INKtelligent printing® of Scale Comprehensive Electrical Connections for Thermal Flow Sensors

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Abstract

New printing technologies of functional structures allow new packaging concepts in order to achieve a high grade of miniaturization for integration of micro electro mechanical systems (MEMS). In this case, a thermal flow sensor, designed and fabricated at IMSAS, has been electrically connected to a printed circuit board by means of INKtelligent printing®. We used a maskless aerosol deposition technique for deposition of silver lines with a minimum width of 10 µm. In this way, no bond wires are disturbing the fluid flow within the channel by causing additional turbulences during flow measurement. Due to the possibility to print structures with a resolution down to ten micrometers, the size of bond-pads and therefore the entire sensor size can be reduced.

Introduction

Miniaturized thermal flow sensors are widely used in different fields of applications e.g. in medical [1], in automotive [2] or in industrial setups [3]. Usually these sensors consist of a heater and temperature sensors, which are located on a thin membrane for thermal insulation [4, 5].

Nowadays a high grade of miniaturization allows the design and fabrication of small sensor devices with structures far below 10 µm. Figure 1 shows a thermal flow sensor that has been developed and fabricated at IMSAS [6]. The sensitive area, consisting of a 600 nm thick silicon-nitride membrane with a heater in its center and thermopiles as temperature sensors, has an outline of 1 mm. The smallest line width that is realized for the thermopiles and for the heater is 10 µm.

A flow channel guides the fluid over the sensitive area. Electrical connections to the heater and to the temperature sensors are located outside or inside the channel. Usually bond wires are used for electrical connection and thereby impose several drawbacks. A connection of heater and temperature sensors outside the flow channel restricts its size. Just small channel diameters and large sensors can be used, because there is a need of a minimum distance between membrane and bond-pads due to the thickness of the channel wall. An electrical connection inside the fluid channel allows the use of smaller sensor devices, but bond wires have to be protected by means of glob tops against fluid. Due to this additional topography in the channel, turbulences will be generated, which might influence the flow measurement negatively. Packaging processes, in which bond wires are used for electrical connection, limit the grade of

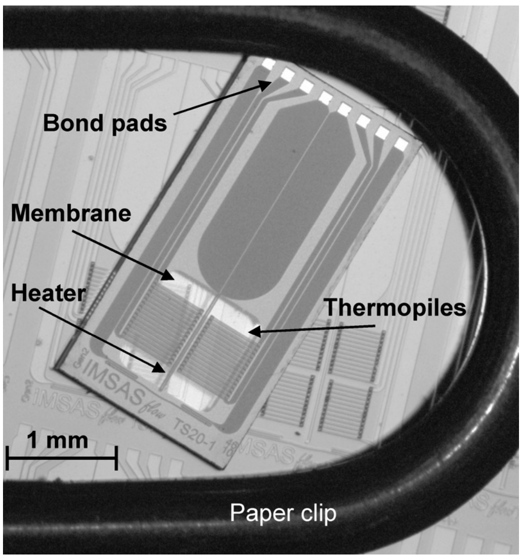

Figure 1: Thermal flow sensor that has been developed and fabricated at IMSAS [6] in between a paper clip.

packaging density. The bond-pads of the flow sensor from IMSAS are placed with a distance of about 1.8 mm to the sensitive area in order to have enough space for placing a flow channel over the membrane. In future, MEMS devices will be directly embedded into various kinds of materials. To ensure a high packaging density, new technologies for electrical connections are necessary. One of those new technologies is INKtelligent printing® [7] for connecting MEMS to printed circuit boards. With the help of contactless and maskless printing technologies as aerosol- or ink-jet printing, functional structures with a height of less than 1µm and with a resolution down to 10 µm can be realized. For these novel printing technologies, new inks consisting of metallic nanomaterials with grain sizes of some 10 nm are required.

INKtelligent printing®

Functional structures can be obtained with the help of ink-jet or aerosol printers. Ink-jet printers are more common than aerosol printers, but aerosol printing allows the generation of smaller structures. The Fraunhofer IFAM uses M^{3}D® (Maskless Mesoscale Material Deposition) for aerosol printing, which has been developed from Optomec Inc. [7] Figure 2 shows the principle of the aerosol jet stream generation. A pneumatic or ultrasonic atomizer produces an aerosol stream of a suspension, which includes the metallic nanoparticles, and transports them to the print head. A sheath gas (nitrogen) inside the print head focuses the aerosol beam and prevents a clogging of the nozzle. The droplet size of the aerosol beam is between 1 µm and 5 µm, which corresponds to a volume of some femtoliter [8]. Over a distance of about 5 mm no broadening of the focused aerosol beam occurs. In this way, step heights of some millimeters can be printed with the aerosol stream without loosing focus yielding a three-dimensional printing technology (see Figure 3).

