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Fabrication of Thermoformable Circuits by Laser Patterning of Metallized Thermoplastic Foils

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Abstract

High-resolution laser patterning offers innovative methods for the manufacturing of three-dimensional interconnect devices. The process chain presented in this paper uses cost efficient metal thin-films sputtered on thermoplastic sheets and two-dimensional high speed laser-processing, whereas the three-dimensional shape of the end product is realized by deep drawing of the machined sheet. Due to the lower fracture strain of metals in comparison to thermoplastics extensive fragmentation of the deposited metal film occurs during deep drawing; therefore picosecond laser fine structuring is used to provide strain relief in the circuitry and to preserve the conductivity after the drawing process.

Keywords: ps-laser, thermoplastic, metal thin-film, MID, molded interconnect devices

1. Introduction

Molded interconnect devices (MID) have a growing importance [1] in many industries today such as automotive, medicine, and telecommunications. Although printed circuit boards are usually more cost efficient to produce than MIDs, the striking technological advantages of MIDs are for example (i) room efficiency by integration of the interconnect device into a unit's casing, (ii) precise three-dimensional mounting of electronic components like an assembly of several sensor components at precise positions not only in x-y but also in all six degrees of motion, (iii) less parts count. Highly integrated systems also enable the production of further distributed systems by individually combining sensoral and logical components that can communicate via bus systems.
Depending on the application and lot size several production methods are established in the industry. Examples are back injection molding, hot embossing, two-shot injection-molding, and

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LPKF-Laser Direct Structuring (LDS)[2], of which the last two use metal seeds in polymers to initiate electroless plating. The LDS method was awarded the ”Hermes Award 2010”[3, 4] for successfuly transferring the basic idea into serial production and highlighting the importance of MIDs for the industry.

In this paper a novel production method is proposed that shifts as many production steps as possible from a three-dimensional into a two-dimensional environment, where masked plasma vapor deposition (PVD) of metal as well as laser structuring can be applied at very high speed. Working with thermoplast sheets allows for an integration of the initial production steps into a roll-to-roll process, additionally a deep drawn metallization can significantly increase the total process efficiency since high growth rate electro plating is applicable. This way the wanted conductor cross sectional area can be achieved much quicker than with the usual methods.

2. Process Chain

Figure 1: Deep drawn polystyrene sheet. The substrate is metallized and laser fine structured.

The proposed process chain consists of four stages (in chronological order):

1. Initial PVD metal deposition:
   The thermoplast sheet is selectively coated with a layer of metal that coarsely depicts the design layout of the interconnect device.
2. Laser fine structuring:
   The circuitry layout is cut into the predefined metal thin-film where surplus material is removed and a micro-structure is applied to the conducting strands to divert stress during deep drawing.
3. Deep drawing:
   The prepared sheet is heated and drawn to a three-dimensional form.
4. Metal plating:
   Metal is added to the circuitry to obtain an adequate conductance level that suits the needs of the end-product.

First, the process chain will be explained without step 3. Afterwards the relevancy of laser structuring for the whole method is highlighted. The manufacturing process is demonstrated by means of three the example substrate materials of industrial grade polycarbonate (PC), polystyrene (PS), and acrylonitrile butadiene styrene (ABS).

Initial Metal Deposition

The proposed process chain commences with metal deposition where a thermoplastic sheet is metal coated to generate a coarse layout of the final circuitry. The metal thin-film consists of a 50 nm chrome layer for improved adhesion followed by an initial metallization of 1 μm copper. Three basic principles of sputtering are tested for metal-coating: DC-Diode sputtering, gas flow sputtering, and Magnetron sputtering, of which the last one seems to be the most promising for this approach, which therefore is used for the following experiments.

Deep Drawing

The pre-metallized foil undergoes deep drawing to reach its three-dimensional end-shape. This is a demanding procedure for the material compound, for the metal-thermoplast bond is affected by both thermal and mechanical stresses. Figures 3 and 8 show a metal thin-film of 1μm thickness that was deep drawn without preceding laser treatment. The observed metal sample cracks with an average width of 10 μm. Obviously, a damage like this prohibits the conductivity of the metallization.

