

Evanescantly-Coupled Hybrid III-V/Silicon Laser Based on DVS-BCB Bonding

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Hybrid III-V/Silicon lasers based on evanescent coupling are one of the most advanced and the most promising devices in the ongoing efforts to build an efficient light source on a silicon platform. Most of the recently reported devices are based on direct die-to-wafer bonding of III-V epitaxial layers to silicon waveguides, which might prove difficult to implement in an industrial-scale fabrication process. As an alternative approach, in this paper, we present an evanescently-coupled, hybrid III-V/silicon laser based on adhesive DVS-BCB bonding. The device layout, the fabrication process and the achieved results are presented and discussed.

Introduction

During the last decade, silicon photonics has emerged as a very promising technology for the fabrication of high-performance photonic integrated circuits. Utilizing silicon's transparency at telecommunication wavelengths and based on the silicon-on-insulator (SOI) material platform that shares the same fabrication procedures and tools with microelectronics, silicon photonics offers the prospect of integrating high-speed communication photonic and electronic devices on a single chip in a cost-effective way. However, due to silicon's indirect bandgap, fabrication of the efficient light sources on this platform remains a serious challenge.

One of the most promising solutions to this problem is heterogeneous integration of III-V materials, providing efficient light emission, and SOI waveguides. Several schemes of coupling the light generated in III-V material to the SOI waveguide were studied, but the evanescent coupling gave the most promising results. In the recent years, researchers have demonstrated several devices based on evanescent coupling between a III-V laser cavity and SOI waveguide optical modes. These included, Fabry-Perot lasers, [1, 2, 3], as well as DBR [4] and DFB lasers [5]. The demonstrated devices were based on a molecular, plasma-assisted, wafer bonding which requires very clean, smooth and contamination-free bonding surfaces. However, to meet such strict requirements in an industrial-scale fabrication process might pose a serious challenge.

In this paper, we propose an alternative approach based on adhesive bonding, using a commercially available DVS-BCB polymer (Cyclotene^{®TM}). We present the layout of the hybrid, Fabry-Perot III-V/Silicon evanescent laser based on DVS-BCB bonding and its fabrication procedure. The achieved results are also presented and discussed.

Evanescantly-Coupled Hybrid III-V/Si Laser Layout

The general layout of the Fabry-Perot hybrid III-V/silicon evanescent laser is given in Figure 1a). It's based on a silicon rib waveguide made on a standard SOI platform, with 1 μm thick buried oxide layer. The waveguide thickness is $H = 500$ nm, the rib etch depth is $R = 220$ nm, the silicon waveguide width is $W = 1.2$ μm , and the trench width is $T = 3.4$ μm . The epitaxial III-V structure is bonded on top of the waveguide, using a

spin-coated DVS-BCB adhesive layer. It consists of the n-type InP spacer layer and the mesa structure which comprises the multiple quantum well (MQW) region (8 InGaAlAs-based QWs and 9 barriers, emitting at $\lambda = 1.31 \mu\text{m}$), carrier blocking (CB) layer, a separated confinement heterostructure (SCH) layer, a p-type InP top cladding layer and an ohmic contact.

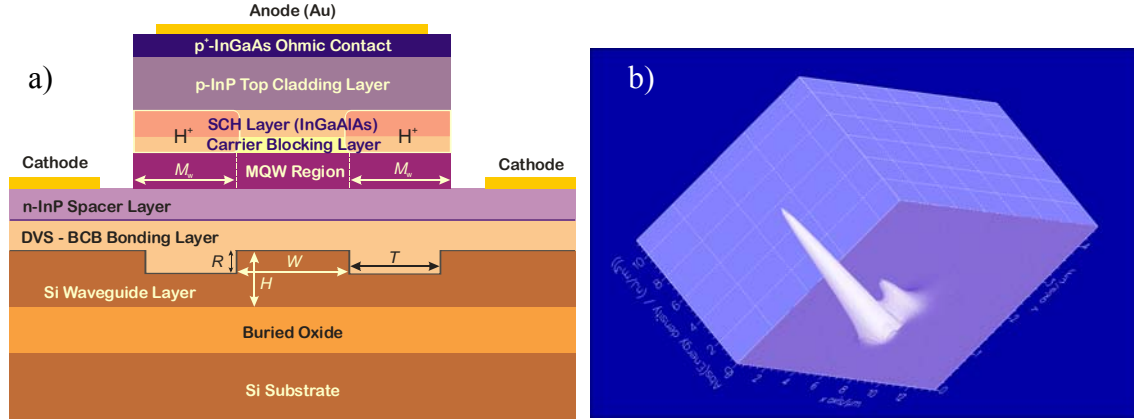


Figure 1. a) Evanescent III-V/silicon hybrid laser cross-section; b) Intensity plot of the fundamental hybrid mode: primary peak is located in Si rib waveguide, while the secondary peak is in MQW region.

