Silicon Nanomembranes: Opportunities for New Si Functionalities via Strain, Flexibility, and Layering

Max G. Lagally
University of Wisconsin-Madison, Madison, WI 53706
lagally@engr.wisc.edu

Abstract-**The prospects for extending the use of Si to new functionalities by using nanomembranes are reviewed, with emphasis on optoelectronic and photonic applications**

I. Introduction

Silicon-on-insulator (SOI) is the source for a new class of nanostructures, Si nanomembranes (SiNMs). By selectively etching the buried oxide in SOI, it is possible to create extremely flexible, thin, single-crystal sheets, with thicknesses from several 100 nm to less than 10nm. These sheets can be strain engineered and patterned to create various shapes (including sheets, tubes, spirals, and ribbons), depending on how one defines a pattern before release [1, 2]. Strain is introduced into membranes by heteroepitaxial growth techniques. Figure 1 shows a summary of the novel features of Si nanomembranes, and the properties that can be modified from those of bulk Si when Si is in the form of a thin membrane The consequence is a wide variety of potential applications in sensors, photonics and optoelectronics, flexible electronics, and thermoelectrics. Even biological applications are likely. Furthermore, nanomembranes are possible in other materials systems and may provide an entirely new platform for nanomaterials applications [3]. Ge-on-insulator (GOI) and combinations of Ge and Si (SGOI) are included in the category of SiNMs, but membranes in III-Vs, ferro- and piezoelectric materials, and most crystalline systems in which one can create a release layer are also possible.

Features	Modified properties
•Thin	•Surface
•Flexible, conformable	•Band structure, quantum properties
•Can be strain engineered	•Electronic transport
•Transparent	•Mechanical properties
•Transferable	•Dielectric properties
•Bondable, stackable	•Phononic properties
•Patternable (sheets, ribbons, tubes)	•Integration of modified properties

Fig. 1. Key features of Si nanomembranes and a list of properties modified from those of the bulk when a thin crystalline sheet is considered.

At the center of potential novel structures and devices involving Si membranes are strain, flexibility, and stackability. Strain modifies the band structure and thereby increases charge carrier mobilities. Flexibility, of course, affects the mechanical properties and allows the membranes to conform to different shapes and also to bond quite readily to most any host. Stackability allows the layering of membranes, with or without interlayers, and thus permits access to three - dimensional structures and devices that may have novel optoelectronic, photonic, or electronic properties.

In the form of nanowires or nanoribbons (easily made by selective pattering before etching to release them) SiNMs may have an additionally modified band structure and density of states introduced by quantum size effects. In restricted dimensions the phonon transport properties are affected, leading to potential applications in thermoelectrics.

II. Fabrication of Si Nanomembranes

To fabricate elastically strained Si nanomembranes from SOI(001) [4] a heteroepitaxial, strained SiGe layer is grown on the Si template layer of SOI. Because Ge has a 4% larger lattice constant than Si, a SiGe alloy layer grown epitaxially on unstrained Si will be compressed. The higher the Ge alloy concentration, the higher the compressive strain becomes in this layer, but to avoid dislocation formation, the layer must be thin. To create flat released membranes, an additional layer of Si is grown to balance the effect of the template Si layer when the structure is released. When this three-layer sandwich is still attached to the oxide, only the middle (SiGe) layer is strained. It cannot relax elastically until the structure is released from the oxide – at that stage the strain in the SiGe layer is shared elastically with the two Si layers on either side. They become tensilely strained while the SiGe becomes less compressively strained.

To release the membrane, the oxide layer is selectively removed by HF. HF attacks SiO_2 but not Si or Ge or their alloys. To increase the etch rate, access holes can be patterned in the layer sandwich before release. These etch holes are visible in the images in Fig. 2. The strain gets divided among the layers, with the strain in the Si layers of opposite sign as that in the SiGe layer; i.e., they are under tension. The SiGe cannot relax completely. The degree of strain in the Si is related to its thickness – the thinner, relative to the SiGe layer, the more strain. In similar fashion, one can strain Ge compressively using GOI.

Transfer of released membranes can occur in a number of ways, including wet transfer, dry transfer, or printing. Transfer of nonstrained Si or Ge nanomembranes directly from SOI

978-1-4244-1932-6/08/$25.00 ©2008 IEEE

or GOI is also possible, and has been the basis of a large effort in flexible electronics by others [5]. These transfer techniques will be described.

