III-V-on-silicon nitride narrow-linewidth tunable laser based on micro-transfer printing

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Abstract: We demonstrate a narrow-linewidth tunable laser through micro-transfer printing a pre-fabricated III-V gain section on imec's 200-mm Si/SiN platform. Lasing in distinct bands in the C+L band is demonstrated, with linewidth down to 2.87-kHz. © 2023 The Author(s)

1. Introduction

With the rapid progress of integrated photonics in past decades, large-scale devices comprising thousands of components, heterogeneous integration between different material systems and the integration of high-performance CMOS electronics with multifunctional photonic integrated circuits have all been realized. The advantages of integrated photonics are gradually generating new application areas and re-inventing existing areas, like quantum computing, neurophotonics, LiDAR, biosensing, etc. Those applications in turn raise the performance requirements of the integrated photonics in many aspects. Owing to the lower propagation loss, higher on-chip optical power handling capability, wider transparency wavelength range and lower sensitivity to fabrication errors, silicon nitride photonic integrated circuits are emerging for better performance and extended application areas [1].

For silicon nitride photonics, heterogeneous integration of III-V gain elements is one of the most critical steps to fully reveal its advantages. However, due to the large refractive index mismatch between III-V active devices and silicon nitride waveguides, this integration is still challenging. To overcome this, a multilayer III-V/Si/Si_3N_4 structure based on wafer bonding has demonstrated [2]. A combination of butt coupling and evanescent coupling through an intermediate dielectric waveguide has also been demonstrated [3]. Our group has proposed using a plasma-enhanced chemical vapor deposition (PECVD) hydrogenated amorphous silicon (a-Si:H) interlayer to bridge the Si_3N_4 and III-V and demonstrated a heterogeneously integrated amplifier and a ring laser by means of micro-transfer printing [4]. In this work, we present the use of micro-transfer printing of pre-fabricated III-V gain elements for the realization of a narrow linewidth tunable laser on imec's 200 mm low pressure chemical vapor deposition (LPCVD) Si_3N_4 platform. Making use of high-Q ring resonators and low loss waveguides on Si_3N_4, kHz-level linewidths are obtained in the 1550 nm wavelength range.

2. Micro-transfer printing of pre-fabricated InP gain section on the imec 200 mm Si_3N_4 platform

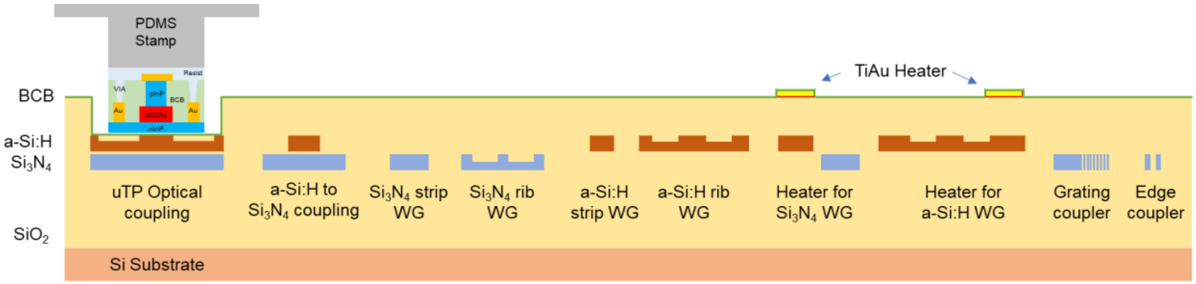

Fig. 1 A schematic view of micro-transfer printing of pre-fabricated III-V components on the Si_3N_4 platform

Fig. 1 depicts a schematic view of the main building blocks on the Si/Si_3N_4 platform. A 400-nm-thick Si_3N_4 was deposited on the silicon substrate through LPCVD on 3.2-μm thermal oxide. After pattern definition on the Si_3N_4

layer and planarization, a 100 nm silicon oxide (SiO_2) interlayer and a 330-nm-thick PECVD a-Si:H layer were deposited which was subsequently patterned (both rib and strip waveguide structures) and planarized by chemical mechanical polishing. After that, another 1.1-µm SiO_2 was deposited on top. Heaters were then fabricated to tune the refractive index of a-Si:H and Si_3N_4 waveguides. Finally, a local recess was opened and the pre-fabricated InP-based gain section was transfer-printed inside the recess to allow optical coupling between the III-V and the a-Si:H/Si_3N_4 waveguides. The detailed two-stage evanescent optical coupling structure from Si_3N_4 to III-V can be found in [4]. A 25-nm-thin DVS-BCB layer was spray-coated on the target wafer prior to the micro-transfer printing process to enhance the bonding strength.

