Quantum Cascade Laser on Silicon at 4.8 µm

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Abstract: Here we demonstrate a room-temperature, 4.8 µm quantum cascade laser (QCL) heterogeneously integrated with silicon-on-nitride-on-insulator waveguides. QCL mesas are defined above silicon waveguides to form lasers.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (130.0250) Optoelectronics; (130.3120) Integrated optics devices.

1. Introduction

The mid-infrared wavelength regime is important for a variety of sensing and detection technologies. Mid-infrared silicon photonics promises to bring low-cost, small-footprint, integrated solutions to these applications. Many components of a mid-infrared photonic integrated circuit have already been demonstrated, including waveguides, resonators, modulators, couplers, arrayed waveguide gratings, and detectors [1]. We previously demonstrated a 2.0 µm laser integrated on silicon, which uses InGaAs quantum wells [2]. However, InP-based diode lasers are difficult to extend to longer wavelengths past near 2.3 µm.

Alternatively, the versatility and performance of quantum cascade lasers (QCLs) at wavelengths throughout the mid-infrared makes them desirable candidates for heterogeneous silicon integration. QCLs have operated at wavelengths from 3 µm to the THz regime, and emit up to Watts of output power [3]. Here we report the first demonstration of QCLs heterogeneously integrated on silicon, which emit 4.8 µm light for operation in pulsed mode at room temperature.

2. Design and Fabrication

The integrated QCL architecture is similar to that employed in [2], consisting of a 4 mm-long hybrid III-V/Si active region coupled to passive silicon waveguide regions on both sides with III-V tapers. Polished silicon facets provide output and feedback for the laser cavity. The optical microscope picture in Fig. 1(a) shows part of a fully-fabricated laser including the passive silicon waveguide region (left), taper (mid), and hybrid active region (right).

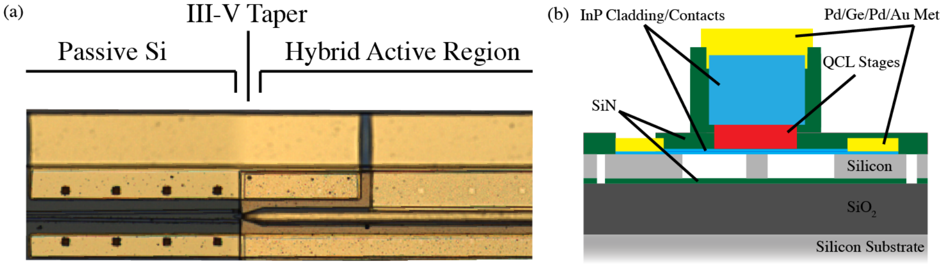

Fig. 1. (a) Optical microscope image of a section of a fully-fabricated QCL heterogeneously integrated on silicon. (b) Schematic of the cross section of a laser's hybrid active region.

Due to its high material absorption in the mid infrared, the SiO_2 employed in traditional silicon-on-insulator (SOI) waveguides is inappropriate at 4.8 µm. Therefore, the lasers in this work are built on the silicon-on-nitride-on-insulator (SONOI) platform, which consists of (from top to bottom) a 1500 nm silicon waveguide layer, a 400 nm LPCVD nitride cladding, and a 3 µm SiO_2 layer on a silicon substrate. While a number of alternative mid-infrared waveguide designs have been suggested or demonstrated previously, this platform has an additional advantage of permitting SiN-on-SiO_2 waveguides to be constructed by etching off the top silicon layer [4]. Since material losses allow SiN-on-SiO_2 waveguides to transmit light from approximately 350 nm to 3.5 µm, while Si-on-SiN waveguides can guide light from about 1.2 to 6.7 µm, the SONOI platform is extremely broadband.

The QCL wafer material with 30 active stages (1.5 µm-thick) has a design similar to that described in [5], but with cladding and contacting layers modified for heterogeneous silicon integration. The wafer was grown by metalorganic chemical vapor deposition (MOCVD) at University of Wisconsin. Figure 1(b) shows a cross section of the hybrid active region. A 6 µm-wide by about 6 µm-tall III-V ridge that includes the QCL active stages sits above a 1.5 μm-tall silicon waveguide. The resulting optical mode in this region is shared by the silicon and QCL. Simulations suggest an optical confinement factor of ~0.7-0.8 in the active QCL region for the fundamental TM mode.

