Slice and Dice, Peel and Stick: Emerging Methods for Nanostructure Fabrication

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ABSTRACT Techniques for nanofabrication are central to nearly every field of nanoscience and nanotechnology. As a result, development of experimentally simple methods with capabilities that can complement or extend those of traditional approaches represents a growing area of research. A new paper by the Whitesides group in this issue demonstrates the ability to exploit precise mechanical cutting operations, performed with an ultramicrotome, as a route to unusual types of nanostructures. Manipulation and assembly of nanomembranes with these structures embedded enables quasi-3D, curved, and other complex layouts. These ideas, particularly when taken together with emerging methods for transfer printing of nanomembranes and related solid nanostructures, have the strong potential for applicability across many areas of nanotechnology.

Discoveries in nanoscience have great potential to yield meaningful nanotechnologies, but only when they can be implemented cost-effectively in realistic systems. The challenges in achieving this outcome are enormous, due mainly to the nature of the starting point: research in nanoscience often involves devices formed by hand, in a manner that resembles a type of craftsmanship, rather than a technology. This gap between nanoscience and nanotechnology has led to the emergence of a distinct area of research that focuses on development of scalable, experimentally simple routes to nanofabrication and assembly. This field has many interesting fundamental and applied aspects and a remarkable diversity of approaches—from adapted versions of techniques with origins in the microelectronics industry to advanced forms of conceptually older methods based on contact printing, writing, and molding.

Over the past 15–20 years, the Whitesides group has made many pioneering contributions to the field of nanofabrication, most notably through the development of methods, known collectively as soft lithography,[1,2] that use elastomeric elements as stamps, molds, and conformable phase masks. In their article in this issue, Whitesides and co-workers introduce a different type of approach that involves, at its core, mechanical cutting of materials with nanometer precision (see Figure 1).[3] This process exploits a device, the microtome, that was originally developed for preparing thin samples for examination in optical microscopes. In fact, the microtome is nearly as old and as important as the microscope itself. Some of the first devices were described in the 17th century, in Robert Hooke's book, *Micrographia*.[4] Over the ∼350 years since this initial work, microtome technology has improved dramatically, driven initially by advances in optical microscopy and then later by the invention of the transmission electron microscope. State-of-the-art instruments, known as ultramicrotomes, offer spectacular precision

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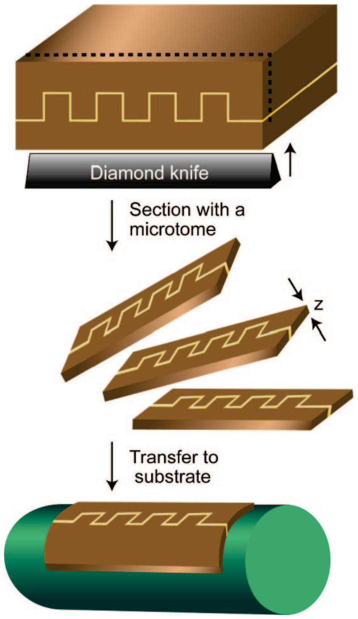

Figure 1. Schematic of the nanoskiving procedure.[3] A thin metal film (yellow) is embedded between layers of epoxy (brown) and sectioned with an ultramicrotome. These membranes are then placed onto a substrate. Since the membrane is flexible, this technique is amenable to curved substrates. The epoxy is removed using an oxygen plasma, leaving behind the metal feature (not shown). Adapted from ref 3.

See the accompanying Article by Xu *et al.* on p 215.

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in cutting—with suitable materials, diamond blades, and staging systems, these devices can achieve controlled and repeatable slicing to produce sheets with thicknesses as small as 20 nm.

