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Ultra-low threshold cw lasing in tensile strained GeSn microdisk cavities

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Abstract— GeSn is proven as a good candidate to achieve CMOS-compatible laser sources on silicon. Lasing demonstrations in this alloy were based on directness of the band structure, this directness being increased with increasing the Sn content above 8 at.%. These past few years the research were consequently focused on incorporating the highest Sn content as possible to achieve high directness and high temperature laser operation. This unfortunately results is increased threshold. In this contribution we discuss the advantages in combining tensile strain engineering with lower Sn content alloys. This approach is motivated by the higher material quality in lower Sn content. The case with Sn content as small as 5.4 at.% Sn will be discussed. The alloy is initially compressively strained, and exhibits an indirect band gap that is turned to direct by applying tensile strain. A specific technology based on transfer On Insulator stressor layer on metal was developed to address strain engineering, thermal cooling and defective interface with the Ge-VS. This led to lasing in $Ge_{0.95}Sn_{0.05}$ microdisk cavities with dramatically reduced thresholds, by two order of magnitude, as compared to the case with high Sn alloys and as consequence enables cw operation.

Keywords—GeSn laser, tensile strain, cw and pulse lasing

I. INTRODUCTION

GeSn has become a well-established group-IV promising material to achieve Si-compatible laser source. Since the first demonstration of laser emission in GeSn alloys[1], it comes out that high lasing threshold, in the hundreds of kW/cm^2 range requiring pulsed excitation is a major issue that is not obvious to overcome.[2] The main key ingredients that would play a major role in reaching low threshold and high lasing temperature would be (i) the directness of the band structure, quantified by the direct-indirect conduction band splitting energy $\Delta E_{L\text{-}\Gamma} = E_L\text{-}E_\Gamma$ (ii) the structural quality of the active layers influencing the carrier recombination dynamics (iii) reduction of the band structure density of state and charge carrier confinement like in MQW structures[3][3]. Alloying Ge with high content of tin is a very interesting approach to increase the directness of the band structure, and was used recently to increase lasing temperature up to 180K, 230K[4][5]. Howether large at.% Sn in GeSn grown on Ge-VS yields in turn high dislocation densities due to lattice mismatch between Sn and Ge. Formation of point defects near the GeSn/Ge interface thus possibly introduce trap levels for carrier. This would explain the high threshold needed to reach laser regime in the material despite a high directness were reached. Applying tensile strain to increase the directness is also an approach that additionally allows to dramatically reduces the valence band DOS by lifting the valence band LH-HH degeneracy [6][7].

In this work we show the potential of low Sn content GeSn alloys, advantaged by high material quality as compared to higher Sn content alloys, but combined with tensile strain to recover the directness of the band structure. A layer transfer technology is used to address both the GeSn/Ge defective interface and tensile strain engineering. An all-around stressor design is used to homogeneously apply high level of tensile strain in the GeSn layer [8]. The design has been adapted to enhance thermal cooling under cw excitation by introducing an intermediate metallic layer [9].

II. EXPERIMENTAL

A. Material and technologies issues

The GeSn layers were grown via reactive gas source epitaxy using Ge_2H_6 and $SnCl_4$ precursor at 375°C on a 2.5µm thick Ge virtual substrate on silicon. The GeSn layers were 300nm thick and contained 5.4 at.% Sn as confirmed by EDX analysis and RBS. The as-grown layer were partially relaxed, with a residual compressive strain of -0.32% as confirmed by X-Ray diffraction (XRD), and Raman spectroscopy. The as-grown layer exhibits an indirect band gap with a directness $\Delta E_{L\text{-}\Gamma}$ of -60 meV. TEM analysis as shown on Figure 1-a allows to assess for the high crystallinity of the GeSn layers above the interface with the Ge-VS.

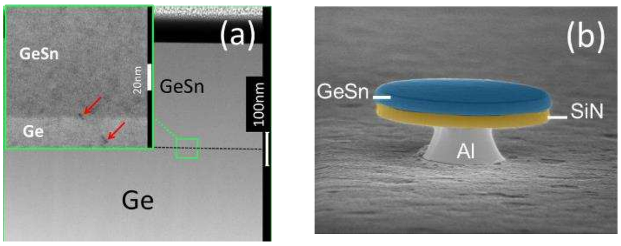

Figure 1 (a) HAADF-STEM micrograph of the grown GeSn layer. The layer is 300 nm thick. The inset shows an Atomically-resolved Bright Field-STEM image centered at the Ge/GeSn interface, a pair of partial dislocations present at the interface. The dislocations efficiently recombine within the first twenty nanometers of the GeSn layer. (b) SEM view of the layer after transferred and patterned into microdisks.

The GeSn layer is transformed into GeSnOI structure using bonding method. Prior to the bonding a compressively stressed SiN layer (-1.9GPa) and Al layers were successively deposited. After bonding and remove of the Si substrate and of the Ge-VS, the defective GeSn layer is removed such that the final layer is reduced in thickness by typically 40nm.

