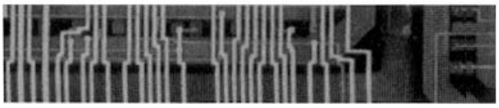
Laser Metal Deposition for High-Density Interconnect

BY Y. S. LIU

Fabrication of interconnect structures using lasers has become increasingly important as demands for discretionary interconnects grow. Patterned deposition of metals and dielectrics are key technologies of interconnect fabrication for microelectronic and optoelectronic applications. Lasers offer the flexibility of *in-situ* process monitoring, tuning, and control, and the capability of interfacing with CAD tools to allow on-the-fly design changes and testing. The integration of optoelectronic devices, optical circuits, and sensors into digital and microwave systems further requires low-temperature, area-selective processing capabilities. As the development cycle for each generation technology shortens and the redesign cost escalates, adaptive laser processing will become cost-competitive in a manufacturing environment. Other technological areas requiring area-selective processing include fault correction of large-area display devices for yield enhancements, localized marking, masking, coating, doping, and planarization.

This paper describes recent developments in patterned laser metal deposition and, in particular, their application for fabrication of high-density interconnect used in high-performance electronic multichip modules. Key material and process requirements for the development of a viable laser-direct-write interconnect technique are addressed.



PATTERNED LASER DEPOSITION TECHNIQUES

Laser deposition of metal and dielectric films on semiconductor, ceramic, or metal substrates has been investigated extensively.[1,2] Recently, as low dielectric constant polymers are becoming preferred dielectric materials for high performance electronic module applications, laser metal patterning has been applied to polymeric materials for fabrication of interconnects.[3] For these applications, laser processing is particularly attractive because polymeric materials are generally easier to process with lasers and the low-temperature nature of laser processing is compatible with process requirements for most polymers.

LASER PATTERNING RESISTS

Lasers have been used for patterning interconnect structures using resists, either organic or inorganic materials, in conjunction with conventional thin film metallization processes. Several laser-based photoresist patterning systems are available for custom gate arrays and printed circuit boards, as well as for thin film hybrid wafer-scale circuits.[4,5] Recently, an adaptive laser lithography has been developed in GE's laboratory for fabrication of high-density interconnects (HDI) in thin film multilayer electronic multichip modules.[6] This HDI process uses polymer overlays laminated over bare chips mounted on a ceramic substrate. The photoresist is spun on the overlays and laser-patterned to fabricate interconnects in conjunction with standard thin film metallization processes.

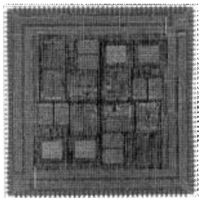
> **PATTERNED DEPOSITION OF METALS AND DIELECTRICS ARE KEY TECHNOLOGIES OF INTERCONNECT FABRICATION . . .**

A novelty of this HDI process is the use of an adaptive laser lithography system that employs a 351 nm UV argon laser controlled by a computer to adaptively perform both metal patterning and via drilling functions to compensate for chip misalignment and displacement. Figure 1 (see page 8) shows a two-level metal interconnect structure of a digital signal processor multichip module fabricated using adaptive laser lithography. The interconnect structure includes 35 μm wide, 5 μm thick copper lines and 50 μm vias in polyimide. The "wiggles" seen in the metal lines were the adapted patterning paths. The inset of the photo shows a completed module having a dimension of 50 mm × 50 mm and containing 36 chips operating at up to 90 MIPS.[7] A commercial version of this laser adaptive lithography system is being developed jointly by Texas Instruments and GE, and will be used as the major processing tool in a MCM foundry at TI by late 1992, under DARPA sponsorship.[8]

LASER DIRECT DEPOSITION

Patterned deposition of films using laser-activated chemistry has been studied extensively. In general, the growth rate of laser-activated deposition processes depends upon beam size, intensity, wavelength, concentration of precursors, and substrate surfaces.[9] Much of the earlier work employed metal carbonyl and metal alkyls as precursors in photo-dissociation processes, using either focused CW lasers or large-area pulsed lasers.[10] In gaseous phase photolysis, growth rates are limited by the transport of reactants and products to and away from the reaction zone, and none of the reported processes appear fast enough for high-speed direct write applications.

