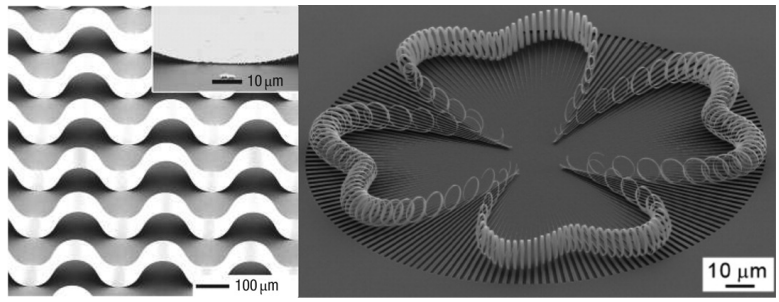
Perspective

Bend, Buckle, and Fold: Mechanical Engineering with Nanomembranes

Dae-Hyeong Kim, and John A. Rogers

ACS Nano, **2009**, 3 (3), 498-501• Publication Date (Web): 24 March 2009



PERSPECTIVE

Bend, Buckle, and Fold: Mechanical Engineering with Nanomembranes

Dae-Hyeong Kim and John A. Rogers*

Department of Materials Science and Engineering, University of Illinois, Urbana—Champaign, Illinois 61801

ABSTRACT Research on nanomembranes and graphene sheets represents the "third wave" of work on nanomaterials, following earlier studies of nanoparticles/fullerenes and, somewhat later, nanowires/nanotubes. Inorganic semiconductor nanomembranes are particularly appealing due to their materials diversity, the ease with which they can be grown with high quality over large areas, and the ability to exploit them in unique, high-performance electronic and optoelectronic systems. The mechanics of such nanomembranes and the coupling of strain to their electronic properties are topics of considerable current interest. A new paper by the Lagally group in this issue combines single-crystalline silicon nanomembranes with chemical vapor deposition techniques to form "mechano-electronic" superlattices whose properties could lead to unusual classes of electronic devices.

See the accompanying Article by Huang *et al.* on p 721.

*Address correspondence to jrogers@illinois.edu.

Published online March 24, 2009.
10.1021/nn9001769 CCC: $40.75

The fields of nanoscience and nanotechnology arguably have their origins in the seminal work on cadmium selenide nanocrystals and spherical fullerenes that began in the early 1980s. Studies of these and related classes of materials soon expanded to include "one-dimensional" nanostructures, in the form of semiconductor nanowires and carbon nanotubes. A key attractive feature of these systems is that they can be much more easily manipulated, contacted, and probed than corresponding particles (*i.e.*, "zero-dimensional" objects) of the same materials. Field effect transistors, diodes, sensors, and related devices that incorporate individual wires or tubes can be built easily. These test structures enable fundamental studies of the physics of charge transport, light emission, and other phenomena. Although they do not appear to provide a robust foundation for a technology, they do clearly suggest the potential for applications. Scalable integration of these nanomaterial structures into circuits, sensors, actuators, or other systems is challenging but might conceivably be achieved *via* guided assembly or growth techniques to yield organized collections of wires/tubes. Meaningful progress has been made toward this goal with schemes that involve dense, horizontally aligned arrays,[1,2] but many difficulties remain.

The most recent trend in nanomaterials research sidesteps this issue by focusing on two-dimensional structures such as semiconductor nanomembranes and graphene sheets. Materials with these geometries offer ease in forming electrical contacts, like wires/tubes; they also space-fill areas, rather than lines, to enable full compatibility with thin-film-based approaches to electronics and optoelectronics technologies. The result is a class of nanomaterial that builds naturally on decades of research in thin-film growth and processing, thereby facilitating integration into realistic devices. These engineering advantages come without any apparent reduction in the intellectual depth or diversity of interesting features in the underlying materials science and physics. Wide ranging classes of materials have been studied in this format, most prominently graphene,[3,4] but also many inorganics including silicon,[5,6] germanium,[7,8] gallium arsenide,[9,10] gallium nitride,[11] and several transition metal oxides.[12]

