but calculations differ substantially on the precise threshold mass implied by the 20-MeV Υ'' width. Paolo Franzini (Columbia) believes his group has good evidence that the Υ'' is less than 100 MeV above threshold. One knows from the spectrum of the charmed mesons that the first excited bottom mesonic state (B^*) should be about 50 MeV heavier than the B. If the Υ'' were more than 100 MeV above $\bar{B}B$ threshold, it could decay into $B^*\bar{B}^*$. Franzini is confident that if this were the case, the CUSB detector would be seeing at least one of the two 50-MeV photons from the subsequent decay of the two excited B^* mesons to the ground-state B's.

Because the semileptonic decays, which provide the best B signature, always involve an undetectable neutrino, there is little hope, Berkelman told us, of seeing the B meson in the near future as a classic bump on an invariant-mass plot of its decay products. But the signals found in the electron, muon and kaon rates all rise strikingly above the nonresonant background, and all agree well with the standard theory that sees the b quark as the lighter member of a top–bottom pair. No trace of the top quark has yet been seen. —BMS

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Laser chemistry for microstructures

The rapidly increasing complexity of microelectronic circuits is confronting the designers and manufacturers of integrated circuitry with new technological difficulties. By the end of the decade it may well be possible to pack a million logic gates onto a single chip. But the yield of defect-free chips falls rapidly with increasing number of components. With current lithographic techniques, the production of custom circuits in small numbers is often uneconomical, and it is widely felt that the semiconductor industry is not meeting the need for such circuits. Furthermore, these lithographic procedures cannot produce large-area integrated circuits bigger than a few square inches, and their slow turnaround time hinders the design testing necessitated by increasing miniaturization.

But laser-induced microchemistry may be coming to the rescue. A group at the MIT Lincoln Laboratory has recently demonstrated the ability of ultraviolet lasers to deposit metallic films and introduce dopants into semiconductor substrates with a spatial resolution of about a micron. At the same time, a Xerox–USC collaboration is using infrared CO_2 lasers to deposit metal structures about 50 microns wide by laser-induced chemical vapor deposition. Both groups believe that these "direct-writing" techniques, by circumventing the usual arduous photolithographic procedures, hold great promise for dealing with the present difficulties and future needs of microelectronic design and fabrication.

The work at Lincoln Lab being done by Daniel Ehrlich, Thomas Deutsch, and Richard Osgood differs from other laser-induced materials-processing techniques, Deutsch told us, which depend essentially on thermal effects. Conventional laser annealing and laser-assisted chemical vapor deposition induce solid-state and chemical processes by heating substrates or by thermal (multiphoton) excitation of vibrational modes in gas molecules. In the Lincoln Lab technique, by contrast, the valence bonds of organometallic gas molecules are photochemically broken by single ultraviolet photons. This direct "photolytic" action of the uv laser beam dissociates the molecules into their metallic and organic constituents.

Ultraviolet beams at wavelengths below about 250 nm have two attributes that suit them particularly well for high-resolution photolytic deposition of metals. First of all, photons in that part of the spectrum have just the right energy to break up organometallic molecules such as metal alkyls, providing free metal atoms for deposition of metallic films or doping of substrates. Secondly, the coherence and short wavelength of these beams make it possible to focus them down to submicron spots at the semiconductor or insulating surface to be processed. The longer infrared CO_2-laser wavelengths (9 to 11 microns), though particularly efficient for heating such substrates, are limited by diffraction to focused spots no smaller than about 20 microns.

The Lincoln Lab group focused the frequency-doubled output (257.2 nm) of a 514.5-nm argon-ion laser at semiconducting and insulating surfaces in contact with a few torr of a metal-alkyl gas such as $Cd(CH_3)_2$ or $Al(CH_3)_3$ in a buffering atmosphere of helium. When the laser was operated in a continuous mode at modest power levels, photodissociation and deposition of metal films took place essentially at room temperature. The group found that they could localize these metal deposits down to about a micron—the limit imposed by the optics in their experiment.[1] By moving the substrate across the laser focus they were able to "write" metal lines one micrometer in width, with deposition rates as fast as 1000 Å (thickness) per second. With better optics, they expect ultimately to be able to do submicron deposition.

It was not initially clear why the resolution of the deposits laid down by this gas-phase photolysis should be so good. It turns out that not all the metal comes from the photolysis of molecules in the gas phase. Some organometallic molecules are initially adsorbed on the substrate surface. The group concludes that the photolytic breakup of these adsorbed molecules at the laser beam focus provide a nucleation or seeding site for the further deposition of metal atoms freed in the surrounding gas. The metal atoms have much higher "sticking coefficients" on this initial metal deposition than on the surrounding substrate material. Thus the deposition pattern appears to be sharpened by this "prenucleation" effect.

Doping and etching on a micron scale have also been demonstrated with the Lincoln Lab laser photochemical technique. Microelectronic etching ordinarily involves the exposure of photoresist films through a lithographic mask. To achieve their "maskless" etching,[2] the group used methyl-halide gases in place of the metal alkyls. When exposed to a frequency-doubled argon-laser beam focused at various semiconducting surfaces, the gas molecules break up, providing the free halogen atoms that etch the surface. With GaAs and InP substrates, the group has achieved laser-induced etching with a spatial resolution of about a micron.

Laser-induced doping as done by the Lincoln Lab group is a hybrid technique, involving laser heating as well as pure photolysis. The group doped

InP substrates with Cd and Zn, using both cw and pulsed ultraviolet lasers to photolyse the metal-alkyl gas. To achieve high levels of cadmium doping, varied and controlled on a micron scale, they used both the fundamental green beam and the frequency-doubled ultraviolet beam from a cw argon laser, both focused on the same spot at the semiconductor surface.[4] The intensity of each beam could be varied independently—the green laser light controlling the heating of the substrate and the ultraviolet intensity determining the rate of photolytic cadmium formation. By varying the ultraviolet intensity as the focal spot moved across the semiconductor surface, the group was able to vary and control the doping level in this direct-write, maskless technique with a resolution of about a micron.

