Low-Threshold Heterogeneously Integrated InP/SOI Lasers With a Double Adiabatic Taper Coupler

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***Abstract*—We report on a heterogeneously integrated InP/silicon-on-insulator (SOI) laser source realized through divinylsiloxane-bis-benzocyclobutene (DVS-BCB) wafer bonding. The hybrid lasers present several new features. The III–V waveguide has a width of only 1.7 μm, reducing the power consumption of the device. The silicon waveguide thickness is 400 nm, compatible with high-performance modulator designs and allowing efficient coupling to a standard 220-nm high index contrast silicon waveguide layer. In order to make the mode coupling efficient, both the III–V waveguide and silicon waveguide are tapered, with a tip width for the III–V waveguide of around 800 nm. These new features lead to good laser performance: a lasing threshold as low as 30 mA and an output power of more than 4 mW at room temperature in continuous-wave operation regime. Continuous wave lasing up to 70 °C is obtained.**

***Index Terms*—Adiabatic taper, hybrid integrated circuits, silicon laser, silicon-on-insulator (SOI) technology.**

I. Introduction

SILICON photonics is drawing increasing attention due to the promise of fabricating low-cost, compact circuits that integrate photonic and microelectronic elements [1]. Today, practical Si-based light sources are still missing, despite the recent demonstration of an optically pumped germanium laser [2]. This situation has driven research to the heterogeneous integration of III–V semiconductors on silicon. In order to densely integrate the III–V semiconductors with the silicon waveguide circuits, mainly DVS-BCB adhesive wafer bonding and molecular bonding techniques are used and are actively reported in state-of-the-art hybrid lasers [3]–[6]. In these approaches, unstructured InP dies are bonded, epitaxial layers down, on a SOI waveguide circuit wafer, after which the InP growth substrate is removed and the III–V epitaxial film is processed. The design space for hybrid InP/SOI lasers is large and in particular the coupling between the optical mode in the top active III–V waveguide and that in the bottom passive SOI waveguide plays an important role. In literature, two main solutions are reported. In a first solution, the silicon waveguide layer is very close to the III–V waveguide layers [3]. In this case, the active waveguide is indeed a hybrid waveguide, with a large III–V mesa on top of the silicon waveguide. The optical mode is strongly confined in the silicon waveguide and the evanescent tail of the optical mode overlaps with the multi quantum well (MQW) layer stack. This solution was originally developed for molecular bonding of III–V dies on SOI [3], [4], but recently also an adhesive bonding version of these hybrid III–V/silicon lasers was presented [5]. The second solution has been specifically developed for the bonding of III–V dies on SOI using an intermediate low index bonding layer [7]. In this case, coupling between the III–V and silicon waveguide is realized by adiabatically tapering the silicon waveguide. It is to be noted that in both solutions, the silicon waveguide thickness is usually larger than 500 nm and the III–V effective waveguide width is quite large (> 4 μm). Such thick silicon waveguides are not compatible with most high-performance modulator designs, which have usually a thickness of less than 400 nm. Moreover, taking into account the fact that the thickness of the active layer should be enough to have sufficient gain confinement factor, the large III–V waveguide width leads to a threshold current larger than 50 mA in most published results for Fabry–Pérot and DBR lasers.

This letter reports on a hybrid laser using DVS-BCB bonding presenting several new features: narrow III–V waveguides in the range from 1.5 to 2 μm, thin silicon waveguide thickness (400 nm) and an adiabatic taper in both the III–V and silicon waveguide. These new features lead to a lasing threshold as low as 30 mA and an output power of more than 4 mW at room temperature in continuous wave operation regime.

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II. Device Structure and Fabrication

Fig. 1(a) shows the adiabatic taper coupler of the laser structure. The structure can be divided into three parts. In the center of the device the optical mode is confined to the III–V waveguide, which provides the gain. At both sides of this section there is a coupling region that couples light from the III–V waveguide to the underlying silicon waveguide. After the coupling region the light is guided by a silicon waveguide without III–V on top.

