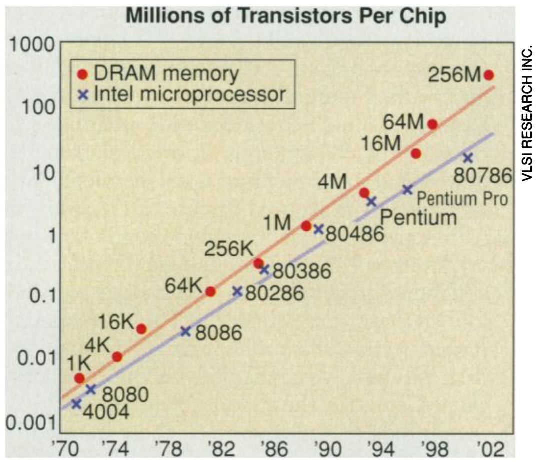
Can Chip Devices Keep Shrinking?

Investigators are working to develop new silicon-patterning technologies for writing features far smaller than those produced by conventional optics

In 1965, Intel Corp.'s co-founder Gordon Moore tossed out the kind of long-range prediction that makes most scientists squirm. Noting early trends in the fledgling microelectronics industry, Moore predicted that the number of transistors on computer chips would double every 18 months, thanks largely to continuous advances in techniques for carving features on silicon wafers, or lithography. Moore's prediction, which industry analysts soon dubbed "Moore's Law," turned out to be oddly prescient: The number of transistors on chips has, in fact, doubled about every 18 months for the past 35 years, helping to propel semiconductor production into a $150-billion-a-year industry.

But many semiconductor experts now fear that Moore's Law could soon be broken. Advances in optical lithography historically have relied on shortening the wavelength of the light used to etch features, because shorter wavelength light can write smaller features, much as a sharper pencil can write a thinner line. Current, state-of-the-art lithography operations use ultraviolet (UV) light, which has wavelengths just below that of visible light. Industry analysts have little doubt that the big shrink driving the semiconductor industry will continue for another 10 years as lithography operations use ever shorter UV light waves. But beyond that, the landscape gets hazy. With chip company brass for the first time facing the prospect of not being able to pack more transistors onto chips, "they are starting to sweat," says IBM physicist John Warlaumont.

Researchers around the globe are working furiously to extend the life of Moore's Law by coming up with alternative chip-patterning techniques for use when current lithographic tools hit the wall. Already, they have come up with a handful of possible contenders, among them, systems that pattern features with showers of electrons, or beams of x-rays or high-energy ultraviolet light. All three have been shown to be capable of writing features far smaller than those etched with conventional optics, says Karen Brown, the director of lithography at SEMATECH, a semiconductor industry consortium based in Austin, Texas. The big question is whether any of them can be scaled up to pattern the billions of features an hour needed for a system to be economically viable.



Ever smaller. Moore's Law has held true for more than 3 decades.

As it will cost the industry billions of dollars to switch to a new patterning technology, most researchers agree that the new lithography techniques won't make it to the market until the industry has squeezed conventional optical-based lithography for all it's worth. And, by most accounts, the technology still has some juice left in it. To pattern silicon wafers, today's optical systems rely on a template, or "mask," made from a sheet of glass topped with a thin coating of a light-absorbing metal. Circuit designers use an electron beam or laser to carve desired features through the mask's metal coating to the transparent glass, much as one can use a Q-tip to trace patterns on a heavily sooted windowpane. To transfer the pattern to a silicon wafer, the system shines UV light through the mask; light that slips through the mask's features is passed through a series of lenses that focuses the light patterns down to about one-fourth their original size.

These tiny patterns are then focused on a thin layer of light-sensitive "resist," which sits atop a silicon wafer. Where it is bombarded by photons, the resist's molecular structure changes. Researchers use a variety of compounds and high-temperature gases to etch away either the altered or unaltered regions of the resist and traces of the silicon underneath, thereby carving features in the wafer.