Applications. The micron-level resolution achieved by these maskless deposition, etching and doping techniques fits nicely the scale of the microelectronic structures on integrated-circuit chips. Although photolytic direct writing is not likely to replace photolithography in routine microcircuit fabrication in the foreseeable future, the Lincoln Lab group believes that it will find prompt application in repair and custom circuitry.

The metal lithographic masks that are widely used in microcircuit fabrication are quite expensive to make. Deutsch says that the semiconductor industry is quite anxious to find a convenient technique for repairing micron-scale defects of such masks. Three common defects of this kind are given the descriptive names "pimples, mousenips and pinholes." Pimples are easily "zapped" by conventional laser blasts, but laser photolysis appears to offer the first convenient technique for repairing pinholes and mousenips by microdepositions of metal.

A significant fraction of the integrated-circuit chips coming off a silicon wafer nowadays must be discarded because of microscopic defects, and this fraction is likely to increase with the growing number of components per chip. The direct-writing capability of laser photolysis may help to increase the yield of usable microcircuits coming out of the fabrication process. Deutsch suggests that in the future, integrated circuit chips will come supplied with spare parts—extra subcircuits on the chips, ready to replace defective sections of the original integrated circuit. Such a scheme requires the ability to make micron-scale connections easily on the chip as one finds and replaces defective parts. To do this by present-day lithographic techniques is cumbersome.

In a similar vein, custom-circuit manufacturers could begin with standard subcircuits arrayed (but not yet interconnected) on a single chip. Using laser-photolytic metal deposition, the manufacturer producing integrated circuits in small numbers could quickly connect up these subcircuits in whatever configuration he wishes—avoiding the long turnaround times involved in the usual lithographic steps. Furthermore, the fact that laser photolysis is mostly done near room temperature spares the chip the thermal stresses that contribute to distortions and defects.

Working with John Fan and his coworkers (also at Lincoln Lab), the group has used photochemical doping to produce p–n junctions in silicon, good enough to function as solar cells with 9.6% efficiency (without an antireflection coating). The variable micron-scale doping capacity of laser photolysis may prove particularly useful in integrated-optics applications, Ehrlich told us, where doping with metal atoms can control the refractive index of integrated light guides.

Chemical vapor deposition induced by infrared CO_2 lasers is being developed by Susan Allen and her colleagues at the University of Southern California,[5] in collaboration with H. Ronald Thomas, Jerry Black, and Charles Duke at Xerox. With a wavelength 40 times that of the ultraviolet wavelengths used in the Lincoln Lab laser photolysis, the collaboration has thus far been able to deposit metal structures with a spatial resolution of about 50 microns. Although such resolution is too gross for working on microstructures within an integrated circuit chip, it is eminently suited, Thomas told us, for making connections between chips on a single wafer or in large-area integrated circuits.

In chemical vapor deposition, organometallic molecules are thermally broken up, liberating free metal atoms for deposition on a substrate. One can heat either the substrate or the organometallic gas directly. In the USC–Xerox work this heating is accomplished by a focused CO_2 laser beam, with a specific wavelength in the 9- to 11-micron infrared laser spectrum chosen to maximize absorption in the substrate or the gas, depending on the substrate and gas employed, and which of the two one chooses to heat. At USC and Xerox, Ni, Cr, Al and Mo from metal-carbonyl gases such as $Ni(CO)_4$ have been deposited on quartz substrates.

At USC, Allen has achieved 60-micron resolution with a 600-micron CO_2 laser spot. Noting this tenfold resolution enhancement, which she attributes to the higher temperature at the center of the laser spot, Allen is hopeful that the spatial resolution of laser-assisted CVD can eventually be pushed well below the diffraction limit (about 20 microns for CO_2 lasers).

Large-area integrated circuits are of great interest today, especially in connection with display technology. One can imagine a thin-film television display panel, consisting of thousands of liquid-crystal pixels, each with its own supporting logic. This would require a multichip integrated circuit arrayed on a silicon substrate the size of a television screen. But it turns out that with present lithographic technology it is practically impossible to produce multichip integrated circuits larger than a few square inches. Lithographic masks cannot anticipate the inevitable distortions of the substrate during thermal processing, which displace the individual chips from their original positions to a degree sufficient to render the masks useless for depositing connectors between chips arrayed over more than a few square inches of substrate.

Thomas envisions a laser-assisted technique that would solve this problem. A computer pattern-recognition program, after determining from an optical display where the connections must go on the distorted substrate, will direct a CO_2 laser spot to write metal strips at the appropriate locations.

A similar approach could be used to render any large-scale logic system cheaper, more compact and easier to design. Nowadays individual chips are connected by ultrasonic welding of gold wires, and then plugged into stacks of printed circuit boards. Not only is the ultrasonic welding an arduous manual task; it also leads to the destruction of a good fraction of the circuit chips. Thomas would like to use computer-guided laser CVD to put such a large-scale circuit "on a single $8\frac{1}{2}\times 11$ sheet, and forget it."

As individual components are miniaturized to submicron dimensions in very-large-scale integrated circuits, designers can no longer rely on computer simulations based on the behavior of the larger circuit elements in use today. Duke believes that laser-assisted CVD can facilitate the circuit testing necessary for the development of new design rules for VLSI circuits, by permitting the quick and easy writing of interconnections in different configurations between chips on a wafer. Such an effort is now underway at Xerox, he told us. —BMS

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