# Shadow masks as an alternative method to lithography for the structuring of thin film layers on LTCC substrates

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## Abstract
The combination of low temperature cofired ceramic multilayer technology with thin film deposition methods enables new functional principles by expanding the available portfolio of materials. Low-stress integration of micromechanical chips can be achieved, for example, by using reactive multilayers as local heat sources, which can be deposited directly onto the ceramics. Shadow masks are ideal for structuring these multilayers. The technology has the advantage that the layers are patterned without the use of etching chemicals and no residues of masking layers or photoresist remain on the non-coated areas. Flexible polyimide used to cover the non-coated areas can adapt to the surface unevenness of the ceramic. The polymer has excellent temperature stability and is compatible with vacuum coating processes. It is available in various thickness gradations and can be easily structured by laser cutting. The accuracy of the mask fabrication by means of laser cut is studied in this work. Structures with a line width of 30 µm can be precisely cut into 75 µm thick polyimide foils. Mask and chip are mechanically aligned, thus a positioning accuracy of 70 µm and better when using the outer edge of mask and chip for alignment is achievable. Major influences of the laser process on the precision of the mask and the resulting transfer fidelity to the ceramic surface are discussed. The method is suitable for reliably reproducing layers with structure sizes from 30 µm with a pitch of 150 µm.

## Key words
Thin film technology; low temperature co-fired ceramics; physical vapor deposition; shadow mask; polyimide

## I. Introduction
The use of shadow masks brings some evident advantages in comparison with classical lithography applied on photoresist. The method can use low-cost materials like polymers [1, 2] or even paper [3] to cover areas in physical evaporation processes (PVD) and protect them from being coated. Therefore, they represent an alternative patterning option for thin film materials on different substrates. However, the alignment of shadow masks is a crucial limit for their use. Recently, it has been shown that the mechanical alignment of mask stacks enables the realization of perovskite solar cells in which the overlapping electrode area is a key functional feature [4].
A major advantage of using shadow masks is that the surface of the substrate to be processed does not come into contact with a photoresist and therefore no residues can remain, which could reduce adhesion, for example. Neither the exposure to chemicals nor temperature treatment is required for structuring. This makes the method interesting for the use in combination with highly sensitive materials, such as 2D materials [1, 5, 6] on various substrates.
Another advantage of using shadow masks arises when materials need to be structured that are difficult to etch, e.g. because of limited selectivity to typical masking materials or high layer thickness that would result in high underetching. The first is the case when reactive multilayers have to be selectively deposited on joining partners. Such layers are used as local heat sources, e.g. for the low-stress assembly of mechanically sensible chips or materials with high mismatch of thermal coefficient of expansion. The necessary layer thickness here is up to 10 µm. Multilayer stacks of aluminum and nickel as an available layer system can neither be etched

wet-chemically nor dry-chemically in one process. The required positional accuracy for the use of the same as local heat sources to melt the solder on assembly pads on ceramic packages is approx. 100 µm. Low temperature cofired ceramics (LTCC) is a class of frequently used material for different types of packages and PVD layers can directly be deposited on their surface. Structured multilayer stacks of alternating aluminum and nickel multilayer that are directly deposited on a LTCC package can serve as local heat source and could be structured by a shadow mask. However, the unevenness of the substrate must be compensated to achieve a high fidelity of the masked pattern. Therefore, the use of laser-structured polyimide films for this application is investigated in this work. The flexible material can level surface deviations, is temperature stable up to 200°C and compatible with PVD processing. Position tolerance and structure limits are evaluated, and influences on the fidelity and accuracy of the deposited structures are discussed.

## II. Experimental

### *A. Design and setup*

An aluminum holder carries the LTCC chips and the masks. It consists of two parts. Pockets with a nominal dimension of 14 mm are milled into the lower part. The mask and the chip are inserted into these pockets with a defined gap. LTCC chips with different nominal thicknesses can be used, the difference in the whole stack thickness is compensated with spacers. Laser-cut polyimide foils with different thicknesses are used for this purpose. The upper part of the holder fits into the pocket with sufficient clearance and clamps the mask and chip to fix the position. The outer edge of mask and chip defines the relative position between the same. The chips are sawed with a dicing saw (ADT Vectus) and the masks with a thickness of 75 µm are laser cut by means of a picosecond laser (microSTRUCT™, 3D-Micromac). The mask material is Kapton® (DuPont de Nemours, Willmington/DE, USA).

