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Heterogeneous integration of III-V photodetectors and laser diodes on silicon-on-insulator waveguide circuits

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Abstract— **InP/InGaAsP photodetectors and lasers were integrated on top of ultra-compact Silicon-on-Insulator waveguide circuits using Benzocyclobutene adhesive bonding. Light is coupled between III-V device and SOI waveguide using an inverted taper.**

I. INTRODUCTION

The integration of optical functionalities on chip has been a long standing goal. Integration of more functions onto a single chip has the benefit of the economy of scale, an increase in performance and reliability. Silicon-on-Insulator (SOI) is an attractive material system to fabricate large scale integrated waveguide circuits due to the large refractive index contrast. Moreover, these waveguide structures can be fabricated using standard CMOS processes, thereby increasing yield and reproducibility [1]. For particular photonic functions like light amplification and electrically pumped lasers at telecom wavelengths, the InP/InGaAsP material system remains the material of choice, despite significant research in Silicon based active opto-electronic devices [2] [3]. For detection of light at telecom wavelengths, both InP/InGaAsP and Germanium are being envisaged for integration on a Silicon platform [4] [5]. Therefore, in this paper we will focus on the integration of InP/InGaAsP laser diodes and photodetectors on top of an SOI waveguide circuit.

Different approaches can be used to integrate the III-V devices on top of SOI. In a hybrid approach fabricated and tested devices are mounted on the SOI waveguide substrate using a flip-chip approach [6]. Due to the needed alignment accuracy and the fact that the alignment has to be done die per die, this is not a cost effective way of integration. Another approach is the hetero-epitaxial growth of III-V layers on top of Silicon. Due to the large lattice mismatch between Silicon and InP/InGaAsP it is difficult to obtain a layer stack with low defect density, although advances are being made [7]. A third approach is to bond the InP/InGaAsP dies or wafers -epitaxial layers down- onto the SOI host substrate, remove the InP substrate and process the devices aligned to the underlying SOI features. By choosing this approach, devices are fabricated in high quality epitaxial layers and the alignment is a lithographic alignment which can be done on a wafer scale. Due to these advantages we chose to use adhesive bonding with Benzocyclobutene (BCB) as a bonding agent [8].

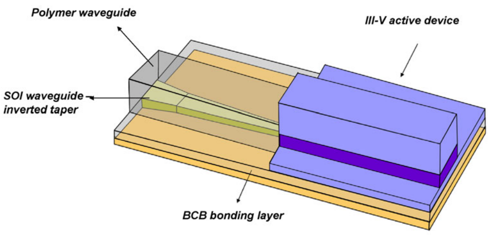

Fig. 1. Light coupling scheme for integration of active III-V devices on top of SOI waveguide circuits

II. LIGHT COUPLING SCHEME

In order to efficiently couple light from an SOI waveguide into an III-V photodetector (or from a laser diode into an SOI waveguide) we used an inverted taper approach to couple light into a polymer waveguide structure on top of the SOI, which is then butt coupled to the III-V active device as shown in figure 1.

This inverted taper structure is typically used to couple light from an optical fiber into an SOI waveguide and is known to have high coupling efficiency and large optical bandwidth [9]. The design parameters of the coupling structure are shown in figure 2. This structure was analyzed and fabricated before for coupling to lensed fiber [10]. The polymer waveguide consists of a polyimide waveguide core (n=1.67) and a BCB cladding layer (n=1.54) which is not drawn for clarity.

The layer stack of the III-V structure was designed for an optimal coupling between the fundamental III-V waveguide mode and the polymer waveguide mode. It consists of a 600nm n-type InP undercladding, six InGaAsP quantum wells with a bandgap wavelength of 1550nm in between two separate confinement layers of 150nm (bandgap wavelength 1.25μm) and a 2μm p-type InP and 150nm p++ InGaAs contact layer Theoretically, coupling loss at the polymer/III-V interface is about 1.5dB.

