

New laser semiconductor processing techniques offer hope for future integrated circuits

Makers eye submicron geometries, elimination of photomasks

As microcircuits become smaller and more complex, and as competition among suppliers continues to heat up, manufacturers are considering broader roles for lasers in fabrication and process diagnostics. They are intrigued by the prospects of having available vast numbers of short-wavelength photons and a selection of high powers at a variety of wavelengths for selective photochemistry.

In the past half-decade a flurry of promising processes have been demonstrated in laboratories, exploiting different laser capabilities. Applications of excimer lasers in lithography take advantage of the dramatic increase in ultraviolet photons over what's available from conventional lamps. Photochemical applications in material treatment employ new continuous-wave lasers that can break chemical bonds and initiate chemical reactions. Other recent applications use the laser's ability to deposit energy on semiconductor surfaces much faster than is now possible in mass production, and to focus the energy to spot sizes measured in small fractions of a micrometer.

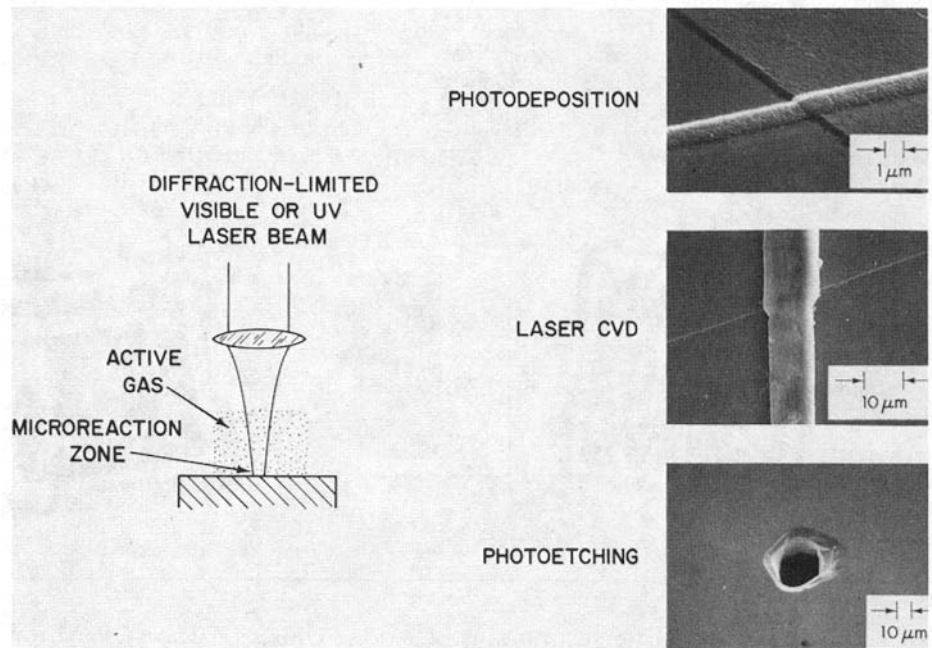
But many manufacturers also hope to adapt laser researchers' ingenuity to proven methods of mass production with better-known laserless equipment, as they have done many times before.

This article describes some of the new fabrication possibilities that are attracting the wary attention of companies around the world. It reviews some past successes of laser technology in electronics manufacture, as well as instances where laser capabilities served to inspire improvements in economically superior alternatives.

EMPHASIS ON PROCESSING

The emphasis here is on processing, not because progress in diagnostics—automatic laser ellipsometers for measuring dielectric-film thickness, for example—is less important, but because it is extensive enough to deserve separate treatment. When the topics are combined, as in the Materials Research Society's annual symposium on photon-induced chemical processing for semiconductor devices (see box), it takes five days to cover the field.

Lasers aren't new to microelectronics manufacture. In the 1970s they carved out at least three permanent niches: trimming resistors to tolerance, separating



DIRECT WRITING: In each example a laser was focused through a reactive or chemically activatable gas or liquid onto a surface. The beam, visible or ultraviolet, activated localized chemistry on the surface. Top photograph shows photodeposited metal produced with submicron resolution in a metal halide at Lincoln Laboratory. Center photo is of laser pyrolytic deposition of polycrystalline silicon from silane. Bottom is a photo-etched hole through a silicon wafer.

silicon slices by scribing, and marking moving parts.

