

nanocluster of molten gold or some other metal. This process results in the formation of an alloy of the catalyst and the semiconductor⁴. When the concentration of the semiconductor in the alloy reaches a sufficiently high level, nucleation occurs and the nanowire begins to grow (Fig. 1). This growth follows a phase diagram involving the catalyst, the semiconductor and the doping material, and it is often difficult to predict the extent of doping, or how dopant atoms are incorporated. The problem is further compounded by the limited number of suitable experimental techniques for analysing the composition of nanowires as a function of position.

It has been reported recently that adsorption on the surface of the nanowire is the main doping mechanism in semiconductor nanowires^{5–8}. Lauhon and co-workers have now shown that there are actually two distinct pathways for dopant incorporation — by using a technique called pulsed-laser atom probe tomography⁹ to determine the distribution of phosphorus dopants in germanium nanowires. In this approach, laser pulses evaporate atoms from the tip of a single nanowire, and the type and position of the atoms are then deduced from the time it takes them to reach a position-sensitive detector¹⁰. This technique allows for a three-dimensional reconstruction of nanowire composition with near-atomic resolution.

The two doping pathways are shown in Fig. 1a. In the vapour–solid (VS) mechanism, dopant atoms are directly deposited on the nanowire surface; in the vapour–liquid–solid (VLS) mechanism, on the other hand, the dopant atoms first dissolve in the catalyst and are then transported across the liquid–solid interface to the core of the nanowire. The Northwestern team clearly show that these two mechanisms proceed at different rates, so there is a much higher concentration of dopants in the shell of the nanowire than in the core (Fig. 1b).

Lauhon and co-workers go on to quantitatively model each doping mechanism. Their treatment connects the dopant concentration in the shell to the rates at which the precursors supplying the phosphorus and germanium decompose at the nanowire surface. Similarly, core doping is described through precursor decomposition rates at the gold nanocluster. What makes this work particularly interesting and important is the simple steady-state model that connects the catalyst composition to the core doping concentration.

The Northwestern work is certainly an important contribution to elucidating the mechanisms of, and limits to, dopant incorporation in semiconductor nanowires. It also demonstrates that there are many unknowns when it comes to rationally doping nanowires and, more generally, other

nanostructures. Many questions remain to be answered. These include understanding, at the molecular level, why dopants get incorporated at low levels into nanowires through the catalyst–nanowire interface, and exploring if these mechanisms also apply to other nanowires and dopants. Furthermore, little is known about the influence of dopant environment/vicinity, location and interactions on the optical, electrical or magnetic properties of nanowires. These and many other questions will ensure that nanowire doping will continue to keep researchers busy in the future. □

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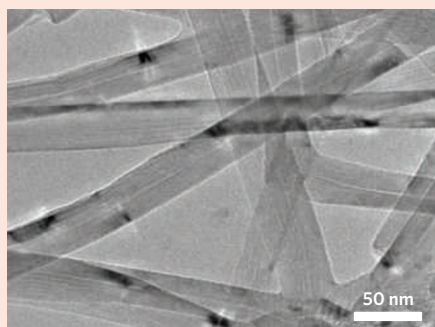
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GRAPHENE PRODUCTION

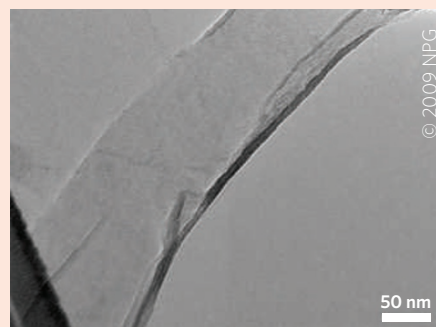
From nanotubes to nanoribbons

Graphene — an individual layer of carbon atoms — is a semimetal. However, thin strips of graphene called nanoribbons can be either semiconducting or metallic. Semiconducting nanoribbons display useful electronic properties that can be used for applications such as transistors. Several methods have been developed for the production of semiconducting nanoribbons, including lithographic and chemical approaches, but they all suffer from a number of drawbacks. Now, two independent research teams have shown that graphene nanoribbons can be produced from multiwalled carbon nanotubes.

Starting from the fact that a nanotube can be viewed as a graphene nanoribbon that has been rolled up to form a cylinder, the two groups have demonstrated different ways to unzip nanotubes lengthwise. Hongjie Dai and colleagues at Stanford University carried out plasma etching to cut open nanotubes that had been partially embedded in a polymer



film (*Nature* **458**, 877–880; 2009). James Tour and colleagues at Rice University, on the other hand, used a solution-based oxidative process to unfurl the nanotubes, followed by a chemical reduction step to remove chemical groups containing oxygen that have an adverse effect on the conductivity of the nanoribbons (*Nature* **458**, 872–876; 2009). The development of similar chemical methods for the production of graphene sheets is currently



the focus of much research (*Nature Nanotech.* **4**, 217–224; 2009).

These transmission electron microscope images taken by Tour and co-workers show the nanotubes (left) and the nanoribbons (right). Both groups demonstrated the quality of their nanoribbons by using them to make field-effect transistors.

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