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Strain Management in Germanium-On-Insulator (GeOI) Substrates for Photonic Applications

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Abstract

High tensile strain values are needed in the germanium to induce a direct band-gap in the material and enable Ge laser integration on Si platforms. Two parameters are essential for that: a high crystalline quality of the Ge layer and the presence of a small tensile strain in the GeOI layer (in order to amplify it thanks to micro-structuring). Different 200 mm GeOI wafers for Si photonics were fabricated starting either with (1) thick Ge layers grown on Si substrates or (2) bulk Ge. We show that the 1st kind of 200 mm GeOI substrate exhibit a homogenous residual strain over the whole wafer surface. Record values of tensile strain were obtained on these substrates after strain amplification. We studied the effect of thermal annealing on the 2nd kind of GeOI substrates in order to detect the eventual presence of a built-in tensile strain.

1. Introduction

One of the main challenges in silicon photonics is the fabrication of efficient laser sources compatible with the technology used in microelectronics. Germanium (Ge) is an interesting alternative to the complex integration of III-V group materials on Si photonic platform. Indeed, it has been demonstrated that high amounts of tensile strain in Ge can improve light emission and transform Ge into a direct band-gap material [1,2], opening the way to mid-infrared lasers fully compatible with Complementary Metal Oxide Semiconductor (CMOS) technology. Theoretical studies predict this transformation to occur from about 4.6% to 5.5% uniaxial or 1.8% biaxial tensile strains [3-5]. Achieving such large strain values while maintaining good crystalline integrity is really challenging. Several methods are currently being explored. The highest strain values reported so far were obtained by strain redistribution [4,6]: suspended micro-bridges were designed to enhance the residual build-in tensile strain [6,7]. This residual tensile strain (close to 0.16% [8,9]) is due to thermal expansion coefficient differences between Ge and Si which comes into play during the cooling-down to room temperature after the epitaxial growth of thick Ge layers on Si. However, the high stress values targeted cannot be achieved starting from Ge layers grown directly on Si or Silicon-On-Insulator (SOI) substrates. Indeed, we are then limited by the reduced mechanical strength of the Ge membranes stemming from the presence of misfit dislocations at the Si-Ge interfaces [7,10]. It is therefore necessary to have a better crystalline quality of the Ge layer to push back the mechanical breakdown limit of highly stressed membranes. To that end, we fabricated 200 mm GeOI substrates tailored for photonic applications using the Smart Cut™ technology from thick Ge layers grown on Si substrate [11,12]. X-ray diffraction was used to assess the Ge crystalline quality and strain homogeneity at the GeOI wafer level. World record tensile deformation along the [100] uniaxial direction [13] and the [001] biaxial direction [6] was obtained using strain redistribution in micro-bridges. In order to further improve the starting material quality, we have also fabricated GeOI wafers from bulk Ge donors and characterized with Raman and XRD measurements the residual strain in the Ge layer as a function of thermal annealing.

2. GeOI substrates

Fabricated from Ge grown on Si donors

GeOI wafers were fabricated using the Smart Cut™ technology starting with 2.5 µm thick Ge layers grown on silicon substrates. The detailed process flow is described in [10]. The resulting 200 mm optical GeOI substrates were made of 0.5 µm to 1 µm thick germanium layers on top of a 1µm thick buried oxide. Only a few small defects are observed at the extreme edges of the wafer (Fig. 1a).

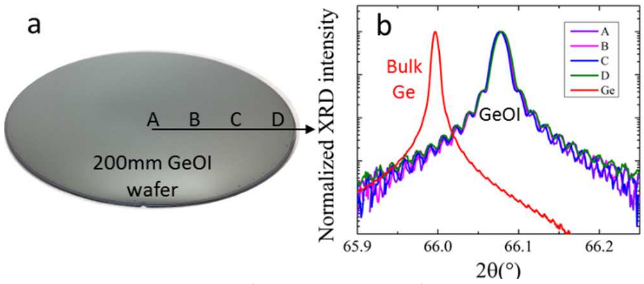

Fig. 1 a) Photograph of a GeOI substrate (from Ge grown on Si) with positions associated with XRD measurements b) XRD ω-2θ scans around the (004) Ge peak for the 4 positions probed on a GeOI and bulk Ge.