III. BCB DIE TO WAFER BONDING

As was shown in [10] the separation between the polymer waveguide and SOI inverted taper has to be below 300nm in order to obtain a compact coupling structure. This means that

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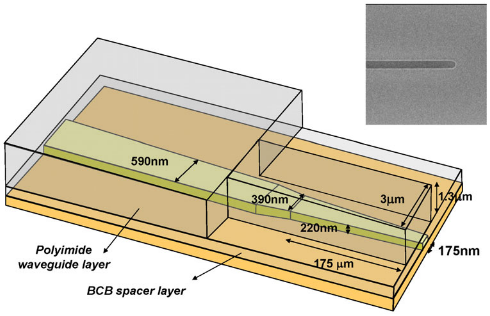


Fig. 2. Design parameters of the inverted taper structure

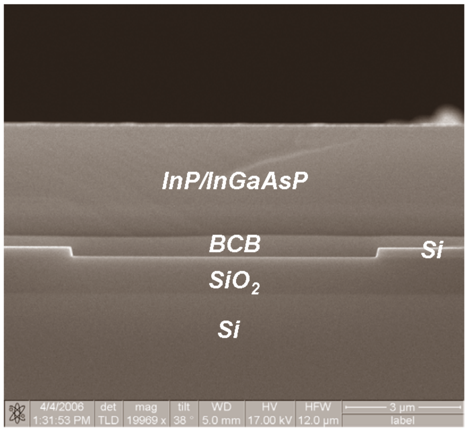
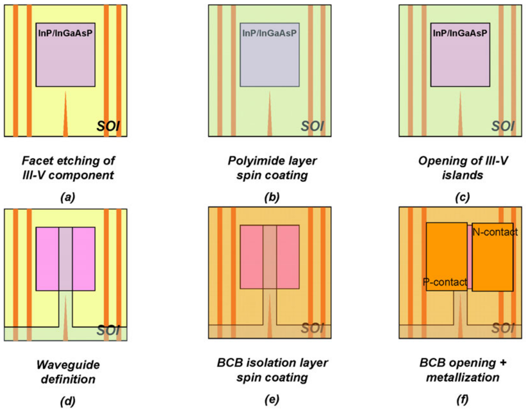


Fig. 3. Cross section of a bonded InP/InGaAsP epilayer structure to an SOI waveguide circuit

the InP/InGaAsP epilayer stack needs to be bonded using a BCB layer thinner than 300nm. The processing sequence is outlined below. The SOI waveguide circuit die with 220nm topography height (the height of the etched through SOI waveguides) is cleaned using SC-1 cleaning at 70C ($1NH_3 : 4H_2O_2 : 20H_2O$) and diluted BCB is spin coated on this topography (a double spin coating step is used to obtain the required planarization of the topography). After spin coating, the liquid BCB is precured at 250C for 2 minutes in order to evaporate the solvents and to partially cure the BCB prior to bonding. InP/InGaAsP dies of $1cm^2$ are cleaned using $1HF : 10H_2O$ and are bonded epi-side down to the SOI substrate. This wafer stack is cured in a nitrogen environment at 250C for 1 hour, using a 300kPa pressure on the wafer stack. After BCB bonding the InP substrate is removed using a combination of mechanical grinding and chemical etching using $3HCl : 1H_2O$ until an InGaAs etch stop layer is reached. An example of an InP/InGaAsP film bonded to an SOI waveguide circuit is shown in figure 3.

IV. FABRICATION OF III-V ACTIVE DEVICES

Both photodetectors and laser diodes were fabricated in the same bonded epitaxial layer structure, as the only difference in device structure is the length of the devices (typically 50μm for a photodetector and 500μm for a laser diode) and both are processed at the same time. The device processing sequence is outlined in figure 4.



Facet etching of III-V component
(a)

Polyimide layer spin coating
(b)

Opening of III-V islands
(c)

Waveguide definition
(d)

BCB isolation layer spin coating
(e)

BCB opening + metallization
(f)

Fig. 4. Processing sequence for the fabrication of bonded photodetectors and laser diodes

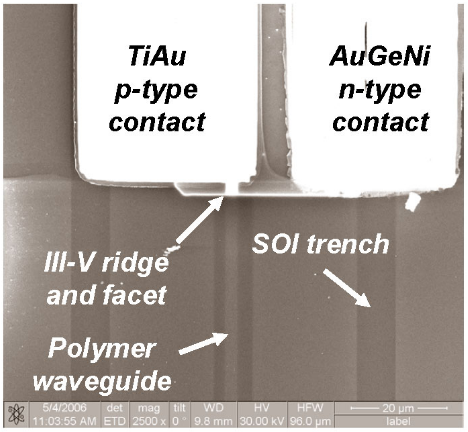


Fig. 5. Top view of the fabricated structures for photodetectors and laser diodes