Within this field of nanomembrane research, the ability to engineer mechanical responses has received considerable attention recently. The Lagally group and their collaborators at Wisconsin are among the leaders in this field. They report in this issue a clever process that yields so-called "mechano-electronic superlattices" by controlled growth on patterned silicon nanomembranes (Figure 1).[13] Their process begins with membranes derived from thin layers of silicon and silicon dioxide on silicon substrates. Such silicon-on-insulator (SOI) wafers are commonly used in advanced silicon

Research on nanomembranes and graphene sheets represents the "third wave" of work on nanomaterials, following earlier studies of nanoparticles/fullerenes and, somewhat later, nanowires/nanotubes.

The engineering advantages of nanomembranes come without any apparent reduction in the intellectual depth or diversity of interesting features in the underlying materials science and physics.

complementary metal oxide semiconductor (CMOS) circuits. Removing the underlying silicon dioxide layer by selective etching in hydrofluoric acid yields nanomembranes of electronics-grade monocrystalline silicon, with spatial layouts that can be defined by conventional lithographic and etching procedures. Structures ranging from nanowires to nanoribbons and large area nanomembranes, in nearly any combination, orientation, or spatial layout can be created easily in this fashion. The Lagally team uses this strategy to form parallel arrays of silicon nanoribbons (widths ~50−250 nm; thicknesses ~5−50 nm; lengths ~1−10 μm), freely suspended along their lengths but tethered to the underlying SOI wafer through anchor points at their ends. Next, they heteroepitaxially grow either germanium or germanium-rich silicon/germanium (Ge/SiGe) alloy simultaneously on the top and bottom surfaces of these ribbons by chemical vapor deposition. Growth begins with the formation of pyramidal islands, known as nanostressors, similar to those that have been observed previously on bulk wafer substrates.[14,15] These nanostressors, as their name implies, create regions of tensile strain in the nanoribbons, due to the slight lattice mismatch between Ge/SiGe and silicon. This strain leads to bowing that induces local compressive strains on the opposite sides of the ribbons, thereby suppressing growth in these regions. Such coupled processes lead to the formation of self-organized arrays of deposits of Ge/SiGe on the top and bottom surfaces of the nanoribbons, phase-shifted relative to one another by one-half of a period.

The Lagally paper convincingly demonstrates this process through careful imaging and modeling studies. A point of particular interest is that the mechanical strains lead to local changes in the band structure of the silicon; changes of the band gap by up to 20% appear possible. The spatial distributions and magnitudes of these changes can be controlled through nanostressor composition and nanomembrane thickness. Such capabilities suggest important new routes to electronic superlattices that could be useful for new devices in electronics, thermoelectrics, and other areas.

THE FUTURE OF NANOMEMBRANES

An important perspective on this interesting system is that it represents one of several recent demonstrations of micro- and nanoscale mechanical engineering with semiconductor nanomembranes. In some of the earliest work, materials grown on top of nanomembranes while they were bonded to a substrate created residual strain that led to curling of the membranes upon release.[7−10] Careful control of this process can yield tubes, helices, and related structures in unsupported or partially supported configurations. Panels a and b of Figure 2 show representative

