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Laser direct writing of aluminum conductors

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We report, for the first time, the laser direct writing of high-conductivity aluminum interconnects from dimethylaluminum hydride (DMAlH). These lines were deposited from this metalorganic gas using a focused deep-ultraviolet laser beam, and the deposition process was studied as a function of several process parameters. Electrical measurements and Auger electron spectroscopy were used to characterize the quality of the laser-deposited films.

Laser direct writing of metals has attracted increasing interest in recent years as a nonphotolithographic tool for making localized metallization patterns on microchips. The fabrication of metal-oxide-semiconductor (MOS) devices using only direct writing techniques has been demonstrated.[1] Also, direct writing has recently been used for integrated circuit customization,[2] and to repair prototype circuits in a large-scale integration (LSI) development unit.[3] Although aluminum is by far the most common conductor metal used in integrated circuits, it has not previously been possible to direct write highly conductive aluminum (at reasonably high rates) from any known metalorganic source. The dissociation chemistry of trimethylaluminum (TMAl) is such that carbon incorporation from organic ligands occurs and results in poor conductors being deposited, and deposition from triisobutylaluminum (TIBAl) is extremely slow because of its very low vapor pressure. Note, however, that it has recently been reported that high quality aluminum can be deposited from TIBAl using a combined laser projection/CVD (chemical vapor deposition) technique.[4]

Here we report for the first time the successful direct writing of aluminum lines of high conductivity using dimethylaluminum hydride (DMAlH) as the metalorganic parent gas and a focused, deep-ultraviolet (UV) laser beam. We attribute the purity of the deposited lines partly to this new metalorganic source, DMAlH, which decomposes with little apparent carbon inclusion, and partly to our relatively high-power UV laser source that leads to a hybrid photolytic/pyrolytic deposition scheme.

In these experiments, the laser sources used were an Ar^+ laser at 275 nm or a frequency-doubled Ar^+ laser. The latter source was obtained by an intracavity frequency doubler at 257 nm. With the relatively high-intensity, deep-UV laser, viz., powers ≈ 60–100 mW, a combination of both photodeposition and pyrolytic growth occurs, as previously reported.[5-7]

The beam was focused with a quartz microscope objective ($16\times$, N.A. $= 0.25$) into a high-vacuum chamber through a quartz window. The substrates used were SiO_2 on silicon and glass (BK-7). The samples were mounted in this chamber, which was evacuated to a base pressure of $\approx 10^{-5}$ Torr using a cryopump equipped with a LN_2 foreline trap for the metalorganics. In the experiments described here, a static fill of unbuffered DMAlH (vapor pressure $= 2$ Torr) was always used. For thickness measurements, the cross sections of the lines were measured using a stylus profilometer and checked with a scanning electron microscope. Resistance measurements of lines deposited between gold test pads, along with stylus profilometry data, yielded a measure of the conductivity. In addition, Auger electron spectroscopy (AES) was carried out on large-area films made by raster scanning the laser beam and a depth profile of elemental composition for these films was made by ion milling successive layers.

We have begun to characterize the deposition of Al from DMAlH using the 275 nm laser wavelength focused to a spot size of 2.3 μm (full width at half-maximum) and using a substrate of 3000 Å of SiO_2 on Si. A plot of deposited thickness versus laser power is shown in Fig. 1. At low power, the thickness increases linearly with power, which is what one expects for a photolytic deposition process. At about 162 kW/cm^2, the thickness starts increasing exponentially with power, which is indicative of pyrolytic deposition. The transition between growth dominated by pyrolytic versus photolytic deposition is illustrated visually in Fig. 2, which shows SEM photographs of lines deposited at various laser powers. At 130 kW/cm^2, a thin (< 500 Å) photolytically deposited line is visible in the photograph. At 162 kW/cm^2 one can see

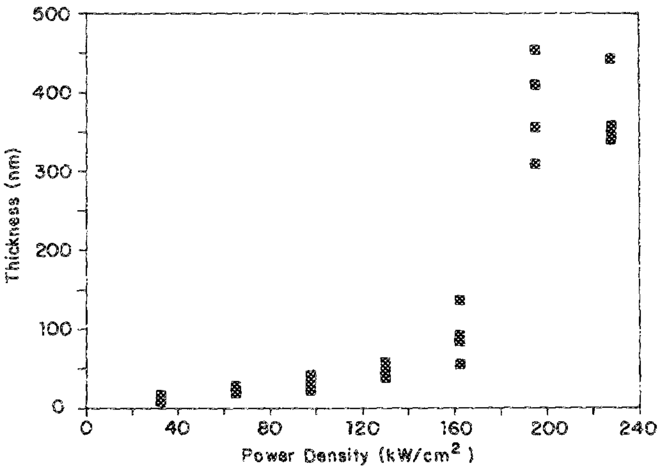

FIG. 1. Thickness of laser-written aluminum lines as a function of incident laser power. The scan speed was 40 μm/s, the laser wavelength was 275 nm, and the DMAlH pressure was 1.0 Torr.