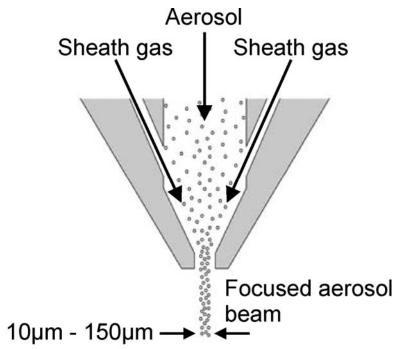

Figure 2: Visualization of aerosol stream generation inside the print head [7].

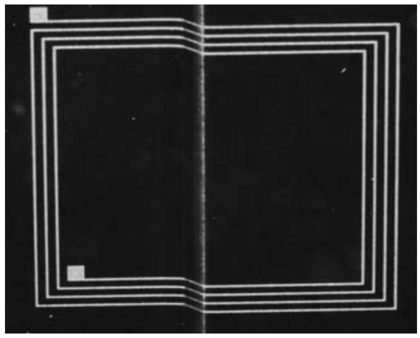

Figure 3: M^{3}D® printed silver antenna across 1 mm level [7].

For both printing technologies, nanoscaled inks with particle grain sizes down to 5 nm to 50 nm are necessary to achieve a high resolution. There are several commercial inks on the market available, which differ in their weight amount of silver, grain size, as well as stabilizers and which fulfill the demands for INKtelligent printing® [7]. Fraunhofer IFAM itself is able to formulate nanoscale suspensions as printable inks by using a physical sputtering process called Vacuum Evaporation on Running Liquids (VERL) [9]. This enables us to develop own inks with known stabilizers like solvents or binders to understand the whole deposition process in more detail. Stabilizers are necessary to avoid agglomeration of the nanosized particles during the printing process.

An advantage of aerosol printing is its wide process latitude regarding viscosity and stability of the inks that can be used. Table 1 summarizes the parameter of ink-jet and aerosol printing technology. Since the drop size, generated during the aerosol printing process, lies in the range of 1 µm to 5 µm and is therefore much smaller than for the ink-jet printing, a minimum structural resolution of 10 µm can be achieved. Aerosol printing allows uniform material deposition on virtually any substrate without ink bleeding effects, which are known from ink-jet printing. This is of special interest for printing on multi-material substrates, like embedded systems.

Table 1: Comparison of ink-jet and aerosol printing [8].

	Ink-jet printing	Aerosol printing
Structural resolution	20 µm – 100 µm	10 µm
Stand-off height	1 mm – 2 mm	up to 5 mm
Deposition speed	50 mm/s - 500 mm/s	up to 150 mm/s
Deposition rate/nozzle	0.1 mm³/s – 0.5 mm³/s	up to 0.25 mm³/s
Drop size	20 µm – 100 µm	1 µm - 5 µm
Drop volume	10 pl – 100 pl	0.01 pl – 0.1 pl
Viscosity of ink	1 mPas – 20 mPas	1 mPas – 1000 mPas

After deposition, the printed particles are arranged in a unconstrained bulk and need to be functionalized by thermal consolidation in a sintering process. The sintering process drives out stabilizers and is necessary to set up electrical resistance. This can be done by using a furnace with temperatures between 150°C and 250°C or by laser sintering in case of thermally sensitive components. The low size of the metallic nano particles benefits towards lower sintering temperatures. This is advantageous for achieving the functionality of the printed structures at low thermal loads. Figure 4 shows a SEM picture of a printed silver line with ANP Silverjet DGH-55-HTG ink [10] having a width of 80 µm and a height of 3 µm. Sintering at 210 °C for 120 minutes leads to a resistivity of about four to six times of bulk silver. Sintering temperature, type and duration of course influence the resistivity of the functional structures.

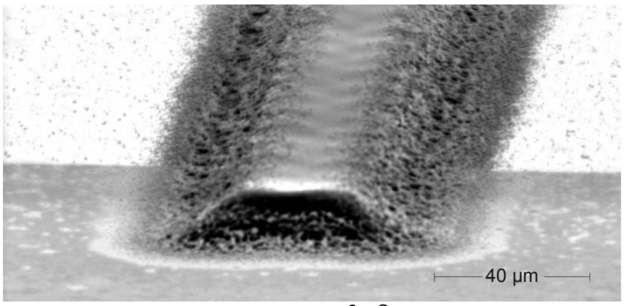

Figure 4: SEM picture of M³D® printed silver line on a silicon substrate sintered at 210 °C for 120 minutes.

