Interband cascade laser on silicon for high-speed applications in the mid-infrared domain

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Quantum cascade structures are nowadays becoming mature solutions enabling mid-infrared (MIR) light-generation for diverse applications, such as free-space communications [1] and precision spectroscopy [2]. In the 3-6-µm transmission window, the interband cascade laser (ICL) is an excellent candidate over the quantum cascade laser (QCL) due to its low-threshold drive power [3]. Such reduced energy consumption meets the requirement for ultracompact devices and photonic integration: the utilization of epitaxial growth of III-V materials on silicon (Si) presents a compelling cost advantage compared to other material platforms [4]. The laser under study is a type-II Fabry-Perot (FP) ICL grown on Si, operating continuous-wave (CW) at room temperature (RT). Despite the high dislocations density and high non-radiative carrier recombination rates [5], the ICL still exhibits performances very similar to those grown on the native GaSb substrate. As shown in the light-intensity-voltage (LIV) characteristics in Figure 1a, the threshold current is 59 mA at 293 K; the maximum output power is around 11 mW per facet, the slope efficiency (per facet) is 0.12 W/A, and the external differential quantum efficiency (related to the two facets) is about 70%. The frequency response in Figure 1b shows a sharp cut-off around 1 GHz, which is promising for multi-Gbit/s wireless transmissions. Ulterior results in this direction will be presented during the conference.

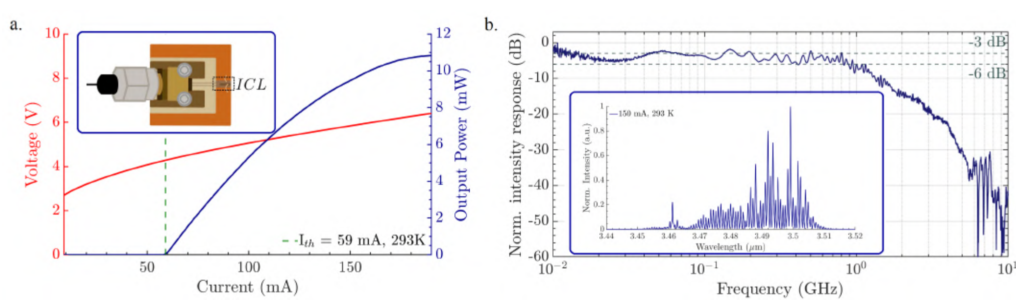

Figure 1: **a.** Light-Intensity-Voltage (LIV) curve of the 3.5 µm ICL. (inset) Schematic of the ICL and its dedicated mounting for high-speed operation. **b.** Frequency response of the ICL for a bias current of 150 mA. (inset) Emission spectrum of the multi-mode ICL, biased at 150 mA at 293 K.

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[3] Meyer, J., et al., *Photonics* 7, 75 (2020).
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Supplementary Pages

Structural characterization

In this work, a type-II ICL is fabricated by molecular beam epitaxy (MBE) on a 2-inch silicon substrate with a slight misorientation of 0.5° along the crystal axis [110] on which 1500 nm of GaSb buffer has been previously epitaxied [6]. The growth starts with a lower optical confinement layer with a thickness of 3 µm, composed of a n-doped AlSb/InAs superlattice. It is followed by the waveguide consisting of 2 layers of n-doped GaSb, surrounding the 7 stages of the interband cascade active region. The type-II quantum wells with a "W" geometry are composed of 2 electron wells of InAs, surrounding the hole quantum well in GaInSb. The thicknesses are chosen to obtain an emission at 3.5 µm. Finally, the top confinement layer is also an n-type superlattice, 1.8 µm thick. After epitaxy, the structure undergoes several technological steps to realize the laser component. Since the realization of ohmic contacts on the silicon substrate is difficult using the technological processes for III-V semiconductors, the two contacts are placed on the front side: one contact was formed on top of the ridge and another one in the AlSb/InAs bottom cladding layer. The 8-µm wide laser mesas are created by UV photolithography and dry etching. The width of the laser is below the 10-µm thickness, where cracks appear in GaSb-based laser grown on Si [7]. The lasers are then cleaved to form a 2-mm cavity and epitaxial side-up soldered. The facets present no coating, so they are not processed [8].

