On-line monitoring and feedback control of inkjet printed capacitors using the modular custom made printing platform MicroStack3D

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Abstract

The paper presents a new feature of our modular printing Platform MicroStack3D [1]. The MicroStack3D system allows one to use inkjet printing for new applications. It has been successfully used to produce freestanding 3D structures using the phase change of an aqueous ink [2] or to print solenoidal receiver coils onto cylindrical glass capillaries [3] to mention two of the already achieved applications. So far the printed structures had a predetermined shape, which was chosen and programmed into the system. The work reported here goes one step further by feeding information about physical properties of the printed structures back into the system. This feedback allows the inline correction of a print. A first application is realised by the printing of capacitors. A silver ink is printed onto a temperature controlled substrate and directly sintered, the resulting change in capacitance is monitored on-line and stops the printing process when a certain value is reached. The principle of a feedback-loop for inkjet printing, not only applies to printing capacitors, but it can be used for the fine tuning of any physical property that can be changed by inkjet printing like, for example, resistors, inductors, mechanical resonators or chemical properties. The modular design of MicroStack3D allows the quick integration of measurement equipment into the system.

Introduction

Inkjet printing deposits small droplets, containing material, onto a substrate [4]. In the case of graphical printing these materials are the pigments. For the printing of freestanding 3D structures the droplets form the building blocks that let the structure grow [2], and for printing resonant receiver circuits for magnetic resonance imaging (MRI) [3, 5] the inks form conductive tracks. These receiver circuits consist of a conductive loop forming an inductance (L). The track is made by printing a silver nano-particle ink onto the substrate and sintering it (U5603, SunTronic, GB). By integrating capacitors (C), a resonant RLC circuit is formed that improves the signal quality. The capacitors for these resonant circuits were fabricated by shaping the overlap area of two conductive tracks on both sides of a thin (50 µm) Kapton foil that is used as substrate and dielectric. The achievable capacitor values can be derived by the following formula:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{1}$$

with the overlap area A, the thickness of the Kapton d, the permittivity ε_0 and the relative permittivity of the material ε_r.

In this design, the capacitance is a purely geometrical property. To calculate the resulting values of the final capacitors, the values for ε_r need to be known. These values can vary for different Kapton sheets, a second source for imprecise predictions are boundary effects. Even though the Kapton foil is quite thin and therefore the two plates are quite close together the inhomogeneous field lines at the edge of the plates mean that the circumferential length has an influence on the resulting value. Another cause for prediction errors is misalignment.

To get an idea of the achievable capacitances and the influence of misalignment errors an example is given. For the MRI applications in a 9.4 Tesla scanner, 4 pF is a common capacitor value. For the 50 µm Kapton the capacitance density was derived through test structure to be 0.55 pF mm^{-2}. For the 4 pF capacitor this results in an overlap area of 7.27 mm^2 a value that can be obtained by the overlap of two 1 mm wide tracks for a length of 7.27 mm. A misalignment of only 100 µm with regard to the 1 mm wide track, would result in a 10% error or 0.4 pF.

All these boundary effects and misalignment problems can be evaded in the final product by measuring and correcting the value of the capacitor while printing it; similar to the process of laser trimming of electronic devices where, for example, the capacitance is modified by changing the size of an electrode [6]. The change of the capacity per droplet is in the range of a few aF, hence a measurement of the value while printing allows one to stop the printing as soon as the target value is reached.

Experimental

The used printing platform MicroStack3D was designed with the aim to assist inkjet printing research in various fields of applications. The design of the printer is based on modularisation; each subtask has its own module [1]. The printer has a central command unit that controls the interactions of the different modules. For the results presented here four modules are needed. Most of the ability comes through the architecture of MicroStack3D. The process can be described by the following steps:

1. A Kapton foil with a prefabricated bottom electrode and a connecting track on the topside is mounted onto a heated substrate and is connected to a capacitance module.
2. By printing silver nano-particle ink onto the top side of the foil, in contact with the existing central track, the size of the connected overlap area is increased.

