Thermal Characteristics of III/V Thin Film Edge Emitting Lasers on Silicon

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Abstract- We present thermal characteristics of a strain compensated InGaAs/GaAs SQW-SCH thin film laser, integrated onto silicon with a metal-metal interface, and contacts patterned on both sides of the epitaxial layer to improve current confinement. A threshold current density of 262 A/cm² is achieved for a 50 μm ridge laser of 800 μm cavity length, with a lasing wavelength of 1001.52 nm. Lasing was achieved up to 60 ºC, and a characteristic temperature T₀= 49.8 °K was obtained. Theoretical modeling estimated a junction temperature of 67 °C for CW operation.

Index Terms- heterogeneous integration, optoelectronic integration, photonic integrated circuits, planar chip-scale sensing systems, thin film lasers on silicon.

I. INTRODUCTION

Photonic integrated circuits, specifically heterogeneous integration of optics and optoelectronics on silicon [1] and Si-CMOS circuits [2], find application in optical interconnects overcoming the bandwidth bottleneck of copper [3], and in chip-scale sensing systems for chemical [4], biological [5] and environmental monitoring [6] and medical diagnostics. These integrated, miniaturized, low power systems have the potential to be more portable than conventional sensing systems. One of the major research thrusts in the field of photonic integration is the integration of compound semiconductor sources such as lasers, for high efficiency, low power, portable, self-contained systems. In this respect, various approaches have been taken for integrating edge emitting lasers, such as heteroepitaxial growth [7], wafer bonding [8] and adhesive bonding [9, 10]. While excellent laser characteristics have been obtained from these methods, almost all of these are limited in their geometries, placement of contacts, and their access to metal surfaces. This compromises their ability to incorporate efficient current confinement and heat sinking methodologies, both of which are primary concerns for power efficient systems.

In this paper, we present fabrication, test and theoretical results for a thin film strained III-V edge emitting laser that has been bonded to silicon with a metal interface. This enables contacts on both sides of the thin film laser, improving current confinement in the active region of the laser, as exemplified by the low threshold current densities of 260 A/cm² achieved, and opens up the possibility of superior heat sinking strategies for the integrated laser. In Section II, we discuss the material design, device fabrication, and integration. In Section III, the measurement setup is discussed along with L-I, spectral, and thermal characteristics. Section IV discusses the theoretical modeling for these lasers.
II. DEVICE DESIGN AND FABRICATION

The epitaxial layer of the laser, grown by metal-organic chemical vapor deposition, is a strain compensated InGaAs/GaAs/GaAsP single quantum well separate confinement heterostructure (SQW-SCH) with an additional InGaP etch stop layer for thin film processing, as shown in Fig 1. The design wavelength is 980 nm. The net strain of the epitaxial layer has been calculated to be 0.5% compressive. More information about the strain compensation design can be found in [11, 12].

Device fabrication, as illustrated in Fig. 2 (a), begins with p-stripe metallization of Ti/Pt/Au using lift-off photolithography, followed by dry etching 10 μm grooves or slots on both sides of the 40 μm wide p-stripe to define a 50 μm ridge to enable index guiding. This is followed by plasma enhanced chemical vapor deposition (PECVD) and patterning of SiO₂ to electrically isolate the laser everywhere except at the p-stripes. Thereafter, as shown in Fig 2 (b), the entire width of the laser is metallized, and a mesa defined by a photoresist mask is selectively etched down to the InGaP etch-stop layer. In Fig 2 (c), the mesa-etched structure is encased in Apiezon W or black wax supported by a polytetrafluoroethylene (Teflon™) carrier, both of which are impervious to acid. The GaAs substrate is etched off completely using a solution of H₂SO₄: H₂O₂: H₂O of 1:8:1. The InGaP etch stop layer is then etched off selectively in concentrated HCl, leaving the p-side processed lasers embedded in Apiezon W with the n-side exposed, as shown in the photomicrograph in Fig. 2 (c). The structure is then bonded to a mylar diaphragm where it adheres due to van der Waal’s forces [13]. The Apiezon W is next dissolved in a chlorinated solvent, resulting in thin film devices on the
mylar diaphragm that can be flexed to create cleaved mirror facets along previously photolithographically defined wedges (Fig 2 (d)) [11, 14]. Then, the structure is transferred to Au-coated silicon, as shown in Fig 2 (e), where a diffusion bond is created by heating the integrated structure to 180 °C for 10 minutes. An alternative method for good adhesion and cleaving is to transfer the thin film lasers to a thermal release tape or sheet and to then transfer it to the Au-coated silicon. Fig 2 (f) illustrates the final structure, with a cavity length of 800 μm. The n-type contact is defined by using photolithography and by metalizing the integrated structure with Au-Ge/Ni/Au, followed by a rapid thermal anneal at 365 °C.