There is one drawback on this technology to be named: an electrical connection is only possible to materials without a native oxide. Typical materials are metallic layers like gold or platinum. Copper or aluminum that are often used as bond-pad or track materials in sensor fabrication cannot be connected electrically so far with INKtelligent printing®. The energy during the printing process is too low to break through their native oxide compared to the wire bonding process.

Electrical Connection of Thermal Flow Sensors

IMSAS is developing and fabricating thermal flow sensors that are usually bond-wired to printed circuit boards for electrical connection. The sensors are operated in a constant difference temperature mode. This means that the heater, located in the center on the thin silicon-nitride membrane, is held constant at a temperature some tens of Kelvin above fluid temperature. The hot junctions of the thermopiles are located close to the heater on the membrane. The cold junctions are placed on the silicon substrate acting as heat sink. The thermopiles measure the flow rate dependent shift of temperature on the membrane. If there is no fluid flowing over the membrane, the distribution of heat in and against flow direction is symmetrical and the difference between both thermopiles is zero (referring to Figure 1). In case of fluid, flow heat distribution becomes unsymmetrical and the thermopile against flow direction measures a lower temperature than the thermopile in flow direction. The difference in temperature between the thermopile up- and down-stream is the output signal of the thermal flow sensor, i.e. the voltage difference between both thermoelectrical voltages of the thermopiles. The design of the sensor has been chosen in this way, that there is enough space between the sensitive area and bond pads to place a channel including a sealing over the membrane. Here, the bond wires are located outside the flow channel. If one wants to measure higher flow rates, the cross section of the flow channel has to be increased and the bond wires have to be placed inside the flow channel. For protection and to avoid electrical short cuts, the bond wires have to be covered with a glob top, which causes additional

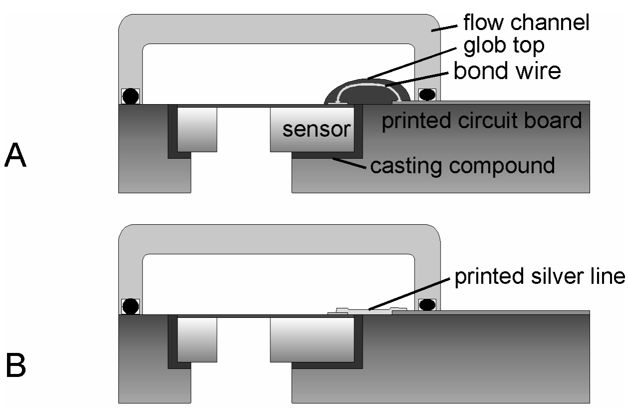

Figure 5: Comparison of standard wire bonding (A) to INKtelligent printing® (B) for electrical connection of miniaturized sensors.

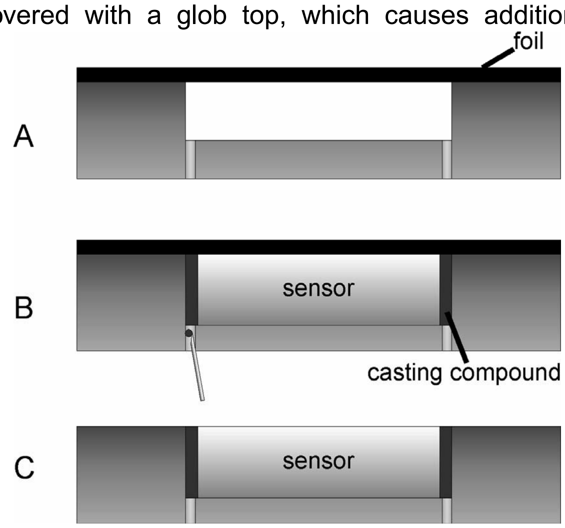

Figure 6: Process flow for integration of thermal flow sensors into a printed circuit board.