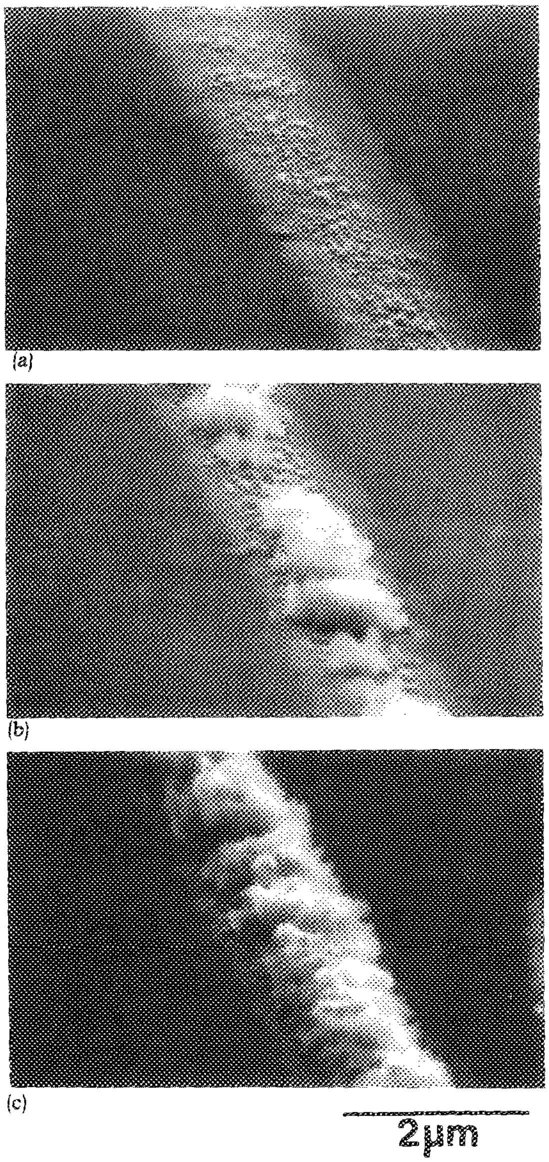

FIG. 2. SEM micrographs of laser-written aluminum lines with increasing laser power. (a) 130 kW/cm^2, photolytic deposition; (b) 162 kW/cm^2, transition regime; (c) 195 kW/cm^2, pyrolytic growth. The conditions are those of Fig. 1.

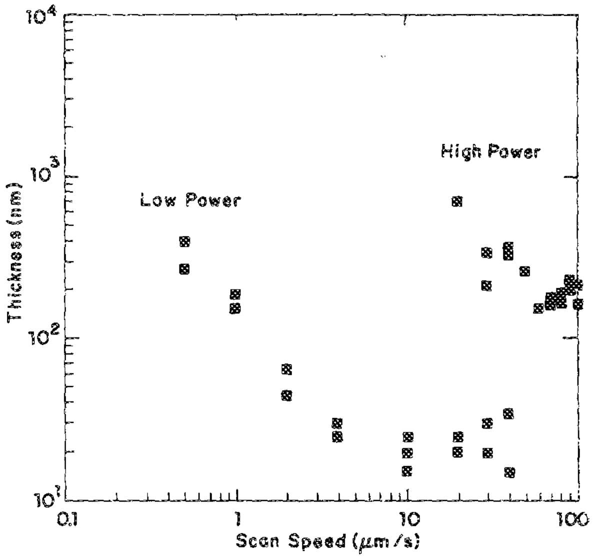

FIG. 3. Thickness of laser-written aluminum lines as a function of laser scanning speed in the photolytic (low power $\approx$ 114 kW/cm^2) and pyrolytic (high power $\approx$ 227 kW/cm^2) regimes. The laser wavelength was 275 nm, and the DMAlH pressure was 1.0 Torr.

bursts of pyrolytic growth occurring. This erratic behavior is possibly due to changes in temperature arising from fluctuations in laser power or variations in deposit properties (e.g., reflectivity or thermal conductivity). By 195 kW/cm^2, the deposition is fully in the pyrolytic regime and a thick (almost half a micron) continuous line is visible in the photograph. A simplified calculation of the temperature rise induced by the laser beam (similar to Ref. 8) allows an estimate of the effective activation energy for the thermal decomposition of DMAlH at the onset of pyrolytic growth. This calculation yields $E_a \approx 16$–22 kcal/mol, which is in rough agreement with a similar experiment using the 257 nm wavelength and glass as the substrate.

