Crystal-direction dependence of uniaxial tensile strain in ultra-thin SOI

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Introduction

Uniaxial strain is promising for advanced silicon technologies because it may be able to preserve enhancement of both hole and electron mobility at large vertical electric fields, unlike biaxial strain [1]. Significant increases in both n-channel and p-channel FET mobilities have been observed for moderate levels of stress parallel to the <110> channel (tensile 200-300MPa and compressive ~500MPa [2], respectively). Furthermore, the mobility enhancement depends on the strain direction relative to the channel [3] and relative to crystal planes [4].

Previously we have demonstrated electron mobility enhancement for biaxially strained SOI obtained by layer transfer and lateral relaxation / force balance of Si/SiGe structures on BPSG [5]. This strain engineering process can easily be adapted to obtain high levels (1.0%) of uniaxial strain in silicon [6]. Here, we show that the magnitude of uniaxial strain obtained by this method depends on the direction of the island orientation. This dependence derives from the anisotropic elastic constants (C_{11}, C_{12}, C_{44}) of silicon and SiGe.

Experiment

Bi-layers of compressively-strained (100) SiGe and relaxed silicon on borophosophorosilicate-glass (BPSG insulator) on silicon are formed by wafer bonding, Smart-Cut™ layer transfer, and selective etching [5,7]. Square and rectangular islands are patterned by dry etch (Fig. 1a). The initial strain ε_o, –1.2% in SiGe and zero in silicon, is maintained in the layers during these processes. Upon annealing at 700-800°C, the BPSG becomes viscous and the layers coherently expand toward force balance, partially relieving the compressive strain in the SiGe and adding tension to the silicon. Micro-Raman spectroscopy at 488 or 514nm is used to measure strain in the long and short island directions, ε_{long} and ε_{short} (Fig. 1b) [8].

Results and Discussion

Lateral expansion of islands with edge length L takes place according to a time constant τ, which scales as L^2 [9]. Square islands result in biaxially symmetric strain while rectangular islands maintain initial strain, ε_o, in the direction of the long island dimension while quickly expanding in the direction of the short dimension. Thus the resulting silicon strain is uniaxial in the surface plane: zero in the direction of the long dimension with significant tension in the short dimension. This uniaxial tensile strain has two contributions, the force balance of the bi-layer and the asymmetry of the rectangular island. This second asymmetry contribution is the focus of this paper.

Force balance originates from the dissimilar stress (σ) in the silicon and SiGe layers. Upon annealing, the SiGe partially relaxes its compressive strain, stretching the underlying silicon so that it becomes tensile. Force balance affects both square and rectangular islands, and in square islands it generates biaxial strain (Fig. 2). Because the layers move coherently, the net changes in strain are equal. The final strain can be calculated from

$$\sigma_{Si} h_{Si} + \sigma_{SiGe} h_{SiGe} = 0 , \qquad (1)$$

where h is layer thickness [10].

The asymmetry contribution, which only affects rectangular islands, comes from the dimensional constraint of the island in the long direction, which forces all the expansion to take place in the short dimension according to Poisson's ratio, ν. The maximum asymmetry contribution is given by $\Delta\varepsilon_{short,\, asymmetry} = -\varepsilon_o \nu$. Poisson's ratio is strongly dependent on crystal direction (Fig. 3). For a single-layer of $Si_{0.7}Ge_{0.3}$ in the (100) plane, Eqs. 2 and 3 give Poisson's ratio in the <100> and <110> directions [11].

$$\nu_{<100>} = \frac{c_{12}}{c_{11} + c_{12}} = 0.276 \qquad (2)$$

$$\nu_{<110>} = \frac{c_{11} + c_{12} - 2c_{44} - 2c_{12}^2 / c_{11}}{c_{11} + c_{12} + 2c_{44} - 2c_{12}^2 / c_{11}} = 0.053 \quad (3)$$

Thus islands aligned along <100> should have greater tensile strain than those aligned along <110>, as confirmed by measured data on narrow islands (short dimension < 40 μm) (Fig. 4). After the given anneal the wider islands (≥ 40 μm) are only partially relaxed and the asymmetry contribution is a fraction of its final value, within the error of our strain measurement. Note that the asymmetry contribution further increases the amount of tensile strain in the silicon layer beyond that obtained solely by force balance.