For an efficient evanescent coupling between the modes supported by the mesa and the underlying SOI waveguide, the distance between the III-V active layers and the SOI waveguide must be sufficiently small ($<100 \text{ nm}$). The device is designed to support the fundamental hybrid optical TE mode which is predominantly confined within Si waveguide, with only a fraction of the optical power within MQW active region, as presented in Figure 1b). Based on the optical simulations (FIMM WAVE), we found the optimal thicknesses of n-type spacer layer and SCH layer to be 235 nm and 210 nm, respectively. These parameters enable the confinement factors for the fundamental mode within Si waveguide (Γ_{Si}) and within MQW active regions (Γ_{MQW}) to be more than 70% and 3%, respectively, in a range of BCB bonding layer thickness between 20 nm and 120 nm [6]. This tolerance to variations in thickness of the BCB layer which are expected to occur in a fabrication process, provide necessary device robustness.

Device Fabrication

Device fabrication begins with the bonding of an unprocessed III-V die on a SOI die, using BCB, as presented in Figure 2a). For this purpose, we have developed a die-to-die bonding process for achieving ultra-thin ($\sim 50 \text{ nm}$) BCB bonding layers, based on the use of Süss MicroTec ELAN CB6L wafer bonding tool [7]. After the bonding, InP substrate is removed by combination of grinding and wet-etching in HCl. Further III-V die processing is presented in Figure 2b). III-V islands that will contain individual lasers are defined using contact lithography and wet etching techniques. After that, mesa structures are fabricated. Top III-V layers (ohmic contact and top cladding) are etched using inductively-coupled plasma (ICP) processes. Mesa definition is completed with the selective wet etching in 1:1:18 $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ solution that removes InAlGaAs layers (including MQW layers) until it reaches the InP spacer layer.

This is followed by N-type metallization, based on deposition of AuGe alloy and Ni. Afterwards, BCB is again spin-coated on the sample and cured in order to provide a physical protection and electrical isolation between the electrodes. In the next step,

reactive ion etching (RIE) plasma technique is used to make openings in a BCB covering layer for N-type and P-type contacts. Simultaneously, an opening in SiO₂ mask on top of the mesa is made, as the plasma used for etching BCB also attacks SiO₂. P-type metallization is done by sputtering a thin Ti layer, followed by deposition of 1.2 μm-thick Au layer. After this, a fast-alloying is performed in a forming gas atmosphere.

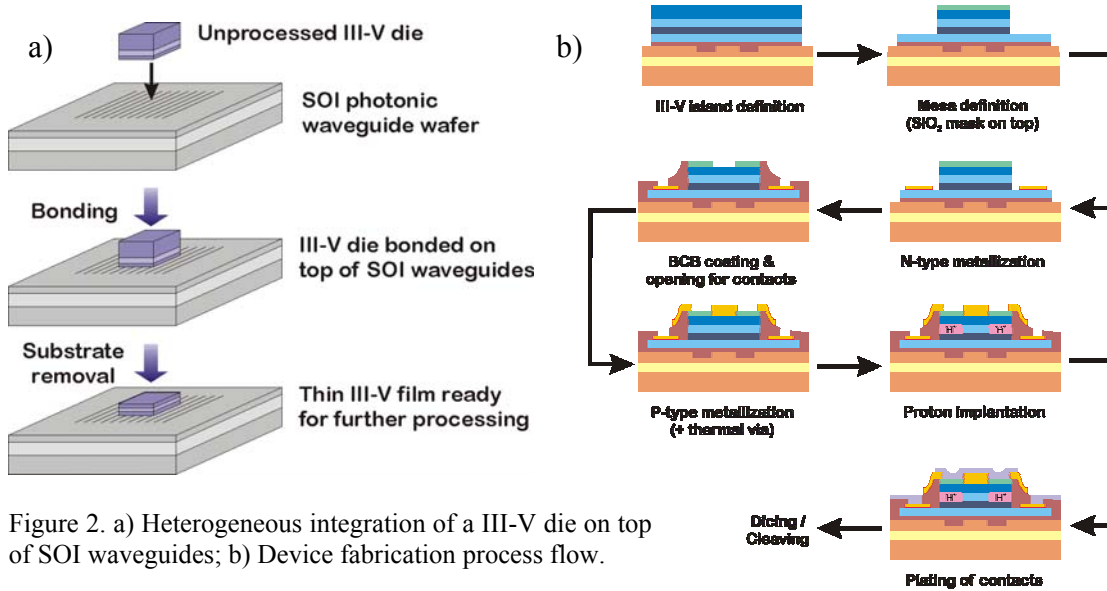


Figure 2. a) Heterogeneous integration of a III-V die on top of SOI waveguides; b) Device fabrication process flow.