Figure 3 shows the deposited thickness versus laser scan speed at two different laser powers, one in the photolytic regime and one in the pyrolytic regime. Both curves exhibit the expected dependence, namely, that thickness decreases inversely with scan speed. Given that the deposit width is ≈ 2 µm, these curves imply a vertical growth rate of about 0.09 µm/s for photolytic deposition at 114 kW/cm^2 and as high as 7 µm/s for the pyrolytic curve at 227 kW/cm^2. In the pyrolytic regime a reasonably thick, 1000–2000 Å line can be written at speeds up to 100 µm/s.

Gas phase absorption spectra were taken for DMAlH (Fig. 4) and exhibited low-absorption cross sections for the UV wavelengths used here, which translates to a very small amount of photodeposition from the gas phase in the deep-UV cases studied here. This observation is in agreement with the slow deposition rate observed when no pyrolysis is occurring. Furthermore, a brief series of experiments confirmed the existence of an adlayer photodissociation mechanism only under deep-UV irradiation. This experiment involved the use of a sapphire substrate which is transparent for the UV wavelengths used here. It was possible to photodissociate the adsorbed layer without the presence of the gas, and this was observed by filling and then evacuating the chamber down to base pressure. Visible lines were written, even in those conditions under deep-UV irradiation. These experiments are consistent with simple estimates of the maximum photodissociation growth rates from the gas phase and the adlayer. Assuming ballistic motion of the gas phase reaction products (the mean free path is much greater than the reaction-zone radius), the photodissociation rate from the gas phase is given by[9]

$$R_g = \alpha N_g \sigma_g P_L / 2\sqrt{2\pi}\, h\nu w_0 .$$

Inserting parameters appropriate to our experiment for the photolytic regime [N_g (1 Torr) $= 3.5 \times 10^{22}$ m^{-3}, $\sigma_g \approx 0.001$ Å^2, $P_L = 8$ mW, $\lambda = 257$ nm, $w_0 = 2$ µm, and assuming $\alpha = 1$] yields $R_g = 3.6 \times 10^{20}$ reactions/(m^2 s). This gives an estimated deposition rate of 0.006 µm/s. This is much lower than the observed rate of over 0.1 µm/s, indi-

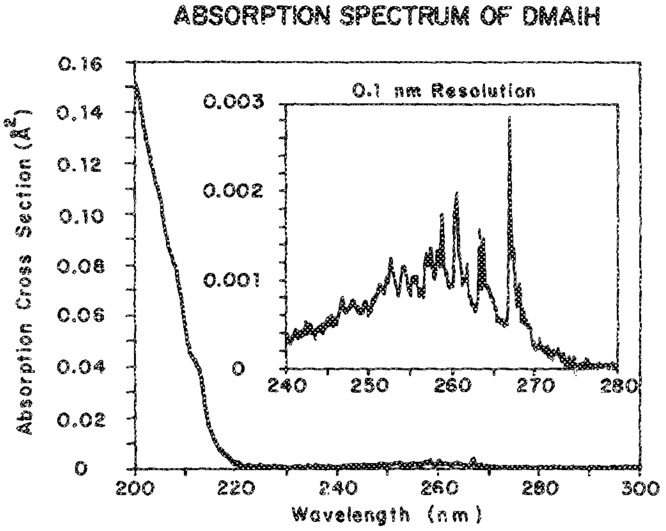

FIG. 4. Gas phase absorption spectrum for dimethylaluminum hydride (DMAlH). Inset: enlarged region of interest.

cating that gas phase photodissociation is not playing a significant role in the photodeposition process. A similar calculation of the maximum growth rate from the chemisorbed layer yields a much higher rate, indicating that deposition from the adlayer is the dominant photolytic process.