Resistor trimming, usually performed with continuous-wave neodymium-yag laser output directed by either galvanometer mirrors or deflection mirrors, now employs more than 1000 lasers, with hundreds of new installations each year. Scribing, by about 40 Q-switched yag and a few pulsed carbon-dioxide lasers, is involved in most U.S. production of power diodes, silicon controlled rectifiers, thyristors and other power devices that use round chips for reasons of breakdown improvement and packaging simplicity. For marking, about 400 laser systems place product numbers on wafers and components for identification by employees as well as a 32-digit bar code on the wafer's active side for subsequent reading by helium-neon lasers to control wafer transport at flow-line junctions.

All three methods rely on ablation; the

laser simply blasts away at a minute spot until the material is evaporated. These mechanical approaches are described condescendingly by one PhD laser photochemist as having "the charm of simplicity."

Another straightforward laser approach is the application of thermal energy to change a material's structure, as in annealing. To appreciate the rise and decline of this laser process, and its promise of revival, it's necessary to recall how integrated circuits are fabricated.

Manufacturers first slice ultrapure crystals of silicon into thin wafers. Then they produce electrically doped regions close to the surface and overlay the surface with insulating and conducting films. These doped regions and films, some as thin as a few hundred atomic layers, form the transistors and other components that make up logic gates and other circuit elements. Others isolate or interconnect

Laser-controlled photochemistry has generated sufficient interest to warrant a meeting of its own. The second annual symposium on laser processing of surfaces is scheduled Nov. 14-18 by the Materials Research Society at the Park Plaza Hotel in Boston. The meeting also will cover use of lasers as diagnostic tools to monitor chemical reactions of importance in semiconductor manufacture. Information is available from A. Wayne Johnson, Sandia National Laboratories, Division 1126, Albuquerque, NM 87185, tel (505) 844-8782 or from Daniel J. Ehrlich, MIT-Lincoln Laboratory, Lexington, MA 02174, tel (617) 863-5500 ext. 4723.

components. Patterns are etched onto each layer by projecting intense light through separate photomasks, as many as 12 masks to a chip, and onto a light-sensitive photoresist that coats the chip. The photoresist is developed to bring out details of the mask's pattern, including interconnections only micrometers wide.

The dopant ions are implanted, typically with high-energy beams of about 200 keV. This bombardment damages the silicon's crystalline lattices, and may even make the silicon amorphous near the surface. Annealing is necessary to recrystallize the silicon.

Annealing was traditionally performed in an electric furnace, where the wafer was subjected to about 1000° C for about half an hour. Heating the entire wafer created problems, however. First, thin wafers are prone to thermal stress-induced damage and to mechanical breakage; this is especially true of large wafers, and the industry is moving toward increasing wafer sizes of 100-millimeter diameter and larger. A second problem with diffusion heating for too long a time was damage to the shallow junctions' conductivity and other junction characteristics. These difficulties caused wide variations in both junction depth and profiles.

It was found that short, energetic pulses of photons from a laser could confine intense heat to a tiny spot near the surface for only fractions of a second while the rest of the wafer remained near room temperature. Heating takes only about 100 nanoseconds with a pulsed laser—usually a Q-switched ruby or neodymium-yag or alexandrite laser—and about one millisecond with continuous-wave laser processing, most often argon-ion or krypton-ion lasers. Wafers 1000 mm in diameter and only 0.2 mm thick have been annealed in this way without thermal stress damage.

Once this improvement in annealing became known, manufacturers took another look at better-understood, less cost-

ly diffusion processes. They concluded that incoherent radiation sources could do the job almost as fast and at much lower cost. With resistance-heated graphite or various arc lamps or halogen lamps, the temperature is ramped to over 1000° in 10 seconds; the wafer remains in the chamber at that temperature for only a few seconds, and then the temperature is ramped down.

