

tomere of a two-cell embryo gives rise to the entire trophoblast and the other to the entire inner cell mass, and that these fates correlate with the localization of Cdx2 protein, a transcription factor. The elegant results of Kurotaki *et al.* clearly demonstrate that the establishment of the E-Ab axis does not depend on cell lineage; that is, each blastomere at the two- and four-cell stage gives rise to cells in the embryonic and abembryonic regions. These results are also consistent with the notion that E-Ab axis formation does not depend on localized molecules within the zygote (3, 6).

Although much attention has centered on the formation of the E-Ab axis, there is still no evidence that this axis has any functional rele-

vance for the development of subsequent axes in the mature organism. Kurotaki *et al.* also show that the zona pellucida is not spherical but rather ellipsoidal and that the E-Ab axis of the blastocyst aligns with the short axis of the zona likely because of the physical constraints exerted by this glycoprotein layer (6). The shape of the zona pellucida and alignment of the E-Ab axis may facilitate the movements of the zona pellucida-enclosed blastocyst from the oviduct into the uterus or movement through the uterus to implantation.

Is this E-Ab axis conserved in other mammals, including humans? Marsupial blastocysts do not have an inner cell mass, and egg-laying mammals do not generate a blastocyst (9). Snapshots of these other

types of mammals still only offer a limited view of the true picture. Their embryonic dances remain a secret.

References

1. Y. Kurotaki, K. Hatta, K. Nakao, Y.-i. Nabeshima, T. Fujimori, *Science* **316**, 719 (2007).
2. P. P. Tam, R. R. Behringer, *Mech. Dev.* **68**, 3 (1997).
3. J. Rossant, P. P. Tam, *Dev. Cell* **7**, 155 (2004).
4. A. K. Hadjantonakis, V. E. Papaioannou, *BMC Biotechnol.* **4**, 33 (2004).
5. J. M. Rhee *et al.*, *Genesis* **44**, 202 (2006).
6. N. Motosugi *et al.*, *Genes Dev.* **19**, 1081 (2005).
7. K. Hatta, H. Tsujii, T. Omura, *Nat. Protocols* **1**, 960 (2006).
8. K. Deb, M. Sivaguru, H. Y. Yong, R. M. Roberts, *Science* **311**, 992 (2006).
9. R. R. Behringer, G. S. Eakin, M. B. Renfree, *Reprod. Fertil. Dev.* **18**, 99 (2006).

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MATERIALS SCIENCE

How Nanowires Grow

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Many controversies boil down to which of two distinctly different explanations, models, or options is the correct one. On page 729 of this issue, Kodambaka *et al.* (1) address a long-standing controversy—whether, below a certain temperature, the growth of semiconductor nanowires involves a liquid droplet or a solid particle of the catalytic material. Unexpectedly, their elegant experiments show that both answers are correct: Under the same experimental conditions, growth may occur via a liquid droplet and via a solid particle.

The results may help to devise methods for controlling the growth of nanowires.

Semiconductor nanowires have emerged alongside carbon nanotubes as a potential building block for future nanometer-scale electronic devices. Yet, in contrast to carbon nanotubes, which may be either semiconducting or metallic, the properties of semiconductor nanowires are always determined by the properties of the semiconductor material they are made of. Furthermore, a variety of semiconductor materials—such as silicon, germanium, gallium arsenide, and gallium nitride—with different electronic and optical properties may be fabricated in the form of nanowires. All these features make semiconductor nanowires especially attractive for future electronic and photonic nanodevices.