High resolution scans around the (004) X-Ray Diffraction order (in a Smartlab diffractometer with a 4 bounces Ge(220) monochromator and a 2 bounces Ge(220) analyzer) were performed along a GeOI wafer radius and on bulk Ge (Fig. 1b). The higher 2θ values of the Ge peak show clearly that the GeOI layer is slightly tensely strained. The extracted in-plane strain at the 4 positions probed is equal to 0.14625%, on average, with strain variations less than 0.005% along the wafer radius. The initial tensile strain in thick Ge strain-relaxed buffers grown on Si(001) substrates (0.16%) is maintained at a similar value (0.14%) after the whole layer transfer process, uniformly over the wafer surface. Using these GeOI wafers, record values have been demonstrated for uniaxial strain (4.9%) [13] and for biaxial strain (1.9%) [6].

Fabricated from bulk Ge donors

We fabricated GeOI substrates from bulk Ge donors, nominally free of dislocations, to reach even higher tensile strains in micro-bridges and improve the directness of Ge. The problem in this case is the lack of strain in the starting Ge substrate. J. Kang *et al.* showed that such GeOI samples were tensile-strained after annealing [14]. Initially, we fabricated GeOI wafers from 200 mm bulk Ge, without ion implantation: a Ge substrate with on top a deposited silicon oxide layer was bonded on an oxidized silicon substrate. After consolidation annealing at 200°C for 2 h, the Ge substrate was thinned by grinding then smoothed by chemical mechanical polishing. The remaining Ge thickness was 10 µm on top of a 1 µm thick buried oxide. The impact of thermal annealing was studied at temperatures ranging from 450°C to 650°C in a N_2 ambient during 1 h. A micro-Raman spectrometer with a 785 nm wavelength excitation laser was used to probe the strain in the Ge. The resulting probing depth was 200 nm with a spot diameter around 1 µm. The Raman spectrometer uncertainty was 0.1 cm^{-1}.The Raman spectral shift was measured by fitting the Raman spectra with Lorentzian functions (Fig. 2). A slight shift of the Ge peak wavenumber is observed on annealed GeOI samples. A tensile strain optimum of about 0.15% is obtained after 600°C anneal for 1 h. These results are closed to the one obtained in [14]. However strain values in the 10 µm thick Ge layer have to be confirmed with XRD measurements since only the first 200 nm was probed.

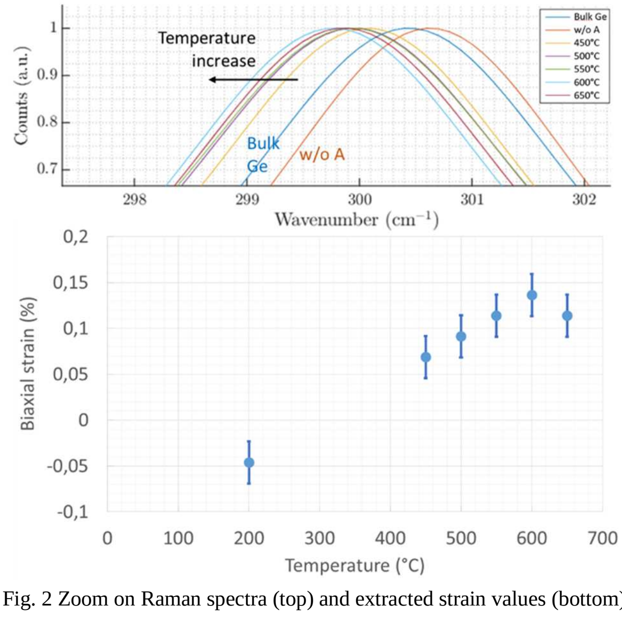

Fig. 2 Zoom on Raman spectra (top) and extracted strain values (bottom) of the GeOI samples as function of annealing temperatures.