Concedes John F. Ready, a specialist in materials working with lasers at Honeywell Inc.'s Corporate Technology Center in Minneapolis: "At present, beam annealing offers no advantage for most devices over furnace annealing. Also, beam annealing probably will remain more expensive." Until circuits are required with design features of "a few tenths of a micron," he adds, manufacturers probably will be unwilling to pay the premium for laser annealing.

In addition to correcting crystal damage caused by ion-beam diffusion of dopants, lasers can diffuse dopants directly without damage to the crystal structure. Junctions can be formed by applying dopants to the wafer, then exposing with a laser. Quality optics provide focused spot sizes of submicron dimensions.

LASER ANNEALING

There are three ways to deposit dopant material on a wafer: vapor evaporation, deposition of doped silicon and painted coatings. A photochemical method, developed at MIT's Lincoln Laboratory, uses a pulsed laser to simultaneously photodecompose a dopant-carrying gas directly above the wafer's surface and to melt the surface, allowing liquid-state diffusion. In a continuous-wave version, an ultraviolet beam causes photolysis and a coincident visible laser beam drives the dopant into the surface.

Developer Thomas F. Deutsch and colleagues have fabricated solar cells by using an ultraviolet laser to photodissociate boron trichloride (BCl₃) over a silicon surface. Because the laser also heats the surface, the boron atoms adsorbed on the surface after the photolytic step diffuse rapidly into the bulk of the material. After irradiation, the silicon is heavily doped with boron near the surface. The p-n junction formed functions efficiently as a photovoltaic solar cell, Dr. Deutsch reports.

Laser diffusion has gained a foothold at Motorola Inc., where a process driven by Q-switched pulses from a Nd-yag laser is diffusing n-type silicon substrates with arsenic and producing surfaces with "excellent" contact characteristics on the back surface. With conventional furnace diffusion, says developer Schyi-yi Wu, the frontal metal deposition and associated patterning steps must be performed on thinned wafers after diffusion has en-

hanced contacts on the back side of the wafer. Otherwise, the front metal would be destroyed by the high temperature of diffusion, and breakage associated with handling the large, thin wafers would seriously reduce device yields, Wu explains.

Rapid laser annealing allows metal to be deposited on the front of the layer, and the associated patterning steps to be done on thick, durable wafers before thinning; diffusion is performed later on the thinned wafer without subjecting the front metal to any appreciable temperature. Small, shallow, closely spaced junctions can be formed by laser diffusion without lithography, and without expensive ion implanters, Wu adds.

Such specialized applications constitute the principal use of laser diffusion at present. Broader application of high-resolution, "direct-write" doping awaits demand for circuit features with dimensions of 0.5 micron and smaller, with dopant-junction depths of a few tenths of a micron. Because furnace annealing



Howard Rausch, the acknowledged "dean" of the laser press corps, is probably best known for his long tenure (1968-80) as editor and then publisher of *Laser Focus* magazine.

He has also held editorial positions with the *New York Times*, *Wall Street Journal*, *Philadelphia Bulletin* and *Electronics* and *Electronic Business* magazines. As chief of the Moscow bureau for McGraw-Hill World News Service, his work appeared in *Business Week* and *Aviation Week* magazines.

His freelance work has appeared in the *Atlantic*, *Harper's*, *Popular Science*, *Popular Mechanics*, *Christian Science Monitor* and the now-defunct *Reporter* magazine.

Rausch is currently an independent consultant in publishing, based in Brookline, Mass. With this article, he begins a series for *Optics News* in which he will assess the status of leading edge electro-optics technologies.

causes migration and redistribution of dopants, beam annealing may become necessary in the second half of this decade, with the more widespread use of very large integration (VLSI). But laser beam annealing will face competition from electron beam annealing, warns Ready at Honeywell.

So laser annealing, after inspiring improvement in competitive methods for repairing crystals, has also prompted development of alternative beam approaches to dopant diffusion. Will the laser ever develop a processing technique that's uniquely its own?