In a clever process that implements ultramicrotomes for nanofabrication, Whitesides and co-workers first deposit a thin layer of metal onto an embossed polymer substrate. They then cast a layer of polymer on top to form a solid block with the metal microstructures embedded. Slicing very thin sheets from this polymer block with the ultramicrotome yields free-standing nanomembranes with integrated features of metal. The thicknesses of the membranes, the angles of the slicing operations, and the geometries of the metal microstructures define the layouts of these features. This simple process provides powerful capabilities in nanofabrication. For example, the slicing operation can yield features with widths defined by the thicknesses of the metal microstructures. This result has significant value in nanofabrication because forming films with nanometer-scale thicknesses is easy; forming features with nanometer-scale widths is not. Furthermore, the heights of these features can be as large as the thicknesses of the slices: thick slices from blocks with thin-film microstructures yield nanostructures with aspect ratios (*i.e.*, heights to widths) that are much larger than those that are possible using traditional techniques. In addition to simple, single layers of metal, multilayer stacks can be deposited in the initial step of the process, to yield closely spaced nanostructures of different materials.

Taking these ideas one step further, Whitesides and co-workers show that their sliced nanomembranes can provide "handles" for mechanically manipulating the embedded nanostructures. For example, draping a membrane over a curved surface provides an easy way to integrate these nanostructures with nonplanar substrates. Placing a membrane across a trench and then etching away the polymer yields free-standing, spanning nanostructures. In an impressive demonstration of this capability, Whitesides and co-workers form arrays of straight metal nanowires (40 nm × 70 nm in cross section and millimeters in length) that bridge recessed features that are ~20 μm wide. Folding, rolling, and stacking the membranes represent other possibilities. As an example of this last option, "quasi-3D" structures can be fabricated by assembling multilayer stacks of membranes in a layer-by-layer fashion. To illustrate the practical utility of these concepts, Whitesides and co-workers form frequency-selective surfaces that operate in the mid-infrared and could be important in thermo-photovoltaics and other systems.

A potentially important perspective on this work is that the capabilities in nanofabrication provided by membrane placement and stacking complement in an appealing manner new approaches for

