ULTRA-THIN BCB BONDING FOR HETEROGENEOUS INTEGRATION OF III-V DEVICES AND SOI PHOTONIC COMPONENTS

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SUMMARY

This paper describes a novel way to integrate active III-V devices and SOI passive devices by bonding a III-V film on top of a processed SOI waveguide substrate using a 200nm thick Benzocyclobutene (BCB) bonding layer.

KEYWORD
heterogeneous integration, BCB, SOI

INTRODUCTION

In recent years, there has been a lot of interest in using Silicon-on-Insulator (SOI) substrates for optical waveguiding applications. Main advantages of this technology are the possible use of standard CMOS technology for the definition of the waveguides [1], which makes mass production possible and the high index contrast between the silicon core (n=3.45) and the oxide buffer layer (n=1.45), which makes ultracompact circuits possible and increases the degree of integration. Although this is a very interesting technology for passive functions, up till now no highly efficient active opto-electronic devices fabricated in Silicon were reported despite significant research. If active functions need to be integrated with the passive Silicon components for telecom wavelengths, a possible approach is to bond InP/InGaAsP heterostructure dies on top of the Silicon components and couple light between both optical layers. In that case the bonding layer has to be very thin for efficient heat sinking of the active component through the bonding layer [2] due to the low thermal conductivity of the polymer bonding layer. Optical coupling between an edge-emitting device through this layer in an efficient and compact way also requires ultra thin bonding layers (~200nm) due to the high index contrast between InP/InGaAsP, bonding layer and Silicon as will be shown later.

Two different types of bonding technology can be applied for bonding these III-V dies on an SOI substrate. In direct bonding the two semiconductor surfaces are mated under elevated temperature or pressure. Direct bonding however requires ultra flat surfaces [3]. Therefore, direct bonding of processed SOI substrates and InP/InGaAsP dies requires advanced chemical mechanical polishing (CMP) to obtain the needed planarity and surface quality. Different types of bonding using intermediate bonding agents are also reported in literature. However, results on submicron bonding layer thickness are scarce. Spin-on glass (SOG) can be used to obtain a thin bonding layer [4] when bonding two substrates. However, the required curing temperature is relatively high (400°C) and to our knowledge bonding on processed substrates has not yet been demonstrated.

Because of these drawbacks, benzocyclobutene (BCB), a spin-on polymer, was investigated as a bonding agent. The planarizing properties of the polymer make a CMP process redundant and curing temperatures are low (250°C). BCB bonding using layer thicknesses above 1µm is well known [5][6]. In this paper we demonstrate for the first time submicron bonding layer thicknesses, thereby enabling good heat sinking and the possibility for optical coupling. Successful bonding with a layer thickness down to 200nm was obtained, even on substrates showing a surface topography of the same order of magnitude.

BCB BONDING

The bonding of InP/InGaAsP heterostructures on both processed and unprocessed SOI was investigated. The SOI wafers consist of a 750µm thick Silicon substrate, a 1µm thick buried SiO_2 buffer layer and a 220nm thick Silicon waveguide layer. Optical waveguides were processed using standard CMOS deep UV lithography at 248nm in an ASML PAS5500/750 stepper and by etching through the Silicon waveguiding layer (i.e. 220nm deep) [1]. The waveguides were defined using 4µm wide trenches and are 30µm apart. The waveguide width varied from 0.3µm to 10µm. Both SOI dies (a few cm^2) and InP dies (0.25-1cm^2) were thoroughly cleaned using acetone, isopropylalcohol (IPA) and deionized water. Samples were dried at 150°C on a hotplate. In a second step BCB is spun onto the SOI substrate. The achievable bonding layer thickness of commercially available BCB, supplied by Dow Chemicals, is limited to 1µm (Cyclotene 3022-35). As this is too thick for most applications where optical coupling is needed, Cyclotene 3022-35 was diluted by adding mesitylene (C_9H_{12}). Measured bonding layer thickness as a function of added mesitylene is shown in Fig. 1. This figure shows that a BCB-mesitylene solution concentration of 2:3 spun at 5000rpm results in a 200nm bonding layer thickness.

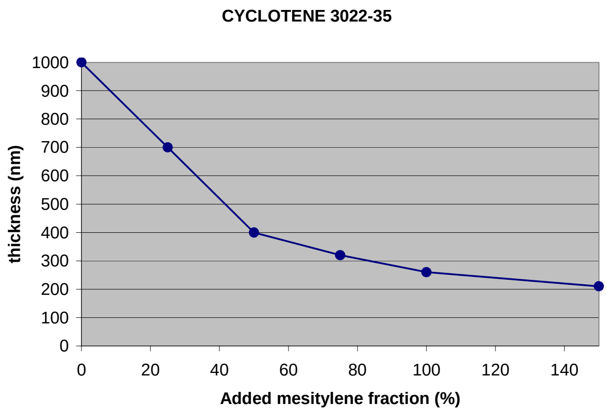

Figure 1: Bonding layer thickness as a function of BCB dilution when spin coated at 5000rpm