Promising answers are appearing in laboratories. One possibility is a group of offshoots of annealing; indeed these methods are frequently lumped erroneously under "annealing." Laser annealing has revealed features and capabilities in silicon crystal growth and solidification that give rise to important new characteristics: formation of amorphous silicon from the melt with very fast solidifications; trapping of unusually large concentrations of dopants, raising the prospect of superdoped shallow junctions that could dramatically enhance the speed of logic devices; and silicon crystal growth on amorphous substrates, creating the possibility of three-dimensional integrated circuits.

At modest temperatures, the amorphous portion of the silicon crystallizes layer by layer, or epitaxially, on the underlying crystal. In epitaxial growth, atoms form a new crystal plane by registering with the atoms of an existing plane. Velocity of the crystallizing interface increases with temperature. At three meters per second, the melt crystallizes with a high degree of epitaxial perfection. In contrast, conventional growth from the liquid phase occurs typically at only 10^{-5} meter per second.

Transient thermal processing allows epitaxial regrowth of polysilicon to produce single-crystal films over insulating layers such as SiO_2 . Silicon-on-insulator

gates and interconnection in metal-oxide-semiconductor devices have been fabricated with carrier mobilities approaching those of bulk silicon. This technique is believed to be on the verge of widespread industrial application.

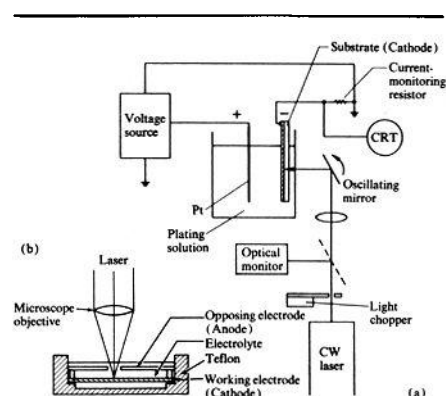
When the polysilicon is vapor-deposited lithographically in small "islands" before scanning with an argon-ion laser, it's possible to grow each island as a single crystal about 20 microns long. Regrowth of continuous polysilicon films to produce a larger-grained material is more difficult because many small crystallites tend to nucleate after the laser beam passes across the surface. These grains compete, so the grain size in regrown material remains smaller than desired.

MASKLESS PROCESSING

By using a spatially shaped laser beam so that one grain is preferred, regrowth with grain size around 50 microns has been achieved. The material compares favorably with the best known silicon-on-insulator material, epitaxial silicon-on-sapphire. The laser-grown silicon islands have been large enough for fabrication of MOS FETS (metal-oxide-semiconductor field-effect transistors).

But there's competition here too. A laser is not the only way to produce a moving molten zone for lateral crystal growth on amorphous substrates. Graphite-strip heaters create a wider molten zone, but they subject the entire substrate to near-melting temperatures that may make such heaters unsatisfactory for building high-rise device structures. Arc lamps are reported to produce nearly as good results as the laser's, at a fraction of the cost.

Because resolution in optical lithography improves with use of shorter wavelengths, there's much interest in light sources in the deep ultraviolet, at 200 to 300 nanometers. Traditional sources, deuterium lamps and xenon-mercury arc lamps, concentrate little power in the desired spectral regions. A 1-kilowatt



ENHANCED PLATING AND ETCHING: With these two arrangements, R. J. von Gutfeld at IBM attains electroplating and electro-etching rates as high as 10 microns per second.

xenon-mercury lamp, emitting through optics with numerical aperture 0.07, delivers only 16 milliwatts in the deep ultraviolet. Larger lamps would create problems in removal of the heat generated by the unwanted radiation. Therefore, exposure times for resists sensitive in the deep ultraviolet, such as PMMA (polymethyl methacrylate), are typically several minutes. In contrast, an excimer laser with 10-watt output in the deep ultraviolet produces enough power density to expose a 13-centimeter wafer in a few seconds.