3. The substrate is heated to 170°C, thereby sintering the arriving silver particle ink directly into a conductive top electrode.
4. The value of the formed capacitor is measured on-line and transferred to the central control unit through the easy expandable data framework of MicroStack3D.
5. Based on the value, further printing is performed if needed.

The four required modules are: a capacitance module to measure the current value of the capacitor, a temperature module to control the temperature of the substrate at the level needed to sinter the silver ink, a timing module that controls the printhead and the xy-stage, and a CPU Module that coordinates the whole data exchange between the modules.

To obtain the described functionality with MicroStack3D, the only new module was the capacitance module. The built capacitance module basically consists of a controlling ATMega and two capacitance-voltage-converters (CVC) ICs (Figure 1).

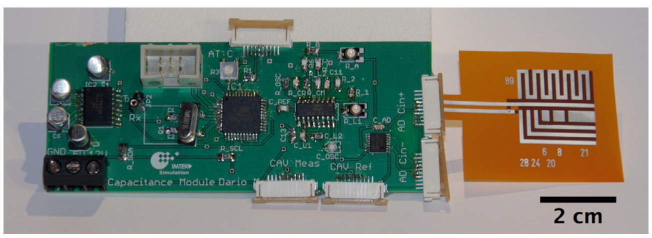


Figure 1. *Capacitance Module offering three different measurement methods. Two are relative measurement, that detect the change of a capacitor relative to a reference. The third method is an absolute one.*

Two different CVCs are used to increase the range of measurable capacities, additionally an RC circuit, based on the µC is implemented. The most accurate of the three options is an AD7745 from Analog Devices (Norwood, Massachusetts, USA), it can detect changes in capacitance of up to ±4 pF. The chip gives a 21-bit digitalised signal over I2C and has an accuracy of 4 fF.

The second chip is the comparative sensor CAV424 from analog microelectronics (Mainz, Germany). The IC measures the capacitance of one capacitor relative to another one, the measurement capacitor must be between 105-200% of the reference capacitor. The device can measure capacities in the range from 10 pF to 2 nF. The created output signal is a voltage level, that is analysed by the ATMega32.

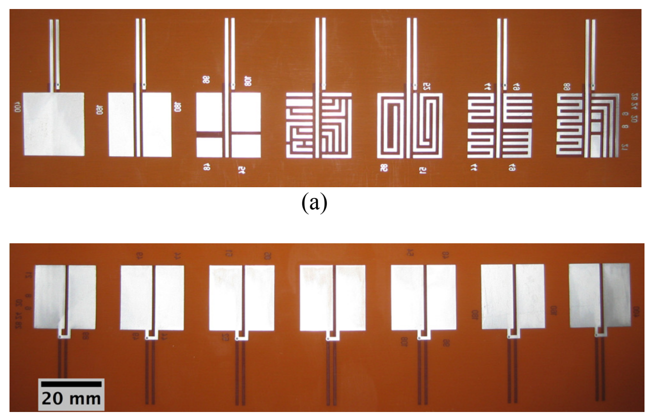
A third option is the use of an RC circuit, it is the most flexible one, the measured capacitance is charged over a known resistor and the time to reach a certain voltage is measured by the ATMega. The voltage at the capacitor, U(t) follows this equation

$$U(t) = U_0(1 - e^{-\frac{t}{RC}}) \qquad (2)$$

with U_0 being the 5 V from the output pin of the ATMega. The time passed till t equals RC, is measured, which indicates when the capacitor is charged by e^{-1} or $\approx$63%. As R is known precisely, C can be calculated. Using different values for R the measurable range can be adjusted. The resolution of the signal is in the time domain and can therefore be measured accurately. The value measured by one of the three approaches is transferred from the capacitance module using the data framework of MicroStack3D to the Display-CPU module. From there it is sent to the timing module, which decides if another droplet is needed and where to place it.