In a first step the device facets are defined by etching the InP/InGaAsP stack using a $CH_4 : H_2/O_2$ plasma (a). After facet etching, the polyimide waveguide layer is spin coated (b) and the polyimide on top of the remaining III-V islands is removed (c). Next, the III-V ridge and polyimide waveguide are defined in the same processing step -using the $CH_4 : H_2/O_2$ plasma- thereby eliminating a possible misalignment between both (d). The III-V waveguide is etched through the core to be able to access the n-type undercladding for contacting. After waveguide definition a BCB cladding layer is applied (e), the BCB is opened and contacts are defined and annealed at 430C (f). An SEM top view of the interface between III-V and polymer waveguide is shown in figure 5. The SOI taper structure is not visible as it is buried underneath the polyimide.

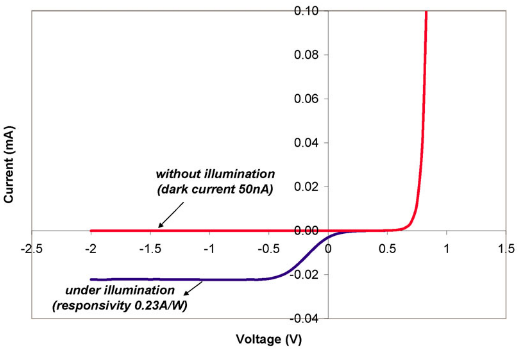


Fig. 6. IV characteristics of a bonded structure with and without illumination

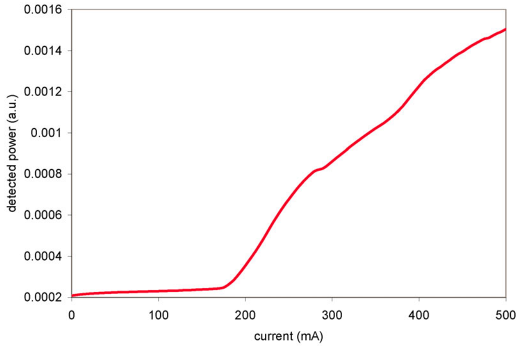


Fig. 7. Laser emission from bonded laser diodes

V. MEASUREMENTS ON FABRICATED STRUCTURES

Photodetectors were characterized by endfire coupling using a lensed fiber with a spot size of 2.5μm. TE polarized light is injected into an 1.2μm wide SOI waveguide and the IV-curves of the device were compared with and without illumination. We assumed that the fraction of the power that is coupled into the SOI waveguide is the theoretical value resulting from numerical simulations, thereby giving a lower limit of the responsivity of the devices. The IV-curves with and without illumination with an estimated 95μW power at 1555nm in the SOI waveguide is plotted in figure 6. This corresponds to a responsivity of 0.23A/W. The length of the device is 50μm.

Laser diodes characteristics were measured by forward biasing the fabricated structures. Laser emission was observed under pulsed electrical injection (1 percent duty cycle). The power versus current characteristic of a 600μm long device waveguide with a width of 2.8μm is plotted in figure 7. This corresponds to a threshold current density of 10.4kA/cm2. This high value is probably due to the roughness of the etched facets and waveguides which reduces the mirror reflectivity and increases the cavity loss. CW operation was not obtained as the thermal resistance of the bonded device was to high, due to the low thermal conductivity of the BCB bonding layer (0.3W/mK) and the buried oxide layer (1.2W/mK). This problem can be solved by mounting the laser diode p-side down on a heat sink or by incorporating a heat sink in the device structure as in [11].

VI. CONCLUSIONS

We fabricated and characterized III-V photodetectors and laser diodes bonded to an SOI waveguide circuit using BCB as a bonding agent. Light is coupled between the SOI layer and the III-V layer using an inverted taper structure. A photodetector efficiency of 0.23A/W was measured, while laser emission only occurred for pulsed current injection and for high threshold current densities. Improvement of the performance of these laser diodes is on the way.

VII. AKNOWLEDGEMENTS

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