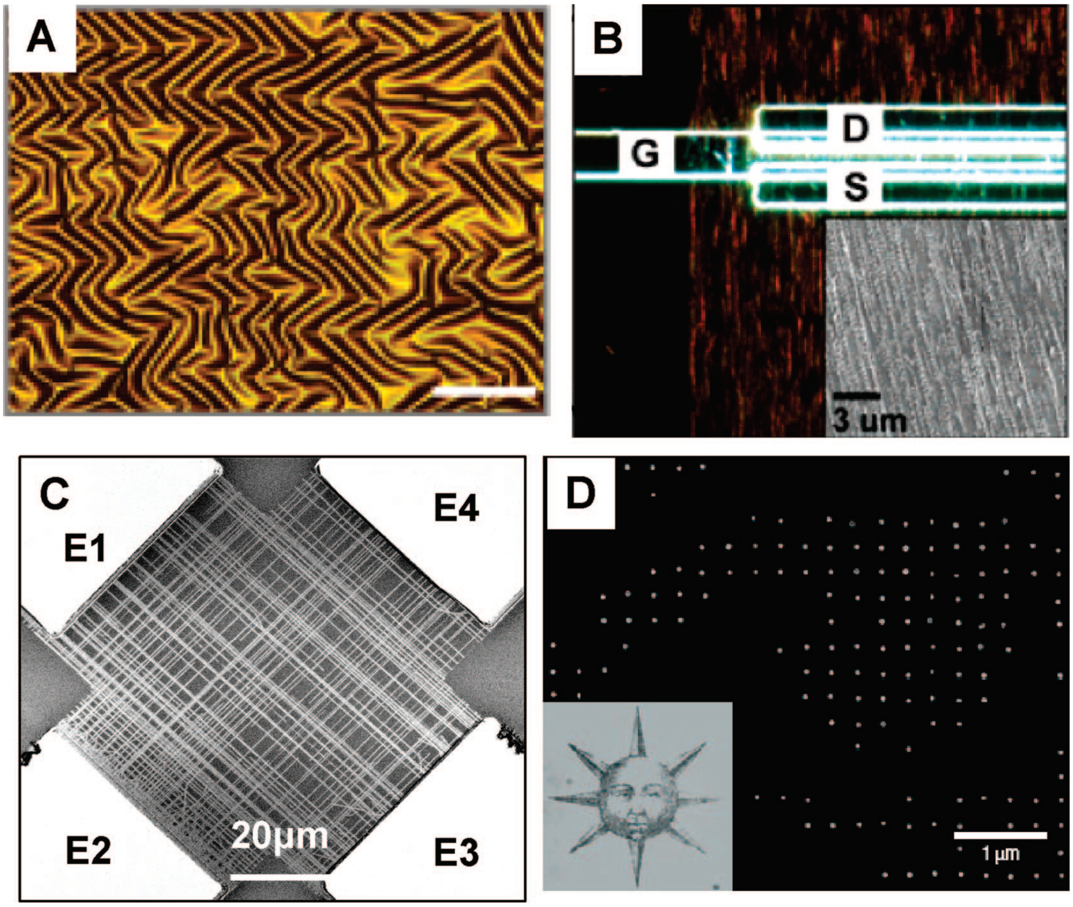

Figure 2. Nanostructures assembled by transfer printing. (A) Stretchable, "wavy" silicon nanomembrane on an elastomeric substrate of poly(dimethylsiloxane). (B) Array of Ge/Si nanowires. (C) Crossed array of single-walled carbon nanotubes with electrode contacts (E1–E4). (D) Gold nanoparticles. Images A–C reprinted with permission from refs 5, 9, and 11, respectively. Copyright 2007 American Chemical Society. Image D reprinted with permission from ref 12. Copyright 2007 Macmillan Publishers Ltd.

Capabilities in nanofabrication provided by membrane placement and stacking complement in an appealing manner new approaches for assembling nanomembranes and other forms of nanomaterials.

assembling nanomembranes and other forms of nanomaterials. Some of the most promising methods rely on adapted versions of soft lithographic printing techniques, in which solid nanoscale objects—*i.e.*, nanowires, nanotubes, nanomembranes, nanoparticles—form the "inks", rather than more conventional molecular materials.[5–15] Recent publications outline procedures for using this type of transfer printing with wide-ranging classes of nanostructures, including semiconductor nanomembranes,[5] ribbons[6] and wires,[7–9] single-walled carbon nanotubes,[10,11] metal and semiconductor nanoparticles,[12] and others, in single or multilayer[9,13,14] geometries on flat or curved surfaces (see Figure 2).[15] Different mechanisms can lift these materials from a source substrate onto the stamp and then release them from the stamp onto a device substrate. These include kinetically controlled viscoelastic effects,[15] asymmetry in surface energies[10–12] or contact areas, surface chemistries,[5] cold welding,[5,14] layers of thin-film adhesives,[6–9,13] and others. Functional systems have been demonstrated ranging from heterogeneous quasi-3D electronic components,[9,13] to flexible and stretchable circuits,[5–7] to nanotube transistors,[10,11] to nanowire sensors[8] and nanoparticle optical structures.[12]

These examples suggest the possibility of combining dissimilar nanofabrication and assembly techniques to yield overall process flows for useful devices and structures. The most meaningful of such approaches bring some combination of capabilities and potential cost structures that are absent from established techniques. The initial interest in such methods is often proportional to their underlying scientific content, their level of conceptual novelty, and their technical capabilities. Ultimate success, however, is measured first by the extent of their adoption for research purposes and then by their use in commercial manufacturing. For techniques that have emerged in the past 15 years or so, there are many examples of the former. Although there are almost none of the latter, several techniques are now in mature stages of development at small and large companies. We believe that within the next 3–5 years, the most promising methods will be introduced into commercial processes at small to moderate volumes. There is tremendous excitement in attempting to overcome the remaining scientific and engineering barriers in these development efforts. Much of the future of nanotechnology depends on a successful outcome.

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