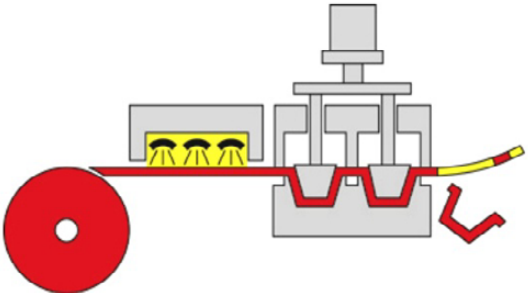

Figure 2: Principle of deep drawing: The plastic sheet is heated an then pressed into a negative form. (Image by Illig Maschinenbau GmbH)

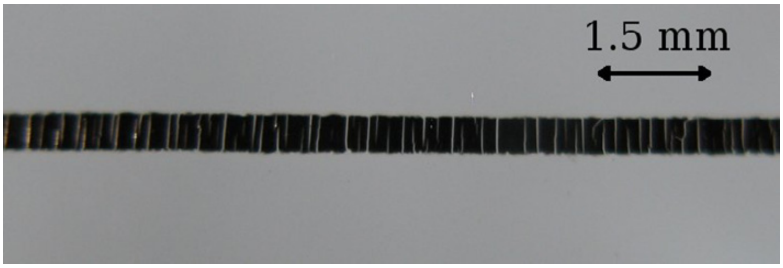

Figure 3: Deep drawn metal thin-film without laser treatment on PC substrate. Thickness 1 μm, width 0.5 mm.

Thinner films (50 nm) are reported [6] to withstand a stretching movement and to possibly remain conductive afterwards; however the conductor cross sectional area is too small to withstand a current that is sufficient for electro-plating.

Metal Plating

The final process step deals with circuitry plating to increase metal thin-film thickness to a level that is sufficiently rated for the needed electrical power. In principle, two processes are possible to accomplish this task. The first is electroless plating; the second is electro-plating. The advantage of the electroless approach is the fact that the initial metallization does not have to be conductive over the whole structure and that small cracks in the material can be annealed during the deposition process. Electro-plating, however, needs a fully conductive circuitry, making a post process step necessary for cutting obsolete metal bridges.

The main disadvantage of electroless plating is a lower deposition rate. It is furthermore susceptible to failure at low substrate surface roughness and if sputtering induced surface imperfections are present in the thin-film. During deposition the electrolyte will infiltrate into the metal surface, if cracks or pinholes are present. Gas bubbles form in these imperfections and can tear off the thin-film from the thermoplastic substrate.

Laser Fine Structuring

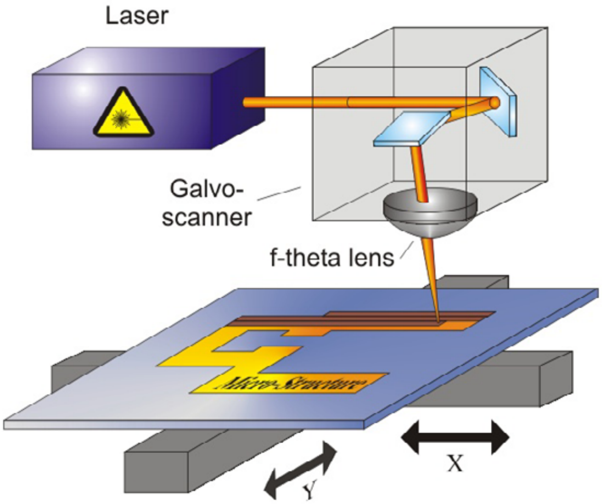

Figure 4: Scanner system as used in the depicted experiments.

As shown in Figure 3 sputtering the circuitry alone is not sufficient for the production of deep drawn electronics. Continuous cracking leads to an interruption of the conducting path that can not be fixed by further post processing.

The lower fracture strain of the metal in comparison to thermoplastics demands a stress relief in the thin-film. The aim is to transform a part of the tensile stress into shear stress; thus lowering the overall stress to a point where the metal thin-film stays intact even after heating and deep-drawing.

Former approaches have been pursued [7] to produce formable electronics on non-rigid materials. However, since thermoplastic substrates are too stiff for the needed movements out of plane during thermo forming a less complex structure has to be used as was proposed in [8, 9]. Other approaches introduce more complex material combinations[12, 13]. An intuitive approach is the cutting of a meander structure into the circuitry to convert the movement from purely translational into a mixture of translational and rotational.

2.1. Setup

A picosecond laser is used for cutting the structure into the metal-film. The used wavelength is 532 nm with a pulse-length is 12 ps. The beam is focussed in a laser-scanner system (Fig. 4) using an f-theta-lens with a focal length of 100 mm to a laser spot-size of <25 µm. An additional x-y-stage can be used to work with big workpieces as well as to simulate roll-to-roll manufacturing.

Fine cuts and wide area ablation are so far both conducted with a laser scan speed of 400 $\frac{mm}{s}$ where the pulse repetition rate is 100 kHz with an average power of 400 mW. This results in a pulse overlap of 68%. Hatched lines overlap at the same magnitude.

