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Selective amplification of self-resistively heated laser-direct-written tungsten lines

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Laser-direct-write pyrolytic deposition of tungsten at 514.5 nm, out of the WF_6/H_2 reduction system, was carried out on Al_2O_3 substrates between sputtered-on gold contact pads. Heat, generated by pulsed current sent through the laser-induced microdeposit, is used to amplify the microstructure by a conventional, however well localized, chemical vapor deposition process. In addition to tungsten, other more volatile materials can be deposited for amplification.

Laser-direct-write techniques have been demonstrated for a variety of applications,[1] including gate array interconnection,[2] high-frequency analog circuit tuning,[3] and submicrometer etching.[4] All these methods have established new capabilities for detailed custom modifications of electronic devices and integrated circuits.

Laser chemical vapor deposition (LCVD) of tungsten is currently under intense investigations for its potential application in very large scale integrated circuits. These include shunting of polycrystalline silicon gate and interconnect lines with a lower resistivity tungsten film to reduce the interconnect time constant,[5,6] formation of a barrier between silicon and aluminum to reduce aluminum spike induced failures,[7] and planarization of the multilevel interconnect process.[8] Tungsten can be deposited via the hydrogen reduction of tungsten hexafluoride WF_6[9-12]:

$$WF_6 + 3H_2 \rightarrow W + 6HF. \quad (1)$$

In the following, we shall describe a combination of laser CVD with conventional CVD, using the latter for amplification of a laser-written microstructure, demonstrated here for tungsten deposition from WF_6/H_2 according to reaction (1).

The experimental setup is schematically shown in Fig. 1. The beam of a 514.5 nm argon ion laser is focused into the chemical vapor deposition reactor containing the ceramic substrate samples. The focusing lens is the objective of a microscope with a working distance of 8 mm, and the laser power on target was about 1.5 W. The reaction cell is placed on top of a computerized microscope scanning table with a scan resolution of 0.25 μm. The stainless-steel CVD reactor has a fused quartz window and two connections, one for gas inlet and outlet, the other for two FeNiCo electrodes. The experiments were mainly carried out with a WF_6/H_2 ratio of 1:10, i.e., 30 mbar WF_6 in 300 mbar H_2. Reaction (1) takes place on the surface of the 96% pure Al_2O_3 ceramic substrate, which is commercially available[13] and was polished down to a roughness of about 2500 Å. Before deposition, each substrate was cleaned with ethanol, and two areas, about 5–6 mm apart, were sputtered with gold, thus creating conducting pads on top of the surface. The electrodes were pressed to the gold pads, which were then interconnected by laser CVD of tungsten with a scanning speed of 250 μm/s.

The volume resistivity of the deposited lines was usually in the range of 13 to 20 $\mu\Omega$ cm (bulk value of tungsten: 5.6 $\mu\Omega$ cm[14]). A connected power supply was used to send a current through the laser-written lines. A video camera is used for process monitoring, and a surface profilometer (Dektak) for a detailed analysis of the induced changes in surface morphology.

A cross section of a tungsten line written with 1.5 W laser power at 514.5 nm onto the rough Al_2O_3 ceramic substrate is shown in Fig. 2. The scanning speed between the two gold pads was 250 μm/s. For constant laser power, the deposition rate on the gold pads was somewhat lower than that on pure ceramic (1.5 μm high in 6 ms), depending on the thickness of the sputtered gold layer. A typical width (full width half-maximum) of 5–6 μm, limited by the optics, and a volume resistivity of 15 $\mu\Omega$ cm are achieved. The gold pad/ceramic transition was reinforced by tungsten direct write of a trident connection.

