

# ELECTRODEPOSITED METAL STRUCTURES IN HIGH ASPECT RATIO CAVITIES USING VAPOR DEPOSITED POLYMER MOLDS AND LASER MICROMACHINING

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**Abstract:** This paper reports a laser-assisted fabrication scheme for three-dimensional (3-D) electrodeposited metal structures into high aspect ratio trenches. A polymer (parylene C) is conformally deposited onto a highly nonplanar surface, selectively laser ablated, and used as an electroplating mold to fabricate metallic structures. Laser ablation of high-resolution ( $< 10\mu\text{m}$ ) features is performed using a 248nm KrF Excimer laser. The ablation parameters for the parylene layer have been characterized for various film thicknesses. Metal lines of  $2\mu\text{m}$  thickness, and  $2.5\mu\text{m}$  width have been electroplated into  $300\mu\text{m}$  deep silicon trenches. The minimum resolution achieved is less than  $5\mu\text{m}$ . This process can potentially be applied toward the fabrication of embedded inductors, high density electrodes, buried interconnects or high voltage circuitry in CMOS and MEMS devices.

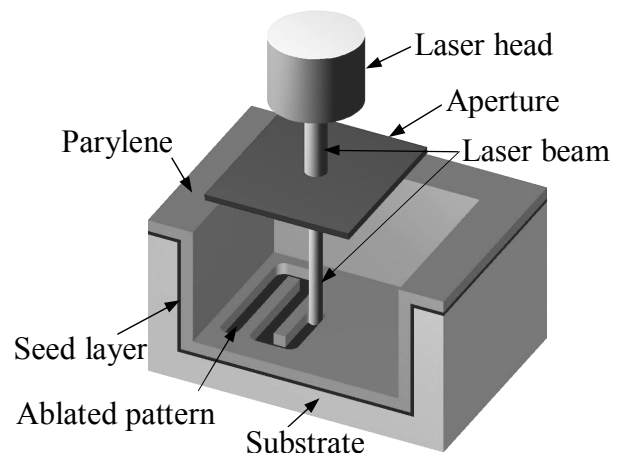
**Keywords:** Excimer laser micromachining, vapor deposited polymer, parylene mold.

## 1. INTRODUCTION

The integration of three-dimensional (3-D) electrodeposited metal structures into high-aspect ratio cavities is challenging primarily due to the difficulties associated with forming reasonably thick, precisely patterned molds at the bottom of such cavities. Although some success has been achieved using ultrathick spin coated photoresists [1], spray coating [2], or electrodeposited resists [3], these approaches suffer from resolution and aspect ratio limitations, due to the proximity effect of photolithography. Coherent light exposure of conformal, vapor-deposited resists could potentially overcome current limitations. This paper explores the limits of laser-assisted approaches for the fabrication of thick electroplated metal structures onto highly non planar surfaces such as deep microchannels.

In order to achieve high resolution ( $< 10\mu\text{m}$ ) thick electroplated structures at the bottom of high aspect-ratio microcavities, a polymer, which acts as an electroplating mold, is conformally vapor-deposited, and selectively laser micromachined. Metal structures are then electrodeposited through the mold. A conceptual rendering of the laser technique is shown in Fig. 1.

Patterning techniques using laser ablation of thin metal layers [4], or the fabrication of electroplated metal lines on either planar surfaces [5], or protruding structures such as inclined SU-8 microtowers, have been reported [6,7]. However, this is the first implementation of such a technique inside high aspect ratio trenches. Potential applications that could benefit from this method are bio-compatible MEMS devices, embedded inductors, high density electrodes, high voltage circuitry, buried and/or backside interconnections for CMOS/MEMS chips or fully integrated Silicon-On-Insulator (SOI)-based powerMEMS devices.



