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# Continuous wave lasing in strained germanium microbridge

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**Abstract – Lasing in the Mid-Infrared region at 3.98  $\mu\text{m}$  is achieved upon 2.15  $\mu\text{m}$  continuous wave excitation in undoped germanium microbridge strained at 6.1 % at low temperature, revealing a closed offset between the  $\Gamma$  and L valleys.**

## I. Introduction

Next generations of high performing and low power consuming computer processors will likely feature electronic-photonic integration in a silicon (Si) chip. As an alternative to the traditional III-V-on-Si laser integration, Germanium (Ge) is a promising candidate for a light source monolithically integrable on Si. To achieve this objective, the band offset  $\Delta E$  between  $\Gamma$  and L of 140 meV has to be reduced in order to increase the radiative recombination efficiency, by tensile strain and/or by alloying with Sn. While tensile strained GeSn based optically pumped lasing have been recently shown up to 273 K [1] and under continuous wave (CW) excitation [2], strained Ge lasing is demonstrated only in pulsed regime, exploiting the blocking of the carriers transfer from the  $\Gamma$  to L valley [3]. Here, we present the first lasing under steady state optical excitation in undoped Ge microbridges (MB) highly strained along the  $\langle 100 \rangle$  direction. The lasing under continuous wave is achieved thanks to (i) the improved cavity quality factor, (ii) the high quality of the Ge-on-insulator (GeOI) layer, and (iii) the strain increase to 6.1% - through which the offset between  $\Gamma$  and L is closed.

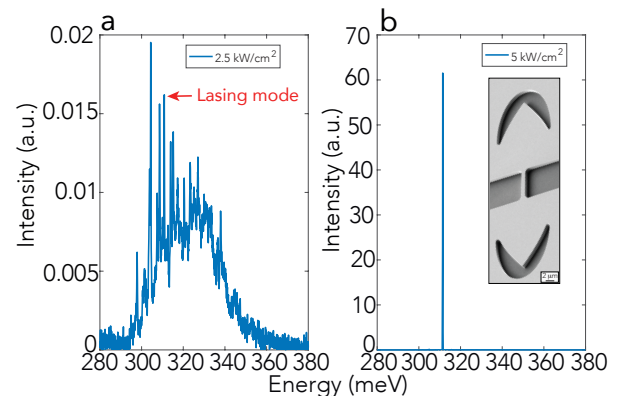
## II. Concept and Structure

The highly strained Ge is obtained by patterning and under-etching an undoped GeOI layer with a built-in biaxial tensile pre-strain of 0.16% [4]. Through e-beam lithography and dry etching, we define two stressor pads, connected by an 8  $\mu\text{m}$  long and 1  $\mu\text{m}$  wide MB. The two edges of the MB are placed in the focus of two corner cube mirrors with a parabolic shape, c.f. inset Fig.1. Simulations performed in time domain indicate empty cavity quality factors of about 2000. The subsequent selective etching of the underlying silicon oxide by vapor HF releases the Ge structure, enabling the pads to elastically relax. As a result, the MB is uniaxially stretched [5] to an amount uniquely defined by the material and the geometry of the patterning. Strain up

to 4.9 % has been reached at room temperature [6]. Even higher strain, and thus smaller offset  $\Delta E$  values, are achieved at lower temperature, as the thermal expansion mismatch between Ge and Si is further enhanced, c.f. [7]. Here we study a micro bridge whose strain increases from 3.9 % at room temperature up to 6.1 % at 15 K.

## III. Results and Discussion

In this study the sample was optically excited at 15 K with a diode laser running in continuous wave mode at 590 meV (2.1  $\mu\text{m}$ ).

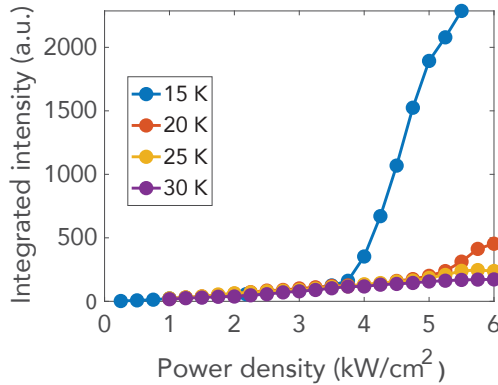


**Figure 1** Spectra of the microbridge sample strained at 6.1 % at 15 K under CW optical pumping. **a** The PL was acquired at 2.5 kW/cm<sup>2</sup>, and the lasing spectrum in **b** at 5 kW/cm<sup>2</sup>. In the inset, tilted scanning electron microscopy image of a Ge microbridge integrated in a corner cube cavity.

