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Laser direct writing of thin-film copper structures as a modification of lithographic processes

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Abstract. This paper presents a flexible, mask-free and efficient technique for UV-laser micro-patterning of photosensitive resist by laser direct writing (LDW). Photo resist spun on gold sputtered silicon wafers has been laser structured by a scanner guided 266nm DPSSL and electroplated. Ablation behaviour and optimum seed layer preparation in relation to parameters like pulse energy, scanning speed and number of scanned cycles and the electroplating results are discussed. The resulting adhesive strength was measured by a μ -sear device and the gold seed layer-plated copper interface investigated by SEM and EDX to explain correlation to identified bonding behaviour. Improved adhesive strength was observed with higher laser pulse energy and reduced number of cycle.

1. Introduction

Photo lithographic processes are used for the production of a large diversity of thin-film sensors and printed circuit boards. However, the required photo masks make this technology less suitable for small and medium batch sizes and provide only limited flexibility during the development phase. The evident need for a more flexible fabrication technology can be addressed by a modification of standard lithography. Several groups investigated the laser direct exposure [1], [2] or the direct ablation of photo resist with excimer laser radiation [3]. This work presents an approach with a less cost-intensive solid state laser, described as Laser Direct Writing (LDW). In this concept, the need for image masks as well as environmentally aggressive development chemicals can be abandoned. Instead, the resist covered wafer will be structured directly by a scanning laser beam. The process parameters have to be adjusted precisely to completely remove the resist without damaging an underlying seed layer, needed for a following electroplating process. Deploying a laser scanner unit for the beam handling, it is obvious that a modification or re-design of the machined resist geometry can be easily implemented by editing a CAD template [4]. Since the direct removal of the resist needs no additional development cycle, the laser-structured substrate can be directly electroplated with no need on further pre-processing.

2. Experimental

A detailed description of the experimental LDW set-up, and of various already accomplished investigations concerning minimum lateral resolution, influence of focal plane distance for the side wall flank angle, geometrical features, material removal rate, etc. have been reported elsewhere [5], [6]. Thus, this paper focuses on effects of the electroplating results of the laser machined structures in relation to the applied process parameters.

The machining concept for the described set-up, figure 1 b), includes a frequency-quadrupled diode-pumped solid-state laser source ($\lambda = 266\text{nm}$, $\tau < 30\text{ns}$), a beam expander followed by a (6x) aperture (7mm) and a galvanometer scan with f-theta optic ($f = 160\text{mm}$). A spot diameter down to $8\mu\text{m}$ can be achieved.

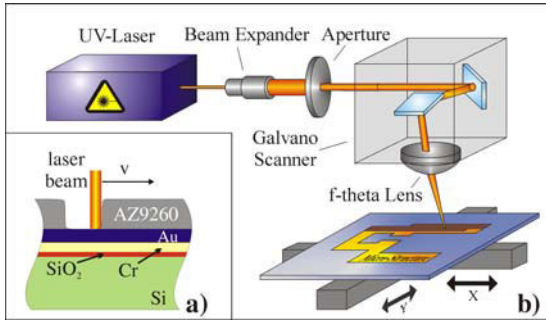


Figure 1: a) Laser Direct Writing (LDW) principle, substrate materials, and b) schematic of experimental set-up for LDW.

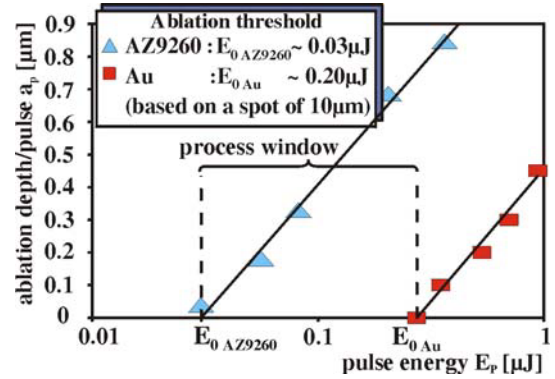


Figure 2: Definition of theoretical process window as distance between ablation threshold of resist and seed layer.

