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3D-printed sensor electric circuits using atomic layer deposition

Authors: Antti Kestilä¹*, Marko Vehkamäki², Leo Nyman³, Mika Salmi⁴, Jarkko Lohilahti⁵, Timo Hatanpää², Ugo Lafont⁶, Mikko Ritala²

Affiliations:

- ¹ Finnish Meteorological Institute; Helsinki, 00970, Finland.
 - ² Department of Chemistry, University of Helsinki; Helsinki, 00014, Finland
 - ³ Department of Electronics and Nanoengineering, Aalto University School of Electrical Engineering; Espoo, 00076, Finland
 - ⁴ Department of Mechanical Engineering, Aalto University School of Engineering; Espoo, 00076, Finland
 - ⁵ Maker3D Ltd. ; Helsinki, 00150, Finland
 - ⁶ESTEC, European Space Agency, Noordwijk, The Netherlands
 - *Corresponding author. Email: antti.kestila@fmi.fi

15 Abstract

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3D-printing, or additive manufacturing has enabled the manufacture of dynamic shaped objects often customized for specific applications. Many applications, such as sensors in the aerospace industry, have demanding mass and volume requirements or need to work in difficult environments that necessitates electronics to be protected. The combination of dynamic shapes and electronics could open new applications not possible previously. We introduce a novel 20 manufacturing method capable of integrating a complex electric circuit consisting of several, commonly available electronic components with a 3D-printed object. It is printed with a commercial printer and coated using atomic layer deposition. Different printable polymers and coatings were tested to find two polymers printable into one object and enabling selective conductivity when coated with conductive coating. Selective conductivity through coating is 25 achieved when one polymer exhibits poorer and more non-continuous coating growth compared to the other. The printed object three-dimensional shape and details were used to create the electrical circuit and aid in achieving selective conductivity. A demonstration consisting of an ultraviolet light (UV) sensor, based on an existing traditional circuit board, was replicated and tested. The novel circuit output closely followed the original. The presented method can combine 30 an electric circuit with the dynamic output of a 3D-printer, enabling savings in existing applications as well as new applications.

Keywords:

35 Additive manufacturing; 3D-printed sensors; UV – sensor; atomic layer deposition; electric circuit

1. Introduction

3D-printing, or additive manufacturing, is a technology which manufactures an object directly from a three-dimensional model adding material on a layer-by-layer basis [1]. 3D-printing is extensively utilized in industries such as aerospace, automotive, medical, consumer electronics and energy [2]. 3D-printed electronics are a rapidly growing field of technology involving 3Dprinting techniques to create electronic components and devices. 3D-printing allows a wide variety of shapes and provides more design freedom than traditional electronics manufacturing technologies. 3D-printing electronics enables rapid prototyping and production of complex electronic devices and offers new possibilities for customization and flexibility in a wide range of applications such as sensors. Precision and elegant techniques are needed in manufacturing of sensors, and AM has been utilized in fabrication of these parts in previous years [3]. The ability to integrate printed circuit boards (PCB) and electronic assemblies directly onto a variety of 3Dprinted structures also opens possibilities for embedded and multi-functional applications. Current PCB-based electronics are limited by their flat shape and require separate attachment and wiring interfaces. Fully integrated systems and less manufacturing steps would improve the manufacturing process. Volume and mass savings can be gained and more demanding applications are achievable when the electronics can be placed more freely. Different 3D-printed electronics manufacturing methods have been developed over the years [4]. Various kinds of conductive and non-conductive materials have also emerged alongside these methods. Typically, 3D-printing processes such as material extrusion and material jetting are used to make electronics and most often parts made are flat or follow a simple surface [5]. Currently 3Dprinted circuit board making is time consuming, have high costs and can be applied in limited use-cases. 3D-printing has been demonstrated for embedded electronics by stopping the printing during the process, with a hybrid process such as combination of material extrusion and vat photopolymerization for 3D structural electronics and stretchable electronics over fabrics [6].

Atomic layer deposition (ALD) [7] is a variant of chemical vapor deposition (CVD). In ALD, reactants are pulsed separately into the reaction chamber and the reactant pulses are separated by inert gas purging steps. This eliminates gas phase reactions and confines growth reactions to the coated material surface. Several benefits are achieved this way, such as excellent and very conformal surface coverage, good pore penetration and large-area thickness uniformity. The most widespread application of ALD grown thin films are in microelectronics [8]. The miniaturization of microelectronics devices has led to extreme nanoscale and extensively three-dimensional device structures, which have material layers that cannot be fabricated by coating methods other than ALD. For example, all current high-end microprocessors and memory devices require ALD films. Another important modern application area is the surface passivation of solar cells with ultra-thin ALD insulator layer [9]. In the past the majority of ALD applications involved film growth on inorganic surfaces, but applications of ALD on organic materials including polymers is a rapidly developing area. For organic materials, the availability of low-temperature ALD processes is an important advantage. ALD has been studied for surface

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modification of thermoplastics [10] and performs well in the deposition of gas-permeation barriers on polymers [11].