Current state-of-the-art systems use UV light with a wavelength of 248 nanometers, which allows them to write features of just 0.25 micrometers. Industry scientists expect that by the year 2001, they'll be able to mass-produce features of 0.18 micrometers by reducing the wavelength of the UV light used to 193 nanometers. And many expect that, with a few more tweaks to the system, optical lithography should be able to produce features of 0.13 micrometers by about 2004. But past that, optical lithography fails, says Franco Cerrina, who heads the Center for X-ray Lithography at the University of Wisconsin, Madison. The problem, he explains, is that at wavelengths shorter than 193 nanometers, conventional quartz lenses absorb rather than refract, or bend, light. If a lithographic successor isn't found by then, the number of transistors on computer memory chips could top out at about 4 billion, compared to today's standard of 16 million.

X-ray visions

Perhaps the strongest candidate for succeeding optical lithography is its close cousin, x-ray lithography. Typical x-ray systems fire photons with a wavelength of just 4 nanometers and so can write far sharper features than their UV counterparts can. As early as 1977, Henry Smith and his colleagues at the Massachusetts Institute of Technology showed that with an x-ray system, they could carve features in silicon wafers as small as 0.017 micrometers—175 times finer than the standard of the day. They and others later built working electronic devices with features of 0.05 micrometers.

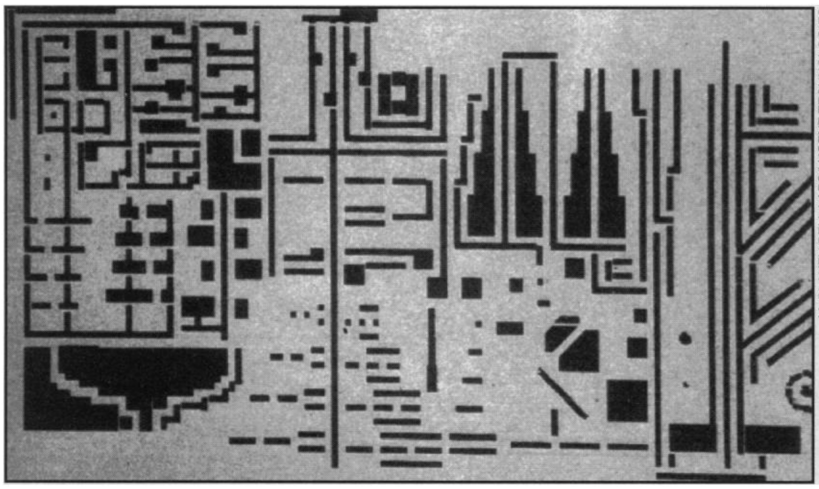
More recently, several groups have developed x-ray systems that can not only produce single devices, but pattern them by the millions in parallel to build densely packed transistors on integrated circuits, an achievement still unmatched by any of the other upstart technologies. In 1994, for example, Warlaumont and his IBM colleagues used x-ray lithography to pattern 64 million transistors on a memory chip known as DRAM. The smallest features, however, were 0.4 micrometers across—much larger than the features today's optical systems are capable of etching.

The IBMers and other groups are working to pull off this feat with devices that have even smaller features. At the IEEE International Electron Devices Meeting, which is being held this week in San Francisco, Kikuchi Yukiko and her colleagues at Toshiba in Kawasaki, Japan, along with co-workers at NTT Basic Research Labs in Atsugi, are expected to report that they have etched 4.7 million devices on a chip with a minimum feature size of 0.13 micrometers, or just half the size of the smallest features on today's best chips. They have yet to pattern an entire wafer with features this small and dense. But if they succeed, they will have crammed a record 4 billion transistors on a single DRAM chip—about 250 times the number on today's standard DRAMs.

Cerrina calls such demonstrations "impressive" because they raise hopes that x-ray lithography can overcome a few serious obstacles. One is that because conventional lenses can't focus x-rays, researchers can't use a lens to shrink a mask's features. As a result, the mask's features have to be the same size as those on the wafer. But such ultrafine features are difficult and time-consuming to write.

