High-performance structures with photo-imageable pastes for mmWave applications

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Abstract

Developments in the field of mobile communication (5G, 6G), (autonomous) mobility and the Internet of Things (smart cities, wearables, object tracking, smart grids, video security) are highly topical in the world wide research and industrial landscape. For this purpose, ever higher transmission bandwidths and thus ever higher working frequencies >60 GHz are required. To be able to exploit this potential, new technologies are required to generate high-frequency circuits with which ever finer conductor tracks with ever narrower distances in the range of 10-30 µm each can be realized. For this purpose, thick-film pastes were developed at Fraunhofer IKTS, which can be photo-imaged using UV light and can enable the desired geometric resolutions. The present work is intended to give an overview of the current developments in photo-imageable (PI) pastes at Fraunhofer IKTS and should give a comparison of the PI technologies. On the one hand side the masked based PI process, which is suitable for mass production and on the other hand side, the laser direct imaging (LDI) process, which offers the possibility of prototype manufacturing.

Key words

Laser Direct Imageing, LTCC, mmWave, Photo-imageable paste, Thick film pastes.

I. Introduction

The entry into the age of 'big data' is driving new applications in the areas of mobile communication (5G, 6G), (autonomous) mobility and the Internet of Things (smart cities, wearables, object tracking, smart grids, video security). These require ever higher transmission bandwidths with low latencies, which results in ever higher operating frequencies, in some cases >100 GHz. This increasingly higher operating frequencies require signal transmission lines with increased structure resolution and, due to increasing transmission losses, high geometric quality, and production reproducibility.

Due to particularly favorable dielectric properties, reliability and suitable technological features (e.g., functional 3D integration), the ceramic LTCC (Low Temperature Co-fired Ceramics) technology is already frequently used for the manufacturing of reliable and high-performance high-frequency assemblies. The screen printing technology previously used in LTCC technology for the deposition and structuring of functional thick films can no longer meet these requirements for high-frequency components. For example, structural resolutions in industrial applications reached 75 µm (line/space) with limited geometry quality [1]. So, high-performance technologies are needed to produce geometrically high-resolution structures for next generation of high-frequency circuits [2-4]. For this the Fraunhofer IKTS has developed since 2019 thick-film pastes that are photo-imageable (PI) using UV light [5]. This technology allows structural geometries less than 20 µm line-space with a very high accuracy of the edge sharpness [6]. This paper is intended to provide an overview of the latest developments.

II. Experiments

Photo-imageable process

The PI technology is based on a UV-curable binder system in which the functional paste components (metals, alloys, oxides, glasses, additives) are mixed. The pastes produced in this way are applied to substrates using screen printing. For better understanding, the photo-imageable process is pictured in Fig. 1. The required functional elements are then created by UV exposure, i.e. selective curing of the photosensitive binder. The exposure can be carried out using photomasks or by direct writing using a UV laser. Areas that have not been exposed are then removed using spray development. In the final sintering step, all polymer components are burned out and a dense and pore-free functional layer is created.

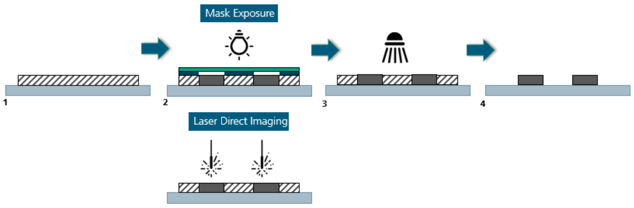

Fig. 1: Structuring using photo-imageable pastes: Illustration of the exposure and development process. 1: Layer after screen printing. 2. Exposure by means of UV light. 3. Development by means of an aqueous solution. 4. Developed structures.

Compared to the conventional thick-film technology, only two additional steps (exposure and development) are required for structuring after screen printing, which needs between 5 and 20 seconds each and can be easily integrated into established production process lines. The main benefit is next to the small line resolutions, that no yellow room is necessary with the current developed pastes.

Materials and Paste preparation

For manufacturing a functional layer, inorganic components, like metals, glass, additives were mixed together with an organic binder, which consists of a polymer and a solvent, to a suspension and then print, dry and fired on a substrate. For standard fineline pastes (Fig. 2a) these are the typical 4 to 5 ingredients. In contrast, the photo-imageable pastes (Fig. 2b) are much more complex and plasticizers, antioxidants and photoinitiators are also added, so that in total 15 to 20 ingredients are in PI pastes. This fact makes paste development significantly more difficult than with standard thick-film pastes.