To connect the capacitors with the CVCs, short cables should be used, as all cables exhibit a certain capacitance per unit length. To keep the cables short the capacitance module should be close to the substrate, therefore, the PCB from Figure 1 is used without a box and placed directly next to the stage.

As the estimation of the capacitor's value with a certain printed overlap area is fairly precise, feedback controlled printing is only needed at the end. Hence, like for the laser trimming, standard devices are fabricated that are then modified. In this case instead of printing the whole capacitor area, plate capacitors are prefabricated using standard flexible PCB technique. To maximise the flexibility the prefabricated capacitors consist of 2 mm x 2 mm counter electrodes and different sized metal patches as top electrodes. Figure 2(a) shows different versions of these patches on the top side of the substrate. In the middle of each capacitor two long tracks can be seen that lead to the contact clamps. The left one is the central track for the top electrode. The right track is for the bottom electrode that is connected through a via.



(a)

(b)

Figure 2. *Top and bottom electrodes fabricated on a flexible Kapton foil using a standard process by Contag. The top electrodes can be modified by inkjet printing silver ink to connect the metal patches to the central track.*

Figure 2(b) shows the bottom electrodes that cover the full 4 mm^2 with the exception of a central area. This space is at the position where the central track runs on the top side, by leaving this metallisation away the offset capacitance is minimised.

The tuning is done by connecting patches to the central track, thereby increasing the overlap area by the size of the patch and the inkjet printed connecting metal part. The inkjet printed silver ink is only conductive if sintered at 130°C. Therefore, the printing platform keeps the PCB on the substrate at 150°C, thereby sintering the arriving droplets immediately. After sintering ($\approx$1 s) the droplet becomes part of the top electrode enlarging the size of the electrode.

To inkjet print the SunTronic silver ink, a 200 µm nozzle diameter PipeJet printhead from BioFluidix was used (BioFluidix GmbH, Freiburg) [7]. The printhead is a 200 µm wide plastic tube that is actuated by a piezo that squeezes a small droplet of ink out of the tube. These printheads were chosen, because they are cheap and operating the printheads with silver ink closely over the heated substrate might lead to accidental, non-reversible sintering inside of the nozzle. The use of such a fairly thick nozzle has a second advantage. The copper layers of the prefabricated PCBs have a thickness of 36 µm, hence the printed silver ink has to overcome that step to form a stable electrical connection. The ink has a silver content of ~2%, even for a 200 µm diameter droplet this only gives a few microns of silver, smaller droplets give respectively less silver per droplet.

Results

Before using the capacitance module in the printing process it is tested and calibrated. The RC circuit is used to measure values from a capacitive decade, which is connected to the setup. Figure 3 shows the results of these measurements. The measured values are on a straight line and the error bars are small, hence the measurements are both accurate and reproducible over a range of 4 orders of magnitude.

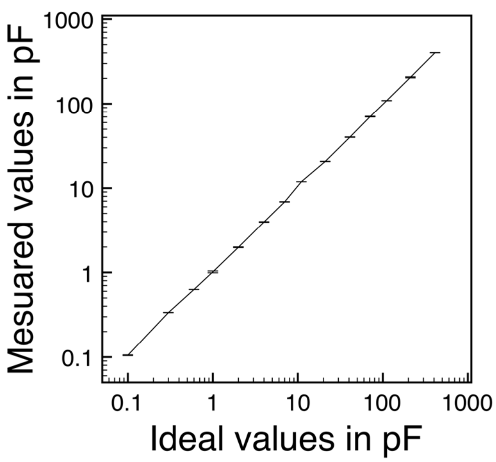


***Figure 3**. Measurement of a capacitive decade using the RC circuit of the Capacitance module. The linearity of the results shows that the measurements are accurate, while the small error bars indicate the good reproducibility.*