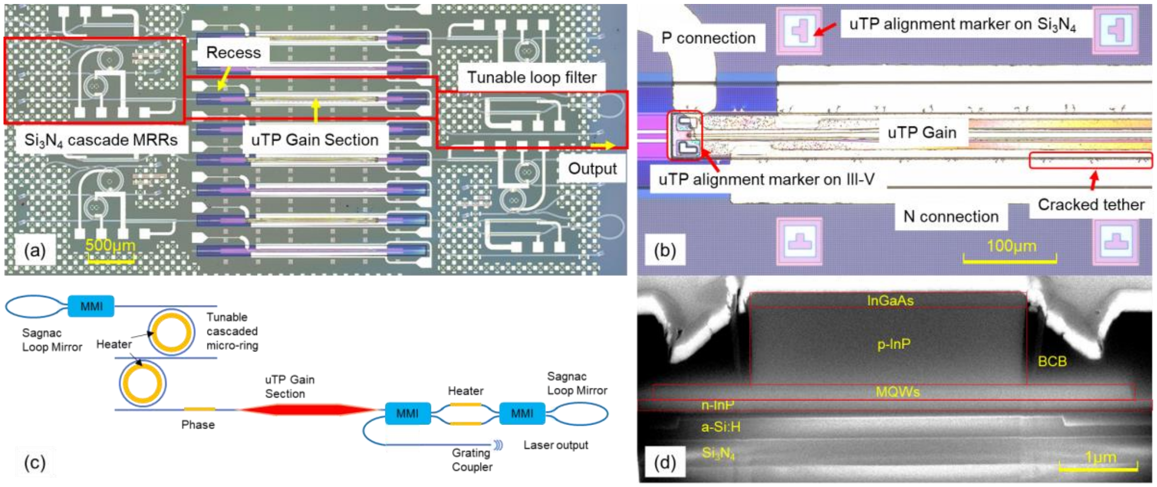

Fig. 2 (a) Microscope picture of the III-V on Si_3N_4 tunable laser chip. (b) A zoom-in view of the transfer-printed III-V gain section on a-Si:H/Si_3N_4 waveguides. (c) A schematic view of the tunable laser cavity structure. (d) SEM image of a cross section of a micro-transfer printed III-V gain element on a-Si:H/Si_3N_4 waveguides. (MRR: micro-ring resonator, uTP: micro-transfer printing, MMI: multimode interference coupler)

Fig. 2 (a) and (c) show a microscope picture of the proposed tunable laser and the corresponding schematic view. In the laser cavity, one mirror comprises two tunable cascaded add-drop micro-ring resonators (MRRs) with a total reflection loop mirror, which realizes both longitude mode selection and wide tuning range through the Vernier effect. The two MRRs have slightly different ring radius of 100 um and 107.45 um, where the combined free spectral range (FSR) is around 26 nm. A measured loaded-Q-factor of around 46,000 is achieved on the 1- µm-wide waveguide and 600-nm-gap MRR. The lasing mode will pass through the MRRs twice per round trip, further enhancing the mode selection ability and increasing the photon lifetime. The other mirror consists of a tunable Mach–Zehnder interferometer (MZI) coupler with a loop mirror. The reflectivity (and hence the threshold and slope efficiency) can be optimized for different operation wavelengths by controlling the phase difference of the MZI arms. Passive components in the laser cavity, containing MRRs, MMIs, loop mirrors and grating couplers were made in the Si_3N_4 layer.

Fig. 2 (b) shows a zoom-in microscope image of a transfer printed III-V gain section (fabricated by III-V Lab) on the a-Si:H/Si_3N_4 waveguide in a recess. The printing process was completed by an X-Celeprint µTP-100 lab-scale printer using a polydimethylsiloxane (PDMS) stamp with a post of 50 µm by 1400 µm. A scanning-electron microscope (SEM) image of a focused ion beam (FIB) cross section of the integrated device after transfer printing is given in Fig. 2 (d). The III-V layer stack contains an n-InP cathode, six-pairs of InGaAlAs quantum wells and barriers, a pair of separate confinement heterostructure layers, a p-InP layer and an InGaAs contact layer. The ridge width of the III-V waveguide is 4 um and the underneath a-Si:H waveguide is 5.5 um. The III-V ridge structure, p- and n-side metals, as well as vias for metal fan-out were pre-fabricated on the InP substrate, which also gives a possibility of measurement of the III-V source wafer prior to integration of the gain elements. After micro-transfer printing, just one step of metal fan-out is needed.

