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Transferred III-V Materials - Novel Devices and Integration

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Abstract: Separating the substrate allows thin layers of III-V photonic semiconductor materials and devices to be integrated on foreign templates using transfer-printing. We demonstrate advanced light emitting and detecting devices based on this principle.
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1. Introduction

The most powerful photonic functionality benefits from the combination of different materials connected in appropriate ways. For communications, as an example, we need photonic circuits which can multiplex different wavelengths, provide high bandwidth signals and detect same. Monolithic integration of devices providing different functions on InP provides the highest performance circuits but is ultimately limited in scaling by circuit complexity allied to the size of InP wafers. Circuits based on Si-on-Insulator – 'silicon photonics' can provide the necessary scaling and cost reduction with increasing volume but has several serious limitations around signal generation which is best performed with III-V materials. Thus, a key challenge is to integrate the light source with the silicon photonic circuit. Epitaxial growth of the device is an appealing strategy and while progress has been made by using quantum dot active media or limited area epitaxy a reliable integration process has not been achieved yet. Successful approaches include flip chip mounting of lasers on the circuit or wafer-bonding and substrate removal to create evanescently coupled lasers [1]. Our approach is based on hybrid integration of optimised components (lasers, modulators detectors) with a target substrate (e.g. silicon photonics) using contact-printing. The strategy is to pre-fabricate devices and transfer the essential parts of these 'known good devices' from their native substrate to the new substrate based on the transfer printing technology [2,3]. Subsequently, it is possible to integrate the laser light with the following waveguides using a butt coupling approach. This allows the III-V materials to be produced in their optimum environment, uses only the minimum amount of material and overcomes wafer size mismatch issues. The transfer print technology permits massively parallel transfer of devices to the new substrate with micron scale alignment accuracy [4]. Here, we describe the technology for the preparation and transfer of the photonic materials and devices. Particularly, we discuss the realisation of transfer printed InP lasers, GaAs power converting cells and nanoscale, optically pumped AlGaInP lasers.

2. Transfer printing of InP based lasers

The transfer print process relies on the ability to define coupons (blocks of material or fully formed devices) on a native substrate, to hold them in place with a tethering system and to undercut the objects so that they retain their positions (Fig.1(a)). Following that, selected arrays of objects can be picked up with a structured elastomeric stamp and transferred to the new substrate in parallel and with high positional accuracy. This sequence needs to be designed and optimised for different materials sets. For the InP based structures needed for telecommunication wavelength lasers, we have developed a resist tethering together with a release layer inserted at the start of the epitaxial structure. The release layer and etch conditions need to provide very high selectivity with the surrounding layers and the tether material. A very smooth (nm scale) exposed surface is required for intimate contact in the subsequent transfer especially if an adhesive free contact is desired for electrical reasons. For laser objects with a width of 60 μm an etch selectivity of >1,000:1 is desired. This selectivity can be obtained with a 0.5 μm thick InGaAs layer surrounded by InP and etching in dilute $FeCl_3$ at low temperatures (2-8 °C) as shown in figure 1. The quality of the undercut (flatness and residual roughness) can be easily evaluated by measuring the properties of the residual stubs.

The pre-processed lasers require the use of etched facets to form Fabry-Perot resonators since cleaving of the facets is not realistic. This means that the laser cavities can be orientated independently with respect to the crystal axes facilitating the undercut etch which is typically faster in directions that are at 45° with respect to the natural cleavage planes. Figure 2 shows a SEM of a pre-processed, ridge

waveguide, etched facet laser before being prepared for transfer. Also shown is a Focussed Ion Beam (FIB) prepared cross-section of the laser following its transfer to a silicon substrate. The excellent bonding achieved without an adhesive layer is evident and is due to the flat mating surfaces and residual flexibility of the coupons which conform to the silicon surface. There is no degradation in the performance after transfer and continuous wave lasing is measured on these transferred devices [5]. The performance is dependent on the reflectivity created by the facet coatings which can be arranged to provide a high and low reflection output.

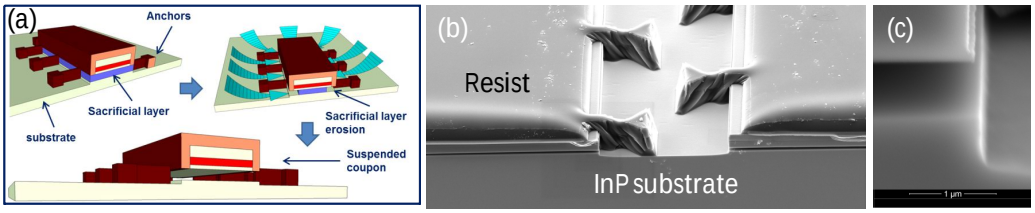


Fig. 1. (a) Schematic of the tethering and release process to leave coupons of devices ready for pick-up and transfer printing, (b) SEM image of InP laser coupons which have been undercut and held in place by resist tethers and (c) close-up of the undercut region.