A Si-wafer ($500\mu\text{m}$ thickness) of 4" diameter contained a 100nm SiO_2 -passivation layer, was sputtered with a 60nm chromium adhesion layer and a $1\mu\text{m}$ thick gold layer to define the substrate shown in figure 1 a) for the following electroplating process. For the experiments, standard photo resist (positive tone Diazo Quione based resin, type AZ9260, Clariant) with a thickness of approximately $10\mu\text{m}$ had been spun on to the wafers. For the final electroplating process of the laser structured wafer a standard copper bath (CUBATH® SC, Enthone®) had been used to realize approximately $10\mu\text{m}$ thick plating (10min @ 1000mA). The realized structures have been analyzed with optical microscope (DM RBE, Leica), SEM (Series 2, Cam Scan, Cambridge, GB) including EDX, profiler (Perthometer, Mahr, Germany) and a μ -shear device (CONDOR 70-3, XYZTEC, NL).

3. Results and Discussion

Since one of the key features for a successful electroplated structure is the complete removal of the resist without destruction of the energy sensitive fundamental seed layer, the ablation threshold of both materials has been investigated. Results are shown in figure 2. Pulse trains with 100 laser pulses each, with varying pulse energy at repetition rate $f_p = 72\text{kHz}$ were applied on both materials and the average depth per pulse a_p calculated as the quotient of the measured ablation depth by a confocal profiler and the number of applied pulses. As noted in different literature [6], [8], a_p increases linearly with the logarithm of the pulse energy E when exceeding the ablation threshold E_0 , below which just minor modification of the material is evident. In figure 2, the theoretical process window is shown as the range $\Delta E = 0.17\mu\text{J}$ between the ablation thresholds for both materials ($E_{0\text{AZ9260}} = 0.03\mu\text{J}$, $E_{0\text{Au}} = 0.2\mu\text{J}$). However, as reported in the literature, energy accumulation [9] and "incubation pulses" [10] play an important role in the explicit ablation rate and threshold behavior. Thus, as shown later in this paper,

even with pulse energy higher than $E_{0\text{Au}}$, successful ablation results have been demonstrated. This observation is comprehensible if one considers that the complete ablation process takes part in several laser scanning cycles, which allow a much longer thermal recovery time between the supplied energy. Furthermore, the experiments showed that

a certain level of seed layer damage is tolerable for a successful electroplating result, since complete removal of remaining resist residues can be insured by this partial seed layer damage.

The variation of investigated process parameters for the executed trials is given in table 1. With a constant repetition rate $f_p = 72\text{kHz}$, the structures were hatched with linear parallel laser lines with a

Table 1: Laser process parameters.

Parameter	Value
Scanning speed v_w	$50/150\text{mms}^{-1}$
Pulse energy E_p	$0.1/0.2/0.3/0.4\mu\text{J}$
No. of scan cycles n	$1 - 50$

separation distance of $5\mu\text{m}$. Former investigations [6] proved that the 50% line-to-line overlap ($10\mu\text{m}$ line width) results in a relatively homogeneous ablation characteristic.

Figure 3 shows three exemplarily ablation results with different numbers of applied scan cycles. The microscope picture (detail of corner) on the left side in figure 3 a) occurs after 7 cycles. It can be clearly seen that a debris covered thin resist layer remains on most of the area of the ablated structure. Only an approximately $10\mu\text{m}$ thick line next to the outer geometry appears clean. The width of this line is equal to the spot diameter of the laser beam which indicates the influence of an additional contour scan cycle in smoothing the outer border of the structure [6]. The SEM picture (figure 3 a), right) displaying the electroplating result of the same structure confirms this thesis. Just a thin wall along the outer border has grown by the electroplating process while the main part of the area appears clean due to the remaining thin resist layer. The wall thickness was measured to be just $2\text{-}3\mu\text{m}$, which is much thinner than the contour scan width. It seems that even the contour scan was not able to completely remove the resist residue. It can be assumed, that additional trenching effects at the resist's steep side walls are responsible for a very thin break-through in the resist residue [11].