A thick gold layer used for P-type electrodes, is required for the next processing step – the proton implantation. The goal is to implant protons in the lateral regions of the mesa and locally increase electrical resistivity so that the electrical current is confined to the central region of the mesa, where the fundamental optical mode is located and where carrier injection is needed for the lasing to occur. P-type electrodes serve as the mask for proton implantation since a thick layer of gold absorbs the high energy protons. In the final processing step, contacts are plated with gold. In the end, individual devices are cleaved (or diced and polished) and tested.

Results

Initially, we have focused on developing a reliable, die-to-die bonding procedure. In our tests, we used commercially available Cyclotene 3022-35, which nominally produces cured BCB films of 1 μm to 2.4 μm thickness. To achieve BCB bonding layers that are an order of magnitude thinner than this, we diluted Cyclotene 3022-35 with mesitylene, in different volume ratios, and used these solutions in the bonding tests. The best results were achieved with 1:3 BCB:Mesitylene solution, showing the best bonding yield and a BCB bonding layer thickness of around 50 nm, as shown in Figure 3a).

For the fabrication, we have prepared lithographic processing masks with variations in the length and the mesa widths of the lasers. After the device fabrication was completed, columns with the individual lasers were cleaved and tested. The best results were observed in a 800 μm-long device, with 17.2 μm-wide mesa. The threshold current in a DC regime was 120 mA, the threshold current density was around 7.1 kA/cm², while the maximum optical output power measured was 610 μW. In the optical power spectrum of the lasing diode, measured in a pulsed regime (5% duty cycle, 100 kHz repetition rate 250 mA) and shown in Figure 3b), we see several longitudinal mode

peaks, characteristic for Fabry-Perot lasers. These peaks lay between 1341 nm and 1347 nm, red-shifted from the expected wavelength of 1310 nm, which may be the consequence of the self-heating of the device.

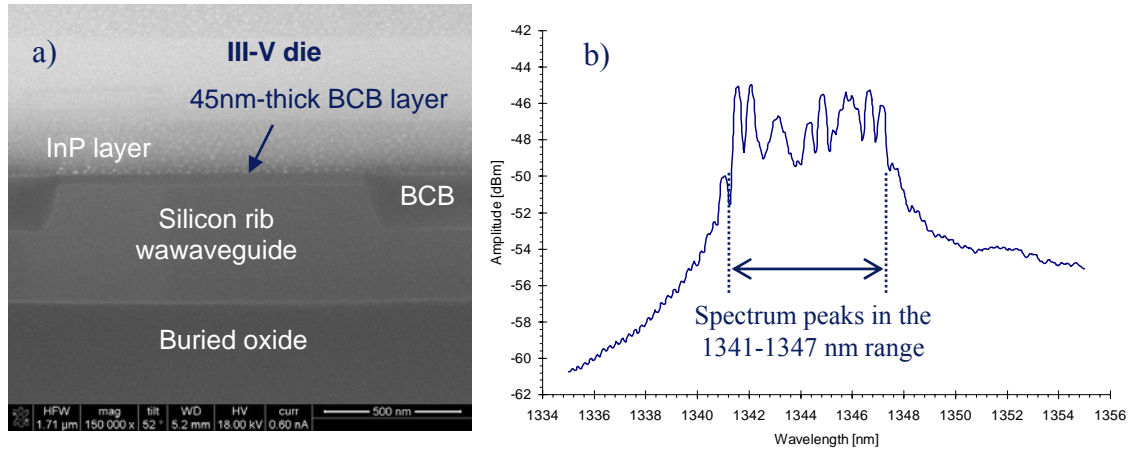


Figure 3. a) Ultra-thin (45 nm) BCB bonding layer on top of a Si rib waveguide, achieved using a 1:3 BCB:Mesitylene solution; b) Spectrum of the fabricated Fabry-Perot laser.

The modest results we have obtained may be explained with the imperfections in the fabrication process and also the problems we have encountered in cleaving the devices, since the quality of the facet is essential for Fabry-Perot lasers. Also, it is possible that a significant fraction of the injected current is running at the edges of the mesa, instead of the centre, as these mesa sections are also covered by P-type electrodes and therefore, protected from the proton implantation.

Conclusions

In this paper we present a Fabry-Perot hybrid III-V/Silicon evanescent laser, based on InGaAlAs multiple quantum wells. Its modest characteristics point out to the need for further improvement in the fabrication process, with a special attention to reduction of the current flow near the mesa edges and the facet quality. In our future work, we plan to improve fabrication procedures and also design and demonstrate DFB and DBR hybrid evanescent lasers.

References

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