Print the Printed Circuit Board – Inkjet Printing of Electronic Devices

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Abstract

Inkjet printing of nano particles is a new technology for the manufacturing of Printed Circuit Boards. Inks containing silver, copper or Carbon Nano Tube particles were deposited on various substrates like polyimide, Fr 4, paper or even wood with a special inkjet system as well as with standard office printers. Depending on the ink composition, at temperatures from 150 -250 ^{o}C sufficient electrical conductivity was achieved. The capability of functional inkjet printing is demonstrated with a FM radio which was printed with silver ink, the components being attached by isotropic conductive glue.

Introduction

Inkjet printing is a technology which is frequently used for office and home applications. Digital photo prints show an amazing quality with respect to resolution and color accuracy. Most of the inks contain pigments which markedly improve the durability of the prints compared to ionic inks. These pigments are nano particles and in principle it is a small step to replace the decorative by electrically functional particles.

At the Georg-Simon-Ohm University of Applied Sciences in Nuremberg/Germany, inkjet printing of nano particles is investigated as an alternative to established PCB manufacturing technologies. The focus of this research is not yet on extreme fine line structures but on the combination of various ink and substrate materials.

Motivation

Standard technologies for manufacturing PCBs comprehend a number of process steps, including photolithography to transfer the layout from a film to a resist, deposition of metals by electroless and electroplating and the final removal of the original copper lamination outside of the layout by an etching process. As an example, the number of process steps for a double sided PCB manufactured in metal resist subtractive technology with hot air leveled surface finish can sum up to 20-40, depending whether intermediate rinsing processes are taking into account or not (Fig. 1). Other state of the art PCB manufacturing technologies like immersion tin or copper/nickel/gold (ENIG) require a similar number of steps and are also based on subtractive techniques.

Compared to the standard technologies, by inkjet printing of PCBs, the number of processes can be reduced to 2-4 (Fig. 2). Some of the expected advantages of functional inkjet printing are:

- Maskless, very flexible
- Few manufacturing steps
- Fine line (<< 100 µm) possible
- Applicable to rigid and flex substrates
- Roll to roll fabrication possible
- Integration of passive components
- Integration of basic active components
- Up- and down trimming of resistors
- Subsequent printing of reactive liquids
- 3D-packaging possible
- Combination with electroplated or hybrid structures
- High automation potential, high volume production by nozzle and printer parallelization
- Completely additive– no waste

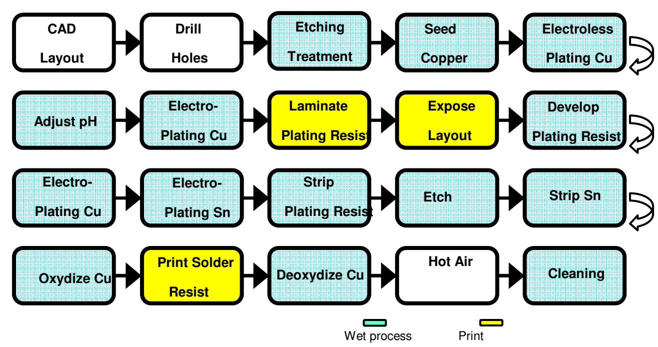

***Figure 1**. Main process steps for metal resist subtractive technology with hot air leveled surface finish*

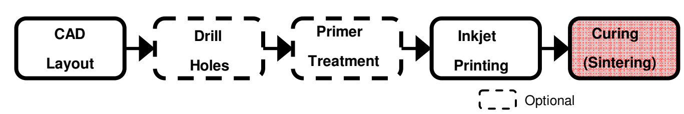

***Figure 2**. Process steps for inkjet printing of PCBs*

Fundamentals of inks with nano particles

Nano particles in inks preferably have a size < 50 nm to take advantage of the nano size effect which means that the melting point drops drastically [1]. However, such small particles exhibit a large specific surface and in a liquid carrier tend to agglomerate to safe surface energy. To prevent the agglomeration and also the sedimentation of metal particles in an aqueous or organic liquid, the particles are coated with a thin organic layer which separates them also electrically. This coating has to be removed during the printing process or afterwards at treatment temperatures and time which strongly depend on the particle size. As a rule of thumb: the smaller the particles are, the lower the sintering temperature and the shorter the sintering time can be. In general, state of the art metal inks for inkjet printing require treatment temperatures of approx. 200 °C or lower allowing the processing of various polymer materials.

