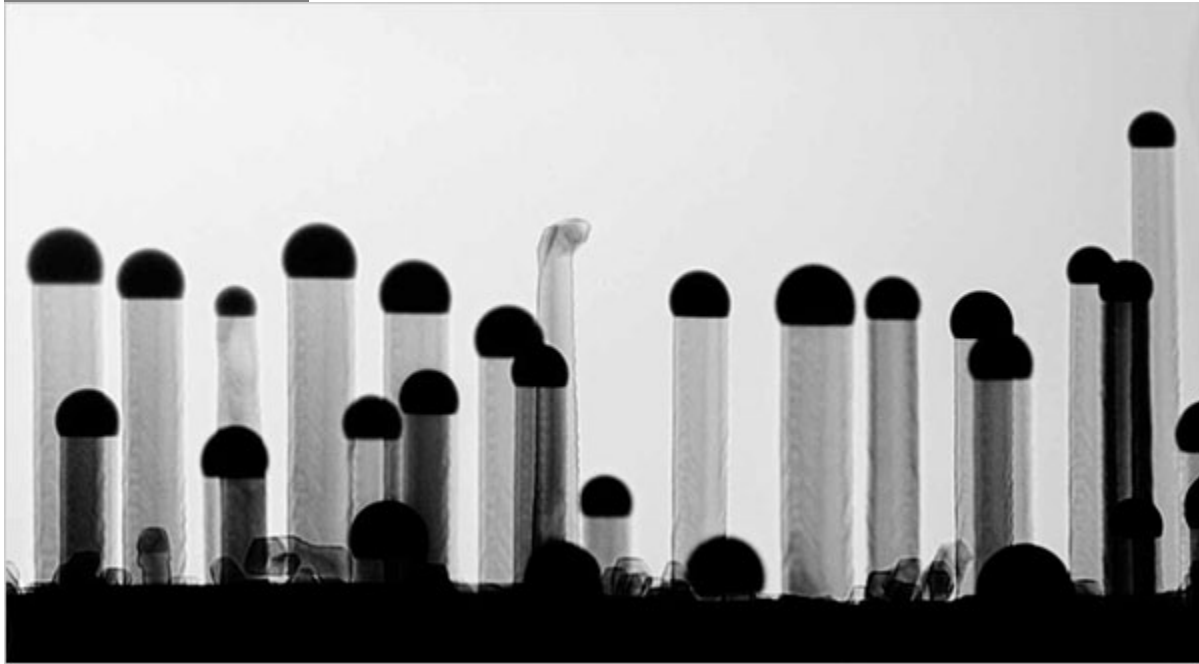


After the Transistor, a Leap Into the Microcosm



IBM

TINY MUSHROOMS A crop of silicon nanowires growing under a transmission electron microscope. The gray columns are the wires, and the black, liquid droplet on top of each catalyzes the growth.

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By JOHN MARKOFF

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YORKTOWN HEIGHTS, N.Y. — Gaze into the electron microscope display in Frances Ross's laboratory here and it is possible to persuade yourself that Dr. Ross, a 21st-century materials scientist, is actually a farmer in some Lilliputian silicon world.

[!\[\]\(17413706fd4997a1a4bdf85c6864eee1_img.jpg\) Podcast: Science Times](#)

First Mention: Transistors, 1948 (September 1, 2009)

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Chris Ramirez for The New York Times

CAPTAIN MINIATURE Frances Ross, a scientist at I.B.M. Research in Yorktown Heights, N.Y., operating an electron microscope, which allows her to study nanowires, about one one-thousandth the width of a human hair, as they grow.

Dr. Ross, an I.B.M. researcher, is growing a crop of mushroom-shaped silicon nanowires that may one day become a basic building block for a new kind of electronics. Nanowires are just one example, although one of the most promising, of a transformation now taking place in the material sciences as researchers push to create the next generation of switching devices smaller, faster and more powerful than today's transistors.

The reason that many computer scientists are pursuing this goal is that the shrinking of the transistor has approached fundamental physical limits. Increasingly, transistor manufacturers grapple with subatomic effects, like the tendency for electrons to "leak" across material boundaries. The leaking electrons make it more difficult to know when a transistor is in an on or off state, the information that makes electronic computing possible. They have also led to excess heat, the bane of the fastest computer chips.

The transistor is not just another element of the electronic world. It is the invention that made the computer revolution possible. In essence it is an on-off switch controlled by the flow of electricity. For the purposes of computing, when the switch is on it represents a one. When it is off it represents a zero. These zeros and ones are the most basic language of computers.

For more than half a century, transistors have gotten smaller and cheaper, following something called Moore's Law, which states that circuit density doubles roughly every two years. This was predicted by the computer scientist Douglas Engelbart in 1959, and then described by Gordon Moore, the co-founder of Intel, in a now-legendary 1965 article in Electronics, the source of Moore's Law.

Today's transistors are used by the billions to form microprocessors and memory chips. Often called planar transistors, they are built on the surface (or plane) of a silicon wafer by using a manufacturing process that precisely deposits and then etches away different insulating, conducting and semiconducting materials with such precision that the industry is now approaching the ability to place individual molecules.

A typical high-end Intel microprocessor is today based on roughly one billion transistors or more, each capable of switching on and off about 300 billion times a second and packed densely

enough that two million transistors would fit comfortably in the period at the end of this sentence.

