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Aerosol Printing of High Resolution Films for LTCC-Multilayer Components

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Abstract—**For the electronic packaging of sensor stable and cost-efficient fine line printing technologies on LTCC and high frequency laminates are needed. Especially common technologies like screen printing and thin film techniques are unsuitable for fine structures or too expensive. In addition, there is no direct write technology for 3D LTCC designs as well as for high reliability cofiring structures. Closing this gap, aerosol printing technology is used to print high resolution conductors on planar and nonplanar substrates.**

Aerosol printing is a direct write noncontact printing technology of functional layers. After pneumatic atomization, the ink is transformed into 1-5 μm droplets. The resulting continuous aerosol stream is focused by a sheath gas in the printing head. Thus, the long standoff distance between the substrate and the deposition tip of max. 5 mm allows 3D printing on nonplanar substrates. With optimized inks and printing parameters, line widths of 10 μm are achievable. This paper will present applications for aerosol printed functional layers on LTCC. These are, for example, aerosol printed films embedded in cofired LTCC, fine line structures for high frequency applications, and the evaluation of printed 3D structures like LTCC stairways. Furthermore, the 90° contact of unconventional sensor designs will be presented.

Keywords—**3D structures, aerosol printing, LTCC, microsystems**

Introduction

Screen printing has been the dominant technology for the deposition of functional films required in ceramic thick-film or LTCC components. Latest developments for an improvement of the fine line ability were aligned on new screen meshes, emulsions, or adopted pastes. Minimum structure sizes, for example, for high-frequency applications presently reached 25 μm [1]. Required optimizations of fine line screen printing are related to improved film thickness homogeneity, better printing reproducibility and enlarged printable areas [1].

Aerosol printing belongs to the class of digital printing technologies. That means the required pattern can be printed directly from the pattern generator of the circuit design software [9]. As an additional deposition technology for ceramic thick-film or multilayer technology, it closes the gap between screen printing and photolithography.

This novel direct writing method for an ultrafine pattern is used in photovoltaic applications [2, 3] and polymer electronics (touch screen, fully printed TFTs) [4-6]. The deposition of high-permittivity materials on PCB substrates [7] and the contacting of stacked dice are further applications for aerosol printing [8].

In the aerosol process, the ink droplets are generated and brought into a gas flow using a spraying (pneumatic) or an ultrasonic atomizer unit. Furthermore, the droplet flow is compacted (virtual impactor) and led to the deposition head where it is finally focused (Fig. 1).

Because of the large standoff distance from the deposition head to the substrate, 3D surfaces can be printed. The minimum diameter of the focused droplet flow is smaller than 10 μm.

Potential applications for aerosol printing within hybrid electronic packaging include Ag metallization lines for LTCC rapid prototyping, ultra fine line printing, for example, high-frequency applications, sensors; and 3D printing, for example, chip contacting, microsystems, and sensors.

Aerosol Printed Inner Layer Ag Conductors Cofired in LTCC

To improve throughput times for LTCC prototype manufacture, delay times for screen manufacturing must be reduced significantly. Using a direct writing technology like aerosol printing is one possible way to reduce the manufacturing times for prototypes or small series.

The goal of the experiments was to determine a material combination (LTCC/Ag-ink) and a suitable processing method (printing, lamination, and firing) for aerosol printed Ag conductor lines. For the investigations, an adapted screen printing paste, a microink, and a nanoink were printed on DP 951 LTCC tapes.

Table I lists the three types of investigated commercial inks and their particle size distribution.

The specific resistivity was calculated by a four-point resistivity measurement and by the analysis of the cross-sectional area of the inner layer conductors. Fig. 2 shows the measured values.

Using the Ag nanoink, a resistivity value near that of bulk silver can be reached. The specific resistivity of the aerosol microink is comparable to screen printed inner layer conductor pastes.

The microstructure of the samples was analyzed using SEM/EDX. Fig. 3 shows the cross section of an inner layer conductor line printed on DP 951 using the silver nanoink. The lines have a width of about 30 μm and a thickness of 15 μm. The high aspect ratio of 0.5 was reached by multiple pass printing

