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GeSn lasers for monolithic integration on Si

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Abstract—Lasing under optical pumping is shown in suspended GeSn microdisks fabricated on a Ge virtual substrate with a lasing threshold below 1 mW at 20K.

Keywords—GeSn; group IV photonics, microdisk lasers, group IV lasers, Si photonics, monolithic integration

I. INTRODUCTION

Intensive research has been carried out in the last years on novel materials for the integration of advanced optoelectronic and photonic systems on silicon motivated by the prospect of cost-effectiveness resulting from compatibility with complementary metal-oxide-semiconductor (CMOS) circuits. To allow compatibility with silicon IC manufacturing facilities, group IV elements and their alloys have attracted special attention as active materials [1]. GeSn is one of the most promising group IV alloys for laser applications due to the transition to a direct bandgap under tensile strain and/or sufficiently high Sn alloy content [2]. Moreover, the smaller bandgap energy of GeSn alloys enables laser operation at the higher end of the near-IR range / lower end of the mid-IR wavelength range, enabling new sensing and bio-photonics applications.

Two types or resonators are mainly considered for monolithic integration on a Si platform: waveguide structures and microdisk resonators (MDRs). Lasing was recently demonstrated using waveguide structures [2]. These may also serve as waveguide photodetectors in which the long cavity (absorption length) allows the efficient collection of photons [3]. Laser cavities based on whispering gallery mode (WGM), such as MDRs, have been intensely investigated because of their simple device structure, high quality factor and relative ease of integration.

Here we present the fabrication on MDRs based on GeSn/Ge/Si heterostructures grown by chemical vapor deposition (CVD) and investigate their suitability as lasers cavities. Optically pumped lasing is demonstrated.

II. EXPERIMETAL AND RESULTS

The GeSn layers were grown on Ge/Si(001) virtual substrates (Ge-VS) using a 200 mm wafer AIXTRON TRICENT reduced-pressure CVD reactor with showerhead design which offers an uniform distribution of precursor gases over the wafer surface [4]. Partially strain relaxed GeSn layers with low residual compressive strain and relatively high Sn contents were used in order to induce a direct bandgap [2]. An increase of the Sn content also leads to a decrease of the GeSn bandgap. This is illustrated in Fig. 1a by reflectance spectra of partially relaxed GeSn layers with Sn contents between 8.5 and 14 at.%. The spectrum of the Ge-VS is shown for comparison. Band structure calculations and experimental data indicate that all investigated GeSn layers are fundamental direct bandgap semiconductors [2]. The temperature dependence of the PL spectrum of a 800 nm thick GeSn layer with a Sn content of 8.5% is shown in Fig. 1b. The Γ-valley luminescence increases towards lower temperatures and shifts to higher energies, as expected for direct bandgap semiconductors.

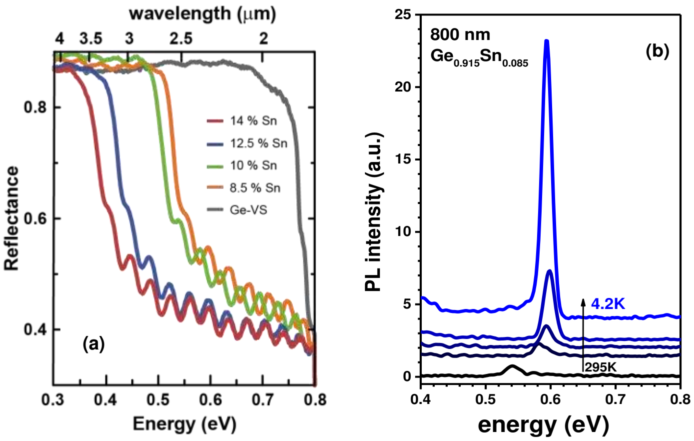

Fig. 1: (a)room temperature reflectance spectra of 800 to 1μm thick GeSn alloys with different Sn concentrations. (b) Temperature dependent PL spectra of a 800 nm thick GeSn alloy containing 8.5 at.% Sn. The spectra are shifted vertically for better readability.

MDRs with large diameters between 20 μm and 40 μm were dry etched into 800 nm thick $Ge_{0.915}Sn_{0.085}$ and 560 nm thick $Ge_{0.875}Sn_{0.125}$ layers using standard Si processing via e-beam lithography and reactive ion etching (RIE). Subsequently to this anisotropic mesa etch, the discs were isotropically under etched by an inductively coupled CF_4 plasma that offers a high etching selectivity between GeSn and Ge.

Mode calculations (Fig 2) indicate that TE_0 and TM_0 ground modes are fully confined in the suspended disk region for undercuts larger than 2 µm. The modes are unperturbed by the Ge pillar at the center of the structure and the effective index is identical to that of a structure with a vanishing pillar. GeSn microdisks with underetching of approx. 3 µm (see SEM image in Fig. 3) are presented here.