In a next step the system was used to measure the capacitor that is modified by connecting the patches on the prefabricated capacitor through inkjet printing. One of the prefabricated capacitors is placed on the heated aluminium substrate. To reduce unwanted effects by the aluminium substrate a 25 µm thick Kapton foil is placed in between the substrate and the PCB. The thin foil separates the bottom electrode of the capacitor from the substrate but does not prevent the heatflow from the substrate to the prefabricated PCB. To further reduce side effects the first overlap area is obtained by closing the gap in the bottom electrode, thereby causing an overlap area of 20 mm^2 from Figure 4. Now the capacitor is placed onto the 25 µm foil with the bottom electrode facing the substrate. The prefabricated PCB is aligned under the printhead and mechanically fixed to the substrate.

The metal patches were connected one after the next. After each inkjet printed connection the ink was given one minute to sinter and form a conductive connection. In Figure 4 the measured capacitor values are plotted against the overlap area that was connected to the central track at the time of measurement. The overlap area was determined, including the printed connection, via optical inspection.

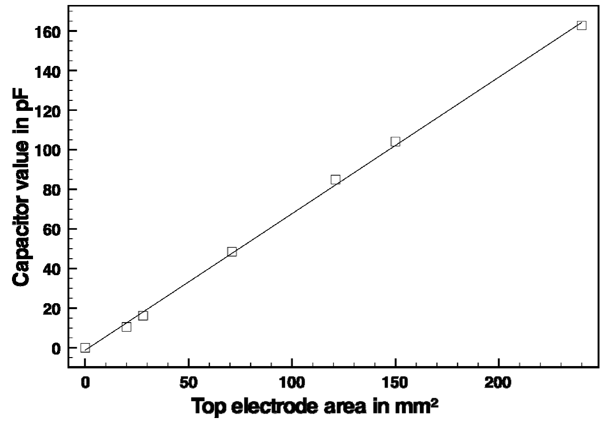


***Figure 4**. The value of the capacitor scales accurately with the increasing overlap area of the electrodes.*

The highly linear increase of the capacitor value with the increase of the top electrode area shows that the approach with the metal patches gives the same capacitance per area as the inkjet printed parts. Therefore, the use of standard prefabricated capacitors with connectable metal patches reduces the production time without reducing the flexibility or linearity.

The values were sent to the computer by the timing module, therefore the values first needed to be transferred from the capacitance module to the timing Module. In the timing module the value can also be used to control the printhead behaviour instead of sending them to a computer. This full feedback control was not yet tested because the printhead started to leak ink due to the heat radiation of the substrate that lowered the ink’s viscosity. A pressurisable reservoir that prevents that leaking is under development.

Conclusions

The functionality needed to use inkjet printing within a feedback controlled production process was implemented and tested for the example of tuning capacitor values. The functionality of the logical structure was tested and works properly. The approach could also be applied for the trimming of resistors, but as the resistivity of the sintered silver is dependant on sintering temperature and time, the measured value might change during some other post-processing or during operation. For the capacitors this is not a critical concern, as the capacitor value hardly depends on the resistivity of the plates.

Outlook

The possibility of using measurement results directly to drive the process allows for a wide range of research topics. This approach can be adapted to all fields of applications where inkjet printing modifies a measurable property. It can be used for the fine tuning of, for example, resistors, inductors, resonators and chemical properties.

References

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Author Biography

Dario Mager obtained his Diploma Degree in MEMS-Technology at the Department of Microsystems Engineering (Freiburg, Germany) in 2004. In his thesis he simulated CMOS based piezo resistive stress sensors. He is currently finishing his PhD Thesis in the Laboratory for Simulation at the same institute. The topic of the work is using inkjet printing for microstructuring. He introduced IJP to the fabrication of resonant receiver circuits for Manetic Resonanc Imaging and built the printing platform used in this paper to make IJP available for different new applications.