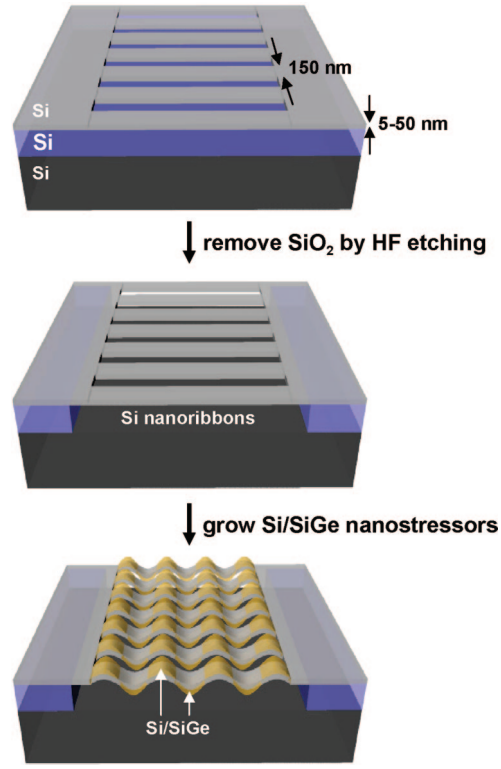


Figure 1. Schematic illustration of the steps used by Lagally and co-workers to create "mechano-electronic superlattices" in organized arrays of nanoribbons. The process starts with a silicon-on-insulator wafer. Thinning the top silicon to a thickness in the range of 5−50 nm followed by lithographic patterning and etching of this silicon layer defines the nanoribbons. Removing the underlying oxide releases them from the wafer along their lengths but leaves them tethered at their end points. Heteroepitaxial growth of germanium or silicon/germanium alloy simultaneously onto the top and bottom surfaces of these nanoribbons leads to the self-organized formation of arrays of Ge/SiGe deposits (*i.e.*, nanostressors) that create an electronic superlattice through coupling of the strain to the electronic properties of the silicon. (Not drawn to scale. The amplitudes of the buckled nanoribbons are exaggerated.)

examples.[7,8] In a different approach, unstrained nanomembranes can be lifted from their supporting substrate and then transferred to another surface that is itself subjected to tensile strain. When this receiving surface is designed to bond mechanically to the nanomembrane in selected regions, release of the strain leads to organized patterns of buckling that involve delamination and out-of-plane deformations in the unbonded regions.[16] Figure 2c shows an example of an array of gallium arsenide nanoribbons manipulated in this fashion. If, by

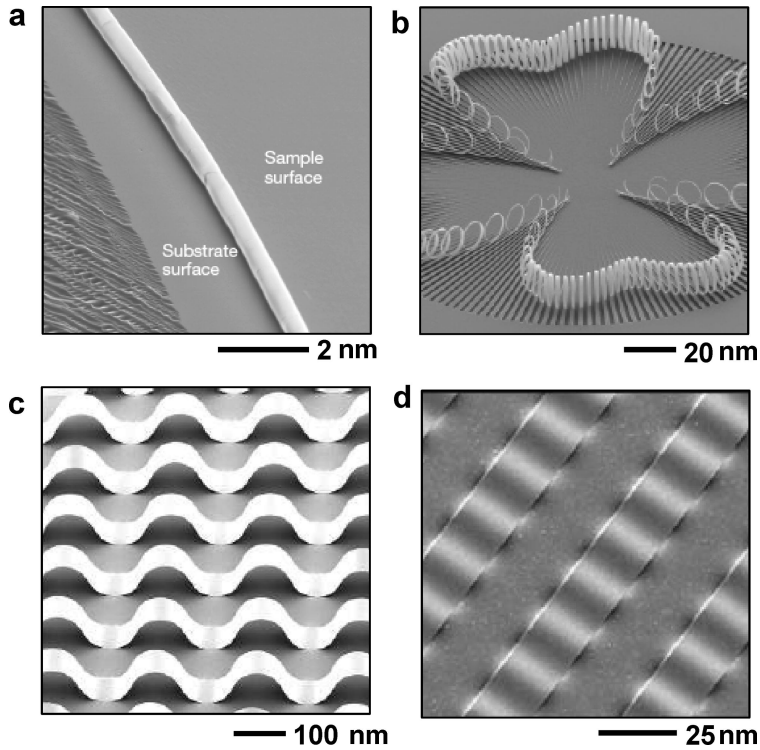


Figure 2. Scanning electron micrographs of structures formed from semiconductor nanomembranes by spatial control of applied or residual strains. (a) Nanotube of SiGe created by release of a bilayer of SiGe/Si (length 20 μm; diameter 530 nm) grown on a substrate with controlled levels of residual stress. Reproduced with permission from ref 7, copyright 2001 Macmillan Publishers Ltd. (www.nature.com). (b) Complex coil structure fabricated from a Si/Cr bilayer. Adapted from ref 8, copyright 2006 American Chemical Society. (c) Array of buckled ribbons of GaAs (thickness 270 nm) formed by patterned adhesion to a prestrained, elastomeric support. Reproduced with permission from ref 16, copyright 2006 Macmillan Publishers Ltd. (www.nature.com/nnano). (d) Array of wavy ribbons of Si (thickness 100 nm) created by uniform adhesion to a prestrained elastomeric support. Reproduced with permission from ref 17, copyright 2006 AAAS (www.sciencemag.org).