The III–V region consists of a p-InGaAs contact layer, a p-InP cladding layer, 6 InGaAsP quantum wells surrounded by two InGaAsP separate confinement heterostructure (SCH) layers, and

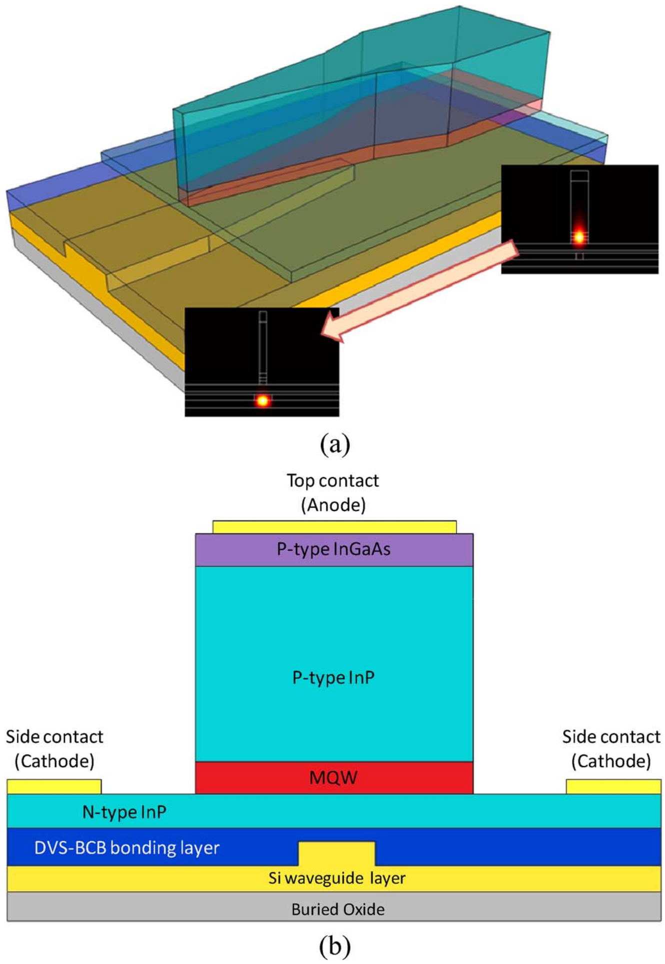

Fig. 1. (a) Three-dimensional view of the coupling structure of the hybrid laser with representative mode profiles in two cross-sections; (b) the detailed cross-sectional view of the taper part of the hybrid laser.

an n-InP layer. The SOI substrate (200 mm wafer manufactured by SOITEC) is composed of a 400 nm mono-crystalline silicon layer on top of a 2 μm thick buried oxide layer on a silicon substrate. The silicon rib waveguides have a height of 400 nm, an etch depth of 180 nm and a width of 1 μm. The III–V epitaxial layers are transferred to the patterned SOI wafer through DVS-BCB adhesive bonding. The bonding layer thickness is around 80 nm.

A. Active Waveguide

The active waveguide structure and the guided mode profile are illustrated in Fig. 1. The straight active waveguide has a width of 1.7 μm. The intensity profiles of the fundamental mode are calculated using the film mode matching method [8]. The calculated optical confinement in the MQW is 11.3%.