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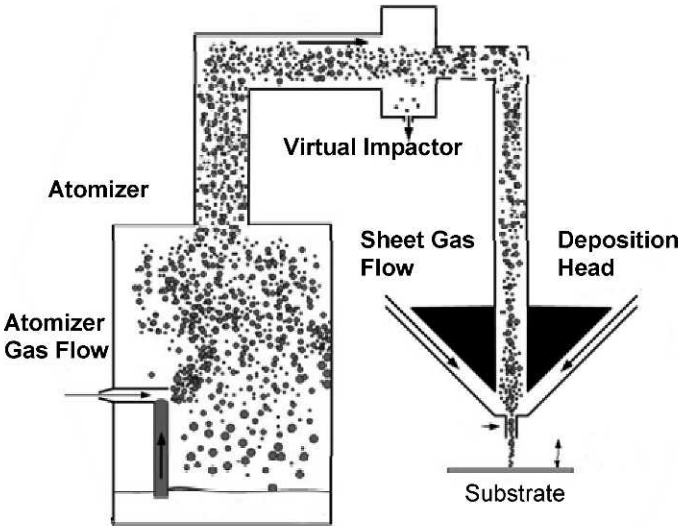

Fig. 1. Principal components of an aerosol printer (Optomec Aerosol Jet) [10].

Table I
Particle Size Distribution: *D*(50)** and *D*(90)*** and Viscosity (η) of Aerosol Printable Silver Inks

	Unit	Ag nanoink	Ag microink	Adapted Ag paste
D(50)	μm	0.06	0.55	1.51
D(90)	μm	0.11	2.08	4.05
η*	Pa·s	0.1	1.9	35.2

*$T = 20$°C, shear rate 10 s^{-1}.
***D*(50) = average particle diameter.
****D*(90) = 90% of the distribution lies below this particle size.

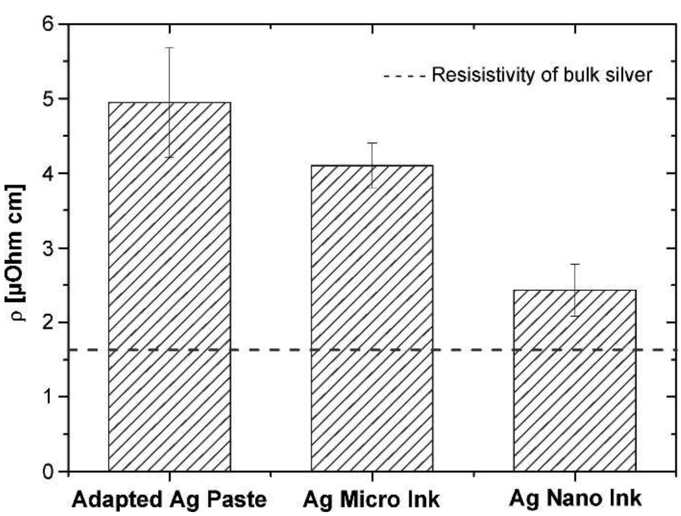

Fig. 2. Specific resistance of the cofired fine line Ag inner layer conductors (embedded in DP 951).

(10 passes). The cross section of the nanosilver shows just a few pores in the line and in the ceramics in comparison with the aerosol microink. EDX analysis detected no silver diffusion in the LTCC interfacial area.

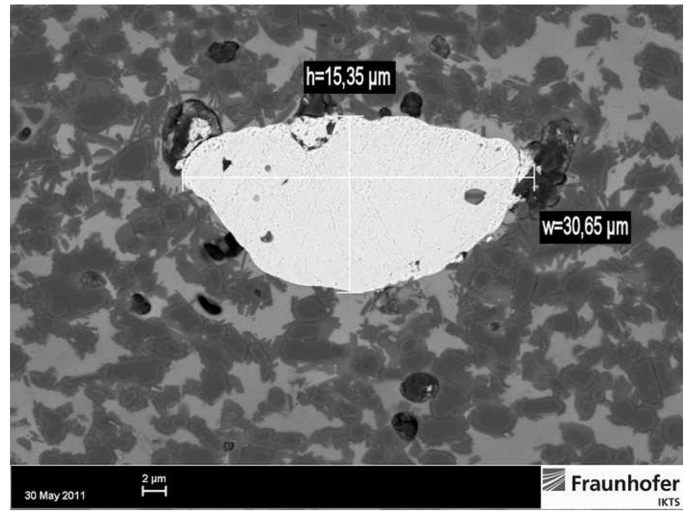

Fig. 3. Microstructure of a cofired aerosol printed conductor line (silver nanoink 10 times printed and embedded in LTCC DP 951).

By varying the printing parameters, line widths between 15-50 μm and line thicknesses between 8-20 μm were achievable for the microink and the nanoink by 10 multiple passes.

Fig. 4 shows the cross section of the adapted paste in DP 951. For 10 printing times, conductor widths of 25-50 μm and line thicknesses between 3.5-5 μm were achieved. Less selective overspray is visible next to the conductor line. A major fraction of particles of the paste were filtered in the pneumatic atomizer and could not be deposited. All printing results of the tested inks are listed in Table II.

