Micro-transfer-printed O-band GaAs QD-on-Si DFB Laser on an advanced silicon photonics platform

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We present wafer-scale micro-transfer printing of III-V devices on an advanced silicon photonics platform. Following this process flow, a GaAs QD-on-Si DFB laser is demonstrated. The resulting device exhibits single mode operation at 1300 nm with about 0.7 mW single-side waveguide-coupled output power and a side-mode-suppression-ratio of 44 dB at 40 °C.

Keywords: *Silicon Photonics, Micro-Transfer Printing, Distributed Feedback Laser*

INTRODUCTION

Silicon photonics (SiPh) attracted renewed interest in the past decades due to its great potential for the realization of powerful and energy-efficient photonic integrated circuits (PICs) with compact sizes. By taking the advantages of mature CMOS industry, complex silicon PICs can be manufactured on 200 mm or 300 mm wafers at low cost with guaranteed yield. However, the integration of low-cost integrated laser sources on Si wafers remains a challenge due to the poor light-emission properties of Si. III-V semiconductors are suitable for light emission in different wavelength ranges due to their direct and adjustable bandgaps. In recent years, III-V quantum dot lasers (QD lasers) have attracted extensive interest due to their superior characteristics, such as high temperature stability, low linewidth enhancement factor, high flexibility in gain bandwidth and emission wavelength engineering, etc. [1]. Different approaches have been developed to combine the best of III-V materials and Si. Multiple die-to-wafer bonding is one practical solution and has been commercialized for the manufacturing of optical transceivers in the past few years, but it requires significant modification to the established Si backend process flow. Hetero-epitaxial growth exhibits significant potential for the integration of III-V devices, especially III-V QD devices due to its lower sensitivity to defects, on SiPh wafers [1]. However, several challenges, such as the leveling between III-V and Si layers, imperfect material quality, etc. still remain to be addressed. In this work, we present the integration of III-V devices on advanced SiPh wafers using micro-transfer printing (µTP) [2]. Following this approach, an O-band GaAs QD DFB laser is integrated on the imec isipp50g platform [3]. The resulting device exhibits single mode operation around 1300 nm at 30 °C. The maximum single-side waveguide-coupled power is measured to be over 0.7 mW.

MICRO-TRANSFER PRINTING

Micro-transfer printing became popular in both academia and industry in recent years. By using a Polydimethylsiloxane (PDMS) stamp, prefabricated device coupons released on the source substrate can be picked up and printed on to a SiPh target wafer one by one or in a massively parallel manner. This process can be fully automated, and the resulting alignment accuracy is up to (<1 µm @ 3σ) or even better depending on the size of the manipulated device arrays. A µTP experiment was first carried out on an industrial µTP tool, where an 8-inch SiPh wafer with pre-defined recesses and InP devices coupons (Fig. 1(a)) were used respectively as the target substrate and the source devices. The sizes of the recesses and the InP coupons are 100 µm X 1600 µm and 45 µm x 1400 µm, respectively. A set of fiducial markers are used to facilitate the automatic alignment by using a pattern recognition function integrated in the µTP tool. 160 coupons were printed one-by-one in an automatic manner. Fig. 1(b) shows an array of transfer-printed InP coupons on the target wafer. The fiducial markers and the recess are shown in Fig.1(c). As depicted in Fig. 1(d) and (e), less than 1 µm misalignment are achieved in both longitudinal and lateral directions for all printed coupons.

PROCESS FLOW OF THE MICRO-TRANSFER PRINTING OF GaAs QD DEVICES

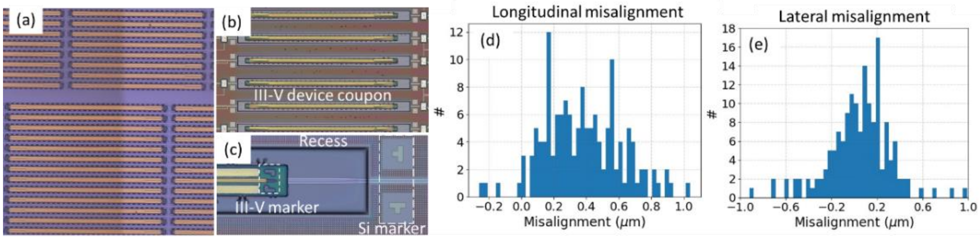

Fig. 1(a) Microscope image of the released InP SOA arrays on a source wafer, (b) An array of micro-transfer-printed InP SOAs on an 8-inch SiPh wafer, (c) Zoomed-in microscope image showing a transfer-printed InP OSA and the alignment makers.

