

Heterogeneous integration in silicon photonics through micro-transfer-printing

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Abstract: Micro-transfer-printing enables the intimate integration of a wide range of opto-electronic micro-components on a silicon photonics platform. This technique allows for wafer-scale integration in a massively parallel manner with high alignment accuracy, high throughput and high yield, therefore leading to a cost reduction of complex photonic integrated circuits.

1. Introduction

Silicon photonics (SiPh) is emerging as the most promising contender for building ultra-compact integrated photonic circuits due to its high refractive index contrast, and has shown a spectacular development in the last two decades. The CMOS compatibility enables leveraging the well-established processes and mature fabrication tools of the CMOS industry, resulting in a high-volume and low-cost production of photonic integrated circuits (PICs) on 200 mm or 300 mm wafers. Over the past years, a variety of passive devices as well as Si/Ge-based active devices have been demonstrated on the SiPh platform, enabling complex and powerful PICs, for applications in optical interconnects, optical sensors, bio-medical instruments, etc. Nevertheless, additional integrated functionalities, especially in the form of optical sources, are desired for an improved performance while maintaining a compact footprint. Different approaches have been followed to realize the integration of non-inherent functionalities on Si PICs.

In case of the integration of III-V-on-Si devices/PICs, the monolithic integration through direct epitaxial growth of III-V semiconductors on the Si substrate, is considered to be the most ideal approach, as it allows for large scale manufacturing and thus low cost. Despite the substantial progress that has been made recently, this integration method is still at an early stage and hardly available for the demonstration of practical devices, especially when they need to be integrated with a silicon PIC. Further to the aforementioned approach, heterogeneous integration through wafer-to-wafer or die-to-wafer bonding has been widely adopted. This technique allows the integration of III-V material on a non-native substrate (e.g. silicon-on-insulator (SOI)) at wafer scale. Simultaneous integration of different III-V materials on the same substrate is possible, but still challenging. Moreover, it requires the modification of the back-end process flow, if Si and/or Ge based active devices are to be included in the PICs.

Micro-transfer-printing is a novel technology that has recently attracted considerable attention for the integration of micro-components in heterogeneous systems. This technique successfully tackles the above

described issues in the wafer/die to wafer bonding technology, while maintaining the advantage of high throughput integration. Moreover, this approach allows for the pre-fabrication and pre-testing of the devices on their native substrate prior to their integration on a Si PIC, thus leading to a higher yield.

In this paper we discuss the demonstration of the heterogeneous integration of various opto-electronic components on SiPh platforms through the micro-transfer-printing approach.

2. Micro-transfer-printing process

The concept of the micro-transfer-printing is schematically illustrated in Fig.1, taking the integration of III-V-on-silicon devices as an example. In micro-transfer-printing a polydimethylsiloxane (PDMS) stamp is used to pick up (arrays of) pre-fabricated devices from a native substrate and print them on a SiPh target wafer. As depicted in Fig. 1(b), a sacrificial layer is required to enable the release of devices from its native substrate [1].

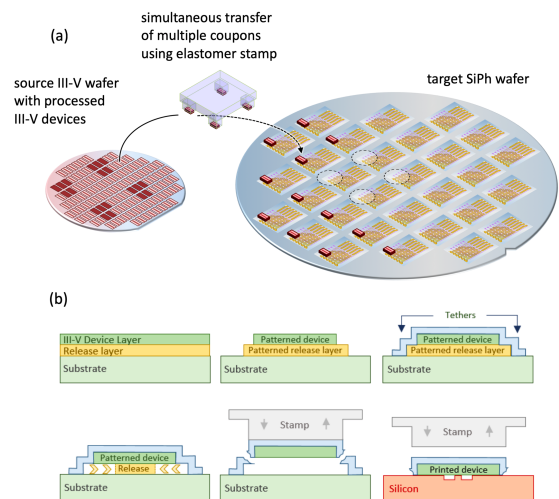


Fig. 1. (a) Schematic of transfer-printing-based integration on 200 mm or 300 mm silicon photonic wafer in a parallel manner; (b) pre-fabrication of III-V devices on its native substrate and transfer printing operation.

