REAL-SPACE STRAIN MAPPING OF SOI FEATURES USING MICROBEAM X-RAY DIFFRACTION

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ABSTRACT

Synchrotron-based X-ray microbeam measurements were performed on silicon-on-insulator (SOI) features strained by adjacent shallow-trench-isolation (STI). Strain engineering in microelectronic technology represents an important aspect of the enhancement in complementary metal-oxide semiconductor (CMOS) device performance. Because of the complexity of the composite geometry associated with microelectronic circuitry, characterization of the strained Si devices at a submicron resolution is necessary to verify the expected strain distributions. The interaction region of the SOI strain extended at least 25 times the SOI film thickness from the STI edge. Regions of 65 nm thick SOI less than 3 µm wide exhibited an overlap in the strain fields because of the surrounding STI. Microbeam mapping of arrays containing submicron SOI features and embedded STI structures revealed the largest out-of-plane strains because of the close proximity of superimposed strain distributions induced by the STI.

INTRODUCTION

In order to maintain the current pace of increasing speed and performance in CMOS technology, new strategies extending beyond traditional scaling of device dimensions have had to be employed. For example, the application of strain within the current-carrying regions of CMOS devices can be tailored to improve carrier mobility. The link between resistivity and the applied stress in semiconductors, first quantified by Smith [1], also relates carrier mobility to the local state of strain. In order to exploit this effect to enhance carrier mobility, CMOS devices can be manufactured using strained layers adjacent to the current-conducting paths in the Si. Existing methods employed to induce strain in the channel regions involve either the deposition of heteroepitaxial SiGe or SiC into Si trenches or the deposition of stressed films above the transistors. In the first case, regions containing SiGe, which possess a larger lattice parameter than that of Si, induce a compressive strain in the plane of the Si channel [2], whereas SiC regions, with a smaller equilibrium lattice parameter, create a tensile in-plane strain. A corresponding increase in hole mobility, required for PFET devices, can be produced through the use of compressively stressed Si [3]. For the case of stressed overlayer films, such as silicon nitride [4], the edges of the gate and spacer regions above the Si channel create stress concentrations, resulting in strain distributions in the channel region of the SOI that possess the same sign of in-plane strain as in the stressed film.

Traditional device modeling often applies the simplification of uniform stress distributions within the CMOS devices. Because the actual channel regions possess heterogeneous strain distributions in both of these implementations, a more comprehensive modeling of the band
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structure realignment is required to determine the overall device response. In addition, modeling of the piezoresistive behavior in Si-based systems, which strongly depends on substrate doping and carrier density in the inversion channel [5], would benefit from a more accurate description of the strain fields. The following sections describe our work on the experimental mapping and mechanical modeling of the strain distributions in semiconductor device structures.

EXPERIMENTAL

STI structures were patterned into a blanket SOI film, approximately 65 nm thick, on a 600 µm thick Si (001) substrate. A cross-sectional transmission electron microscope image of a typical interface between the SOI features and the surrounding STI structures is shown in Figure 1. A 150 nm thick, buried oxide (BOX) layer exists underneath both the SOI as well as the STI regions, which are used to electrically isolate adjacent CMOS devices. Trenches, created in the SOI layer using conventional lithography and reactive-ion-etch processing, were filled with high-density plasma (HDP) oxide and planarized by chemical-mechanical polishing. X-ray diffraction experiments were conducted using the APS 2ID-D microbeam apparatus, where a Fresnel zone plate with an order sorting aperture was used to focus the beam to a nominal beam FWHM of 0.25 µm [6]. A beam energy of 11.2 keV was chosen so that the angle of the Si (008) diffraction peak, measured using symmetric diffraction conditions, was at a relatively large value (2θ ~ 108°). Diffraction optics included 100 µm wide receiving slits that were placed in front of the scintillation detector. Because the underlying Si single-crystal substrate and SOI layers were offset by approximately 0.4°, Si (008) diffraction peaks could be obtained from both of these regions independently.

MODELING

Mechanical modeling was performed using an Eshelby inclusion method for elastic distortions in a semi-infinite elastic medium. Mindlin and Cheng [7] developed an analytic expression for the strain distributions in a linear elastic half-space because of an embedded inclusion which possesses an eigenstrain, ∆ε. The model, refined by Davies [8], assumes a plane strain condition along the direction of the edges of the embedded features, which are rectangular in cross-section. Because the SOI regions under investigation possessed lengths much larger than the dimension over which the features were mapped, the plane strain condition is satisfied. Isotropic elasticity is also assumed in both the embedded features and surrounding matrix, in which the elastic constants are identical. Because the model is linear-elastic, the strain fields induced by each of the inclusions can be superimposed to simulate arrays of inclusions with arbitrary geometries. The depth-averaged out-of-plain strain is determined by dividing the difference in vertical displacements at the top and bottom of the SOI by its thickness [9].
RESULTS AND DISCUSSION

