

Experimental and Theoretical Analysis of Thermal Impedance in a Hybrid Silicon Evanescent Laser

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Abstract

We present experimental and theoretical analysis for thermal impedance (Z_T) in a hybrid silicon evanescent laser. For an 850 μm long Fabry-Perot, we observe Z_T of 41.8 $^{\circ}\text{C}/\text{W}$ experimentally and 43.5 $^{\circ}\text{C}/\text{W}$ theoretically, which is in excellent agreement.

I. Introduction

Recently, there has been significant attention devoted to the development of an electrically pumped laser source that can be integrated with Silicon based photonics and electronics. Several potential solutions have been proposed and demonstrated, including optically pumped Raman lasers [1], nano-crystalline Si structures [2], and rare-earth doped Si rich oxides [3]. Of these integrated solutions, one of the most attractive is a wafer bonded hybrid silicon laser. In this approach, a III-V active region is wafer bonded to a silicon on insulator (SOI) substrate. Devices fabricated in this manner have demonstrated CW operation up to 60 $^{\circ}\text{C}$ and output powers in excess of 1.8 mW at 1550 nm [4]. Although significant progress has been made, one of the potential drawbacks to making lasers in this fashion is that the buried SiO_2 layer ($k_{\text{SiO}_2} \sim 1.3 \text{ W}/\text{m}^{\circ}\text{C}$) in the SOI substrate has a significantly lower thermal conductivity than crystalline Si ($k_{\text{Si}} \sim 130 \text{ W}/\text{m}^{\circ}\text{C}$). This will inhibit heat transfer from the laser active region to the temperature stabilized backside silicon.

In this work the thermal impedance (Z_T) of a Fabry-Perot (FP) hybrid Si evanescent laser is theoretically analyzed using two dimensional (2D) finite element analysis, and verified experimentally using a combination of pulsed and CW experiments. Measurements and simulation are in excellent agreement and give a Z_T of 41.8 $^{\circ}\text{C}/\text{W}$ and 43.5 $^{\circ}\text{C}/\text{W}$ respectively. The effect of the buried oxide layer is also examined using the theoretical model. It is found that the by including the 1 μm oxide layer in the SOI, the Z_T is raised from 18.3 to 43.5 $^{\circ}\text{C}/\text{W}$.

II. Device Overview

The cross section of the hybrid laser is shown in Fig 1(a). The hybrid Si FP laser consists of a III-V active region wafer bonded to a pre-patterned SOI wafer. After bonding, additional fabrication is performed on the III-V for laser definition, including a proton (H^+) implant step for current confinement. Devices are then diced and facets are polished to define the laser cavity. Details of the fabrication process and device epitaxial structure can be found in [4]. The device has a 2 μm wide Si waveguide, a 12 μm wide III-V mesa, an un-implanted mesa width of 4 μm , an epitaxial Si height of 0.7 μm , and a 1 μm buried oxide.

The dissipated electrical power in the laser that leads to device heating arises from a variety of sources. These include resistive heating in the p-InP mesa and n-InP contact layer, and the diode drop (0.8 V) associated with the active region. TLM patterns were used to extract the resistance from the p-InP mesa (3.3 Ω) and the n-InP contact layer (1.57 Ω) for an 850 μm long FP laser.

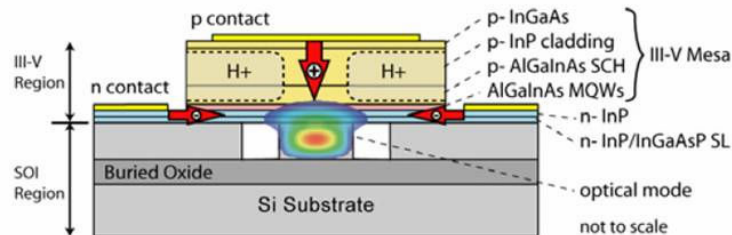


Fig 1. (a) Schematic of the hybrid evanescent Si laser. Electron and hole currents flow from the p-contact and n-contact to the active AlGaInAs QW region. The layers above the p-InGaAs contact layer and n-InP n-contact layer are Au metal contacts.

III. Experimental Thermal Impedance

The thermal impedance of the hybrid laser is measured using a combination of pulsed and continuous wave (CW) measurements [5]. The first set of experiments is used to establish a baseline for the shift of the lasing wavelength as a function of active region temperature. The experiment is performed pulsed (500 ns pulse width, 1 kHz repetition rate) to eliminate device heating aside from what comes from the temperature controlled stage. The device is driven at 125 mA (threshold 65 mA) and the output

spectrum is monitored in an optical spectrum analyzer. Results for the shift in wavelength of an individual longitudinal FP mode as a function of active region temperature ($d\lambda/dT$) are given in Fig 2(a) along with the lasing spectrum at 15 °C and 30 °C. In the second set of experiments, the CW electrical power to the laser is varied at a fixed stage temperature (15 °C). The shift of a single longitudinal FP mode as a function of dissipated power ($d\lambda/dP$) is shown in Fig 2(b) along with an inset of the laser spectrum at 165 and 232 mW of electrical power. By dividing $d\lambda/dP$ by $d\lambda/dT$, the thermal impedance is found to be 41.8 °C/W.

