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# Microtransfer printing enabled advanced photonics integration

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***Abstract:*** *Lasers, modulators and detectors are integrated with silicon waveguides using transfer printing where 50 Gbps signaling is demonstrated. The technique is versatile enabling components from InP, GaAs, GaSb, GaN and lithium niobate to be integrated.*
***Keywords:*** *Si photonic and heterogeneous platform, Semiconductor lasers, Optical modulators, Photodetectors*

## I. INTRODUCTION

Continued demand for bandwidth is driven by new applications, currently artificial intelligence and machine learning on mobile devices and in data centres. The bandwidth density needs to increase and be implemented over ever shorter distances. Scaling this bandwidth requires it to be delivered with reduced cost and energy consumption per bit meaning that integrated photonics is required. Photonics is a complex technology employing multiple functionalities of light generation, waveguiding, multiplexing, modulation and detection. While most of the passive functions can be realised with a common waveguide platform, the active devices require individual structural optimisation. Complete monolithic integration of high-performance transceiver circuits has been most successful using InP platforms [1]. However, the technology is proprietary and challenging to scale. Photonic integrated circuits (PICs) based on the foundry-compatible silicon-on-insulator (SOI) platform have been introduced taking advantage of the years of investment in silicon electronics technology. Active components such as lateral p-n junction based modulators and germanium detectors can be monolithically integrated, though with non-ideal performance and with high thermal budget respectively. Recent progress has been made with epitaxy of laser structures on Si substrates but full waveguide integration is some years away.

## II. TRANSFER PRINTING

Heterogeneous integration of the active components onto SOI waveguiding platforms is a solution for compact functional PICs. Laser light can be brought to the circuit by hybrid edge-coupling of reflective semiconductor amplifiers (RSOAs) or with pre-assembled external sources using grating coupling [2]. Bonding of arrays of III-V dies followed by substrate removal has been commercialized [3]. It permits accurate and reproducible alignment for evanescent coupling between the Si and III-V waveguide though requires removal of the expensive substrate. Microtransfer printing is an alternative strategy where the III-V epilayers are selectively undercut and released from the growth substrate while being held in place by tethers enabling, by the use of an appropriate stamp, the repeated pick and print of individual or arrays of devices to the target SOI substrate [4-5]. The transfer takes place with the epitaxial side up, which allows the growth with the conventional of p-on-n arrangement. In principle, the substrate can be recycled. It is capable of transferring individual devices with micron lateral scale to those with sizes of several hundred microns. The coupons can be printed in trenches enabling edge-coupling to waveguides. Devices with different properties (eg lasers and modulators) can be printed in close proximity to each other. All compound semiconductor III-V materials (As, P, N, Sb) in addition to multiple other materials such as lithium niobate (LN) can be configured for release. The technique is applicable to different waveguide platforms such as SiN on oxide or LN on insulator.

A suitable release structure and chemistry is required to produce flat coupons with sub-nm roughness if direct bonding is required. This structure needs to be optimised for different material systems. In the case of InP-based coupons, a dual layer combination of AlInAs/InGaAs was found to result in the smoothest surface [6]. Stress originating in the epitaxial layers or during the coupon processing (e.g. physical structure, dielectric and metal layers) should be managed. Coupons can be prepared from a wide variety of materials where a releasing mechanism can be engineered. For example, <111> oriented silicon can be used to deposit appropriate materials by sputtering or evaporation, which can be then released by using TMAH etching. Dry release of structures from SOI is possible using $XeF_2$ to undercut the Si or from an oxide layer using HF vapour etching.

Optical coupling between the waveguide and the III-V device can be achieved using grating, evanescent or end-fire methods noting that alignment precision well below 1 μm between the Si waveguide and the waveguide of the active component is required in the latter cases. Grating coupling is most suitable for up-coupling to transferred detectors but suffers from limitation in the transmission bandwidth. Evanescent coupling requires matched waveguide tapers to ensure high coupling efficiency. There, depending on the epitaxial structure, the device can act as a semiconductor optical

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amplifier or as an in-line modulator. End-fire coupling to waveguides requires the preparation of trenches into the wafer together with matching of the alignment and sizes of the modes. The buried oxide in SOI is typically 2 µm thick, which acts as a very convenient etch stop providing a smooth surface to high thermal conductivity Si and with suitable mode height for a typical laser structure. The advantage of this approach is the device can act as an independent laser, which could be pre-tested, or as an RSOA and coupling to a feedback structure on the wafer. The gain chip coupling does not intrinsically require a tapered coupler but may be used to match the modes.

