

## ELECTRONIC MATERIALS

## Buckling down for flexible electronics

Inorganic nanoribbons can be attached to an elastic surface at selected positions to make wave-like structures that maintain their semiconducting properties when stretched or compressed. These nanostructures will prove to be immediately useful in flexible electronics.

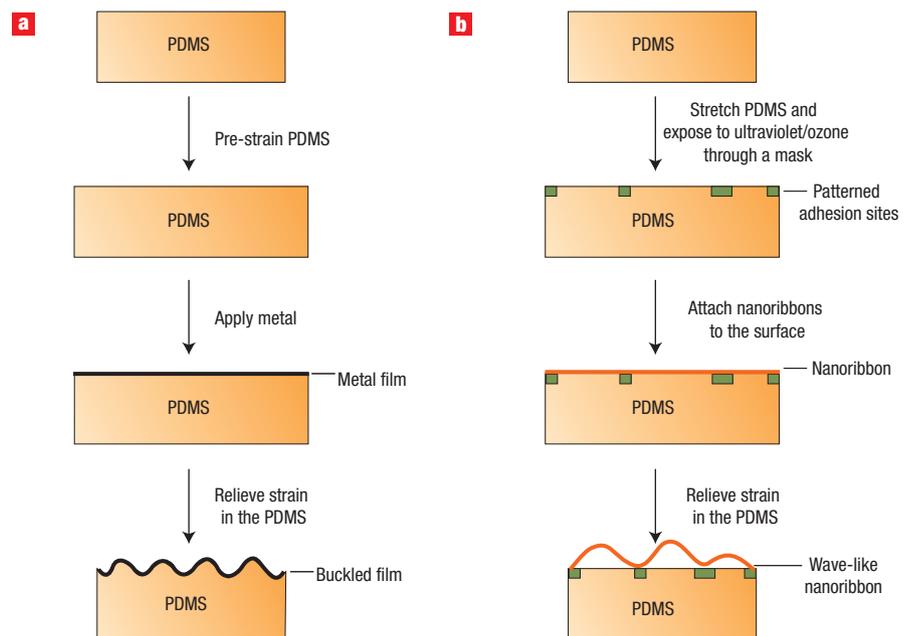
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The success of electronic paper, roll-up displays and many other potential applications of flexible electronics will depend on the availability of electronic materials that can be stretched, compressed and bent. Previous efforts to develop electronic materials that can be mechanically deformed without breaking have mainly focused on small organic molecules and polymers. Unfortunately, these materials often have low charge-carrier mobilities and short operating lifetimes, so electronic devices made from them cannot compete with devices made from inorganic materials such as silicon and gallium arsenide.

Inorganic materials, however, are notorious for their brittleness. They tend to fracture under a tensile strain of about 1%, so it is impractical to incorporate them directly into flexible electronic devices. On page 201 of this issue, John Rogers and co-workers at the University of Illinois at Urbana-Champaign and the Argonne National Laboratory, both in the US, overcome this problem by demonstrating that spectacular bendability, compressibility and stretchability can be accomplished for both silicon and gallium arsenide<sup>1</sup>. Their approach relies on controlling how single-crystal nanoribbons made from these materials buckle when they are attached to a flexible substrate. This work opens new avenues for controlling the three-dimensional shape of inorganic nanostructures and offers immediate opportunities for fabricating flexible electronic devices with superior performance from the inorganic materials currently used in microelectronics.

Buckling has been applied to a variety of fabrication tasks since it was first demonstrated in 1998 (ref. 2). In a typical approach, a thin layer of the inorganic material, which is naturally stiff, is



**Figure 1** Wave-like metallic and semiconductor structures can be produced in different ways. **a**, The PDMS is stretched before a thin layer of metal is deposited. When the strain is released, the metal film buckles into a wave-like pattern<sup>2,5</sup>. **b**, Rogers *et al.*<sup>1</sup> pattern a prestretched PDMS substrate with reactive silanol groups before laminating the semiconductor nanoribbons onto the surface. The nanoribbons bind to the silanol groups, again producing wave-like structures when the strain is released.

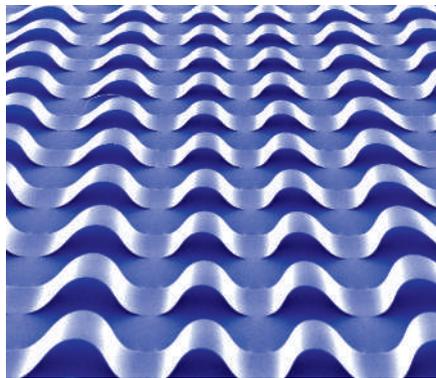
deposited on top of a relatively thick substrate made of an elastic polymer (elastomer) that has been stretched by mechanical force or thermal expansion (Fig. 1a). When the stress in the elastic substrate is relieved, a sinusoidal pattern will develop in the stiff layer in an effort to minimize the total elastic strain energy of the system. Both the wavelength and amplitude of the wave-like pattern depend on the thickness of each layer, as well as their mechanical properties. Because the wavelength increases linearly with the thickness of the stiff layer, there is a simple correlation between the buckling wavelength and the elastic moduli of the materials, which can be used to measure the elastic properties of polymeric thin films<sup>3</sup>.