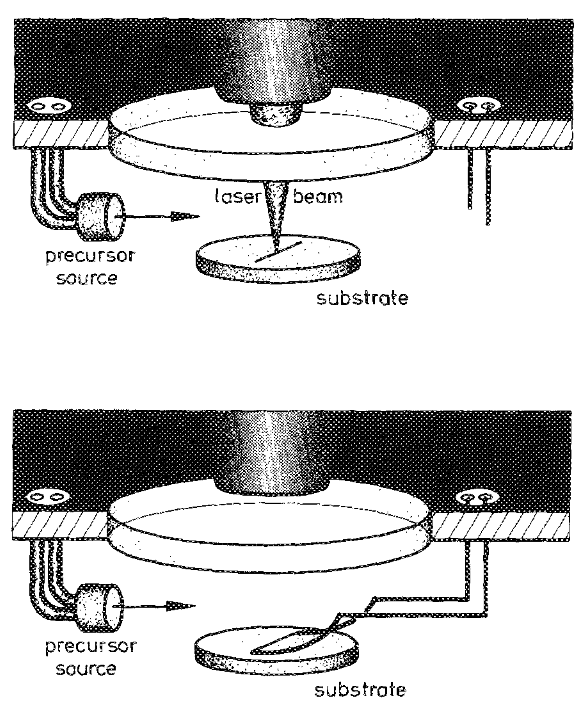

FIG. 1. Schematic view of the experimental setup for laser-direct-write deposition of tungsten (top), followed by amplification via current heat-induced conventional CVD (bottom).

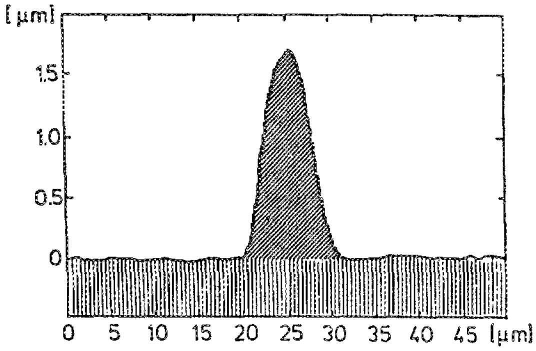

FIG. 2. Line shape of a laser-direct-write tungsten line on an Al_2O_3 ceramic substrate for 1.5 W laser power at 514.5 nm and a scanning speed of $v = 250$ μm/s in a 1:10 WF_6/H_2 mixture of 330 mbar total pressure.

A current was sent through the laser-deposited line, thereby generating heat and inducing the start of conventional CVD. Initial experiments showed that the use of continuous current easily leads to a temperature increase not only of the laser-written line but also of the surrounding substrate thus prohibiting a selective amplification of the line. Inspection of the areas on both sides of the tungsten line clearly showed tungsten on either side of the line on the substrate material. Also too high currents easily lead to the cracking of this substrate material (0.6 mm thick) due to high-temperature gradients.

Therefore, a pulsed current was used. Current pulse duration, repetition rate, and amplitude of the rectangular pulses are critical parameters. The current range for the experiments reported in this letter was between 200 and 240 mA with a voltage ranging from 15 to 25 V and pulse durations of 5 s with 10-s-long pauses between consecutive pulses.

Initial experiments with a pulse sequence having 15–30 ms rectangular pulses every 100 ms with an amplitude on the order of 10 V give further improved selectivity.

The adhesion of the lines is excellent, the Scotch tape test is passed, and the lines stick to the substrate even when this is destroyed. No tungsten was found on the ceramic in the area next to the current-heated line, if the energy was supplied in a pulsed form with proper pulse duration and repetition rate depending on the experimental conditions.

An example of the samples used can be seen in Fig. 3, showing at the top the ceramic sample with the two gold pads approximately 6 mm apart and below a close-up view of a reference and an amplified tungsten line, the latter recognizable by the trident connection between the gold pad/ceramic transition.

The amplification of a laser-direct-written line is shown in Fig. 4, where Dektak surface profilometer traces are given of the substrate material (a), the laser-written line (b), and lines amplified for 5 min by 3 W (c) and 6 W (d) electrical energy through a laser-written line.