Experimental setup

For our experiments, we are using 3 types of inkjet printing systems.

The first one is based on a single piezo-electric printhead of 100 µm nozzle diameter which replaces the pen in an x/y - plotter. The movement of the plotter is controlled by HPGL commands via a PC.

The second system is a modified Epson D 88 printer. A heating element built by carbon nano tubes printed on a small ceramic substrate was installed underneath the paper transport which provides at 20 V and .8 A a temperature of approx. 150 °C (Fig. 3).

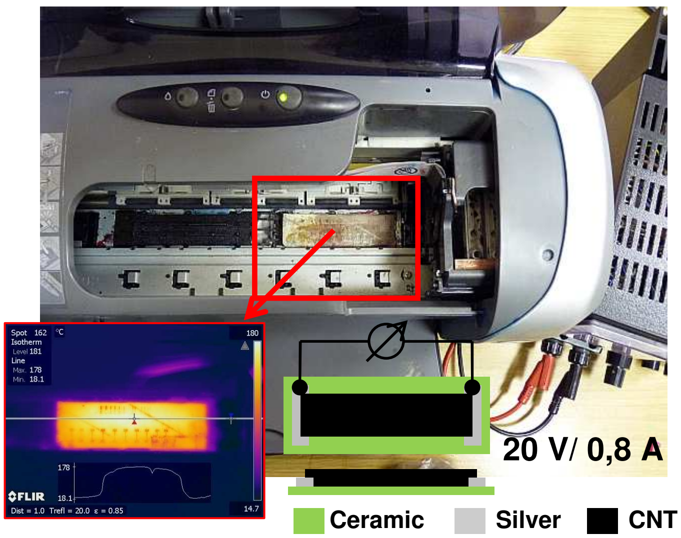

***Figure 3**. Modified Epson D 88 office printer*

The third system is a modified Epson R 800 printer which allows – in contrary to the D 88 – the printing on rigid substrates up to a thickness of 2 mm.

Depending on the ink and the substrate (e.g. polymer foil or paper), the heating during the process improves print quality and is minimizing sintering temperature and time for removal of the organic particle coating and formation of a compact metal structure. To achieve a sufficient thickness of the structures (3 -4 µm), the inkjet printing is repeated 3 – 5 times.

In our experiments, 4 types of inks were printed:

- Silver ink A (particle size approx. 5 – 10 nm)
- Silver ink B (particle size approx. 20 – 30 nm)
- Copper ink
- Carbon Nano Tube ink (double walled)

As substrate material, predominantly 125 µm polyimide foil and various types of (photo-) papers were investigated, to a lower extend ceramic, glass and wood.

Temperature treatment was performed in an oven with air atmosphere.

Printing results

Depending on carrier liquid and viscosity, the printing behavior of the 2 silver inks are very different. Ink A, based on an organic carrier, is spreading on polyimide when printed at room temperature. The wetting angle which should be in the range 60 – 80o is evidently smaller which means that neighboring lines will cause shorts. However, this is only valid for the polyimide substrate, on photo paper the print quality is fine. To achieve good results with ink A on polyimide, the substrate has to be heated during the printing to a temperature of 150 – 200 °C (fig. 4).