In summary, the nanoink shows the best results regarding resistivity, porosity of the conductor cross section, and fine line printing ability in the inner layer conductor tests. An aspect ratio of 0.5 is printable in LTCC. The microink offers the best deposition rate, with 5 μm per print repeat. A reduced overspray was detected for optimized printing parameters for both inks.

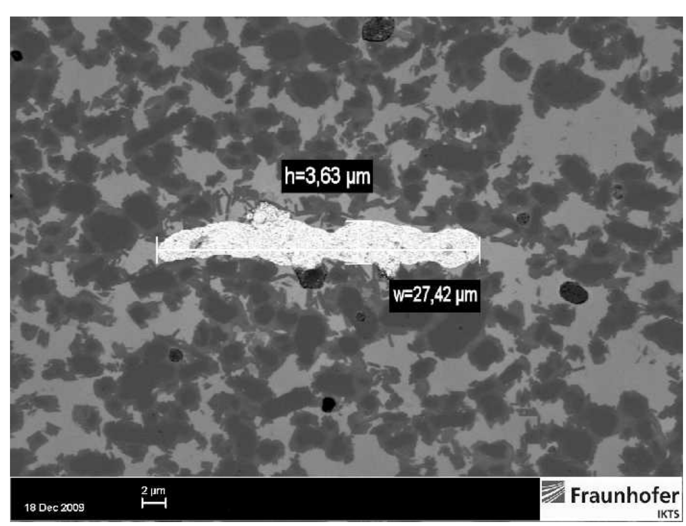

Fig. 4. Microstructure of a cofired aerosol printed conductor line (adapted silver paste embedded in LTCC DP 951).

Table II
Printing Results (Optimized Printing Process)

	Unit	Ag nanoink	Ag microink	Adapted Ag paste
Print quality*	—	+++	+++	+
Over spraying*	—	no	no	some
Maximum deposition rate (dried)	µm/print	4	5	1.5
Minimal line width	µm	15	20	25
Firing temperature	°C	875	875	875
Specific resistivity	µOhm·cm	2.43	4.10	4.95

* +++ = very good, + = well suited.

The screen printing paste is just an alternative for both inks. Less than half of the printable silver cross section area of the microink could be deposited for the same conductor width.

A. Application Example for Ag Inner Layer Conductors Cofired in LTCC

An application example for a cofired functional layer is a high frequency test structure printed with the Ag microink on Heraeus CT708 tape as shown in detail in Fig. 5. In this layout, fine line conductors are mixed with laminar shapes which have to be filled by aerosol printing. To get high quality filled shapes, the single lines of the line raster were printed with a width of 30 µm to avoid overspraying effects at the edges. By the fourth printing pass, the thickness in the unfired state is ca. 10-20 µm.

3D Aerosol Printing of Postfired Ag Conductors

In addition to fine line printing on planar substrates, the unique 3D printing ability of the Aerosol Jet printer will be discussed. The 3D ability of aerosol printing results from the combination of the long standoff distance of the aerosol printing nozzle and the large focus length of the droplet flow. The nozzle can be adjusted up to 4-5 mm above the substrates.

Fig. 6 shows 30-50 µm wide conductive lines printed over 280 µm high LTCC stairways with silver micro ink. To print over a 90° step, the nozzle or the substrate as well as the substrate table have to be shifted (up to 20°) to reach similar deposition angles.

Another 3D application could be printing over an adhesive ramp which is dispensed at the edge of a 90° step. The advantage of this technology is that the nozzle or substrate does not have to be shifted. As shown in Fig. 7, the conductor lines are continuously contacting a 350 µm high chip. For this application, the sintering temperature is restricted to be up to 200°C because of the temperature-sensitive chip. The required sintering temperature is determined within the required temperature range, as Fig. 8 shows. For this reason, the Ag nanoink was used.

A. Contacting of g-Accelerometer by Aerosol Printing

For a novel, high-g-shock silicon accelerometer design (Fraunhofer EMI), a true 90° 3D contact can be demonstrated by aerosol printing. As a result of the unconventional geometry of the spring-mass system, in that the sensing direction is aligned in the wafer plane, the contact pads of the g-accelerometer are perpendicular to the substrate. The aerosol printing technology offers the ability to contact these accelerometer chips in an efficient and space-saving way to the next substrate level.

