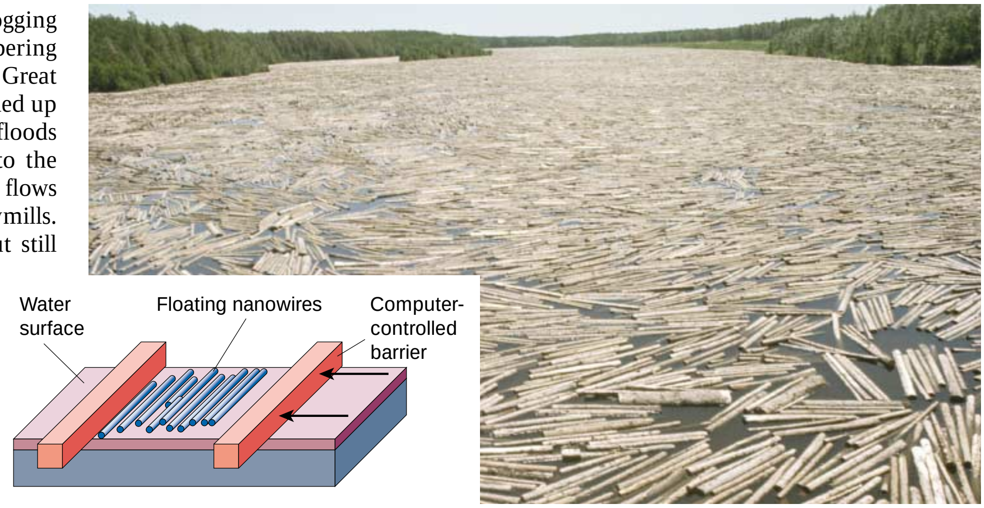
Wires on water

Peidong Yang

A centuries-old technique for transporting timber is the inspiration for a new method of assembling nanowires into large-scale, ordered patterns that could form the basis of a new generation of electronic devices.

In the nineteenth century, river logging became one of the principal lumbering operations in the area around the Great Lakes of North America. Logs were piled up through the winter. When the spring floods came, the logs were rolled down into the snowmelt-fed rivers, whose rapid flows carried them downstream to the sawmills. This log drive became a familiar, but still spectacular, sight, with aligned timbers covering many miles of river surface (Fig. 1). Reporting in *Nano Letters*, Whang *et al.*[1] and Tao *et al.*[2] have adopted a similar 'logs-on-a-river' approach on a nanoscopic level, to align semiconductor and metal nanowires on a water surface.



B. ROWAN; PROGRESSIVE IMAGE/CORBIS

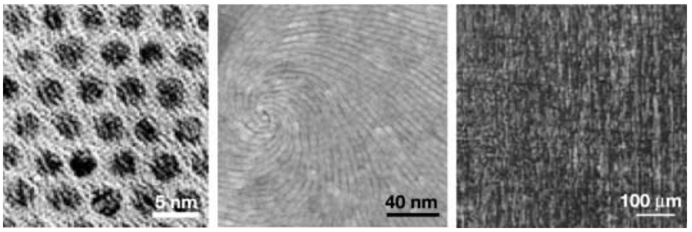
Figure 1 **Logging and 'nano-logging'. Timber harvested from the forests of North America is floated downriver to sawmills. Whang *et al.*[1] and Tao *et al.*[2] have used a similar approach (inset) to guide the assembly of nanowires — floating the nanowires on a water surface and guiding their progress with computer-controlled barriers.**

What do logs and nanowires have in common? They are both essentially one-dimensional objects, their diameters insignificant compared with their length. Over the past few years, one-dimensional nanostructures (whether you call them nanowires, nanorods or nanowhiskers) have attracted much attention, and considerable progress has already been made in their synthesis and their application in devices[3]. A formidable challenge still to be faced, however, is the hierarchical organization of these nanoscale building-blocks into functional assemblies and, ultimately, useful systems. If nanowires could be aligned and arranged into patterns, the impact would be tremendous in many areas, from nanoscale electronics and optoelectronics to molecular sensing.

Earlier attempts at nanowire alignment used microfluidic[4,5] and electrical[6] methods; more recently, a nano-imprinting technique using semiconductor superlattices as templates showed an impressive capability for aligning nanowire arrays of very high density[7]. But, despite some degree of success in nanowire alignment and patterning, all of these techniques fell short of achieving large-scale assembly — a milestone that has now been reached using the 'logs-on-a-river' approach[1,2].

