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# Tensile strained GeSn mid-infrared light emitters

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**Abstract**—Compressively strained GeSn alloys grown on Ge buffers on Si (001) substrates were fabricated into microdisks and strained using silicon nitride stressors. The strained disks are measured to be tensile by Raman spectroscopy, and demonstrate direct bandgap emission in the 3–5  $\mu\text{m}$  gas sensing window.

## I. INTRODUCTION

Recently, low temperature lasing has been demonstrated in direct bandgap GeSn alloys, demonstrating enormous potential for efficient Group IV light sources [1][2]. Alloying Ge with Sn, or applying tensile strain reduces the 140 meV energy difference between the L and  $\Gamma$ -valleys, eventually leading to a crossover to a direct bandgap semiconductor [1][3]. GeSn alloys grown directly on Ge buffers are compressively strained, which counteracts some benefits of the Sn alloying. Strain relaxation by misfit formation has the unwanted effect of introducing trapping centers, leading to optical loss and high lasing thresholds. In this work, a combination of strain engineering and Sn alloying is used to create direct bandgap alloys with minimal dislocation densities. This is achieved by growing  $\sim 40$  nm thick  $\text{Ge}_{1-x}\text{Sn}_x$  alloys ( $x \leq 0.107$ ) pseudomorphically on Ge virtual substrates (VSs), which are fabricated into  $\text{Ge}_{1-x}\text{Sn}_x/\text{Ge}$  microdisks, and strained by high stress silicon nitride layers, leading to high-quality, direct-bandgap alloys.

Furthermore, the red-shift associated with both techniques leads to emission beyond 3  $\mu\text{m}$  wavelength, in the mid-infrared (MIR). This is in keeping with a shift in the focus of the Si photonics field towards MIR waveguides and passive optics using Si and Ge [4]. Tensile strained GeSn alloys could complement such technologies, and leverage Si foundry processes to allow for low cost Group IV gas sensing systems in the 3 to 5  $\mu\text{m}$  wavelength window, with applications in healthcare, pollution monitoring and security.

## II. RESULTS

### A. Growth and fabrication

Germanium virtual substrates (VSs) were grown on (001) Si wafers in a commercial ASM Epsilon 2000E tool, by reduced-pressure chemical-vapour deposition (RP-CVD). These layers are 650 nm thick, and have 0.18 % tensile strain due to the thermal expansion mismatch between Ge and Si. Subsequently,  $\sim 40$  nm thick, nominally undoped GeSn alloys were grown on the VSs. The alloys were characterized by symmetric (004) and asymmetric (224) X-Ray Diffraction (XRD), Fig. 1, and were found to be fully pseudomorphic to the Ge layers. The

alloys were calculated to have Sn concentrations of 8.4 % and 10.7 %, with compressive strains of  $\sim 1.10$  % and  $\sim 1.44$  % respectively. The materials are calculated to be indirect bandgap as grown, and show temperature dependent photoluminescence (PL) in keeping with high quality indirect GeSn alloys (not shown here) [5].

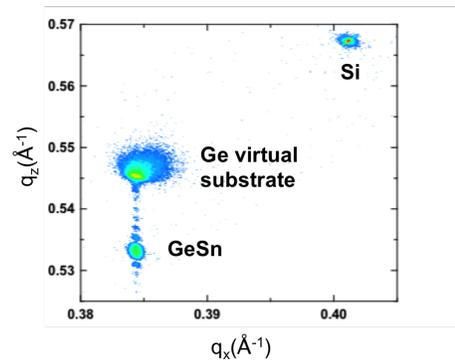


Fig. 1. X-Ray diffraction reciprocal space map about the (224) reflection for  $\text{Ge}_{0.916}\text{Sn}_{0.084}$  alloys. Shows there is no relaxation in the alloy.

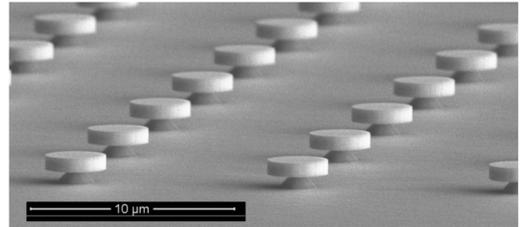


Fig. 2. Scanning electron microscope image of undercut GeSn/Ge disks with Si pillars.

Microdisk structures were patterned in hydrogen silsesquioxane (HSQ) resist by a Vistec VB6 electron beam lithography tool, with diameters ranging from 10 to 3  $\mu\text{m}$ . The disks were dry etched in a low damage mixed  $\text{SF}_6$  and  $\text{C}_4\text{F}_8$  recipe, through to the Si substrate. Subsequently, the disks were undercut to allow for a high tensile strain transfer at the top plane [6], Fig. 2. This is achieved by using tetramethylammonium hydroxide (TMAH) and isopropyl alcohol wet etch, which selectively etches the Si to undercut the GeSn/Ge disk by approximately 1.2  $\mu\text{m}$ . The disks were passivated by  $\text{Al}_2\text{O}_3$  layers, deposited by atomic layer deposition, and subsequently stressed by high stress SiN

stressor layers. The SiN is deposited by an inductively-coupled-plasma plasma-enhanced-chemical-vapour-deposition (ICP-PECVD) tool at room temperature, producing a layer with a compressive stress of  $\sim 2.3$  GPa (as measured by the curvature method), which transfers tensile strain to the disk when it relaxes [6].

