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Integration of Quantum Dot Lasers with SOI Waveguides using Micro-Transfer Printing

(Student paper)

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We demonstrate the integration of long (2.4 mm) 1.3 µm etched facet quantum dot (QD) laser diodes into 7 µm deep recesses on an SOI wafer by micro transfer printing (µTP). Inverse tapered waveguide couplers were used to edge-couple the light from the QD laser to the 220 nm thick Si waveguide layer. Characterization exhibits that the QD lasers with 2 mm cavity length have threshold currents ~20 mA with output powers above 10 mW at 80 mA. A waveguide-coupled power of ~1mW was obtained.

Keywords: *Butt Coupling, Quantum Dot Laser Diodes, Silicon Photonics, transfer printing*

INTRODUCTION

Si-based photonic integrated circuit (PIC) platforms provide a powerful route to scaling the performance (bandwidth, energy consumption) of optical transceivers while reducing the manufacturing cost [1]. These circuits require integrated light sources which introduces co-integration challenges. Several integration approaches have been explored including wafer/die bonding [2-3], flip chip technique [4] and micro-transfer-printing (µTP) [5-6] for wafer level integration of devices such as laser diodes, modulators, and photodetectors. Each technique has its own advantages and drawbacks. We achieve integration through edge-coupling the laser via µTP inside recesses to the waveguide, which offers high throughput, parallel device integration and the opportunity of pre-integration testing.

The target recesses are 120 µm wide and 2.5 mm long on a silicon-on-insulator (SOI) wafer, Fig. 1(a). 7 µm deep trenches are formed with two etch steps. The receiving Si waveguides with single inverse tapered tip (Fig.1(a) inset) are designed and fabricated on the imec 220 nm silicon photonics platform with a 2 µm buried oxide and a 5 µm SiO_2 over-cladding (Fig. 1(b)). An edge coupling efficiency of above 60% (-2 dB) for the quantum dot waveguide is simulated for the laser mode with a lateral and vertical misalignment tolerance of ± 1.3 µm and ± 0.5 µm respectively, for a -3 dB coupling penalty as shown in Fig. 2(a). The vertical tolerance is rather smaller than that in the horizontal direction as a result of the strong vertical mode confinement in the QD region. In addition, the longitudinal spacing between the laser facet and receiving Si waveguide has a 5 µm -3 dB coupling tolerance with an in-fill refractive index of 1.5 as given in Fig. 2(b).

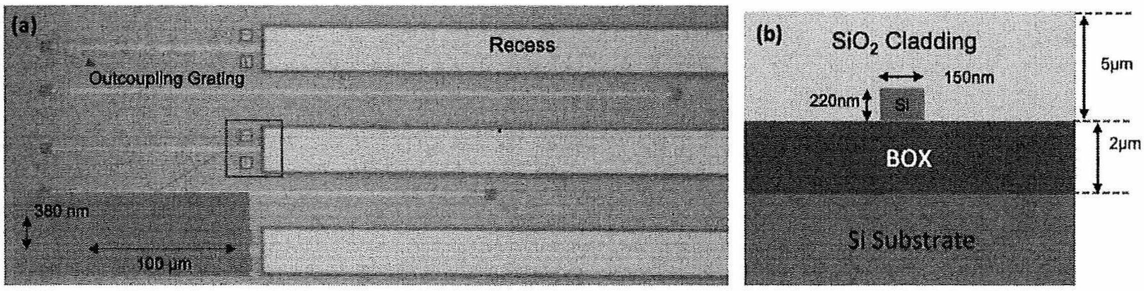

Fig. 1.a) 2.5 mm long and 120 µm wide recess on SOI wafer (Inset: schematic of Si waveguide coupler inverse tapered from 150 nm to 380 nm over 100 µm distance) and b) Cross section of a single tip inverse taper coupler design.

