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Laser beam steering approaches for microstructuring of copper layers

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Abstract:

We have investigated the process of copper layer ablation with a tightly focused Q-switched 532 nm laser. Focusing 40 ns long laser pulses to a micrometer-sized spot results in high energy density and gives rise to ablation phenomena not seen during laser processing with larger beam diameters. Use of acousto-optic deflectors (AODs) enabled us to test different laser beam steering approaches in terms of choosing the position for each laser pulse independently of the previous pulses. Random addressing of desired positions across a microstructure proved to be the most efficient method compared to various scanning approaches. Assigning a random order to the spatial sequence of laser pulses resulted in the fastest microstructuring process and featured lowest residual heating of the substrate.

Keywords:

direct laser microstructuring; copper layer microablation; Q-switched laser ablation; acousto-optic laser beam steering; printed circuit board prototyping

1. Introduction

Modern tools for rapid printed circuit board (PCB) prototyping use pulsed lasers to ablate parts of the copper layer leaving precisely defined conducting copper traces and pads untouched. Typical laser beam spot size is around 20 μm and approximately the same beam size is used in various fields of experimental science, such as PCB prototyping on rigid and flexible substrates [1,2], studies of nanosecond laser ablation processes [3–5], and studies of other thin metal material ablation [6,7]. Smaller spot size of around 5 μm was used in ablation experiments on 20 nm thin copper layers [8]. Minimal dimensions of the resulting structures are close to the laser beam size. Modern electronic devices are getting ever smaller and demand for precise copper structuring on traditional and flexible substrates is constantly growing. Our experiments were therefore aimed to achieve higher precision and smaller feature size using a tightly focused laser beam with a 1 μm spot size, on 5 μm thick copper layers. The aim was to reduce both the laser spot size, typical minimal dimensions of resulting structures, and isolating gaps between the structures for approximately an order of magnitude. Observing the ablation results on a micrometer scale enabled us to identify the processes of copper layer microstructuring with tightly focused laser beams and develop an efficient approach with low heat impact to the substrate.

Picosecond laser pulses, cause ablation through a two-step energy transfer from laser pulse to photoexcited electrons to the lattice keeping most of the surrounding material intact, in the process of so called non-thermal melting [9]. Longer pulses, such as nanosecond pulses used in our experiment, transfer the energy through the electron-phonon coupling to the lattice, causing thermal melting [9–11]. The result is that a nanosecond pulse heats a greater volume of a copper layer compared to a sub-picosecond pulse. As laser pulse energy is deposited into the copper layer the temperature rises and copper undergoes two phase transitions, first from solid to liquid state and then from liquid to vapour. During microstructuring hot copper fumes and molten debris come in contact with both the substrate and with the non-structured parts. Heat affected zone and damage to the substrate are important aspects of direct laser structuring that cannot be neglected and need to be controlled.

Advanced laser pulse positioning approaches aim to minimize the accumulated heat during the microstructuring. Generally the approaches can be divided into sequential and random-pulse approaches. In a sequential approach the positions of the subsequent laser pulses are chosen so that a whole row is structured in an orderly fashion followed by another row, which is not necessarily neighbouring the previous one. Mechanical scanners can reproduce every sequential approach without a significant speed loss. The same is not true for random-pulse approaches, as each laser pulse can have its position defined independently of the others.

Acousto-optic deflectors were chosen for our experiment for their ability to deflect subsequent laser pulses to arbitrarily chosen locations at a constant repetition frequency. Testing different approaches was thus possible with a single optical setup.

