Low-Loss Substrate-Removed (SURE) Optical Waveguides in GaAs–AlGaAs Epitaxial Layers Embedded in Organic Polymers

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***Abstract*— Low-loss single-mode semiconductor rib optical waveguides fabricated in GaAs–AlGaAs epitaxial layers are removed from GaAs substrates and bonded to transfer substrates using a benzocyclobutene organic polymer. Optical quality facets were obtained by cleaving through the transfer substrate. An average propagation loss of 0.39 and 0.48 dB/cm at 1.55 μm wavelength for TE and TM polarizations, respectively, were measured. This was on average 0.05 dB/cm greater than control guides fabricated in GaAs–AlGaAs epilayers on GaAs substrates with air as the top cladding. This demonstrates the feasibility of a process enabling semiconductor polymer integration and processing both sides of an epitaxial layer.**

***Index Terms*—GaAs–AlGaAs materials/devices, optical device fabrication, optical waveguides, optoelectronic devices, organic polymer materials/devices.**

I. Introduction

FOR ALL integrated optoelectronic devices functionality is provided by the epitaxial layer. In most cases a substrate is not desirable but has to be present for epitaxial growth and handling during processing. There are significant disadvantages associated with the presence of the substrate. All compound semiconductor substrates have high relative dielectric constants resulting in excessive capacitance. Combined with the high sheet resistance at microwave frequencies, substrates hinder the performance of high-speed devices such as modulators [1] and photodetectors [2]. Compound semiconductor substrates also have high thermal resistances resulting in inefficient removal of heat and thermal crosstalk. Therefore, removing the substrate eliminates these difficulties while introducing further advantages. After removing the substrate, the remaining epilayers can be bonded to transfer substrates using organic polymers resulting in semiconductor polymer integration. Hence, low propagation loss, low cost, and easier fiber pigtailing of polymer waveguides can be combined with the superior electrooptic properties of semiconductor waveguides. Furthermore the ability to pattern and process both sides of an epilayer enables new and novel high performance devices. In this letter, we investigate the feasibility of removing high performance optical waveguides from their substrates and bonding them to transfer substrates using organic polymers. We also characterize these waveguides to see how they perform with the addition of new processing steps and materials. Such waveguides could be the basic building blocks of future high-performance optoelectronic devices.

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II. Waveguide Fabrication

Cross-sectional profiles of the two types of waveguides fabricated in this letter are shown in Fig. 1. Fig. 1(a) shows the substrate-removed (SURE) waveguides fabricated in gallium arsenide/aluminum gallium arsenide (GaAs–AlGaAs) epilayers and embedded in an organic polymer called benzocyclobutene (BCB). This polymer is known to produce easily fiber pigtailed high quality optical waveguides [3]. Fig. 1(b) shows a conventional waveguide fabricated using the same material structure. These types are used as control waveguides.

First, an appropriate unintentionally doped epitaxial layer was designed and grown by molecular beam epitaxy (MBE). The epitaxial layer shown in Fig. 1 is the same for both types of waveguides and is designed for optical waveguiding at 1.55 μm. It consists of a 2.05-μm-thick $Al_{0.3}Ga_{0.7}As$ bottom cladding to prevent the leakage of the guided mode of the conventional waveguide into the substrate, a 0.73-μm GaAs core layer, and a 0.8-μm $Al_{0.3}Ga_{0.7}As$ top cladding layer. There is also a 0.1-μm-thick AlAs layer between the bottom cladding and the substrate. This layer is used as an etch stop layer during substrate removal. Two separate samples were cleaved from this wafer. The first sample was used for the novel SURE waveguides and the other for the control waveguides.

On both epitaxial layers, straight 4-μm-wide waveguides were patterned with photoresist using standard lithography. The single-mode guides were then wet etched 5000 Å using a 10:1 1M citric acid:H_2O_2 solution. At this point the fabrication of the control sample was complete and it was cleaved, mounted and measured.

To continue with the fabrication of the SURE waveguides a mechanical grade semi-insulating GaAs transfer substrate was solvent cleaned, spin coated first with AP-8000 adhesion

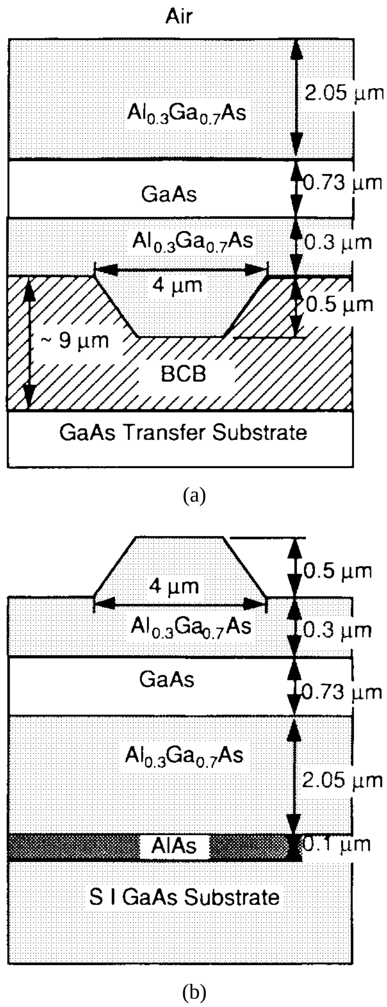

Fig. 1. (a) Schematic cross-sectional profile of the SURE waveguide. (b) Conventional rib waveguide.