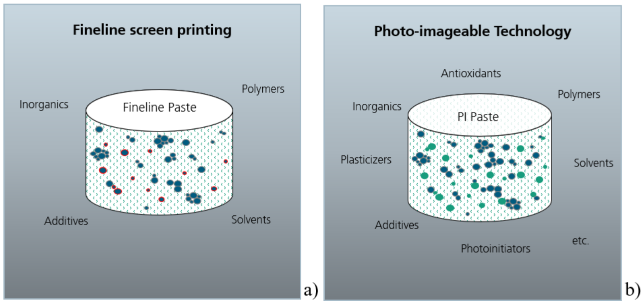

Fig. 2: Comparison of the paste ingredients of a) Fineline screen printing pastes versus b) Photo-imageable pastes.

In recent years, Fraunhofer IKTS has successfully developed organic base binder systems for the PI technology presented, which have been used to produce photo-imageable pastes based on silver (Ag), gold (Au), platinum (Pt), copper (Cu), ruthenium dioxide (RuO_2) and glass / dielectrics. Fig. 3 shows the current PI paste portfolio processed by mask-based technology (365 nm wavelength), as well as the possible specific applications.

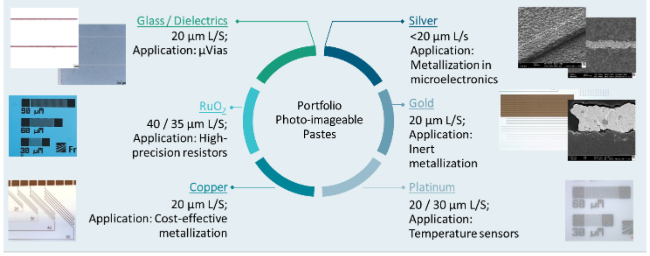

Fig. 3: Portfolio Photo-imageable pastes (UV mask technology, λ=365 nm).

Using PI silver pastes as an example, the manufacturing process will be briefly described and the results between fineline screen printing, PI mask process and PI LDI process will be compared in chapter III. First of all, the organic vehicle, which includes polymer, solvents, antioxidants and organic additives were heated up in an oven at 65 °C for 10 minutes and directly mixed in a SpeedMixer^{TM} (DAC 150 FVZ Hauschild & Co. KG) for homogenization.

Afterwards the inorganic powders (silver, glass, inorganic additives) were also mixed together in a Speedmixer for 30 seconds. The organic and inorganic mixtures were then transferred into each other and mixed together with the photoinitiator. The pre-dispersed suspension was finally homogenized using a three-roll mill (EXAKT 120E). Nearly all photo-imageable pastes will be formulated by this method, also for the fineline paste the same procedure is done with less ingredients.

Test layouts and Characterization

The fineline paste was printed on ceramic substrates (52x52 mm²) using a semi-automatic screen printer (M2H, EKRA GmbH) and characterized in terms of their printing behavior. The characterization layout, the so-called Siemens star, is shown in Fig. 4a. The structure of the Siemens star enables to determine the printing resolution by optical evaluation. The test pattern consists of a circle with 30 printed circular sectors whose line widths reduce from the edge to the center from 150 µm to 13 µm.

For the PI pastes a full area layout was printed on ceramic substrates and afterwards the dried layer was exposed via mask (HIBRIDAS) or LDI exposure (µMLA, Heidelberg Instruments Mikrotechnik GmbH). For this the layout shown in Fig. 4b was used, where a variation of line width and spaces were tested between 10 µm and 50 µm. Also meander structures with line widths of 30 µm, 60 µm and 90 µm are included as well as a Siemens star with 150 sectors of lines between 105 µm and 4 µm.