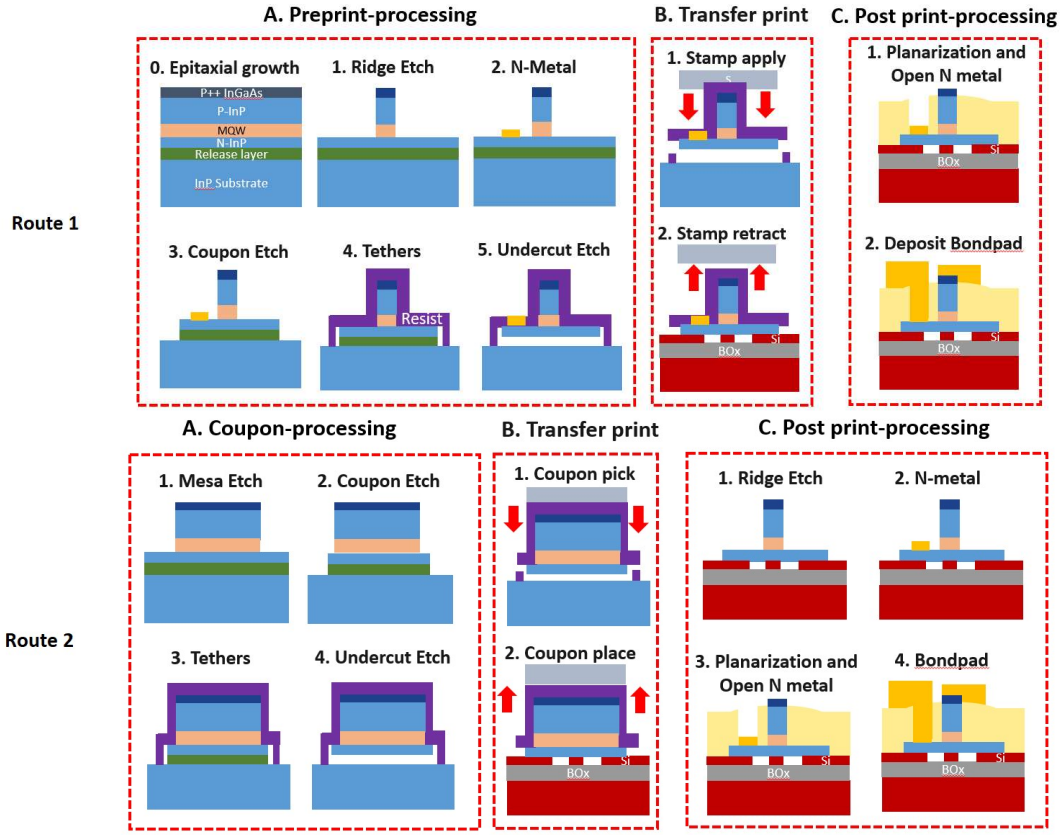


Fig. 1. Schematic process flow demonstrating the methodology to pre-process devices in advance of integration (Route 1) or where the material itself is transferred and all the device fabrication steps are subsequently completed on the target wafers (Route 2).

## III. Examples of Integrated Devices

Lasers were integrated with SOI waveguides according to Route 1 [7]. Coupons of unpatterned O-band InP-based multiple quantum well gain material with lateral dimensions of 1000 µm × 60 µm were prepared. After release the coupons were transferred using direct bonding to the 400 nm-thick SOI wafer which had been prepared with rib waveguides and feedback gratings. An oxygen plasma on the target Si wafer helps with strong bonding. All the device fabrication steps were performed on the SOI including high temperature (400°C) annealing. The coupling region has laterally tapered regions in both waveguides and the alignment has lithographic accuracy enabling evanescently coupling. The fabricated distributed Bragg reflector lasers shows lasing around 100 mA current injection with > 1 mW of output power coupled to a single mode fiber.