contrast, bonding occurs everywhere *and* the receiving substrate has a modulus that is much lower than the nanomembrane, then a wavy structure forms in which intimate, atomic-scale contact is maintained along the entire bottom surface.[17] Figure 2d shows arrays of wavy silicon nanoribbons of this type. The thicknesses of the ribbons and the moduli of the materials define the wavelengths and the amplitudes of these structures. When formed on elastomeric substrates, the material systems of Figure 2c,d, or analogous ones that involve full two-dimensional nanomembranes, have completely linear elastic responses to large applied compressive or tensile strains. Here, the amplitudes and wavelengths of the structures change to accommodate the strains in ways that avoid fracture of the brittle inorganic materials. The result is a route to stretchable electronic and optoelectronic systems for applications such as wearable, rugged devices that can be integrated naturally with the human body.[18,19] Similar systems can also be wrapped around curvilinear surfaces to allow biologically inspired device designs that cannot be achieved with conventional technologies that rely on rigid, planar semiconductor wafers. Advanced imaging devices that have the layout of the human eye represent one example.[20] Collectively, this emerging body of results in nanomembrane research suggests compelling future directions for fundamental and applied work, with many new opportunities for unusual materials science and inventive device engineering.

Nanomembrane systems can also be wrapped around curvilinear surfaces to allow biologically inspired device designs that cannot be achieved with conventional technologies that rely on rigid, planar semiconductor wafers.

REFERENCES AND NOTES

1. Kang, S. J.; Kocabas, C.; Ozel, T.; Shim, M.; Pimparkar, N.; Alam, M. A.; Rotkin, S. V.; Rogers, J. A. High-Performance Electronics Using Dense, Perfectly Aligned Arrays of Single-Walled Carbon Nanotubes. *Nat. Nanotechnol.* **2007**, *2*, 230–236.
2. Fan, Z.; Ho, J. C.; Jacobson, Z. A.; Razavi, H.; Javey, A. Large Scale, Heterogeneous Integration of Nanowire Arrays for Image Sensor Circuitry. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105*, 11066–11070.
3. Geim, A. K.; Novoselov, K. S. The Rise of Graphene. *Nat. Mater.* **2007**, *6*, 183–191.
4. Morozov, S. V.; Novoselov, K. S.; Katsnelson, M. I.; Schedin, F.; Elias, D. C.; Jaszczak, J. A.; Geim, A. K. Giant Intrinsic Carrier Mobilities in Graphene and Its Bilayer. *Phys. Rev. Lett.* **2008**, *100*, 016602-1–016602-4.
5. Baca, A. J.; Ahn, J.-H.; Sun, Y.; Meitl, M. A.; Menard, E.; Kim, H.-S.; Choi, W. M.; Kim, D.-H.; Huang, Y.; Rogers, J. A. Semiconductor Wires and Ribbons for High-Performance Flexible Electronics. *Angew. Chem., Int. Ed.* **2008**, *47*, 5524–5542.
6. Roberts, M. M.; Klein, L. J.; Savage, D. E.; Slinker, K. A.; Friesen, M.; Celler, G.; Eriksson, M. A.; Lagally,