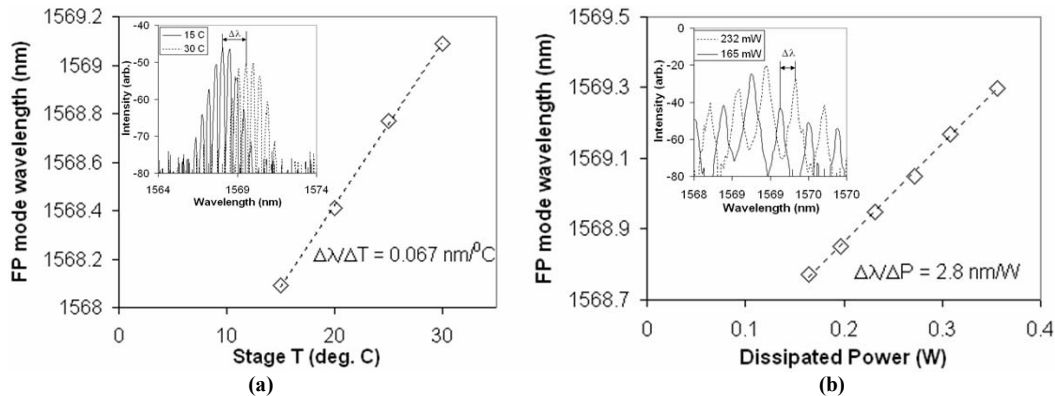


Fig 2. Experimental results from pulsed and CW measurements used for extraction of hybrid laser thermal impedance. (a) Experimental results for wavelength shift vs. device temperature ($d\lambda/dT$). (b) Experimental results for wavelength vs. dissipated laser power ($d\lambda/dP$).

IV. Theoretical Thermal Impedance

A two dimensional finite element solver was used to model the temperature profile in the laser as a function of bias current. The thermal properties of the various layers in the simulation are shown in Fig 3(a). Results for the maximum temperature rise (ΔT_{\max}) as a function of injected current, along with the dissipated power from the resistive heating in the p-InP region, n-InP region, and active region are shown in Fig 3(b). To extract the thermal impedance, ΔT_{\max} is divided by the dissipated power for a given applied current. Based on the power dissipation and the temperature rise, the Z_T for the hybrid Si FP laser is 43.5 °C/W. To examine the effect of the buried oxide, Fig 3(b) also shows the thermal impedance of the device with the buried oxide removed. The predicted Z_T in this case is 18.3 °C/W.

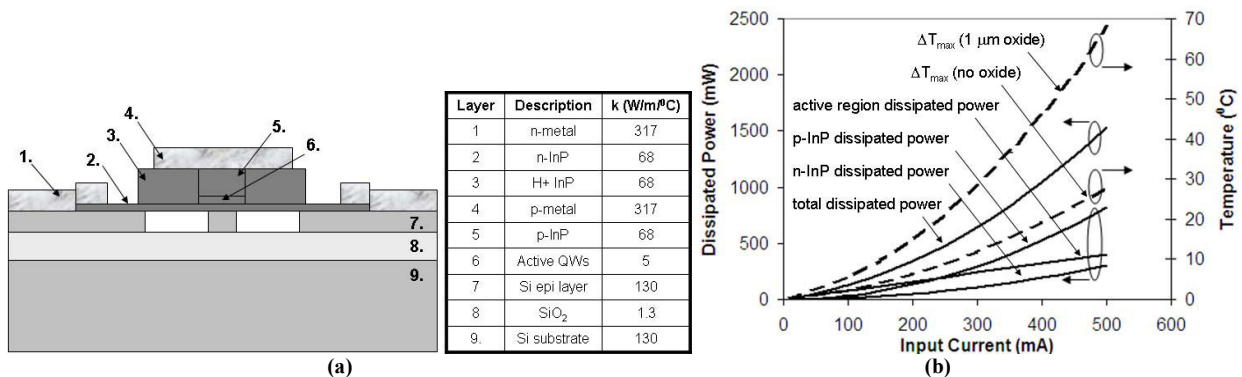


Fig 3.(a) Cross section of the hybrid laser epitaxial structure, including thermal conductivities of each of the layers used in the 2D finite difference model. (b) Dissipated power as a function of injected current along with the predicted ΔT_{\max} of the laser

IV. Conclusions

We have experimentally measured and modeled the performance of a hybrid Si evanescent FP laser. Experimental and theoretical results are in excellent agreement, where the experimental Z_T is 41.8 °C/W and the predicted Z_T is 43.5 °C/W. The effect of the buried oxide in the SOI substrate has been theoretically investigated and it has been shown that by including a 1 μm thick SiO₂ layer, Z_T is raised from 18.3 °C/W to 43.5 °C/W.

References

- [1] H. Rong, "A continuous-wave Raman silicon laser," *Nature* **433**, 725-728 (2005).
- [2] S. G. Cloutier, P. A. Kosyrev, and J. Xu, "Optical gain & stimulated emission in periodic nanopatterned crystalline silicon," *Nature Materials* **4**, 887 (2005).
- [3] S. Lombardo, "A Room-temperature luminescence from Er³⁺-implanted semi-insulating polycrystalline silicon," *Appl. Phys. Lett.* **63**, 1942–1944 (1993).
- [4] A. W. Fang, R. Jones, H. Park, O. Cohen, O. Raday, M. J. Paniccia, and J. E. Bowers, "Integrated AlGaInAs-silicon evanescent race track laser and photodetector," *Optics Express* **5**, 2315-2322, (2007).
- [5] L. Coldren and S. Corzine, "Diode Lasers and Photonic Integrated Circuits," New York: Wiley 1995.