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Tensile Strain of Germanium Micro-Disks on Freestanding SiO_2 Beams

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Abstract

Tensile strain is crucial to expect the direct recombination in germanium (Ge), towards monolithic light sources on silicon (Si). Freestanding beams of Ge are known to produce strong tensile strain, however, it is not trivial to construct a cavity in a freestanding structure. Here, we fabricated Ge micro-disks on freestanding oxide beams, and observed Whispering-Gallery-Modes (WGM) by photoluminescence. The tensile strain was larger in shorter beams, which is consistent with simulations.

1. Introduction

Ge is expected to be useful as an active material for Si Photonics, that is also compatible with Complementary Metal-Oxide-Semiconductor (CMOS) processes [1]. Proposed applications include monolithic light sources, Franz-Keldysh modulators, mid-infrared waveguides, and so on [1]. Ge can be turned into an optical gain material by applying tensile strain and doping *n*-type impurities [2, 3]. Strain is utilized to deform the conduction band (CB) of Ge in order to reduce the energy difference between the direct (Γ) and indirect (L) valleys, consequently increasing the probability of direct-gap recombination and reducing the population inversion threshold [2]. Among various tensile strain engineering methodologies, such as the use of buffer layers and external stressors [4], freestanding structures can produce the highest strain by physical bending of beams [5]. However, embedding a cavity within a beam is not straightforward, if we are using a Ge beam.

In this paper, we examined Ge micro-disks on freestanding SiO_2 beams. This configuration combines a simple cavity and a freestanding beam, whose strain can be tuned through beam designs.

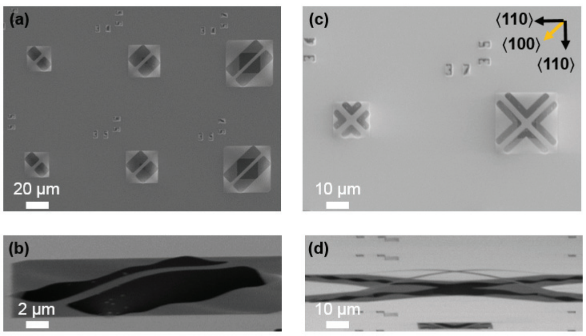

Fig. 1 Scanning electron microscopy (SEM) images of beams. (a) Plane and (b) bird's-eye view of beams for uni-axial strain. (c) Plane and (d) bird's-eye view of beams for bi-axial strain.

2. Structure and Fabrication

We used a commercially available Ge-on-Insulator (GOI) wafer with a Ge layer of 100-nm on a Buried-Oxide (BOX) of 145-nm. After cleaning the wafer using hydrofluoric (HF) and hydrochloric (HCl) acids, Ge disks with diameters ranging from 1 to 10 µm were dry etched. Then, the surface was passivated using SiO_2 with the thickness of 100-nm, deposited using Plasma-Enhanced Chemical-Vapour-Deposition (PECVD) at 350 ˚C. Afterwards, we fabricated various beams with different lengths, and crossed beams, for applying both uni-axial and bi-axial strain (Fig. 1). The beams were made of the BOX layer with Ge disks located at the centre, using dry and subsequent wet etching steps. SiO_2 beams were suspended by locally removing the Si substrate by Tetra-methyl-ammonium hydroxide (TMAH). Beams were aligned with the ⟨001⟩ direction [6]. The deflection of the beam upon suspension imposes tensile strain on the top Ge disk, due to the change in beam length. Beam lengths (L) were varied from 10 to 100 µm, while beam widths (W) were within the range of 1 – 12 µm.

3. Results and Discussion

Three-dimensional simulations were made assuming that beams buckle into the first eigenmode with fixed boundary conditions, which will be justified for beams with rigid girder. According to simulations, straight beams (Fig. 2(a)) impose a tensile strain component along the beam direction, x, while the other in-plane, y, and out-of-plane, z, components are compressive (Fig. 2(b)).

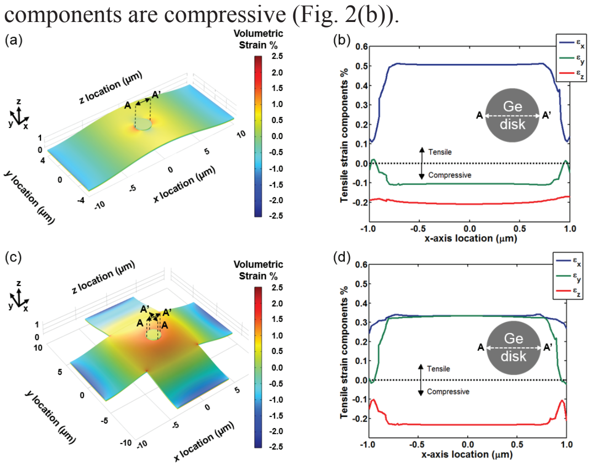

Fig. 2 Three-dimensional simulations showing (a) volumetric strain distribution and (b) individual strain components along the diameter of a Ge disk on a freestanding SiO_2 uni-axial beam. (c) & (d) shows results for a bi-axial beam with similar dimensions.

