An Optically Pumped Silicon Evanescent Laser

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Abstract *A laser utilizing wafer scale heterogenous integration of silicon waveguides with offset AlGaInAs quantum wells is demonstrated. This laser has a threshold of 30 mW and a maximum power of 1.4 mW and has the ability to integrate photonic devices with Si VLSI CMOS technology.*

Introduction

Silicon is of great interest for the integration of photonic devices because of Si VLSI CMOS technology and its transparency at the telecom wavelengths, 1.3 μm and 1.5 μm. A major hurdle for silicon has traditionally been its light emission inefficiency due to its indirect bandgap. Efforts to overcome this hurdle have come in the form of a Raman Laser [1, 2] and LEDs [3, 4] that utilize material engineering to increase the light emission efficiency of silicon. Another approach has been the heterogeneous integration of Si with III-V semiconductors including heteroepitaxial growth [5] and wafer bonding. Prior work in wafer bonding has been carried out by bonding III-V lasers onto a silicon substrate confining the optical mode in the III-V region [6]. The work demonstrated here is done by defining the optical mode in the silicon and leaving the III-V quantum well region homogeneous across the wafer. With this approach, most of the optical mode is confined in the silicon waveguide providing high coupling efficiency with other passive silicon-based photonic devices while still achieving high optical gain through evanescent coupling into the III-V region. We report here the first demonstration of a silicon evanescently coupled laser (SEL). It operates at 1538 nm with an optically pumped threshold of 30 mW and a maximum power output of 1.4 mW at 12 ˚C.

Device Structure and Fabrication

Figure 1 shows the SEL device structure. The SEL is divided into two regions: the silicon-on-insulator (SOI) passive-waveguide structure and the III-V active region that provides the optical gain. The SOI structure consists of a Si substrate, a 500 nm-thick SiO_2 lower cladding layer, and a Si rib waveguide with a height (H), width (W) and rib-etch depth (D) of 0.97 μm, 1.3 μm, and 0.78 μm respectively. The III-V region consists of a two-period InP/1.1 μm-InGaAsP superlattice (SL), a 110 nm-thick InP spacer, a 50 nm-thick unstrained 1.3 μm-AlGaInAs separated confinement heterostructure (SCH) layer, strain-compensated AlGaInAs quantum wells, a 500 nm-thick unstrained 1.3 μm-AlGaInAs SCH layer, and an InP upper cladding layer. The SL region employs 7.5 nm-thick alternating layers of InP/InGaAsP to inhibit the propagation of defects from the bonded interface to the QW region [7]. Five 70-nm-thick AlGaInAs quantum wells with compressive strain (0.85 %) and 100-nm-thick 1.3-μm-composition barriers with tensile strain (-0.55 %) are used. The resulting hybrid structure supports a fundamental transverse mode with a Si waveguide transverse confinement factor of 82.7 % and a QW transverse confinement factor of 1.7 % for five quantum wells.

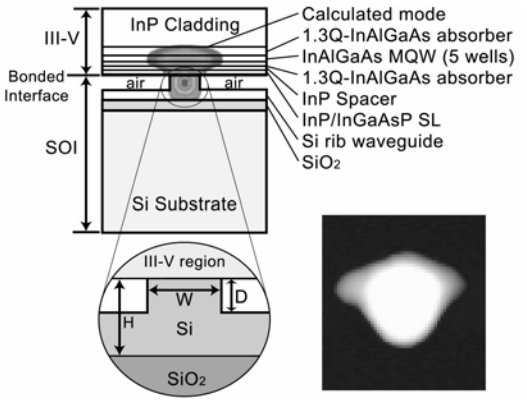

Figure 1: Cross-section of an SOI rib waveguide bonded to a III-V active region epitaxial structure. The near field TE mode image is also shown.

Silicon rib waveguides are formed on an undoped (100) SOI wafer using inductively coupled plasma (ICP) etching with Cl_2/BCl_3. The SOI and III-V samples are bonded together via oxygen plasma assisted bonding [8]. After a low temperature anneal (~250 ˚C), the InP substrate is removed with HCl. Finally, the devices are diced and the facets are polished and coated with a broadband dielectric HR coating (~87 %) consisting of three periods of SiO_2/Ta_2O_5. The final device length after dicing and polishing is 600 μm.