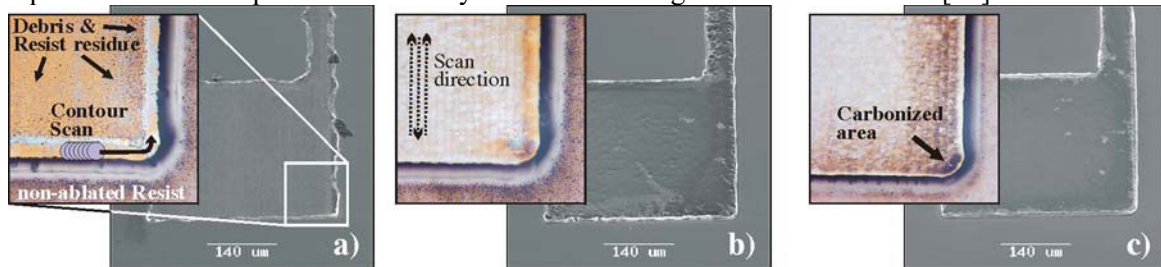


Figure 3: Optical microscopic images of ablated resist areas (upper left) and SEM images (right side) of the electroplated structures. The resist in the SEM picture has been stripped. Scanner speed $v_W = 50\text{mm s}^{-1}$, pulse energy $E_P = 0.2\mu\text{J}$, and number of scan cycles a) $n = 7$, b) $n = 15$, c) $n = 40$.

After 15 cycles, figure 3 b), left, the laser structured area appears relatively clean, with a light spotted pattern most probably indicating a very thin resist residue between the laser beam-scanned lines. Furthermore, first indication of carbonization of resist residue in the structures corner is visible. The electroplated result in the right SEM picture appears relatively homogeneous in the center area but shows evidently retarded growth in the border area. After 40 scan cycles, figure 3 c), left, a uniform center of the structure but even stronger carbonized corner and border areas are shown. However, the electroplated result indicates a homogeneous growth of the complete ablated structure which has been confirmed by a profiler. It seems that the electroplating bath's constant pH value of 2.5 enables the dissolving of minor particles of carbonated resist contaminating the seed layer surface, which enables a proper growth.

The basic ablation of resist with UV radiation is well reported in literature. It can be noted that the described debris and residue free cleaning of the gold seed layer is absolutely essential for the electroplating quality and has to be adjusted precisely. For further durability investigation, adhesion tests have been conducted to analyze the bonding of the electroplated structures. Due to the low adhesive strength of the $1\mu\text{m}$ thin seed layer on the Si substrate, these forces are expected to be relatively small. Therefore, a precision μ -shear device was deployed to provide an increasing force from one side of the pad structures until shearing from the seed layer occurs. A graph of a typical shear trial is shown inset (upper left) in figure 4. It can be seen, that when the shear chisel touches the pad (A), the force rises linear until it drops instantly when the structure breaks off the substrate (B).

Figure 4 shows the distribution of the force peak values F_S depending on pulse energy E_P and number of scan cycles n of the laser processing. It is obvious that for each of the displayed energies the adhesion rises up to a certain number of cycles after which a distinct drop is visible. The peak of the graphs show the optimum number of cycles for each E_P after which the resist is completely removed and the seed layer is still not damaged or heavily contaminated with byproducts like debris.

As expected, for higher pulse energy a lower number of cycles is needed to realize a determined shear force. For example, to obtain a peak adhesion force of 0.4N, $n_{0.1\mu\text{J}} = 15$; $n_{0.2\mu\text{J}} = 9$ and $n_{0.4\mu\text{J}} = 6$ cycles are needed. Furthermore it is obvious, that the decreasing flank is steeper for higher energy, which indicated the raised damage of the seed layer for high pulse energy.