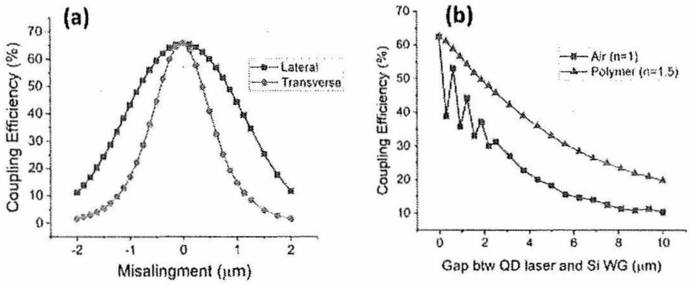

Fig. 2.a) Lateral and transverse misalignment tolerance simulation for an inverse single tapered waveguide, and b) Longitudinal tolerance as a function of spacing and refractive index of filling material.

The GaAs QD laser coupons were designed to be 65 µm wide with physical lengths of 1.5 mm, 1.8 mm, and 2.4 mm (corresponding laser cavity lengths in these coupons are 1 mm, 1.5 mm, and 2 mm, respectively) including bond pads for probing the devices. Laser devices were fabricated based on an epitaxial structure grown by Innolume that contains an active region comprising of a stack of 14 InAs QD layers separated by GaAs spacers. The waveguide is clad by 1.2 µm thick p- and n- doped AlGaAs layers. After device formation, encapsulation and tether definition, laser coupons were released using diluted HCl by selectively etching an $Al_{0.95}Ga_{0.05}As$ sacrificial layer which was added to the epitaxial structure in between the substrate and the n-GaAs layer in order to permit the release of the device from the native wafer. The suspended QD laser coupons then were transfer-printed into the deep recess containing 100 nm spray-coated Benzocyclobutene (BCB) by EVG prior to printing. The fabrication and integration flow is depicted in Fig. 3.

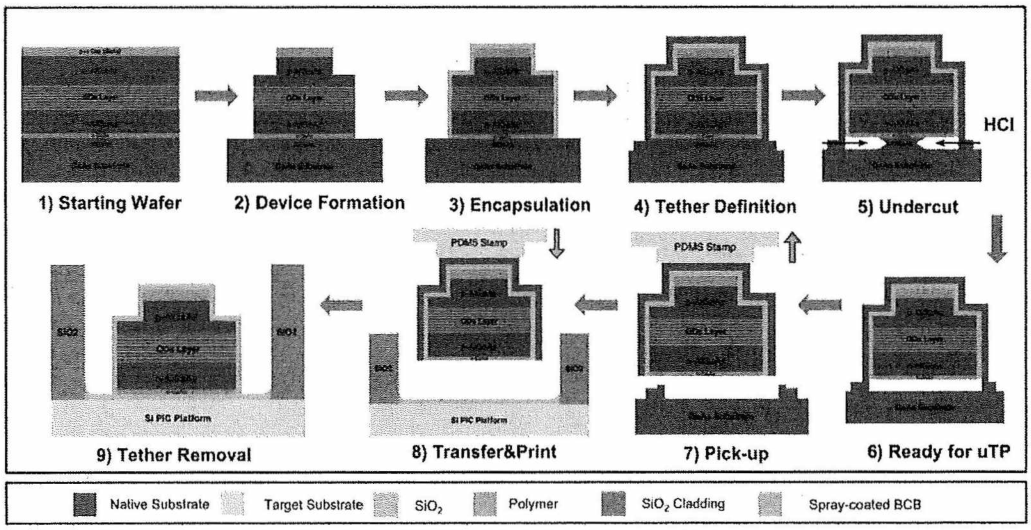

Fig. 3. Device fabrication flow on an epitaxial structure including an AlGaAs release layer (1-2). Coupons were encapsulated by SiO_2 for facet and epitaxial structure protection during release etch (3). A polymer (resist) anchor system (4) keeps coupons in place during sacrificial layer etch by HCl:DI (5). Then, devices are picked-up by a PDMS (Polydimethylsiloxane) stamp (7) and transfer-printed into 7 µm deep Si recess (8). Finally, the resist tethers were removed for electrical connection (9).