*Fig. 1 Rendering of the laser patterning of a vapor deposited polymer mold into deep cavities.*

## 2. FABRICATION

The fabrication process starts with the formation of dry etched deep trenches into a 300 $\mu\text{m}$  thick substrate of a SOI wafer, as shown in Fig. 2(a). An optimized Bosch process is used to achieve vertical sidewalls. The thicknesses of the device layer and the buried oxide are 2.2 $\mu\text{m}$  and 1 $\mu\text{m}$ , respectively. For low temperature process compatibility, a 1 $\mu\text{m}$  thick PECVD oxide is deposited at 300 $^{\circ}\text{C}$ , followed by the deposition of a seed layer (30 nm Ti/ 600nm Cu) using a sputterer, and the polymer, parylene-C (*Specialty Coating Systems*, Indianapolis, IN). The thickness of the vapor deposited polymer is controlled by the amount of material that is loaded into the deposition chamber. Ablation of the polymer mold at the bottom of the microchannels is performed using a 248nm KrF Excimer laser. The metal structure is plated using either the patterned polymer or the passivated sidewalls of a microchannel as molds. Finally, the parylene and the seed layer are removed using RIE and wet etching, respectively (Fig. 2(f)).

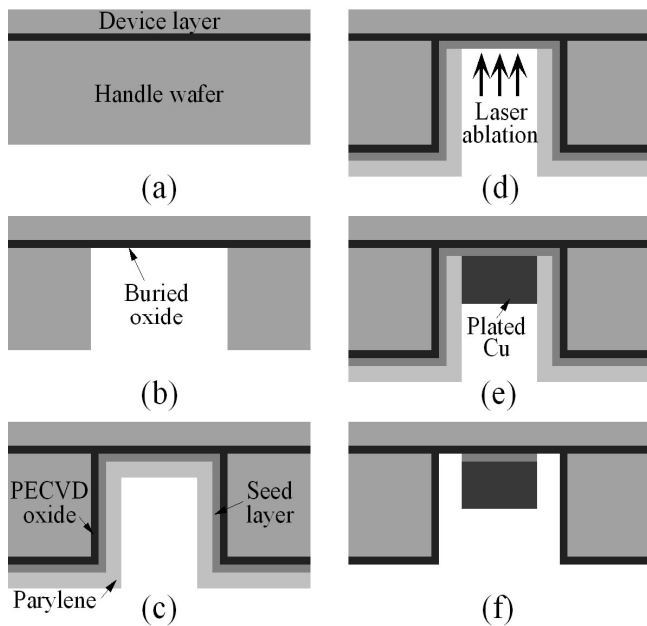


Fig. 2 Process Flow; (a) SOI wafer, (b) ICP etched trenches, (c) conformal deposition of PECVD oxide, Ti/Cu layer and parylene-C, (d) Laser ablation of the polymer at the bottom of the trenches, (e) metal electroplating, (f) Removal of the parylene and the seed layer, respectively.

## 3. ABLATION CHARACTERIZATION

Detailed characterization of the laser-ablation process of fine patterns in thick, vapor-deposited parylene films has been performed. Parameters such as energy, power transmission, number of pulses, and frequency were systematically varied. Fig. 3 depicts optical micrographs of test patterns on a glass substrate with a 500nm gold seed layer, and 10 $\mu\text{m}$  thick parylene.

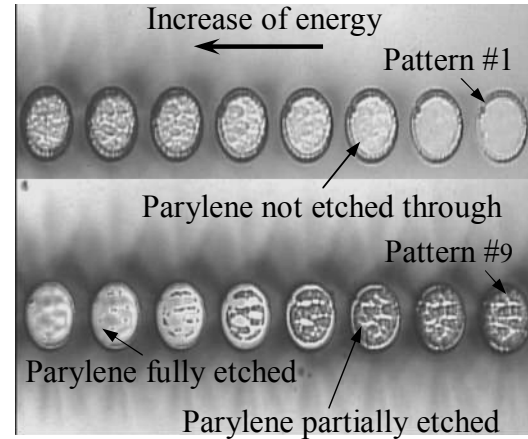


Fig. 3 Microscope view of test patterns with the increasing energy delivered by the laser.

The image shows the effect of increasing the number of pulses at a specific fluence (defined as energy per unit area) on the depth of the ablation. Linear relationships between the depth of ablation and the number of pulses are established for several fluences, as presented in Fig. 4.