Mask patterning for x-ray lithography is typically done with a conventional "direct-write" electron beam machine, which painstakingly carves out the features one at a time, much as a pencil draws lines on paper. To carve features as tiny and numerous as those in these masks can take from a day to weeks, says Warlaumont, yet to make the technique commercially viable, chipmakers would need to be able to produce at least one mask an hour.

Another concern, according to Cerrina, is mask distortion. In most x-ray systems, masks are made of a patterned layer of an x-ray–absorbing material, such as tungsten, deposited on a thin, rigid layer of material that is transparent to x-rays, such as silicon carbide or silicon nitride. But in part because of poor atomic alignment between the two layers, strain often builds up between them, which can "induce distortions into the tungsten," warping the mask's features, says Cerrina. Fortunately, many of the distortions are predictable, and maskmakers are experimenting with changing the shape of the mask's features slightly to compensate for anticipated distortions. Also, researchers are working to create masks out of metal alloys that bond with less strain, such as tungsten-titanium and tantalum-boride. The effort, says Cerrina, is "going in the right direction," but is not there yet.



M. BLAKEY/BELL LABS/LUCENT TECHNOLOGIES

Detailed work. Researchers beam showers of electrons through patterns carved into a mask *(above)* to etch features on silicon chips.

Electron showers

Researchers are trying to circumvent some of the problems arising from the use of high-energy light by relying on high-energy electrons to etch features on chips. Researchers have long used direct-write electron "pencils" not only to carve masks but to etch tiny features directly on chips built for research purposes. But pencil-writing is far too slow for manufacturing purposes, says Lloyd Harriott, who heads advanced lithography research at Bell Labs, the research arm of Lucent Technologies in Murray Hill, New Jersey. He and others are working on a patterning system that shines whole showers of electrons through masks. Such attempts aren't new. But past efforts have faltered, largely because many of the projected electrons get absorbed by the mask, which heats it and deforms the features.

To minimize heating, Harriott and his colleagues have constructed a mask from thin layers of metals, such as chromium and tungsten, that scatter rather than absorb electrons. These metal layers, into which the patterns are etched, are supported by a thin, rigid layer of silicon nitride that is transparent to electrons. In the Bell Labs setup, both the electrons that slip through the mask's features and those scattered by the metal coatings pass through the silicon nitride and then through a magnetic lens, which focuses the unscattered electrons down through a tiny aperture in a molybdenum sheet. Most of the scattered electrons miss the hole and are absorbed by the molybdenum. A second lens below the aperture then focuses the refined beam on the chip substrate, reducing patterns to just one-quarter their size on the original mask.

At a conference last June, the Bell Labs team members reported that with the technique, they were able to write features as small as 0.08 micrometers. SEMATECH's Brown calls the work "exciting progress." However, she notes that just like the x-ray masks, electron-shower masks have distortion problems stemming from the poor atomic alignment between the top, etched metal layer and the silicon nitride beneath, among other factors. To give the mask additional rigidity, Harriott and his colleagues have attached a grid of silicon struts beneath the silicon-nitride, like 2 × 4s beneath a plywood floor. The grid has reduced the distortion. But the struts block electrons, so the features directly above the struts don't get printed onto the wafer, an effect the researchers are working to correct.

Going to extremes

Other researchers are exploring the limits of optical lithography with a patterning scheme that relies on mirrors to focus light at wavelengths too short for lenses. Called extreme ultraviolet lithography, the technique bounces EUV photons off an elaborate setup of flat and curved mirrors—including a mask made out of reflective materials—which ultimately focuses the photons on a resist-coated silicon wafer. The photons have a wavelength of 13 nanometers, or less than one-tenth the wavelength of light used by today's most advanced optical systems.