3. Micro-transfer printing of opto-electronic components onto PICs

Fig. 2(a-c) shows some examples of the micro-transfer-printing-based integration of different types of III-V photodetectors (PDs) on PICs. A yield up to 98.8% (83 of 84 printed C-band III-V PDs) in a parallel (2×2) integration process was obtained (Fig. 2(a)). Fig. 2(b) shows the integration of an array of O-band III-V PDs on a PIC with Si ring modulators and Fig. 2(c) depicts GaAs metal-semiconductor-metal (MSM) photodetectors on SiN waveguide circuits. Besides III-V semiconductors, any other material/device that can be released from its native substrate are transfer-printable. As an example, a Ge waveguide PD was released by underetching the 2 μm thick buried silicon dioxide layer of the SOI wafer and printed on a Si PIC (Fig. 2(d)).

Fig. 2 (a) A zoom-in microscope image of transfer-printed III-V-on-Si PD array; (b) InP based p-i-n PDs on full platform PIC; (c) GaAs MSM PDs integrated on a SiN waveguide circuit; (d) transfer-printed Ge PDs on a 220 nm thick passive Si waveguide circuit.

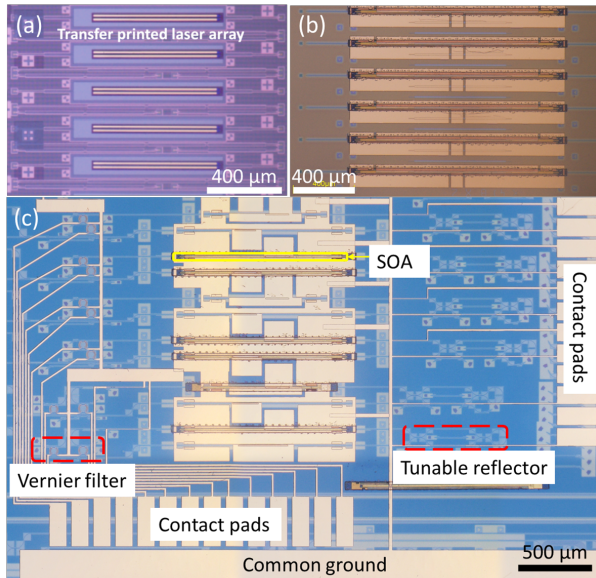


Fig. 3 Microscope image of an array of transfer printed etched facet Fabry-Perot lasers (a); (b) evanescently coupled SOAs; (c) widely tunable III-V-on-Si lasers.

As already mentioned, optical sources are urgently desired on Si PICs. Currently two major approaches are intensively studied for realizing integrated light sources through micro-transfer-printing. One route is by transfer printing a pre-fabricated III-V laser in a trench that reaches the silicon substrate. By using a co-designed spot size converter (e.g. a Si taper structure) in the PIC and thanks to a sub-micrometer alignment accuracy provided by the micro-transfer-printing system, milliwatt-level coupling to the silicon waveguide was successfully demonstrated (Fig. 3(a)). The other approach is based on evanescent coupling. As the commonly used III-V epitaxial materials have high refractive indices, SiPh platforms with a thicker silicon device layer (typically 400 nm) are adopted, and a III-V adiabatic taper structure is used to enable the coupling between the III-V and the underlying Si layer. Fig. 3(b) shows an array of fabricated III-V-on-Si integrated SOAs, which have an up to 19 dB small signal gain at 190 mA bias current. By incorporating a pair of DBR reflectors at the sides of the SOAs, L-band single mode operation DBR lasers were realized with a maximum waveguide coupled output power over 6 mW. Furthermore, III-V-on-Si integrated widely tunable lasers were also demonstrated in the same way. A micro-ring-based Vernier filter is incorporated in the laser cavity to achieve a single mode operation and a wide tuning range. The threshold of the fabricated lasers is 70 mA and, the series resistance is found to be 15 Ω at a bias current of 110 mA. Over 48 nm tuning range is achieved by actuating both thermal heaters of the ring resonators, and the waveguide-coupled power varies between -1.8 dBm and 5.2 dBm over the entire tuning range.

3. Conclusion

In this paper we summarized the heterogeneous integration of different types of opto-electronic components in PICs by means of micro-transfer-printing, which reveals the great potential that micro-transfer-printing has for the realization of complex and advanced PICs.

Acknowledgements

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