In practice, these two contributions are intertwined and the full solution must be obtained by solving Eq. 1 under the long island constraint ($\varepsilon_{long,\,final}=\varepsilon_o$), which yields an equation of the form

$$\varepsilon_{short,Si} = \frac{-\varepsilon_o}{A + B \cdot h_{Si} / h_{SiGe}}, \quad (4)$$

where A and B are functions of strain type (biaxial or uniaxial) and island crystal direction as given in Table 1. In Fig. 5, this model is compared to measured data from different Si/SiGe stacks. As predicted, uniaxial strain is always greater than biaxial strain for the same bi-layer structure, and rectangular islands aligned along <100> have larger uniaxial strains than those aligned along <110>. As the silicon layer is thinned we achieve greater uniaxial silicon tension, up to 1.0% for a tri-layer of 5.5nm SiN_x / 10nm Si / 30nm SiGe. For the bi-layer case with 1-2nm Si / 30nm SiGe, the asymmetry contribution dominates relaxation of rectangular islands, generating SiGe tension in the short direction, while the long direction remains compressively strained.

Conclusions

Strain engineering by lateral relaxation is a powerful method for generating large biaxial and uniaxial silicon strain in an SOI structure. By choosing the crystal direction of the features, one should be able to control not only the mobility enhancement, but also maximize the uniaxial strain. Uniaxial tensile strain as large as 1.0% in the <100> direction can be achieved in 10-nm silicon films. Work is ongoing to measure direction-dependent mobility enhancement in these structures due to uniaxial tensile strain.

Acknowledgements

The authors would like to thank T. Margarella at Northrop-Grumman for deposition of BPSG, and T.S. Duffy and S.R. Shieh of Princeton University's Geosciences Dept. for use of the Raman measurement setup. This work supported by DARPA (N66001-00-10-8957) and ARO (DAAG55-98-1-0270).

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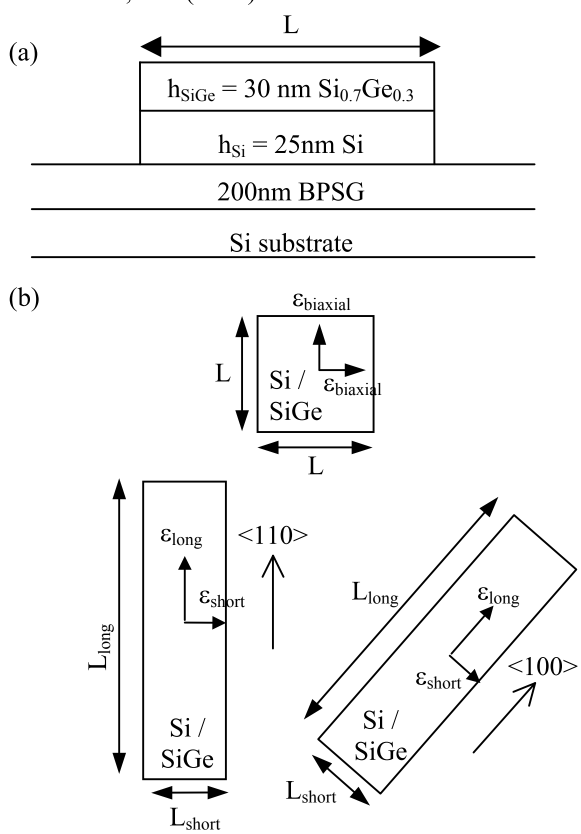

Fig. 1 Schematics of (a) island cross-section (b) top-down view of square islands (top) and rectangular islands aligned to <110> (bottom left) and <100> (bottom right). All islands are in the (001) plane.

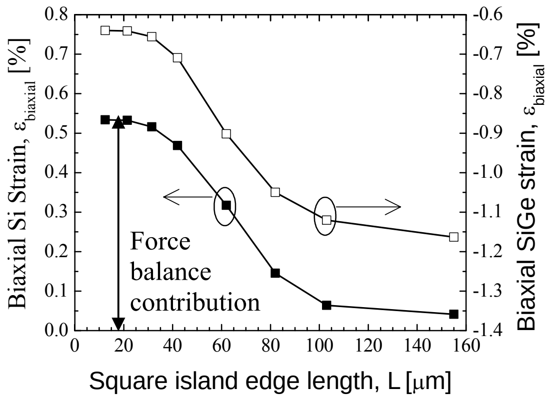

Fig. 2 Silicon (closed symbol) and SiGe (open symbol) biaxial strain as a function of square island size after 30min anneal at 800°C, for the stack of Fig. 1a. Small islands can expand and reach force balance while large islands do not have enough time. Measurement error in Raman is ±0.06% with 3μm spatial resolution.

