

Dynamics of uniform Si/SiGe uniaxial strain generation on compliant insulating substrates

R. L. Peterson* and J. C. Sturm

Princeton Institute for the Science and Technology of Materials and Department of Electrical Engineering
Princeton University, Princeton, NJ, 08540 USA
Phone: 1 609 258 1575, Fax: 1 609 258 1177, E-mail: sturm@princeton.edu

1. Introduction

In recent work, we demonstrated a process based on the relaxation of Si/SiGe bilayers of different geometries to obtain up to 1.0% uniaxial tensile strain in silicon and 1.5 GPa uniaxial compressive stress in SiGe [1,2]. The process generates uniform uniaxially strained silicon on insulator or uniaxial stress in SiGe layers over large islands, and is tunable between biaxial and uniaxial strain on the same wafer. In this work we examine the dynamics of the process and establish process windows for maximum strain asymmetry. The simulation results agree well with experimental data.

2. Strain-Generation Approach

A bi-layer of biaxially-strained SiGe and unstrained silicon epitaxially grown on (001) silicon is transferred by wafer bonding and Smart-Cut™ layer transfer to a silicon wafer coated with borophosphosilicate glass (BPSG) (see Fig. 1a) [3]. The SiGe/Si layers are patterned into islands (Fig. 2). Upon annealing at high temperature (> 700°C), the underlying BPSG flows and the SiGe/Si layers laterally expand to reach stress balance, with the SiGe less compressively strained and the silicon tensile (Fig. 1b). If the silicon layer is very thin (1-2 nm) compared to the SiGe layer (typically 30 nm), the SiGe layer can fully relax to a zero-stress, zero-strain state. No dislocations mechanisms are involved in the relaxation process.

The resulting type of strain depends on island shape. The strain at the center of the island relaxes exponentially according to a time constant [4],

$$\tau_L = \eta \cdot L^2 / (h_{BPSG} \cdot c_{11} \cdot h_{film}), \quad (1)$$

where η and h_{BPSG} are BPSG viscosity and thickness, L is the island edge length, and c_{11} and h_{film} are the (SiGe) film elastic stiffness coefficient and thickness.

For squares islands, strain and stress are biaxially-symmetric in the two in-plane directions. When the island is rectangular, along the short island dimension the films quickly reach stress balance (zero stress in the case of a single SiGe film), while in the long dimension the film strain is effectively pinned at its initial value because $\tau_L \sim L^2$ (Fig. 2b,c). The result is highly asymmetric strain that is further enhanced by

the Poisson effect which causes additional tension in the short dimension [2].

3. Numerical Model and Experimental Results

We extend the numerical model of Ref. 4, previously used for square islands, to rectangular islands of arbitrary aspect ratio ($AR=L_{long}/L_{short}$). We model a single $Si_{0.7}Ge_{0.3}$ layer with initial strain $\varepsilon_0 = -1.2\%$ and island edges aligned to $\langle 100 \rangle$, assuming the BPSG is linearly viscous and the SiGe film remains flat throughout.

In Fig. 3 the modeled normalized strain ($\varepsilon/\varepsilon_0$, where 1.0 is full compression, 0 corresponds to zero strain and negative values indicate tension) is plotted across island mid-sections. Rectangular islands expand laterally in the short direction, starting at the edges, to quickly reach a state of tension, which for the final simulation point is uniform within 9% (Fig. 3a). The maximum normalized tension is $-\nu$ (Poisson's ratio) [1], and thereby depends on the film material properties and island crystal direction [2]. In the long island direction, the central 70% of the island maintains >90% of the full initial compressive strain (Fig. 3b) at the final simulation point. The asymmetric strain is thus highly uniform across the island.

For long anneals, strain in all island directions will converge at the stress balance value, i.e. a single layer will reach a zero strain state, regardless of the island aspect ratio (Fig. 4a). However, for rectangles with $AR \geq 5$, the maximum strain asymmetry of $\varepsilon_{short} - \varepsilon_{long} = -(1+\nu) \varepsilon_0$ is achievable by correct choice of the process window. For $AR=5$, the strain asymmetry is at least 90% of its maximum value from $t/\tau_L=0.30$ to 1.04 (Fig. 4b), where τ_L is calculated with $L=L_{short}$. As the aspect ratio increases, the anneal time process window for maximum asymmetry widens.

The model results for single layers can be scaled to predict SiGe/Si bi-layer behavior, using bilayer values for τ_L and ε_{final} [5]. Such bi-layer structures generate uniaxial strain in the silicon layer as the bilayer expands in the narrow direction, with the silicon retaining its original unstrained state in the long direction. After anneal, the SiGe can be selectively removed to give uniaxially-strained SOI. Experimental results of uniaxial silicon strain from SiGe/Si bi-layers show excellent agreement with the model (Fig. 5).

* Current address: Optoelectronics Group, Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK, email rlp38@cam.ac.uk, phone +44 1223 337 570.

4. Conclusion

We have developed a model of the time dependence of asymmetric strain generation in Si/SiGe bilayers on compliant substrates, and established a process window for maximum strain asymmetry. The resulting uniaxial silicon strain of 0.75% tension is well-controlled and uniform across the SOI islands.

Acknowledgements

The authors thank R. Huang for providing the original matlab script used to model expansion of square islands [4]. Funding for this work was provided by DARPA and Applied Materials.

