL peaks at laterally adjacent regions on the wafer. The regions had PL peaks at 1280, 1336, 1260, and 1320 nm, listed in order of their growth on the substrate. Each region had a thickness of 1 μm, for a total epitaxial film thickness of about 4 μm.

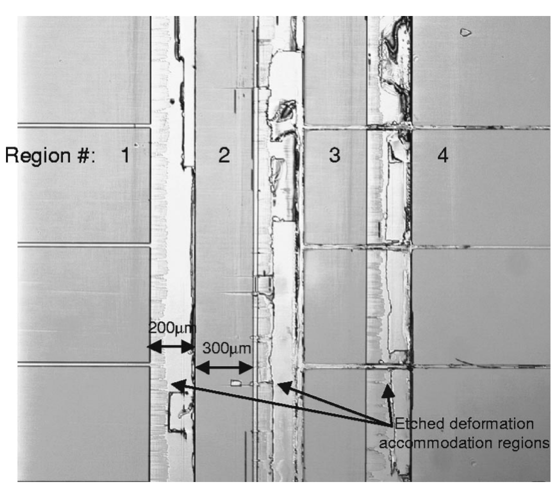

FIG. 3. Optical photograph of the surface of the transfer substrate after substrate removal and the etch back of the excess epitaxial layers. The etched deformation accommodation regions separate the four well-bonded different epitaxial regions.

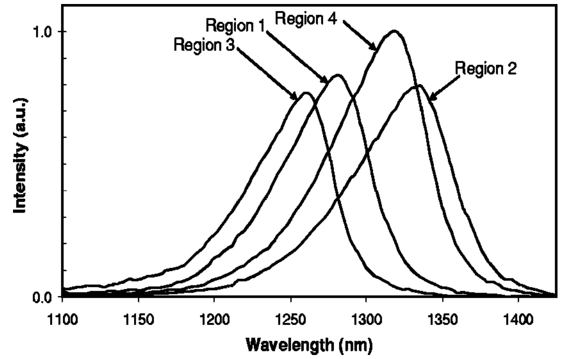

FIG. 4. Photoluminescence from the four different bonded epitaxial regions after the nonplanar wafer bonding process.

The epitaxial layers were selectively chemical etched with a step profile to reveal a different region on each step level. The step levels were 500 μm wide and 1.025 μm high. The one square centimeter substrate was thinned to 200 μm and the backside was chemically etched with the same step profile as the epitaxial film side, except with a 200 μm lateral step edge offset. The photoluminescence of the wafer was measured at each step level prior to the direct wafer bonding of the epitaxial layers to a (100) GaAs substrate. The semiconductor direct wafer bond was performed at 630 °C for 30 min in a nitrogen gas ambient under pressure in a graphite fixture. The pressure used (3 MPa) was in the same range used in the planar bonding of InP to GaAs in the fabrication of 1.55 μm vertical-cavity surface-emitting lasers.[6]

After direct bonding of the InP to the GaAs transfer substrate, the InP substrate was removed by a selective chemical etching. The excess epitaxial layers and the deformation accommodation regions were etched back by selective chemical etching to reveal well-fused stripes of MQW active regions across the GaAs transfer substrate surface. Figure 3 shows the stripes of epitaxial regions separated by the etched deformation accommodation regions. The roughness of the deformation accommodation regions is due to the uneven etching of the GaAs transfer substrate during the etch-back process. PL measurements recorded after wafer bonding are shown in Fig. 4. The PL prior to wafer bonding is not shown, but comparison with the PL plots in Fig. 4 indicates no degradation in the intensity, no shift in the wavelength, and no broadening of the PL peaks after wafer bonding. Optical inspection of the surface shows a well-bonded surface with very little damage due to bonding. Scanning electron microscope (SEM) micrographs of the bonded interface also reveal a uniform wafer bonded interface. Figure 5 shows cross-section SEM micrographs of the sample at the two observation points labeled α and β in the schematic of Fig. 2(b). These micrographs were recorded prior to the InP substrate removal step.

The combination of good PL and a mechanically well-bonded surface leads us to conclude that the nonplanar wafer bonding technique shows promise as a method for achieving vertical and lateral heterogeneous integration across a wafer. We believe that this technique may allow for the monolithic integration of various optical, electrical, and micromechanical components on a single wafer. This technique allows ep-

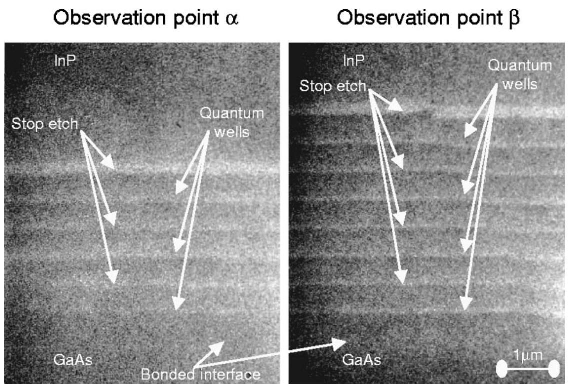

FIG. 5. Cross-section scanning electron micrographs of the bonded interface recorded at the two observation points schematically depicted in Fig. 2(b). These micrographs were recorded prior to the InP substrate removal.

itaxial regions, optimized for specific applications, to be integrated onto a single planar wafer in a single step. Specific applications may include wavelength division multiplexed laser arrays and the integration of electronics with lasers, photodetectors, and modulators. This technique may also allow an increase in the level of integration in photonic integrated circuits by allowing many different kinds of devices to be combined on a single semiconductor chip. Coupling between areas can be accomplished by three-dimensional photonic integration techniques,[7] or by other waveguide deposition techniques.

We have demonstrated the use of nonplanar wafer bonding to achieve vertical and lateral heterogeneous integration on a wafer. SEM and optical inspection have confirmed the good bond quality of the direct nonplanar wafer bond. Photoluminescence after wafer bonding confirms that the optical properties of the MQW active regions were maintained after the bonding process. This technique can be used to integrate many different device structures on a single chip and may represent an advance in the level of optical, electrical, and micromechanical integration possible.

The authors would like to acknowledge Gore Photonics and DARPA via HOTC for financially supporting this research.

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