Micro-transfer printing for advanced scalable hybrid photonic integration

(Invited paper)

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ABSTRACT

Integrated photonics has lagged the complexity possible with electronics by orders of magnitude. This is changing with the development of photonic integrated circuits on silicon photonics which has allowed thousands of optical components to be integrated and where many applications in communications and sensing can be addressed. Nevertheless, the key component of a gain block is missing while other functions can have better performance with separately optimised materials. Micro-transfer printing is emerging as an effective, accurate and massively parallel technique for the heterogeneous integration of photonic and electronic devices to different platforms including silicon photonics. We describe some recent development in this technology.

Keywords: Heterogeneous integration, photonic devices, lasers, coupling, silicon photonics.

1. INTRODUCTION

The optimal device structures are distinct for different photonic functions which makes their co-integration challenging. While excellent progress has been made with photonic integrated circuits (PICs), especially using InP platforms for telecommunications, these PICs are expensive to produce due to the limited wafer sizes and complexity of the manufacturing processes. Silicon photonics has now emerged as a scalable large-area platform for integrating photonic devices where waveguides, multiplexing, routing, detection and modulation can be performed [1]. The light source or an optical amplification function has yet to be monolithically integrated on the platform though advances are been made with selective area epitaxy. In the meantime the laser light has to be provided to the silicon waveguides from a separate InP (or GaAs) based material structure. Laser light can be coupled to these silicon waveguides using grating, evanescent or edge coupling. Associated methods to achieve these couplings are, respectively, fibre coupling of an external laser, integration using wafer/die bonding or flip-chip of laser devices.

An alternative approach that is being investigated is the use of the micro-transfer technique [2], [3]. This technique involves the formation and registration of thin (typically < 5 μm thick) coupons of a material structure, releasing these coupons from their source wafer, the sequential, parallel transfer of stamp-selected arrays of the coupons and their bonding to selected matching locations on a target substrate. The technique requires that there is a means to separate the coupons from the source wafer which is achieved with a buried release layer in the layer structure. The process is indicated schematically in Fig. 1. Note that the technique transfers the coupons in an 'epitaxial-side-up' configuration. The primary requirement for bonding on the new substrate is that the mating surfaces are locally flat and co-planar. This can be achieved by a coating the surface of the target substrate with a thin layer of polymer which also assists the bonding. A direct bond can also achieved between the semiconductor surfaces through van der Waals forces that are particularly enabled for thin and small dimensioned coupons. The micro-transfer printing approach allows the material to be transferred to structured substrates such as fully processed target wafers. The source coupons can be unprocessed material or part / fully processed into devices with the appropriate structuring and contacts present. In the former case the coupons have to be structured into the appropriate devices post transfer. This then requires compatibility between the process technologies and material compatibility in the foundry. However, this approach allows for lithographic alignment between waveguides [4]. In the latter case the devices can be tested before transfer and only known-good-die transferred. This also allows the source wafers to be processed in their optimum environment – ie without process limitations. Additional stresses on the coupons due to the process technology need to be managed. Transfer print has been demonstrated for multiple materials including III-V devices (InP, GaAs, InAs, GaN), silicon, graphene, and dielectrics. One example of the integration of large numbers of different components on a single substrate is with displays where separate red, green and blue LED together with a control circuit have been integrated for each pixel in the display [5].

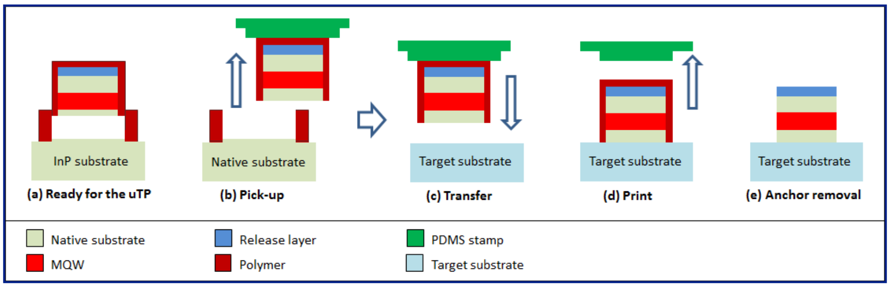

Figure 1. Schematic of the micro-transfer print process indicating the preparation, pick-up and transfer of a single coupon.

2. Transfer of InP lasers to Si

The transfer of InP devices to Si wafers is a pertinent example. InP is the material of choice for lasers, modulators and detectors operating in the 1300 nm to 2000 nm wavelength range. The device structures are typically grown on 50 mm or 75 mm diameter wafers. The wafer size is clearly not compatible with 200 mm or 300 mm diameter wafers from silicon foundries. Yet, the resulting InP wafers are very valuable as many thousands of high performance devices can be made with the material. For example, one 75 mm wafer can produce lasers with a total bandwidth of >10 Tb/s. The aim with the transfer printing process is to distribute these lasers so that they can be integrated and aligned with appropriate waveguides.

