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Strain-Engineering in Germanium Membranes towards Light Sources on Silicon

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Abstract

Bi-axially strained Germanium (Ge) is an ideal material for Silicon (Si) compatible light sources, offering exciting applications in optical interconnect technology. By employing a novel suspended architecture with an optimum design on the curvature, we applied a biaxial tensile strain as large as 0.85% to the central region of the membrane.

(Keywords: Si Photonics, Germanium, Light source)

Introduction

Bi-axially suspended germanium membranes exhibit extremely high strain values reducing the direct band-gap and thus enhancing light emission [1, 2]. Previous works have demonstrated high biaxial strain up to 1.9% [1] and 2.4 times PL enhancements [2] by using Ge-On-Insulator (GeOI) wafers. Despite the successful demonstrations by GeOI wafers [1, 2], the cost might be increased. We have utilized Ge on bulk Si wafers to manufacture suspended membranes.

Design, Simulation and Fabrication

2D Simulations were performed in COMSOL Multiphysics 5.2. The "Structural Mechanics" module was used with elasticity matrix defined in Voigt notation to simulate the strain values. The "dilute species" module was also used to simulate the diffusion of the solution during the wet etching to identify the boundaries of the etched Si substrate.

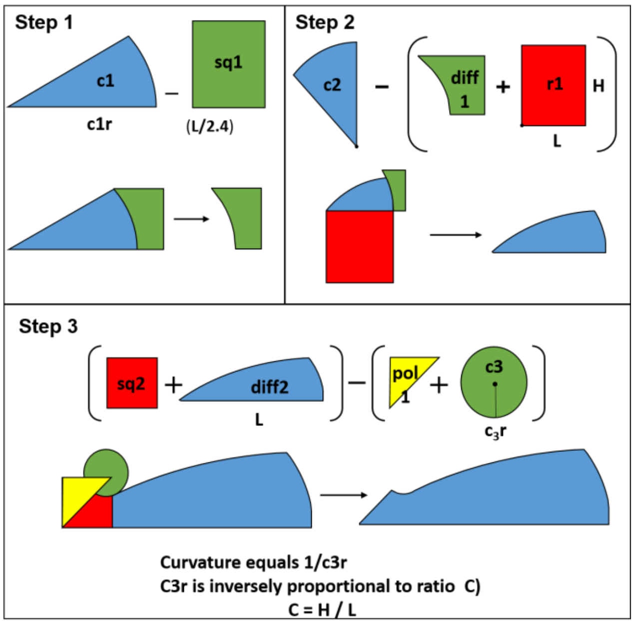

Fig 1: Schematic of design process for half an arm with curvature ratio *C*.

The design steps are shown in Fig. 1 with the curvature ratio, *C*, defined in terms of the comprising primitives.

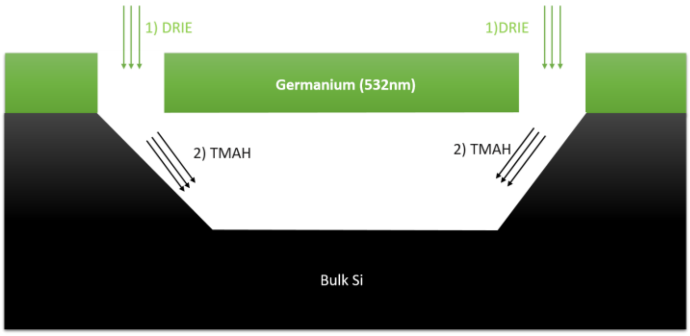

Fig 2: Schematic of the wafer stack and the main etching steps. DRIE defines the etch windows followed by an anisotropic wet TMAH under etch.

An intrinsic Ge on Si wafer was patterned using electron-beam lithography. The etching windows were patterned using deep reactive ion etching (DRIE) with 38 sccm Ar and 12 sccm CHF_3 at 200W RF power. Finally, the suspended Ge membranes were made using a Tetra-Methyl-Ammonium-Hydroxide (TMAH) wet etching process. Fig. 2 shows the wafer and main etching steps.

