Interband Cascade Laser on Silicon

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***Abstract*—We demonstrate the first interband cascade lasers heterogeneously integrated with silicon waveguides. The 3.6 µm wavelength lasers operate in pulsed mode at room temperature, with threshold currents as low as 394 mA.**

I. INTRODUCTION

Because numerous chemicals display strong fingerprint absorption features in the mid-infrared (MIR) wavelength regime, ~2-20 µm, MIR silicon photonics has attracted significant attention as a potential platform for inexpensive and compact sensing packages. Following recent demonstrations of optical components, detectors, and light sources [1] operating on silicon, the technology now appears ready for the next step of combining elements into a fully-integrated MIR photonic integrated circuit.

Active elements can be heterogeneously integrated by bonding III-V layers above silicon waveguides. This technique, which allows the optimal laser technology to be chosen for each application, has already been used to integrate light sources spanning 1.3-4.8 µm. We previously reported the integration of silicon waveguides with diode lasers and amplifiers operating near 2.0 µm [1]. Most recently, we demonstrated the integration of InP-based quantum cascade lasers (QCLs) emitting near 4.8 µm on a silicon-on-nitride-on-insulator (SONOI) waveguide platform. Fabry-Perot [2] devices emitted peak powers up to 31 mW from a silicon facet in pulsed mode at room temperature, and distributed feedback [3] QCLs emitted 211 mW from a hybrid III-V/Si facet with threshold current densities < 1 kA/cm^2. Those devices continued to operate up to 100 ºC.

However, there have been no previous reports of GaSb-based interband cascade lasers (ICLs) [4] bonded to silicon. Because ICLs operate in the 3-6 µm spectral band, with drive powers 1-2 orders of magnitude lower than QCLs, they are expected to play a central role in future on-chip sensing technologies. Although integrating GaSb-based devices with silicon presents special fabrication challenges, here we report the first successful operation of ICLs bonded to silicon. Tapered couplers transfer the 3.6-µm light, which is generated in a hybrid III-V/Si gain section, into silicon waveguides.

II. DESIGN

Figure 1(a) shows a schematic of the heterogeneously integrated ICL, which consists of a Fabry-Perot cavity formed between two polished Si facets. An ICL mesa above the Si waveguide forms a hybrid III-V/Si active region, while III-V tapers on both sides of the mesa couple the optical mode in the active region into passive Si waveguide regions. Figure 1(b) shows a scanning electron microscope image of a III-V taper above the Si waveguide, while Fig. 1(c) shows a schematic of the hybrid III-V/Si active region prior to deposition of the probe metal. The fundamental TE_{00} mode overlaps the 290 nm-thick active region with a confinement factor of $\Gamma \approx 0.17$.

The ICL material with 7 active stages was grown on a GaSb substrate by molecular beam epitaxy (MBE). Its active, separate confinement, and cladding layers were designed to support the hybrid III-V/Si optical mode.

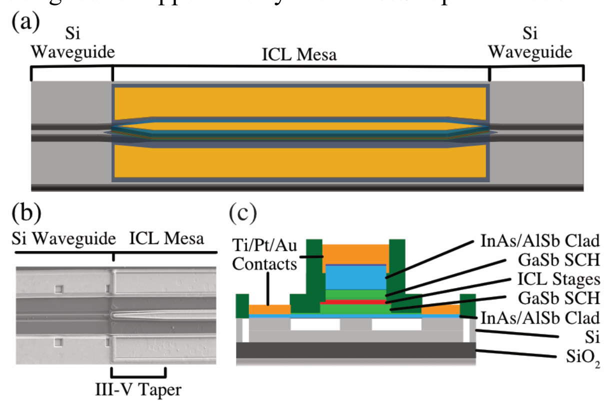

Figure 1: (a) Schematic of the heterogeneously integrated ICL. (b) Scanning electron microscope (SEM) image of the III-V taper region. (c) Cross-sectional schematic of the hybrid Si/III-V ICL active region.

The lasers were fabricated on a silicon-on-insulator (SOI) wafer with a 1500 nm Si layer and 1 µm buried SiO_2 (BOX) layer above the Si substrate. Partially-etched, 1-3 µm-wide, Si rib waveguides were formed with a $C_4F_8/SF_6/Ar$ inductively coupled plasma (ICP) reactive ion etch (RIE).

The ICL layers were bonded above the Si waveguides with hydrophilic, plasma-assisted die bonding, and the GaSb substrate was removed by mechanical lapping followed by a chemical etch

(CrO_3:HF:H_2O). This etch selectively slows on an InAsSb etch-stop layer. The 5-15 µm wide ICL mesas were defined with a BCl_3 ICP RIE. Ti/Pt/Au metal contacts were deposited on the InAs bottom and top contact layers, and the devices were encapsulated with ~1 µm of SiN deposited with plasma assisted chemical vapor deposition (PECVD). The laser bars were diced, and the silicon waveguide facets polished to form mirrors for the Fabry-Perot laser cavities.