In a 2nd step, we fabricated 200 mm GeOI substrates from bulk Ge using the Smart Cut™ technology. The same Smart Cut™ process flow was used [10] except that we started with a 8 in. p-type bulk Ge (100) donor wafer. Fig. 3a shows the scanning acoustic microscope (SAM) image of the bonding quality. The wafer surface is free of bonding defects leading to a 200 mm GeOI substrate without any macroscopic defects (Fig 3b). The Ge thickness average at the end of the process is 940 nm (Fig 3c). Fig. 4a shows cross-section TEM images of a 1 µm thick GeOI layer on top of a 1.15 µm thick buried oxide. A high crystalline quality is highlighted (inset).

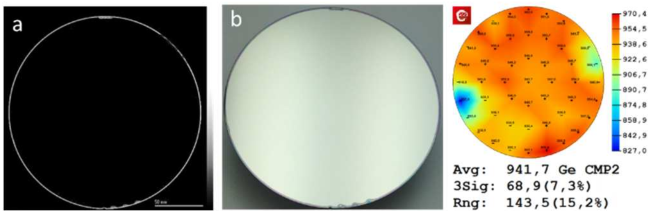

Fig. 3 a) SAM images of the 200 mm bonded Ge and Si wafers. b) Photograph of a 200 mm GeOI wafer fabricated from bulk Ge. c) Spectroscopic ellipsometry measurement of the top Ge layer thickness.

The impact of thermal annealing (up to 650°C) was also studied. Raman spectroscopy measurements did not show any clear evolution of the strain as a function of annealing (data not shown). We performed XRD measurements on GeOI wafers without annealing and with a 550°C annealing (Fig. 4b) which confirmed the Raman results. The non-annealed substrate showed an in-depth strain gradient and a macroscopic out of plane strain value close to zero (0.014%). The strain gradient was removed in the annealed substrate but the macroscopic strain value stayed close to zero (-0.008%). These results indicate that it is essential to develop another technological solution to slightly strain the Ge film of GeOI wafers fabricated from bulk Ge donors.

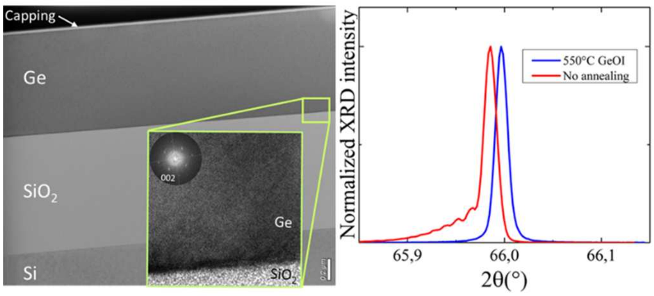

Fig. 4 a) Cross-section TEM and HR-TEM images of a GeOI wafer fabricated from bulk Ge donor. b) XRD ω-2θ scans around the (004) Ge peak for GeOI (from bulk Ge donors) with and without 550°C annealing.

3. Conclusion

We have fabricated high quality 200 mm GeOI wafers from thick Ge layers grown on Si and from bulk Ge donors. Unprecedented high uniaxial and biaxial Ge strains were obtained using GeOI wafers (fabricated with the Smart-Cut™ technology from Ge grown on Si) and strain redistribution in suspended micro-bridges. We succeeded to have some tensile strain in GeOI substrates fabricated from bulk Ge but more comprehension is needed. The crystalline quality of those GeOI wafers is expected to be strongly improved, with a very low dislocation density in Ge. Our results open the way to further increases in the directness of strained Ge.

References

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