2. Materials and methods

Optical setup was designed around a nanosecond Q-switched pulsed laser source working at 532 nm (SLDP20/2F, LPKF Laser & Electronics d.o.o.). Typical pulse duration was around 45 ns at a chosen repetition rate of 71 kHz. Laser had a precisely synchronised pulse emission timing with a pair of acousto-optic deflectors used for beam deflection. Acousto-optic deflectors (AODs) with specially adapted driver electronics and software (Aresis d.o.o.) were a key part of the experiment. Precise and mutually independent positioning for subsequent laser pulses made AODs the only suitable choice for testing different pulse positioning approaches without changing the optical setup. AODs deflected a laser beam for up to 20 mrad in each direction, giving us a working area of 300 x 300 μm^2 on the sample. Relay optics were used to guide the laser beam pivoting point from the AODs to the back aperture of the working objective. We used a 20x magnification microscope objective with numerical aperture (NA) of 0.5 (Nikon Plan Fluor 20x/0.5). The calculated laser beam focus diameter was approximately 1 μm and its Rayleigh length just above 2 μm . Experimental setup is shown in Fig. 1.

Experiments with different exposure patterns were performed on a 5 μm thick copper layer deposited on a typical rigid-flex substrate for printed circuit boards. Thicker copper layers were used to see how the tightly focused laser beam performs in microstructuring layers of greater thickness than the beams double Rayleigh length. Every sample was mounted on a mechanical stage used to level the sample in the objective's focal plane.

Fig. 1 a) Schematics of important parts of the experimental setup. b) Detail of the laser focusing objective and sample leveled in the focal plane.

3. Results

3.1 Single pulse ablation

A single pulse incident on the copper layer is partially absorbed, causing local heating, melting and evaporation of parts of the copper layer. Shortly after laser pulse absorption in the material a plasma appears (typical time scale is in tens of nanoseconds [12]), followed by material ejection [13,14]. Ejection of vaporized and molten material happens on the typical time scale between 200 ns and 1.5 μ s after the laser pulse absorption [12,10]. A 45 ns pulse is significantly shorter than this, thus allowing the assumption that the non-reflected part of the laser pulse energy is absorbed in the copper layer regardless of the total pulse energy and no energy is transmitted through copper to the substrate. The single pulse ablation process results in a cylinder shaped crater in the copper layer (Fig. 2).

Fig. 2. SEM image of a crater left after the laser ablation. Solidified molten copper can be seen on the inner walls of the crater. Minute quantities of ejected copper are surrounding the crater, scattered across the already uneven surface.

According to literature [15] we have expected that a crater with radius r_0 made by a laser pulse with a Gaussian intensity profile would be scaled by laser pulse energy E_{pulse} as given by the equation

$$r_0^2 = 2w_0^2 \ln(E_{\text{pulse}}/E_{\text{th}}), \text{eq. 1}$$

where w_0 is the width parameter of the Gaussian intensity profile and E_{th} is the threshold energy needed for ablation. A Gaussian shaped intensity profile was defined as

$$I_{\text{Gaussian}} \propto A * \exp(-2r^2/w_0^2), \text{eq. 2}$$

The experimental data does not correspond well to this model. To solve this discrepancy we have assumed that even parts of the laser beam profile below threshold intensity add energy needed for crater creation. Due to the tightly focused laser beam, where typical dimensions are comparable to heat transfer distances during the pulse duration, such an assumption is justified. Heat transfer times were confirmed by the simulation.

Total absorbed energy in the copper layer was calculated from the delivered laser pulse energy that got absorbed inside the diameter of the crater. Total absorbed energy E_{tot} can be expressed as

$$E_{tot} \propto A(1 - \exp(-2r^2/w_0^2)), \text{eq. 3}$$

where A is normalised intensity. The craters volume V equals to $V = h \cdot r_0^2$ where h is the copper layer thickness. Energy needed to ablate a given volume of copper is proportional to its volume and can be expressed as

$$E \propto r_0^2, \text{eq. 4}$$

We have performed an experiment using different laser pulse energies and measured crater diameters. Combining the equations Eq. 3 and Eq. 4 gives a relationship

$$A(1 - \exp(-2r^2/w_0^2)) \propto r_0^2, \text{eq. 5}$$

which was tested on the data set shown in Fig. 3 b). An excellent agreement between experimental data and the fitted function shown on the graph confirms the assumptions given by Eq. 3. Only one fitting parameter was used, fixing the laser beam profile w_0 .

