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Integrated optical transmitter with micro-transfer-printed widely tunable III-V-on-Si laser

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Abstract: We demonstrate a C-band optical transmitter with an integrated widely-tunable III-V-on-silicon laser on the imec iSiPP50G platform using micro-transfer printing. Back-to-back operation at 40 Gbit/s non-return-to-zero On-Off keying over the C-band is presented.

1. Introduction

Silicon photonics (SiPh) has attracted extensive attention from both academia and industry. By using established CMOS fabrication infrastructure, photonic integrated circuits can be realized on 200 mm or 300 mm SOI wafers with high uniformity and yield. However, not all optical functions can be realized on a SiPh platform. Therefore materials with superior properties over Si in some aspects have been introduced. A good example is the monolithically integrated high-speed germanium photodetectors (Ge PDs) and Ge electro-absorption modulators (EAMs). Integrating optical gain elements and/or lasers in a scalable way is however still in high demand. Heterogeneous integration of III-V-on-Si lasers through multi-die-to-wafer bonding has been intensively investigated in the past few years and has been adopted by Intel for the production of optical transceiver modules from 2016 [1]. This however requires developing dedicated III-V process flows and modified back-end process flows in a CMOS fab to enable this integration. Alternatively, flip-chip integration approaches can be pursued. In this case the III-V devices can be integrated after the SiPh back-end. However, the integration is sequential, resulting in limited throughput and involves handling and coating individual dies. Several activities are ongoing on hetero-epitaxial growth. While being a very interesting approach, much work is still needed to incorporate this technology in a complex Si photonics platform. In this work, we present the use of micro-transfer printing (µTP) for the realization of a C-band optical transmitter with an integrated widely tunable III-V-on-Si laser on an advanced SiPh platform - the imec iSiPP50G platform [2]. This approach is not only wafer-scale compatible, but also requires minimal disruption to the Si photonic process flow, is a high-throughput integration process and does not require singulation of III-V chips.

2. Micro-transfer printing

The µTP process is based on the use of an elastomeric poly-dimethylsiloxane (PDMS) stamp. The devices of interest (here C-band III-V-on-Si semiconductor optical amplifiers(SOAs)) are at first processed in dense arrays on the source wafer and then undercut by selectively etching the release layer. A PDMS stamp with a single post or a post array is used to pick-up and print the devices of interest on the target substrate. Using the most recent tools, 0.5 µm alignment accuracy can be obtained using a stamp with 2 cm by 2 cm post array (60 sec printing cycle). An introduction of µTP for III-V semiconductors on SiPh integrated circuits can be found in [4]. Fig. 1 depicts the µTP of pre-fabricated III-V devices on the imec iSiPP50G platform, which includes active devices (e.g. Ge PDs, Ge EAMs and Si modulators) supporting 56 Gbit/s and beyond. Only a local recess is require on the target SiPh substrate to allow an intimate contact of the III-V device with the Si waveguide, enabling evanescent optical coupling. In order to enhance the bonding strength a thin (10s of nanometer) DVS-BCB layer is spray-coated on the target wafer prior to the µTP process.

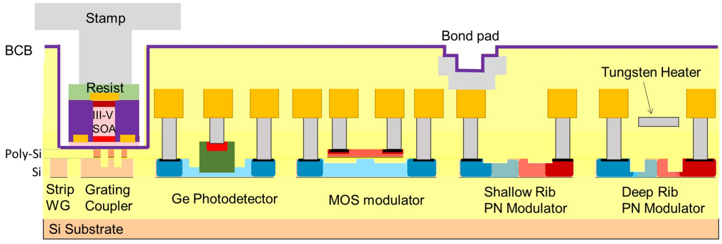

Fig. 1. Schematic of µTP of a pre-fabricated III-V component on an advanced silicon photonics platform.

3. Micro-transfer printing of pre-fabricated InP-based SOAs on the imec iSiPP50G platform

Fig. 2(a) depicts the transmitter, which consists of an integrated widely-tunable III-V-on-silicon laser, which is connected to an MZI switch with one output port feeding into a high-speed balanced silicon Mach–Zehnder interferometer(MZI) modulator and the other channel connecting to a Ge photodetector to monitor the laser output. The MZI modulator incorporates a pair of 1.5 mm long phase modulators and a thermal phase shifter. The widely tunable laser comprises a ring laser cavity incorporating a pair of micro-ring resonators with a slight different radius (25 µm and 27 µm) for the wavelength selection using integrated micro-heaters, as depicted in Fig. 2(b). The combined free spectral range of the microring-based Vernier filter is around 40 nm in C-band. A Sagnac loop mirror is connected to one port of a ring resonator to provide an external feedback to couple the clockwise and counter-clockwise mode thereby obtaining unidirectional operation [3]. The overall length of the laser cavity is around 3.4 mm and the length of the III-V SOA is 1.15 mm, including a pair of 220 µm long adiabatic tapers for an efficient coupling. A continuous poly-Si/c-Si (160 nm/ 220 nm thick) waveguide is used under the SOA to achieve efficient optical coupling between the III-V device layer and the underlying Si waveguide. An additional taper structure is used to couple the optical mode to the 220 nm crystalline Si wire waveguide. The design and fabrication of the III-V SOAs are described in detail in Ref. [5].

