Islands of Growth

Working out a building code for atomic structures

By IVARS PETERSON

Forget the architect. Throw away the blueprints. Dismiss the workers. Instead, let bricks rain down from the sky and assemble themselves flawlessly into the structure you want to build.

Applied to the construction of an office building, this strategy sounds absurd. In the realm of atoms, however, such a process may prove the most efficient, least costly way of fabricating the nanocircuitry of the future.

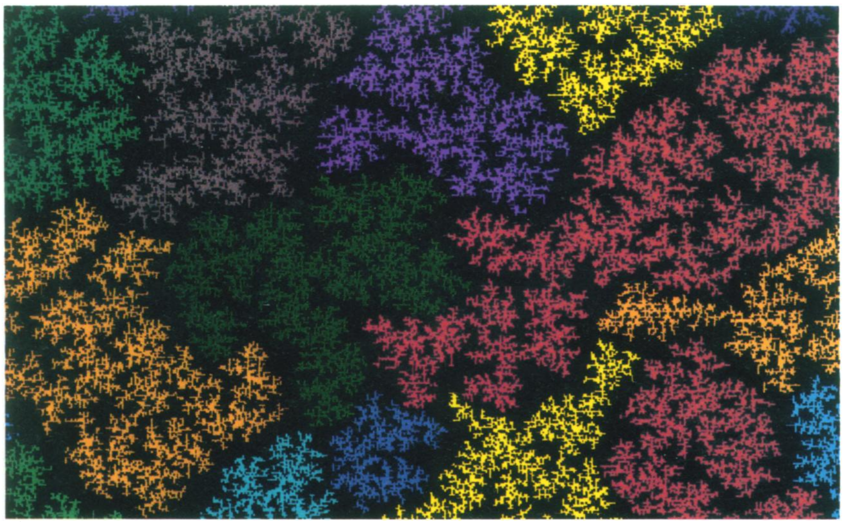
Thanks to the exquisite detail revealed by scanning tunneling microscopes, researchers have over the last few years discovered that surfaces churn with activity during crystal growth. When deposited on a crystal, atoms make contact with the surface, then migrate, meet, and stick. They arrive and diffuse randomly, yet they often end up settling into particular patterns, forming lengthy strands, distinctively shaped islands, or arrays of steps, ledges, and terraces.

"You wouldn't think that you could build anything by random motion, but you get structures with well-defined shapes," says Horia I. Metiu of the Center for Quantized Electronic Structures at the University of California, Santa Barbara. "You can make thousands of islands, all the same shape, and you can repeat [the process] over and over again."

Such observations have raised a host of fundamental questions about how crystal growth occurs. What are the factors that regulate the shapes of the structures formed by deposited atoms? How are these shapes constructed? What are the proofreading and editing mechanisms that lead to nearly perfect structures? Can these growth processes be controlled at the atomic level to create specific features for electronic circuitry?

"There is a lot of interest in nanostructures," says Klaus Kern of the École Polytechnique Fédérale de Lausanne in Switzerland. "If you could manipulate nature to build large numbers of these structures for you, you could use conventional techniques to explore their unique physical and chemical properties."

Deciphering nature's building codes could point the way to nanoengineering.


Jensen et al.

A simple computer model incorporating deposition, diffusion, and aggregation of atoms on a crystal surface generates ragged, branched structures similar to those observed in the laboratory.

Kern and his coworkers have demonstrated that they can control growth patterns on a crystal surface by adjusting the rate of atomic deposition and the temperature at which deposition occurs.

For example, depositing silver atoms on platinum at 40 kelvins creates small clusters – each consisting of a pair of silver atoms – scattered uniformly across the platinum crystal surface. Thus, a low temperature and a moderate deposition rate lead to the formation of a large number of small islands.

In contrast, at 110 kelvins and a low deposition rate, silver atoms gather into large, tenuous, intricately branched clusters that sprawl over the platinum base. In this case, an atom landing on the surface can cover large distances to find a partner. Pairs form early, and atoms readily join existing pairs to create a few large islands.

The creation of order out of random motion depends on the amount of energy it takes for deposited atoms to move from one place to another on a given surface. In general, the migration of a single atom on a surface requires the least amount of energy. Moving along the edge of an atomic island or dropping down from one step to another of a terraced landscape requires more energy.

