the 26 January issue of *Science* (p. 630), they reported using a combination of prepatterned lines of adhesive compound and moving fluids to arrange nanowires in parallel arrays, triangles, and crossbars, resembling the crossbars made by Heath's group. To make the crossbars, the team started by crafting a flat, rubbery mold prepatterned with tiny parallel channels. They placed this mold atop a silicon substrate and flowed a suspension of nanowires in an ethanol solution through the channels, aligning one layer of nanowires in the same orientation. They then turned their mold 90 degrees and repeated the procedure, depositing another row of parallel nanowires atop the first. (See figure, p. 784.)

To show that the arrays were electrically active, Lieber's team made a 2 × 2 crossbar that resembled a tic-tac-toe board. They then used e-beam lithography to place tiny electrical contacts to the outside world at each end of the four wires in the array. By applying voltages between the various pads, they showed that they could produce transistor-like performance at any of the four junctions they chose. "Using solution phase, bottom-up assembly, we can make functional devices," says Lieber.

A hybrid future?

Crossbars and nanotubes may be fine for basic research. But many researchers doubt whether they will ever produce circuitry that can run Quake, surf the Web, or even handle a simple word processor. Early on, researchers in the field "made all kinds of crazy promises," says Edwin Chandross, a materials chemist at Bell Laboratories, the research arm of Lucent Technologies in Murray Hill, New Jersey. In particular, says Chandross, molecular electronics researchers pushed the notion that engineers would make computing devices out of single molecules. That's nonsense, he says, because a single unruly molecule could disrupt a device and thus corrupt the larger system. Today, Chandross is pleased by what he sees as a more realistic approach of using ensembles of molecules to work together in individual devices. Still, "it's a real long way off from being practical," says Rick Lytel, a physicist at Sun Microsystems in Palo Alto, California. Sunlin Chou, who helps direct Intel's work on advanced circuitry, agrees: "It's very blue sky."

"Gee, the vacuum tube guys said that too" about semiconductor electronics, says Heath, undaunted. "If we can make a nano–integrated circuit and interface it to lithography, you've got to argue that's pretty interesting," he says. "I want to know how far we can go."

Heath, Mallouk, and many others expect that even increasingly sophisticated molecular-electronics devices are unlikely to make it into the computing world on their own. Rather, they will form a hybrid technology that combines self-assembling molecular electronics components with traditional silicon electronics made by lithography. "I think the most likely approach will use lithography to get down to submicrometer dimensions and then self-assemble the little pieces inside," says Mallouk.

Even in the established world of silicon electronics, that vision is opening eyes. In addition to Hewlett-Packard, companies including IBM and Motorola are starting to pump research dollars into the area. So are start-ups such as Molecular Electronics Corp. of State College, Pennsylvania. "A number of companies are looking at this, because none of them want to be in a position of not being up on the technology if and when the breakthroughs come," Mallouk says.

Those breakthroughs may or may not ultimately make circuitry smaller than high-tech silicon fabs can achieve today. But if molecular-electronics researchers can teach circuits to assemble themselves, that trick will give them a cost advantage that no chipmakers will be able to ignore.

–ROBERT F. SERVICE

NANOCOMPUTING

EUV LITHOGRAPHY

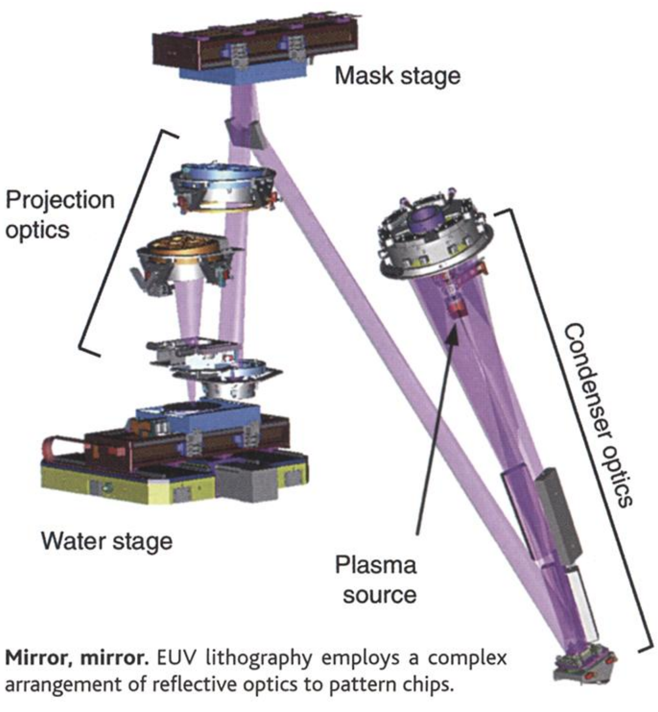
Optical Lithography Goes To Extremes—And Beyond

