Nanoscale accurate heterogeneous integration of waveguide devices by transfer printing

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***Abstract* - The vertical micro-assembly of membrane photonic devices across a range of materials is presented, including polymers, silicon and III-V semiconductors. Fully-fabricated waveguide structures are integrated with sub-100nm absolute placement accuracy. Light-emitting diodes, silicon photonics and nanowire lasers are examples of the deployment of this technique.**

Keywords – Silicon-on-Insulator, Hybrid Integrated Circuits, Nano-positioning

I. INTRODUCTION

Since the initial demonstration of transfer printing (TP), a significant amount of effort has been applied to develop this methodology for high throughput heterogeneous device integration. The power of the technique lies in the ability to synthesize systems from building block devices [1] taken from a range of material platforms and integrated on a single chip. The post-fabrication nature of the technique means that devices can be fabricated in their respective foundries and integrated without the need for further critical processing stages. Typically, thin membrane devices are detached from their native wafers (donor substrates) using a polymethylsiloxane (PDMS) stamp and transferred to a host substrate with pre-patterned features. The transfer stamps can be fabricated to pick up arbitrary spatial arrangements of membrane devices from arrays, making it an inherently parallel method. Notable demonstrations of the technique include the fabrication of opto-genetic probes [2], micron-size light-emitting diodes and arrays [3, 4], lasers on silicon [5] and nanowire lasers integrated with polymer waveguides [6].

Thus far the absolute accuracy of the printing process has been limited to the micron range, i.e. the spatial alignment between pre-fabricated features on the transferred membrane and those on the host substrate [7]. In order to create micro-assembled, single-mode waveguide devices the alignment accuracy of the method is required to be in the 100 nm range to ensure controllable optical coupling. This requires two critical capabilities: (1) the ability to accurately reference the spatial position of structures on the donor and host substrates relative to one another and (2) the ability to transfer a membrane without relative motion to the stamp. The first condition can be met using advanced optical registration techniques. The second condition is particularly challenging when working with membranes with thicknesses in the hundreds of nanometers range.

In this work we present a highly accurate positioning system using a computer-aided overlay alignment technique. This capability is then used to demonstrate the integration of vertically stacked and optically coupled single-mode silicon micro-resonators, and free-standing III-V micro-disks side-coupled to silicon waveguides. These devices are enabled by a TP absolute positioning accuracy of 100 nm ± 70 nm, transfer of ultra-thin membranes and deposition without use of polymeric interlayers for adhesion.

II. EXPERIMENTAL AND RESULTS

The TP demonstrated here relies on a highly modified commercial dip-pen lithography system that provides 6 degrees of freedom. Typically, the linear stages are capable of ±25 nm repeatable precision over 40 mm travelling range, with a minimum of 5 nm encoder step, roll and pitch are by angular steps of ±25x10-5 ° and the yaw angle by 2x10-6 °. The stage stack is coupled to a microscope that serves to image the devices through the manipulating PDMS printing head (stamp). The entire system is computer controlled through a custom

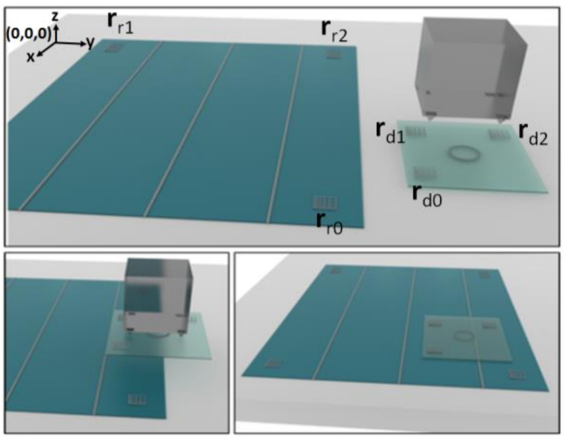

Fig. 1. Schematic of the TP process with referencing to the machine absolute coordinates, where $r_{ij} = (x_{ij},y_{ij},z_{ij})$