Strain mapping of the SOI structure was performed by determining the change in the out-of-plane lattice parameter, $c_{Si}$, by collecting $\theta/2\theta$ scans and translating the sample using 0.2 $\mu$m increments. The depth-averaged strain was calculated using Eq. (1):

$$\bar{\varepsilon}_{zz} = (c_{Si} - a_{Si})/a_{Si}$$

where $a_{Si}$ represents the unstrained lattice parameter of Si, as measured from the substrate. Figure 2 depicts a plot of the depth-averaged out-of-plane strain measured as a function of position from the STI / SOI edge in a wide (75 $\mu$m) SOI feature. Because the features possessed dimensions on the order of millimeters along the orthogonal, in-plane direction, a plane strain state is assumed. A positive value of out-of-plane strain corresponds to a tensile state of strain, induced by Poisson expansion from an in-plane compressive strain. Measurements conducted at the center of the SOI region, which corresponds to the blanket SOI layer, indicated that a residual out-of-plane strain of -31 $\mu$ε is present in the SOI. This residual strain must be superimposed onto the modeling results that predict the strain induced by the STI regions. The distribution of strain is clearly observed in Figure 2, where the measured out-of-plane strain decreases as a function of distance from the STI / SOI interface. In fact, the effect of the STI can be observed at a distance of approximately 25 times the SOI thickness from the STI / SOI interface. The actual strain in the STI cannot be measured by X-ray diffraction because it is non-crystalline. However, a fit of the magnitude of the eigenstrain, $\Delta \varepsilon$, to the observed data results in an equivalent eigenstrain of -0.55% in the STI.

In order to assess the impact of smaller stressor regions on the SOI strain, sections that possessed 3 $\mu$m wide SOI features separated by thin STI regions were investigated. Measurements conducted on 3 $\mu$m wide SOI features on either side of an STI region approximately 0.85 $\mu$m wide are depicted in Figure 3. These structures also extend for several millimeters in length so that a plane strain assumption is still valid. In these SOI structures, the influence of the large STI regions, which extend over 25 $\mu$m from the outer SOI / STI interfaces, as well as the STI interposed between the SOI, impact the overall strain state of the system. Modeling results are also depicted in Figure 3, where the fitted value of $\Delta \varepsilon = -0.55\%$ for the STI, as determined from the previous example, was used. The measured strain profile follows the curve corresponding to
the inclusion model with small differences near the interfaces. The large gradients in SOI strain present at these edges are convoluted by the finite width of the X-ray microbeam, leading to the minor discrepancies.

Figure 4 contains the diffraction data from an array of SOI features, each of which is less than 0.2 µm in width, surrounded by STI structures. Although statistically significant variations in the magnitude of strain across the array are observed (σ = 150 µε), a strong convolution of the strain distribution is created in the experimental data because of the comparable dimensions of the beam size and the SOI feature widths. The average out-of-plane strain across all of the measured values was 0.152%, where the resolution of the individual measurements is approximately 50 µε. In order to compare the experimental data to the model predictions, the calculated strain profiles from the inclusion model were numerically convoluted with an assumed Gaussian beam shape of 0.25 µm FWHM. Because this convolution needed to be applied to the strain distribution and not to the diffracted intensity, it had to be performed in such a way that the non-diffracting regions (i.e. the STI) did not contribute to the convoluted strain distribution. The simulated out-of-plane strain field, also included in Figure 4, resembles the observed X-ray diffraction information. Because the plane strain assumption is violated for several of the measured structures, large deviations between the data and predicted values can be seen. However, the calculated average out-of-plane strain across the entire SOI array, 0.152%, matches that from the experimental measurements, confirming the equivalent eigenstrain of -0.55% in the STI. From the inclusion model, the calculated average in-plane SOI strain across the array is approximately -0.28%, corresponding to an average in-plane stress of -460 MPa.

SUMMARY

Strain distributions within blanket and patterned SOI regions induced by STI were mapped at a submicron resolution using X-ray microbeam diffraction. The measurements indicate that an out-of-plane tensile strain in the SOI, produced by Poisson expansion from the in-plane compression of the STI, extended up to 25 times the SOI film thickness from the STI / SOI interface. The measured SOI strain profiles were compared to calculated values from an analytical, embedded inclusion model yielding an equivalent STI eigenstrain of approximately -0.55%. In the case of 65 nm thick SOI, the strain fields induced by the adjacent STI were observed to overlap in SOI.
features of 3 \( \mu m \) width and less. Submicron arrays of SOI features surrounded by embedded STI exhibited the largest out-of-plane strain values, approximately 3 times greater than those measured near a single STI / SOI interface, because of the superposition of the strain fields from multiple STI structures in close proximity to the SOI.

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