The transferred layer is then patterned into GeSn/SiN free-standing microdisk sustained by an Al pedestal as shown in figure 1-b. At this stage the bottom SiN acts as a bottom stressor layer, applying tensile to GeSn by relaxing the initial compressive stress. To reach the all-around stressor design enabling homogeneous strain transfer from stressor to the GeSn layer volume, a final SiN deposition is performed on the whole disk pattern. The final disk structure is shown in the inset of Fig. 2. A biaxial tensile strain of 1.4-1.5 % were obtained by Raman spectroscopy, yielding a directness around 70meV as expected from **k.p** modelling [6]. The tensile strain induces a lift of the valence band degeneracy the light hole band being set as the fundamental band for holes.

B. Results

Low temperature laser emission experiments were performed using a µ-PL setup, where the excitation from a Nd:YAG continuous wave laser beam at 1064nm wavelength is focused into a 12µm spot diameter on the sample surface. The PL emission spectra were analysed as a function of the pump power as presented in Fig.2. Clear laser emission features are obtained, linewidth narrowing and threshold behaviour of L-L curve.

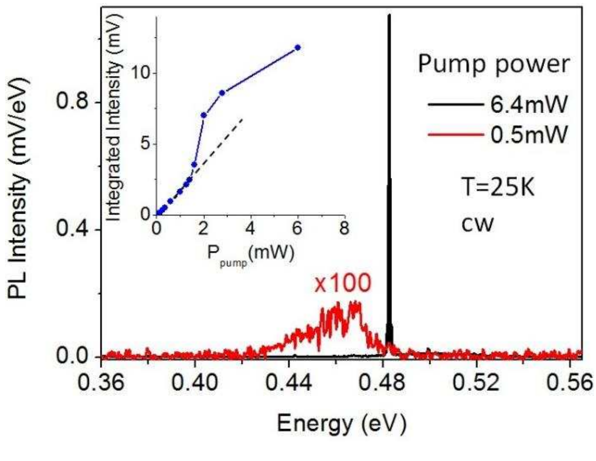

Fig 2: CW PL emission spectra from a 7µm diameter GeSn disk all-arrounded by a SiN stressor at 25K, below and above lasing threshold. The insets shows the L-L curve as obtained under cw excitation.

Below threshold, at pump power lower than 1mW, broad emission spectrum is obtained, associated to the direct recombination involving Γ-LH transitions. When power is increased the spectrum abruptly turns into a dominant mode pattern at 0.483eV. Figure 3-a shows the emission spectra above threshold in a log-scale, 2-3 order of magnitude larger intensity is observed for the laser pattern with respect to the broad spontaneous emission. The L-L curve as shown in Figure 2 is based on integrated spectrum which turns from weak and broad out-coupled emission to a sharp but intense emission. The integrated peak intensity as function of incident power is shown in Fig.3-b. The obtained L-L curve shows more clearly the threshold dynamics of the lasing mode peak, i.e. for emitted light coupled with the cavity WGMs and susceptible to be amplified by gain.

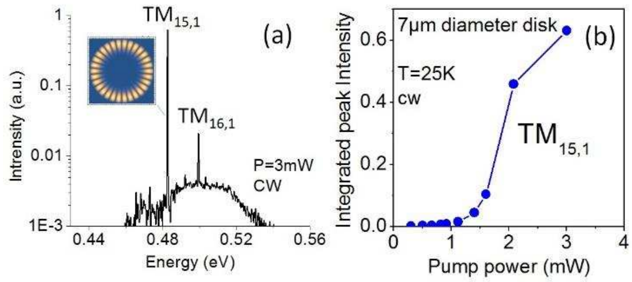

Fig. 3 : (a) CW laser emission spectra from a 7µm diameter GeSn disk all-arrounded y a SiN stressor in Log-scale (b) L-L curve using the lasing mode $TM_{15,1}$ integrated peak intensity.

One specificity of tensile stressed structure along the xy-plane is making the gain polarized along the z-axis, according to Γ-LH transition matrix selection rule [6][7]. As a consequence TM emission from the disk is much more amplified than in TE. Modelling of whispering gallery mode, assuming TM-polarized propagating waves in the GeSn layer, predicts WGMs with radial number n=1, $TM_{15,1}$ and $TM_{16,1}$ at 0.486eV and 0.502 eV respectively, leading to a mode spacing of 16meV. The modelling is consistent with the experimental spectrum in Fig.3-b, showing the dominant lasing mode at 0.483 eV and a second modes at 0.499eV, indicating that gain is indeed operating for TM-polarization.

Additional measurements were performed under pulsed excitation, enabling lasing operation up to 90K with lasing threshold in the kW/cm^2 range while cw lasing operation were observed up to 50K.

III. CONCLUSIONS

We show the advantages in reducing Sn content in GeSn combined with tensile strain for lasing. Experimentally we study the WGM mode lasing in tensile strained GeSn µ-disk cavities under cw-excitation. Steady state lasing in GeSn will be discussed for the first time. The cw and pulsed operation will be compared and improvement possibilities will be discussed.

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