Heterogeneous integration of III-V material and Silicon: fabrication and devices

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Abstract – We present the use of benzocyclobutene (BCB) and Indium as a means of integrating III-V thin film opto-electronic devices and Silicon circuitry. We present the realization of BCB bonded thin film laser diodes and indium bonded thin film LEDs. Fabrication procedures are outlined. Applications include the integration of light emitting and detecting devices onto CMOS circuitry for inter and intra - chip optical communication as well as building a platform for complex photonic systems on a chip.

I. Introduction

As there is not one material available that has optimal electrical and optical properties, in complex high-end systems different materials need to be integrated. Of course Silicon is the workhorse in CMOS industry, where its electrical behavior is very well understood and processes are optimized. Even from an optical point of view Silicon is an interesting material. Recently, optical waveguides and devices [1] – both based on total internal reflection and bragg confinement – have been defined into Silicon-on-Insulator (SOI) material using the standard CMOS lithography processes as shown in Figure 1. In this work the SOI consisted of a 220nm thick Silicon core layer (n=3.45) separated from the Silicon substrate by a 1µm thick SiO2 buffer layer (n=1.45).

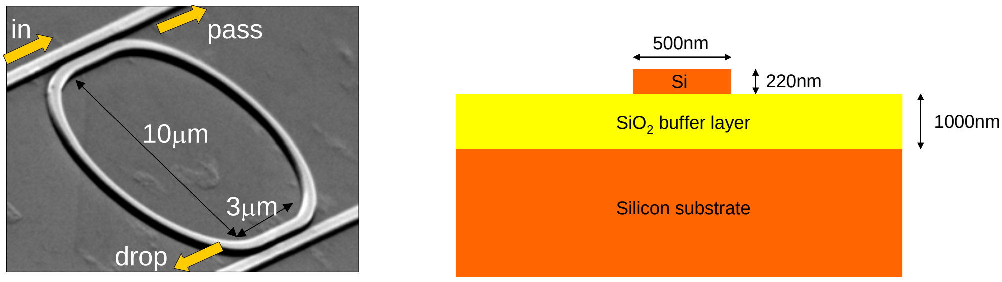

Figure 1 Fabricated ring resonator in SOI [2] **and typical dimensions of an SOI nanophotonic waveguide**

However, as Silicon is an indirect bandgap material, light emission efficiency is expected to be poor. In spite of a lot of research, Silicon has never been – and may never become – a suitable material for particular photonic functions as light emission and high speed modulation and switching. To circumvent this deficiency, III-V material – with the InP/InGaAsP material as the preferred candidate due to its track record in long haul telecommunication and the optical transparency of SOI waveguides at 1300 and 1550nm - needs to be integrated together with the Silicon.

There are different ways to achieve this integration. Direct growth of InP on Silicon results in high dislocation densities due to the large mismatch in lattice constant, hence resulting in poor material quality. In direct wafer bonding [3] two polished wafer surfaces are fused together. This technique requires advanced chemical mechanical polishing (CMP) of structured surfaces to meet the requirements for bonding. To overcome these difficulties, there is a lot of interest to use an intermediate layer material – polymer [4], metal [5] or spin on glass [6] – to bond III-V thin films onto a Silicon substrate. In this paper we will focus on the use of benzocyclobutene (BCB) and Indium as a bonding material for heterogeneous integration. As this is a very generic technology, the applications can be diverse: from building a photonic system-on-a-chip with passive SOI waveguides and active III-V devices to building CMOS chips with inter and intra-chip optical interconnects or optical clock distribution.

II. Device Fabrication

A. BCB bonding

Benzocyclobutene is supplied by Dow Chemicals under the commercial name Cyclotene. It is widely used in the microelectronics work as a dielectric and passivation layer. It exists in two varieties: a photosensitive one and a dry-etch one. The dry-etch BCB can be bought in several varieties each differing in viscosity and therefore in achievable layer thickness (varying from 1 to 25µm). We have worked with the Cyclotene 3022-46 with layer thicknesses from 2.4 to 5.8 µm.

The bonding procedure is performed in a class 100 clean room. The processing can be roughly divided into three parts: die cleaning, die-to-wafer bonding and InP substrate removal [7]. The BCB bonding procedure starts with a thorough cleaning of both the transfer substrate and the die by means of acetone, isopropylalcohol (IPA) and a final rinsing in deionized water. The samples are then dried in an oven at a temperature between 100 and 120°C. An adhesion promoter (AP-2500) is then spun onto the dried transfer substrate to ensure a reliable bonding, followed by spinning of the BCB itself. The BCB is spun at a speed of 2000 to 3500 rpm, depending on the desired layer thickness. The sample is then placed on a hot plate (150°C), thereby rendering the BCB somewhat less viscous and allowing an initial outgassing. The use of the hot plate seems to be an important issue with respect to the obtained bonding quality. Next, the III-V semiconductor die is placed on the BCB. It can still be moved around to accurately align the cleavage planes of the transfer substrate with those of the die. After the positioning of the die on the BCB layer, the bonded sample is placed in an oven and is cured at 250 °C for one hour. This is done under a nitrogen atmosphere since the presence of oxygen can lead to oxidation. The polymerization process is based on a thermal rearrangement process, meaning that no by-products are created. After baking, the original substrate is removed by means of mechanical thinning until a substrate thickness of about 50µm is reached. The remaining InP is chemically removed in a HCl etching solution. This etching stops automatically on an InGaAs or InGaAsP etch stop layer that is embedded in the die.