Fig. 9 shows a g-accelerometer contacted by aerosol printed 40 µm Ag conductor lines. An important element is the adhesive for fixing the chip and works as a substrate-chip passage

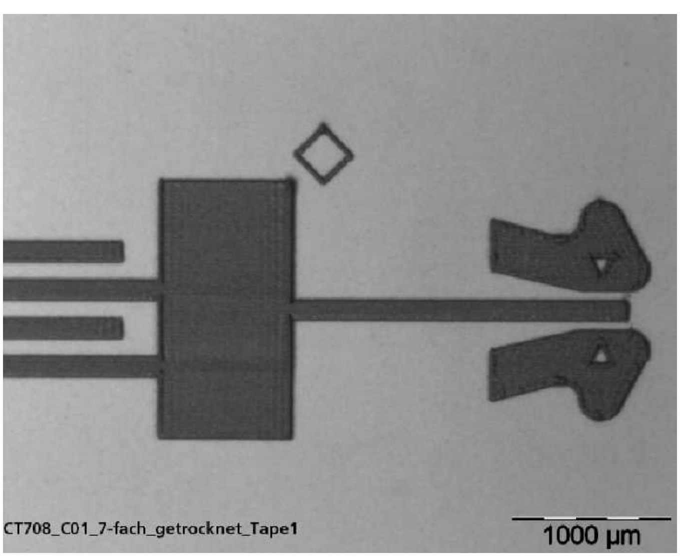

Fig. 5. High frequency test pattern on LTCC for cofiring tests.

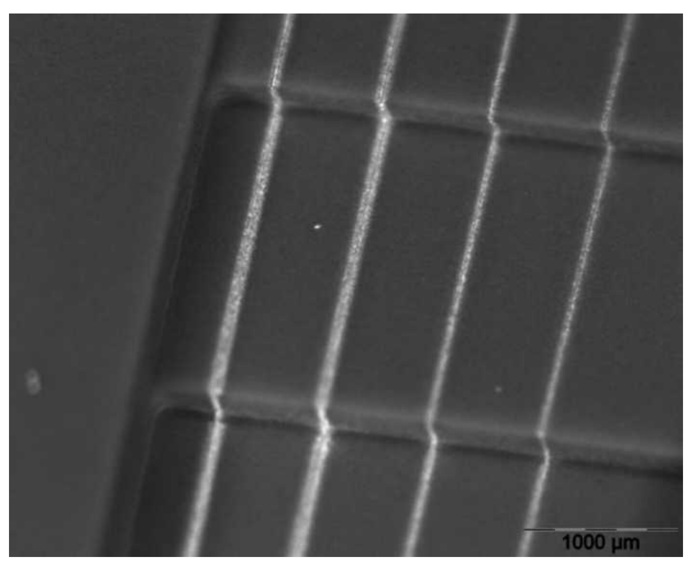

Fig. 6. 3D printing on LTCC stairways (step height 220 µm, DP 951) with aerosol printed Ag micro ink.

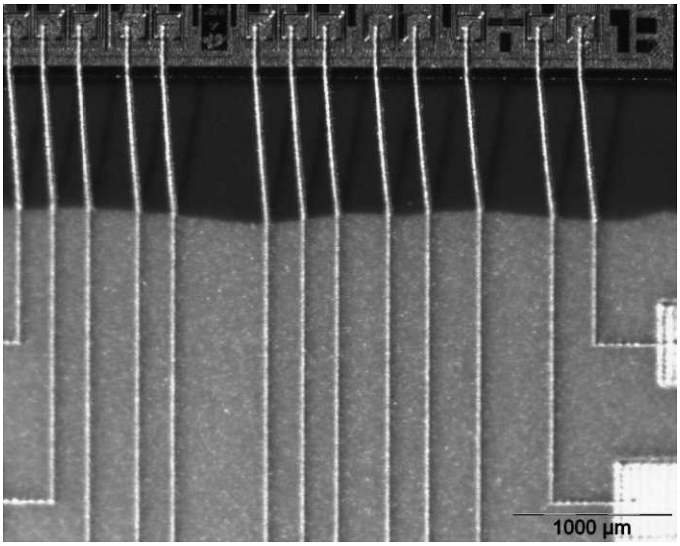

Fig. 7. Aerosol printed 3D chip contact.