III. EXPERIMENTAL RESULTS

The integrated laser bonded onto silicon was tested by bonding the Si to a copper stage with thermal grease, and varying the stage temperature with a Peltier element (Marlow, DT-3-6) controlled by a thermal controller (Thorlabs, TED-350). The laser was directly probed with DC probes, driven by a pulsed current source (ILX Lightwave, LDP-3811) with a 1 KHz pulse rate, and 0.5 μs pulse width, and the light was captured using an HP 81521B optical detector head connected to an HP 8163A power meter.

Fig. 3 (a). L-I curves for laser with p-stripe=40 μm, p-ridge = 50 μm, n stripe = 40 μm and cavity length = 800 μm.

Fig. 3 (b). Plot of stage temperature vs ln(I_{th}), yielding T₀ = 49.8 °K, and I₀ = 67.2 mA.

Fig. 3 (a) illustrates optical output power as a function of laser drive current (L-I) curves for stage temperatures ranging from 22°C to 60°C. The threshold current has a value of 105 mA, corresponding to an injected current density of 262 A/cm², assuming lateral current spreading equivalent to the ridge width.

Fig 3 (b) shows the variation of the natural log of the threshold current I_{th} with stage temperature T, in accordance with Eq. 1:

$$I_{th} = I_0 e^{T/T_0}$$  \hspace{1cm} (1)

where T₀ is the characteristic temperature. The L-I data was captured through a Labview interface. The extremely low duty cycle prevents junction heating of the laser, so it can be assumed that the junction temperature is equal to the stage temperature. A linear fit of the plot leads to a value of T₀ = 49.8 °K, and I₀ = 67.2 mA. The T₀ is low given the material system and is attributed to leakage from the shallow well, though it should be offset to some degree due to the GaAsP tensile barriers. A higher T₀ value can be expected by employing a larger energy bandgap separate confinement region to suppress carrier leakage from the quantum well active layer.

The spectra in Fig. 4 were measured by coupling the laser light through an aspheric lens to a multimode fiber connected to an optical spectrum analyzer (Ando, AQ-6315E). The lasing wavelength was measured to be 1001.52 nm, with a linewidth of 78 pm at 22°C.

Fig. 4. Optical spectrum analyzer (Ando, AQ-6315E) showing the lasing wavelength at 1001.52 nm with a linewidth of 78 pm.
The variation in the lasing wavelength from the design wavelength is attributed to material composition variations from different parts of the wafer. Also, some change in the lasing wavelength with and without the substrate may occur due to strain relaxation. The temperature dependence of the peak wavelength is $389 \text{ nm/} \degree \text{C}$, which is typical for a single quantum well.

### IV. SIMULATIONS

FEM-based thermal modeling for the increase in junction temperature as a result of the duty cycle is presented in Fig. 5. Based upon these simulations, the lasers studied herein, bonded onto silicon substrates, would have an active temperature of 67 °C in continuous wave (CW) operation. The junction temperature of the laser on a GaAs substrate (the growth substrate for these lasers) is plotted for comparison. Thermal diffusivities of 0.79 cm$^2$/s for Si and 0.26 cm$^2$/s for GaAs were used for this calculation. It is interesting to note that, due to the higher thermal diffusivity of silicon compared to GaAs, and the metal/metal bond of the laser to the silicon substrate, that the junction temperature of the laser that is bonded to silicon by metal is lower than that of the same laser remaining on the GaAs growth substrate for the same duty cycle.

### V. CONCLUSIONS

The material design, device fabrication, testing, thermal performance characterization, and thermal modeling of a strain compensated InGaAs/GaAs thin film laser of thickness 3.8 μm that has been integrated on metal coated silicon is reported herein. A low threshold current density of 262 A/cm$^2$ for this single quantum well laser was achieved, indicating the possibility of designing portable, low power, integrated planar chip-scale optical systems with integrated laser sources. By enabling both sides of the epitaxial layer to be patterned and processed under the support of either the growth substrate or the host substrate, current confinement can be optimized for low threshold current densities. Our theoretical modeling indicates that the use of metal-metal bonding of the thin film lasers to the
Si substrate can remove heat more efficiently than the laser on the growth GaAs substrate.

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REFERENCES