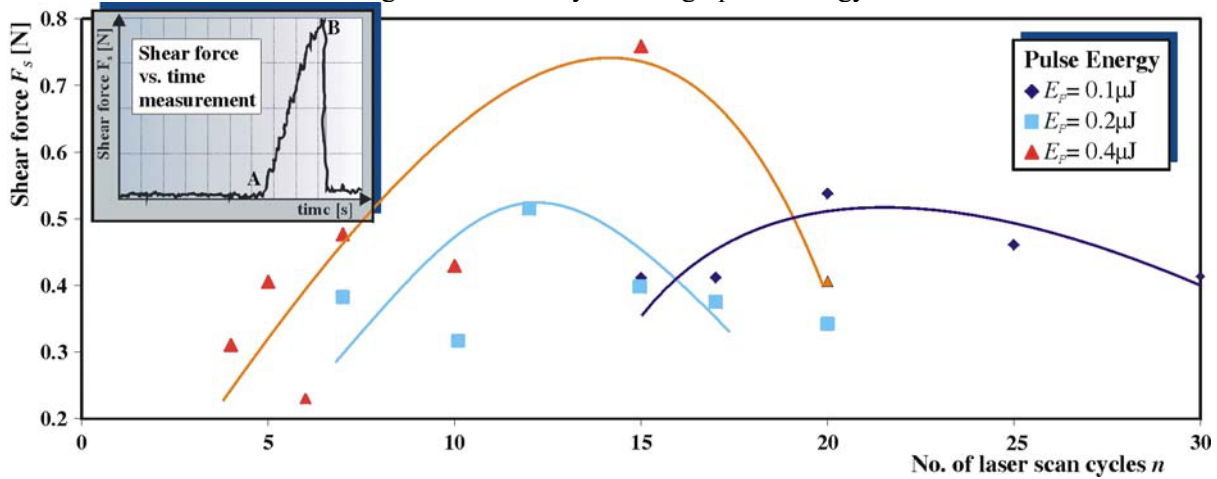


Figure 4: Shear force peak values F_s vs. no. of laser scan cycles n for different pulse energy.

The maximum force F_s for $E_p = 0.4\mu\text{J}$ is approximately 40% higher than for the other pulse energy trials. A reason for this may be an increasing ratio on the photo chemical to the photo thermal component underlying the laser ablation process at lower pulse energy. This means that the decomposition and evaporation part of the "cold" ablation of resist (at higher energy) realizes an improved seed layer preparation compared to the emphasized melting process near the ablation threshold.

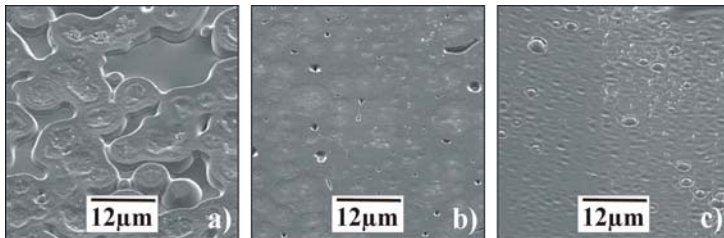


Figure 5: Surface topography of backside of sheared copper electroplated structures for $v_W = 50\text{mm s}^{-1}$ and a) $E_p = 0.2\mu\text{J}$, $n = 10$, b) $E_p = 0.2\mu\text{J}$, $n = 12$, and c) $E_p = 0.4\mu\text{J}$, $n = 15$.

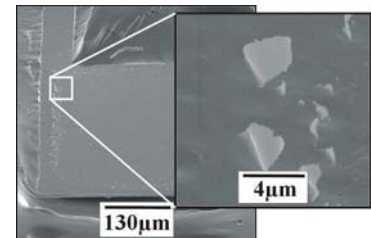


Figure 6: Seed layer particles on backside of electroplated structure.

For an advanced understanding of the adhesion behaviour of the copper structures on the seed layer, the geometrical structure of the backside of the sheared-off structures have been investigated. In figure 5 a), it can be observed that for $E_p = 0.2\mu\text{J}$ and 10 cycles the contact area with the seed layer shows inhomogeneous growth. Due to remaining resist residue or byproduct settlings, successful electroplating was suppressed which resulted in a low shear force of $F_s = 0.4\text{N}$. Figure 5 b) shows the result after 12 cycles with a much smoother surface of the grown metal structure's backside. Just a few pores remain, though the blurred regular bright spotted areas may represent very thin residual resist, which has been overgrown by the copper. Hence, just a minor rise of the shear force up to $F_s = 0.47\text{N}$ occurs. With $E_p = 0.4\mu\text{J}$ and 15 cycles, a maximum adhesion with $F_s = 0.76\text{N}$ can be realized. The corresponding figure 5 c) shows minor damage of the gold layer. The resist residues (blur spots) seem to be accurately removed, while defined crater like structures reflect imprints of starting seed layer damage due to high energy laser pulses. However, this minor damage did not disturb the smooth electroplated surface of the structure. Furthermore, this result verifies the conclusion given earlier in this paper that even pulse energy above the ablation threshold of the start layer may lead to successful

electroplating. In the upper right quarter of the SEM picture, well defined bright lines are visible, which have been analyzed in figure 6. It displays the backside of the electroplated structure and a magnification of the same bright particles. An EDX analyzes clearly identified the material as gold (contrary to the copper grown structure). This indicates that in some areas the adhesion realized by electroplating is stronger than the bond of the seed layer to the silicon oxide surface of the wafer.

4. Conclusion

Laser direct ablation of photo sensitive resist as a modification of standard lithography cycles was presented. Seed layer damage free laser removal allowed a smooth and regular growth of copper electroplated structures. Adhesion test characterization confirms the structure quality. Determining a detailed process window for a successful electroplating of LDW thin-film structures will be a task for the future.

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