This is sufficiently thin to allow direct optical coupling between the Silicon and InP waveguide layer [9] and have efficient heat sinking of active opto-electronic devices. The thinned BCB needs to be ultrasonically agitated before application to allow reproducible bonding layer thicknesses. After the BCB is spun onto the substrate both samples are bonded at 150°C to drive out any residual solvents and to allow a maximum bonding strength. Bonded samples are cured at 250°C in nitrogen ambient for 1 hour. After curing the InP substrate is mechanically thinned down to 50µm. A final chemical etching step using HCl removes the rest of the substrate until an etch stop layer is reached. The processing sequence is shown in Fig. 2.

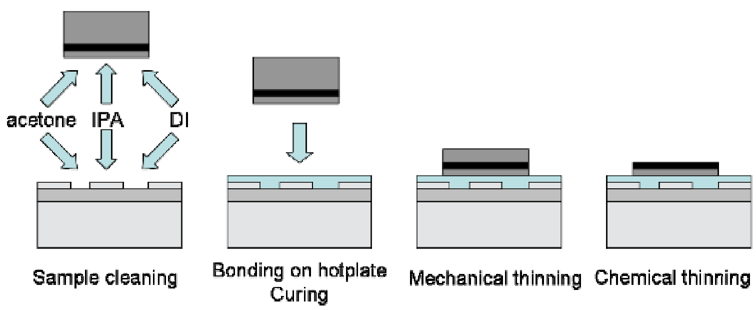

Figure 2:Processing sequence for bonding III-V dies onto a processed SOI waveguide substrate

Different solution concentrations of BCB-mesitylene up to 2:3 were successfully used to bond onto both processed and unprocessed SOI. SEM pictures of the interface of bonded samples are shown in Fig. 3. Fig. 3a and fig. 3b show the bonding of an InP-die onto an unprocessed and onto a processed SOI substrate respectively, in both cases using a 200nm thin bonding layer. Due to the excellent planarizing properties of BCB, these thin bonding layers can be applied on a substrate with 220nm topography height without introducing voids

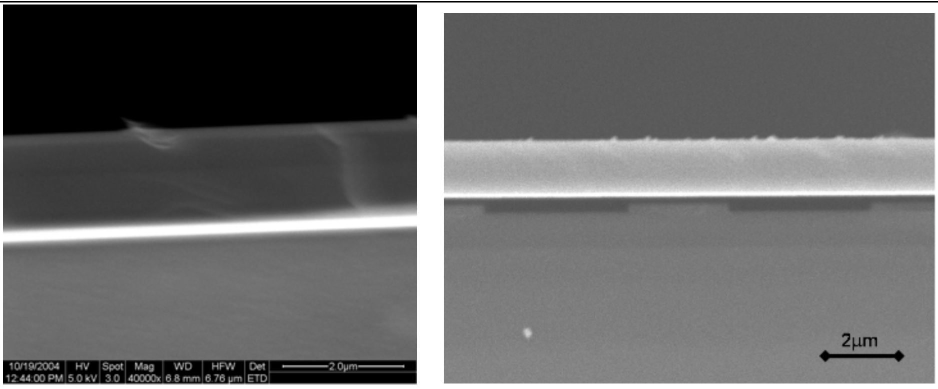

Figure 3: Ultra-thin BCB bonding of an In/InGaAsP thin film on an unprocessed SOI substrate (a) and on an SOI waveguide substrate (b). Waveguides are defined using 4µm wide trenches and by etching 220nm deep.

OPTICAL COUPLING

As the technology for integrating an III-V active layer on top of a processed waveguide substrate was described above, we will now present an optical coupling scheme to couple light from an edge emitting device (i.e. an edge emitting Fabry-Perot laser diode) into an SOI waveguide. Although a myriad of coupling schemes can be envisioned we will focus on a coupling scheme based on an adiabatic taper due to its tolerance to fabrication errors (waveguide misalignment), its large optical bandwidth and its high efficiency [7]. A bonded III-V waveguide is butt-coupled to a polymer waveguide as shown in figure 4. Underneath this polymer waveguide an SOI taper is defined which transforms the fundamental polymer waveguide mode to the fundamental mode of the SOI waveguide.