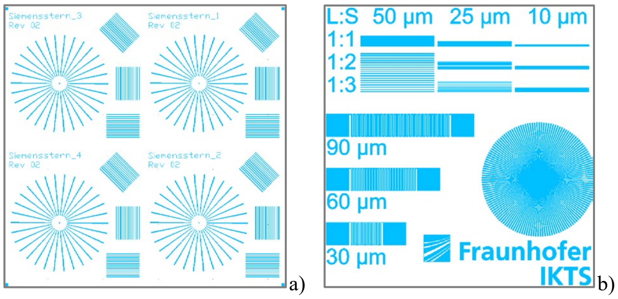

Fig. 4: Layouts of a) Fineline screen printing pattern (Siemens star) and b) photo-imageable exposure layout (conductor lines, Siemens star).

The following characterization methods were carried out to give an overview about the possibilities of PI pastes and the advantages regarding standard screen printing technology.

- Microscopic examinations (light / FESEM) for geometric and structural evaluations,
- Electrical (resistance measurements) and
- Mechanical characterizations (wire-peel test).

III. Results and Discussion

A. Fineline Printing versus Photo-imageable Process

Fig. 5 shows a comparison of the surface topography of silver transmission lines on alumina substrates on the one hand side printed by fineline pastes (Fig. 5a) and on the other hand side using photo-imageable pastes, which were mask exposed (Fig. 5b). Compared to conventionally printed conductor lines, which has a very uneven surface in case of screen printing effects, the realized cross-sections and the surface of the transmission lines of the PI pastes have an almost even and rectangular shape, which is essential for high-frequency applications.

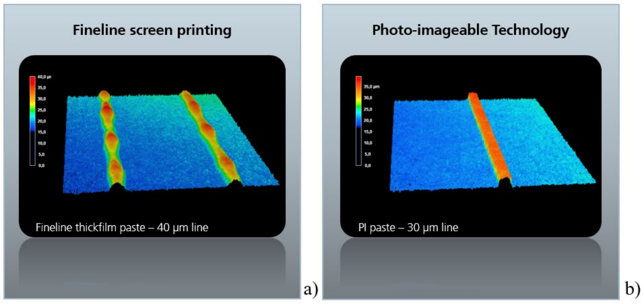

Fig. 5: Comparison of the surface topography in the top view of silver transmission lines, enlarged 20 times, produced using a) fineline screen printing (line width: 40 µm) and b) PI technology, mask process (line width: 30 µm).

Table 1 summarizes an overview of the properties of the used silver PI paste for Al$_2$O$_3$ substrates with regard to geometric resolution, electrical conductivity, adhesion and viscosity properties. Outstanding is the line/space ratio of 20/20 µm with a sintered layer thickness in the range of 8-12 µm, which is also very important for high-frequency applications. Also, adhesion and solder properties are comparable to standard thickfilm silver metallizations.

Table I: Overview of the silver PI paste properties for Al$_2$O$_3$.

Characteristics	Unit	Value
Viscosity[1]	Pa·s	40…90
Sheet resistivity[2, 3]	mOhm/Sq	≤ 3.5
Fired film thickness[3]	µm	8…12
Line Resolution Line/space	µm/µm	20/20
Solder acceptance[3, 4]	%	≥95
Adhesion[5]	N/4 mm^2	≥20

[1] *Rotational viscometer ARG2 with cone/plate combination (2 cm, 2°) at 10 s^{-1} and 22±0.2 °C.*

[2] *Sheet resistivity, calculated for fired thickness of 10±1 µm.*

[3] *Firing profile: total cycle time 60 min, 10 min at 850 °C.*

[4] *Flux: Alpha 611, 220 °C, 5 s dip.*

[5] *90° wire-peel-test according to DIN 41850-2, 2 x 2 mm^2 pads, Sn/Pb/Ag 63/35,5/1,5 solder.*

The results show that there is an enormous increase in geometric resolution when using the PI process compared to fineline screen printing. Considering that only two additional process steps of 5 to 20 seconds more are necessary, which can also be easily integrated into an existing screen printing process, PI paste technology is one of the most promising technologies for high frequency applications in the current research and industrial landscape.

B. High Frequency substrate material

The essential innovative approach of the photo-imageable pastes lies in the possibility of generating high structure resolutions with the necessary surface quality for the cosintering process in LTCC and thus transferring the LTCC technology to mass production for operating frequencies above 100 GHz. The advantages of thin and thick film technology are combined using existing material systems and processes already established in the industry; the pastes and processes are be adapted to commercially available LTCC or other substrate types, which increase the market acceptance. One example for adapting the PI paste to LTCC substrate types is shown in Fig. 6, where a new silver PI paste was exposed and sintered successfully on LTCC GT951.