topographies in the fluid channel, as Figure 5 illustrates. To overcome this drawback, $M^3D^®$-printing technology has been used.
The flow sensor has been flush mounted into a printed circuit board in order to achieve a smooth surface for printing. Figure 6 shows the process flow for the packaging concept of the thermal flow sensor. At first a foil has been laminated on the front side of a printed circuit board (A). The printed circuit board contains a recess, in which the thermal flow sensor has been placed from the backside. The front side of the sensor shows in direction of the foil, so the thin silicon nitride membrane is in direct contact with it. The foil has been used here to achieve a smooth surface transition between the silicon sensor and the printed circuit board. From the backside a casting compound has been used to fill the cavity between sensor and board (B). The foil on the front side acts here additionally as fluidic stop, so that no casting compound will reach the front side of the membrane. After hardening of the compound the foil has been removed by means of solvents (C). For electrical connection of the sensor to the printed circuit board, the aerosol printing has been chosen due to its ability to realize smaller structures than ink-jet printing. Although the $M^3D^®$-technology allows three-dimensional printing, cracks cannot be overprinted and a very smooth transition with the compound is extremely important. The printed silver lines have to be thermally treated for functionalization. Therefore, materials with adapted thermal expansion coefficients with respect to silicon for the printed circuit board and casting compound have to be chosen. Otherwise cracks occur between the silicon sensor, printed circuit board and casting compound during the sintering process and may cause defects in the printed silver line (see Figure 7). Silicon has a thermal expansion coefficient of 2.5 ppm/K, thereby standard epoxy used for printed circuit boards lies in the range between 10 ppm/K and 290 ppm/K. We have chosen a fiber glas net-based polymer resin with ceramic filling (Rogers RO 4003C) as printed circuit board material [11]. It has a glass transition temperature of 280 °C and a thermal expansion coefficient in the xy-direction of 11 ppm/K to 14 ppm/K and in z-direction of 46 ppm/K. As casting compound, we used an epoxy with a temperature stability up to 180 °C (Vitralit 2007F L [12]). Besides the ability of being UV-hardening, the most important advantage of the this material is its flexibility after hardening. It acts as a buffer between the printed circuit board and the silicon sensor. Beside the use of components with adapted thermal expansion coefficients, a silver ink with lower sintering temperature has been used for realization of the electrical connection. The ink DGP-45LT-15C from ANP can be already sintered at only 150 °C. In this way, we demonstrated successfully the potential of this new technology and connected a thermal flow sensor to a printed circuit board as shown in Figure 8. The resistance value of one track silver line is about 3 Ohm - 4Ohm.

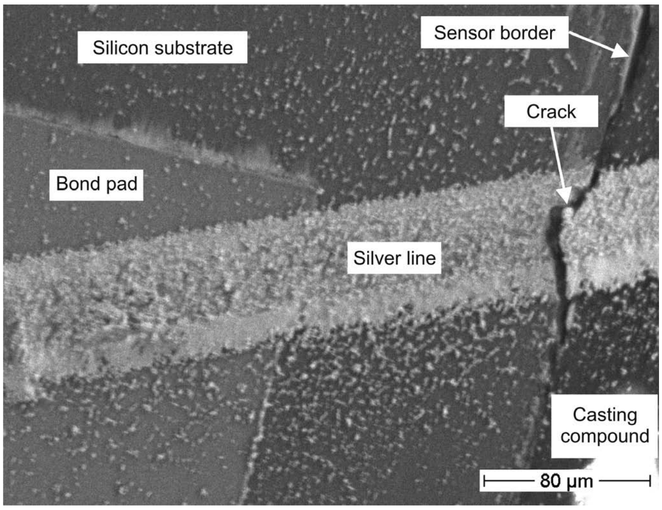

Figure 7: SEM picture of a crack in a printed silver line between thermal flow sensor and casting compound after sintering.

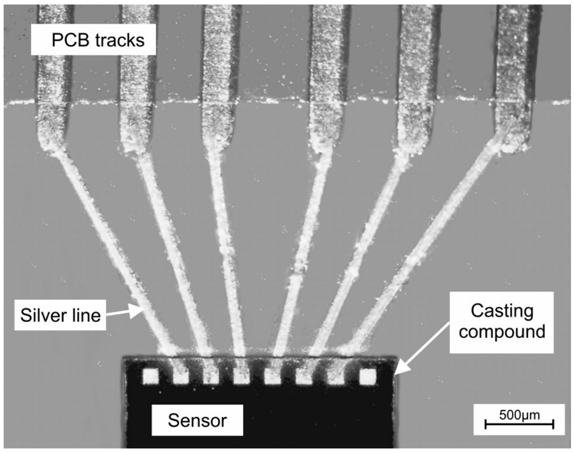

Figure 8: Thermal flow sensor electrically connected with INKtelligent printing® to a printed circuit board.

Conclusion

We presented a new way for the electrical connection of miniaturized thermal flow sensors by using INKtelligent printing® technology. With the help of aerosol printing a thermal flow sensor, which has been flush mounted into a printed circuit board, has been contacted successfully. Due to thermal treatment for functionalization of the printed silver line, temperature stable casting compounds and printed circuit board materials with adapted thermal expansion coefficients to silicon have been used. We showed the application of this new technology for reaching a high packaging density. For the case of the flow sensor we achieved a smoother surface as compared to wire bonding, what is important during flow measurement within fluid channels.

Acknowledgement
The authors thank the German Government for financial support within the project Nanoskala (ref. no. 16SV3571) in the BMBF program "Mikro-Nano-Integration".

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