In pyrolysis processes, reactants of higher concentrations can be used and, as a result, higher growth rates can be realized. Solid or liquid thin film precursors containing metallo-organic compounds are applied to a substrate surface and the metal is reduced to zero-valent element when exposed to a laser.[11] This method is widely used because it is compatible with standard



photolithographic techniques and requires no special handling equipment. Among the numerous elements and compounds that have been deposited using lasers, those more relevant to interconnect applications are polysilicon, tungsten, aluminum, and copper. They are described below.

Polysilicon Deposition

Polysilicon has been deposited by pyrolysis of silane or disilane. Dopants can be incorporated by introducing phosphine or diborane into the reactions. Laser direct write polysilicon from gas phase decomposition of silane was reported with scan speeds of 100 μm/sec and linewidth to 0.2 μm.[12] At these speeds, however, applications of laser direct write are limited to short run interconnects and local circuit restructuring. Adding disilane into the gas mixture improves the deposition rate.

Laser-deposited polysilicon at writing speeds of about 1 mm/sec with a resolution of about 3 μm was reported for CMOS gate array interconnect.[13]

Tungsten Deposition

Deposition of tungsten and tungsten silicide has been studied as metallization materials for VLSI interconnect for their high conductivity and good contact characteristics. Laser-induced tungsten deposition using WF_6 on p-type silicon substrates has been reported to produce very thin (500 Å) tungsten spots.[14] High-speed laser direct write of tungsten lines was later demonstrated.[15] In this work, a thin a-Si film of 5000 Å was pre-deposited on the substrate, and the reaction took place in a reactor containing 100-torr WF_6 via heterogeneous reduction reaction of WF_6 on Si. Smooth tungsten lines with linewidths of 1-20 μm and thickness to about 2000 Å were deposited at writing speeds to several centimeters per second using a 514 nm argon laser operated at powers less than 50 mW. Use of a thin a-Si layer improved the absorption of laser radiation and circumvented the local variation of optical/thermal properties on substrates, a problem frequently encountered in laser processing.

Fabrication of tungsten interconnect lines with abrupt square sidewall and high purity was reported based on WF_6 chemically reduced by silicon hydride vapors. By optimizing a gas mixture containing WF_6 and SiH_4, tungsten lines 3-20 μm wide and 0.1-4 μm thick were written at scan speeds of 0.1 mm/sec at argon-ion laser (488 nm) powers of 30-60 mW.[16] These experimental efforts later led to the development of the first argon-ion laser based direct-write system for fabrication of application-specific ICs interconnects up to 5,000 gate arrays using two-level tungsten metal, for interconnecting a total run length of about 1.5 m. The processing time for 10,000 gates is about 30 min in a self-contained CVD reactor made up of tungsten hexafluoride, chlorine, nitrogen, and silane.[17]

Aluminum Deposition

A gaseous phase precursor, dimethylaluminum hydride has been used to yield highly conductive Al lines with a deep-UV laser at 257 nm.[18] In another experiment, high purity and highly conducting Al lines were pyrolytically laser deposited using a solid phase precursor, trimethylaluminum hydride.[19] Recently, direct write of Al on Si substrates was reported using a liquid TIBA precursor. At a scan speed over 1 mm/sec and an argon laser power of about 0.5 W, Al lines of about 1 μm thick were fabricated with a resistivity of about 2-3 times that of bulk aluminum. The laser-deposited Al lines were of submicron polycrystaline structures.[20]

Projection patterned of Al using ArF and KrF excimer lasers has also been reported, and the selection of precursor materials was found critical to the deposition. Tri-isobutylaluminium (TIBA) was found to yield better results than tri-methylaluminum (TMA) in these experiments. In addition, selection of the right surface, rather than gas phase reactions is a key element for achieving a good quality film using laser projection-patterned deposition techniques.[21]