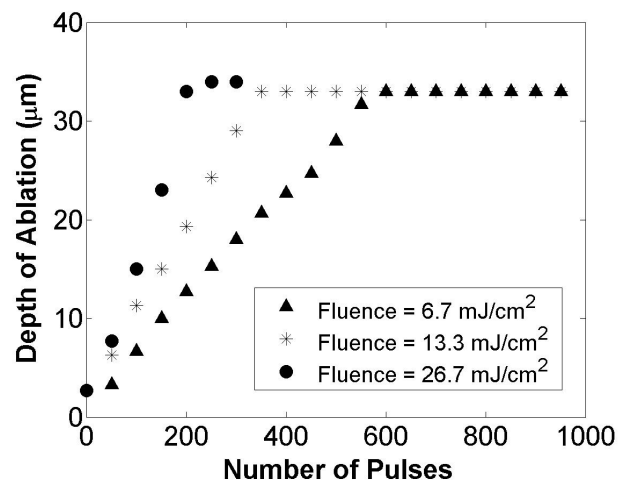


Fig. 4 Ablation rate of a 32 $\mu\text{m}$  thick parylene layer as a function of the number of shots for several fluences (energy per unit area).

The plateaus observed show that the total energy (defined as the product of fluence, area of the beam path, and the number of pulses) is high enough to ablate the full thickness of the parylene layer. Also, thin metal layers can be ablated using the Excimer laser. By determining the ablation threshold of a particular metal seed layer (depends on the material, method of deposition, and its thickness), and by operating under this threshold, an excellent selectivity between the ablation rates of the polymer mold and the seed layer is achieved. In the experiment related in Fig. 5, the ablation threshold of the Ti/Cu seed layer (30nm of Ti, and 600nm of Cu) is approximately  $15\text{mJ}/\text{cm}^2$ . At any fluence below this energy, increasing the number of pulses to ablate the mold does not damage the seed layer. Above this threshold, the seed layer is etched as shown in the test at a fluence of  $26.7\text{mJ}/\text{cm}^2$ , where a depth of  $33\mu\text{m}$  has been measured ( $\sim 1\mu\text{m}$  thick seed layer). Optimum settings are summarized in Table 1 for several thicknesses of parylene.

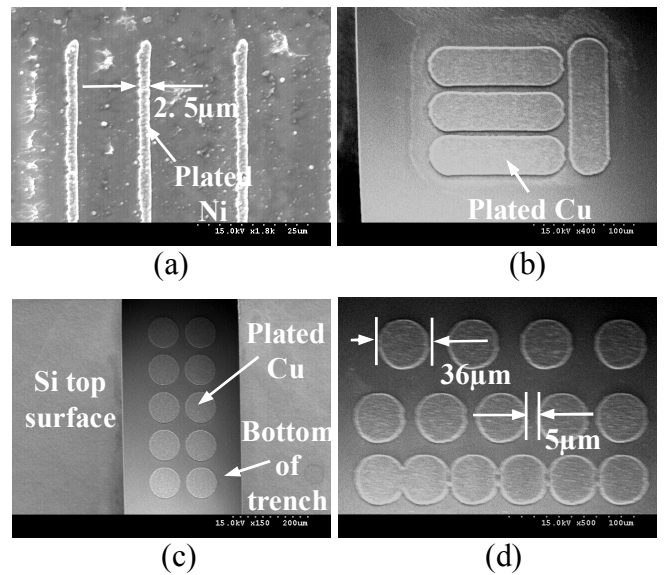
*Table 1 Optimum laser settings for several thicknesses of parylene layer*

Parylene Thickness	Fluence ( $\text{mJ}/\text{cm}^2$ )	Number of pulses	Energy per micron etched ( $\text{mJ}/\mu\text{m}$ )
2 $\mu\text{m}$	3	20	90
5 $\mu\text{m}$	8	20	96
10 $\mu\text{m}$	10	60	240
25 $\mu\text{m}$	25	200	600
32 $\mu\text{m}$	27	250	625

As the parylene thickness increases, redeposition of the etched polymer in the mold was observed. To attempt to address this redeposition issue, a vacuum wand was placed in proximity to the parylene film during ablation to try and remove any ejected material prior to redeposition. Even using this technique, redeposition could not be fully prevented, although no attempt was made to optimize this removal process. This redeposition effect manifested itself as an increase in the amount of energy necessary to etch one micron of parylene as the thickness of the parylene layer increases.