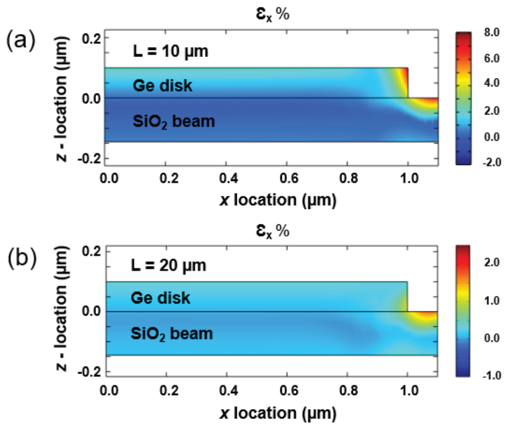

Fig. 3 Distribution of the radial strain component across the disk radius for (a) 10 µm and (b) 20 µm beam lengths (L).

On the other hand, crossed beams (Fig. 2(c)) produce biaxial strain (Fig. 2(d)). Consequently, crossed beams have a larger total strain in volume compared to uni-axial beams with similar dimensions, and the deformation in the conduction band of Ge becomes larger [7]. In both cases, the applied tensile strain increases with decreasing L, while the dependence of W is not significant for beams longer than 10 µm. Cross-sectional maps in Fig. 3, indicate that the strain is mostly tensile within the disk, although it varies across the location. Remarkably, the highest radial tensile strain component is at the edges of the disk, which is advantageous for WGMs.

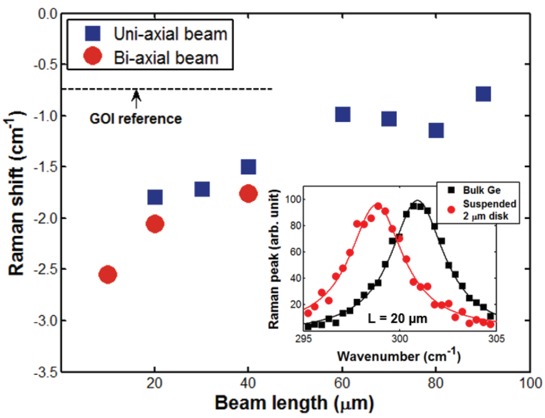

Fig. 4 Raman spectroscopy measurements of 2 µm Ge disks on freestanding SiO_2 beams with different lengths (width = 4 µm). Inset shows actual Raman spectra before and after suspension.

Raman spectroscopy analysis was made using an excitation laser with a wavelength of 532-nm. We measured the power dependence of the Raman shift relative to bulk Ge (301 cm^{-1}) in order to subtract the impacts of heating [6]. We confirmed that shorter beams had higher strain values in agreement with simulations.

Photoluminescence (PL) measurements were made using an excitation laser with a wavelength of 730-nm. Accumulation of modest tensile strain within the Ge disks after suspension is confirmed by the shift in PL spectra. WGM resonances were observed from a 3 µm Ge disk on a freestanding uni-axial beam with curved edges [6]. A Raman shift of -1.1 cm^{-1} was observed from this disk, and a PL peak at 1592 nm, indicating a uni-axial strain of approximately 0.73%.

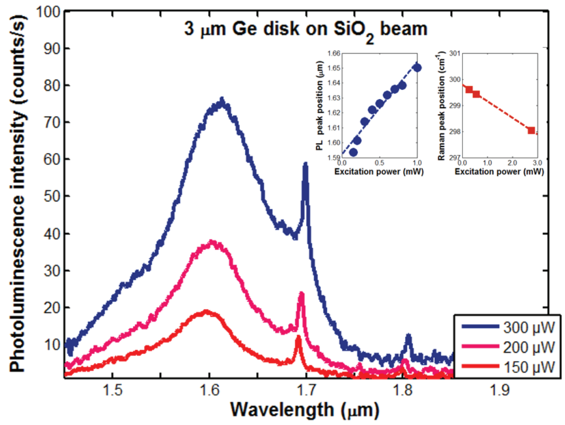

Fig. 5 Photoluminescence (PL) spectra of a 3 µm Ge disk on a freestanding SiO_2 beam. Insets show the power dependence of Raman and PL peaks.

4. Conclusions

The use of GOI wafers permits the fabrication of simple Ge micro-disk cavities on freestanding SiO_2 beams. Accumulation of tensile strain within the disks is achieved upon suspension. The nature of this strain, and its value, can be controlled through the design of the beams. Shorter beams have higher strain, which was confirmed experimentally. Crossed beams have biaxial strain with more deformation in the CB of Ge. The proposed Ge micro-disks on freestanding beams enable us to optimize further by designing optical cavities and strain profile, independently.

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