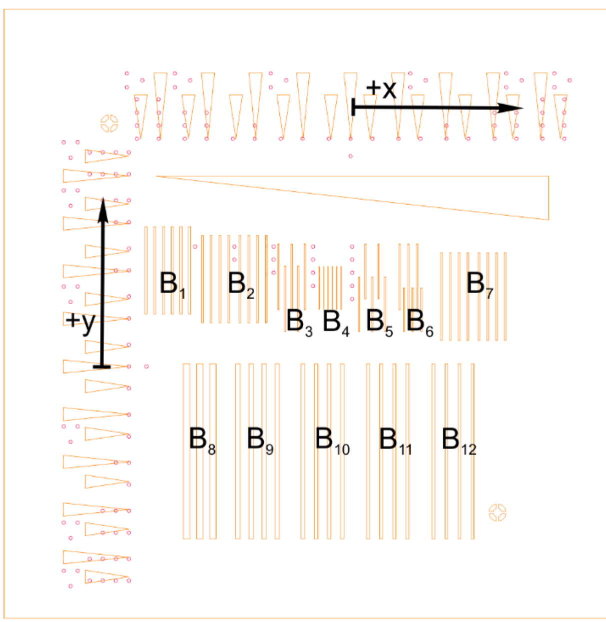


*Figure 1: Test layout with Vernier scale and resolution pattern (lines and spaces). Lines, spaces and overlapping length of the space area vary. The sizes are summarized in Table 1.*

*Table 1: Test feature dimensions in µm*

| Block | Line | Space | Pitch | Overlap |
|---|---|---|---|---|
| B1 | 50 | 150 | 200 | 2000 |
| B2 | 40 | 160 | 200 | 2000 |
| B3 | 30 | 120 | 150 | 1000 |
| B4 | 10 | 90 | 100 | 1000 |
| B5 | 30 | 120 | 150 | 500 |
| B6 | 30 | 70 | 100 | 500 |
| B7 | 40 | 160 | 200 | 4000 |
| B8 | 150 | 150 | 300 | 4000 |
| B9 | 100 | 200 | 300 | 4000 |
| B10 | 80 | 220 | 300 | 4000 |
| B11 | 70 | 230 | 300 | 4000 |
| B12 | 60 | 240 | 300 | 4000 |

Figure 1 depicts the used test layout of the polyimide mask. A Vernier scale allows an accurate reading of the relative position between the via pattern as position marks on the ceramic chip and evaporated wedges in the mask with an accuracy of 10 µm. Test structures with varying line width and pitch are arranged in 12 blocks. Additionally, circular alignment control structures are situated on two edges and a wedge structure allows the estimation of the possible resolution. The design dimensions of the mask are summarized in Table 1.

The overlapping length of different test features varies too. The smallest overlap is 500 µm and the largest 4000 µm.

### *B. Chip and mask preparation*

The LTCC chips are sawed in squares with a nominal value of 13.9 mm. This size was determined by sawing test chips with a graduation of 50 µm. Chips with an edge length of 13.95 mm could not be fitted into the pocket, therefore the measure for the edge length is defined to be 13.9 mm. The reference point for the saw cut is located in the center of the LTCC chip.

The used power for the laser cut of the polyimide mask with a thickness of 75 µm amounts to 3.5 W. The number of cut turns vary for the inner test patterns and the outer frame. When cutting the outline, a total number of 20 turns is sufficient to separate the piece fully, while the finer, inner features require 35 turns. Due to the conical shape of the edge, the line width differs from the design value. Table 2 lists the deviation of the different mask features according to

*Table 2: Mask tolerances, the given deviation amounts to the difference between design value and measured value.*

| Deviation from line width [µm] | | | Deviation from space width [µm] | | |
|---|---|---|---|---|---|
| Pitch 100 µm | Pitch 150 µm | Pitch 200 µm | Pitch 100 µm | Pitch 150 µm | Pitch 200 µm |
| -22.17 ± 2.1 | -23.25 ± 1.6 | -25.1 ± 2.1 | 22.75 ± 2.8 | 23.5 ± 1.8 | 25.1 ± 1.9 |

the related pitch. The measurement was performed on a measuring microscope (VMSergo, Walter UHL GmbH) after deposition in transmitted light mode with 5:1 objective lens.