The aerospace industry has been one of the most active adopters and users of additive manufacturing. Regarding space industries and in-space use, application areas of additive manufacturing (3D-printing) can be divided into several categories. Production of basic structural elements is an obvious application area, and many in-use satellites already have additively manufactured components. Arguably, in this area, the biggest impact in the future will come from in-space manufacturing capability. In-space printing of tools and spare parts has been demonstrated in the International Space Station (ISS) [12]. NASA's OSAM-2 project aims to demonstrate a ten-meter extended structure using additive manufacturing on orbit [13]. When mature, this technology could enable on-orbit production of large-scale antenna, solar array as well as micrometeoroids and orbital debris shielding [14] systems, without the inherent limitations (such as volume and mechanical) imposed by the launch phase. 3D printing can also be used to produce compliant mechanisms (CM). These types of mechanisms have many benefits when used in spacecraft, such as enabling the designer to avoid lubricated joints, that in the long term suffer from degradation due to the space environment. In this respect, 3D-printed compliant mechanisms have been developed for use in spacecraft [15], one good example being flexible joints for solar arrays. Other attempts were made to promote the use of 3D printing for spacecraft component production: a CubeSat consisting of integrated 3D-printed structures with embedded electronics using a vat photopolymerization method was launched but the photocurable materials used did not provide the required durability for long-term operation [16].

Integrating electronics into 3D-printed parts that are designed to have flexibility can enable new application areas and can enhance the performance of existing technologies. For example, electronics can be embedded into inflatable structures or structures that need to withstand morphing, enabling health monitoring and other important functions. [17][18] discuss many examples of flexible electronics in space applications including sensors, memory and logic functionality, communication systems, batteries, integrated electrical paths and their structural, thermal and electrical durability.

This work presents the results of a study aiming to integrate electric circuits into a 3D-printed part for a sensor application by combining 3D-printing of thermoplastics using the Fused Filament Fabrication (FFF) process and ALD. A freeform polymer shape is first produced with a 3D-printer and then coated with a thin conductive coating. The shape and the chosen material affect the quality and uniformity of the coating. However, such process combination enables selective conductivity and the creation of detailed electrical pathways that can be used to build a circuit using small electrical components. The components connected to the circuit using with silver epoxy and can be attached anywhere onto the coated print. The electric paths can go through the 3D printed parts via tunnels. A wide variety of shapes are possible, such as protrusions, depressions, cavities and thin shapes, and are limited only by the 3D printer resolution and ALD-reactor capabilities. In order to show that the concept was feasible, an existing ultraviolet (UV) light sensing sensor circuit was selected as baseline, reproduced with

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the method described in this work and tested. This type of sensor was chosen based on its potential application in space – as polymers subjected to degradation are vulnerable to UV-light, an integrated UV-sensor would be a valuable addition.

A novelty in this approach is that multi-component circuits can now be integrated into a plastic part printed with a household printer. The process imposes no special requirements on the electrical components themselves, so commonly available components can be used and be connected onto the circuit. In order to create the conductive path, the produced parts need to be coated using a specialized ALD-reactor, with the advantage that the coating is done in one step and that several 3D printed parts can be coated simultaneously. Compared to existing methods where wires and components need to be embedded during printing with the need of constantly stopping and resuming the printing process, this method is easier and faster with great potential for mass production.

For space applications, choice of circuit material is limited to the one with compliant outgassing properties as per ECSS-Q-ST-70-02C standard [19] where only material with a Recovered Mass
Loss < 1% (RML) and a Collected Volatile Condensable Material < 0.1% (CVCM) can be used in space. For the present work, selection of polymer materials and coatings enabling selective conductivity was performed based on previous results that demonstrated good (compliant) outgassing tendency of ALD-coated 3D-printed polymer-samples in a vacuum environment [20] [21], showing that ALD Al₂O₃ coating reduces outgassing significantly, specifically by approximately 50% as shown in [21]. The outgassing was measured by utilizing a residual gas analyzer (RGA), and by integrating the sum of partial pressures of the constituent components in the RGA data. Besides enabling novel surface properties, the ALD coating thus also increases the choice of available thermoplastics for space application.