### B. Analysis of strained disks

The local strain of the GeSn layer was measured using a confocal  $\mu$ -Raman spectroscopy system with a 0.9 NA,  $100 \times$  objective and a 532 nm source. The measurement probes the Ge-Ge vibration, which changes frequency with both Sn content, and strain. Using the XRD data from the as-grown epilayers, a strain shift coefficient  $\sim 420 \text{ cm}^{-1}$  was calculated, assuming a Sn shift coefficient of  $83.1 \text{ cm}^{-1}$ . The  $3 \mu\text{m}$  strained  $\text{Ge}_{0.916}\text{Sn}_{0.084}$  and  $\text{Ge}_{0.893}\text{Sn}_{0.107}$  disks were found to have tensile strained regions of 0.62 % and 0.45 % respectively, which suggests that both layers are direct bandgap, based on bandgap bowing parameters and deformation potentials [1]. Raman maps of the strained  $3 \mu\text{m}$  disks are shown in Fig 3. According to the constants used here, a Raman line less than  $\sim 295 \text{ cm}^{-1}$  indicates direct bandgap for both alloys.

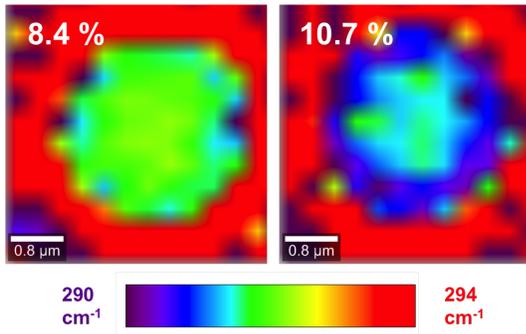


Fig. 3. Raman spectroscopy maps of strained  $\text{Ge}_{0.916}\text{Sn}_{0.084}$  (left) and  $\text{Ge}_{0.893}\text{Sn}_{0.107}$  (right) microdisks.

Photoluminescence measurements were taken using a Fourier transform infrared (FTIR) spectrometer, with a nitrogen cooled InSb detector and a 532 nm excitation source. The system was operated in step-scan mode to remove the contribution of ambient blackbody radiation. Intensity increases were observed for all disk structures with the addition of SiN stressors. The highest strained disks ( $3 \mu\text{m}$  diameter) for the 10.7 % Sn alloys showed emission extending into the  $3 - 5 \mu\text{m}$  region, Fig. 4. Notably, the long wavelength side of the emission overlaps with a  $\text{CH}_4$  absorption line at  $\sim 3.3 \mu\text{m}$ , suggesting such disks could be used as emitters for gas sensing.

The peak splitting observed could appear to be due to separate  $\Gamma$ -valley to valence band transitions, with the valence band splitting from tensile strain, however, the dip in intensity ( $\sim 3.1 \mu\text{m}$ ) was found to be present for a range of disks (not shown), and has been attributed to absorption and/or scattering from the N-H stretching bond in the high stress SiN layer. This is also observable as a sharp edge of the long wavelength emission for the strained 8.4 % disk in Fig 4.

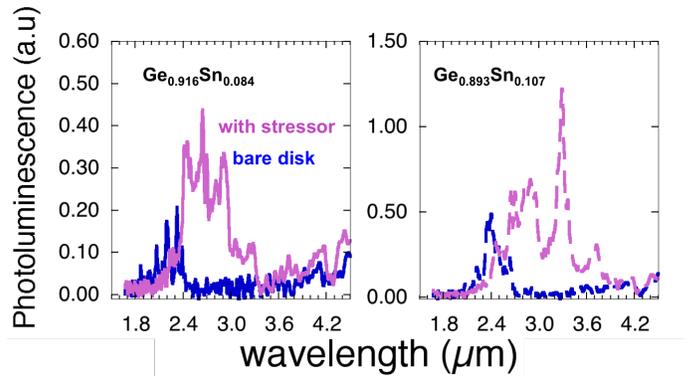


Fig. 4. Room temperature photoluminescence from strained and unstrained GeSn/Ge disks.

Using the bandgap bowing parameters in [1], and taking linear extrapolations of the deformation potentials from Ge [7] and Sn [1], the 10.7 % strained  $3 \mu\text{m}$  disks should have a  $\Gamma$ -valley as much as 85 meV below the L-valley. This is significant, as it demonstrates the largest  $\Gamma - \text{L}$  energy difference demonstrated from GeSn alloys, a metric that is key to achieving low threshold lasing.

### III. CONCLUSION

Pseudomorphic  $\text{Ge}_{0.916}\text{Sn}_{0.084}$  and  $\text{Ge}_{0.893}\text{Sn}_{0.107}$  alloys were grown on Ge virtual substrates, on (100) Si wafers. The alloys were characterized by XRD and found to be fully coherent to the Ge VS, with compressive strains of 1.10 % and 1.44 % for the 8.4 and 10.7 % alloys respectively. The alloys are indirect bandgap as-grown. Undercut GeSn/Ge microdisks were fabricated using Si foundry compatible processes, passivated by  $\text{Al}_2\text{O}_3$  layers, and subsequently stressed by SiN stressor layers. This results in direct bandgap, tensile GeSn emitters without the requirement for strain relaxation by misfit formation. The red-shift from tensile strain and Sn alloying leads to emission in the MIR, with the highest strained structures showing PL above  $3 \mu\text{m}$  wavelength. This emission has a good overlap with the methane molecular absorption lines, and highlights the potential for strained GeSn technologies in Group IV gas sensing applications.

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