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 the 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.

The design steps are shown in Fig. 1 with the curvature ratio, *C*, defined in terms of the comprising primitives. 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. 4 shows a titled optical micrograph of a structure with *C* of 3.0, in which the shadows show successful suspension. 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. 6 shows the Raman spectra at various *C* with Lorentzian fittings. 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. 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 2*D* 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 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.

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

This work is supported by EPSRC Manufacturing Fellowship (EP/M008975/1), EU FP7 Marie-Curie Carrier-Integration-Grant (PCIG13-GA-2013-61811), and EPSRC Institutional Sponsorship Research Collaboration. The data from the paper can be obtained from the University of Southampton e-Print research repository: http://doi.org/10.5258/SOTON/

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