One way to improve efficiency is to develop resists whose optimum spectral characteristics match available laser-emission lines. Lincoln Laboratory and other groups are developing such resists, including at least one that requires no development step. Another group, at General Electric's Corporate Research Laboratory in Schenectady, N.Y., is developing a way to improve the imaging properties of conventional photoresist by applying a photobleachable layer to the resist surface.

Another way to improve the match between laser output and photoresist sensitivity is to modify the laser wavelength. Kanti Jain and colleagues at IBM's San Jose Research Center use a Raman-shifted excimer laser that can produce one of several wavelengths within a broad spectral region. From the point of view of collimation, optical design in a deep-ultraviolet contact printer should be considerably simpler than with incoherent sources, Jain asserts. Suitable optical materials already are used with present lamp systems, he notes. Speckle, considered the foremost problem with laser lithography, is absent. Image degradation due to standing waves is minimal and can be further reduced by use of multi-wavelength exposure, which is possible with a Raman shifter.

Photomasks offer additional oppor-

	<i>Ruby</i>	<i>Nd:YAG</i>	<i>Alexandrite</i>	<i>Argon</i>
Wavelength, nm	694.3	1060 or 530	750	514 (primary)
Pulse Duration, nsec	50	100	100	N/A
Dwell Time, msec	N/A	N/A	N/A	.5
Beam Size, mm	15 (dia)	0.15 (dia)	3 × 3	.1 (dia)
Max. Power, watt	1	10 or 2	10	20
Processing Fluence, J/cm ²	1	5 or 1	2	40
Overlapping, %	40	50	20	30
Scan Rate, cm/sec		113	27.7	20
Heated Depth, μm	.1-.5	1-1	.1-1	50
Throughput, 4 in. wafers per hr		40	120	10
Cost, \$100		150	200	150

LASERS FOR ANNEALING: Typical laser parameters, throughput and system costs were tabulated by Schyi-yi Wu at Motorola. Values may vary according to individual requirements of a selected system.

tunities for lasers. Electro Scientific Industries Inc. in Portland, Ore., is offering samples of masks produced with a Nd-yag laser from a computer-aided design with features as small as 10 microns. "This may be an inexpensive way to get a mask quickly," says Thomas R. Richardson, director of engineering. Quality and resolution are sufficient for both thick and thin films, he reports, but perhaps not yet adequate for some semiconductor fabrication.

With photomasks valued at \$500 to \$2000, many manufacturers are repairing minute opaque defects in hard surfaces of chromium or iron oxide, using laser machining, precise positioning equipment and data-interaction functions. More difficult than removing unwanted material is the ability to repair pinholes, transparent defects. A "well developed technical solution," based on direct laser writing, patches holes with submicron resolution, reports Daniel J. Ehrlich at Lincoln Lab.

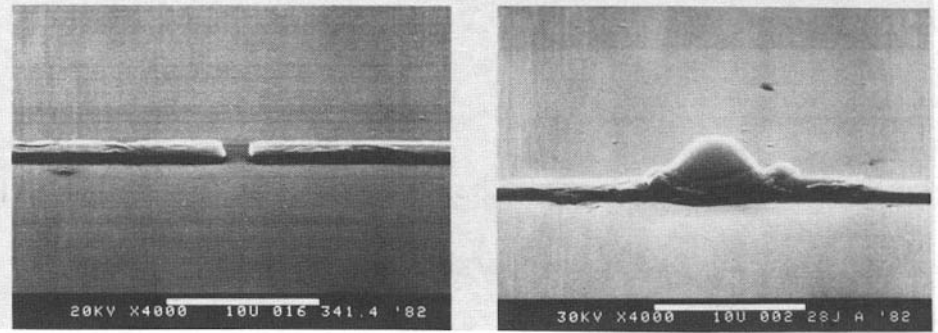
An attractive goal is elimination of photomasks altogether. They're expensive, they take a long time to produce, and they require several processing steps. Direct production of the patterns would reduce the number of processing steps, especially if "dry" processing could be conducted at an ambient temperature near room temperature. Such capabilities also are under development.

