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Direct Bandgap GeSn Microdisk Lasers at 2.5 µm for Monolithic Integration on Si-Platform

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Introduction: The demonstration of optically pumped lasing action in CMOS-compatible group IV GeSn alloys [1] along with recent progress in optical detection [2] and fiber transmission at 2 µm represent a major step towards the creation of fully integrated electronic and photonic circuitry [3] extending Si-based optical communications into the short-wavelength infrared (SWIR: 2 – 3 µm) [4]. In this paper, we present the first demonstration of group IV GeSn/Ge microdisk (MD) lasers. The evidence of lasing is supported by detailed analyses on strain-dependent photoluminescence (PL) of GeSn alloys with Sn concentrations ≥ 12 at.%. The presented CMOS-compatible fabrication of compact MD permits monolithic integration of group IV laser devices. Moreover, this cavity design is a mean to reduce the compressive strain within the GeSn epilayers which significantly improves the laser performance compared to their Fabry-Perot counterparts [1].

Direct bandgap GeSn epilayers: One of the visions in semiconductor physics is to create a direct bandgap group IV semiconductor suitable for lasers and compatible with the powerful Si electronics, allowing further functional integration and realization of new energy efficient concepts. GeSn layers with x_{Sn} = 12-13 at.% were grown on Ge-buffered Si(001) substrates using an industrial 200 mm RP-CVD tool with showerhead technology [5] at growth temperatures of 340-350°C [6]. Although these direct bandgap GeSn layers are partially strain-relaxed via misfit dislocations, the epilayers exhibit exceptionally high crystalline quality proved by TEM imaging and ion channeling/RBS measurements (Fig. 1 and 2). Figure 3 shows the 8x8 band k·p calculations of critical points of the Brillouin Zone (BZ) for $Ge_{0.875}Sn_{0.125}$ layers as function of biaxial compressive strain. At approx. -1.0 % compressive strain, the transition to a fundamental direct bandgap semiconductor occurs. The theoretically predicted indirect-to-direct transition is experimentally observed by means of temperature-dependent PL measurements (Fig. 4). The strong PL peak is attributed to electron-hole recombination at the center of the BZ (Γ-valley). The steady increase of the integrated PL intensity with decreasing temperature observed for samples B-D indicates a fundamental direct bandgap of the material [1]. For the fully strained sample A, the integrated PL intensity increases with temperature similar to well-known indirect bandgap group IV semiconductors like Ge [7] (Fig. 5) where the electrons are thermally excited from the L-valleys into the Γ-valley and recombine at the center of the BZ. At low temperatures the probability for this carrier transfer from L-valleys to the Γ-valley becomes ever smaller and, consequently, the luminescence vanishes. For further laser fabrication, -0.4 % strained 560 nm thick $Ge_{0.875}Sn_{0.125}$ layers are used with an energy offset between the L- and Γ-valleys of the conduction band, $\Delta E_{L\text{-}\Gamma}$, of approx. 50 meV (Table 1).

GeSn microdisk laser: The mesa for the $Ge_{0.875}Sn_{0.125}$/Ge MD cavities were deeply (900 nm) dry-etched into the Ge buffer using Cl_2/Ar and subsequently underetched using an anisotropic and highly selective CF_4 plasma. After standard pre-high-k deposition cleaning, a 10 nm thick Al_2O_3 passivation layer was deposited by atomic layer deposition (ALD) in order to reduce surface recombination (Fig. 6 a - d). A scanning electron micrograph of a $Ge_{0.875}Sn_{0.125}$ MD is shown in Fig. 7. The obtained undercut of the GeSn MD results in an increased optical mode confinement within the optically active GeSn as well as in elastic strain relaxation towards the edge of the disks as verified by Raman mappings (Fig. 8). This relaxation leads to an increase of the energy separation between the L- and Γ-valleys ($\Delta E_{L\text{-}\Gamma}$ ~ +80 meV, Fig. 9) enabling a larger population of the Γ-valley towards the MD edge. Consequently, the carrier confinement is supposed to be increased compared to Fabry-Perot laser devices presented in Ref. [1]. The optically excited 8 µm disks emit coherent stimulated light in the SWIR range with a peak emission at 2.5 µm (0.5 eV) at 50 K (Fig. 10). The PL intensity increases abruptly by more than three orders of magnitude when increasing the optical excitation by a factor of 4 indicating a clear lasing threshold. Additionally, the linewidth collapses at 221 kW/cm^2 from 36 meV to 3 meV (Fig. 11). The light-in light-out (L-L) curve displayed in Fig. 12 is the final piece for the evidence of lasing. The determined unambiguous lasing threshold of 221 kW/cm^2 is approx. 1/3 lower compared to thresholds for GeSn Fabry-Perot cavities reported in [1].