The excitation energy is small enough to ensure zero free carrier absorption for light propagation outside the constriction. In Fig.1a, we show the broad photoluminescence (PL), modulated by the Fabry-Perot cavity modes, emitted when the sample is excited at 2.5 kW/cm<sup>2</sup>. When the excitation is increased to 5 kW/cm<sup>2</sup>, as shown in Fig.1b, the spectral emission is made uniquely of a single mode peak, with an intensity about three orders of magnitude above the broad PL background. The red arrow in Fig.1a indicates the mode which lases, once the excitation power is increased above the threshold of 3.75 kW/cm<sup>2</sup>. The mode competition reveals the presence of net material gain,

which, together with the characteristic threshold signatures in the total power (Fig.2), are vast proofs of lasing.

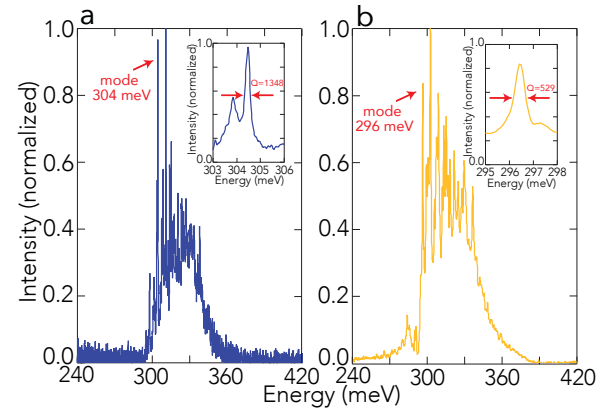
In Fig.2 we show the so-called light-in light-out curves for different temperatures. At 15 K a strong increase in intensity is observed when the threshold is exceeded. At higher cryostat temperatures, the lasing threshold power increases and the lasing efficiency quenches rapidly. No lasing is observed at 30 K and above. Typically enough, cavities on the same GeOI chip but processed with strains of 5.9 % or less showed no lasing threshold at all.



**Figure 2** Light-in light-out curves of the microbridge excited in CW at 590 meV for temperatures up to 30 K.

The latter observation confirms that the strain needed to have a direct bandgap configuration is much higher for Ge than previously anticipated [3]. Nevertheless, higher strain is not a sufficient condition to ensure lasing. In Fig.3a we show the sub-threshold PL emission of the lasing sample, when the cavity is excited at 3 kW/cm² at 15 K and we compare it, c.f. Fig.3b, to the spectrum of a reference cavity, from the same GeOI but processed in a previous fabrication run. This cavity with a nominal strain of 6.3 % is excited under the same CW conditions. But, although the latter sample has a higher strain than the former one, no lasing operation is observed once the power is increased. The lack of lasing stems from cavity losses estimated to be a factor of 2 higher. From the analysis at 3 kW/cm², the mode at 304 meV of the lasing sample has  $Q=1348$ , while the mode at similar energy at 296 meV in Fig.3b shows  $Q = 529$ , as reported in Fig.3. Finally, we address the abrupt quench of lasing and the strongly reduced lasing efficiency when the temperature is increased by just 5 K, less than an equivalent energy of 1 meV. From Fig.2, the threshold shifts from 3.75 kW/cm² at 15 K up to 4.5 kW/cm² at 20 K, while the intensity slope is reduced approximately by a factor of 4. We attribute these features to a redistribution of the carrier population between the  $\Gamma$  and L valley followed

by an increase of absorption at the higher excitation intensity. The first feature is a signature of the exact alignment of the band offset ( $\Delta E \sim 0$  meV) while the second one is likely due to parasitic intervalence band absorption (IVBA) which builds-up nonlinearly with the total carrier density and strongly increases with the temperature. These effects taken all together makes the temperature range at which CW lasing occurs narrow, in spite of the fact that the lattice temperature stays low thanks to Ge's excellent heat conductivity, higher than  $10 \text{ W}\cdot\text{K}^{-1}\cdot\text{cm}^{-1}$ .



**Figure 3.** Normalized PL spectra taken at 15 K and upon CW excitation of 3 kW/cm² of the **a** cavity lasing beyond 3.75 kW/cm², and of the **b** trial cavity emitting PL at power higher than 3 kW/cm². The insets show a larger view of the modes indicated in the main figure, with the corresponding Q factor. The spectrum in **b** is taken at longer integration time.

#### IV. Conclusion

We achieved lasing action under steady state excitation in undoped Ge microbridges, embedded in high quality cavity. We find that at about 6 % of strain the offset between the  $\Gamma$  and L valleys is essentially closed and that CW lasing operation comes from the high quality of both the cavity processing and the GeOI layer. Higher strain samples to increase the maximal operational temperature as well as the effects of n-doping will be probed in up-coming experiments.

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