Figure 2 depicts the measures of the outlines of the different structures. The nominal value of the milled pocket is 14 mm, the median of the real measured dimensions amounts to 13.98 mm. Mean and median of mask and chip are approximately 50 µm smaller than the pocket dimensions. The position of the tolerance fields guarantees that every structure fits in each pocket.

## III. Results and discussion

### A. Position tolerance

The resulting position tolerance is obtained by chaining up the position tolerances of the structures in the polyimide mask and on the LTCC chips with their respective outer edge. The alignment of chip and mask to each other in the milled pocket is done randomly by centering along the outer edges. The highest position mismatch can occur if the clearance between the outline and the pocket for both, mask and chip is maximal. Figure 3 depicts the evaluated position tolerances, distinguishing between x and y direction. The results of the statistical evaluation are given in Table 3. A tendency towards negative values in both, x and y direction is evident.

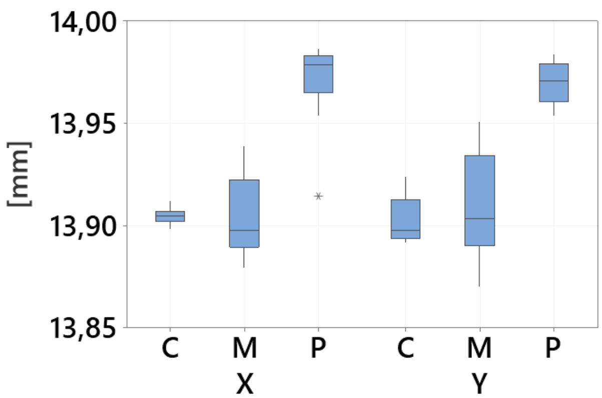


*Figure 2: Tolerances of chip, mask and pocket in the holder in X and Y direction; C = Chip dimension, M = mask dimension, P = pocket dimension.*

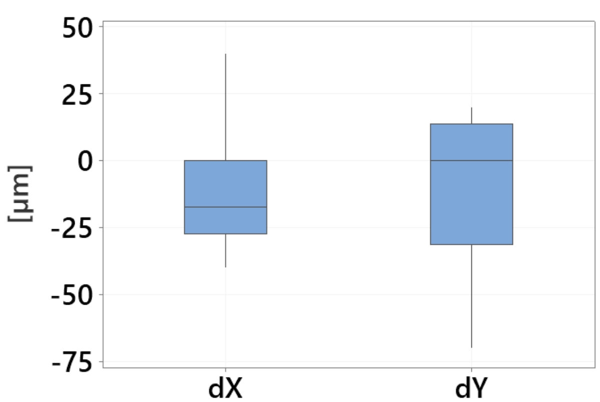


*Figure 3: Position tolerance evaluated by the Vernier scale, the statistical values are summarized in Table 3.*

*Table 3: Statistical characteristics of the position tolerance.*

| | Mean | Min | Q1 | Median | Q3 | Max |
|---|---|---|---|---|---|---|
| dX | -10,42 | -40,00 | -27,50 | -17,50 | 0,00 | 40,00 |
| dY | -8,75 | -70,00 | -31,25 | 0,00 | 13,75 | 20,00 |

When comparing the values for chip, mask, and position in the x and y directions, it is noticeable that the values in the y direction have a greater deviation than in the x direction. The effect is particularly obvious in the case of the masks. An initially suspected influence of the measuring direction of the microscope could not be confirmed. Presumably, the differences can be explained by the positioning stages and their higher repeatability in the respective machining direction.

### B. Mask and structure deviation

The deposition is carried out in the e-beam station of a PVD cluster (CS 400, von Ardenne GmbH). A layer sequence of 50 nm Ti as adhesion promoter and 300 nm of copper is deposited. Figure 4 depicts the mask and the evaporated layer on the LTCC substrate.