When working with normalised intensities below $A = 0.16$ not every laser pulse creates a crater through the whole thickness of copper. Uneven surface of the copper layer causes a slightly varying ablation effect depending on the exact position on the layer. Surface around an ablation crater was imaged by a SEM microscope (Fig. 2) and surface roughness can be estimated to below 1 micrometer. Normalised intensity $A = 1$ corresponds to laser beam energy density of approximately 10 kJ/cm² on the sample surface.

Fig. 3 a) 27 single laser pulses caused ablation of the copper layer, leaving 27 craters behind. Normalised intensity A was set to 0.8. b) Measured crater diameters at different normalised intensities with a best fit of function in eq. (3).

3.2 Ablation with multiple pulses

Different exposure regimes were tested. A classical point-by-point line-by-line illumination is a direct equivalent of using mechanical scanners to deflect a laser beam, represented on Fig. 4 a). A bit more advanced illumination regimes are identified by the way of choosing the next line to scan. Those illumination regimes can also be replicated with mechanical scanners while only sacrificing a small fraction of speed. Namely, the next line to scan can be either chosen randomly or with a sequential approach. Sequential approach is easier to implement and aims to minimize the thermal influence on the material. As shown on Fig. 4 b), every 16th line is illuminated, then starting in the 8th row the process repeats and so on. The unique approach using AODs is a totally randomized selection of the next illuminated point Fig. 4 c).

Two parameters have the strongest effect on the microfabricated structure: laser pulse energy and number of pulses. First a suitable laser pulse energy was chosen so that at least the majority of single pulses would create a crater through the whole thickness of the material. The parameter A was set to 0.2 for all experiments with different illumination regimes.

Fig. 4. Simulated time evolution of the structure during different illumination regimes. a) Lines are scanned from left to right and from bottom to top. Subsequent pulses are neighbouring each other. b) While subsequent pulses are still neighbouring, lines are chosen according to a system – each line is 16 lines away from the previous one to minimize the thermal stress. c) Choice of the next illuminated point is defined by a randomization algorithm.

3.3 Random approach

First experiments were performed using the random pulse distribution with a variable number of pulses. Random distribution was considered because the typical times between the illuminations of two neighbouring points in the microstructure are very long. Thermal load on the substrate is therefore reduced. Images in Fig. 5 show results of illumination using randomly distributed pulses at constant pulse energy. The left-most picture shows the experimental result done with 3 μm spacing between neighbouring pulse locations. Most of the microstructured area is still covered by a thin copper layer. When microstructuring with multiple pulses the final effect is not necessarily a sum of single pulse effects. Due to partial melting of the copper layer not all of the material is ejected away from the substrate as the single pulse results would suggest. When a pulse is incident on a location on the copper layer that already has its surroundings at least partially removed, the molten material is also ejected towards the substrate or along the substrate. This causes copper recoating of the already cleaned substrate areas. As a result of this process more pulses are needed to successfully create a microstructure. In the case of randomly assigned subsequent laser pulse positions the needed spot spacing was 1 μm which resulted in around 60 thousand pulses

Fig. 5. Results of illumination using randomly distributed subsequent laser pulses at constant pulse energy. Regime is illustrated on Fig. 4 4 c). From left to right the spatial separation between neighbouring pulses diminishes from 3 μm to 2 μm to 1 μm and the number of pulses increases accordingly.

per 300x300 μm^2 structure shown in Fig. 5 c).

3.4 Sequential approaches

Further experiments were performed to assess other possible illumination regimes, also achievable with more common scanning techniques such as mechanical scanners. As the starting parameters for all other tests the best parameters from the random distribution experiments were taken.