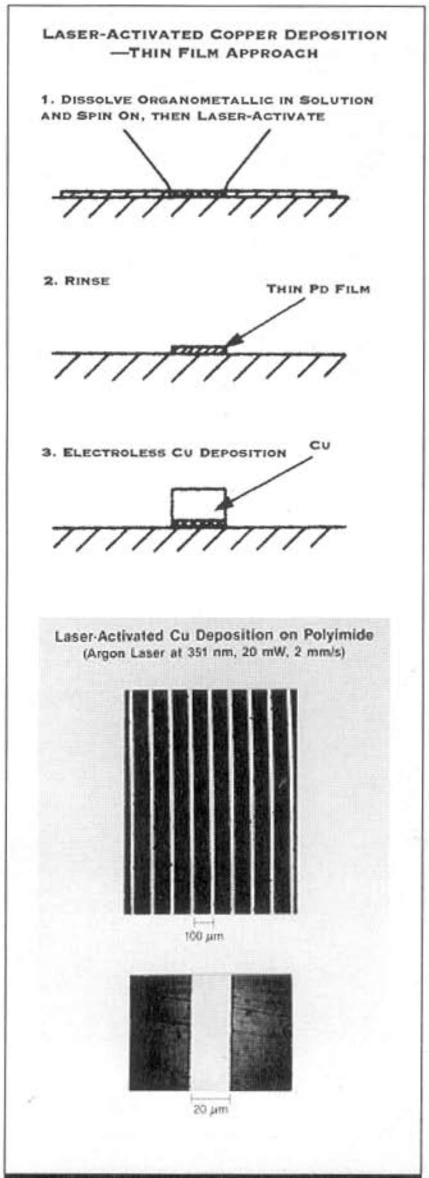


FIGURE 2. A SCHEMATIC OF A TWO-STEP SELECTIVE ELECTROLESS COPPER DEPOSITION PROCESS AND THE RESULTING COPPER LINES FABRICATED USING THIS APPROACH.

Copper Deposition

Direct write copper deposition has been investigated using a focused argon ion laser at 514 nm by photothermal decomposition of copper formate films on quartz and silicon substrates. Writing speeds to 10 mm/sec were reported for deposition of micron-thick copper films.[22] This process has also been applied on Al_2O_3, AlN, polyimide, and aluminum substrates with higher writing speeds to 5 cm/sec, and copper lines were fabricated to interconnect to Al pads through vias opened in polyimide