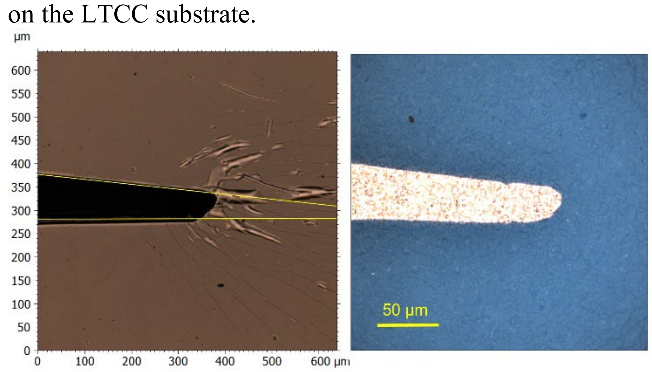


*Figure 4: Mask after evaporation (left) and resulting PVD structure on LTCC (rigth).*

On the left picture in Figure 4 showing the mask, the designed structure is marked as a yellow line. The radius of the mask opening amounts to 36 µm. The smallest evaporated structure is 30 µm, approximately. Both radii on the mask and the metal structure are not symmetrical, indicating that the laser beam is not uniform. Figure 5 shows the circular alignment structures. The deformation of the circular shape is clearly visible.

Figure 6 depicts the box plots of the structure deviation for lines and spaces. The lines are smaller than the design value and the spaces larger. The mean deviation of lines is -12.3 µm and of the spaces is 17.5 µm. Comparing these measures with the mask dimensions shows that the absolute value of the overall deviations of both, line structures and spaces, are smaller. The effect may be due to the fact that the edges appear wider when measuring the mask in transmitted light due to overshadowing. The standard error of the

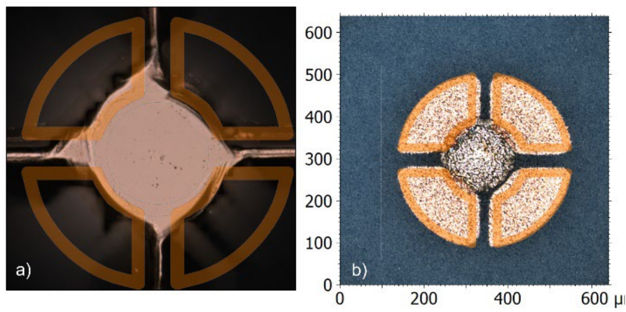


*Figure 5: Adjustment mark on mask (left) and after deposition (right). The via serves as orientation. Orange line marks the designed CAD feature.*

metallization is larger compared to the mask. This is attributed to the deformation of fine structures caused by thermal stress during laser cutting, which leads to the fact that the ridges do not touch the chip surface and the projected shadow becomes narrower.

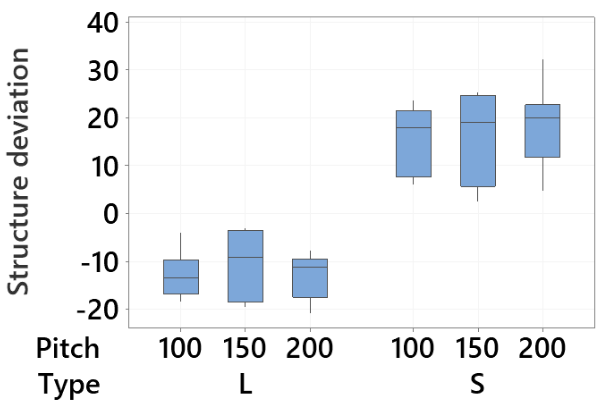


*Figure 6: Deviation of lines and spaces of the metal structures from the design value in µm.*

## IV. Conclusion

When using laser-cut polyimide as a shadow mask, objects with minimum dimensions of 30 µm lines and 120 µm spaces can be produced. Deviations between realized line width and design value result from the conical shape of the laser cut and the non-uniform cut shape.

The non-uniform cut shape is further the suspected cause for a systematic shift of the structures towards negative values in x and y direction. Despite of these influences, required position tolerance of 100 µm can be ensured by the use of flexible polyimide masks and a laser process.

For the further compensation of this offset, it is recommended to move the frame structure by the corresponding value relative to the functional structure of the mask in the design, compensating the fabrication influence. Hence the position accuracy can be further improved by design measures. The influence of the projection of deformed structures due to thermal stress during lasering contributes significantly to the structure deviation and limits the minimum structure spacing. A lower pitch can therefore only be achieved when using mask materials that do not distort during machining. Sheet steel or other metals are therefore investigated in future works.

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