Results

Fig. 3 shows an optical 3-Dimentional (3*D*) micrograph of a structure with *C* of 3.0. The etching profile can be seen with etched slopes corresponding to the <111> crystallographic plane.

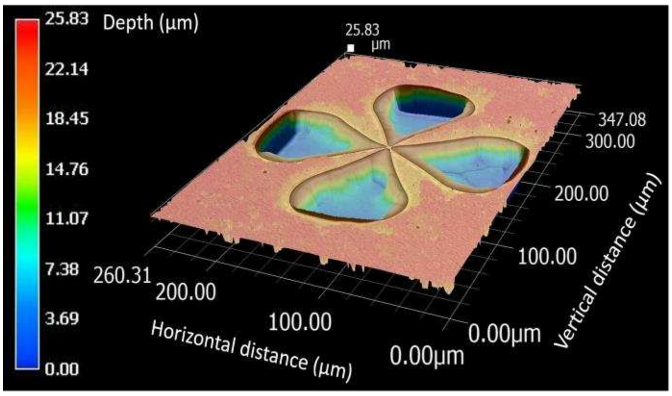

Fig 3: 3D micrograph of structure with *C* of 3.0

Fig. 4 shows a titled optical micrograph of a structure with *C* of 3.0 and the etched window, in which the shadows show successful suspension.

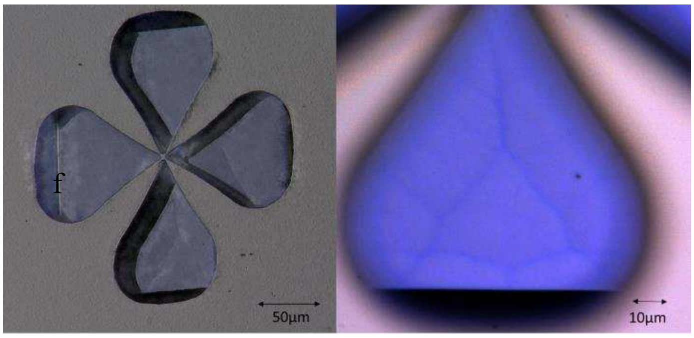

Fig 4: a) Tilted micrograph of structure at *C* of 3.0. b) Normal micrograph of etch window with etched Si crystallographic planes visible.

Fig. 5 shows strain distribution at the extremities of *C* of 1.6 and 3.0. These simulations show improved homogeneity in the membrane with *C* of 3.0 relative to that with *C* of 1.6.

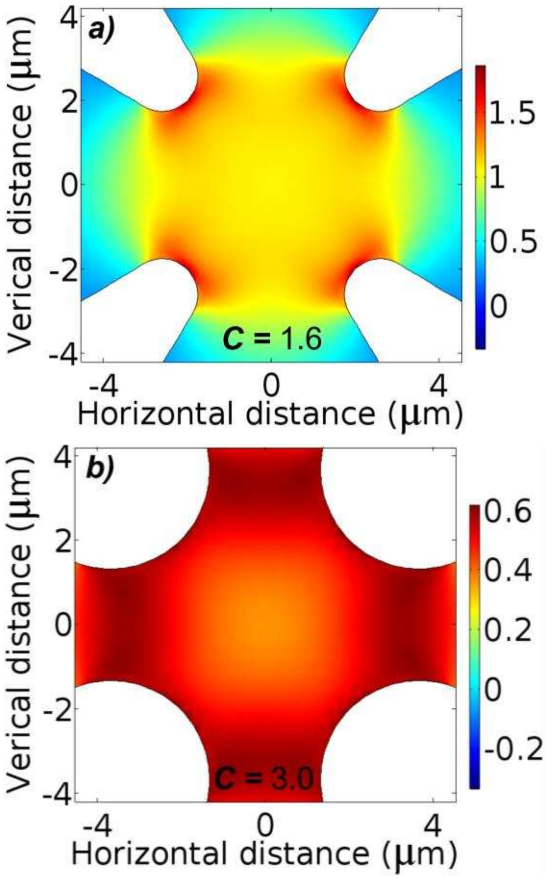

Fig 5: Simulated strain distributions with *C* of a) 1.6 and b) 3.0. As *C* increases the strain homogeneity increases.