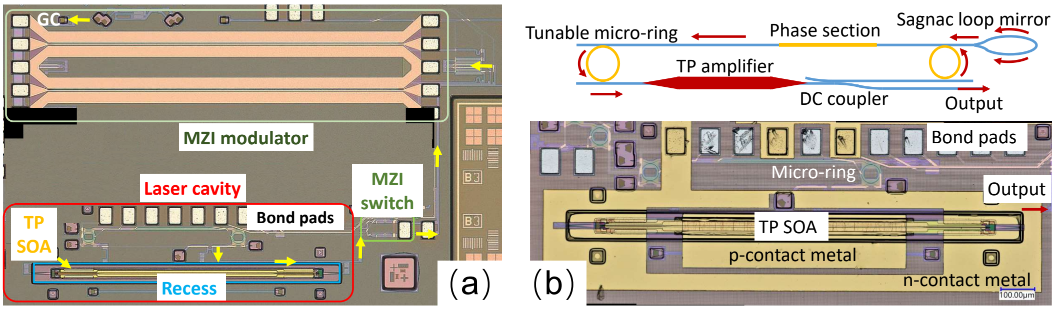

Fig. 2. (a) Schematic layout of the laser cavity.(b) Microscope image of the widely tunable laser with a transfer-printed III-V amplifier in the active region (before metallization of the SOA).

To enable the µTP a combination of RIE and BHF wet etching was first used to remove the back-end stack to form the recess where the III-V amplifier will be integrated. Then a thin DVS-BCB layer ($<$ 50 nm) was spray-coated on the photonic chip. After 15 minutes soft bake at 150 °C the sample was loaded on an X-Celeprint µTP-100 lab-scale printer and a PDMS stamp with a post of 50 µm by 1200 µm was used to transfer the III-V thin film SOAs. The III-V coupon was aligned to the silicon waveguide circuit using pattern recognition. As shown in Fig. 2(a), a pre-fabricated III-V amplifier has been transfer-printed in a locally opened recess, whose size is slightly bigger than the amplifier. After transfer printing, oxygen-plasma etching was performed to remove the photoresist encapsulation, followed by a DVS-BCB full curing procedure. The final process step then involves the electrical contacting of the devices. Fig. 2(b) shows a microscope image of a photonic chip with a transfer-printed III-V amplifier in a recess, thereby defining the widely tunable laser cavity.

4. Characterization

The widely tunable laser was first characterized on a temperature-controlled stage which was stabilized at 20 °C. Fig. 3(a) shows the current–voltage (I-V) and waveguide-coupled power–current (L-I) characteristics of the resulting device at 1553 nm. The differential resistance of the µTP III-V SOA is 6.5 Ω and the waveguide-coupled (calibrated to the output port of the laser) power is 2 mW at 130 mA bias current.The threshold current is around 100 mA. Discrete wavelength tuning over 40 nm with a step of an FSR of a microring (around 4 nm) was realized by thermally tuning one of the microrings and the phase section, as shown in Fig. 3(b). By actuating both heaters of the ring resonator Vernier filter and the phase section simultaneously, the wavelength can be finely tuned to obtain full wavelength coverage.

For high-speed characterization an AWG was used to generate two identical 2^9-1 long non-return-to-zero On-Off keying signals, which are boosted by RF amplifiers. A pair of bias-Ts and a GSGSG RF probe were used to load the amplified RF signals and bias voltage to the MZI modulator. The operating point of the MZI modulator was tuned using the integrated thermal phase shifter. In the transmission test, the integrated III-V SOA in the laser cavity was pumped at 130 mA, whereas the wavelength of the tunable laser was adjusted by thermally tuning the two micro-ring resonators and the phase section. The modulated signal was coupled to a optical fiber probe through a grating coupler and was then fed into a commercial high-speed optical receiver after being boosted through an EDFA. A sampling scope was used to present the obtained electrical signal from the receiver. Due to the insertion losses of the grating coupler and the MZI modulator, the fiber-coupled average power was around -9 dBm, which was amplified to 0 dBm using the EDFA. Fig. 3(c) shows a set of representative recorded eye diagrams for 28 Gbit/s and 40 Gbit/s operation at different wavelengths within the C-band.

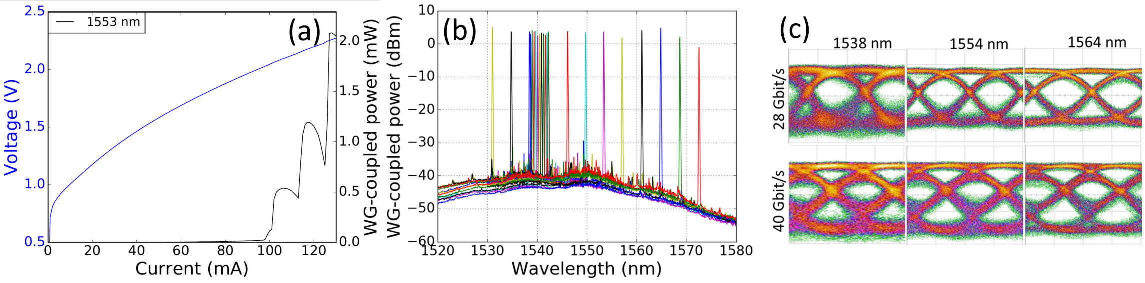

Fig. 3. Performance of the resulting widely-tunable laser: (a)L-I-V plot, (b) wavelength tuning behavior and (c) representative eye diagrams at 28 Gbit/s and 40 Gbit/s at different wavelengths in the C-band.

5. Conclusion

We demonstrate for the first time the integration of a III-V-on-Si tunable laser and a high-speed modulator on the imec iSiPP50G platform by micro-transfer printing a pre-fabricated III-V SOA. Only a local back-end opening is needed to facilitate the integration. This approach creates opportunities for the realization of complex photonic integrated circuits with integrated non-native opto-electronic functions on an advanced SiPh platform.

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