The amplification of laser-direct-written lines by conventional CVD, as demonstrated in Fig. 4, has certain advantages. In addition to low cost, the automatic compensation of inhomogeneities in laser-written lines can be achieved. Narrow parts of the line become hotter and grow faster than broad parts of the line. The amplification is not

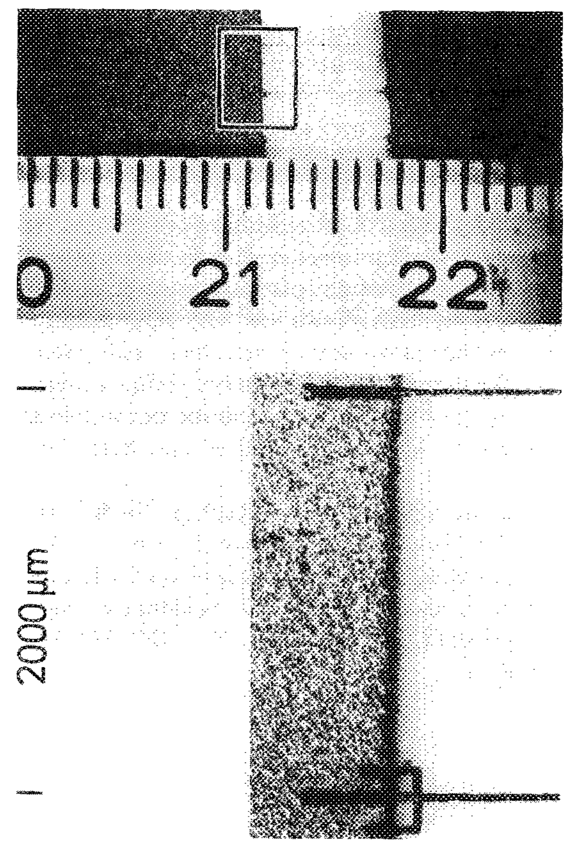

FIG. 3. Photos of the experimental sample. Top: Sample with the gold pads about 6 mm apart, connected by laser-written tungsten lines. Bottom: Close-up view of two tungsten lines, 2000 μm apart, one with the trident connection after amplification, the other a reference line.

limited to tungsten. Other more volatile materials—including insulators, semiconductors, and superconductors—can be deposited on top of the localized tungsten microstructure. Thereby the whole expertise from the conventional CVD literature can be used. This may have tremendous potential

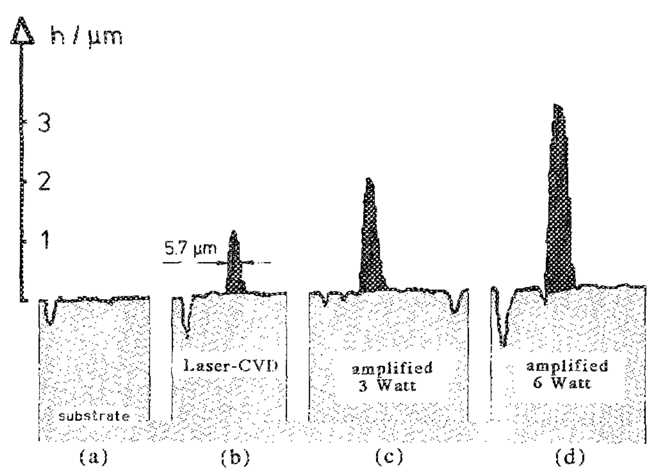

FIG. 4. Surface profilometer traces of an Al_2O_3 ceramic substrate (a) surface polished to 2500 Å roughness, (b) after deposition of a tungsten line by laser direct write, scanning speed $v = 250$ μm/s, (c) after sending current (3 W electrical energy) through the laser-deposited line for 5 min in the WF_6/H_2 environment of Fig. 2, (d) after sending current (6 W electrical energy) through the laser-deposited line for 5 min in the WF_6/H_2 environment of Fig. 2.

for the formation of low-cost localized microstructures and even heterostructures from organometallic precursors, even in cases where exposure of sensitive organometallics to laser light has to be avoided. Initial experiments on the gold and aluminum coverage of the microstructure tungsten line, using CVD from organometallic gold[15] and aluminum compounds,[16] have been successful.

In conclusion, selective amplification of self-resistively heated laser-direct-written tungsten lines between two gold electrode pads on top of a ceramic substrate was demonstrated for the first time. This allows low-cost amplification of microstructures with a variety of materials. This method may have implications for the automatic compensation of inhomogeneous laser-written lines, and for the simple and localized generation of microstructures and heterostructures.

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