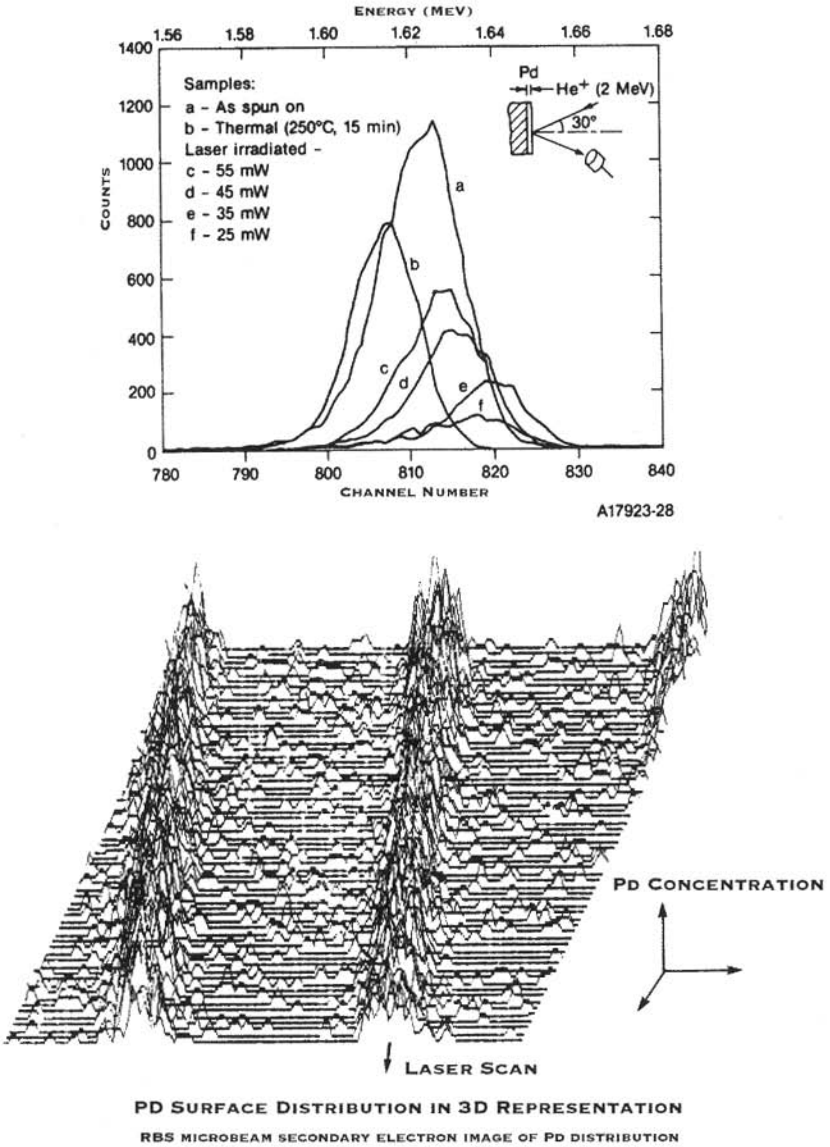


FIGURE 3. (A) PD-ATOM SURFACE CONCENTRATIONS AT VARIOUS LASER POWERS MEASURED WITH MICRO-IONS BEAM RUTHERFORD BACKSCATTERING SPECTROSCOPY; THE 20 μM PD-LINES WERE THERMALLY DECOMPOSED FROM A PD-ACETATE THIN FILM SPUN-ON ON POLYIMIDE; (B) CORRESPONDS TO A 3-D PD-ATOM IMAGE OF LASER-SCANNED TRACES. FROM THESE ANALYSES, A SURFACE CONCENTRATION OF ABOUT 10^{15} PD-ATOMS/CM^2 WAS DETERMINED, WHICH IS EQUIVALENT TO ABOUT MONOLAYER COVERAGES.

in a test multichip structure.[23]

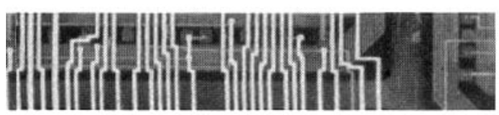
PATTERNED DEPOSITION VIA SURFACE MODIFICATION: TWO-STEP PROCESSES

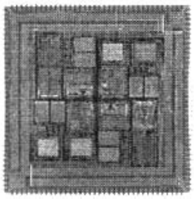
The writing speed is a critical requirement of any viable direct-write process for interconnect applications. For long interconnect runs, a writing speed greater than several cm/sec is required for fast process throughput. In addition, metals such as Al, Cu, and Au with sufficiently high conductivity are of interest to packaging applications. Most reported photochemical direct-write processes are not fast enough to meet this requirement, and further research effort in this area is certainly warranted. One approach to circumvent the problem is to use a two-step process: first, laser irradiation is used to selectively modify the surface properties, followed by a batch thin film process to fabricate interconnects of desired electrical and mechanical characteristics. The xerography used in the daily photocopy machine is a good example in which a paper is first charged (Step 1), then the ink powder is fixed onto the charged region to form a positive image (Step 2). This concept has been explored by various researchers recognizing that first monolayers on a substrate surface often control surface reactivity or nucleation of new phases at the surface interface. Therefore, laser irradiation can be used to deposit monolayer thin films, which behave as surfactants to initiate the subsequent reactions.[24]

Other kinds of energy sources such as synchrotron radiation[25] and incoherent VUV excimer lamps have also been explored using this two-step approach for patterned deposition.[26] Two examples of two-step processes investigated in GE's laboratory are described below.

Selective Electroless Metal Deposition

Positive Metal Patterning Technique: In electroless deposition, a metallization process commonly used for deposition of copper on nonconducting substrates such as polymers, a substrate surface is first sensitized with Pd-containing complexes, and immersed in an electroless plating bath to deposit copper from the solution via auto-catalyzing reactions. Figure 2 illustrates a positive metal patterning process using the two-step method: a substrate is either placed in a reactor containing gas phase metallo-organic compounds, or is coated with a thin film precursor such as Pd-acetate.[11] A laser is then used to selectively decompose the compound and catalyze the surface via photochemical or pyrolytic processes. After irradiation, the sample is rinsed in an organic solvent to remove the metallo-organic compound in the unexposed areas and leave Pd in the laser-scanned area forming a





latent image on the surface. Once the sample is immersed in an electroless plating solution, a positive copper pattern is formed.