It is necessary to include a release layer early in the epitaxial structure. The layer should be lattice-matched and its release chemistry be compatible with the other layers within the structure. We compared InGaAs and InAlAs as release layers using a dilute $FeCl_3$ etching solution which is compatible with the standard resists that act as tethers to hold the coupons in place while being undercut. Both release layers are etched with a high selectively with respect to the surrounding InP material. We found that the InGaAs etch rate is highly crystallographic with the etch proceeding along the <010> directions [6]. If the eventual ridge waveguides need to be aligned along the <011> directions, as is used in conventional device processing, then the releasing etch takes several hours with some resultant dishing of the release InP surface. In that case the width of the devices can be limited. On the other hand, the etching of InAlAs has low crystallographic selectivity and also much reduced times to release the coupons. As a result wider coupons can be more easily accommodated with the InAlAs release layer.

We have considered two situations for integrating the laser with silicon waveguides. The first is to use evanescent coupling to an underlying waveguide which couples to gratings in the silicon which provide the feedback [7]. A second approach is to produce stand-along lasers which can be integrated by butt coupling (see below). In that case the laser is fabricated with etched facets to provide feedback [8]. The width of the laser coupons are 60 µm and have a metal-coated rear facet. The device length is 500 µm while the coupon length is longer in order to accommodate bond pads on the chip. Figure 2 shows an optical image of the 1550 nm emitting devices after transfer to a flat silicon substrate and the temperature-dependent light-current characteristics. The performance after transfer is superior to that before transfer due to an improvement in the heat sinking.

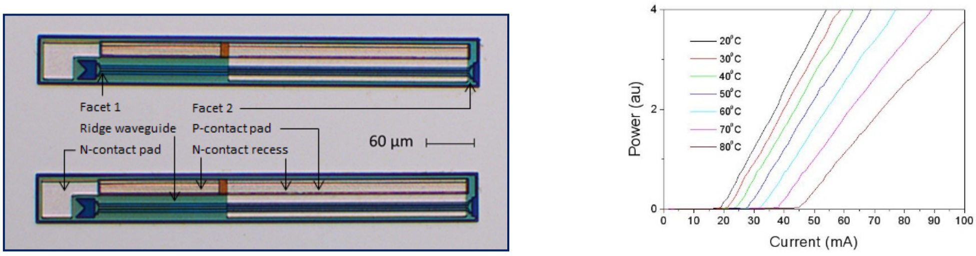

Figure 2. Optical image of transferred etched facet lasers on silicon (left) and temperature-dependent light-current characteristics of transferred 1550 nm ridge waveguide laser (right)

3. Integration with Si waveguide

We are developing a butt coupling approach where the lasers are to be aligned with respect to waveguides on a silicon photonic platform. This requires that there be alignment of the laser and silicon waveguides. The height dimension on the silicon side is controlled by the thickness of the buried oxide layer. A facet is etched at the waveguide end using a chrome mask with the etching stopped at the interface with the thermally-conductive silicon substrate. The laser waveguide height is then referenced with respect to this surface. To obtain the highest potential coupling efficiency the laser mode field should be matched to that of the Si waveguide. The lateral alignment of the laser relies on high contrast fiducials present on both the laser and on the target substrate. Figure 3 shows a schematic of the concept for the laser alignment together with an optical microscope image of the aligned laser. The laser is recessed from the waveguide facet by ~3 micron. The figure shows the spectrum from the laser when out-coupled using the grating on the waveguide.

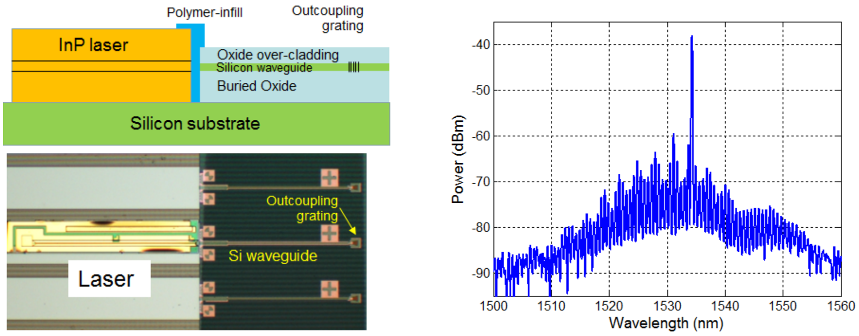

Figure 3. Schematic cross-section of heterogeneously integrated InP laser butt coupled to a silicon photonics platform; optical image of the printed laser aligned to Si waveguide and the outcoupled spectrum

4. CONCLUSIONS

The technology for transfer printing of InP based devices is being developed. Solutions for the transfer of many other thin and small materials can be achieved by engineering. Transfer printing has the potential to be a game changing technology for the heterogeneous integration of components for scalable smart photonic systems.

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