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Continuous-Wave Electrically Pumped 1.55-μm Edge-Emitting Platelet Ridge Laser Diodes on Silicon

Joseph J. Rumpler and Clifton G. Fonstad, Jr., Fellow, IEEE

Abstract—We report the successful integration on silicon of small footprint, low-threshold electrically pumped edge-emitting lasers by a new approach incorporating microcleaving technology to produce 6-μm-thick platelet lasers with cleaved facets, microscale pick, and place assembly to position them on the substrate, and diaphragm pressure solder bonding to attach/connect them permanently in place. InP-based ridge-waveguide platelet lasers integrated on silicon lase at 1550-nm continuous-wave to 55 °C (pulsed to 80 °C) with output powers as high as 26.8 mW, external differential quantum efficiencies as high as 81%, and threshold currents as low as 18 mA.

Index Terms—Fabrication, indium compounds, integrated optoelectronics, laser cavity resonators, ridge waveguides, semiconductor lasers, silicon.

I. INTRODUCTION

FOR OVER 40 years, silicon has been the material of choice for high-density microelectronics in large part because of the performance advantages of high speed, low static power, complementary metal–oxide–semiconductor technology. With the maturity of silicon fabrication processes gained over this time, and the ever-increasing prominence of silicon devices in the marketplace, researchers are now looking to extend the technology by manufacturing optoelectronic devices directly on silicon substrates for applications such as optical interconnects [1], [2] and biomedical sensors and instrumentation [3], [4].

Silicon-based compounds are regularly used to make passive optical devices such as waveguides, splitters, couplers, and wave-division multiplexers [5]. In fact, silicon, and silicon-based materials such as silicon–oxide–silicon nitride, and silicon–oxy–nitride, are the predominant materials used in commercial optical planar waveguides today [6]. The development of silicon active optical devices like lasers and optical amplifiers, however, has proved to be much more challenging. The difficulty lies in the fact that silicon is an inefficient light-emitting material due to its indirect energy bandgap. Silicon laser research efforts have investigated ways to circumvent this limitation by using materials such as nano-porous silicon [7], rare-earth-doped silica glasses [8], [9], silicon nano-crystals [10], and strained germanium-on-silicon [11], or have exploited phenomena such as the Raman effect [12]. Although these demonstrations represent tremendous breakthroughs, each requires an additional laser to pump the devices and achieve light emission. To make silicon the material of choice for monolithic optoelectronic integration, the development of an efficient electrically pumped laser is necessary.

Approaches to achieve electrically pumped lasers on silicon have typically involved the hybrid integration of III–V semiconductor lasers onto silicon substrates. Most often these efforts have involved bonding epitaxial III–V active structures directly on silicon [13], [14]. Pollentier et al. and Seo et al. reported pulsed lasing of GaAs-AlGaAs single quantum-well (QW) lasers on silicon and InP-InGaAsP multiple QW ridge lasers on silicon, respectively; however, continuous-wave (CW) lasing was not achieved [13], [14]. Rojo Romeo et al. reported ultralow threshold pulsed lasing of microdisk lasers consisting of InP membranes molecularly bonded on Si [15]. Researchers at the University of California at Santa Barbara and Intel have recently demonstrated an electrically pumped CW diode laser [16] made by oxide-bonding a III–V semiconductor QW active gain region and upper cladding layers to silicon waveguides on SiO$_2$ on Si. This novel evanescently coupled, hybrid cavity laser structure has several attractive features, but it uses epitaxial material inefficiently and can only integrate devices fabricated from the same heterostructure layer sequence.

This letter reports the successful integration of small footprint, low-threshold electrically pumped CW III–V semiconductor edge-emitting lasers on silicon by a new approach incorporating a microcleaving technology to produce platelet lasers with cleaved facets, microscale pick and place assembly to position them on the substrate, and diaphragm pressure bonding to solder and connect them permanently in place. The lasers reported here are designed for coaxial integration with waveguides on silicon, but they have features that make them excellent candidates for many other applications as well. The technology described is highly modular so that it can be applied to wide varieties of devices, materials, and substrates; it is also well suited for integrating different wavelength lasers on the same substrate. More details of the integration technology can be found in [17] and [21].