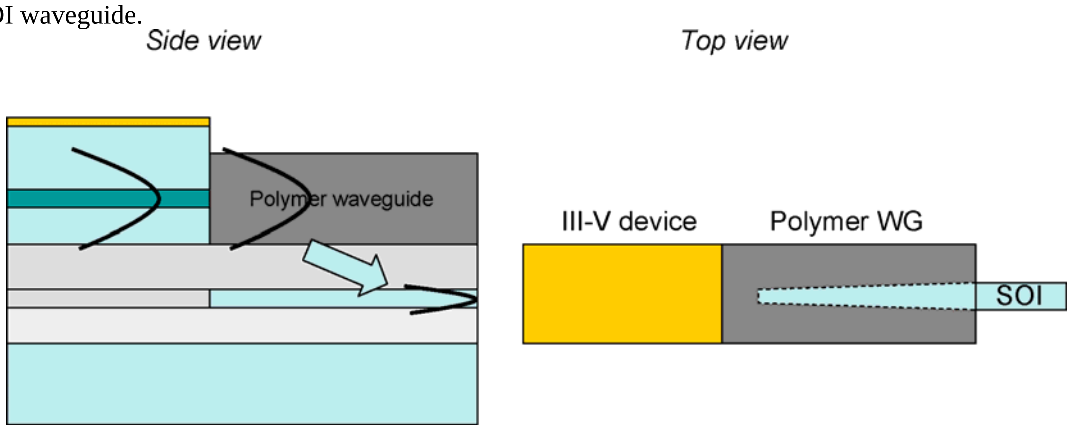

Figure 4: Proposed coupling scheme using an SOI adiabatic taper structure

The length of the taper is critically dependent on the bonding layer thickness. A rectangular polymer waveguide core of 1.5µm thick and 2.5µm wide is assumed. The refractive index of the core is assumed to be 1.65 and has a BCB cladding (n=1.54). The SOI waveguide tapers from 0.1µm to 0.35µm. The silicon waveguide core is 220nm thick. If the waveguide spacing (measured from the top of the silicon waveguide core to the bottom of the polymer waveguide core) is varied from 200nm over 400nm to 800nm, the taper length to have 90% efficiency varies from 90µm over 175µm to 700µm. From these results it is clear that a thin bonding layer is necessary to achieve a compact coupling structure.

The proposed device and optical coupling structure requires technologically more than bonding the III-V to processed SOI substrates. On the III-V processing side a polymer waveguide layer needs to be butt-coupled to a III-V device. Facets with optical quality need to be etched in the bonded III-V film and the III-V waveguide and the polymer waveguide need to be aligned with respect to each other. On the SOI processing side, SOI taper tips of 100nm wide need to be fabricated using standard deep UV lithography (λ=248nm). An overview of what is achieved so far is shown in figure 5. Figure 5a shows the definition of a polyimide waveguide layer next to a III-V layer (by spin coating the polyimide and removing the polyimide on top of the InP). In figure 5b a vertically etched facet (etch depth 2.5µm) using a Cl_2 inductively coupled plasma technique is shown. Figure 5c shows the definition of both InP and polymer waveguide in a self aligned way. On the SOI side, the fabrication of narrow taper tips (100nm) was developed using deep UV lithography as shown in figure 5d.

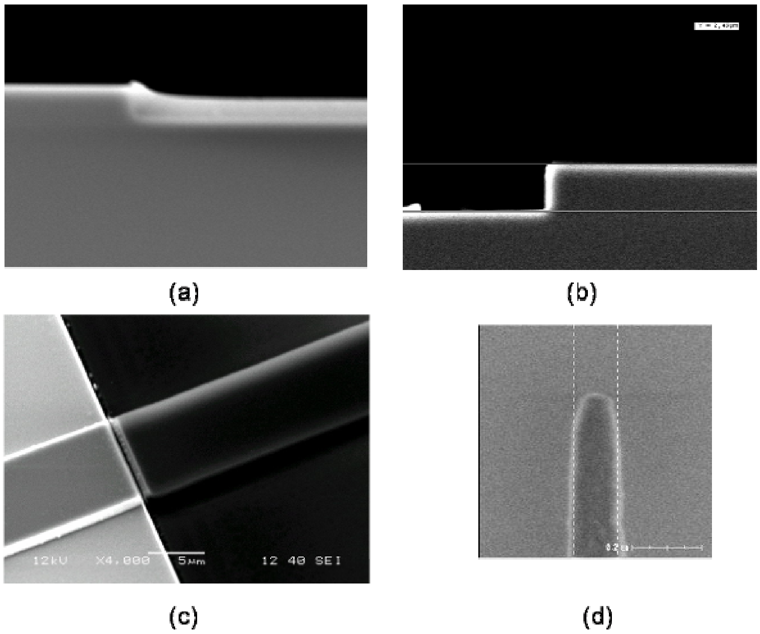

Figure 5: development of processing for proposed coupling structure

CONCLUSION

We demonstrated for the first time the ultra thin bonding of III-V epi-layers on a processed SOI substrate using BCB. These thin bonding layers make good heat sinking possible through the bonding layer and allow compact optical coupling to the SOI waveguides. A coupling structure based on an adiabatic taper structure is proposed. First developments towards fabrication of the structure are presented.

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