3. Device characterization

The heterogeneously integrated tunable laser was electrically contacted through DC-probes on a temperature-controlled stage. The operation temperature was set to 16 ^oC and controlled by a thermo-electric cooler (TEC). Fig. 3 (a) shows a typical measured power-current-voltage (LIV) curve. The differential resistance is 12 Ω for a 1200-

um-long gain section, which contains a 180-um taper on each side. The fiber coupled output power is 0.36 mW at 124-mA injection current. It should be noticed that the output power contains a -6.2 dB coupling loss of the grating coupler on the Si_3N_4 layer probed by a cleaved standard single-mode fiber. Fig. 3 (b) shows optical spectra in distinct bands in the C+L band that were realized by thermally tuning the two MRRs and slightly adjusting the tunable loop mirror. It can be seen that the continuous tuning range is separated in three parts which corresponds to three Vernier periods. Due to the limited power handling of the heaters, each MRR can only be tuned for about half a FSR in the current experiment, which limits the continuous tuning range. Thanks to the additional mode selection through the gain spectrum and tunable loop mirror, single mode lasing is achieved in three different Vernier periods and a side mode suppression ratio (SMSR) > 40 dB is achieved over the whole tuning range. The frequency noise of the laser is measured using an OEwaves OE4000 laser noise analyzer. The measured frequency noise spectrum at 1571.25 nm is shown in Fig. 3 (c) and the insert shows a zoom-in view of the spectrum from 10 MHz to 50 MHz. The obtained white-noise-limited frequency noise level is 910 Hz^2/Hz, giving a Lorentzian linewidth of 2.87 kHz. The linewidths over the whole tuning range are below 30 kHz as shown in Fig. 3 (d).

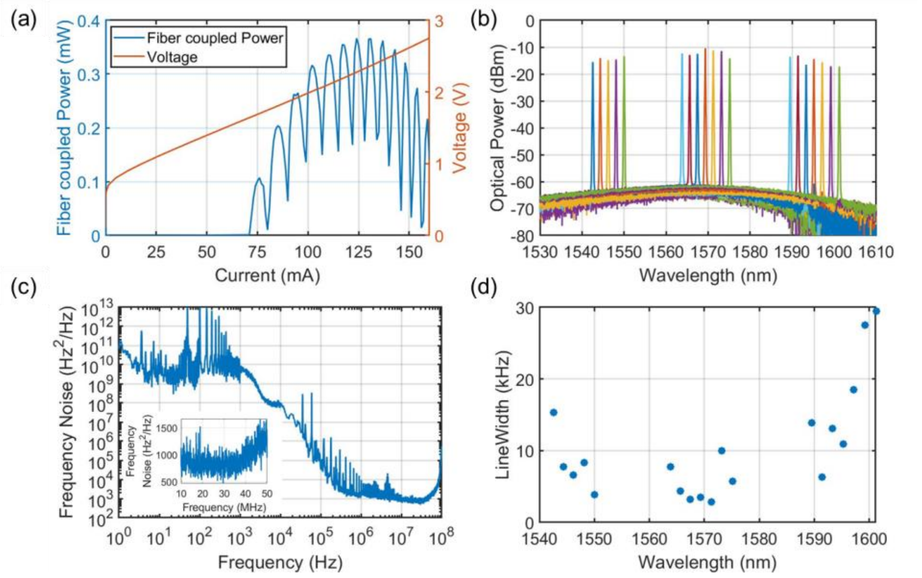

Fig. 3 (a) Fiber-coupled LIV curve of III-V on Si_3N_4 tunable laser. (b) Optical spectra under different operation wavelengths. (c) Laser frequency noise spectrum at 1571.25 nm (inset: zoom-in view of the spectrum from 10 MHz to 50 MHz). (d) Lorentzian linewidths as a function of wavelength.

4. Conclusion

We demonstrate a heterogeneously integrated narrow-linewidth tunable laser on imec’s 200 mm silicon nitride platform through micro-transfer printing. Lasing in distinct bands in the C+L band is demonstrated, with linewidth down to 2.87-kHz. By using a pre-fabricated III-V gain section, the quality control of both the III-V and Si_3N_4 in its own foundry is possible, which would greatly impact the integration yield and pave the way for large scale integration.

5. Acknowledgement

This work was supported by the European Union’s Horizon 2020 research and innovation programs under agreement No. 101017088 (INSPIRE), No. 8225453 (CALADAN) and No. 871345 (MEDPHAB).

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