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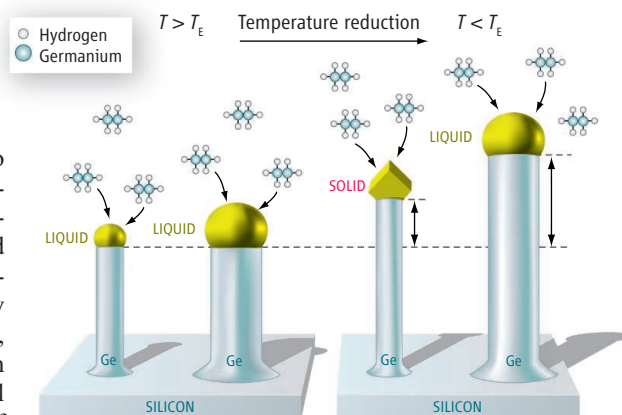
Most semiconductor nanowires are fabricated by the vapor-liquid-solid (VLS) process originally suggested and investigated more than 40 years ago by Wagner and Ellis (2). In this process, the semiconductor material (usually supplied as a gas) is absorbed by liquid nanodroplets of an appropriate catalytic material such as gold. These nanodroplets, located at the nanowire tips, serve as seeds for nanowire growth and also determine the nanowire diameters. The semiconductor material condenses at the interface between

A controversy about the way in which semiconductor nanowires grow has been resolved.

the droplet and the nanowire, thereby extending the length of the nanowire. Morales and Lieber were the first to use the VLS process in 1998 in the context of nanoelectronics (3), triggering a worldwide avalanche of research activities into nanowire synthesis (4).

In VLS growth, the liquid droplet consists not only of the catalytic material but also of a certain amount of the semiconductor material in question. This is because the mixed material has a much lower melting temperature than each of the two constituents, for example, gold and germanium. The lowest possible melting temperature for a specific composition is called the eutectic temperature, T_E . For the gold-germanium system, this temperature is 361°C and occurs at a Ge:Au ratio of 7:18.

Above the eutectic temperature, semiconductor nanowires grow via the VLS mechanism. However, nanowire growth has also been reported to occur at temperatures below the eutectic temperature (5–9). Any growth observed in these cases should involve a solid catalytic particle. However, errors in the temperature measurement could not be excluded; furthermore, the eutectic temperature may shift as a result of nanometer-scale size effects. It there-



Germanium nanowires. The mechanism by which Ge nanowires grow may depend not only on the temperature but also on the diameter of the nanowire, as shown by Kodambaka *et al.* Above T_E (left), the nanowires have a liquid gold cap and grow via VLS growth. Below T_E (right), the cap of relatively thick nanowires is liquid, whereas the cap of relatively thin nanowires becomes a crystalline solid. The latter nanowires grow via a different mechanism that is slower than VLS growth.

fore remains hotly debated whether the catalyst in this case is a liquid droplet or a solid particle.

The problem with most investigations on this subject was that detailed structural analyses, for example, with electron diffraction methods, could only be performed after the growth had terminated, leading to additional uncertainties. In contrast, Kodambaka *et al.* (1) investigated the growth of gold-catalyzed germanium nanowires in situ in a transmission electron microscope that allows for the supply of germanium vapor in the form of digermane (Ge_2H_6) gas.

For the gold-germanium system, several reports have suggested nanowire growth below the eutectic temperature (5, 6). A key indicator was the shape of the gold at the tip of the nanowire. A liquid gold droplet has a smooth, almost half-spherical shape, whereas solid gold shows planes, edges, and corners that may easily be identified.

As expected, above the eutectic tempera-

ture, nanowire growth involves a liquid droplet on top of the germanium nanowires (see the figure, left panel). However, when the authors reduced the temperature to below the eutectic temperature while keeping the supply of germanium constant, they observed two distinctly different phenomena (see the figure, right panel). Some gold nanodroplets remained liquid even though the temperature was, in one case, more than 100°C below the T_E of 361°C . The authors observed this VLS-type growth mostly for nanowires with relatively large diameters.

In contrast, for nanowires with relatively small diameters, the gold droplet became solid as the temperature fell below T_E . The nanowires continued to grow, but did so much more slowly than in the case of VLS growth (see the figure, right panel). Further cooling experiments showed that the transformation of the gold caps from liquid to solid at temperature below T_E could be delayed for tens of minutes. Kodambaka *et al.* show that this delay depends on various parameters, such as the vapor pressure, the temperature, and the

diameter of the nanowires.

The experiments of Kodambaka *et al.* clearly demonstrate that—even well below the eutectic temperature—the gold catalyst droplet can remain liquid, corresponding to VLS growth, and that solid gold particles can also catalyze nanowire growth. Which situation is actually present in an experiment depends on specific parameters, including the thermal history of the samples. This opens new opportunities to control of the growth of germanium and other semiconducting nanowires, which will bring nanowires one step closer to real applications.