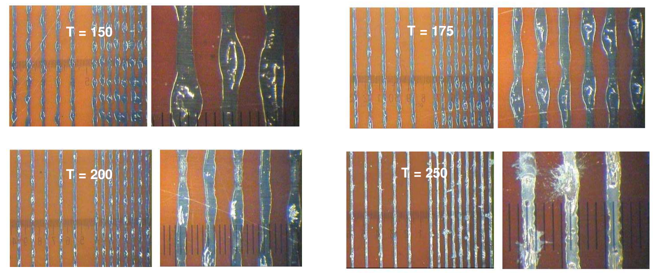

***Figure 4**. Lines printed with ink A with the single printhead at various temperatures*

As also can be seen in fig. 4, at temperatures > 200 oC splashing occurs causing many satellite droplets. Such satellite droplets are a permanent problem accompanied with inkjet printing. Main reasons for satellite droplets are:

- Splashing due to high substrate temperature
- Splashing due to high drop velocity
- Partially clogged nozzles

The printing accuracy with respect to line width was determined for the layout of a FM radio. Lines printed with silver ink A on polyimide using an Epson D 88 are in the average 11 % smaller than specified by the CAD program (fig. 5) if no pretreatment is applied. By cleaning the polyimide surface with a hydrophilic or hydrophobic liquid prior to inkjet printing , the line width could be increased or further decreased.

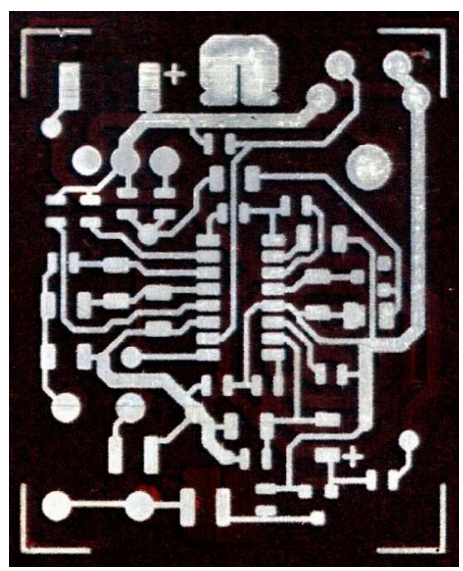

***Figure 5.** FM radio layout printed with silver ink A on polyimide with Epson D 88*

Sintering and conductivity

The removal of particle coatings can be done by various methods like heat, microwave radiation, plasma or even a light flash of very high energy. In our experiments we apply conductive or radiation heat by a small ceramic heater underneath the substrate during printing or afterwards in an oven. Both silver inks exhibit a very different sintering behaviour. Whereas good electrical conductivity is achieved with ink A when the substrate is heated during printing to a temperature of 150 – 250 °C, this treatment is insufficient for the coarser grained ink B (fig. 6). But after an additional sintering process for approx. 1 hour, the electrical conductivity of lines printed with ink B is comparable to or even slightly better than ink A.

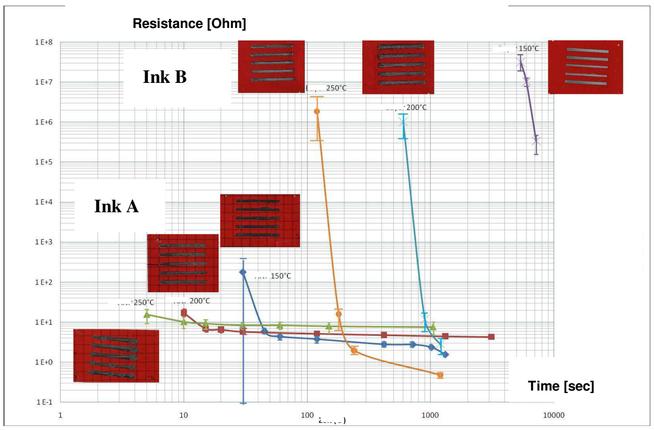

Figure 6. Resistance of silver lines as a function of sintering time and temperature

A strong indication for the removal of the organic coating is the steep increase of the micro hardness of conductor lines (fig. 7).

This also indicates that sintering had occurred, however the microstructure (nano-crystalline, micro-crystalline, amorphous ?) of the silver lines still has to be investigated.