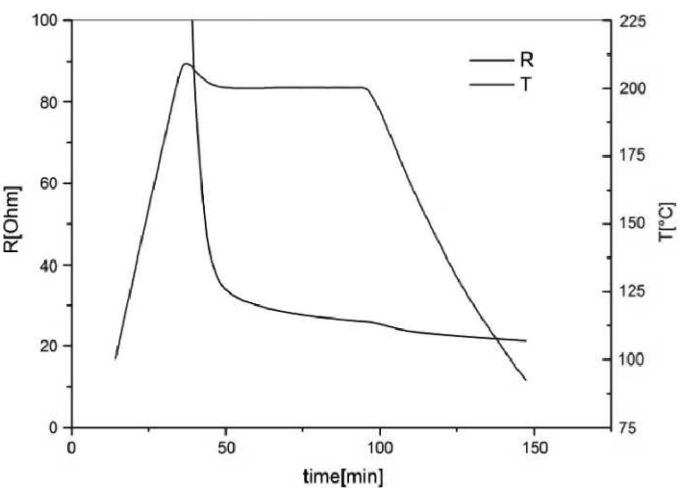

Fig. 8. Sintering curve of the applied Ag nanoink (test structure embedded in LTCC DP 951).

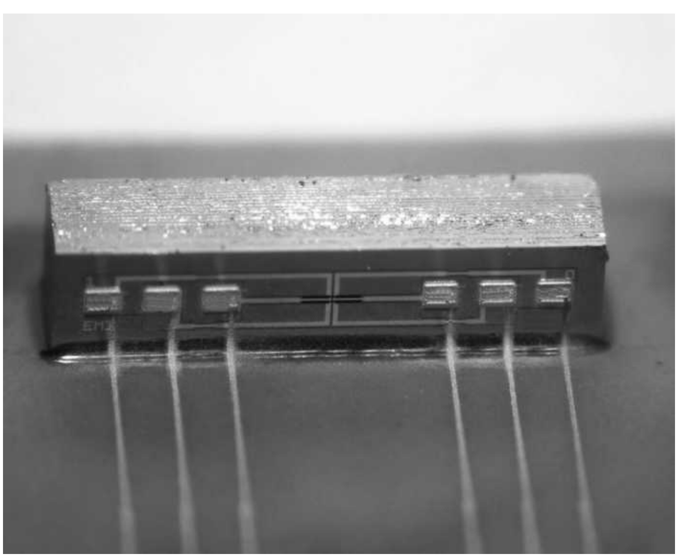

Fig. 9. Contacted g-accelerometer by aerosol printing.

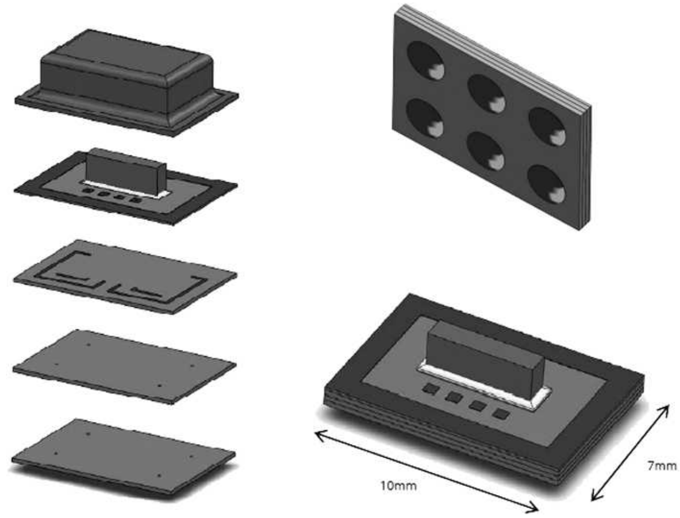

Fig. 10. Packaging concept of aerosol contacted g-accelerometer in LTCC.

for the conductor lines, as well. It should offer a low temperature coefficient (< 50 ppm K^{-1}) and should be temperature resistive up to 250°C. The first temperature shock test of 82 cycles from -55°C to 80°C at the bare contacted sensors showed a slight drift in the resistance value of the contacts.

For the current accelerometer design, a ball grid area packaging concept in LTCC in combination with aerosol and screen printing conductors was designed to get a robust sensor system with an overall dimension of 7×10 mm^2 (see Fig. 10).

Conclusions

The paper discusses the applicability of aerosol printing as an additional technology for the deposition of functional films required in ceramic thick-film or multilayer components.

Aerosol printing is very well suited for LTCC cofiring and postfiring applications. Application examples for aerosol printed Ag lines include LTCC rapid prototyping, 3D printing, and contacting of unconventional sensors and packages with the help of low temperature sintering Ag inks.

With this application portfolio, aerosol printing technology closes the gap between screen printing and photolithography regarding the printing resolution. Furthermore, the packaging of sensors and specialized chips could become more flexible and space saving.

Current projects are focused on the development of aerosol printable inks (nonsilver metallization, suited glasses and resistors) and the optimization of the process repeatability, as well as the application of aerosol printing for the fabrication of electronic packages, sensors, and microsystems.

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