M. G. Elastically Relaxed Free-Standing Strained-Silicon Nanomembranes. *Nat. Mater.* **2006**, *5*, 388–393.
7. Schmidt, O. G.; Eberl, K. Thin Solid Films Roll Up into Nanotubes. *Nature* **2001**, *410*, 168–173.
8. Zhang, L.; Ruh, E.; Grützmacher, D.; Dong, L.; Bell, D. J.; Nelson, B. J.; Schnenberger, C. Anomalous Coiling of SiGe/Si and SiGe/Si/Cr Helical Nanobelts. *Nano Lett.* **2006**, *6*, 1311–1317.
9. Malachias, A.; Mei, Y.; Annabattula, R. K.; Deneke, C.; Onck, P. R.; Schmidt, O. G. Wrinkled-Up Nanochannel Networks: Long-Range Ordering, Scalability, and X-ray Investigation. *ACS Nano* **2008**, *2*, 1715–1721.
10. Chun, I. S.; Li, X. Controlled Assembly and Dispersion of Strain Induced InGaAs−GaAs Nanotubes. *IEEE Trans. Nanotechnol.* **2008**, *7*, 493–495.
11. Rogers, D. J.; Teherani, F. H.; Ougazzaden, A.; Gautier, S.; Divay, L.; Lusson, A.; Durand, O.; Wyczisk, F.; Garry, G.; Monteiro, T. Use of ZnO Thin Films as Sacrificial Templates for Metal Organic Vapor Phase Epitaxy and Chemical Lift-Off of GaN. *Appl. Phys. Lett.* **2007**, *91*, 071120-1–071120-3.
12. Singh, S.; Festin, M.; Barden, W. R. T.; Xi, L.; Francis, J. T.; Kruse, P. Universal Method for the Fabrication of Detachable Ultrathin Films of Several Transition Metal Oxides. *ACS Nano* **2008**, *2*, 2363–2373.
13. Huang, M.; Ritz, C. S.; Novakovic, B.; Yu, D.; Zhang, Y.; Flack, F.; Savage, D. E.; Evans, P. G.; Knezevic, I.; Liu, F. Mechano-Electronic Superlattices in Silicon Nanoribbons. *ACS Nano* **2009**, *3*, 721–727.
14. Tersoff, J.; Teichert, C.; Lagally, M. G. Self-Organization in Growth of Quantum Dot Superlattices. *Phys. Rev. Lett.* **1996**, *76*, 1675–1678.
15. Holy, V.; Springholz, G.; Pinczolits, M.; Bauer, G. Strain Induced Vertical and Lateral Correlations in Quantum Dot Superlattices. *Phys. Rev. Lett.* **1999**, *83*, 356–359.
16. Sun, Y.; Choi, W. M.; Jiang, H.; Huang, Y. Y.; Rogers, J. A. Controlled Buckling of Semiconductor Nanoribbons for Stretchable Electronics. *Nat. Nanotechnol.* **2006**, *1*, 201–207.
17. Khang, D. Y.; Jiang, H.; Huang, Y.; Rogers, J. A. A Stretchable Form of Single Crystal Silicon for High Performance Electronics on Rubber Substrates. *Science* **2006**, *311*, 208–212.
18. Kim, D.-H.; Ahn, J.-H.; Choi, W.-M.; Kim, H.-S.; Kim, T.-H.; Song, J.; Huang, Y. Y.; Zhuangjian, L.; Chun, L.; Rogers, J. A. Stretchable and Foldable Silicon Integrated Circuits. *Science* **2008**, *320*, 507–511.
19. Kim, D.-H.; Song, J.; Choi, W. M.; Kim, H.-S.; Kim, R.-H.; Liu, Z.; Huang, Y. Y.; Hwang, K.-C.; Zhang, Y.; Rogers, J. A. Materials and Noncoplanar Mesh Designs for Integrated Circuits with Linear Elastic Responses to Extreme Mechanical Deformations. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105*, 18675–18680.
20. Ko, H. C.; Stoykovich, M. P.; Song, J.; Malyarchuk, V.; Choi, W. M.; Yu, C.-J.; Geddes, J. B; Xiao, J.; Wang, S.; Huang, Y.; *et al.* A Hemispherical Electronic Eye Camera Based on Compressible Silicon Optoelectronics. *Nature* **2008**, *454*, 748–753.