Following the demonstration of micro-transfer-printed GaAs QD-on-Si DFB lasers in [4], an optimized process flow for the integration of GaAs QD lasers on advanced SiPh platforms is developed, as descripted in Fig. 2. The first few steps (Fig.2(a)-(c)) are the same as those explained in Ref. [4]. After the n-contact metal deposition the GaAs QD rib waveguide is passivated with a SiN layer (Fig.2(d)), which is also used as a hard mask to define the first coupon mesa by etching into the GaAs substrate. The coupon mesa is then encapsulated with a thick SiN and a thin SiOx layer (Fig.2(e)). After planarizing the III-V waveguide structures using a thick BCB layer and p-contact metal deposition, the second coupon mesa is defined by RIE etching to expose the SiN layer around the first coupon mesa (Fig.2(f)). After patterning the tether structures in the exposed SiN layer with a photoresist soft mask, the coupons are ready to release (Fig.2(g)). A 15 °C 1:1 37% HCl:DI solution is used in this work (Fig.2(h)). Fig. 2(i) shows the schematic of a SiPh substrate with pre-defined recesses. A spray coating process is applied to deposit about 60 nm DVS-BCB in the recess (Fig.2(j)). Prior to µTP process, the SiPh substrate is baked at 150 °C for 15 minutes. A PDMS stamp with a single post of 60 µm X 1800 µm is used to print the coupon (Fig.2(k,l)). The post-transfer printing processing includes photoresist encapsulation layer removal, BCB curing, and metal deposition (Fig.2(m)).

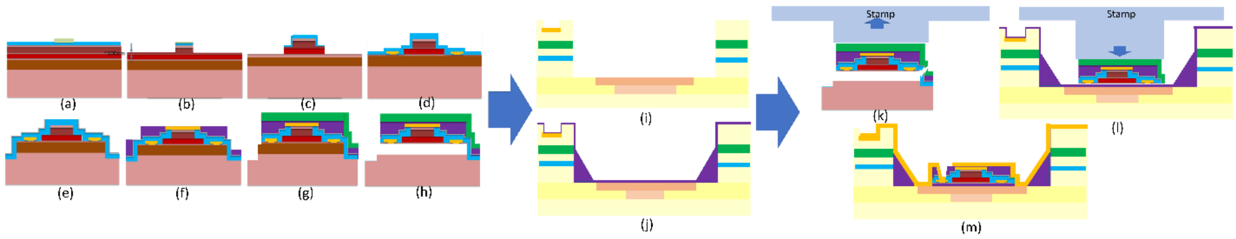

Fig. 2. Full process flow for the integration of GaAs QD devices on an advanced SiPh platform. (a-c) Rib waveguide definition, (d) n-contact metal deposition, (e) the first coupon mesa definition and SiN encapsulation, (f) the second coupon mesa definition, (g) tether definition, (h) release etch, (i) target SiPh wafer with pre-defined recesses, (j) DVS-BCB spray coating, (k) pick-up GaAs device using a PDMS stamp, (l) µTP GaAs SOA into the recess, (m) final metallization.

DESIGN AND FABRICATION OF GAAS QD-ON-SI DFB LASER

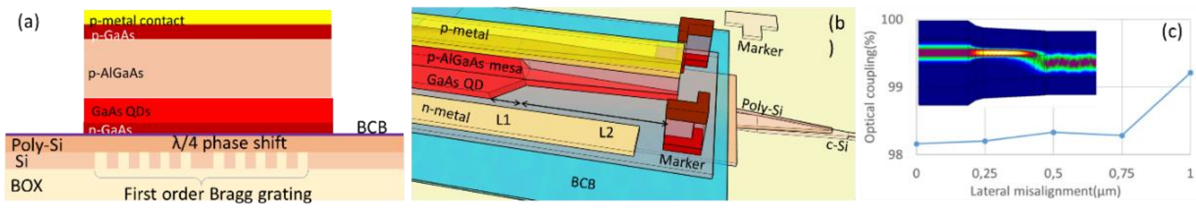

Fig. 3.(a) Schematic of the GaAs QD-on-Si DFB laser, (b) Schematic of the alignment-tolerant III-V/poly-Si/Si taper structure, (c)Simulated coupling efficiency as a function of lateral misalignment.

The Si waveguide circuits consists of a 220 nm thick crystalline Si device layer, a 160 nm thick polysilicon (poly-Si) overlay layer and a multiple-layer backend stack, which is opened locally over the DFB laser cavity to allow for close contact of the III-V layer to the exposed poly-Si layer. The GaAs QD/Si DFB laser cavity is schematically depicted in Fig. 3(a). The III-V/Si hybrid waveguide structure consisting of a GaAs QD rib waveguide and an underlying poly-Si/Si waveguide. The major design of the GaAs QD waveguide structure was kept the same as in Ref. [4], but a 1 µm thick p-$Al_{0.8}Ga_{0.2}As$ cladding and a 350 nm thick n-GaAs contact layer are used in this work. The Bragg grating is defined in a 9 µm wide crystalline Si layer with a 40 µm wide poly-Si layer on top. The length, period and duty cycle of the grating are 1 mm, 205 nm, and 50 %, respectively. A III-V/poly-Si/Si taper structure is used at each side of the laser cavity to couple the light to the underlying poly-Si/Si hybrid waveguides and then the Si wire waveguides, as shown in Fig.3 (b). With a 340 µm (L1=90, L2=250) long III-V/poly-Si/Si taper structure, efficient optical coupling with excellent lateral alignment tolerance (>1 µm) can be achieved for the case of a 30 nm thick DVS-BCB bonding layer, as shown in Fig.3 (c).