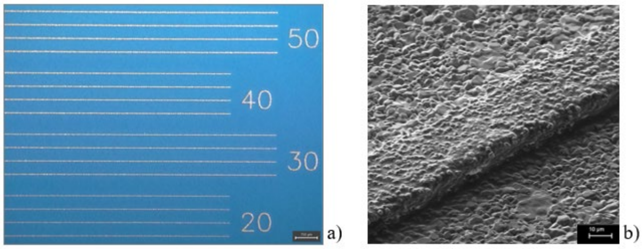

Fig. 6: Silver PI paste on LTCC (GT951), postfiring. a) Light microscopic image, line width: 20 to 50 µm. b) FESEM image, line width 20 µm.

The developed paste enables LTCC build-ups in the post-firing and cofiring process (Fig. 7). For cofiring line widths of less than 20 µm (Fig. 7a) and gap widths of 16 µm (Fig. 7b) were realized in the co-sintered state.

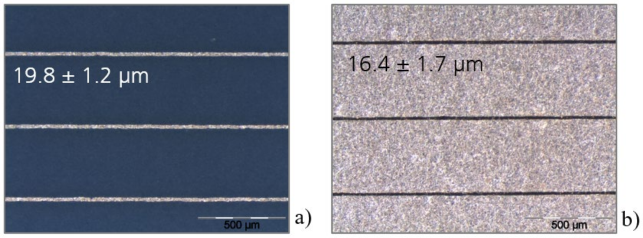

Fig. 7: Silver PI paste on LTCC (GT951), cofired. a) Light microscopic image, line width: < 20 µm. b) Light microscopic image, gap width: < 17 µm.

C. *LDI process*

Initial investigations have also shown that the IKTS-PI pastes are suitable for direct laser exposure. Fig. 8 gives an overview of realized cross-sections of a dried silver PI layer (Fig. 8a) and a sintered layer (Fig. 8b) on Al_2O_3 substrates. It can be seen, that also with LDI a rectangular shape could be achieved. Some washout effects were observed in the dried layer, but these were no longer visible after sintering.

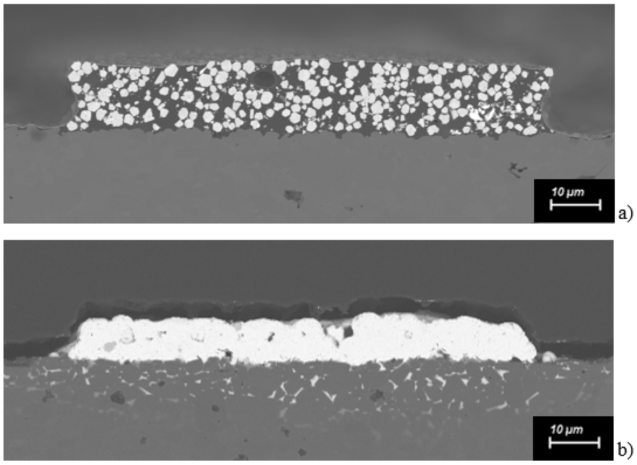

Fig. 8: FESEM images of silver PI pastes exposed with LDI. a) dried 90 µm line, b) sintered 90 µm line.

Currently, the LDI process in post-firing on Al_2O_3 can realize structures of 30 µm line width and spaces (Fig. 9). It can be seen that the exposed and developed LDI layers are within the target range in terms of edge sharpness and structure resolution and form the basis for technology validation in LTCC technology. An important point for the use of LDI in LTCC is the possible spatially resolved shrinkage adjustment. As the LDI process allows a high degree of geometric freedom, it is possible to generate complex-shaped components freely on the substrate and adapt the design almost at will. This is particularly important when sintering LTCC green films, as inhomogeneous, batch-dependent shrinkage can occur across the substrate surface for material-related reasons, which can cause deviations in the millimeter range on a substrate. However, the desired structure sizes of metallization for high-frequency circuits are in the lower micrometer range. Using the LDI process, it is possible to correct shrinkage-related geometric deviations in a spatially resolved manner (shrinkage adjustment). The desired geometric properties are then achieved after sintering.