Using this technique thin film laser diodes have been processed and characterized. A SEM cross-section of the device is shown in Figure 2. The laser diodes were bonded onto a GaAs substrate to allow easy cleaving of the devices. Threshold current in pulsed operation doubled compared to unbonded reference laser diodes. Due to the large thermal resistance of the BCB bonding layer CW operation was prohibited. This problem could be solved by adding a low thermal resistance path through the BCB layer to the substrate, i.e. using a thick plated n-contact. The processing sequence is shown in Figure 3. As was shown in [8], efficient coupling of light from these laser diodes to an underlying SOI circuit is possible. Fabrication of this kind of coupling structures is ongoing.

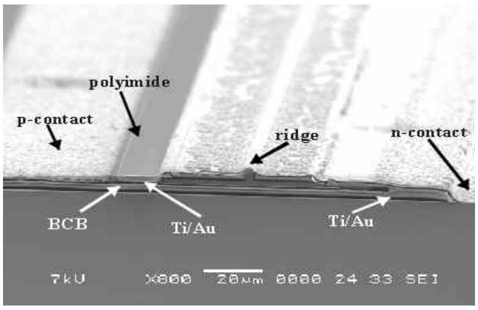

Figure 2 SEM cross-section of fabricated devices: thin film laser diode bonded onto a GaAs substrate using BCB bonding. Polyimide was used as an isolation material.

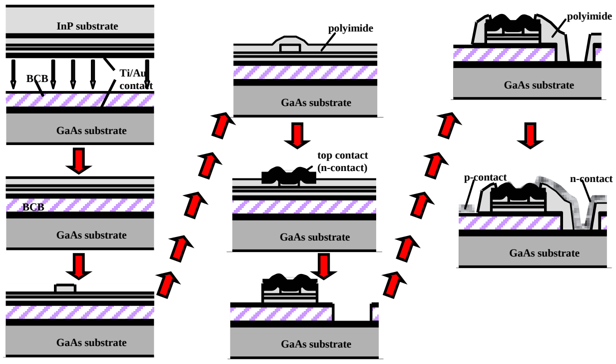

Figure 3 Processing sequence of bonded laser diodes: before bonding Ti/Au layers are deposited on both the GaAs substrate and InP die. Samples are bonded using BCB and the InP substrate removed. The laser ridge is defined and a top contact (n-type) is fabricated. Now this contact is used as a mask to laterally isolate the lasers and a contact opening is etched in the BCB. Polyimide is used as an isolation material to define the final contacts. The n-type contact may serve as a heatsink for the device.

B. Indium bonding

As the low thermal conductivity of BCB prohibits CW operation of the fabricated devices without special heatsink structures, we investigated the use of solder as a bonding material. While a hard solder material makes the bond very brittle due to its small plastic deformation ability, the use of a soft solder material reduces the stress in the bonded structure. As electronic industry moves towards the use of lead-free materials we investigated indium as a means of fabricating III-V thin film devices.

The bonding procedure starts by depositing a Ti (100nm) and Au (300nm) layer onto an InP die and silicon substrate. Then 2μm In is deposited on the Si substrate. Formed oxides are removed by immersing the silicon substrate into a diluted HCl solution. The samples are attached and bonded by allowing the solder to melt (220 °C for 10 minutes). After bonding the InP substrate is thinned both mechanically and chemically until the etch stop layer is reached. An example of an In bonded film onto a silicon substrate is shown in Figure 4a. Bonding strength is sufficient to allow subsequent processing, as LEDs were fabricated into the thin film as a proof of principle. LED characteristics are shown in Figure 4b. Compared to fabricated BCB bonded LEDs thermal resistance decreased by a factor of 15.

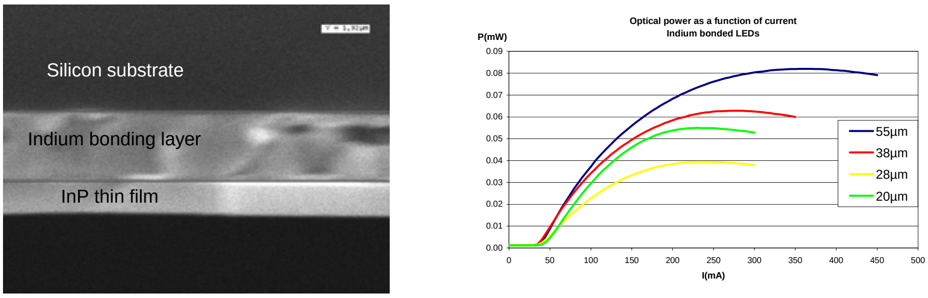

Figure 4 SEM cross section of In bonded thin film onto a silicon substrate (a). LED characteristics for different LED radii are shown in (b).

III. Acknowlegdements

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