III. RESULTS

After fabrication, the ICL bars were mounted with thermal paste on a thermoelectrically-cooled copper block for testing. The lasers were driven with 500 ns pulses at a repetition rate of 20 kHz. The light was collected with a Boston Electronics PVI-4TE-5 photovoltaic detector, which was placed several cm from the laser end-facet to prevent saturation. The power was roughly calibrated by focusing the light on the 1x1 mm^2 detector element with a chalcogenide aspheric lens while the laser was operated at low drive current. Since the photodetector failed to detect all of the emitted light, the powers reported here significantly underestimate those actually emitted by the devices.

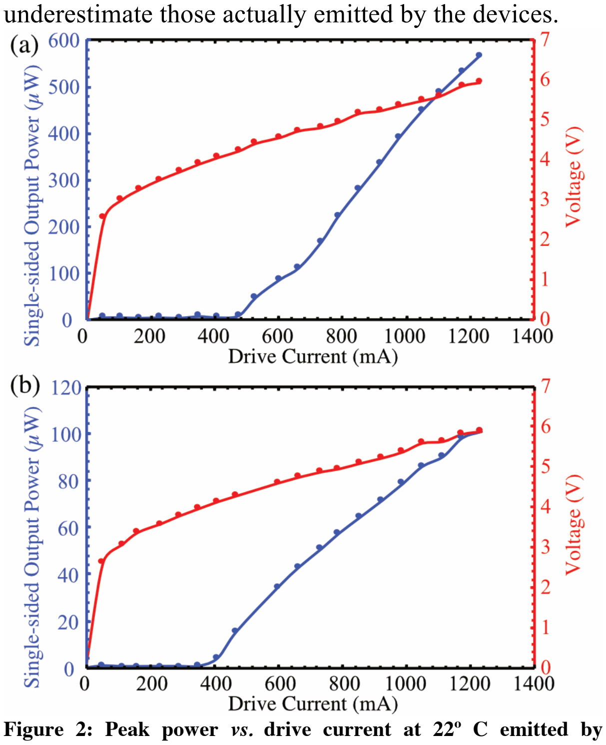

Figure 2: Peak power *vs.* drive current at 22º C emitted by integrated ICLs with III-V mesa widths of (a) 10 and (b) 7 μm.

Figure 2 shows the light emission *vs.* drive current for two integrated ICLs with III-V mesa widths of 10 µm (a) and 7 µm (b). The threshold currents are 448 mA (1.5 kA/cm^2) and 394 mA (1.9 kA/cm^2), respectively, and the wider device emitted up to 566 µW of peak power from one silicon facet. The high threshold current densities and low output powers are likely attributable to additional losses within the III-V tapers within the Fabry-Perot laser cavity.

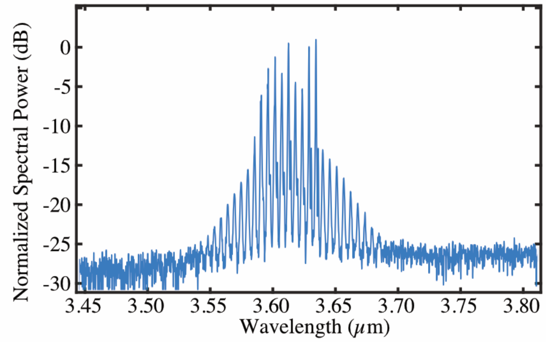

Figure 3: Normalized optical spectrum of an integrated ICL at 20 ºC, driven with 1200 mA pulses.

The optical spectrum was observed by coupling light through the chalcogenide lens into a Bruker Vertex 70 Fourier-transform infrared (FT-IR) spectrometer. Figure 3 shows the normalized optical spectrum of a device with central wavelength near 3.61 µm. The wide free spectral range of 5-6 nm confirms that the laser receives feedback from a cavity shorter than that between the silicon facets, namely by reflections between the III-V taper tips and silicon end facets.

IV. CONCLUSIONS

We report here the first heterogeneous integration of ICLs with silicon waveguides. The devices emit up to 566 µW of pulsed power centered at a wavelength near 3.6 µm, and operate with threshold currents as low as 394 mA. By optimizing the fabrication process and the III-V design, it should be possible to dramatically improve the efficiency and achieve continuous-wave (CW) operation. Integrated ICLs will be ideal for power-efficient sensing and detection applications in MIR silicon photonic systems.

V. ACKNOWLEDGMENTS

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