3D Printed structural electronics

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3D Printed structural electronics: embedding and connecting electronic components into freeform electronic devices


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3D Printed structural electronics: embedding and connecting electronic components into freeform electronic devices


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ABSTRACT
The need for personalised and smart products drives the development of structural electronics with mass-customisation capability. A number of challenges need to be overcome in order to address the potential of complete free form manufacturing of electronic devices. One key challenge is the integration of conductive structures and components into 3D printed devices by combining different materials and printing techniques that have nearly incompatible printing conditions. In this paper, several methods to integrate electronic circuits and components into a 3D printed structure are discussed. The functional performance of the resulting structures is described. Structural parts were manufactured with a stereolithography-based 3D printing technique, which was interrupted to pick and place electronic components, followed by either direct writing or squeegee filling of conductive material. A thermal curing step was applied to enhance the bonding and improve the electrical performance. Optical micrography, 4-point resistance measurement and cross-sectional analysis were performed to evaluate functionality.

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Introduction
Additive manufacturing (AM), also known as 3D printing, allows the manufacturing of products with complex geometrical structures. Furthermore, it allows more freedom to design and customisation of products, enabling (for example) the construction of micro channels and other internal structures which can be used for cooling integrated components. This enables a resource efficient production and faster time to market of critical products in small volumes [1].

Combining AM and electronic integration can give rise to immense potential in manufacturing electronic devices that are free of printed circuit boards (PCBs). This method is referred to as 3D printed structural electronics (3DPSE) [2]. 3DPSE is an emerging field of technology that enables complete freedom of manufacturing in various form factors. This technology combines conventional AM techniques with pick and place and direct write techniques, in order to fabricate complex structural parts with integrated electronics, without the need for product-specific tooling. It has the potential to unlock various application domains where conventional manufacturing techniques are not cost-effective. Potential applications include (but are not limited to) customised lighting [3], antenna structures [4] and wearable electronic devices [5]. There are a number of challenges in terms of materials, tools and processes that need to be overcome to achieve this high integration potential. More specific challenges in achieving a high level of 3D integration, a good electric performance and a reliable and cost-effective process are addressed. In this paper, we discuss the state-of-art and challenges related to the integration of conductive tracks for functional electric circuitry in 3D printed parts.

Experimental methods
As mentioned in the introduction various technologies have to be combined to achieve the full freedom in manufacturing of products. This section discusses an overview of the experimental methods used to demonstrate the 3DPSE capability.

Additive manufacturing
In this study, we focused on SLA (stereolithography)-based techniques for manufacturing of the experimental parts into which the conductive tracks and the components were integrated. Two types of systems were used to build the 3D products from an experimental photosensitive resin mixture. A number of test specimens were built using a mercury-vapor-lamp-based S60 mini SLA system from RapidShape (see Figure 1). Additionally, the larger and geometrically more complex products (TNO logos) were 3D printed on
an experimental multiple 405 nm laser-diode proprietary research platform (see Figure 2).

The resin mixture was designed to withstand elevated temperatures in the range of 100–150°C for extensive periods, thus enabling them to be combined with patterning technologies that require thermal processing steps. The resin mixture contained UDMA (provided by Vertex), Bis-EMA-4 (SR540, provided by Arkema) and 2 wt-% photo-initiator Irgacure 819 (provided by BASF), and 0.017 wt-% of a blue light-blocking dye. All test specimen was printed in 50 µm layers and at an energy density of 20 mJ cm$^{-2}$, either by simultaneous illumination of the complete layer in case of the S60 printer, or by scanning illumination at 100 mm s$^{-1}$ by the laser-array based printer. To house and align electronic components and wires, cavities and channels of various sizes were printed within the specimen, as shown in Figure 3. After placing the components the channels were filled by conductive material in a subsequent process step to form PCB-like conductive circuitries (tracks).

After placement of the electronic components and conductive tracks, additional layers were 3D printed to encapsulate the electronic circuitry and to finalise the 3D part (see Figure 4). During the entire manufacturing process, the parts were attached to the same build platform to ensure the required alignment between the successive process steps. After each printing step, the test specimen was cleaned ultrasonically with ethanol.

**Component placement**

A key challenge of the entire process was the alignment accuracy of integrated electrical components into the defined cavities. Most of the electronic component packages were designed for 2D placements and not for 3D integration. In most of the cases, the pad locations were defined relative to the overall package dimensions. Furthermore, these components appeared to have large tolerances that become a challenge since the 3D printing process has an accuracy of ±10 µm.