References

1. S. Kodambaka *et al.*, *Science* **316**, 729 (2007).
2. R. S. Wagner, W. C. Ellis, *Appl. Phys. Lett.* **4**, 89 (1964).
3. A. M. Morales, C. M. Lieber, *Science* **279**, 208 (1998).
4. C. M. Lieber, Z. L. Wang, *MRS Bull.* **32**, 99 (2007).
5. G. A. Bootsma, H. J. Gassen, *J. Crystal Growth* **10**, 223 (1971).
6. H. Adhikari *et al.*, *Nano Lett.* **6**, 318 (2006).
7. A. I. Persson *et al.*, *Nat. Mater.* **3**, 677 (2004).
8. K. A. Dick *et al.*, *Nano Lett.* **5**, 761 (2005).
9. Y. Wang *et al.*, *Nat. Nanotech.* **1**, 186 (2006).

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CHEMISTRY

The New Face of Catalysis

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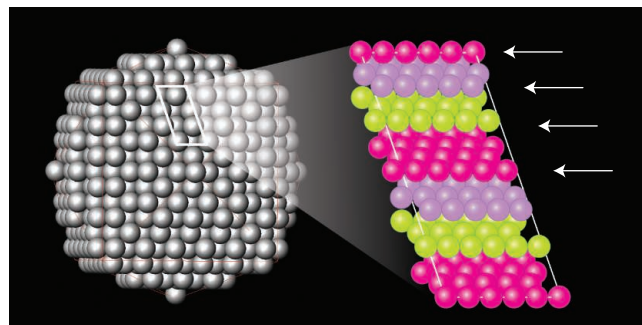
A secure energy future depends heavily on whether chemists and materials scientists can discover more efficient, stable, and economical catalysts for the production and use of alternative fuels. Indeed, a recent report by the Department of Energy describes this as a grand challenge, specifically citing the need to understand the relationship between catalyst structure and chemistry, and to exploit advances in the synthesis of nanoscale materials (1). As reported on page 732 of this issue, Tian *et al.* have made a breakthrough in the synthesis of nanoscale catalysts (2). They describe the synthesis of platinum nanoparticles of an unusual shape. Remarkably, the crystals each possess 24 faces (see the figure), which confer an enhanced ability to oxidize organic fuels, such as formic acid and ethanol, compared with the analogous spherical polycrystalline particles.

Researchers have known that a material's size and shape strongly affect its properties since the 1850s, when Michael Faraday postu-

lated that the color of ruby glass was due to finely divided gold particles. To test his hypothesis, Faraday developed a method for preparing aqueous gold colloids (3). Suspended in solution, these spherical colloids exhibited the same brilliant red colors observed in ruby glass. Today, the controlled synthesis of gold and silver rods, cubes, hollow shells, and triangular prisms allows their colors to be tuned across the visible spectrum and into the near-infrared range (4).

The catalytic properties of metal nanoparticles are every bit as dramatic as their optical properties. Long considered an inert metal, gold nanoparticles supported on TiO_2 are highly active catalysts for the oxidation of CO (4). Moreover, gold reactivity appears to peak at nanoparticle diameter of 3 nm. The catalytic activities of platinum nanoparticles with tetrahedral, cubic, and spherical shapes also vary

Platinum nanocrystals with unusual shapes show unusually high catalytic activity, suggesting possible ways to enhance catalysis in other materials.



Multifaceted particles. Platinum nanoparticles with 24 high-index [730] faces (left) have an abundance of low-coordination, high-reactivity atomic edges sites (right). [Adapted from (2)]

significantly (5). These reactivity differences can be attributed in part to the potential binding sites presented by atoms situated at the corners and edges of a nanoparticle. Indeed, the data show that the rate of a catalyzed reaction increases exponentially with the percentage of these atomic sites (5). A major challenge for catalysis researchers lies in understanding how to control nanoparticle shape to maximize the number of coordinatively unsaturated (open) surface sites.

For this reason, the results of Tian *et al.* are

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