Summary: We demonstrated the strain-dependent transition from an indirect to direct bandgap group IV semiconductor in $Ge_{0.875}Sn_{0.125}$ epilayers. The 560 nm layers which offer the largest optical confinement have been used to fabricate the first Si-based direct bandgap group IV microdisk laser at a lasing wavelength of 2.5 µm via standard CMOS-compatible processing.

References:

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Sample	x_{Sn} (±0.5) at.%	Thickness (±5) nm	Calculated $\Delta E_{L\text{-}\Gamma}$ (meV)
A	12	46	-57
B	13	172	6
C	12.5	280	44
D	12.5	414	50
E	12.5	560	50

Table 1: Results of the GeSn layer characterization by means of RBS. The directness $\Delta E_{L\text{-}\Gamma}$ was determined using 8-band k·p calculations and indicates a strain-dependent indirect-to-direct transition.

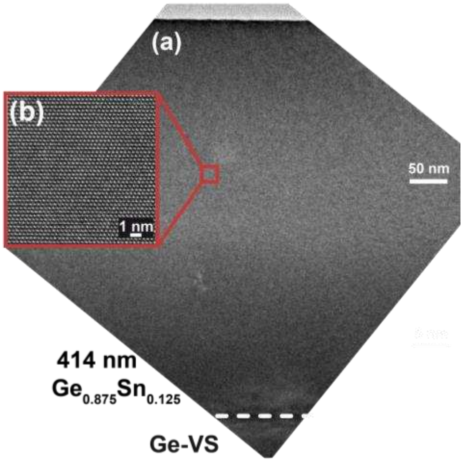

Fig.1: TEM micrographs of a 414 nm $Ge_{0.875}Sn_{0.125}$ layer showing (a) no Sn segregation/precipitation and (b) high monocrystalline quality.

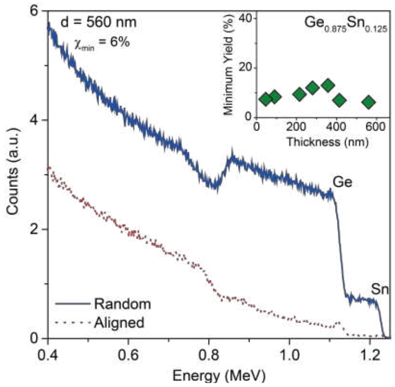

Fig.2: Random and aligned RBS spectra of a 560 nm $Ge_{0.875}Sn_{0.125}$ layer with a χ_{min} of 6%. The crystalline quality does not degrade for thicker layers (inset).

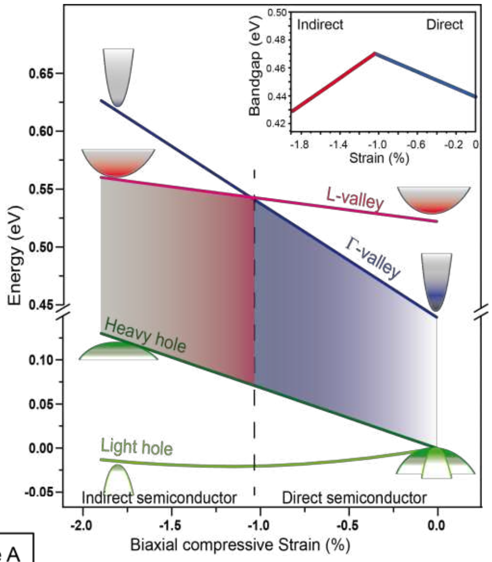

Fig.3: Results of strain-dependent k·p band structure calculations for $Ge_{0.875}Sn_{0.125}$ alloys. A fundamental direct bandgap can be achieved for $\varepsilon > -1$ %.