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2. Materials and Methods

The steps in the manufacturing process described by this work are shown in Fig. 1. The process starts with a circuit design from which the 3D-printed part is designed. The Rhino 6 CAD-software was used for the design, but any commonly used design software is sufficient. The design was exported to an STL-format file, which was then sliced into a G-code file with the publicly available UltiMaker Cura. The G-code file is the input with which the 3D-printer prints the part. Several parts were 3D-printed during one session and visually inspected. The parts were placed in an ALD-chamber and coated. The electric conductivity of the coated part was evaluated. Finally, the electric components were glue on their designed surface locations using conductive silver epoxy.

In this work Al_2O_3 and copper ALD processes were used. The main limitation for the choice of ALD materials is the need to deposit them at around 100 °C to minimize thermal degradation of the 3D-printed polymers. For Al_2O_3 , a growth process based on trimethyl aluminum $Al(CH_3)_3$

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and water, originally demonstrated by Higashi and Fleming [22], was used. This process shows excellent pore penetration, good growth rate and typically good adhesion on many kinds of materials. The only key weakness of ALD-grown amorphous Al_2O_3 is its poor etch resistance in aqueous solutions. For conductive coating materials, the choice of good low-temperature processes is limited. The copper process using Bis(dimethylamino-2-propoxy)copper(II), Cu(dmap)₂, and tert-butyl hydrazine produces good quality copper films in the temperature range 80-120 °C [23] and was selected for this work. The ALD films were grown in a Picosun R-150 reactor at a growth temperature of 100 °C. The passivation and copper steps were done as separate steps, typically by batch processing Al_2O_3 on multiple 3D-prints and then ALD coating a single 3D-printed and Al_2O_3 passivated piece with copper together with a reference silicon wafer.

For the 3D printing process, fused filament fabrication (FFF) was chosen using a Ultimaker S5 Pro Bundle with two extruders (Ultimaker B.V., Utrecht, Netherlands). The building platform was a glass plate. The materials selected were acetonitrile butadiene styrene BASF ABS Fusion+ (BASF SE, Ludwigshafen am Rhein, Germany) and polypropylene Ultimaker PP (Ultimaker B.V., Utrecht, Netherlands). They were selected due to their easy printability, good resilience to selected coating reactor temperature and different coating qualities, enabling selective conductivity. BASF ABS Fusion+ was printed with 0.25 mm nozzle (printcore AA025), printing speed 55 mm/s and extruder temperature of 225°C. Ultimaker PP was printed with a 0.4 mm nozzle (printcore AA04), printing speed 25 mm/s and extruder temperature 205°C. Infill setting for both materials was 100% and layer height 0.1 mm.







Fig. 1. a) The original baseline circuit and PCB [24] b) A CAD-design of the 3D-circuit. The original circuit is implemented in a new 3D-printed form. c) Cross-section printing patterns of one print layer for the printed sensor as seen in the print preparation slicing software. Red indicates where the polypropylene is, while yellow, gray and green are where ABS has been printed. d) Two examples of the ABS (black) – polypropylene (white) printed substrate. e) The coated part. f) The 3D-printed sensor with its electric components. Conductive silver epoxy is used to attach the electrical components and is not shown in this image.

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3. Results and Discussion

The printed sensor was designed to show clear novel and three-dimensional elements, while replicating as close as possible the functionality of the original circuit (Fig. 2). All of their electronic components and circuit layout were the same. The UV-sensor is capable of sensing UV-A and UV-B. The electrical components were chosen to be surface mounted and represent typically used components. A 'hill-like' protrusion was printed to show how critical electrical paths such as electrical ground can traverse along a complex three-dimensional shape with thin shapes. A tunnel was printed into the protrusion to connect one electrical pathway between the microcontroller and the UV-sensor.



Fig. 2. The printed sensor overview and layout. The print outer dimensions are 33 x 23 x 8 mm. The print included a protrusion over which the circuit paths had to go, and a tunnel for one path. The valley bottoms were made out of insulating polypropylene and the main body was printed from ABS. The sidewall structures (holes, deep valleys and sidewalls with sharp corners), together with the buried insulator, work to provide electrical isolation of printed regions.

20 The electrical circuit paths were formed by surrounding them with deep valleys easy to make with additive manufacturing. The valleys bottoms were polypropylene while main body was printed from ABS. The polypropene was to act as a non-growth surface where neither ALD Al₂O₃ or copper grow. Valleys with polypropene bottoms act thus as insulating areas.