2.2. Cutting patterns

Within the scope of this investigation meander spacings of 40, 60, 100, and 200 µm are produced (Figure 5). Both ABS and PS are laser ablated by hatching for removal of surplus material and line scanning for cutting the micro meander structure.

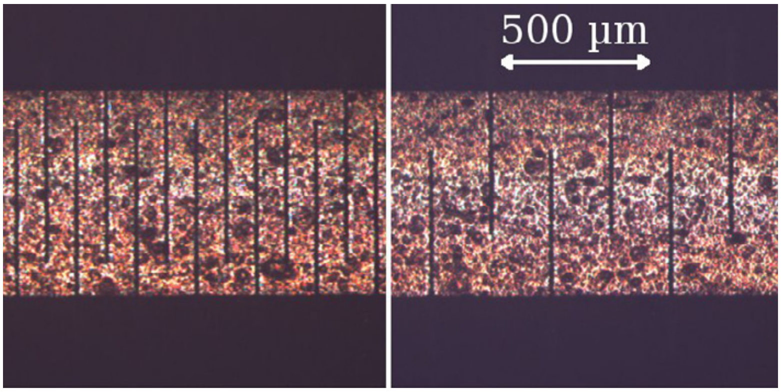

Figure 5: Meander cut into the metal thin-film, substrate is ABS (black), the meander spacings are, left 100 µm, right 200 µm.

Due to instable bonding between substrate and metal on PC an alternation of the ablation process is neccessary. As depicted in Figure 6 simple hatching on the metal thin-film leads to a delamination of the top layer. Consequently, the delaminated metal starts to curl up into flakes shadowing the incoming laser beam and inhibiting the proper irradiation of the then focussed point.

This way a reliable removal of metal cannot be ensured. Due to the small area of the shadowed zone its adhesion is very low and the metal is prone to ablation during the metal-plating stage. This is an operational risk during the chemical process since ablated metal flakes can block filters and can damage fluid-mechanical components.

The solution to that problem is the application of a cut overlay-structure prior to hatching over the metallized areas to be ablated. Figure 8 shows the remainder of the cuts in the substrate

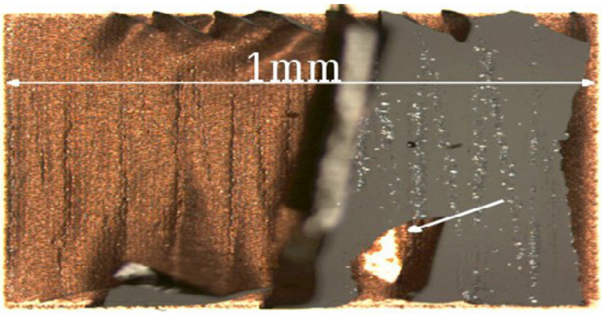

Figure 6: Delaminated copper film on polycarbonate surrounded by untreated copper. Blurred: Rolled up copper. Marked by an arrow: Area that was shadowed by the curled up copper flake.

material in the shape of a checkered pattern bordering the meander. By structuring this way the copper film starts to delaminate as expected but the delamination stops at the next cut and the flake is blown off before winding up far enough to shadow any material to be treated afterwards.

2.3. *Deep drawn structured metal thin-films*

After deep-drawing the PS substrate the meander appears deformed depending on the width of the conductive path. As seen in Figure 7 smaller widths seem to be more stable regarding longitudinal strain. All structures show an angular deformation as expected. The 40 µm meander (Figure 7, left) shows an interesting behavior: Here a transversal movement of the substrate is added to the expected longitudinal movement. The thickness of the 40 µm structure is too low to withstand the transversal movement and the conducting path is interrupted

Due to surface roughness ($R_a = 1$ µm) non-visible cracks seem to occur that deny the flow of a notable current even if the conducting path optically appears unharmed. But this material combination can be electrolessly plated and during this process the aforementioned cracks are filled with deposited metal and become conductive again. This refilling works with meander sizes of 60 µm.

Figure 7: Deep drawn metal thin-film with meander cut. Substrate is PS. Meander spacing: left: 40 µm, middle: 60 µm, right: 200 µm

ABS shows a similar behaviour as PS but here even the structures with 40 µm appear intact when optically inspected. The conductor is interrupted as well, but like PS, ABS is electroless-plateable. Therefore small cracks can be filled.