One pass across the material using the simplest pulse-by-pulse line-by-line scanning consistently gave the result shown in leftmost part of Fig. 6. Scanning direction was left to right and bottom to top. Recoating due to resolidification of copper is notable – bottom and left sides of structures are well defined compared to top and right sides as the last laser pulses in each line push copper residue to previously cleaned areas. Two different approaches were tested to improve the outcome. First a higher number of pulses was used resulting in a higher density of pulses absorbed but the result improved only marginally. The method of multiple passes yielded better results as demonstrated in Fig. 6. Copper was gradually removed and after four passes the result is similar to the random approach. Two important differences have to be noted – a) the scanning approach is four times slower compared to random approach to obtain the equal results and b) greater residual heating of the substrate occurs both due to an increased number of pulses and due to the sequential approach, as the copper does not have time to cool down before a subsequent laser pulse is absorbed in the direct vicinity.

Fig. 6. Spot spacing is kept at 1 μm but the illumination regime is changed to a simple pulse-by-pulse line-by-line scanning. From left to right the number of passes is increased (1, 2, 4) as the material was not successfully removed in one pass. In comparison to the random distributed pulses four times as many laser pulses were needed for the successful removal of the material.

Results using sequential line scanning were obtained using three different yet similar approaches. The next scanned line was chosen either randomly or by skipping a certain number of the neighbouring lines. Two different periodic arrangements were tested, skipping 8 and 16 lines respectively. To illustrate the concept from Fig. 4 b), skipping 16 lines refers to starting in line 1, going to line 17, etc. to the edge of the field and jumping back to line 9, going to line 25, etc. Again an increased number of passes eventually yields a quality structure, as shown in Fig. 7. Additional passes after the fourth tend to slowly cause damage to the substrate.

Fig. 7. Spot spacing is kept at 1 μm but the illumination regime is changed to a systematic line scanning skipping to every 16th line. From left to right the number of passes is increased (1, 2, 4) as the material was again not successfully removed in one pass. In comparison to the random distributed pulses successful removal of the material demanded four times as many laser pulses.

Next comparison between the random approach and scanning approaches was done on a more heat susceptible thin and flexible PCB substrate based on polyimide material. When structuring thin lines defined as one

dimensional row of laser pulses we saw a significant difference in the structuring quality. As shown on Fig. 8 when a line of single pulses is done by random approach the lines are consistently well defined.

On the other hand the scanning approach doesn't yield useful results. Heat susceptible substrate material affects the copper melt redistribution and copper is temporarily removed by a laser pulse only to be redistributed by the next pulse. This can be seen on the lower right part of Fig. 8 where only the last pulse in the line left a permanent crater. Additional passes were not an option in this case as polyimide materials have low heat resistance. Structuring of copper on resistant substrates can be done with scanning approaches but not on heat susceptible substrates where random approach appears to be the only option.

Fig. 8 A line of single pulses done by the random approach (upper part) and by line scanning from left to right (lower part). Equal number of pulses and pulse energies result in fundamentally different outcomes.

3.5 Random approach properties

As random approach was giving better results compared to scanning approaches some additional experiments were performed to gain a better understanding of mechanisms influencing the quality of the resulting structures.

Experiments were performed using a thicker copper layer on a flexible substrate, precisely DuPont made AP8525R all-polyimide material with an 18 μm thick rolled-annealed copper layer. Using a right number of laser pulses for a given pulse energy resulted in a precisely defined structure of conducting copper traces and pads (Fig. 9, left part). At the same parameters the process of microstructuring was stopped half-way through and the result is shown in the right part of Fig. 9. It shows a layer-by-layer progress – first half of the pulses removed material from the whole surface, but not the complete thickness of the copper layer. Laser pulse energy density was set to about 20 kJ/cm^2 , as structure quality declines with higher energy densities. A single laser pulse of the chosen energy density

does not ablate the whole 18 μm copper thickness. Image was taken with both reflective and transmissive illumination and grey parts of the image show light coming through the substrate.

Fig. 9. A full number of laser pulses required to successfully remove the whole thickness of the copper layer was shot on the left part of the structure. On the right half a randomly chosen half of the pulses was shot on the material. The image clearly shows that structuring of thicker materials (18 μm copper layer) using the random approach is done in a layer-by-layer fashion.