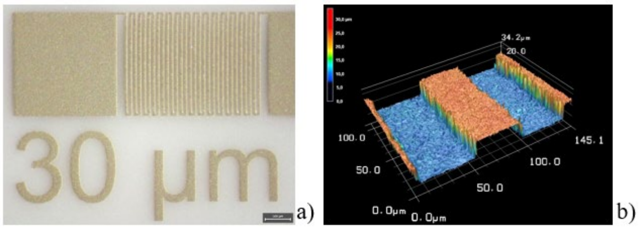

Fig.9: Silver PI pastes exposed with LDI, line width: 30 µm. a) Light microscopic image, b) surface topography image.

For this the LDI silver paste was also tested on LTCC and sintered in cofiring. For this purpose, both PI processes (mask vs. LDI) were compared using test structures for RFID tags. Fig. 10 shows a comparison of the two processes. On the one hand, the results in the dried state, directly after exposure and development (Fig. 10a, 10c), and on the other hand in the sintered state, cofired with LTCC GT951 (Fig. 10b, 10d). No significant differences were found between the two PI processes. Overall, the LDI silver paste shows slight shrinkage problems in the outer layer when cofired with GT951, especially with very small structures. An adjustment of the inorganic composition should provide a solution.

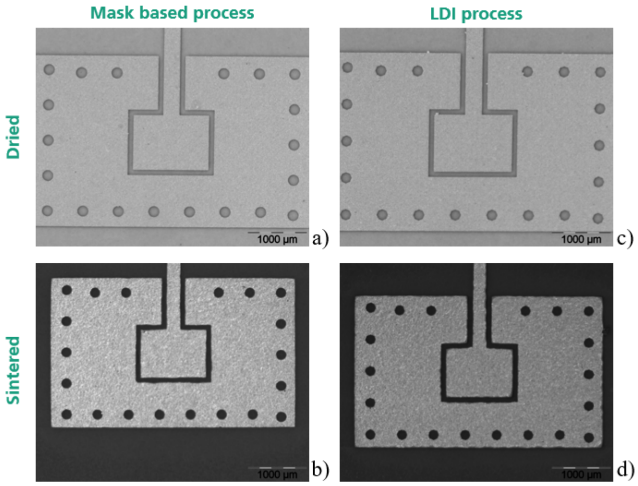

Fig.10: FESEM images of silver PI pastes. a) mask exposed dried state, b) masked exposed sintered state, c) LDI exposed dried state, b) LDI exposed sintered state.

The results show, that the LDI process can also produce high-resolution structures with high edge definition and surface quality, is compatible with the cofiring process and thus offers an alternative to the technologies already in use. This can surpass the state of the art and open up new fields of application that were not accessible due to the aforementioned disadvantages of thick-film technology.

IV. Conclusion

The work presented on the investigation and development of PI pastes shows a promising mass and industrial process with low investment costs and only slightly higher production time, with which components can be manufactured that enable significantly better RF performance at higher frequencies than before and allow significant miniaturization in the future.

References

[1] D. Schwanke et al., Enhancement of Fine Line Print Resolution due to Coating of Screen Fabrics, Journal of Microelectronics and Electronic Packaging, 2009, 6 (1), 13-19.

[2] L. Jiang, Low-loss Materials for 5G and 6G 2023-2033 – Trends, technologies and forecasts, IDTechEx, accessed 22.05.24.

[3] M. Swaminathan, Packaging for mmWave Communications, 2021 iNEMI Tech Topic Series: 5G/mmWave, Available: http://thor.inemi.org/webdownload/2021/Packaging_for_mmWave_Comms.pdf, accessed 22.05.24.

[4] A. Watanabe et. al., A Review of 5G Front-End Systems Package Integration, IEEE-Trans. On Comp. , Vol. 11, No. 1.

[5] K. Reinhardt; Fotostrukturierbare Pasten – Neuste Innovationen in der Fineline-Dickschichttechnik; PLUS 2/2022, Februar 2022, Band 24, p. 217-219, ISSN 1436-7505, B49475.

[6] R. Perrone, Erweiterung des Frequenzbereichs und der Integrationsdichte von LTCC-Modulen mittels Photostrukturierung und Designoptimierung, ISLE Verlag, 2007.