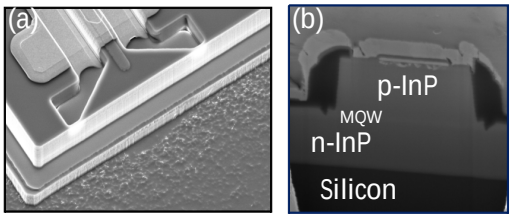


Fig. 2. (a) SEM image of the anisotropic etched laser facet, (b) FIB cross section of ridge section of pre-fabricated ridge waveguide laser after release and transfer bonding to a silicon substrate.

3. GaAs based power converters

Energy, delivered by light over optical fibre, will be useful in powering remotely operated nodes for sensing and communications applications or in environments where there electrical connections compromise the operation of the system such as high voltage environments or in the human body. By engineering the wavelength of the incident light with respect to the bandgap of the absorber material very high power conversion efficiencies (>60%) can be expected. Cells can be integrated using transfer printing providing a compact, low profile power supply. We are investigating GaAs based cells with active region from 50μm to 400μm in diameter with an overall chip dimension of ~ 500μm x 500μm. To achieve the deep undercut of the 2.65μm thick cells a 0.5μm thick lattice matched AlInP layer has been included. The GaAs structure is grown as p-on-n and cells are prefabricated on wafer. The release is performed with HCl diluted in H_2O or H_3PO_4 using thick resist tethering (Fig. 3). We have deposited Au-Ge-Ni on the backside of the array and then bonded the devices to an Au coated silicon substrate. The transferred coupons are measured to be flat.

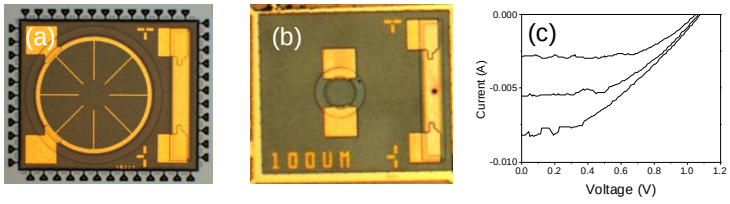


Fig. 3. (a) Optical image of tethered and undercut GaAs cell, (b) optical image of cell transferred to Au coated Si substrate and (c) measured characteristics of transferred device under illumination with fibre coupled 808 nm laser.

4. Submicron optically pumped red lasers

Nanophotonic devices can also benefit from active layers being transferred from a growth substrate to well defined environments. We have investigated reducing the size of red emitting lasers to sub-micron dimensions by using plasmonic effects to confine the optical modes. Pure dielectric confinement fails

when the dimensions of the resonator become less than 1 μm. To engineer such resonators, we have transferred a pre-structured gain medium to a plasmonic surface comprising of a thin (6 nm) Al_2O_3 layer on an Ag coated substrate. The gain medium is 110 nm thick comprising of a 50 nm thick unstrained GaInP active layer clad by wider bandgap AlGaInP layers. The spacer on the metal side is only 20 nm to enable the interaction of the optical mode with the plasmonic confinement. A 100 nm thick $Al_{0.75}Ga_{0.25}As$ layer was incorporated at the start of the structure to act as an etch stop. Structures with minimum dimensions from 300 nm to 2 μm were created by electron beam lithography using HSQ resist and subsequent dry etching. In this case, the active structures were separated by etching the substrate and then transferred to the plasmonic surface. We have measured optically pulsed lasing in rod, disk, ring, and square shaped cavities with submicron dimensions [6]. The 50 nm thick active layer results in high overlap with the hybrid photonic-plasmonic mode that is needed to compensate for the loss in such small cavities. Figure 4 shows the evolution of the lasing spectrum in a in a 450 nm × 490 nm oval disk with threshold pump energy (1.4 mJ/cm^2). The close connection to the substrate enables excellent thermal dissipation. It is feasible to develop a tethering arrangement for transfer printing of such structures to precise locations which will allow the possibility to electrically pump such lasers. It will be essential to minimise surface leakage and associated non-radiative recombination.

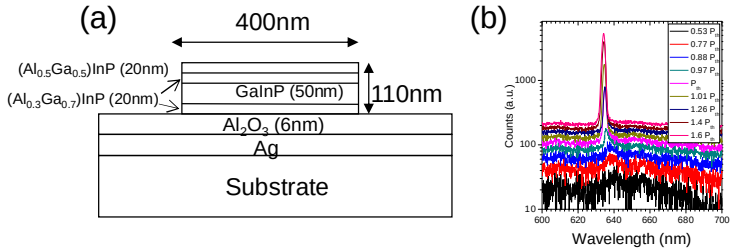


Fig. 4. Schematic of III-V gain medium integrated with plasmonic surface and (b) evolution of the emission spectrum from a 450 nm × 490 nm, 110 nm thick oval shaped cavity under pulsed optical excitation.

5. Conclusions

We have shown that a wide variety of III-V based active photonic materials components can be engineered for their separation from the native substrate and printed on a locally flat host substrate. These transferred devices have low profile permitting global heterogeneous interconnection with other functional components. This technology will be a valuable enabler for smart system integration.

6. Acknowledgements

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