Galway, Ireland
e-mail: colin.odowd@cmas.demon.co.uk
‡Finnish Institute of Occupational Health, Topeliuksenkatu 41 a A, FIN-00250 Helsinki, Finland
§Institute of Spectrochemistry and Applied Spectroscopy, 44139 Dortmund, Germany

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Nanomechanics

Response of a strained semiconductor structure

The nanomechanical properties of thin silicon films will become increasingly critical in semiconductor devices, particularly in the context of substrates that consist of a silicon film on an insulating layer (known as silicon-on-insulator, or SOI, substrates). Here we use very small germanium crystals as a new type of nanomechanical stressor to demonstrate a surprising mechanical behaviour of the thin layer of silicon in SOI substrates, and to show that there is a large local reduction in the viscosity of the oxide on which the silicon layer rests. These findings have implications for the use of SOI substrates in nanoelectronic devices.

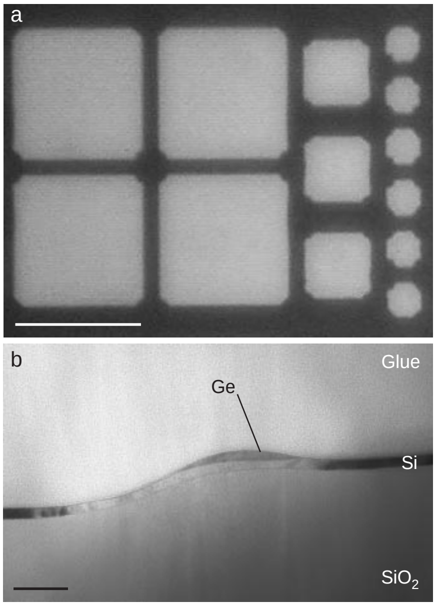

Figure 1 Anomalous local bending of the thin silicon-template layer in silicon-on-insulator (SOI) substrates induced by the growth of germanium (Ge) nanocrystals. **a,** Mesa structures patterned and etched on a SOI substrate wafer. **b,** Transmission electron microscope image showing a Ge nanocrystal and the bent Si-template layer underneath. The Ge nanocrystals, which grow in register with the Si lattice, have a 4% greater lattice constant than the Si, and thus cause it to bend locally. The local shear stress is sufficient to reduce the viscosity of the oxide underneath the thin Si layer so as to allow the oxide to flow locally. Scale bars, 20 μm (**a**) and 50 nm (**b**).

We use SOI substrates consisting of a handle wafer (a thick silicon (Si) layer), a thin oxide (a 400-nm thickness of SiO_2) and a very thin (10 nm) template layer of crystalline Si on top of the oxide. The template layer is patterned to form micrometre-sized (5–20 μm) mesas (Fig. 1a). About 10 monolayers of germanium (Ge; total thickness 1.6 nm) are deposited by molecular-beam epitaxy at 700 °C. Germanium has a lattice constant 4% greater than that of silicon.

Figure 1b shows the formation of Ge nanocrystals (about 10 nm high, with 100-nm bases) that are crystallographically in register with the Si template, and an anomalous local bending of the Si template layer underneath each individual nanocrystal. The curvature underneath the islands is greater than $0.005\ \mathrm{nm}^{-1}$. This new mode of local bending (Fig. 2a) of a nanometre-scale thin film is different from the commonly observed extended, uniform bending mode (Fig. 2b) that is induced by strained-layer film growth on thick Si(001) (refs 1, 2).

Our calculations show that the local bending curvature depends on the nanocrystal's density and shape (Fig. 2c, d). On a thick substrate, local bending is suppressed[3], resulting in an overall extended bending that can be estimated using Stoney's formula[4] and which is independent of nanocrystal density and shape, as would be the case in a uniform film of equivalent thickness.

The local bending mode and large bending magnitude indicate that the Si template layer behaves as a 'free-standing' layer during the growth of Ge nanocrystals, an outcome that can be achieved if SiO_2 acts as a fluid with substantial viscous flow. The viscosity of SiO_2 at 700 °C (the growth temperature) is ordinarily much too great for such a large degree of relaxation to occur. However, this viscosity can decrease almost exponentially with increasing applied shear stress[5].

From the bending curvature, and hence the bending stress, we estimate[5] that the viscosity of SiO_2 can be reduced by three to five orders of magnitude in the regions beneath the bent Si layer below the Ge nanocrystals. The relaxation time for SiO_2 flow is then reduced by a few orders of magnitude, to well within the deposition time of about 150 s. Thus, the large bending stress in the Si layer greatly enhances the viscous flow of SiO_2, which in turn helps to increase the bending of the Si layer, because the Si film can then behave as a free-standing film.

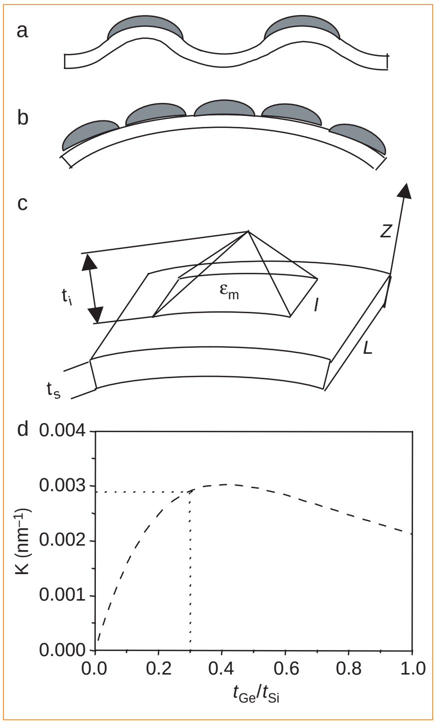

Figure 2 Different bending modes of thin silicon-template layer in SOI substrates induced by growing germanium nanocrystals. **a,** Local bending mode that occurs only when the density of nanocrystals (dotted domes) is low. **b,** Extended bending mode that occurs at high nanocrystal densities. For a thin Si layer, a transition from local to extended bending occurs with increasing nanocrystal density. **c,** Some parameters used to calculate the bending induced by a pyramidal nanocrystal acting as a local stressor. t_i is the thickness of the Ge nanocrystal, t_s is the thickness of the Si membrane, l is the base dimension of the nanocrystal, ε_m is the misfit strain in the nanocrystal, Z is the normal to the membrane, and L is the dimension of the bent region of membrane underneath the nanocrystal. **d,** The calculated bending curvature, **K**, of a free-standing, 10-nm Si layer as a function of the equivalent film thickness, t_{Ge}, normalized to the Si-layer thickness, t_{Si}. Arrow indicates the curvature (local thickness, local bending) that corresponds to the observed 10-nm Ge nanocrystal height; this is consistent with the data in Fig. 1b.

The local stressor on the thin Si template layer of SOI substrate modifies both the mechanical properties of the Si layer and its electronic properties, providing a unique method for electronic (band) engineering on a nanometre scale. For these reasons, local stressors in SOI substrates could also become a significant issue for the semiconductor industry, which is increasingly using such substrates to manufacture devices.

Feng Liu*, Paul Rugheimer†, E. Mateeva‡, D. E. Savage†, M. G. Lagally†
**Department of Materials Science and Engineering, University of Utah, Salt Lake City, Utah 84112, USA*
†Department of Materials Science and Engineering and Physics, University of Wisconsin, Madison, Wisconsin 53706, USA
e-mail: lagally@engr.wisc.edu
‡Colorado School of Mines, Golden, Colorado 80401, USA

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