Because the differences between these energies is often quite large, it's possible to find temperature windows for which some atomic motions occur and others are practically forbidden. By selecting appropriate temperatures and deposition rates, researchers can influence the resulting patterns.

"To control the structure, you have to find the temperature window to get what you need," Kern says.

For example, a complicated, branched structure forms when the temperature is set to allow only the motion of single, isolated atoms. The atoms simply stick wherever they first make contact with an island. If such islands are heated to higher temperatures to allow atomic movement along an island's edge, their shapes become more rounded.

Several groups of researchers have found that deposited atoms can, under certain conditions, form islands displaying very precise shapes. Such well-defined patterns reflect different aspects of the geometry of the underlying crystal surface.

In one striking example, platinum atoms deposited on a platinum surface form equilateral triangles at 425 kelvins, hexagons at 450 kelvins, and triangles again (but in a different orientation) at 550 kelvins. "What's interesting is that a small change in temperature, which [corresponds to] a small change in the energy of the atoms, can lead to totally different shapes," Metiu says.

As reported in the Nov. 11, 1993 NATURE, Kern and his group have also succeeded in growing strands of copper, only one atom wide, on a palladium crystal surface at room temperature. Deposited copper atoms automatically gather and align themselves in a particular direction on the surface to create the ultimate in thin wires.

"You just dump [the copper atoms], and it takes less than a second to make those wires," Metiu notes.

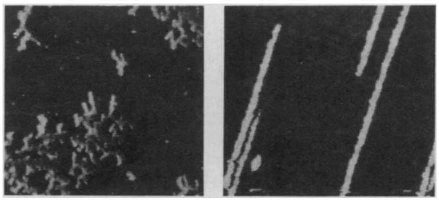
To help explain how these structures form, several groups have developed computer models that produce shapes like those observed in the laboratory. In the March 3 NATURE, Pablo Jensen of Claude-Bernard University (Lyon I) in Villeurbanne, France, and his collaborators at Boston University describe a simple model that generates a variety of branched structures.

In their simulations, particles land at randomly selected positions on a checkerboard surface. Then, at each time step, a randomly chosen cluster of connected particles moves one unit up, down, left, or right. If two particles happen to end up occupying adjacent squares, they stick.

"Our model allows one to distinguish the effects of deposition, diffusion, and aggregation," the researchers report. "We find that tuning the relative strength of, for example, deposition and diffusion generates a rich range of [shapes]."

Jensen and his collaborators are now modifying their model to include the motion of particles along the fringes of islands. "Just by adding the probability that a particle attached to another can break away and continue to move, we get compact shapes," Jensen says.

Recently, Kern and his colleagues have explored the slight changes in atomic behavior that can yield a symmetrical pattern reminiscent of a snowflake instead of a ragged, branched structure. "It comes down to a complicated interplay between the rate of deposition and the rate of diffusion along the borders of the islands," Kern says.


Kern et al./NATURE

These scanning tunneling microscope images show the formation of ragged clusters of silver atoms on a platinum surface (left) and copper "wires" just one atom wide on a palladium surface (right).

By taking advantage of the tendency of atoms deposited on a crystal surface to organize themselves into distinctive structures, researchers have an attractive alternative to the time-consuming, painstaking process of using a scanning tunneling microscope to position atoms individually to create a certain pattern (SN: 10/9/93, p.228). They can potentially mass-produce dozens of copies in a fraction of the time it takes to build a single structure by hand.

Kern and his colleagues have found that it's possible to create a large number of nearly identical atomic clusters simply by heating up a surface already patterned with islands of different sizes. During heating, the atoms rearrange themselves to form clumps containing roughly the same number of atoms.

The availability of such well-defined atomic clumps may make it possible to study systematically how the physical and chemical characteristics of clusters depend on the number of atoms present.

"Crystal growth is important for a lot of technology, but it's still treated like a kind of magic," Kern remarks. "We really have to understand on an atomic level all the processes involved to control growth and get the structures we want."

"If you want to grow something, your best bet is to go with what the atoms want to do," Metiu adds. "We are learning to accept that crystal growth resembles a construction site more than a riot. Perfectly random motion can lead to self-organization." □