The size of the print was made slightly larger than the original PCB to better investigate how well it works, and its base plate was designed to be large enough for easy handling and safe placement into the ALD-reactor.

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A combination of a thick (> 1 micron) Al_2O_3 passivation coating and a thin copper layer was found to work well in making the 3D-printed sensor template surface conductive. Thinner passivation layers (100–200 nm) were also tested, but more variation in local conductivity, as measured with simple 2-point probe contacts, was observed. The best results, namely conductivity over sidewall structures and low enough overall resistance was obtained with thicker passivation coatings.

The reference silicon wafer was used to determine the Al_2O_3 and copper coating quality. It also served to determine the conductivity of the coating itself without the influence of the polymer substrate. After the 3D-printed part was coated, visual and SEM-based inspection was performed to understand what defects in the polymer substrate decreased surface conductivity.

The printed UV-sensor functionality was compared to the original reference UV-sensor [24]. Both were placed under an Osram Ultra Vitalux 300 W UV-lamp and their circuit outputs were recorded when the lamp was started (see Fig. 3).



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Fig. 3. (left) The functional test setup. Both the printed sensor and the original were placed directly under a OSRAM Ultra Vitalux 300W UV-lamp and measured the strength of the emitted UV. V_s represents 5V supply voltage and V_o is the circuit output signal. (right) The printed sensor used in the functional tests compared to the reference. The original circuit is a regular PCB-based UV-sensor [24]. Both have identical components and electrical designs.

The interaction between the 3D-print polymer surface features and the coating affects the coating quality. Due to the layered manufacturing process 3D-printed objects have discrete lateral layers and wire mesh-like material texture. The contact interfaces between printed layers and lines are the most challenging features for any follow-up coating process. A thick oxide can effectively fill any cracks, voids or buckling on the object, facilitating the formation of a continuous conductive surface during copper deposition. The choice of polymer material has a strong

influence on the surface conductivity. The polypropylene used in the 3D printed valley structures is not favorable to ALD growth, and even after successfully coating the surrounding ABS material, Al_2O_3 and copper do not form continuous layers on the polypropylene surface. The demo UV-sensor discussed in this work had film thicknesses of 1.1 micron and 40 nm for the Al_2O_3 and Cu layers, respectively. Besides the ALD coating, the print surface was not post-processed.

The 3D-prints themselves had constraints typical for a FFF-based manufacturing method. The print shape can be very dynamic, but details such as sharp features and bridges need to be more carefully considered. Tunnels through the 3D-print acting as conducting channels are possible and demonstrated with the UV-sensor demo.

The functional test results can be seen in Fig. 4. The shape of the output signal is very similar to that of the original circuit, indicating that the circuit of the printed sensor functions well. The main difference comes from the ALD-coating. It increased resistance to around 10 - 50 ohms per cm and this additional resistance shifted the measured output as the effective resistor values in the circuit changed.

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Fig. 4. Comparison of the 3D-printed sensor functionality with the reference sensor acting as baseline. Several measurements were performed, represented by the individual lines. The UV-source lamp is activated and it warms up until maximum UV emission is reached when the circuit output becomes downward linear. After that the UV-source slowly within hours converges towards a certain value. The difference between the outputs (ΔV_1 and ΔV_2) is due to the small additional resistance in the 3D-printed sensor circuit lines introduced by the conductive coating layer, but overall the 3D-printed sensor is able to replicate well the original version.

4. Conclusions

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A complex circuit utilizing commonly available electronic components could be manufactured on a dynamically shaped 3D-printed structure. Shapes and features utilizing three-dimensions such as tunnels, deep valleys and protrusions were designed into the print. The circuit electrical design was kept identical to the reference UV-sensor manufactured with traditional methods. The demonstrator shown in this work produced an output signal close to the original.

Though not tested in the work, sealed circuits within a printed part might be possible. The 3Dprint is printed, stopped at a suitable layer, and the circuit coated and prepared. After that, the printing could be continued sealing the circuit inside the structure. The 3D-print itself was manufactured using a relatively common, commercially available 3Dprinter and open-source software. The limiting factors in this circuit manufacturing method are on one side printable polymer material properties and 3D-printer performance such as printing resolution, and on the other side ALD-chamber size, duration and temperature required by the process used for the coating material. If the chamber is large enough, several prints can be coated in one session.

The work has presented a manufacturing method that can improve existing sensing applications by integrating electronics with 3D-printed structures with dynamic shapes or tailored to specific application and enable novel applications that have demanding engineering parameters such as volume and mass constraints. Besides the ALD-reactor, widely available commercial-off-theshelf equipment was used.

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