The meander on PC show less angular movement than on PS; nevertheless structures with a 40 µm spacing remain conductive after the deep-drawing process (figure 8). Microscopically a

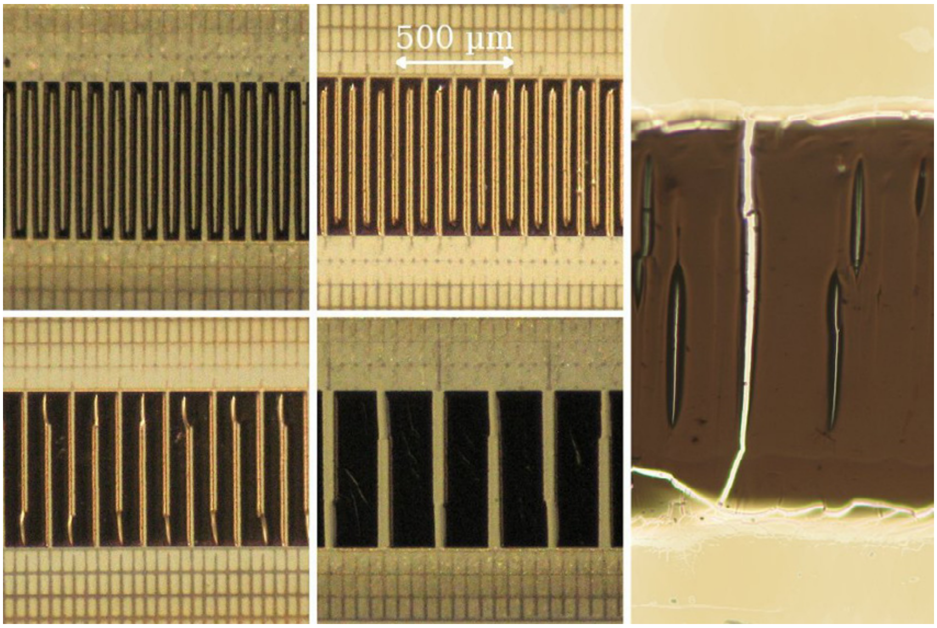

Figure 8: Left: Deep drawn meander structures on PC-substrate. Meander spacings top row: 40, 60 µm bottom row: 100, 200 µm. Surrounding checkered overlay structure visible on the substrate. Right: An untreated metal film that was deep drawn.

contraction of the thin-film can be observed starting from the pivot point of the structure (Figure 9). This contraction concurs with [10] and [11], e.g. the film is not ruptured immediately but is starting to thin and loses integrity along a beginning crack. The effect is the more prominent the wider the structure width is. On the right of figure 8 an outtake of figure 3 is shown for comparison of the cracking behaviour of treated and untreated metal films.

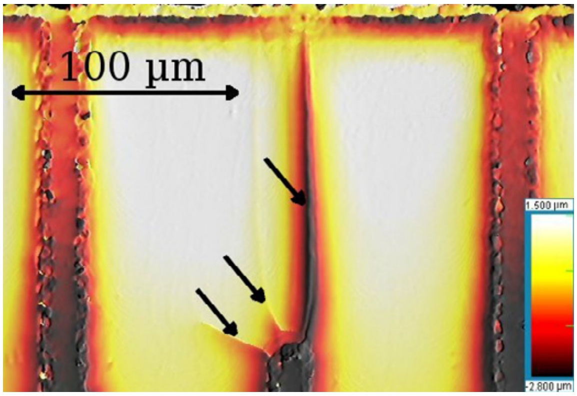

Figure 9: Confocal image of a deep drawn meander structure on PC. Arrows indicate two starting and one complete crack through the metal film.

Electroless plating is not possible due to the low surface roughness of the PC substrate

(R_a=43 nm) that promotes infiltration of electrolytes. In comparison the roughness of PS (R_a=1037 nm) and ABS (R_a=738 nm). But due to the overall conductivity of the 40 µm structure electroplating is possible as a post processing step. This way another possible parameter set is found.

3. Conclusion

We have shown that it is possible to thermo form electrical condutors on several thermoplastic substrates to a certain extent, and that laser micro structuring was an essential part of the preparation for deep drawing. Certain obstacles during the process were shown and solutions ware presented. We demonstrated that some deep-drawn structures are plateable and therefore have the potential for being used as interconnect devices.

4. Outlook

After the successful demonstration of the ability to produce thermoformable metallization on thermoplastics the process will be refined to improve the circuitry reliability by adding more redundancy, reduce the notch effect, as well as to explore new cutting patterns which will enable stretching movements in arbitrary directions to the circuit path.

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- Enthone GmbH
- LLT Applikation GmbH

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