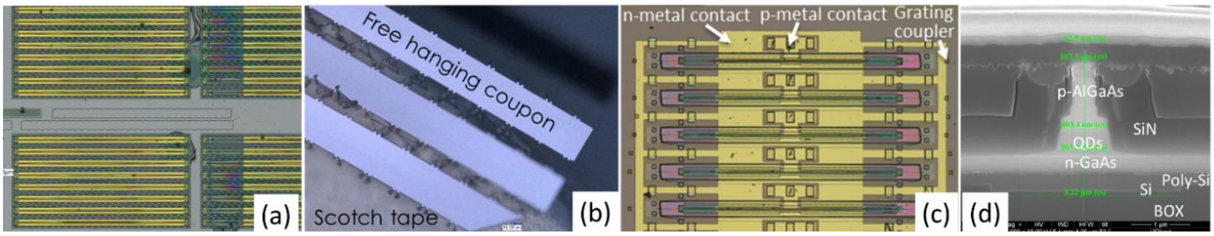

Fig. 4. (a) Microscope image of the released GaAs device coupons,(b) Bottom surface of the released coupons, (c) An array of DFB lasers with metal-contact pads,(d) Focused Ion Beam cross section at the taper section, showing a perfect alignment.

Fig. 4(a) shows a microscope image of a source wafer after release etching. The size of the coupons is 55 µm x 1700 µm. Smooth and defect-free bottom surface is observed under microscope, as shown in Fig. 4(b). The µTP process was carried out using an X-Celeprint µTP-100 lab-scale tool at room temperature in the cleanroom of Ghent university. Fig. 4(c) shows the resulting DFB lasers with metal contact pads. Fig. 4(d) shows a FIB cross section at the III-V/poly-Si/Si taper section. The thickness of the resulting DVS-BCB bonding layer is around 20 nm and the alignment is almost perfect.

CHARACTERIZATION

The resulting GaAs QD-on-Si DFB lasers were characterized on a vertical setup, which consists of a temperature-controlled stage, a pair of single mode fibre probes, a Keithley current source, a pair of DC probes, an HP power meter and an optical spectrum analyser. Fig. 5(a) shows the measured current-voltage curve, which shows a differential resistance of 4.6 Ω at 150 mA. Fig. 5(b) shows the recorded light-current curve, which reveals a threshold current of 65 mA and close to 0.7 mW single-side waveguide-coupled power. The abrupt fluctuation of the optical power indicates the existence of strong parasitic reflections. Fig. 5(c) shows a set of laser spectra at different bias levels. The measured device exhibits single mode operation around 1300 nm with 44 dB side-mode-suppression-ratio (SMSR). The sharp spurs shown in the DFB stopband also verifies the parasitic reflections to the laser cavity.

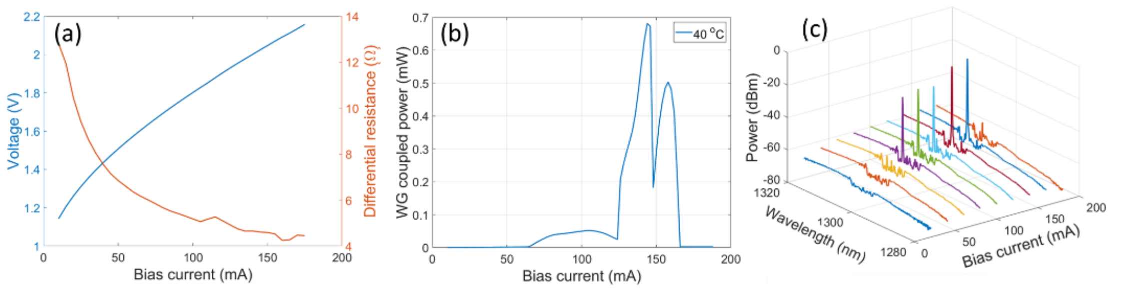

Fig. 5. Performance of a representative GaAs QD on Si DFB laser at 40 ℃, (a) V-I curve and differential resistance, (b) P-I curve (c) Superposition of the output spectra with the increase of the applied bias current.

CONCLUSION

We demonstrated the µTP of 160 InP devices on an 8-inch SiPh wafer with <1 um alignment accuracy using an industrial µTP tool and developed a full process flow for the µTP of GaAs QD devices on advanced SiPh platforms. Following this process flow, a GaAs QD-on-Si DFB laser operating at 1300 nm with 44 dB SMSR is demonstrated. This work paves the way for the realization of III-V-on-Si devices/circuits on SiPh wafers using µTP.

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