Experimental Results and Discussion

The SEL is optically pumped through a cylindrical lens through the top cladding layer by a 980 nm laser. The pump laser is operated pulsed to increase the pump power. The SEL also lases cw with a cw pump laser. The SEL output is collected with a lensed fiber from the waveguide into a spectrum analyzer or photodetector. The TE/TM near-field images of the output mode are recorded on an IR camera through a polarizing beam splitter and an 80x lens at the opposite waveguide facet.

The inset of Fig. 1 shows a TE near-field image from the laser. The lasing mode is predominantly TE and its mode profile is similar to the calculated mode superimposed on the device structure. The extinction ratio between TE mode and TM mode was measured to be > 20 dB above threshold.

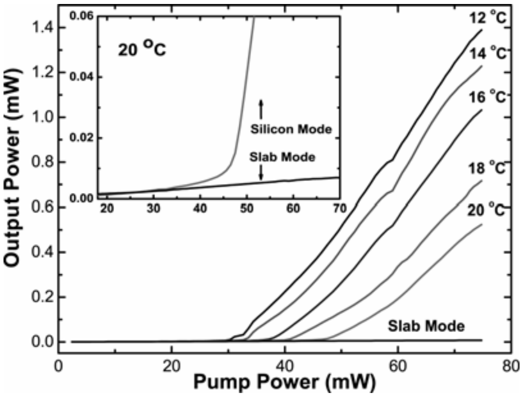

Figure 2: Single-sided fiber-coupled output power of the evanescently coupled Si laser as a function of pump power for several temperatures.

Figure 2 shows the laser output power collected by a lensed fiber through a single facet as a function of pump power and temperature. The threshold is typically 30 to 50 mW, and has a temperature coefficient (T_0) of 18 K. The maximum output power of 1.4 mW is limited by the pump laser power available, and is not thermally limited. The single output differential quantum efficiency is approximately 3.2 % at 12 ˚C, and the total efficiency taking into account the light from both facets and the coupling losses is approximately 15%. It is important to note that lasing only occurs in the optical mode defined by the Si waveguide region. In other words, slab modes in the III-V region do not support lasing. This can be seen from the inset of Fig. 2, which compares the light output for pumping in the two regions.

The optical spectrum in Fig. 3 shows a lasing peak centered at 1538 nm. The spectrum consists of the expected Fabry-Pérot response for the 600-µm-long cavity, with a group index of 3.7.

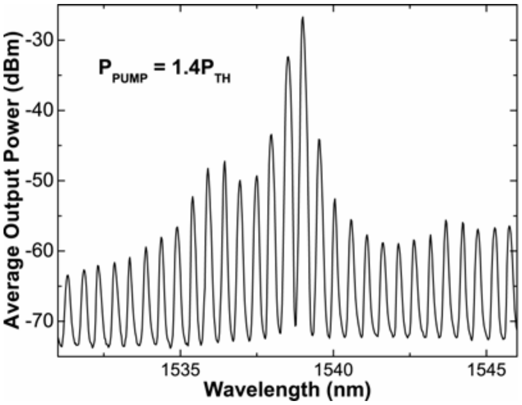

Figure 3: Evanescently coupled Si laser spectra lasing at 1538 nm measured at 1.4 times the threshold power at 12 ˚C with 0.1 nm resolution

Conclusion

This is the first report of a novel laser structure consisting of silicon waveguides integrated with offset quantum well gain regions. The optically pumped 1538 nm SEL was successfully demonstrated with a threshold pump power of 30 mW and a single-sided slope efficiency of 3.2 %. The fabrication procedure includes standard CMOS-compatible processing of the silicon waveguides and a low-temperature oxide-mediated wafer bonding process for heterogeneous integration. This work is a first step to integrate high performance active optical circuits with silicon VLSI electronics and can be extended directly into electrically pumped lasers as well as other optically active devices including amplifiers, modulators, and detectors.

Acknowledgements

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