High bandwidth integrated electro-absorption modulators (EAMs) using the quantum confined Stark effect in InP-based multiple quantum wells were demonstrated [8]. Notably, the devices were evanescently coupled to the preferred 220 nm-thick SOI. The devices were processed according to the Route 1 where the waveguides were defined on the InP wafer before the devices were released and integrated using transfer printing and direct bonding. The printing accuracy of the device was within ±0.5 µm. At 1550 nm, the printed EAMs had a measured electrical bandwidth of up to 40 GHz, an extinction ratio (ER) of 30 dB for 0 to −6 V, and an insertion loss of 6.5 dB, which reduces with longer wavelengths. An ER of 25 dB was obtained over a spectral bandwidth of 30 nm with biasing to −8 V. Open eye-diagrams were measured up to 50 Gbps in a back-to-back measurement. This device is suitable for applications in high-speed communications and sensing, leveraging the added advantage of III–V absorption modulation on a silicon photonics platform.

Pre-fabricated InGaAs photodetector coupons with small lateral dimensions of 21 × 57 µm$^2$ and total device thickness of only 675 nm were fabricated (Route 1) and transferred to a 500 nm SOI platform using a direct bonding [9]. With such device dimensions around 1 million devices can be attained from a 75 mm diameter InP wafer. The same device

configuration was used to couple light from Si waveguides to the detector using three different coupling techniques namely butt, grating and evanescent schemes. Responsivities of 0.13, 0.3 and 0.6 A/W were obtained respectively for each of the techniques. The thin device thickness enables a simplified high-speed connection to the device without the need of an interlayer dielectric such as BCB. Using these connections a back-to-back data on-off keying communication rate of 50 Gb/s obtained. Using four-level pulse-amplitude modulation (PAM4) a data rate of 100 Gb/s is realized.

Lithium Niobate (LN) has a strong electro-optic effect due to a high nonlinear coefficient and is transparent across the infra-red and visible spectrum making it an important material for high bandwidth modulators and second harmonic generation. Thin film LN-on-insulator (LNOI) has achieved prominence as a platform for high performance modulators, but lacks monolithic detectors and light sources. The active photonic components can be transfer printed to the LNOI platform. Equally, the LN can be separated from the LNOI substrate by selective etching of the buried oxide and transferred to other waveguide platforms. Using this approach, coupons of x-cut LN with thickness of 300 nm and lengths up to 2.4 mm were transferred to 300 nm thick SiN waveguides. Mach-Zehnder modulators were fabricated with metal separation of 9 µm to obtain high extinction ratio modulation.

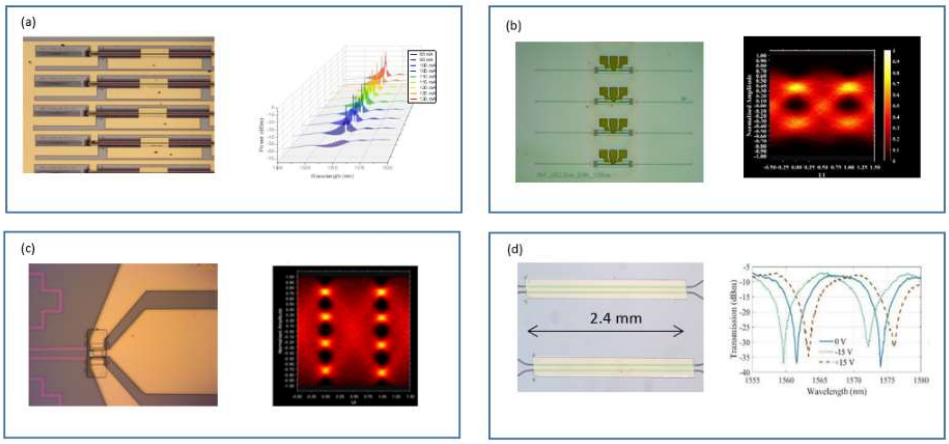


Fig. 2. (a) SOA printed on 400-nm SOI and lasing spectra [7]; (b) Electro-absorption modulators on 220-nm SOI and eye diagram at 50 Gbps [8]; (c) InGaAs photodetector printed on 500-nm SOI with PAM4 eye diagram [9]; (d) LN coupon printed to SiN waveguide and Mach-Zehnder response.

## IV. CONCLUSIONS

It is clear that transfer printing is a very versatile technique for the heterogeneous integration of dissimilar materials. The method was used in the production of high volumes of concentrator solar cells [10]. By appropriate design, a wide variety of materials and structures covering an extensive wavelength range can be engineered for transfer and different optical coupling schemed can be arranged. The technique is particularly suitable for structures with lateral dimension of mm and smaller. Coupons of materials could be transferred to wafers in a foundry environment and collective fabrication of the active devices completed using process design kits (PDK).

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