Fig. 6 shows the Raman spectra at various *C* with Lorentzian fittings. The peak widths and peak positions was then extracted from this data.

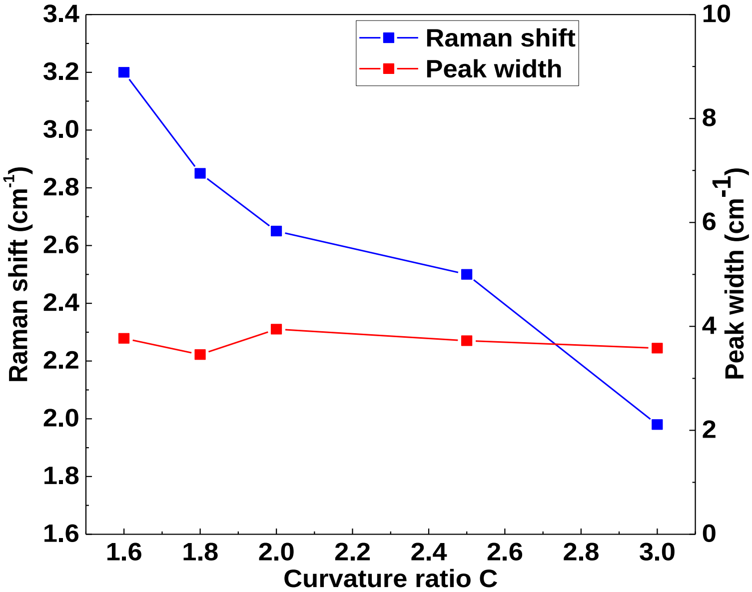

Fig 6: Raman spectra with Lorentzian fitting plotted over with increasing *c*

Figure 7 shows the effect of *C* on the peak widths and the Raman shifts. The peak widths remained relatively constant with increasing *C*, suggesting no major change in crystalline qualities. The decrease of the Raman shift on increasing *C* corresponds to the decrease of strain.

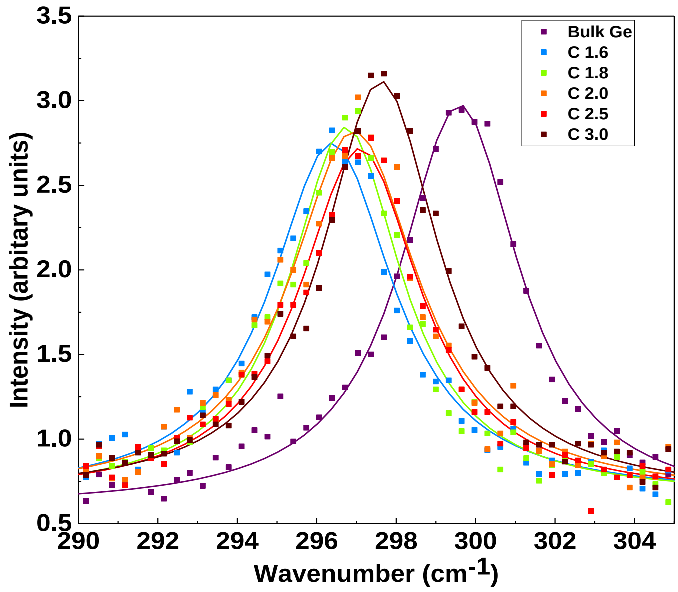

Fig 7: Raman shift and peak width with increasing *C*. Peak width remains relatively constant suggesting no significant change in crystalline quality. Raman shift decreases corresponding to decreasing central strain.

Fig. 8 shows the strain estimated from the Raman shift in comparison with the simulated values. Both the measured and simulated strain values decreased with increasing *C*, with a maximum strain of 0.85% observed at *C* of 1.6. The small differences between experimental and simulated values would be attributed to the simulated boundaries assuming *2D* isotropic wet etching, while actual wet etching was highly anisotropic. This highlights the need for a more sophisticated simulation for defining the profile taking into account the anisotropic etching of the silicon crystal in three dimensions.