A candidate for maskless processing is laser-enhanced electroplating and etching. Here a focused laser beam heats an absorbing substrate that serves as one electrode in an electroplating bath. Laser heating increases the operation's speed by three and even four orders of magnitude, report Robert J. von Gutfeld and colleagues at IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y. They have produced highly localized electrodeless plating at high deposition rates, and enhanced localized chemical etching, making possible maskless pattern generation. Copper lines in microcircuits have been connected with laser-enhanced electroplating, for example.

The plating technique also offers the prospect of substantial savings of precious metals in electronics manufacture. It localizes the plating of materials such as gold, for contact points on connector pins or in crucial contact regions within pin receptacles. Von Gutfeld also notes the possibility of local plating in difficult-to-reach regions, such as the inner periphery of small connector holes.

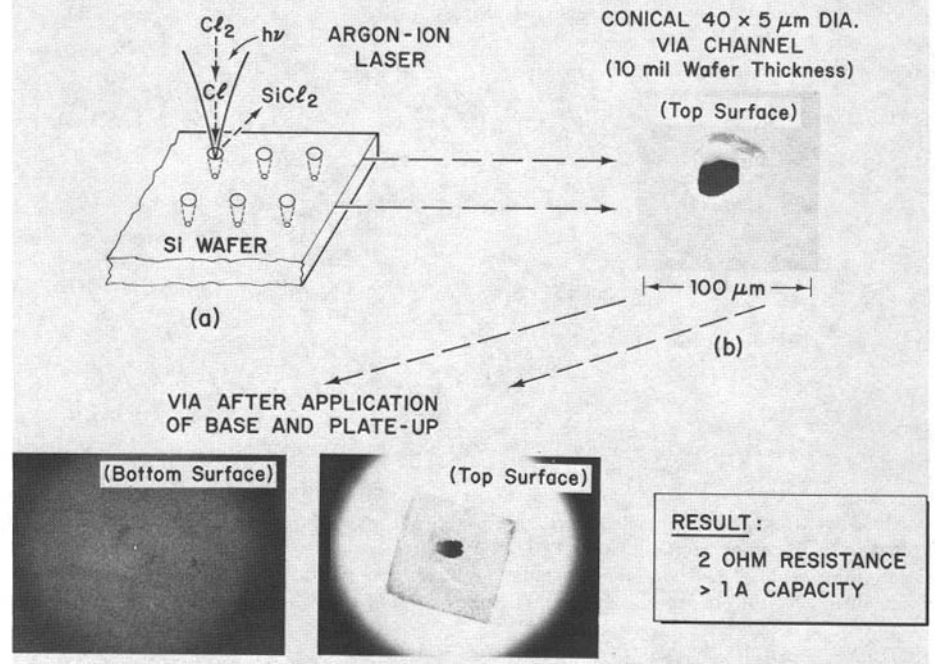
In the secretive world of semiconductor manufacture, the richest hints at what a company is doing are often contained in what it *doesn't* discuss. Participants at a January meeting in Los Angeles suspected that such a hint was dropped when Bell Laboratories withdrew, with only superficial explanation, what appeared to be a review paper on link blowing to disconnect faulty elements on random access

LINK STRUCTURE BEFORE AND AFTER SILICON DEPOSITION [20 ms Exposure in $\text{SiH}_4/\text{B}(\text{CH}_3)_3$]



CLOSING A LINK: Pyrolytically deposited silicon bridges a gap in aluminum line to complete a discretionary link on a wafer containing an array of such gaps. Application of the link specifies operation of a complex circuit of very large scale integration (VLSI). Photo courtesy of Lincoln Laboratory.

THROUGH-WAFER VIAS BY LASER CHEMICAL ETCHING



THROUGHWAYS IN SILICON: For bonding, conductors are "drilled" through silicon wafer by thermal etching in molecular chlorine that has been separated photolytically; then metalization is performed by photodeposition at Lincoln Lab.

memories (RAMs) and to connect healthy replacements.