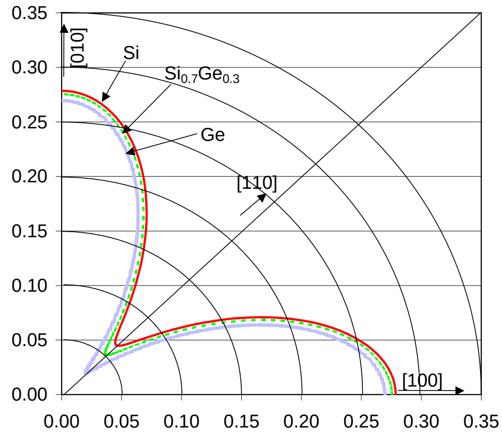

Fig. 3 Poisson's ratio, ν, vs. crystal direction in Si, $Si_{0.7}Ge_{0.3}$ and Ge, after Ref. 11.

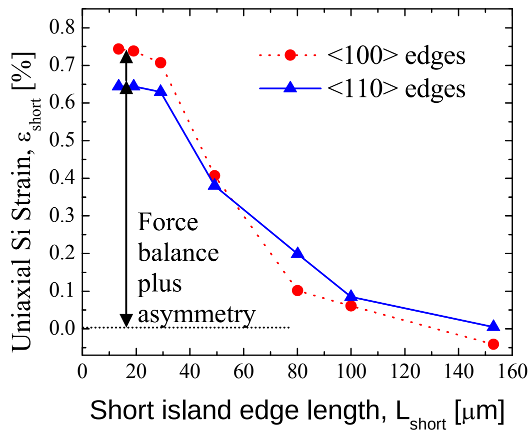

Fig. 4 Uniaxial silicon strain in rectangular islands with L_{long}=150μm vs. short edge length after 30min anneal at 800°C. Symbols indicate islands aligned along <110> (triangles) and along <100> (circles). ε_{long} is fixed at zero by the large L_{long} that prevents relaxation.

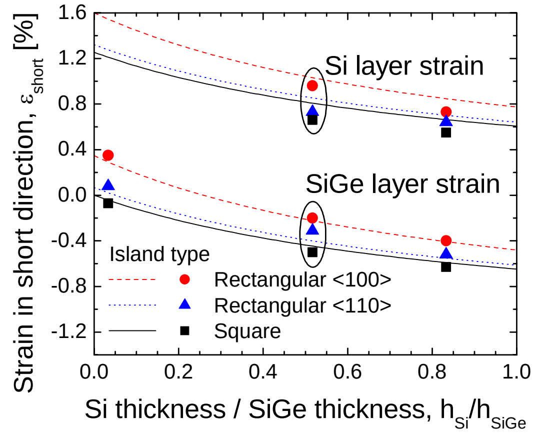

Fig. 5 Silicon and SiGe strain in the short direction vs. h_{Si}/h_{SiGe}. Lines are the combined force balance and asymmetry model of Eq. 4. Symbols are measured data: the right-most symbols are for the stack shown in Figs. 1a; the other samples are described in the text.

Table 1. Coefficients to calculate final silicon strain in the short island direction (in both directions for biaxial) from Eq. 4. C_{11}, C_{12} and C_{44} refer to elastic constants of SiGe, while D_{11}, D_{12} and D_{44} refer to those of silicon.

Biaxial strain $\varepsilon_{long}=\varepsilon_{short}$	A = 1 B = $\left(D_{11}+D_{12}-2\cdot\frac{D_{12}^2}{D_{11}}\right)\Big/\left(C_{11}+C_{12}-2\cdot\frac{C_{12}^2}{C_{11}}\right)$
Uniaxial strain in <100> $\varepsilon_{long}=\varepsilon_o$	A = $\left(C_{11}-\frac{C_{12}^2}{C_{11}}\right)\Big/\left(C_{11}+C_{12}-2\cdot\frac{C_{12}^2}{C_{11}}\right)$ B = $\left(D_{11}-\frac{D_{12}^2}{D_{11}}\right)\Big/\left(C_{11}+C_{12}-2\cdot\frac{C_{12}^2}{C_{11}}\right)$
Uniaxial strain in <110> $\varepsilon_{long}=\varepsilon_o$	A = $\left(C_{11}+\frac{H_C}{2}-\frac{C_{12}^2}{C_{11}}\right)\Big/\left(C_{11}+C_{12}-2\cdot\frac{C_{12}^2}{C_{11}}\right)$ B = $\left(D_{11}+\frac{H_D}{2}-\frac{D_{12}^2}{D_{11}}\right)\Big/\left(C_{11}+C_{12}-2\cdot\frac{C_{12}^2}{C_{11}}\right)$ Where $H_C=2\cdot C_{44}+C_{12}-C_{11}$ and $H_D=2\cdot D_{44}+D_{12}-D_{11}$