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Strained germanium lasing in the Mid-Infrared

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Abstract – Mid-Infrared lasing between 3.20 and 3.66 μm is achieved in undoped germanium microbridges strained up to 5.9 % and up to a temperature of 100 K under optical pulsed excitation of 100 ps, exploiting a non-equilibrium carrier dynamic.

I. Introduction

Being CMOS-compatible and having “near” direct bandgap, Germanium (Ge) is a promising candidate for a fully Si-compatible light source, and an alternative to the traditional III-V-on-Si laser integration. The offset $\Delta E = E(\Gamma) - E(L) = 140$ meV of Ge can be reduced by tensile strain and/or by alloying with Sn, increasing the radiative recombination efficiency. The recent demonstration of lasing in GeSn showed the viability of this approach [1]. We present here lasing in Ge microbridges (MB) highly strained along the $\langle 100 \rangle$ direction. We show the main lasing features and argue that lasing is accessed via a non-equilibrium distribution of carriers between the Γ and L valleys.

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% [2]. Through e-beam lithography and dry etching, we define two stressor pads, connected by an 8 μm long and 1 μm wide MB. The two edges of the MB are placed in the focus of two corner cube mirrors with a parabolic shape, c.f. Fig. 1. Simulations indicate quality factors above 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 [3] 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 [4]. Even higher strain, and thus smaller offset ΔE values, can be

readily achieved at lower temperature, as the thermal expansion mismatch between Ge and Si is further enhanced, c.f. [5]. Here we study a microbridge whose strain increases from 3.8 % at room temperature up to 5.9 % at 20 K.

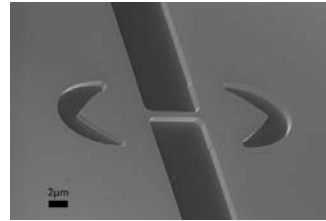


Fig. 1 Tilted scanning electron microscopy image of a Ge microbridge strained along $\langle 100 \rangle$ and integrated in a corner-cube cavity.

III. Results and Discussion

In this study the sample was optically excited by employing two different light sources: a diode laser running in continuous wave (CW) mode at 590 meV and an optical parametric oscillator (OPO) enabling pulsed excitation of 100 ps at 83 MHz repetition rate, whose energy is tunable between 370 and 551 meV. In both cases, the excitation energies run below the relaxed Ge band gap, ensuring zero free carrier absorption in the pads. In Fig. 2, we show in grey the broad photoluminescence (PL) emitted when the sample is excited with the CW excitation at 4 kW/cm^2 . This spectrum of the Fabry-Perot cavity modes reminds previously published Ge lasing studies [6,7]. The emission upon OPO excitation, at similar average power of 2 kW/cm^2 , is shown in green. Peak intensity is found to be 1400 times stronger than under CW excitation and mostly from only one mode. We found, from a calibrated emission experiment, that the differential quantum efficiency is approaching 1 when we excite near resonance at 407 meV; then the radiative losses are dominating material losses. This, together with the mode competition and the occurrence of a threshold are unmistakable fingerprints

of lasing. In fact, the spectra taken with the OPO below the threshold (at about 0.5 kW/cm^2 , on average), exhibit broadness and cavity modes modulation similar to the CW spectrum. We thus ascribe the latter to (possibly amplified) spontaneous emission.

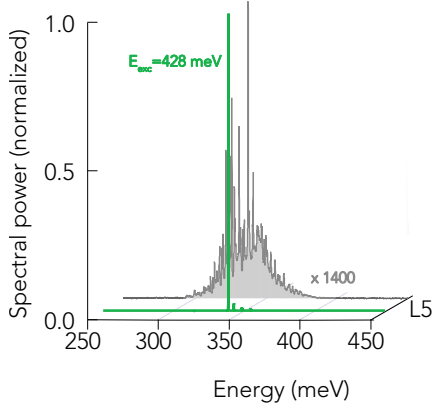


Fig. 2 Normalized spectra of a microbridge sample with 5.9% of strain at 20 K. The PL (in grey and multiplied by 1400) is taken at 4 kW/cm^2 of power under CW pumping, while the lasing spectrum (green) upon the OPO excitation with an average power of 2 kW/cm^2 .

In Fig. 3 we show the lasing spectrum dependence on the temperature for the above sample, upon near resonant excitation of 407 meV . The main lasing mode at 338 meV abruptly quenches around 80 K , while the higher energy modes still lase up to 100 K . For higher excitation energies, quenching occurs at lower temperatures, i.e. at 60 K and 75 K for 551 meV and 468 meV excitations, respectively.

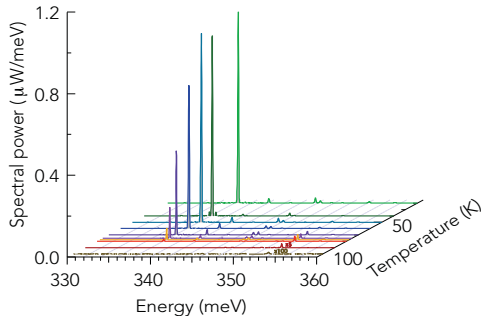


Fig. 3 Temperature dependence of lasing spectra for the 5.9 % strained micro bridge sample at 407 meV and 2.9 kW/cm^2 excitation power

The fact that lasing does not occur under steady state excitation, but in pulsed mode at remarkably low excitation densities (the estimated threshold is at electron densities below 10^{17} cm^{-3}) we attribute to: (i) the band structure, even at about 6 % of strain, is only marginally direct, excluding CW

lasing and (ii) a non-equilibrium carrier distribution is build-up, not accessible with CW steady state excitation, but only in pulsed regime.

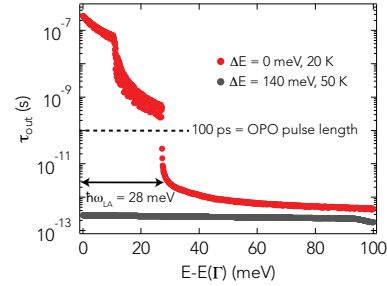


Fig. 4 Γ to L phonon-assisted scattering time as function of the carrier energy relative to the bottom of the Γ valley, plotted for two temperatures and two ΔE offsets. The zone boundary longitudinal-acoustic phonon energy is indicated.

While (i) is expected from tight binding calculation results presented in [8], we assign (ii) to a blocking of the phonon mediated scattering of electrons from an initial state in Γ with excess energy E_{ex} below the energy of the zone boundary longitudinal-acoustic phonon to a final state in L. For the unstrained case, the scattering time is calculated as 200 fs , in close agreement with previous time resolved experiments [9]. However, when the offset ΔE is 0 meV , in line with our experiment, the electrons with E_{ex} below the 28 meV zone-boundary phonon, may stay in Γ longer than the 100 ps time scale of our experiment, c.f. Fig.4

IV. Conclusion

We achieved lasing action in undoped, highly strained Ge microbridges under pulsed excitation. We find that the crossing to a direct band gap configuration takes place at around 6 % of strain. Highly efficient lasing is achieved at low temperature thanks to a non-equilibrium blocking of carriers. Their dynamics between the Γ and L valleys will be experimentally addressed by time resolved lasing measurements.

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