Figure 3 shows the Pd-atom surface density at various scanning laser powers measured using micro-ion-beam Rutherford backscattering spectroscopy. A corresponding 3-D image depicts the surface Pd-atom density of 20 μm wide laser scanned lines. From these analyses, a surface density of about 10^{15} Pd atoms/cm^2 was determined, which is equivalent to monolayer coverages. Fast laser scans over several centimeters per second are therefore possible. Strong coupling between polyimide and argon laser 351 nm radiation reduces the laser power requirement to tens of mW for thermally decomposing most metallo-organic compounds. Copper linewidths of about 7-50 μm with a thickness of 1.5 μm have been fabricated with excellent morphology and conductivity.[27]

Negative Patterning Technique

Photo-patterning has been used in the electroless metal deposition process for forming negative images. The process involves pretreatment of a substrate with a reducible or oxidizable metallic salt solution, such as stannous chloride, followed by patterned exposure of the sensitized substrate with UV light. Typically, photochemical reactions are involved in which desensitization of catalytic metallic nuclei takes place, and as a result, autocatalytic reactions in electroless plating processes are inhibited. High power excimer lasers now available are useful for selectively removing catalysts on the surface by ablation or photo-oxidizing the surface, thus forming a negative image. This process has good resolution and is extremely sensitive because the ablation threshold for polyimide irradiated with a 248 nm KrF excimer laser is about 20 mJ/cm^2, which compares favorably with typical photoresist sensitivities of about 100 mJ/cm^2.[28]

SELECTIVE ELECTROLYTIC DEPOSITION

Electrolytic deposition is a metallization process commonly used in electronic packaging and printed circuit board fabrication. The deposition has a high deposition rate, and metal patterns of several microns thick can readily be fabricated. In our study, we observed that electrolytic deposition takes place selectively on certain metal surfaces such as copper and gold, but not on certain other types of metal such as titanium. The selectivity observed in the electrolytic deposition process is attributed to the presence of a very thin but highly resistive surface oxide layer. Such subtle differences exhibited in the surface electrochemical properties and their consequences for the selectivity observed in metal deposition have led us to investigate the selective electrolytic deposition process for patterning applications.[29]

There are many possible schemes to implement this process. For example, a substrate is sputtered with a thin layer of Ti followed by a thin layer of Au. A UV argon laser is used to irradiate the sample to cause Au inter-diffusion into Ti. The sample is then placed in an Au etchant to remove pure Au in the unirradiated areas. When the sample is immersed in a Cu or Au electroplating solution, Cu or Au was selectively deposited in the laser-irradiated area to form a pattern.

We have reviewed several patterned deposition processes using lasers. These adaptive laser processing techniques will become increasingly important for interconnect applications. Investigation of electrical as well as mechanical properties of patterned laser-deposited films is required to better understand interfacial properties between laser-deposited films and the substrate. For high-density interconnect, direct-write laser processes with high writing speeds are critical. Two-step processes using surface modification described here are a particularly attractive approach for achieving high writing speeds.

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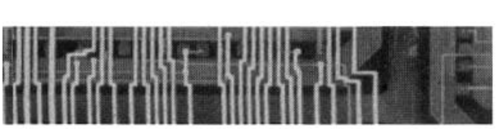