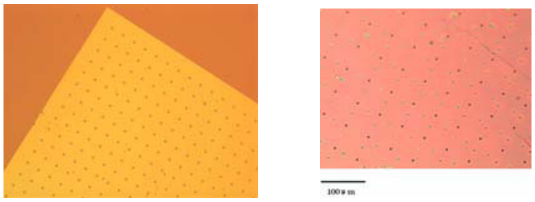

Fig. 2. Optical microscopy images of transferred Si nanomembranes. Left: strained Si/SiGe/Si NM about 100nm total thickness, transferred to new Si host. Right: a stack of three SiNMs separated by spin-on oxide to create a Bragg mirror [6]. Holes in each of the membranes are visible, showing transparency of membranes. Scale bar on left is 100 micrometers, hole spacing in right figure is the same as in left.

III. Applications in Optoelectronics and Photonics

The ability to stack membranes and to place them where desired opens opportunities for creating novel optoelectronic and photonic devices. Figure 2, left panel, shows the simplest of such devices, a stack of Si membranes that acts as a Bragg reflector. Three membranes give ~100% reflectivity [6]; because membranes have virtually no surface roughness, such layering does not increase surface roughness in the manner that growth does.

Significant advances can be expected in the area of photodetectors using Si and Ge membranes. A first example, a flexible photodetector using Ge membranes, has been demonstrated [7]. Here a lateral structure was used. Stacking layers of Ge and Si membranes allows, in principle, a more elegant device to be fabricated. Such vertical structures could also create highly efficient photovoltaic devices.

A clear advantage of the use of membranes can be seen in the development of photonic crystals and waveguides, because effectively one can create each layer of the crystal separately and stack them in the proper crystalline configuration. One can introduce a membrane of a different material to create defects in the photonic crystal. Three-dimensional wave guiding is in principle possible. These and other opportunities will be described in this talk.

This work was supported primarily by AFOSR, and also by DOE and NSF. The work has been performed with D.E. Savage, Z.Q. Ma, M.A. Eriksson, I. Knezevic, R. Blick, K. Turner, S. Scott, H.C. Yuan, W. Peng, and G.K. Celler.

References

[1] Minghuang Huang, C. Boone, M. Roberts, D. E. Savage, M. G. Lagally, N. Shaji, H. Qin, R. Blick, J. A. Nairn, and Feng Liu, "Nanomechanical Architecture of Strained Bilayer Thin Films: From Design Principles to Experimental Fabrication," *Adv. Mater.* vol. 17, p 2860 (2005).

[2] S. A. Scott and M. G. Lagally, "Elastically Strain Sharing Nanomembranes: Flexible and Transferable Strained Silicon and Silicon-Germanium Alloys," *J. Phys. D. (Applied Physics)* vol. 40, p. R1 (2007).

[3] M.G. Lagally, "Silicon Nanomembranes," *MRS Bulletin* vol. 32, 57 (2007).

[4] M.M. Roberts, L.J. Klein, D.E. Savage, M. Friesen, G. K. Celler, M.A. Eriksson, and M.G. Lagally, "Elastically Relaxed Free-Standing Strained-Si Nanomembranes," *Nature Materials* vol. 5, p. 388 (2006).

[5] Weina Peng, M. M. Roberts, E. P. Nordberg, F. S. Flack, P. E. Colavita, R. J. Hamers, D. E. Savage, M.G. Lagally, and M. A. Eriksson, "Single-Crystal/Amorphous Multilayer Heterostructures Based on Membrane Transfer," *Appl. Phys. Letters* 90, p. 183107 (2007).

[6] E. Menard, K.J. Lee, D.Y. Khang, R.G. Nuzzo and J.A. Rogers, "A Printable Form of Silicon for High Performance Thin-Film Transistors on Plastic," *Applied Physics Letters* vol. 84, p. 5398 (2004).

[7] Z.Q. Ma, personal communication; for earlier work, see H.C.Yuan, Z.Q. Ma, M. M. Roberts, D. E. Savage, and M. G. Lagally, "High-Speed Strained-Single-Crystal Silicon Thin-Film Transistors on Flexible Polymers," *J. Appl. Phys.* vol. 100, p. 013708 (2006).