RESULTS and ANALYSIS

QD laser coupons up to 2.4 mm long were transfer printed with high yield (>90%) on both flat Si substrates and in the trenches on the SOI target, Fig. 4(a). In order to evaluate the device performance after release and transfer, laser diodes printed on flat Si coated with 1 µm Intervia were characterized under continuous wave (CW) conditions. Light-Current-Voltage (LIV) characteristics showed that laser can deliver an output power > 10 mW at 80 mA with an 18 mA threshold current, Fig. 5(a), which confirms that there is no degradation (i.e. threshold current) after printing. At 150 mA more than 20 mW is obtained. The emission wavelength is measured to be 1290 nm, Fig. 5(a) inset. The waveguide coupled edge-emitting transfer-printed lasers were characterized under CW using the setup depicted in Fig. 4(c). Up to 250 µW light coupling to the receiving single mode fiber is measured from the waveguide with single tip inverse taper design (Fig. 5(b)) with a 1.8 mm long laser coupon with threshold current 25 mA. The slight increase in the threshold current is because of the polymer in-fill between the QD laser and Si coupler which reduces the facet reflectivity. As the coupling loss due to the grating and fibre is ~6 dB, a waveguide power of 1 mW is estimated. Considering the amount of power that the laser is capable of producing, waveguide coupled light suffers from misalignments due to tight tolerance of edge-coupling in lateral, longitudinal and transverse direction. The main reason for the low power is the longitudinal misalignment of > 5µm as measured in SEM image (Fig. 4(b)).

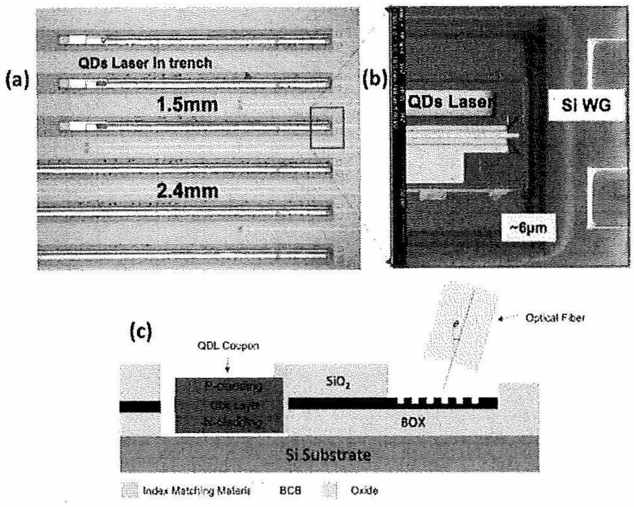

Fig. 4. a) Optical image that shows QD laser coupons >1.5 mm length transfer-printed into a deep trench on SOI, b) SEM image of a laser coupon inside a recess next to a Si waveguide coupler and c) Edge coupling schematic describing light coupling from laser to Si waveguide and from Si grating to fiber.

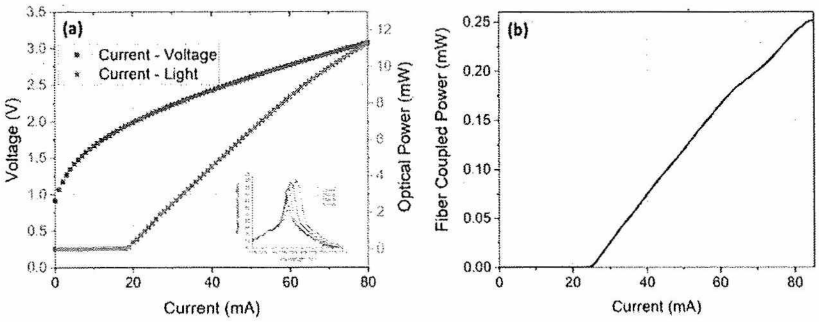

Fig. 5. a) LIV plots of a transfer printed 1.8 mm QD laser on 1 µm Intervia on Si (Inset: spectrum at different bias current) and b) Current versus coupled light into the Si waveguide from a 1.8 mm long laser coupon.

CONCLUSION

Integration and waveguide coupling of low threshold and high efficiency edge-emitting QDs laser coupons was demonstrated. QD laser devices longer than 1.5 mm showed a threshold current of 20 mA with output power above 10 mW at 80 mA. 250 µW of light is measured from the outcoupling grating to a single mode fiber and it is expected that much higher powers in the Si waveguide are achievable with optimum positioning of the laser.

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