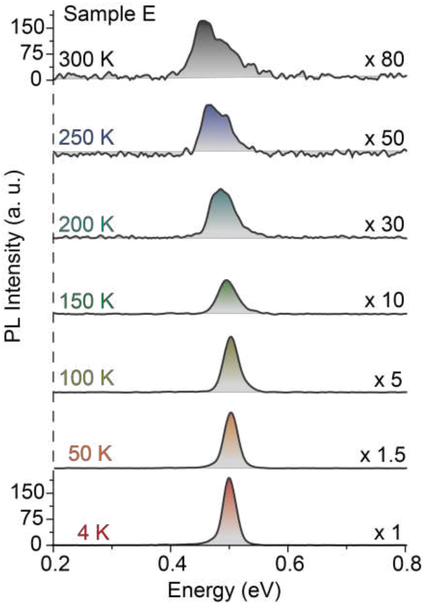

Fig.4: Temperature-dependent (300 – 4 K) PL spectra of sample E. The peak intensity as well as the integrated PL signal steadily increases with decreasing temperature.

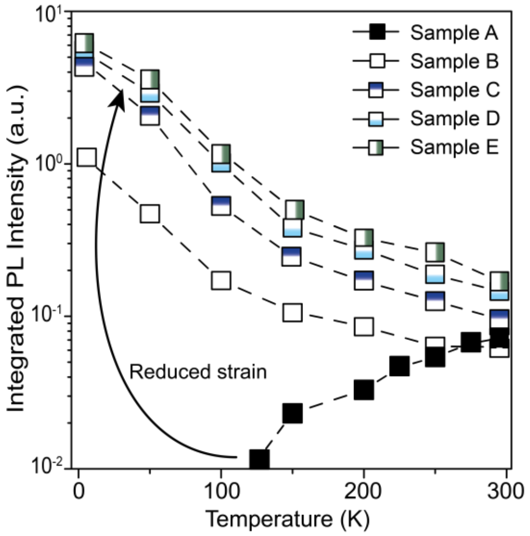

Fig.5: Temperature-dependent integrated PL intensities for samples A-E. The results indicate a fundamental direct bandgap for samples B-E, while the fully strained layer A is supposed to be an indirect semiconductor.

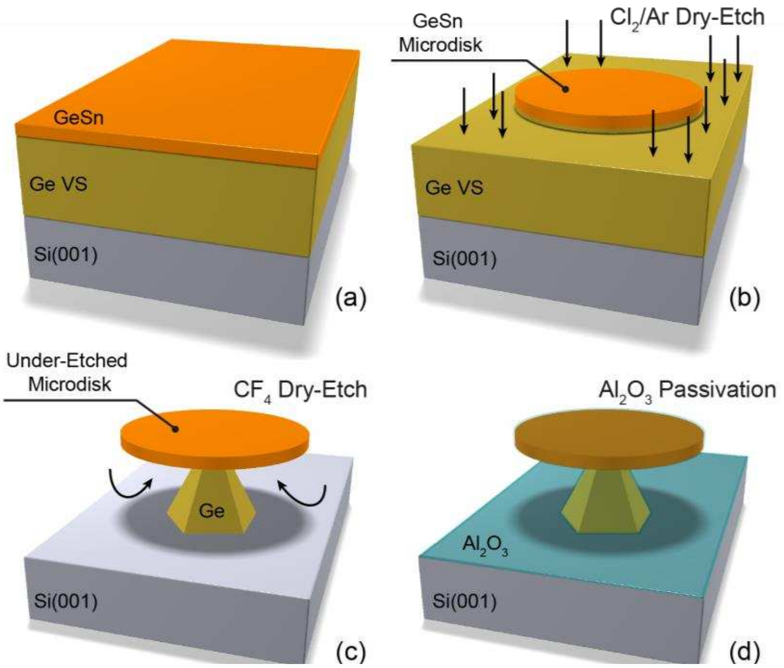

Fig.6: Sketch of the fabrication process of the underetched microdisks (MD). After the epitaxy (a), the MD mesa is defined using a Cl_2/Ar dry-etch (b). For the undercut a CF_4 plasma is used (c). Subsequently, the disks were passivated with a 10 nm Al_2O_3 layer (d).

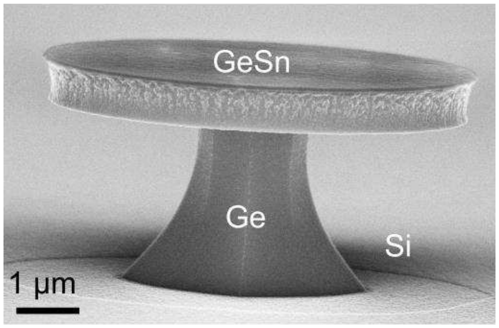

Fig.7: Scanning electron micrograph of an underetched $Ge_{0.875}Sn_{0.125}$ MD with a diameter of 8 µm from layer E.