Accordingly, the systems can etch far smaller features than those produced by their longer wavelength counterparts. Researchers based in Livermore, California, at Lawrence Livermore National Laboratory and Sandia National Laboratory, have designed an EUV system that can pattern features as small as 0.08 micrometers. And this spring, Richard Stulen and his Sandia colleagues reported that they had made the first working transistor by EUV lithography. Its minimum feature size is 0.13 micrometers.

But as Brown points out, EUV developers face "technical challenges on several fronts." For one, EUV mirrors—typically made with coatings of alternating films of silicon and molybdenum—are far less efficient reflectors than the household variety. Indeed, EUV mirrors only reflect about 65% of the photons that hit them. Because in EUV systems photons bounce a total of eight times before they hit the wafer, the losses mount until only 1% to 2% of the original photons wind up hitting their target. Fewer arriving photons means long, costly exposure times to pattern wafers. To make the system cost-effective, researchers would need to boost the reflectivity of their mirrors to at least 72%, says Brown. Livermore's Donald Sweeney believes that goal can be reached, although it may take a few years. He notes that researchers have already had some success in making higher reflectivity mirrors from new combinations of materials, such as molybdenum and beryllium.

No winners?

Investigators are pursuing a host of other lithographic schemes that create circuit patterns with everything from beams of ions and neutral atoms to arrays of miniature electron guns and atomic imaging probes (*Science*, 1 November, p. 723). Research also is under way on embossing resist layers on silicon wafers with miniaturized polymer stamps (*Science*, 5 April, p. 85). Still, some industry experts aren't optimistic about any of the technologies' market prospects.

The fundamental obstacles are not only technological but economic, says Abbas Ourmazd, a physicist and lithography expert at the Institute for Semiconductor Physics in Frankfurt, Germany. Silicon technology is driven by cost reduction, and soon, economic incentives for packing more transistors on chips may evaporate, contends Ourmazd. As the number of devices integrated on a chip increases, each additional device represents a smaller fraction of the total, thus providing a smaller economic benefit, he says. At the same time, as the number of devices per chip goes up, so does the chance that a chip will contain enough defective transistors that it has to be discarded. These economic realities aren't new. In fact, researchers have long sought to counter the creeping increase in the discard rate by making lithographic systems ever more reliable. But achieving the added reliability is becoming increasingly costly, says Ourmazd, which is why he thinks the big shrink may exhaust itself by about 2010.

He's in the minority, though. According to Bijan Divari, a silicon integration expert at the IBM Semiconductor Research and Development Center in East Fishkill, New York, smaller has meant better for over 30 years, and that probably won't change for a while. With just the feature-size reductions promised by the optical systems under development, chip designers will, for the first time, be able to fully integrate the two principal types of device functions—logic and memory—into a single chip. Says Divari, "That [alone] could have a tremendous [economic] impact. The economics of integration ... warrants the pain we have to go through to come up with new lithographic techniques." As long as these economic incentives don't disappear, chipmakers may have a shot at extending the life of Moore's Law.

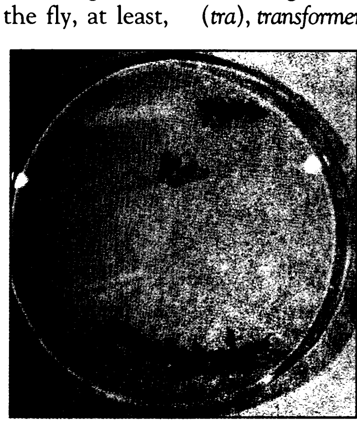
–Robert F. Service

In an upcoming issue, Science *will explore the new types of devices made possible by these technologies.*

GENETICS

Fly Sex Drive Traced to *fru* Gene

Humans are far from being the only animals with complicated sex lives. Take the fruit fly *Drosophila melanogaster*, in which males stalk the females and woo them with song before mating with them. Yet in the fly, at least, most of this complex repertory turns out to be controlled by a single gene.



JEFFREY HALL/BRANDEIS UNIVERSITY

Chain gang. Males with a mutant *fru* gene court each other, sometimes forming chains.