The SONOI platform is constructed beginning with a nitride-on-insulator (NOI) wafer purchased from Rogue Valley Microdevices. These wafers contain a silicon substrate with a 3 μm thermal oxide, then a 400 nm LPCVD SiN deposited on both sides. To form the Si waveguide layer, an SOI wafer with 1500 nm Si is bonded to the NOI wafer. The SOI substrate and SiO_2 layers are then removed. Waveguides are defined in the silicon layer by a $C_4F_8/SF_6/Ar$ inductively coupled plasma (ICP) dry etch.

The QCLs are fabricated by first bonding QCL material above the silicon waveguides and then removing the InP substrate. The QCL mesa is formed by a combination of Methane/H_2/Ar reactive ion etch (RIE) for the InP cladding layers, and H_3PO_4/H_2O_2/DI wet etches to etch through the active QCL stages. Pd/Ge/Pd/Au (10/110/25/1000 nm) is deposited on n-InP for both bottom and top metal contacts.

3. Results

The two lasers shown here were tested in pulsed mode at 20 ºC. Device A has a 6 μm-wide QCL mesa, a 1 μm-wide silicon waveguide, and a 20 μm-long III-V taper, while Device B has a 6 μm-wide mesa, 1.5 μm-wide silicon waveguide, and 45 μm-long taper. Output light was collected with an f/1 ZnSe lens and focused onto a room temperature MCT detector with an f/2 ZnSe lens. Figure 2(a) shows *L-I-V* plots for the two heterogeneously integrated QCLs. The threshold current for Device A is 380 mA, which corresponds to a threshold current density of about 1.6 kA/cm^2. The maximum single-sided output power was about 30 mW for Device B.

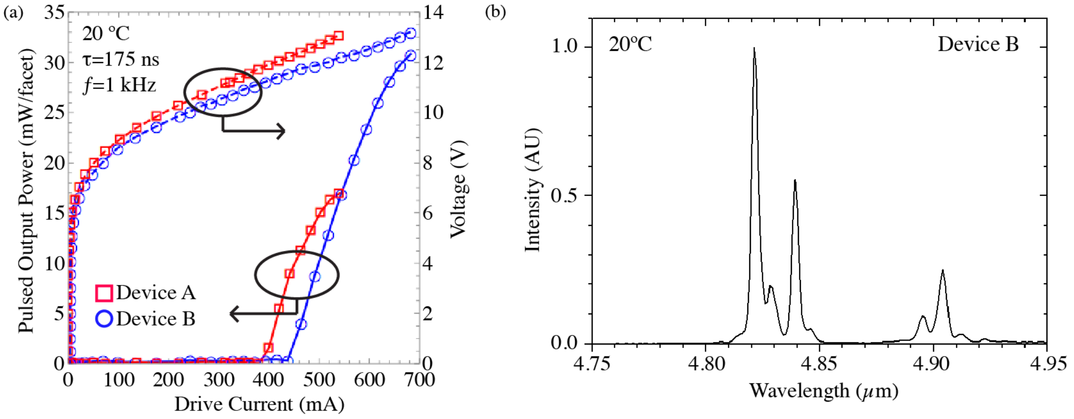

Fig. 2. (a) Voltage and single-sided output power *vs*. pulsed drive current for two heterogeneously integrated QCLs. (b) Emission spectra for Device B.

Figure 2(b) shows the laser emission spectrum for device B, taken with a Digikrom ½ meter monochromator with a resolution of 1.5 nm.

4. Conclusion

We report the first demonstration of quantum cascade lasers heterogeneously integrated with silicon-on-nitride waveguides on the SONOI waveguide platform. The threshold current densities observed for pulsed operation are low enough that CW operation should become possible with design improvements for better heat dissipation and performance. Bonding materials from different QCL wafers should enable devices emitting at a wide range of wavelengths to be heterogeneously integrated on the same silicon chip. This work is supported by the Office of Naval Research (ONR) and the National Science Foundation Graduate Research Fellowship Program (NSFGRFP). We thank Chul Soo Kim and Mijin Kim of NRL for useful discussions.

5. References

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