#### 4. 3-D ELECTROPLATED STRUCTURES

The process capabilities of this technique, such as the minimum feature size, and the resolution (line and space width) are shown on the SEM images of Figs. 5. An array of  $2.5\mu\text{m}$  wide nickel lines has been electrodeposited into a  $300\mu\text{m}$  deep microchannel using the parylene layer as an electroplating mold (Fig. 5(a)). A  $10\text{mA}/\text{cm}^2$  current density and a nickel sulfamate bath were used for this experiment. The resolution between two features is less than  $10\mu\text{m}$  as pictured in Figs. 5(b~d). The copper structures were plated at a current density of  $10\text{mA}/\text{cm}^2$  in a cupric sulfate bath. These results show that this process demonstrates excellent capabilities in achieving very fine 3-D metal structures in deep etched cavities. Unlike conventional UV photolithography that would suffer from the proximity effect (diffraction of the UV light due to the large gap separating the chrome mask and the bottom of the cavities), the coherence of the laser beam enables high resolution features at the bottom of high aspect ratio microchannels.



*Fig. 5 SEM images of (a)  $2.5\mu\text{m}$  wide nickel lines into a  $300\mu\text{m}$  deep microchannel, (b~d)  $4\mu\text{m}$  thick copper test patterns into a  $300\mu\text{m}$  deep microchannel.*

The above-mentioned technique, which consists of laser patterning the parylene mold at the bottom of cavities, differs from a second approach that directly uses the silicon microchannels as a plating

mold. The parylene is fully ablated at the bottom of the microchannels, and the metal is electrodeposited, as presented in the process flow (Fig. 2(d~f)). An example of this process is shown in Fig. 6.

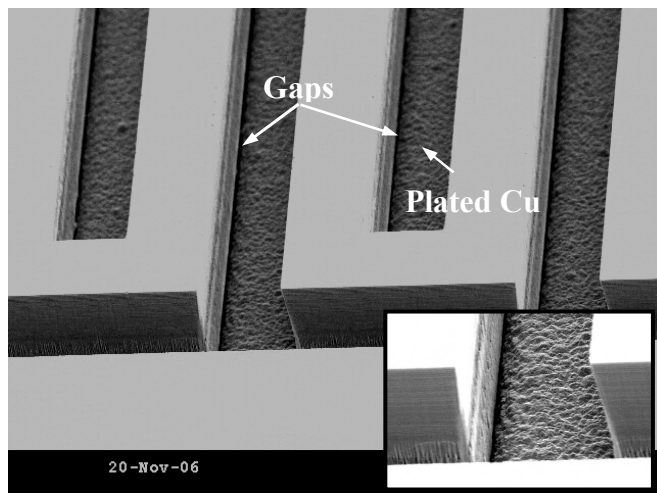


Fig. 6 Fully filled trench with 40 $\mu$ m thick copper structure. The black area near the sidewall depicts the gap between the metal structure and the silicon sidewall.

A 40 $\mu$ m thick copper layer was electroplated. Once the polymer and the seed layer are removed, there is a gap of approximately 4-5 $\mu$ m between the silicon and the metal structures. This demonstrates that the sidewall insulation during the metal electroplating step is ensured by the conformal deposition of the polymer. Thus, the metal structures are not shorted with the silicon device, which is important for backside micro circuitry applications. Such a small gap would be very difficult to achieve with conventional lithography.

## CONCLUSIONS

High-resolution, 3-D electroplated structures were fabricated into high aspect ratio microchannels. A polymer layer was conformally deposited onto the microchannels and selectively laser micromachined to form the electrodeposition mold. A resolution of 5 $\mu$ m, and feature size of the order of 2 $\mu$ m have been achieved in 300 $\mu$ m deep trenches. Although this experimental study was performed using serial processing, the process

throughput can be greatly increased by exposing the microchannels through an appropriately-patterned stencil mask placed in the beam path. Further, as expected, the depth of the microchannels does not influence the quality of the laser ablation, which means that this process is applicable to ultra deep trenches (>0.5mm).

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