II. DEVICE FABRICATION AND INTEGRATION

The starting semiconductor material used in this work was a standard 1550 nm ridge laser epitaxial structure grown on a (100) InP substrate by a commercial foundry. The only change made in the foundry’s standard heterostructure product was the incorporation of a 500-nm-thick n++ InGaAs etch stop layer next...
to the InP substrate. The front-side device processing began with the deposition and lift-off of Ti–Pt–Au Ohmic metal stripe contacts to the p+ InGaAs contact layer. The semiconductor waveguide ridges were then formed using standard contact photolithography and concentrated hydrochloric acid etching. The wet etch stopped on a 7-nm InGaAsP etch stop layer, thereby precisely controlling the ridge height. The wafer was then planarized using benzocyclobutane (BCB), the BCB surface was etched back to reveal the stripe contacts on top of the ridges, and large area Cr–Au electrical contacts were deposited and patterned on top of the devices. Grooves were etched through the BCB and semiconductor layers down to the lower n+ etch stop layer to delineate long notched bars containing four lasers. At this stage, the wafer front-side was coated with a protective polymer and mounted face-down on a rigid carrier substrate.

Backside processing began with the removal of the InP substrate with hydrochloric acid. This etchant stopped on the 500-nm n+ InGaAs layer. A combination of contact photolithography and e-beam deposition of Ni–Au–Ge–Au–Ni–Au was then used to form the backside ohmic contacts to the n+ InGaAs layer on each device. Then, the remaining n+ InGaAs not covered by the ohmic metal was removed by wet etching in a solution of 1 : 1 : 20 H₂SO₄ : H₂O₂ : H₂O.

Next, the bars of devices were released from the carrier substrate by dissolution of the protective polymer. The individual devices were then separated (and their end facets were simultaneously formed) using a novel microcleaving process [18] that results in cleaved end-facets and a nominal laser cavity length of 300 μm (Fig. 1).

Fully processed microcleaved ridge laser platelets were assembled on a silicon substrate by a microscale pick and place technique. The assembly tool is a small quartz micropipette (pulled to form a 20-μm inner diameter tip that was subsequently beveled at 45°) affixed to a three-axis micropositioning stage, which allows precise positioning of the platelets under a microscope. The platelets were positioned on a silicon substrate covered with 250-nm Au and 400-nm In, and thermo-compressively solder bonded in place under a thermoplastic membrane at a pressure of 40 to 45 PSI and temperature of 210 °C for approximately 6 min (Fig. 2).

**III. EXPERIMENTAL RESULTS AND DISCUSSION**

CW characterization of microcleaved ridge lasers on silicon was performed with the Si substrate mounted on a temperature-controlled stage. Output powers as high as 26.8 mW (at \( T = 10.3 °C \)) were detected and the device lased at stage temperatures as high as 55 °C (Fig. 3). At 20 °C, the peak differential external quantum efficiency \( \eta_d \) was 73%; at 10.3 °C it was 81%.

The output emission spectrum measured just above threshold at a drive current of 30 mA (Fig. 3, insert) shows an output peak just below 1542 nm, and a Fabry–Pérot mode spacing of 1.1 nm, consistent with a group index of 3.6.

Pulsed lasing (1-kHz repetition rate, 0.45% duty cycle) was measured to a temperature of at least 80 °C, the temperature limit of the thermoelectric cooler used. A log-linear plot of the threshold current (pulsed) as a function of stage temperature yields a value for the characteristic temperature \( T_0 \) of 42.9 K.

Derivative analysis of the electrical characteristics gives a value of 8.8 Ω for the diode series resistance, \( R_{series} \), and a
value of 1.3 for the diode ideality factor $n$. With more attention spent on the contact metallurgy, this resistance value could likely decrease by an order of magnitude [19]. The thin microcleaved ridge platelet lasers integrated onto silicon outperformed conventionally cleaved ridge lasers processed simultaneously with the microcleaved lasers, but left on their native InP substrates and cleaved by conventional techniques, in terms of maximum operating temperature, characteristic temperature, output power, and differential efficiency [18]. The improved thermal properties are believed to be due in part to the fact that silicon is a better thermal conductor than InP, and in part to the fact that the gold-based bonding layers act to spread heat from the active region [20].

IV. CONCLUSION
The platelet lasers integrated on silicon in this study operate CW with performance superior to that of comparable lasers on their native substrates. While this work used a relatively simple ridge laser design and rudimentary process tool set, the platelet fabrication and microcleaving processes developed can just as easily be used with more sophisticated, higher performance laser diode geometries and processes incorporating, for example, better lateral current confinement, narrower stripe widths, and lower resistance contacts. The integration process itself is modular, places few restrictions on the laser processing, and can be used with different types of devices, as well as with a wide variety of substrates. It is particularly significant that the platelet devices are integrated as single units, and that they can be tested and screened prior to being integrated. Integrating individual units also means that lasers emitting at widely different wavelengths can be integrated together on a single substrate. Integrating laser diodes as individual platelets in dielectric recesses coaxially aligned with dielectric waveguides, with little or no gap between the laser and recess facets, also makes efficient use of heteroepitaxial materials and results in a unit with a relatively small footprint.

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