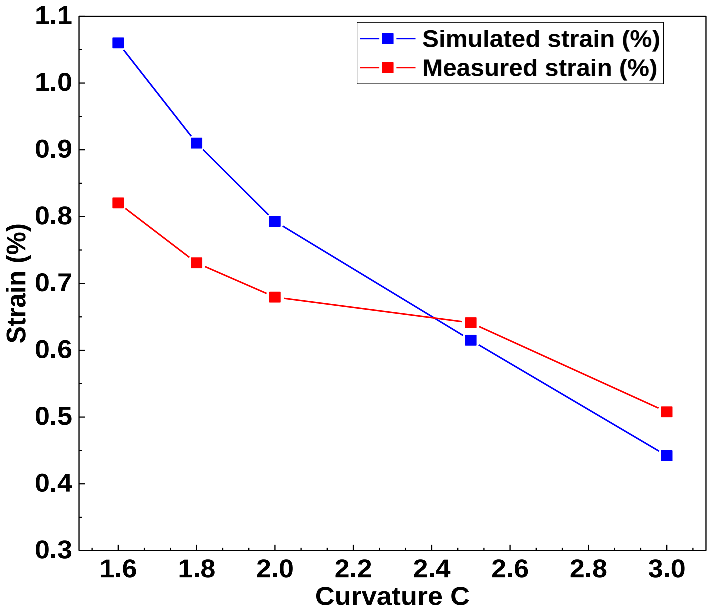

Fig 8: Simulated and measured strain at various *C*. Both simulated and measured strain decreases with increasing *C*. There is a discrepancy between the two sets of values is due to a simple isotropic etching profile being assumed.

Fig. 9. shows the micro-PL spectra at the center of structures with increasing *C*. Surprisingly, the devices with smaller *C* and thus higher central strain values exhibit smaller PL intensities. One explanation of this trend could be increased dislocations and thus increased non-radiative recombination due to higher strain values. In fact, we found significant local increase of the tensile strain at the edges of the membrane with *C* of 1.6 (Fig. 5 (a)). The steeper strain gradient resulted in the local band-gap distribution, and carriers might be recombined at the edges [2].

The peaks identified in the spectrum in Fig. 9 from the membrane with *C* of 3.0 would be attributed from the splitting of Light-Hole (LH) and Heavy-Hole (HH) bands with the presence of biaxial strain.

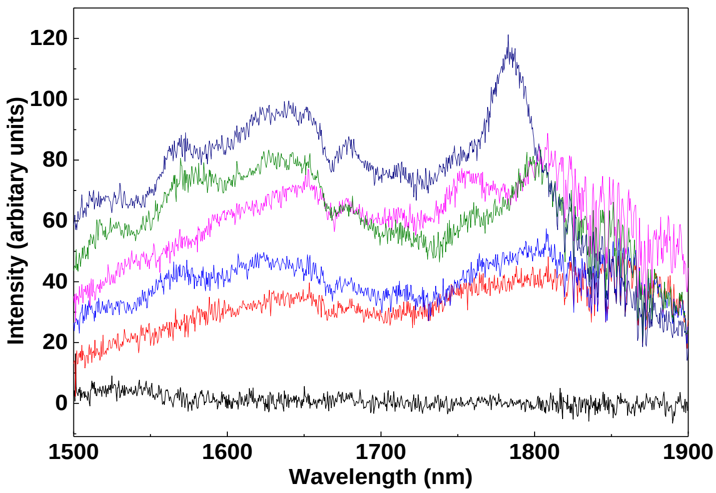

Fig 9: PL spectra at various *C* and bulk Ge. HH and LH splitting can be visualized as well as a decrease in intensity with increasing *C* despite the central strain value increasing.

Conclusion

We have successfully fabricated bi-axially suspended membranes using Ge on Si wafers with the tensile strain up to 0.85%. We found that the inhomogeneity of the strain reduces the PL intensities, so that the homogeneous strain-engineering would be critical towards developing monolithic Ge light sources on Si.

Acknowledgments

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