promoter and then with 9-μm of Cyclotene 3022-57 BCB [4]. The rib waveguides fabricated earlier were spin coated with the same adhesion promoter and were placed epi side down on the BCB coated GaAs transfer substrate. Following this a full cure of BCB at 250 °C for one hour was performed in a nitrogen purged oven. When fully cured the BCB thin film acts as a glue that keeps the transfer substrate bonded to the substrate containing the epilayer and the fabricated waveguides. In the curing process there are no volatile by-products.[1] The entire stack was mounted on a glass microscope slide, GaAs transfer substrate down, using wax. This exposed the growth substrate only. To remove the growth substrate from the epi layer, a wet spray etch was performed. This consisted of a 30:1 mixture of H_2O_2:NH_4OH sprayed as a fine mist onto the substrate. This etch stops on the AlAs etch stop layer after the entire substrate is removed. After removing the substrate, the AlAs etch stop layer was removed in a 1:1 HF:H_2O solution. This left the thin epi layer with optical waveguides on it bonded to the GaAs transfer substrate via the BCB layer. At this stage the waveguides are as shown in Fig. 1(a). The remaining exposed epi layer was very smooth and uniform in spite of being on top

[1] Form No: 296-01211-493NP&M, Dow Plastics, The Dow Chemical Company, 2040 Dow Center, Midland MI 48674.

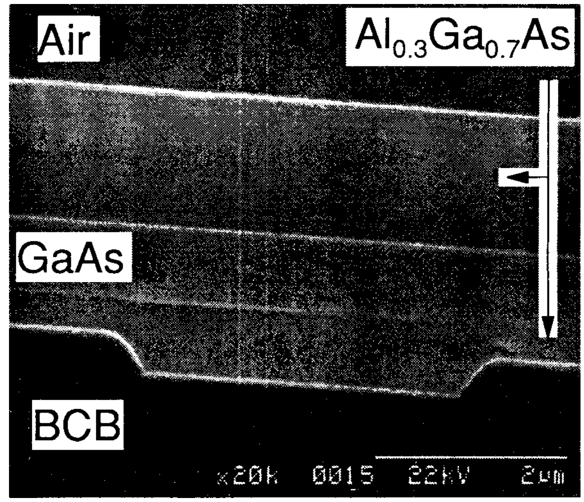

Fig. 2. SEM photograph of a cleaved facet of a waveguide in a substrate removed GaAs–AlGaAs epitaxial layer embedded in BCB.

of the BCB. No cracks, waviness or bubbles were observed on epilayers as large as 2.5 cm by 2.5 cm. The planarity of the epi was good enough for another lithography. We were able to fabricate patterns as small as 2 μm and as long as 2 cm on such epilayers using conventional optical lithography. Part of the reason for this uniformity was the lack of volatile by-products during the curing of BCB and the very smooth and planar BCB surface obtained after spinning and curing.

Optical quality facets are needed to characterize the SURE waveguides. This is achieved by cleaving the GaAs transfer substrate together with the epilayer bonded to it. This requires the alignment of the crystal planes of the transfer substrate and the substrate containing the epilayer during bonding. We observed that BCB becomes less viscous at high temperatures during curing, causing the samples to move around on top of the transfer substrate coated with BCB. We took advantage of this by placing the samples on a 10° angled block after a rough alignment of the cleaved edges of both substrates. The substrate containing the epilayer was free to move during the cure so as to allow the cleaved edge of the substrate containing the epi layer to align to the cleaved edge of the BCB coated transfer substrate. For such low angles, the liquid tension near the edge prevented the sample from falling off of the BCB coated transfer substrate. This aligned the cleavage planes of the epilayer and the transfer substrate to a high enough precision. Finally, optical quality facets were made by cleaving. This was done by nicking the corner of the transfer substrate with a sharp blade, then by applying pressure to allow the cleave to propagate both laterally and vertically through the BCB and the epi layer. Despite cleaving through a ~500-μm-thick transfer substrate, 9 μm of BCB polymer, and the epi layer, good quality facets shown in Fig. 2 were obtained. It should be pointed out that this is not the only way to obtain optical quality facets. This approach is used to obtain high-quality facets easily in order to be able to carefully study the feasibility of the substrate removal process. Dry etching is another very viable possibility. This would allow any other substrate with good adhesion to BCB and resistance to substrate etching to be used. For cleaving, one can use other