The phenomenon of buckling has also been used to turn intrinsically rigid inorganic materials into flexible ones, and several groups have shown that buckled structures with built-in stress can be compressed, stretched or bent without being damaged<sup>4-6</sup>. However, the maximum strain that such structures can accommodate is limited. Buckled silicon ribbons, for example, can only sustain tensile strains of less than 15% (ref. 4). Now Rogers and co-workers have overcome this limitation by patterning the surface of a pre-stretched elastic substrate with reactive groups, allowing them to control how the ribbons buckle when the strain is released. They have demonstrated that the stretchability of nanoribbons made of single-crystal

silicon and gallium arsenide can be as high as 100%.

For most experiments that involve buckling, poly(dimethyl siloxane) (PDMS) is a popular choice for the supporting substrate. This elastomer is also widely used for 'soft' lithography<sup>7</sup>, a collection of patterning techniques based on printing, moulding and embossing with a patterned stamp. Commercially available for a variety of applications, PDMS has many attractive properties. For example, its mechanical flexibility allows one to change the design and feature size of the pattern on the stamp by mechanical stretching or compressing<sup>8,9</sup>. The surface of PDMS can also be readily modified by ultraviolet/ozone plasma treatment.

By including surface treatment and patterning in the traditional approach to buckling experiments, Rogers and co-workers are able to fabricate wave-like inorganic nanostructures that can survive mechanical manipulation. In a typical procedure, a flat PDMS block is mechanically stretched and treated with ultraviolet/ozone plasma through a mask to generate an array of patches terminated with silanol (Si-OH) groups (Fig. 1b). These silanol groups can react with those found on the surface of silicon dioxide that forms naturally on the silicon nanoribbons — or is deposited on the gallium arsenide



**Figure 2** The flexible wave-like semiconductor structures fabricated by Rogers *et al.*<sup>1</sup> could have applications in electronics and optoelectronics.

nanoribbons — to form strong chemical bonds. When the strain in the PDMS substrate is released, those regions of the nanoribbons that are not chemically bonded to the PDMS will buckle to form wave-like structures (Fig. 2).

The shapes of the nanoribbons are mainly determined by the dimensions of the adhesive and non-adhesive regions patterned on the PDMS surface. If the built-in stress is optimized, the buckled nanoribbons can be stretched by up to 100% and compressed by up to 25%

without any mechanical failure. To showcase these mechanical properties in electronic devices, Rogers and co-workers fabricated a fully compressible and stretchable metal–semiconductor–metal photodetector from buckled GaAs nanoribbons. Such a photodetector could have applications in spherical 'fly's eye' detectors that are able to detect optical signals from all directions in space.

It is not hard to imagine that this technique could be extended to many other types of inorganic semiconductors, as well as metals. And for silicon and gallium arsenide nanoribbons, it will be possible to modify their electrical and optical properties by doping, which will pave the way for the fabrication of a variety of applications in electronics and, maybe, optoelectronics. A new horizon is about to come into view for flexible electronics.

#### References

1. Sun, Y., Choi, W. M., Jiang, H., Huang, Y. Y. & Rogers, J. A. *Nature Nanotech.* **1**, 201–207 (2006).
2. Bowden, N., Brittain, S., Evans, A. G., Hutchinson, J. W. & Whitesides, G. M. *Nature* **393**, 146–149 (1998).
3. Stafford, C. M. *et al. Nature Mater.* **3**, 545–550 (2004).
4. Khang, D.-Y., Jiang, H. Q., Huang, Y. & Rogers, J. A. *Science* **311**, 208–212 (2006).
5. Lacour, S. P., Jones, J., Wagner, S., Li, T. & Suo, Z. G. *Proc. IEEE* **93**, 1459–1467 (2005).
6. Gray, D. S., Tien, J. & Chen, C. S. *Adv. Mater.* **16**, 393–397 (2004).
7. Xia, Y. & Whitesides, G. M. *Annu. Rev. Mater. Sci.* **28**, 153–184 (1998).
8. Xia, Y. & Whitesides, G. M. *Adv. Mater.* **7**, 471–473 (1995).
9. Xia, Y. *et al. Science* **273**, 347–349 (1996).

## NANOMATERIALS

# Live-action alloy nanowires

With high-resolution transmission electron microscopy, it is now possible to explore to what extent the random distribution of atomic elements in an alloy is preserved when it is reduced to a linear atomic chain, one atom thick.

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**N**ature provides us with only 70 metallic elements to choose from, which is often not enough to satisfy our technological needs. In order to fine-tune properties such as ductility, conductivity, magnetism, yield strength and so forth, we have, since ancient times, learned to mix the elements into alloys. In view of their tremendous technological

relevance it is perhaps surprising that, to date, alloys have received so little attention in nanoscience. The explanation probably lies in the fact that the tools needed to analyse the composition of nanosize alloys have only recently become available.

Metallic alloys should behave unpredictably at nanometre size scales. Indeed, for a random distribution of atoms the fluctuations in the number,  $N$ , of each type of atom varies as the square root of  $N$ . When  $N$  is small the fluctuations are nearly as large as  $N$  itself. Moreover, differences between the atomic properties of different

elements may give rise to demixing and segregation. On page 182 of this issue, Jefferson Bettini and colleagues from the Laboratorio Nacional de Luz Sincrotron in Brazil<sup>1</sup> demonstrate by a combination of high-resolution transmission electron microscopy and molecular dynamics simulations that subtle forces lead to self-organization when an alloy of gold and silver is reduced down to a linear chain of atoms. It is generally perceived that self-organization on the atomic scale can be exploited to improve nanofabrication. With videos that follow the rearrangement of atoms in a