**Integration of conductive tracks**

Conductive tracks were deposited on the 3D printed part using a commercially available conductive paste (5064H) from Dupont. This paste contains 63–66 vol.-% of micro-sized silver flakes and has a viscosity of between 10 and 20 Pa s [6]. The deposited paste was dried/cured in an oven at 120°C to obtain the required conductivity. For this paper, we considered two different methods of track deposition, (i) the filling
of predefined channels via a squeegee and (ii) the dispensing of material using a direct write system.

For the squeegee method, the 3D printed part was cleaned and dried in an oven at 40°C for 30 min, and then again cleaned using a water/soap mixture and left to dry for 24 h. The conductive paste was deposited in the channels using a rubber squeegee, by applying a large amount of paste at one side of the sample, and then manually pushing it to the other side with the squeegee at a 20–30 mm s\(^{-1}\) speed. The squeegee was held at an approximate 45° angle at all times, as a light downwards directed force (estimated 4–8 N) was applied. In this way, several channel widths and depths were filled. Although expected to have an influence on the ability to fill structures of various dimensions (for example width and depth of the channels), the following parameters were not varied: speed, pressure, angle, squeegee shape and squeegee material.

Several technologies are available for direct deposition of the printed tracks such as inkjet [7], aerosol jet [8] and extrusion [9]. In this research, the extrusion technology has been selected because of the high-viscous ink capability [5]. It is also one of the most commonly used techniques in microelectronic industry in dispensing conductive and nonconductive materials. High-viscous micron-particle-based inks, which contain larger particles and less binder content, were applied because of their inherent good conductive performance. As these inks result in improved connections between components and wires, they allow for more flexible designs.

In extrusion based direct write systems, proper considerations must be given to the start/stop behaviour and print height adjustments. Proper care was taken in designing the extrusion system to address these issues. As an initial set of experiments, the process parameters listed in Table 1 have been investigated. These experiments were all performed with the 5064H material. As can be seen in the table, nozzles as small as 0.1 mm are used. The smallest nozzle clogs quickly, which may be caused by high extrusion pressures required. Track widths as small as 0.2 mm can thus be made reliably. This is comparable to the industry standard of around 10 mil (0.254 mm) for the smallest PCB track width in a regular PCB.

### Analysis

The results obtained with the squeegee and the direct deposition method are discussed in this section. As the squeegee process is a non-standardised, exploratory process, it is tested for passive component integration, microcontroller integration and multilevel via the integration potential. As mentioned in the section 'Experimental methods', the conductive tracks are defined first by the channels formed by the 3D printing process and later filled by the conductive materials.

### Squeegee method and embedding components

The squeegee and extrusion methods were applied to make samples with conductive tracks and embedded components. A key advantage of the squeegee method over the extrusion technique is the capability to print large areas in one stroke. In addition, the pattern definition of the circuitry is defined by the 3D print process. The squeegee method, however, requires a planar surface without holes, which limits the design space. However, this problem can be solved using a support material. In the future, we envision the use of both techniques in unison towards realising freeform electronics.
Figure 5 shows the test sample which has conductive tracks made by filling the channels using the squeegee technique after the components were placed into the cavities. The sample consists of 6 SMD resistors (0805 type package) that are connected in parallel, and 6 SMD capacitors (also 0805 type package) that are connected in parallel as well.

A cross-sectional analysis was carried out to study the quality of the track connections onto the contact pads of the components. The result is shown in Figure 6. Cross-sectional images were taken using a Keyence VHX600 digital microscope with ×20–200× objective.

From Figure 6 it can be seen that the SMD components are well embedded in the printed structure. No voids can be observed around the components. This indicates that the small space between the components and the 3D printed cavities was nicely filled with resin during the placement of the component and that this resin was cured during post-curing of the part. There is no apparent effect of the polymerization-shrinkage of this resin, although some minor internal stresses are expected to be present. It can also be seen that the conductive paste has shrunk extensively during drying and curing. Especially on top of the components contact points (where the paste layer was at its thickest) shrink holes are visible and the printed track seems distorted. Nevertheless, this compaction seems to have rarely caused contact break between the conductive track material and the SMD components and/or the printed part. Moreover, all the components showed galvanic contact that proves that the tracks are connected to the embedded components. Cross-sectional images of the same areas were taken using a FEI Quanta 600 SEM with an accelerating voltage of 15 kV, see Figure 7.

The SEM image indicates that the drying/curing of the paste resulted in a well densified track, that is well adhered to the electrical contacts of the SMD components. With the same manufacturing method, a second test sample with a microprocessor (Atmel 32U4, TQFP package) was integrated in a 3D printed part with conductive tracks connecting the pads and pins, see Figure 8.

Unlike the previously mentioned passive components, this specific component has protruding connecting pins. A cross-section through the centre of one of the contact pins was made for SEM analysis, see Figure 9.