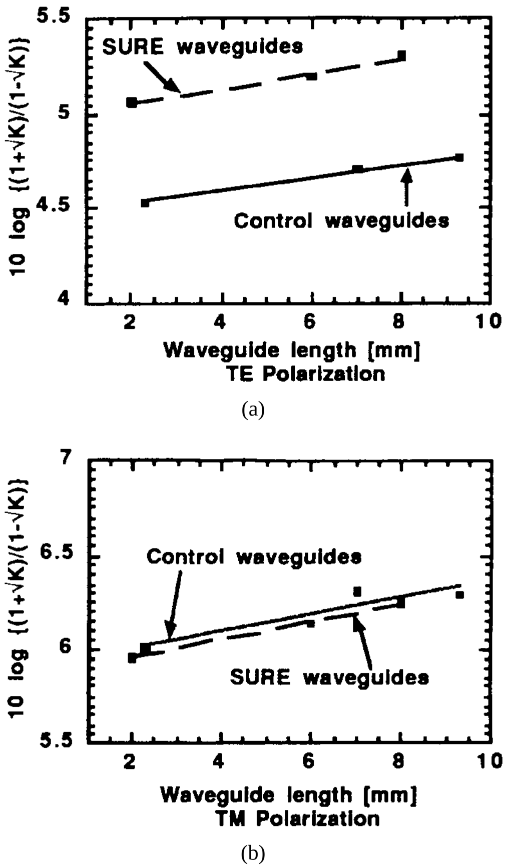

Fig. 3. $10\ \log\ \{(1+\sqrt{K})/(1-\sqrt{K})\}$ as a function of different sample lengths for control and SURE waveguides for TE and TM polarizations. K is the ratio of the minima and maxima of the transmission through the waveguides when the input wavelength is changed slightly.

substrates that can be cleaved, even noncrystalline substrates that can be broken along a straight edges.

III. Experimental Results

Both waveguide samples were mounted and characterized on an optical bench. The output of a fiber pigtailed 1.55-μm distributed-feedback (DFB) laser was coupled into the waveguides using cleaved fiber. The near-field pattern at the output was imaged on a vidicon camera using a microscope objective and a collimating lens. The image was displayed on a monitor. We observed the near-field mode patterns and measured the propagation loss of the waveguides. Both types of waveguides were single mode. The Fabry–Perot resonance technique and sequential cleaving were used to measure the propagation loss and facet reflectivity of the waveguides [4], [5]. The output power was detected using a Ge photodetector connected to an optical power meter. We varied the temperature of the DFB laser through an external thermoelectric temperature controller. This results in slight changes in the operating wavelength of the laser which in turn modifies the transmission through the Fabry–Perot cavity formed by the cleaved facets of the optical waveguides. Noting the ratio of the minima and maxima of this transmission, K, and plotting $10\log\{1+\sqrt{K})/(1-\sqrt{K})\}$ as function of different sample lengths, one can determine the propagation loss and facet reflectivity of the waveguide. Specifically, the slope of this plot is propagation loss in dB/length and the intercept is $10\log(R^2)$, where R^2 is the facet power reflectivity. The experimental results are shown in Fig. 3.

Twenty waveguides with an initial length of 9 mm, cutback to 7 and 2 mm, were measured on the control sample. A linear fit to the measured data produced an average waveguide loss of 0.34 and 0.45 dB/cm for TE and TM polarized inputs, respectively. The initial length of the SURE waveguides was 8 mm, which were then cutback to 6 and 2 mm. The average TE and TM propagation loss for ten such waveguides was 0.39 and 0.48 dB/cm, respectively. On average, the loss of the SURE waveguides was 0.05 dB/cm higher than the control waveguides, which was well within the experimental error of the measured values. This shows that the propagation loss increase due to this novel process was marginal. The extrapolated facet reflectivity of the control waveguides were 0.36 and 0.25 for TE and TM polarizations, respectively. Corresponding values for SURE waveguides were 0.32 and 0.26. The slight variation again indicates overall good quality facets. No measurable variation was observed between the mode shapes of the two types of waveguides.

IV. Conclusion

We have successfully demonstrated the feasibility of substrate removal and bonding the remaining epilayer on transfer substrates using BCB in the fabrication of optoelectronic devices in the GaAs–AlGaAs material system. In particular, optical waveguides fabricated in epilayers removed from substrates and embedded in BCB had an average propagation loss of 0.39 dB/cm and 0.48 dB/cm at 1.55 μm for TE and TM polarizations respectively. This was only on average 0.05 dB/cm greater than control guides fabricated on GaAs substrates with air as the top cladding. The substrate removal process produced a smooth epi layer on which fine-line lithography was possible. This demonstrates the feasibility of processing both sides of an epilayer. Optical quality cleaved facets were also produced by aligning the crystal axis of the growth and transfer substrates during bonding. Presently, we are utilizing this novel process to fabricate low-voltage high-speed electrooptic modulators.

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