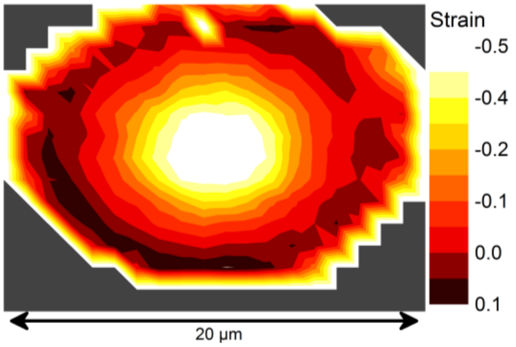

Fig.8: Raman map of a 20 µm $Ge_{0.875}Sn_{0.125}$ MD from layer E showing the strain relaxation towards the edge of the disk.

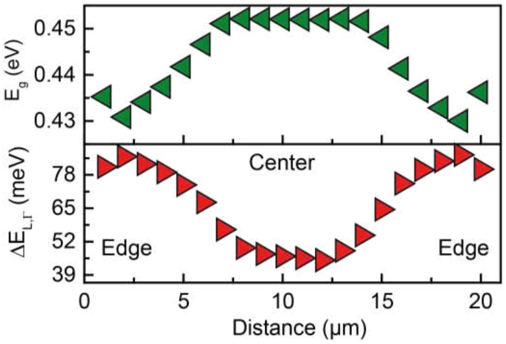

Fig.9. k·p simulation indicating a higher offset between the Γ- and L-valleys as well as a lower bandgap at the edge of the MDs.

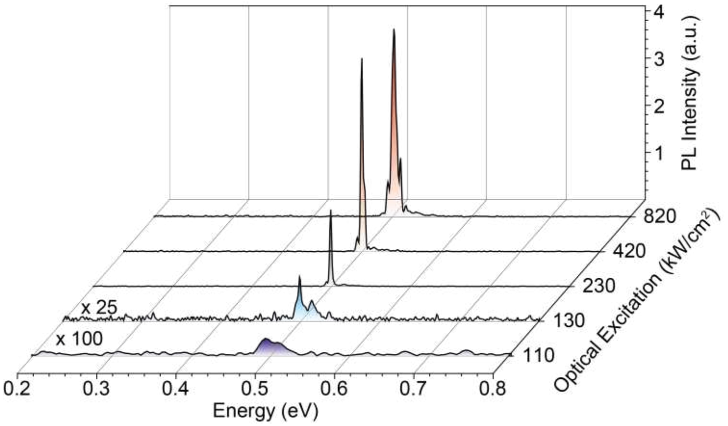

Fig.10: Power-dependent PL spectra of an 8 µm diameter $Ge_{0.875}Sn_{0.125}$ MD from layer E at 50 K. The intensity abruptly increases at approx. 230 kW/cm^2.

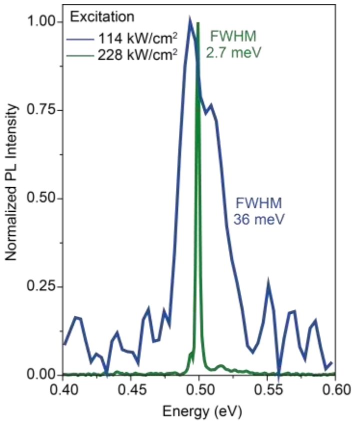

Fig.11: Normalized PL intensities below (114 kW/cm^2) and above (228 kW/cm^2) lasing threshold. Above threshold the linewidth decreases by more than one order of magnitude.

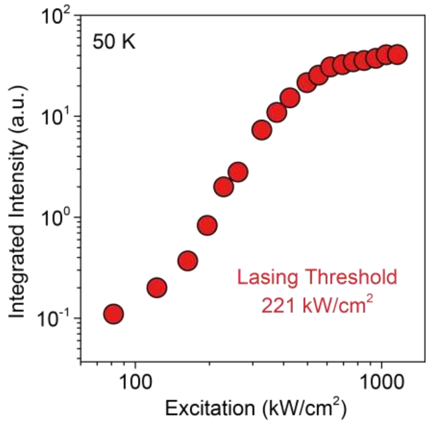

Fig.12: LL-curve of an 8 µm GeSn MD laser. The lasing threshold amounts to approx. 220 kW/cm^2.