A combination of tight focusing and random pulse distribution gradually removes a copper layer in a layer-by-layer fashion. Despite the tight focusing the structure walls as seen in Fig. 10 are near perfectly vertical. The aspect ratio is 3:1 or better with the copper layer thickness of 18 μm compared to the structure width that is below 6 μm . Low thermal effects are demonstrated by the thin features themselves – heating thin copper stripes causes a lift-off process, as demonstrated in [16].

Fig. 10. Process of layer-by-layer material removal results in well-defined structures with near perfectly vertical walls with aspect ratios higher than 3:1 (copper layer thickness 18 μm vs. structure width below 6 μm).

3.6 Heat transfer simulation

A 40 ns laser pulse is long enough that heat is transferred to the surrounding material a few micrometers away from the laser pulse position. Molten metal material is present for a short time before the ejection process happens [12,17]. Heat transfer simulation (finite element analysis software) in a copper layer was used to predict the temperature differences induced solely by different copper structure geometries that occur during structuring. We have reviewed the structuring process done by different approaches and the only significant difference was found in geometry. For example, during a sequential structuring from bottom left to upper right side, every pulse except the first one will impact on a similarly formed copper structure. Above the laser spot and to the right will always be unstructured material. In comparison, during a random approach structuring, a number of pulses during the beginning will be absorbed in an unstructured copper layer while the rest will be absorbed in different geometrical shapes of copper.

The simulation compared four different geometries, shown in the upper part of Fig. 11, representing the first pulse in a given area, a border pulse, a pulse incident between two existing ablation craters, and the last pulse, which needs to remove a small volume of remaining copper layer. Heating of a 5 μm thick copper layer with a 40 ns laser pulse was simulated with phase change of the material included. Laser pulse energy density chosen for the simulation was significantly lower compared to the experiments in order to evaluate only effects of copper layer geometry on the heat distribution.

The most important finding of the simulation is that geometry does affect the maximum temperature reached. More confined geometries result in a higher temperature, indicating that the conduction of heat within the copper material is the governing process, while radiation to the environment is a lesser factor. The highest temperature point always appears directly under the centre of the laser pulse. A difference of about 15% in the absolute value of the maximum temperature is visible on the graph in Fig. 11.

Fig. 11. Upper part: Positions of laser pulses on copper surfaces with different geometries as defined inside the simulation. A - a centered pulse on unstructured surface, B - a border pulse, C - a pulse between two existing ablation craters, and D - a pulse on the last remaining unstructured area.

Lower part: Time evolution of the maximum temperature. Differences between peak temperatures are a consequence of different geometries.

The experiments have shown that the random structuring approach yields more efficient material structuring. In this case a significant part of all the laser pulses is absorbed in small, confined copper structures, represented in the simulation by the last pulse and the pulse between two existing craters. Such geometries do not occur when structuring in a sequential fashion. Higher temperatures reached in such scenarios, as can be seen on graph in Fig. 11, lead to a more efficient ablation process, with a greater ratio of vaporized versus molten material. Residual molten material resolidified around the copper structures can be seen on Fig. 6 and Fig. 7.

5. Conclusion

Combining tight laser beam focusing and a green nanosecond pulsed laser at 532 nm creates a powerful tool for precise copper microstructuring. Due to tight focusing the heat affected volume is localized in all three dimensions, reducing heat damage both to the substrate and the unstructured copper.

Random pulse positioning uses the advantages of tight focusing to precisely structure the copper layer with the least heat dissipated. Gradually removing copper in a layer-by-layer fashion results in well-defined features with steep walls and high aspect ratios.

Efficient microstructuring of copper layer on soft, flexible and heat susceptible materials is not always possible. The substrate material must at least survive the brief contact with molten copper debris. Minimizing the temporal and total heat distributed gives both tight focusing and random approach an advantage over other approaches.

Experimental results indicate that acousto-optic deflectors offer an important combination of a unique ability to independently choose a position for each laser pulse while keeping a high positioning speed and accuracy. Successful reproduction of copper microstructures on heat susceptible substrates with feature sizes in the range of single micrometers requires advanced pulse positioning algorithms that can be more efficiently realized with AODs compared to standard scanning techniques.

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