In fact, this year, the chip industry is preparing to begin the transition from a generation of microprocessor chips based on a minimum feature size of 45 nanometers (a human hair is roughly 80,000 nanometers in width) to one of 32 nanometers — the next step down into the microcosm. But the end of this particular staircase may be near.

“Fundamentally the planar transistor is running out of steam,” said John E. Kelly III, I.B.M.’s senior vice president and director of research.

“We’re at an inflection point, you better believe it, and most of the world is in denial about it,” said Mark Horowitz, a Stanford University electrical engineer who spoke last week at a chip design conference in Palo Alto, Calif. “The physics constraints are getting more and more serious.”

Many computer scientists have been warning for years that this time would come, that Moore’s Law would cease to be valid because of increasing technical difficulties and the expense of overcoming them. Last week at Stanford University, during a panel on the future of scaling (of which the shrinking of transistors is one example), several panelists said the end was near.

“We’re done scaling. We’ve been playing tricks since 90 nanometers,” said Brad McCredie, an I.B.M. fellow and one of the company’s leading chip designers, in a reference to the increasingly arcane techniques the industry has been using to make circuits smaller.

For example, for the past three technology generations Intel has used a material known as “strained silicon” in which a layer of silicon atoms are stretched beyond their normal atomic distance by depositing them on top of another material like silicon germanium. This results in lower energy consumption and faster switching speeds.

Other researchers and business executives believe the shrinking of the transistor can continue, at least for a while, that the current industry standard Mosfet (for Metal-Oxide-Semiconductor Field-Effect-Transistor) can be effectively harnessed for several more technology generations.

Technology executives at the Intel Corporation, the world’s largest chipmaker, say they believe that by coupling more advanced photolithographic techniques with new kinds of materials and by changing the design of the transistor, it will be possible to continue to scale down to sizes as small as five nanometers — effectively taking the industry forward until the end of the next decade.

“Silicon will probably continue longer than we expect,” said Michael C. Mayberry, an Intel vice president and the director of the company’s component research program.

Both Intel and I.B.M. are publicly committed to a new class of transistors known as FinFETs that may be used as early as the 22-nanometer technology generation beginning in 2011 or 2012. Named for a portion of the switch that resembles a fish fin, these transistors have the dual

advantage of offering greater density because they are tipped vertically out of the plane of the silicon wafer, as well as better insulating properties, making it easier to control the switching from a 1 to a 0 state.

But sooner or later, new materials and new manufacturing processes will be necessary to keep making computer technology ever cheaper. In the long term, new switches might be based on magnetic, quantum or even nanomechanical switching principles. One possibility would be to use changes in the spin of an individual electron to represent a 1 or a 0.

“If you look out into the future, there is a branching tree and there are many possible paths we might take,” Dr. Mayberry said.

In Dr. Ross’s laboratory at I.B.M., researchers are concentrating on more near-term technology. They are exploring the idea of constructing FinFET switches in a radical new process that breaks away from photo etching. It is a kind of nanofarming. Dr. Ross sprinkles gold particles as small as 10 nanometers in diameter on a substrate and then suffuses them in a silicon gas at a temperature of about 1,100 degrees Fahrenheit. This causes the particles to become “supersaturated” with silicon from the gas, which will then precipitate into a solid, forming a wire that grows vertically.

I.B.M. is pressing aggressively to develop this technology, which could be available commercially by 2012, she said. At the same time she acknowledged that significant challenges remain in perfecting nanowire technology. The mushroom-shaped wires in her laboratory now look a little bit like bonsai trees. To offer the kind of switching performances chipmakers require, the researchers must learn to make them so that their surfaces are perfectly regular. Moreover, techniques must be developed to make them behave like semiconductors.

I.B.M. is also exploring higher-risk ideas like “DNA origami,” a process developed by Paul W. K. Rothmund, a computer scientist at the California Institute of Technology.

The technique involves creating arbitrary two- and three-dimensional shapes by controlling the folding of a long single strand of viral DNA with multiple smaller “staple” strands. It is possible to form everything from nanometer-scale triangles and squares to more elaborate shapes like smiley faces and a rough map of North America. That could one day lead to an application in which such DNA shapes could be used to create a scaffolding just as wooden molds are now used to create concrete structures. The DNA shapes, for example, could be used to more precisely locate the gold nanoparticles that would then be used to grow nanowires. The DNA would be used only to align the circuits and would be destroyed by the high temperatures used by the chip-making processes.

At Intel there is great interest in building FinFET switches but also in finding ways to integrate promising III-V materials on top of silicon as well as exploring materials like graphene and carbon nanotubes, from which the company has now made prototype switches as small as 1.5 nanometers in diameter, according to Dr. Mayberry. The new materials have properties like increased electron mobility that might make transistors that are smaller and faster than those that can be made with silicon.

“At that very small dimension you have the problem of how do you make the connection into the tube in the first place,” he said. “It’s not just how well does this nanotube itself work, but how do you integrate it into a system.”

Given all the challenges that each new chip-making technology faces, as well as the industry’s sharp decline in investment, it is tempting to suggest that the smaller, faster, cheaper trend may indeed be on the brink of slowing if not halting.

Then again, as Dr. Mayberry suggests, the industry has a way of surprising its skeptics.

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