B. Coupling Structure

To achieve index matching between the two waveguides a deep ridge III–V waveguide is used in the double taper region. As shown in Fig. 1(a), a double taper structure is used to allow the efficient coupling of the fundamental mode from the III–V waveguide to the silicon waveguide [9], [10]. In the double taper region, the silicon waveguide tapers from 350 nm to 1 μm, while

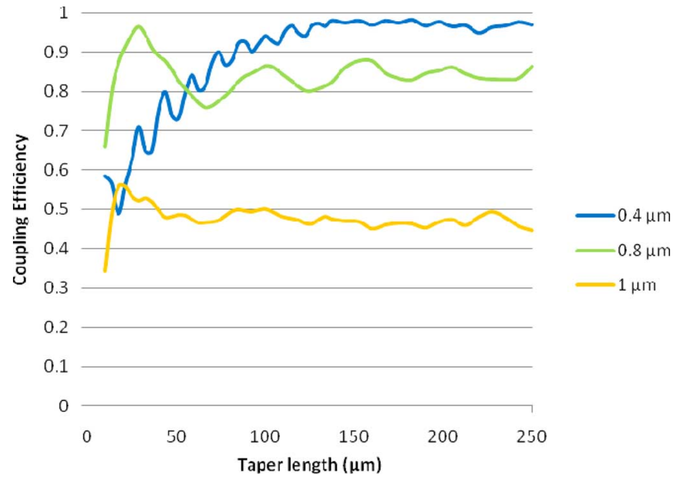

Fig. 2. Coupling efficiency for different III–V taper tip widths as a function of the double taper length.

the III–V waveguide taper has two linear parts: the first part of 30 μm long with the decrease of width from 1.7 to 1.0 μm, and the second part of 150 μm long starting with a III–V waveguide width of 1.0 μm. Fig. 2 shows the coupling efficiency of the double adiabatic taper (while the DVS-BCB bonding layer thickness is 80 nm) for three values of the III–V tip width: 0.4, 0.8 and 1 μm. We can see that the perfect coupling can only be achieved using a tip width of 0.4 μm or less. Such a requirement on the tip width is due to the 400 nm silicon waveguide thickness. For thicker silicon waveguides a larger tip width can be tolerated. We can also observe highly efficient coupling for short taper length (around 30 μm). However, the coupling efficiency varies quickly with the taper length and other parameters for such a taper length. Longer (> 100 μm) tapers are preferred in order to get more robust coupling.

C. Fabrication

After DVS-BCB adhesive bonding and InP substrate removal, an SiO_2 hard mask was defined using 248 nm UV contact lithography. ICP etching was used to etch through the InGaAs layer and partly etch the InP p-doped layer. The InP p-doped layer etching was completed by chemical selective etching. The MQW layer was etched by CH_4:H_2 RIE. Fig. 3 show a scanning electron microscope (SEM) picture of the III–V taper. We can see that the tip width is around 0.8 μm. This is due to the peculiar topology of the hybrid sample, which makes it impossible to achieve the designed dimension of the taper tips by contact lithography.

The active waveguide is encapsulated with DVS-BCB. A Ti/Pt/Au alloy was used for metallization on both p and n sides. Finally, the III–V/silicon wafer is cleaved after being thinned to 100 μm, to form a Fabry–Pérot laser cavity. No coating was applied to the facets.

III. Characterization Results

The device is mounted on a temperature controller set to different temperatures. The laser output is collected by a photodiode located in front of the cleaved facet. The L–I at different temperatures and V–I curves at 20 °C are shown in Fig. 4 for

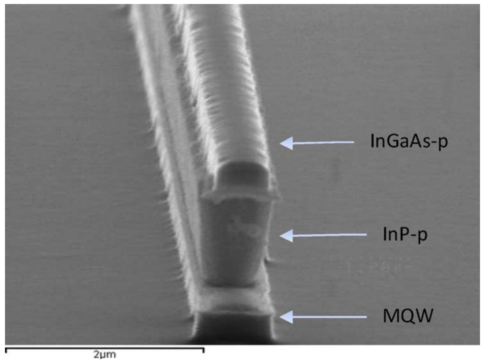

Fig. 3. SEM picture of a III–V waveguide taper tip.