In search of ever finer detail, chipmakers are pushing conventional printing techniques toward the physical limits of light

LIVERMORE, CALIFORNIA—The speed of light sets an upper limit for those dabbling in relativity, but makers of computer chips are concerned with another of light's limiting properties: its wavelength. Current chipmaking technologies may soon bump up against that limit, say proponents of molecular electronics and other futuristic computing schemes, and that will confound the semiconductor industry's ability to shrink transistors and other devices. Craig Barrett, CEO of the world's largest chipmaker Intel, begs to differ.

In April, Barrett and other leaders of a chip-patterning research consortium gathered here to unveil a first-of-its-kind machine that uses extreme ultraviolet light to print features on chips. The new machine has already created features as small as 80 nanometers across on silicon wafers, a resolution that is expected to boost the speed of integrated circuits from 1.5 gigahertz today to 10 gigahertz in 2005–06. Ultimately, Barrett and others argue, the technology will be able to turn out features as small as 10 nanometers, nearly the same scale as molecular electronic devices.

The triumph makes the technique, known as extreme ultraviolet (EUV) lithography, "one of the leading horses in the race" to succeed today's optical lithography for carving ever smaller features into silicon, Barrett says. Today, conventional lithography patterns chips by shining ultraviolet light through a stencil with slits in the shape of features to be transferred onto a chip. Lenses below the stencil then reduce that pattern to one-quarter its original size and project it onto a region of a silicon wafer coated with a polymer known as a resist. The light transforms the resist so that chemical etchants can eat away either the region hit with the light or the shaded region. Engineers can then carve away part of the silicon wafer below and fill the



Mirror, mirror. EUV lithography employs a complex arrangement of reflective optics to pattern chips.

CREDIT: SCIENCE AND TECHNOLOGY REVIEW, LLNL space with metals, insulators, or other materials for making transistors.

The shorter the wavelength of the light used, the smaller the features that can be printed on chips. As a general rule of thumb, a given wavelength can make features down to half its length. Because the current generation of optical lithography devices use 248-nanometer light, the smallest features they can make are about 120 nanometers.

Assembly required. Technician works on the EUV machine.

Recent advances in lithography have come by continually switching to shorter and shorter wavelengths. Chipmakers are now in the process of converting their equipment from using 248-nanometer light to 193-nanometer light. In a few years they expect to switch again to light 157 nanometers long. That's likely to be an excruciating change, as it means lithography toolmakers will have to give up reliable fused silica lenses—which are not transparent at that wavelength—and adopt ones made from calcium fluoride, a soft, temperamental, and rare material.

Still, most chip engineers believe that technological leap will be simple compared to what comes next. No materials are transparent to electromagnetic radiation below 157 nanometers—the realm of EUV light, or soft x-rays. As a result, lenses cannot be made to focus light patterns. That limitation will finally put an end to optical lithography's incredible run. "When you go to EUV, everything changes," says David Merkle, the chief technical officer with Ultratech Stepper, a lithography toolmaker in San Jose, California.