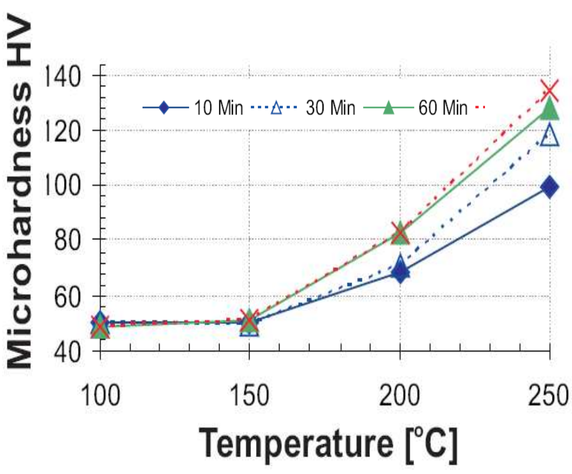

Figure 7*. Micro hardness of silver lines (ink A) as a function of sintering time and temperature*

Comprehensive tests were performed using silver ink A with Epson D 88 printers on various photo papers. After printing at room temperature, the samples were sintered at 150 -250 °C for up to 60 minutes. Surprisingly the photo papers can withstand such high temperatures without being damaged or even slightly changing their color. The prints were repeated 5 times resulting in a sheet resistance of approx. .1 - .04 Ohms/square (fig. 8). As can be seen, a sintering time of 3 minutes is sufficient for all temperatures, increasing the sintering time does not give a significantly better conductivity. Fig. 8 also indicates that the printing direction i.e. parallel or vertical to paper transport does not influence the result. In comparison, silver ink printed on a polycarbonate foil shows a similar conductivity already at a sintering temperature of 180 °C. The better conductivity on the polymer can be explained that probably some of the ink is soaked into the paper surface whereas it remains on top of the polycarbonate substrate.

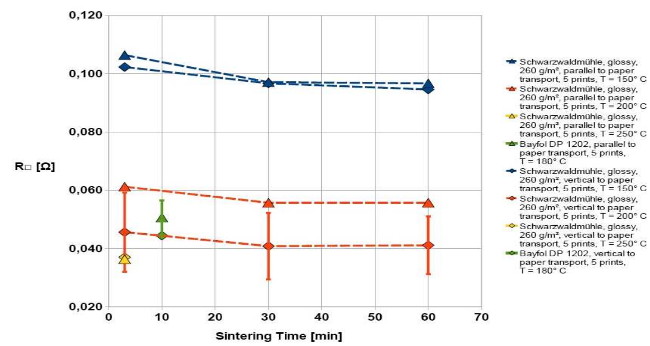

Figure 8. *Sheet resistance of silver lines as a function of temperature and time for different photo papers in comparison with a polycarbonate substrate*

Further experiments

Inkjet printing of an aqeous carbon nano tube (CNT) ink seems to be a viable method to integrate resistors into electric circuits. At a low concentration of the CNTs, we achieved a sheet resistance of a few kiloohms on glass as well as on copier paper. The sheet resistance can be varied by:

- Concentration of the dispersed CNTs, limited by increased tendency of nozzle clogging
- Saturation of the “color” in the office program
- Saturation adjustment in the printer driver

The lines printed on a glass substrate with CNT ink just have to be dried, a thermal treatment up to 40 minutes at 300 °C did not change the sheet resistance. When the CNTs were printed on paper, the sheet resistance was slightly depending on the thermal treatment conditions but this still has to be investigated in detail.

First tests of printing silver ink on wood look promising (fig. 9). In direction of the wood fibers, there is an extended ink flow which can be either prevented by a heat treatment of e.g. approx. 350 °C and/or by printing a primer prior to the metal ink. The second method will also reduce the costly metal ink consumption as the firstly printed inks are deeply soaked into the surface of the wood. Moving towards “Green Electronics” wooden substrates might be a very interesting material in the future.

Mounting discrete components (SMDs) on an inkjet printed structure is a challenge due to the small thickness of the pads. So a standard interconnection technology will be the application of isotropic conductive glue which is widely used for thin-film hybrid circuits and for a limited extend also for thick-film hybrids. The conductive glue has no leaching effect on the pad metallization and can be cured at moderate temperatures of 100 – 150 °C for approx.

30 – 10 minutes. But besides the high cost, conductive glue is difficult to process. It has to be stored at temperatures below -20 ^{o}C and the wetting is similar on polymer and metal surfaces. This can initiate shorts underneath small components or between the leads of fine pitch ICs.