The Bell Systems's manufacturing arm, Western Electric Co., performs this operation routinely on all fault-tolerant, 64-kilobit RAMs produced at the company's principal memory facility in Allentown, Pa. Bell is also reported to be working on extending the system to other memories, including the difficult upgrading to a 256-K size where tight design rules would require narrowing the laser spot size and tightening of targeting accuracy to within one micron.

In contrast to its enthusiasm over laser blowing of links, where "you can get payoff in a few weeks or months depending on volume," Bell is officially skeptical of many other laser applications. In annealing, for example, "whatever you can do with a laser in milliseconds you can do with rapid thermal annealing in seconds," declares Ami Kestenbaum, a senior member of the research staff in Princeton, N.J. "The unique advantages which were demonstrated with the laser may not be so unique.

"The kinds of arguments made for laser

processing can also be made for rapid thermal annealing. That includes scalability down to micron levels, and the ability to make unique structures which cannot be obtained by 'conventional' techniques. Remember that RTAs aren't conventional processing techniques either," he concludes. Kestenbaum hastens to add that his comments are confined to thermal processing, and don't apply to photochemistry.

More quiet, although showing every bit as intense interest in laser link blowing, is the other giant American supplier of memories: IBM. Judging from its heavy attendance at meetings like the one in Los

Angeles, from questions its employees ask at other laboratories, and from its relatively meager output of official information, it's universally assumed that the computer giant has an active program under way in laser applications to fault-tolerant memories.

In photochemistry, the most exciting and varied capabilities are promised by "laser direct writing," a laboratory technique that avoids lithography but involves etching, deposition, doping, polymerization reactions and other processes in microelectronics fabrication. Developed at Lincoln Lab, it uses focused laser beams to produce structures as small as

0.4 micron and, in one case, 0.3-micron linewidth.

In addition to potential for repairing pinholes in photomasks, as previously described, it has added links to memories by polysilicon deposition. This additive process allows creation of links anywhere, rather than being confined to breaking or activating preestablished links. Making connections also requires much less real estate on the chip, and opens the prospect of interconnecting large circuits as a means to avoid faults or to produce complex circuit structures, says Ehrlich, a developer of the process.

NEW TECHNIQUES

Here are a few other promising capabilities demonstrated in the lab:

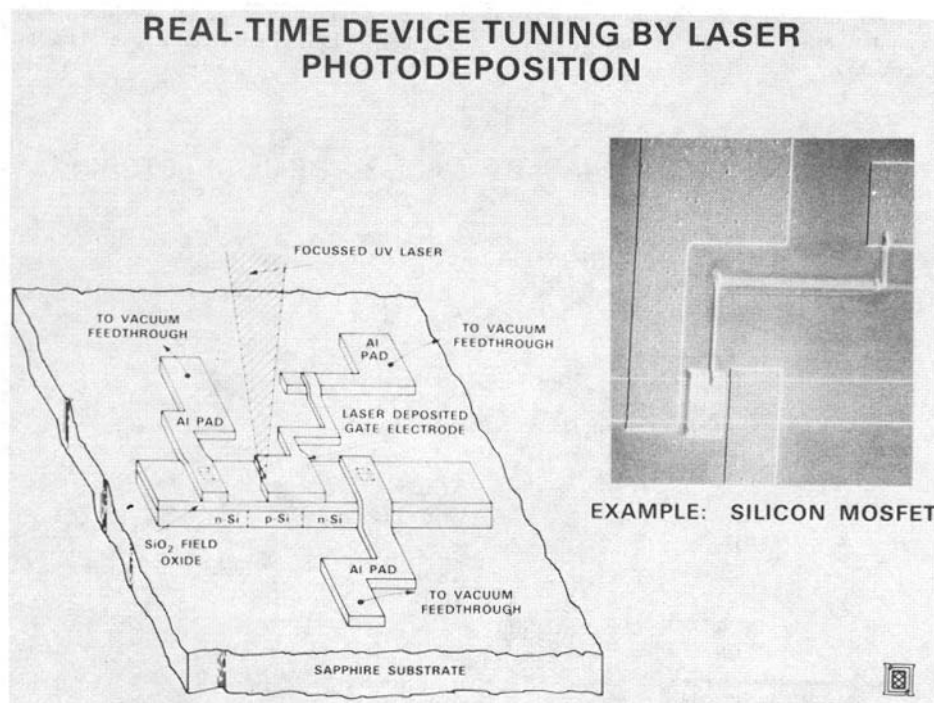
- Production of "via" holes through a wafer in a two-step process. First, holes are drilled with high aspect ratio—"verticality." Next comes etching, with growth of an oxide to isolate the channel from the wafer. Then the channel is plated by laser photodeposition, followed by electrochemical plating. The result is a conductor that passes through the wafer for use in bonding.