Experiments to test the conductivity of these lines have shown good results. With 257 nm light and glass as the substrate, pyrolytically deposited lines written with ≈ 200 kW/cm^2 at 100 μm/s yielded thick 0.5 μm lines with resistivities as low as two to three times that of bulk aluminum.[10] For 275 nm light under the same conditions, the resistivity was typically twice as high. With SiO_2/Si as the substrate, the pyrolytically deposited lines were not nearly as conductive. This is probably due to the higher thermal conductivity of silicon yielding a lower temperature at the surface and, hence, causing a smaller amount of thermal curing of the deposit. However, photolytically deposited lines written on SiO_2/Si using 257 nm with ≈ 100–200 kW/cm^2 at 10–50 μm/s yielded thin, 200–500 Å lines with resistivities of two to ten times that of bulk aluminum. Again, results with 275 nm light were typically not as good, but resistivities of less than ten times the bulk were obtainable. In addition, it was found that the conductivity of these lines did not significantly degrade with time after being exposed to air over a periods of several months.

Auger electron spectroscopy (AES) measurements were carried out on large-area films (100 μm^2) that were deposited by raster scanning the deep-UV beam. The films were deposited on silicon using 257 nm light with 216 kW/cm^2 at a scan speed of 23 μm/s and while flowing DMAlH gas. With the aid of *in situ* ion milling, it was possible to reconstruct a depth profile of the elemental composition of these films. The surface layers and the first few hundred angstroms were characterized by a high carbon content of 40% and a high oxygen content of 30%, a result typical of a rough air-exposed aluminum film. At a depth of 200–300 Å, the carbon level was less than 10% and the oxygen level was approximately 5%. These results indicate a reasonably pure aluminum film. However, it must be noted that these films were deposited on silicon under conditions which generally yielded a poor conductor. Therefore, the highly conducting films presented earlier probably have significantly higher purity. In addition, these films typically had a surface roughness greater than the 200–300 Å milling depth, so that even after milling some unmilled surface may remain which will lead to an erroneously high measurement of the impurity level.

In addition to applications requiring metal interconnects, it was demonstrated that this technique is also suitable to direct-write aluminum gates for GaAs MESFET transistors. These were fabricated conventionally minus the gate metallization step, which was direct written along with its interconnect, and yielded working transistors, without the need for any special preparation.

We have thus demonstrated a laser writing technique that is fully compatible with current integrated circuit technology, and can be used to repair and customize integrated circuits *in situ* without the need of a masking step.

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[1] B. M. McWilliams, I. P. Herman, F. Mitlitsky, R. A. Hyde, and L. L. Wood, Appl. Phys. Lett. **43**, 946 (1983).

[2] J. G. Black, S. P. Doran, and D. J. Ehrlich, in Technical Digest, Conference on Lasers and Electro-Optics, Washington, DC, 1986, paper TUO3; J. G. Black, S. P. Doran, M. Rothschild, and D. J. Ehrlich, Appl. Phys. Lett. **50**, 1016 (1987).

[3] S. Kishida, Y. Morishige, F. Uesugi, and H. Yokoyama, in Technical Digest, Conference on Lasers and Electro-Optics, Baltimore, MD, April 1987, p. 282.

[4] G. S. Higashi, G. E. Blonder, and C. G. Fleming, Mater. Res. Soc. Symp. Proc. **75**, 117 (1987); G. E. Blonder, G. S. Higashi, and C. G. Fleming, Appl. Phys. Lett. **50**, 766 (1987).

[5] H. H. Gilgen, T. Cacouris, P. S. Shaw, R.R. Krchnavek, and R. M. Osgood, Jr., Appl. Phys. B **42**, 55 (1987).

[6] H. H. Gilgen, R. R. Krchnavek, T. Cacouris, and R. M. Osgood, Jr., in *Beam-Induced Chemical Processes*, edited by R. J. von Gutfeld, J. E. Green, and H. Schlossberg (Materials Research Society, Boston, 1985), p. 117.

[7] R. R. Krchnavek, T. Cacouris, H. H. Gilgen, and R. M. Osgood, Jr., in *Beam-Induced Chemical Processes*, edited by R. J. von Gutfeld, J. E. Green, and H. Schlossberg (Materials Research Society, Boston, 1985) p. 140.

[8] D. Bauerle, *Chemical Processing With Lasers* (Springer, Berlin, 1986), Eq. 2.19.

[9] T. H. Wood, J. C. White, and B. A. Thacker, Appl. Phys. Lett. **42**, 408 (1983).

[10] T. Cacouris, G. Scelsi, R. Beach, R. M. Osgood, Jr., and R. R. Krchnavek, inTechnical Digest, Postdeadline Papers, Conference on Lasers and Electro-Optics, Baltimore, MD, April 1987, p. 289.