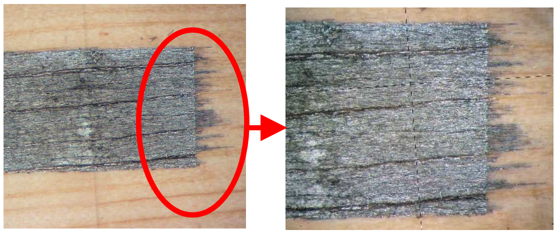

Figure 9. *Silver ink printed on wood*

Compared to conductive gluing, reflow soldering would be the preferred interconnection technology. However, it is known, that silver is sensitive to the leaching effect, i.e. silver structures in contact with molten solder will be quickly dissolved in the solder melt. First tests with eutectic Sn37Pb solder paste in contact with silver printed lines on photo paper look promising (fig. 10). After reflow soldering with a peak temperature of 245 ^{o}C for 3 minutes, a perfect meniscus is formed at the component metallization and the component sticks to the substrate. Of course, this is just a first indication that reflow soldering might be a possible interconnection technology also for inkjet printed structures.

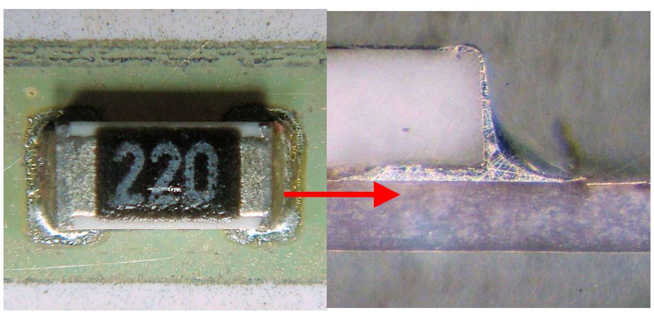

Figure 10. *Resistor type 1206 reflow soldered on photo paper with inkjet printed silver metallization, top view (left) and microsection*

FM radio

A miniaturized (32 mm x 40 mm) FM radio is built by students of our university to get familiar with standard PCB technologies like photolithograpy, electroless and electroplating and etching. The shape of the housing is the Ohm symbol so we call this radio "Ohm radio" according to the name of our university (fig. 11).

This Ohm radio has been taken to demonstrate step by step the potential of functional inkjet technology. Already in 2008, an Ohm radio was built by inkjet printing the lines on both sides of a polyimide foil. The walls of vias and feed through holes were covered with inkjet printed silver as well and the sound quality of this demonstrator was comparable to the Ohm radios manufactured with standard metal resist subtractive technology. The only change in layout was a slight widening of the line connecting the 3 V battery to get sufficient voltage for the circuit as the inkjet printed lines only exhibit a thickness of approx. 3 µm just 10 % of the line thickness achieved with standard technology.