Following the same manufacturing process, samples with multilayer conductive tracks were made, as shown in Figure 10. The rationale behind this experiment was to see if a via structure can be made using the 3D printing process and that this via can be used to connect two crossing conductive tracks. The galvanic connection was confirmed using a Keithley DMM2000 multimeter. Cross-sectional images were taken using the Keyence VHX600 digital microscope with ×20–200× objective, see Figure 11. The images show a good connection between the horizontal tracks through a relatively thin vertical connection. The bottom track appears to be shrunk less than the other tracks, which indicates...
that the original *shrink hole* was partially refilled when the vertical connection (the via) was created.

The cross-section of the bottom track in Figure 11 was measured to be 0.049 mm$^2$ by pixel counting. The resistance over a 10 mm distance was measured to be 152 m$\Omega$ using a 4-point measurement setup using a Time Electronix DC Current Calibrator model 1024 set to 10 mA, in combination with a Fluke 289 Multi-meter set to the mV range. A resistivity of $744.8 \times 10^{-9} \Omega \cdot \text{m}$ was calculated, ignoring potential variations is cross-section. This calculated resistivity is approximately 44 times higher than that of bulk copper.

**Direct write and embedding components**

The extrusion method to make conductive tracks via direct write without predefined channels was discussed in the section ‘Experimental methods’. The cavities for the SMD component placement were still needed for complete seamless integration. Building of 3D printed circuitry samples was done by 3D printing of the cavities, placement of the SMD components and extrusion of the conductive tracks to connect the leads to form a circuitry. In a next step, a resin layer was deposited to encapsulate the entire circuitry. A technology demonstrator was fabricated, consisting of a 3D printed body, an embedded microcontroller, a battery casing, integrated LEDs with a capacitive touch sensor (using conductive paste) and interconnects. Figure 12 shows the functional device with a functioning LED light.
In order to analyse the robustness of the process, a cross-sectional analysis of the sample was performed with the images taken by the Keyence VHX600 digital microscope, see Figure 13. It can be seen that the track is well covered with the top resin layer that acts as an encapsulation layer.

Discussion

The custom photo curable 3D print material seems to combine very well with the conductive track material; no disadvantageous effects were observed caused by the thermal drying and curing cycle at 120°C. It appears that due to a very good wetting and bonding of the two materials, no cracks were observed in any of the sections made. There was a significant amount of shrinkage noted in the conductive material after drying and curing. This resulted in a distortion of the track geometry which leads to holes or hollowing of the tracks.

Both the squeegee filling and the direct writing of tracks resulted in functional structures. The squeegee filling method allows for more control over the exact track geometry in both width and depth, but the downside of this approach is the potential contamination of surfaces alongside the channels and in the cavities of the printed part by the conductive paste, which will remain in position during the successive printing of layers and may eventually cause short circuitry. In the case of direct writing of the conductive tracks, care needs to be taken to assure a good alignment between the subsequent process steps, and optimised tooling paths need to be developed in order to improve the connection between tracks and connecting pins and pads and between tracks in case of a via.

Although a working via was presented, it remains uncertain if longer (deeper) vias are possible. The shrinkage of the conductive paste upon drying and curing may be a limiting factor when multiple layers of conductive material are stacked on top of each other and subsequently dried and cured. It may be necessary to repeat the process of via filling and subsequent drying/curing multiple times to compensate for the shrinkage effect.

Conclusions and future outlook

This paper demonstrates that 3D printing of compact 3D structures with integrated electronic components and conductive tracks is possible by combining a SLA process with pick-and-place techniques, squeegee filling and direct write technologies. An off-the-shelf conductive paste 5064H by Dupont has been used in combination with a specially developed photopolymer mixture which is thermally stable at the elevated temperatures that are required to cure the conductive paste. Standard SMD components were fully embedded, resulting in a virtually pore-free integration.

There was substantial shrinkage found of the conductive paste after drying/curing, which resulted in distorted track geometry. Nevertheless, in none of the cases this shrinkage resulted in disconnection between the track and the embedded components, which indicates that a reliable process is feasible.

Resistivity of the squeegee-applied track material was found to be approximately 44 times higher than that of bulk copper, which makes it feasible for a wide range of low current electronic applications. Further research is recommended targeting improved geometrical quality of the printed tracks by reduction of, or compensating for the drying and curing shrinkage of the conductive material. In addition, the conductivity of the tracks can be increased by further development of the material and improvement of the post-processing. The various process steps can be further automated and integrated using vision systems. Finally, thermal management of the heat dissipated by the embedded components and electric reliability of the structures by conformal (3D printed) cooling can be addressed by tuning the thermal material properties.

Disclosure statement

No potential conflict of interest was reported by the authors.

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