Geneticist Jeff Hall of Brandeis University first showed in the 1970s that the gene, called *fruitless* (*fru*), influences sexual preference; males with a mutation in the gene court both males and females. But in the new study, which appears in today's issue of *Cell*, a multiuniversity team of researchers, including Hall, reports that males with more severe mutations aren't just indiscriminate, but sexless. That finding, along with evidence that the protein encoded by *fru* can turn other genes on and off and is present in only a handful of nerve cells, suggests that *fru* is a high-level regulatory gene that somehow equips specific centers in the brain to coordinate male courtship behavior, the scientists say.

"It's a real breakthrough," says Dean Hamer, a researcher at the National Institutes of Health who studies whether sexual orientation in humans has a hereditary component. "It confirms what everyone suspected but no one had really proven—that sexual behavior can indeed be genetically programmed in an animal." But Hamer and other researchers caution that the study sheds little direct light on sexuality in *Homo sapiens*, because the genes influencing sexual differentiation in flies and mammals are unrelated.

Researchers have known for several years that four genes called *sex-lethal* (*sxl*), *transformer* (*tra*), *transformer-2* (*tra-2*), and *doublesex* (*dsx*) largely determine a fruit fly's sex. In females, *sxl* activates *tra* and *tra-2*, and the Tra and Tra-2 proteins splice *dsx* messenger RNA into a female-specific form. The Dsx protein made from this RNA then activates various genes lower on the genetic ladder that build female body parts. In males, *sxl*, *tra*, and *tra-2* are inactive, so default machinery splices Dsx RNA into a form encoding a male-specific protein.

In 1992, however, Oregon State University geneticist Barbara Taylor found that the growth of a specific muscle found only in male flies, the Muscle of Lawrence (MOL), is controlled by Tra and Tra-2, but not by Dsx. "That said there had to be a separate branch in the sex-differentiation gene hierarchy, analogous to the *dsx* branch" but regulating MOL development, Taylor explains.

Reasoning that the Tra proteins work the same way for the MOL-controlling gene as for *dsx*, Lisa Ryner, who works with Stanford University geneticist Bruce Baker, looked for other genetic sequences containing the target site used by Tra and Tra-2 to regulate *dsx* splicing. And she found a big one: a gene fragment that mapped to the same spot in the fly's chromosomes where Hall and postdoc Don Gailey had roughly located *fru* in genetic studies several years earlier. At the same time, Taylor found that females exposed to male Dsx acquire male anatomy but don't display courtship behavior, an indication that the MOL-controlling gene branch also influences behavior.

Using Ryner's gene fragment and other pieces of *fru* identified by developmental geneticist Steve Wasserman and graduate student Diego Castrillon at the University of Texas Southwestern Medical Center in Dallas, the Baker, Hall, Taylor, and Wasserman labs eventually cloned the entire *fru* gene, finding that the protein it encodes is likely a transcription factor, a protein that turns other genes on or off. An independent group led by geneticist Daisuke Yamamoto of the Mitsubishi Kasei Institute of Life Sciences in Tokyo also cloned part of the gene.

Consistent with *fru*'s proposed role in regulating male sexual behavior, the U.S. group now reports that the RNA making its protein product is spliced together in distinctive male and female forms by Tra and Tra-2, just as Dsx RNA is. And males with severe mutations in *fru* lose the will to follow other flies, play courtship songs on their wings, or attempt copulation, indicating that the gene somehow orchestrates these behaviors. Further supporting that idea, Taylor showed that *fru* is expressed primarily in nine small clusters of nerve cells, including several previously mapped by Hall as "courtship centers."

And that means researchers are "starting to get a handle on how the neural circuits that generate complex behaviors are put together," says Michael McKeown, a developmental geneticist at the Salk Institute in La Jolla, California. These circuits are bound to be even more complex in humans, McKeown says, but the latest insight into fruit fly sex is "a major step"—or maybe six—toward understanding them.

–Wade Roush