- Fabrication of optical waveguides by titanium diffusion. The titanium is "laid down" by photodecomposition, then is diffused into lithium niobate by conventional high-temperature processing. Scattering losses are as low as the best results obtained at the lab by any means, Ehrlich and colleague Jeff Y. Tsao report. The laser deposition offers a way to grade the index along the guide by varying the thickness of the deposited titanium as the guide is "written". The graded index can be used to optimize mode properties or coupling properties between guides, or in principle can be used to produce entirely new modulated guided-wave structures.

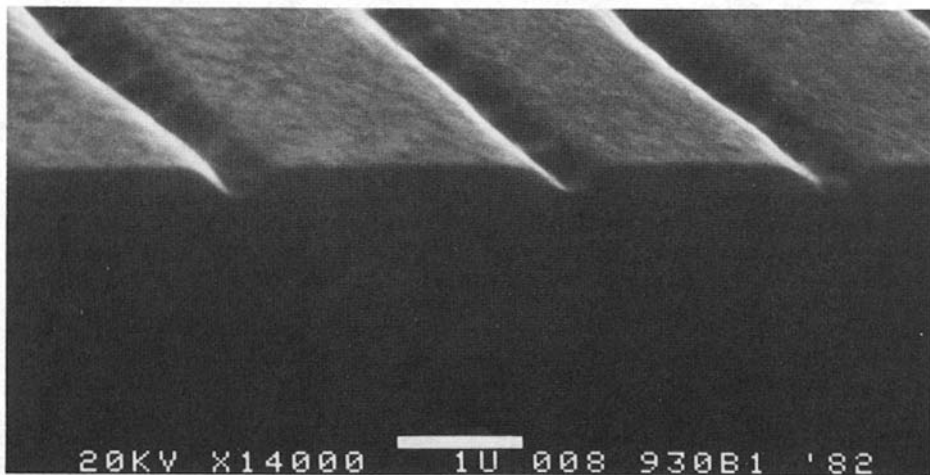
- Creation of structures which could be incorporated into devices. An example is a grating of resolution as fine as 65-nanometer periods, significantly finer than any that can be produced holographically, according to Ehrlich.

Most major microelectronics manufacturers are believed to have such processes under consideration. They certainly have them under observation. Emissaries make frequent forays to government and university laboratories like Lincoln Lab, as many as five at a time. Reports one shirt-sleeved researcher: "At least once a week they come around, men in three-piece suits asking a lot of questions usually boiling down to 'what's this all about?' We tell them, and then they disappear for a while, back to Texas Instruments or Mostek or IBM. They're clearly updating their assessment on a regular basis."

When the first big manufacturer's assessment of laser direct writing is positive, you can expect dramatic changes in the industry. — Howard Rausch



TUNING IN REAL TIME: Semiconductor gate electrode was fabricated, adjusted and photodeposited on a silicon-on-sapphire MOS FET in a single step by laser-assisted direct metalization without lithography. The device, made in an atmosphere of metal alkyl, can be tailored in a predictable manner, according to process developer D. J. Ehrlich at Lincoln Laboratory.



HALF-MICRON RESOLUTION: In direct writing, this regular array of grooves was etched in a wafer of silicon using laser-separated molecular chlorine. Wafer, cleaved, is viewed in edge profile in electron microscope at Lincoln Lab.