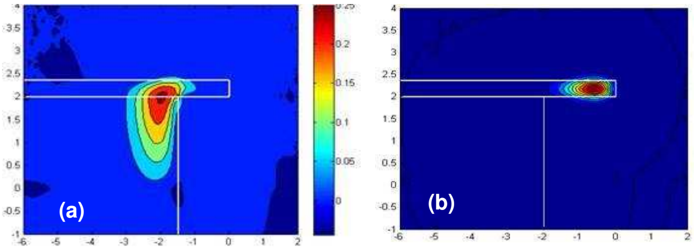

Fig 2: Mode calculations for (a) 1.5 µm and (b) 2 µm undercut. For undercuts above 2 µm the modes are unperturbed by the Ge pillar.

Strain mapping measurements using micro-Raman spectroscopy indicate complete strain relaxation over a large portion of the under-etched region and even slight tensile strain at the microdisk edges. A reduction of the compressive strain in the GeSn active region translates into an increased energy separation between the Γ and L valleys, which leads to an increased electron population of the of the Γ-valley as well as a suppression of Γ- to L-valley carrier transfer. This is shown in Fig. 4a. The bandgap of the alloy is modified by the biaxial strain of the thin film; therefore, an increased relaxation also leads to a reduction of the bandgap energy. The shift of the laser emission towards lower energies relative to the residual PL background presumably originating from the non-suspended central region of the microdisk is consistent with the mode confinement in the periphery of the MDR (whispering gallery mode).

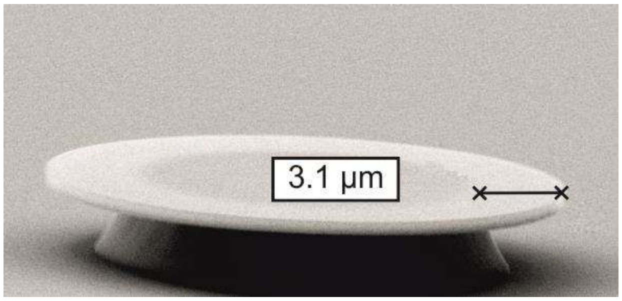

Fig. 3: Scanning electron micrograph of a $Ge_{0.875}Sn_{0.125}$ microdisk with a diameter of 20 µm and 3 µm undercut.

Fig. 4b shows PL spectra of a 10 µm $Ge_{0.875}Sn_{0.125}$ microdisk at low temperature (T=20K) as a function of optical excitation. Lasing is observed at 1 mW pump power and above with a sharp peak at an energy of 0.485 eV. In the inset, the reduction of the full width at half maximum (FWHM) of the stimulated emission peak (1.4 meV) compared to the spontaneous emission background (20 meV) is emphasized (the two curves are normalized to facilitate comparison). Even though the 1.4 meV linewidth would correspond to a moderate cavity Q-factor of 360 in a passive structure, the absence of emission from other resonances at 1 mW is a further indication for lasing. At higher pumping power the lasing spectrum broadens due to multi-mode operation in a higher number of WGMs with a free spectral range of 6.2 meV. This FSR is larger than expected from the calculated group indices of the TE_0 and TM_0 ground modes, leading to the hypothesis that higher order WGMs with larger radial numbers and lower index are being excited. This could be due to a lower overlap with surface roughness of the etched MDR circumference and is currently under investigation. The spontaneous emission is also increased for higher pumping, which may be related to the central region of the disk being spatially separated from the lasing circumference.

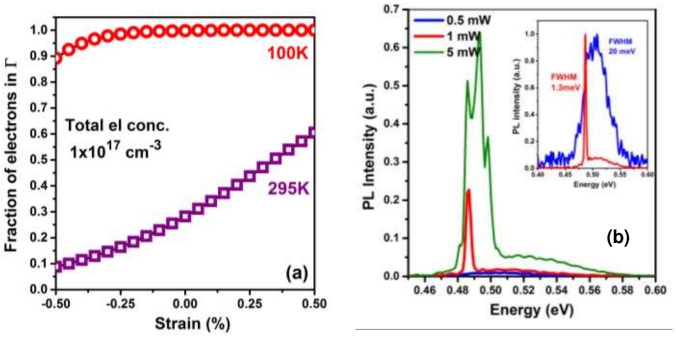

Fig. 4: (a) Calculated electron fraction occupying the Γ valley at 100K and 295K for a total electron concentration of $1\text{x}10^{17}$ cm^{-3}. (b) PL spectra at 20K as a function of optical excitation. The linewidth narrowing above the lasing threshold is shown in the inset.

Laser emission of the micro-disk resonators is in excellent agreement with the recently demonstrated lasing with a waveguide resonator geometry [2]. Furthermore, lasing in GeSn microdisks with different GeSn layer thicknesses, Sn contents and diameters will be discussed as well as the temperature dependence of the laser emission. The MDR structures investigated here will serve as a basis towards further investigation of electrically pumped structures.

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