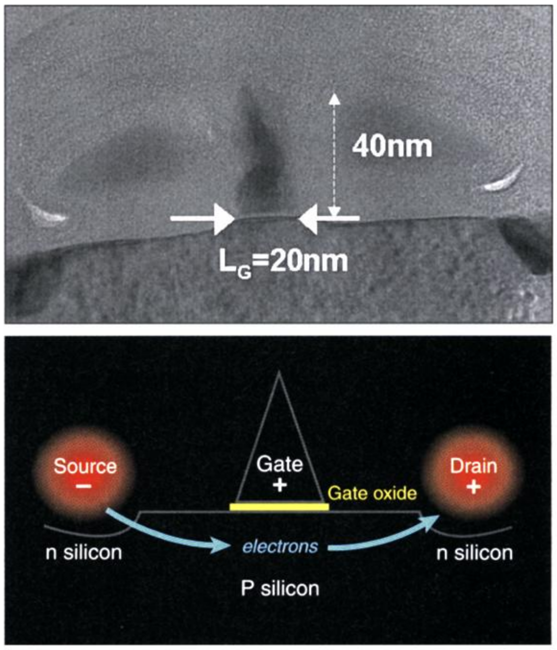
To get EUV lithography to work, the consortium's engineers have had to transform some parts of the technology almost beyond recognition. Most important, they switched from using transparent lenses to reflective mirrors to reduce the size of image patterns. First, to generate EUV light, researchers focus a laser on a jet of xenon gas. The gas emits 13-nanometer light that is then focused on a reflective stencil. To reduce this image, researchers engineered curved mirrors coated with 80 alternating layers of silicon and molybdenum, polished with atomic-scale precision. Because air absorbs EUV radiation, the entire apparatus must be placed in a vacuum. The result is a 3-meter-by-3-meter machine that stands some 4 meters high and is ensconced in a clean room to keep out possible contaminants. The fact that such a demanding scheme can work at all "is truly a major technical achievement," says Merkle, whose company is not affiliated with the EUV consortium.

The accomplishment didn't come quickly. EUV research started in the 1980s at AT&T Bell Laboratories, now a part of Lucent Technologies, and Japan's Nippon Telephone and Telegraph. Sandia National Laboratories and Lawrence Livermore National Laboratory did early work as well, and along with AT&T and Intel formed two cooperative research programs on the topic in 1991. Congress cut funds for the programs in 1996, calling them corporate welfare. The change prompted Bell Labs to bail out. But feeling the need for a successor to optical lithography, Intel, Advanced Micro Devices, and other semiconductor companies stepped in, committing $250 million over 5 years to develop a prototype EUV machine.

Even with a working prototype in place, EUV's success isn't sealed. IBM and others continue to pursue alternative technologies, including methods of patterning chips with tight beams of electrons. But some of these alternatives have taken hits recently. Last year, IBM phased out an initiative that used more energetic hard x-rays to pattern chips, a program it had supported for decades. And in March, IBM announced that it was joining the EUV consortium. Another contender, which uses beams of ions, also appears to be faltering without a major corporate backer. And although IBM, as well as Canon—a major lithography tool producer in Japan—continue to pursue e-beam technology, "EUV is the prime contender," Merkle says. Barrett says Intel hopes to begin using EUV lithography for chipmaking in 2005. But to get the prototype technology ready for the factory floor, Merkle estimates that chip and lithography toolmakers will have to spend another $2.5 billion.

That illustrates the lengths to which the chip industry will go in pursuing ever greater processing power. It also underscores the semiconductor industry's desire to squeeze every ounce of juice out of silicon circuits, rather than turning to novel computing schemes such as molecular electronics or quantum computing. Computer chips are now a nearly $1-trillion-a-year business. And that constitutes a potent economic driver for continued improvements to silicon-based technologies, says Rick Stulen, who heads the U.S.-based EUV consortium. "I learned a long time ago never to bet against an economic driver," he adds. For researchers hoping molecular electronics will have a future, that means they'd do well to find a way to work with silicon electronics rather than try to overthrow it.

–ROBERT F. SERVICE



World's Smallest Transistor

Suppose researchers slash the size of silicon-chip circuit elements to one-tenth their current size, or about 20 nanometers. Will standard transistors still work normally? Many researchers fear not. Metal wires, they suspect, will lose their ability to keep electrons from wandering off into the surrounding material, dissipating energy and information. But in June, Intel researchers led by Robert Chau reported making a standard three-terminal transistor—the architecture used in today's chips—with the smallest features ever reported, including an insulating barrier only three atoms wide. Far from being crippled, the tiny device could switch at a blinding 1.5 trillion times per second, more than 10 times faster than devices that sit on current chips.

–R.F.S.

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