Scientifically, the process is known as the Langmuir–Blodgett technique[8]. Its history can be traced back to experiments carried out by Lord Rayleigh, who found that a film of oil on water would form a layer just one molecule thick. Subsequently, Langmuir showed that monolayers of fatty acids could be compressed and made into a solid-like ordered state on the surface of water. Langmuir and Blodgett further realized that such monolayers could be transferred from the water surface onto a solid substrate by slowly passing an appropriately treated substrate through the interface between water and film.

The Langmuir–Blodgett technique has proved hugely successful in preparing monolayers of fatty acids and many other amphiphilic molecules that can be floated on the surface of water. It has been used extensively in the preparation of monolayers for molecular electronics, and more recently to create nanocrystal monolayers with tunable properties[9]. Three years ago, my colleagues and I were the first to apply this technique to one-dimensional nanostructures[10]; we succeeded in assembling short-aspect-ratio nanorods on a water surface to create textures that resembled liquid crystals (Fig. 2).



AAAS/AM. CHEM. SOC.

Figure 2 **Langmuir–Blodgett assembly: (left to right) dots[9], rods[10] and wires[1].**

From nanocrystals to nanorods, now the Langmuir–Blodgett technique has proved equally powerful for the assembly of nanowires with much larger aspect ratios: Whang *et al.*[1] have created a system of silicon nanowires, Tao *et al.*[2] of silver nanowires. In both cases, suspensions of nanowires (capped or mixed with surfactants) are dispersed on the water surface of a Langmuir–Blodgett trough, the interaction between the surfactants and the nanowires causing the nanowires to float on the water surface. Then the floating nanowires are compressed to higher density on the surface, with computer-controlled trough barriers mimicking the banks of the logging river (Fig. 1). Many nanowires reorient themselves and align parallel to the trough barrier, finally forming a closely packed monolayer. This monolayer can then be transferred onto any substrate, such as silicon wafers or other plastic substances.

There are several important features of such assemblies. First, the pitch (or repeat distance) of the nanowire pattern can be controlled at nanometre or micrometre scales through the compression process. This is critical if the nanowires are to be the building-blocks of ultra-high-density microelectronics. In fact, as a first step, Whang *et al.*[1]

have already demonstrated that these dense nanowire arrays can be interconnected with reliable metal contacts. Second, it is possible to transfer monolayers, layer by layer, to form parallel and crossed-nanowire structures that could serve as optoelectronic components.

Just as the log drive can extend over many miles of river, the Langmuir–Blodgett technique can be used to assemble large areas of nanowire monolayers on a water surface — up to 20 cm^2 is easily achieved. The monolayer area is limited only by the number of the nanowires dispersed on the trough surface. This type of large-scale nanowire assembly is unprecedented, and could be applied to many other one-dimensional nanostructures, including carbon nanotubes, for example. The feasibility of transferring multiple layers of metal or semiconductor nanowires onto flexible substrates also points to new directions for flexible electronics and optoelectronics.

Transforming spaghetti-like, tangled nanowires into an ordered, large-area array by the Langmuir–Blodgett technique is a remarkable feat. As Whang *et al.*[1] point out, this process offers a flexible pathway for the step-by-step assembly of virtually any nanowire material into the highly integrated and hierarchically organized nanodevices that are needed for a broad range of functional nanosystems. But this is not the end of the story. For nanostructured technology to be competitive, being able to create high-density arrays is not enough: how to address individual elements in a high-density array and how to achieve precise layer-to-layer registration for vertical integration are just two of the many challenges still ahead. ■

Peidong Yang is in the Department of Chemistry, University of California, Berkeley, California 94720, USA.
e-mail: p_yang@uclink.berkeley.edu