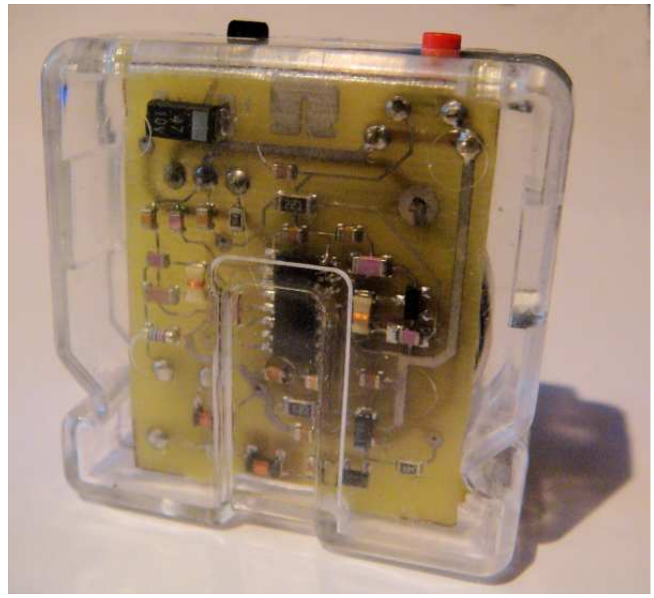

Figure 11. *FM radio manufactured in standard subtractive technology*

Meanwhile, the quality of inkjet printed structures has been improved (fig. 5, 12) by moving from the one nozzle vector printing system to standard Epson printers of the series D 88 and R 800. The surface mounted components are attached to the substrate by isotropic conductive silver glue cured at 120 ^{o}C for 30 minutes. Variations of the substrate already investigated are paper and rigid FR 4. In addition, we will try to build the first radio on a wooden substrate. The resistors will be integrated by inkjet printed CNTs and it is planned to integrate the smaller capacitors as well.

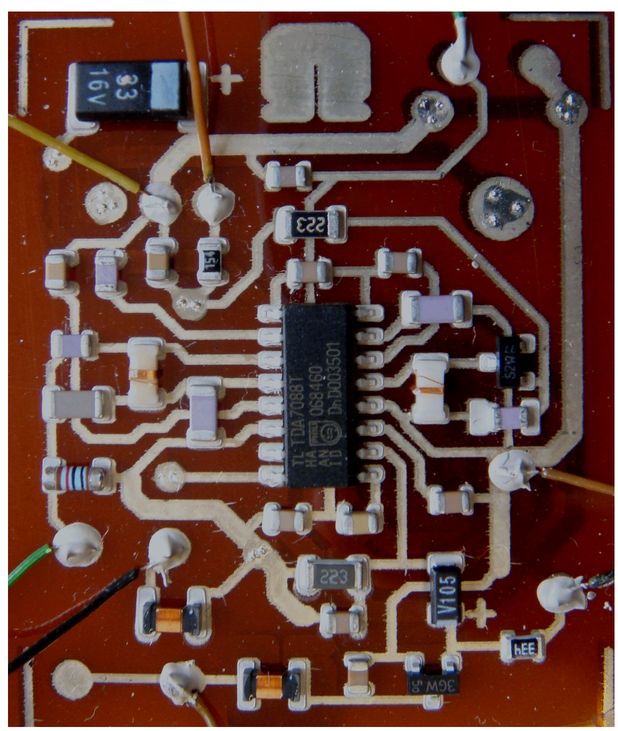

Figure 12. *Assembled, inkjet printed double sided PCB of the Ohm radio*

Conclusions

Inkjet printing of PCB structures provides many advantages over standard manufacturing technologies. Most important might be the flexibility with respect to layout changes and substrate material and the waste-free completely additive process. Issues are the line thickness below 10 µm which limits current density and the attachment of components by isotropic conductive glue. For high power applications however, a combination of standard thick copper PCBs or thick-film may be useful, where the signal layers are printed on top of the PCB or hybrid structures by inkjet printing of silver or copper lines.

The potential of functional inkjet printing is well recognized especially in Asian nations like Japan or South Korea. In South Korea e.g. the strong interaction between inks and inkjet printers is investigated by a cooperation of several companies, universities and research institutes [2]. The whole range of inks (metal, CNT nano wire dielectric) and inkjet printers (from small lab to high volume printers) is available there.

Before inkjet printing will become a standard PCB manufacturing technology, comprehensive reliability tests like thermal cycling, humidity storage and adhesion tests have to be performed. An application where a high and verified reliability of the PCBs is not required is the manufacturing of prototypes. To inkjet print just a few PCBs to check whether the circuit is working or not should be possible for a 6 or 8 layer multilayer within a few hours.

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References

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[2] S. S. Kim "Inkjet Technology an Application in Korea", LOPE-C, Frankfurt, May 31-June 2 2010

Author Biography

Werner Jillek received his diploma and PhD in Materials Science from the Friedrich Alexander University in Erlangen/Germany. After working 10 years in an international telecommunication company he became a professor at the Ohm University of Applied Sciences in Nuremberg/Germany. He is heading the Electronic Packaging Lab and supervised several research projects. In recent years he focused his research on functional inkjet printing. He published many papers and was co-editor and co-author of the German PCB Handbook Vol. 4. Prof. Dr.-Ing. Werner Jillek is a member of IMAPS.