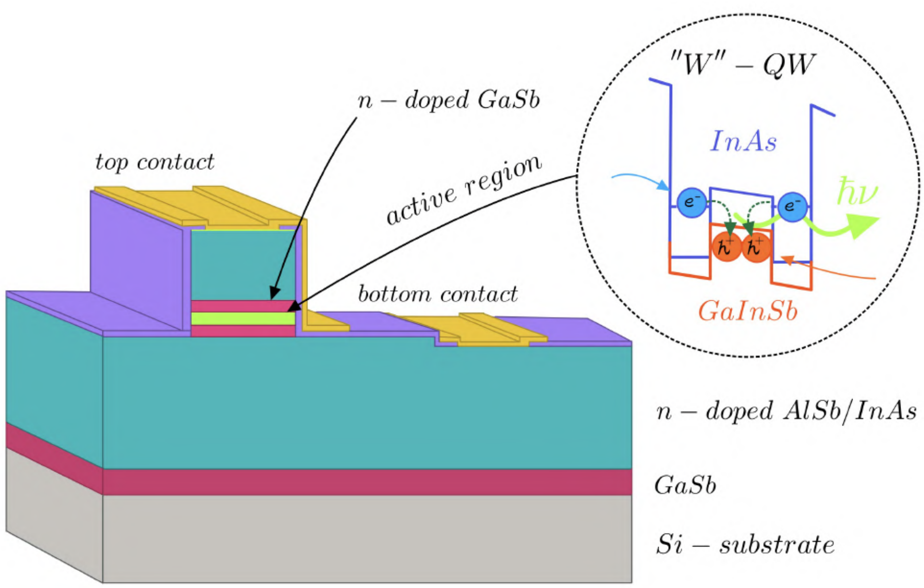

Figure 2: Schematic representation of the processed ICL grown on Si-substrate.

Optical characterization

Figure 3 displays the experimental setup to perform the optical response measurement. The continuous bias is provided by a low-noise current source (ILX Lightwave, LDX-3232), while the ICL is kept at a temperature of 293 K by a temperature controller (ILX Lightwave, LDT-5412) and a thermistor. A converging lens is employed to focus the beam on an interband cascade infrared photodetector (ICIP) [9], placed at a distance of roughly 20 cm. The ICIP is connected to a Pasternack bias tee: the DC part serves for the detector biasing through a Keithley source; the AC contribution is connected to the receiver of a 40-GHz-bandwidth vector network analyzer (VNA, Rohde&Schwartz-ZVK). It performs a 10-GHz sweep in frequency to retrieve the bandwidth of the system, by computing the relationship between the input and output ports as a function of the source signal frequency. In this experiment, the source signal of the VNA is plugged on the AC input of the laser's bias tee. Since the ICIP's bandwidth is 1.7-GHz, the system is frequency-limited by the ICL, displaying a cut-off of about 1 GHz, as evicted from Figure 1b.

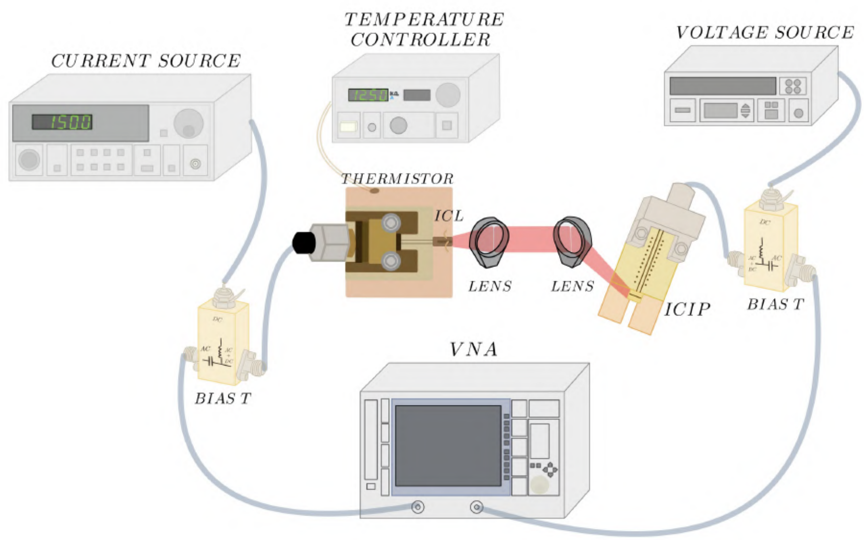

Figure 3: Experimental setup for the determination of the optical response. The ICL is operating at 293 K, biased at 150 mA. The ICIP is biased at 4 V.

The emission spectrum of the laser is measured with a Fourier Transform Infrared Spectrometer (FTIR, Thermo Scientific, Nicolet iS50). A converging lens is used to collimate the signal, before sending it at the input of the aforementioned instrument. The signal interferogram is generated by a Michelson interferometer and collected by a Deuterated-Triglycine-Sulfate (DTGS) Potassium-Bromide (KBr) detector. The interferogram is then digitalized and a Fast Fourier Transform (FFT) algorithm is performed to display the spectrum. The resolution is high (0.125 cm^{-1}) and directly related to the interferometer's properties.
From the emission spectrum, additional optical and physical properties can be estimated: the free-spectral-range (FSR) of the laser, defined as the distance between two consecutive side-modes, is 0.8 nm. Finally, given the central wavelength λ_c, the cavity length L and the FSR, it is possible to determine the effective refractive index n of the laser, following the theoretical relation:

$$n = \frac{\lambda_c^2}{2 \cdot FSR \cdot L}$$

The estimated value for n is 3.78.

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