1. Whang, D., Jin, S., Wu, Y. & Lieber, C. M. *Nano Lett.* **3,** 1255 (2003).
2. Tao, A. *et al. Nano Lett.* **3,** 1229 (2003).
3. Xia, Y. & Yang, P. *Adv. Mater.* **15,** 353–389 (2003).
4. Messer, B., Song, J. H. & Yang, P. *J. Am. Chem. Soc.* **122,** 10232–10233 (2000).
5. Huang, Y., Duan, X., Wei, Q. & Lieber, C. M. *Science* **291,** 630–633 (2001).
6. Duan, X., Huang, Y., Cui, Y., Wang, J. & Lieber, C. M. *Nature* **409,** 66–69 (2001).
7. Melosh, N. A. *et al. Science* **300,** 112–115 (2003).
8. Ulman, A. *An Introduction to Ultrathin Organic Films: From Langmuir–Blodgett to Self-Assembly* (Academic, San Diego, 1991).
9. Collier, C. P., Saykally, R. J., Shiang, J. J., Henrichs, S. E. & Heath, J. R. *Science* **277,** 1978–1981 (1997).
10. Kim, F., Kwan, S., Akana, J. & Yang, P. *J. Am. Chem. Soc.* **123,** 4360–4361 (2001).

Molecular biology

MicroRNA is here to stay

Philip N. Benfey

A form of gene regulation that uses small RNA molecules to bind to longer RNAs was first described over a decade ago, but was thought to be of little significance in controlling cellular processes. No longer.

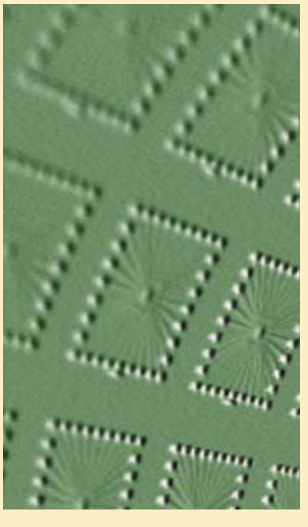
The first glimpse of the wave was more than a decade ago, when a strange form of gene regulation was described that involved the binding of one RNA molecule to another[1]. Then last year, with reports that there are hundreds of small RNAs in the genome[2–5], it came into view. There was the possibility that a whole layer of gene regulation involving very small RNA molecules called microRNAs had been overlooked for 40 years. But still there were doubts as to the importance of microRNAs — the wave might yet turn out to be scarcely a ripple, let alone a tsunami. With the description by Palatnik *et al.* of the role of microRNAs in controlling plant

Electronics

Nanotechnology goes large

Discovering new ways of making and manipulating materials at nanometre scales should help to maintain the computer industry's relentless drive towards ever greater miniaturization and performance. But in this issue, Xiangfeng Duan and colleagues show that, in addition to allowing the development of high-performance nanoelectronics, these techniques may also be useful for making flexible electronics over large areas and at low cost (*Nature* **425,** 274–278; 2003).

At present, making microelectronics involves a lot of waste. More than 95% of the bulk of the precious silicon wafers from which most microchips are made serves no other purpose than as a mechanical support for the circuitry patterned into its surface. For laptop computers, digital cameras, portable music players and other high-value gadgets, the cost associated with such waste is easily absorbed into



X. DUAN, NANOSYS INC.

the price. But for products such as 'smart clothing' or electronic paper — which involve higher volumes, large areas and more modest price tags — this cost becomes prohibitive. Moreover, the high temperatures required to grow crystalline silicon (in excess of 1,400 °C) make many such products difficult to produce at any price. But by growing only as much semiconductor material as is needed for electronic circuitry on the surface of an inexpensive substrate material such as glass or plastic (see picture), significant reductions in cost can be achieved.

Commercially, large-area electronic devices are based on either amorphous silicon (used in most LCD displays) or, more recently, organic semiconductors (as in the display on James Bond's electric shaver). The performance of these materials, however, is poor compared to conventional crystalline semiconductors, and is always likely to be so. But by using newly developed techniques for growing crystalline semiconductors in the form of tiny nanometre-diameter wires and ribbons — techniques that are currently being pursued for making nanoscale devices (see "Wires on water" by Peidong Yang, above) — Duan *et al*. show that high-performance, low-cost macroelectronics could be just around the corner.

By aligning silicon nanowires or cadmium-sulphide nanoribbons between metal electrodes, the authors can create field-effect transistors — the fundamental building-blocks of modern electronic circuitry — with characteristics better than those of similar amorphous silicon or organic semiconductor devices, and approaching those of polycrystalline silicon devices. By increasing the density of wires and ribbons between the metal electrodes, Duan *et al*. expect soon to be able to improve this performance even further. And with the recent advent of nanowires made from high-mobility materials such as indium phosphide and indium arsenide, such devices could in future exceed the performance of crystalline silicon devices. **Ed Gerstner**