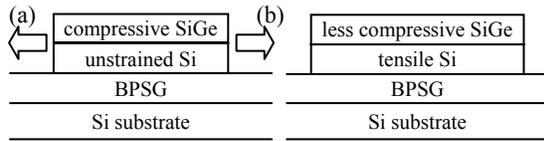


Fig. 1. Schematic cross-sections of (a) SiGe/Si bilayer as bonded. Arrows indicate lateral relaxation. (b) SiGe/tensile Si bilayer after relaxation.

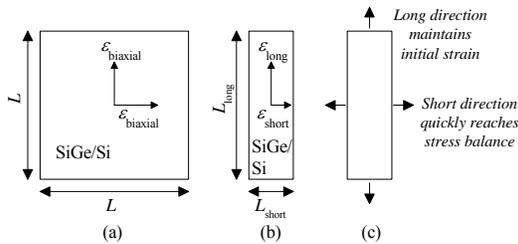


Fig. 2. Schematic of (a) square and (b) rectangular islands. Part (c) shows how rectangles lead to asymmetric strain. A typical rectangular island is 20 μm x 150 μm .

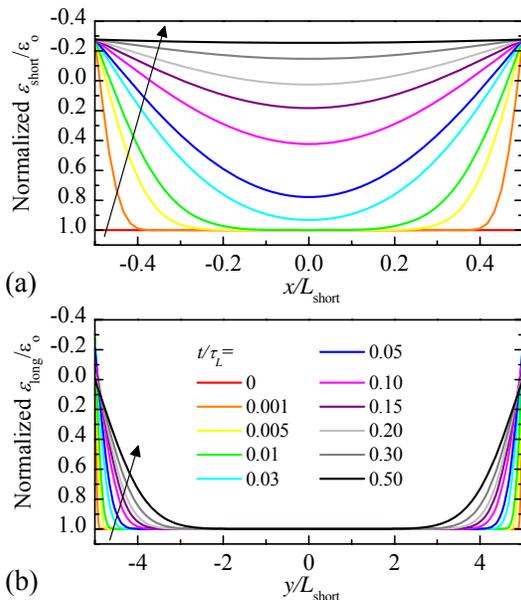


Fig. 3. Modeled strain across island mid-sections after various anneal times: (a) ϵ_{short} and (b) ϵ_{long} , for a rectangular island with $L_{\text{long}}/L_{\text{short}}=10$. Strain is normalized by ϵ_0 and time by τ_L with $L=L_{\text{short}}$.

References

- [1] H. Yin, R. L. Peterson, K. D. Hobart, S. R. Shieh, T. S. Duffy, and J. C. Sturm, *Appl. Phys. Lett.*, **87**(6), 061922 (2005).
- [2] R. L. Peterson, K. D. Hobart, H. Yin, and J. C. Sturm, *IEEE Int. 'l SOI Conf. Proc.* (2004) p. 39-41.
- [3] K. D. Hobart, F. J. Kub, M. Fatemi, M. E. Twigg, P. E. Thompson, T. S. Kuan, and C. K. Inoki, *J. Elec. Mat.*, **29**(7), 897 (2000).
- [4] R. Huang, H. Yin, J. Liang, K. D. Hobart, J. C. Sturm, and Z. Suo, *Mat. Res. Soc. Symp. Proc.*, **695**, 15 (2002).
- [5] H. Yin, K. D. Hobart, F. J. Kub, S. R. Shieh, T. S. Duffy, and J. C. Sturm, *Appl. Phys. Lett.*, **82**(22), 3853 (2003).

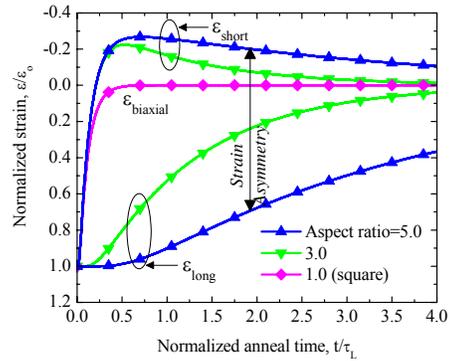


Fig. 4. Model of normalized (a) strain and (b) strain asymmetry ($\epsilon_{\text{short}} - \epsilon_{\text{long}}$) at the island center vs. anneal time, for variously-sized islands, for a single SiGe layer.

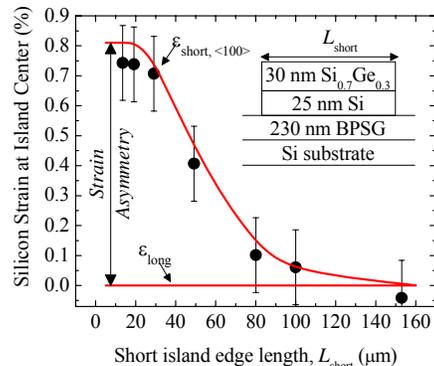


Fig. 5. Comparison of strain in long and short directions (model as lines; experimental points) vs. L_{short} ($L_{\text{long}}=150 \mu\text{m}$) for a SiGe/Si bi-layer as shown on inset, annealed for 30 min at 800°C. Note uniaxial Si strain of 0.75% is achieved.