REFERENCES

1. See D.J. Ehrlich and J.Y. Tsao, eds., *Laser Microfabrication: Thin Film Processes and Lithography*, Academic Press, San Diego, Calif., 1989.
2. R.M. Osgood, "Laser fabrication for solid-state electronics," IEEE Circuits and Devices **6**, 1990, 25-31.
3. H.S. Cole *et al.*, "Laser patterning of polymers for electronic packaging," Proc. of the Third U.S. and Japan Seminar on Dielectric and Piezoelectric Ceramic, T. Yamaguchi, ed., Keio University, Japan, 1986, 118-119.
4. Y.S. Liu, "Laser microfabrication systems for direct writing and projection lithography," in *Laser Microfabrication: Thin Film Processes and Lithography*, D.J. Ehrlich and J.Y. Tsao, eds. Academy Press, 1989, 1-84.
5. D.B. Tuckerman, "Laser patterned interconnect for thin film hybrid wafer scale circuits," IEEE Elect. Dev. Letts. EDL-8 **11**, 1987, 540-544.
6. C.W. Eichelberger *et al.*, SPIE Symposium on Innovative Science and Tech. Paper 877-15, 1988.
7. M. Gdula *et al.*, "High Density IC Packaging Technology," Final Report, DARPA Phase 2 Program, GE Research and Development Center, Schenectady, N.Y., Dec. 1990.
8. P.J. Klass, "New chip interconnect techniques," Avionic Week, Sept. 23, 1991.
9. D.J. Ehrlich and J.Y. Tsao, "A review of laser microchemical processing," J. Vac. Sci. Tech. B1(**4**), 1983, 969-984.
10. R.L. Jackson and G.W. Tyndall, "Photodissociation of the metalcarbonyls and metal dialkyls," Chemtronics **4**, 1989, 127-134.
11. M.E. Gross, "Laser direct-write metallization in thin metallo-organic films," Chemtronics **4**, 1989, 197-201.
12. D.J. Ehrlich *et al.*, IEEE Elec. Device Lett. **EDL-5**, 1984, 32.
13. A.F. Bernhardt *et al.*, "Laser microfabrication technology and its applications to high speed interconnect of gate arrays," in "Photon, beam, and plasma simulated chemical processes at surfaces," **75**, Materials Research Society, Proc. 1987.
14. I.P Herman *et al.*, Proc. Of Materials Research Society **29**, 1984.
15. Y.S. Liu, "Laser direct write tungsten deposition for VLSI applications," in *Tungsten and Other Refractory Metals Deposition for VLSI Applications*, R.I. Blewer, ed., Materials Research Society, 1985, 43; also Y.S. Liu *et al.*, Vac. Sci. and Tech. B3(**5**), 1985, 1441.
16. J.G.Black *et al.*, "Low-temperature laser deposition of tungsten by silane- and disilane-assisted reactions," Appl. Phys. Letts. **56**, 1990, 1072.
17. P. Burggraaf, Semiconductor International, 1988, 116.
18. T. Cacouris *et al.*, "Laser direct writing of aluminum," Mat. Res. Soc. Symp. Proc. **101**, 1988, 43-48.
19. T.H. Baum *et al.*, "Laser-induced chemical vapor deposition of high purity aluminum," Mat. Res. Soc. Symp. Proc. **129**, 1989, 119-123.
20. H.W. Lee and S.D. Allen, "High deposition rate laser direct write of Al on Si," Appl. Phy. Letts. **58**, 1991, 2087-2089.
21. G.S. Higashi, "Excimer laser projection-patterned deposition of aluminum using alkyl-aluminum precursor molecules," Chemitronics, **4**, 1989, 123-126.
22. A. Gupta and R. Jagannathan, "Direct write of copper lines from copper formate film," Proc. of Mat. Res. Soc. Symp. **101**, 1985, 95-100.
23. H.G. Muller *et al.*, "Laser direct write of copper on various thin-film substrates," Appl. Surf. Sciences **46**, 1990, 143-147.
24. J.Y. Tsao and D.J. Ehrlich, "Patterned photonucleation of chemical vapor deposition of Al by UV-laser photodeposition," Appl. Phys. Letts. **45**, 1984, 617-619.
25. Y. Zhang and M. Stuke, "Synchrotron processing of thin palladium acetate spin-on films for metallic surface patterning," Chemitronics **4**, 1989, 213-215.
26. H. Esrom *et al.*, "VUIV light-induced deposition of palladium using an incoherent Xe2 excimer source," Chemitronics **4**, 1989, 202-208.
27. H.S. Cole and Y.S. Liu, "Laser-induced selective copper deposition on polyimide," Appl. Phys. Lett. **53**, 1988, 2111.
28. Y.S. Liu and H.S. Cole, "Laser surface modification for copper deposition on polyimide," Chemtronics **4**, 1989, 209-211; also Y.S. Liu and W.T Grubb, "Method for photopatterning metallization via UV laser ablation of the activator," U.S. Patent #4,882,200, Nov., 1989.
29. Y.S. Liu and H.S. Cole, "Area-selective laser processing techniques for multichip interconnect," in "Electronics Packaging Materials Science IV," Materials Res. Soc. 1989, 11-19; also, Y.S. Liu *et al.*, "Selective electrolytic deposition on conductive and non-conductive substrates," U.S. Patent #4,988,412, Jan. 1991.