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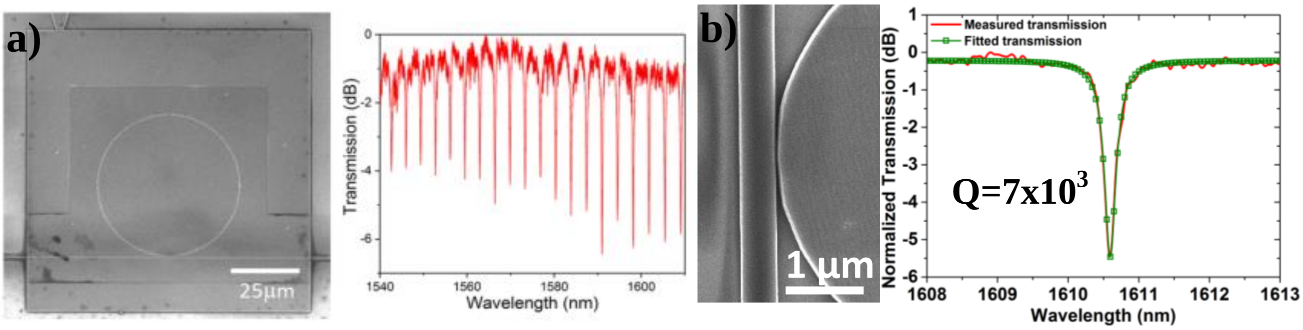

Fig. 2. a) Si ring resonator membrane TP onto SOI single-mode bus ridge waveguide demonstrating vertical evanescent coupling and corresponding transmission; b) III-V micro-disk resonator TP onto SOI bus waveguide with controlled coupling gap.

graphical user interface. During the TP process the PDMS stamp is used to pick up, carry over and release devices from the donor wafer onto the receiver surface. Pick up and release of devices relies on the competitive adhesion between the stamp, the device and the surface (donor or receiver) which can be further controlled using a reversible adhesion technique by topological structure of the stamp [1]. A computer aided overlap registration technique is used to reference marker structures (fig. 1) on the donor and receiver substrates to the spatial grid of the TP system. This then provides an absolute reference for transfer of membrane devices onto the host substrate. Fig. 1 gives a schematic overview of the alignment markers located on the membranes to TP for the donor and at specific locations on the receiver substrate.

The first demonstration of nano-scale accurate alignment of single-mode waveguides was realized using 500 nm wide silicon ridge waveguides. The donor and receiver silicon samples were fabricated using 220nm-thick silicon on a 2 µm SiO_2 buried oxide layer. Si membrane ring resonators were fabricated on SOI technology using ICP and e-beam lithography to pattern the resonator and HF vapor under-etching of the buried oxide to release the membrane. The 100 µm square membranes were held suspended on the donor wafer by sacrificial tethers that break once the membrane is picked up by the stamp head. Transferred ring resonators show transmission spectra with loaded Q-factors controllable by the lateral offset of the vertically coupled waveguides. Fig. 2.a) shows a SEM image of the 3D coupling of Si membrane 25µm-radius resonator over a Si bus waveguide and the wavelength dependent transmission spectrum of the ring, with the expected FSR of 4 nm.

Heterogeneous materials integration was then demonstrated by integrating III-V micro-disk resonators with single-mode silicon waveguides. The III-V wafer donor wafer consisted of a 270nm-thick AlGaAs (Al=30%) layer grown on GaAs substrate. The micro-disks were fabricated as free-standing devices on central pedestals using e-beam lithography and reactive ion etching to define the disk structure followed by a selective HF wet-chemical underetch process. The fully fabricated disks, with a radius of 5 µm, were then directly printed onto a silicon waveguide receiver chip. The disks were printed onto the buried oxide surface, adjacent to the silicon waveguide. In order to achieve adequate evanescent field coupling between the III-V micro-disk and silicon waveguide, the spacing between the structures must be in the 100 nm arrange. In addition, this placement accuracy has to be controllable to tune the coupling coefficients from one structure to the other. Fig. 2. b) shows a micrograph of the in-plane integration of a III-V micro-disk resonator with Si waveguide with a coupling gap of ~75 nm. The optical performance of the device is also shown in fig. 2. b), exhibiting a clear resonator mode at 1610.6 nm with a loaded quality factor of $7x10^3$, confirming optical coupling between the structures and the high quality of the III-V micro-disk resonator after the TP process.

III. Conclusion

The TP method is demonstrated with sub-100nm controlled absolute placement accuracies for the assembly of various materials into single photonic systems. Vertically coupled multi-layer, single-mode silicon devices and side-coupled III-V micro-disk resonators demonstrate control over absolute position placement in the 100 nm range. This technique is not limited to these material platforms and has already been applied to applications from flexible polymer waveguide technology to the integration of nano-wire laser with on-chip waveguide technology.

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