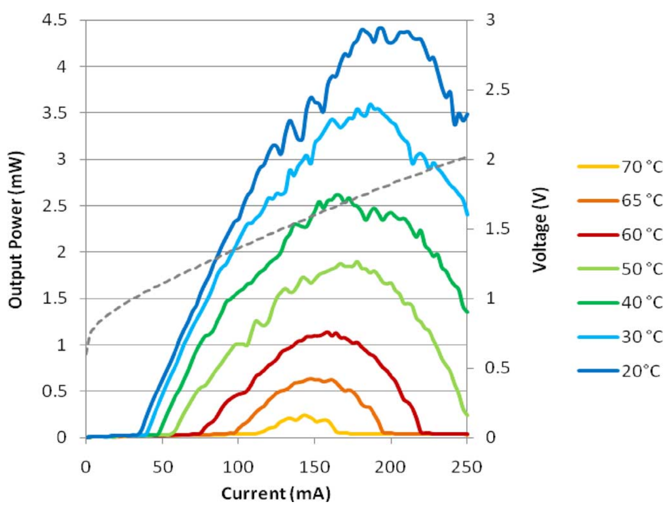

Fig. 4. Continuous-wave single facet laser power as a function of drive current at different stage temperatures and the (dotted) I–V curve of the laser at 20 °C.

a hybrid laser with a III–V waveguide width of 1.7 μm. The length of the straight III–V waveguide section is 490 μm. The coupling section length is 230 μm. The overall cavity length is 1700 μm, including the passive silicon waveguide. The device has a threshold current of 30 mA and a maximum single facet continuous wave output power of 4.5 mW at 20 °C. At 60 °C the laser still exhibits an output power of more than 1 mW. The series resistance is 5 Ohms, while the slope efficiency is 0.043 W/A. Based on these results we extract a characteristic temperature T_0 for the threshold of 69 K and a characteristic temperature T_1 for the external efficiency of 94 K. The kinks in the L–I characteristics are due to the jumps of the dominant lasing mode.

Fig. 5 shows the optical spectrum for an injection current of 100 mA. One can see the Fabry–Pérot modes of the laser cavity. However, some perturbations are observed on the emission spectrum, due to parasitic reflections created by the taper tip. Considering the III–V tip width of 0.8 μm in our case, we estimate that the coupling efficiency between the III–V and silicon waveguides is around 80% and the power reflection coefficient due to the taper is 3%.

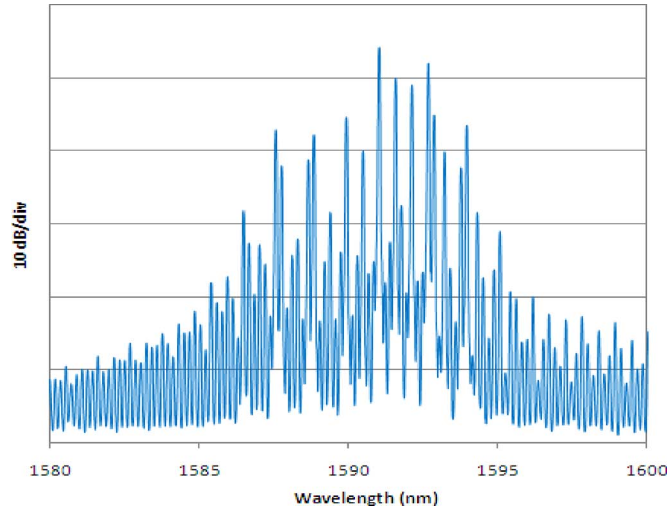

Fig. 5. Lasing spectrum of the hybrid laser.

IV. Conclusion

We demonstrate a low-threshold (30 mA) DVS-BCB bonded III–V on silicon laser based on the adiabatic transfer of the optical mode between the III–V waveguide layer and silicon waveguide layer. To the best of our knowledge this is the lowest threshold current value ever reported in literature for a heterogeneous III–V/silicon Fabry–Pérot or DBR hybrid ridge laser. The low power consumption of this kind of device makes it suitable for access network application. Following this proof-of-principle demonstration more complex laser configuration such as DFB and DBR lasers based on the same coupling principle can be envisioned.

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