Additive Manufacturing 18 (2017) 156–163

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Full Length Article

3D printing electronic components and circuits with conductive thermoplastic filament

Patrick F. Flowers, Christopher Reyes, Shengrong Ye, Myung Jun Kim, Benjamin J. Wiley *

Department of Chemistry, Duke University, 124 Science Drive, Box 90354, Durham, NC 27708, United States

ARTICLE INFO

Article history:
Received 29 April 2017
Received in revised form
13 September 2017
Accepted 1 October 2017
Available online 2 October 2017

Keywords:
Fused filament fabrication
3D printing
Electronics
Conductive filament
Circuits

ABSTRACT

This work examines the use of dual-material fused filament fabrication for 3D printing electronic components and circuits with conductive thermoplastic filaments. The resistivity of traces printed from conductive thermoplastic filaments made with carbon-black, graphene, and copper as conductive fillers was found to be 12, 0.78, and 0.014 Ω cm, respectively, enabling the creation of resistors with values spanning 3 orders of magnitude. The carbon black and graphene filaments were brittle and fractured easily, but the copper-based filament could be bent at least 500 times with little change in its resistance. Impedance measurements made on the thermoplastic filaments demonstrate that the copper-based filament had an impedance similar to a copper PCB trace at frequencies greater than 1 MHz. Dual material 3D printing was used to fabricate a variety of inductors and capacitors with properties that could be predictably tuned by modifying either the geometry of the components, or the materials used to fabricate the components. These resistors, capacitors, and inductors were combined to create a fully 3D printed high-pass filter with properties comparable to its conventional counterparts. The relatively low impedance of the copper-based filament enabled its use for 3D printing of a receiver coil for wireless power transfer. We also demonstrate the ability to embed and connect surface mounted components in 3D printed objects with a low-cost ($1000 in parts), open source dual-material 3D printer. This work thus demonstrates the potential for FFF 3D printing to create complex, three-dimensional circuits composed of either embedded or fully-printed electronic components.

1. Introduction

Printed Electronics has to date generally added value in high-volume production applications where low-cost is critical, and high-performance is not required. Printed electronics have most commonly been made by printing functional inks onto flat surfaces using printing processes usually used in the graphics industry (screen, ink-jet, flexo, gravure, etc.) [1]. Applications for low-cost printed electronics currently include RFID tags, sensors, displays, smartcards, keypads, and packaging [2]. The recent development of tools for additive manufacturing has spurred interest in applying similar techniques to the development of 3D printed electronics. Combining electronically functional materials with the ability of additive manufacturing to create complex 3D geometries from multiple materials can enable the creation of devices that simply are not possible with conventional 2D printing methods designed for the graphics industry, such as multilayer circuit boards, electrical connectors, 3D antennas, mission-specific satellite components, 3D structures with embedded electronics, and batteries [3–6]. Ultimately, the field of 3D printable electronics hopes to enable low-volume, on-site/on-demand production of highly complex and easily customizable electronic structures while reducing material waste, energy consumption, prototyping time, and cost relative to conventional electronics fabrication methods [2].

Current approaches to 3D printing electronics generally fall into one or more of the following categories: (1) surface direct write, (2) post-processing by injection or electroplating, (3) freeform 3D printing [2,7]. The surface direct write technique involves printing on a 3D surface rather than printing free-standing 3D structures. Processes that fall into this category include droplet-based (Ink-jet, Aerosol Jet^{TM}) [3,8–11], laser-based [12,13], and extrusion-based methods [14–17]. The strengths and weaknesses of these various techniques have been described in depth elsewhere [2,18]. Interest in 3D printed electronics has motivated the development of several new commercially available equipment that use these different processes. For example, Nano Dimesion's DragonFly 2020 (available for ~$50 k and released in 2016) enables multilayer printing of conductive traces using an inkjet technique at a lateral resolu-

* Corresponding author.
E-mail address: bjw24@duke.edu (B.J. Wiley).

https://doi.org/10.1016/j.addma.2017.10.002
2214-8604/

tion of ∼30 μm [19]. Currently this printer utilizes proprietary Ag and dielectric nanoparticle inks. In general, it can be very difficult and time consuming to develop novel electronic inks for ink-jet processes due to the need to tune the surface tension and viscosity (8–12 cp) of the ink to obtain a desired droplet size (∼30 μm) and reproducible jetting characteristics. In addition, clogging can be an issue if the size of the particles or amount of solids in the ink is too high. The Aerosol Jet™ process, developed by Optomec, circumvents many of these issues by enabling the printing of smaller droplets (1–5 μm) from inks with a wider range of viscosities (1–1000 cp) [20]. The Aerosol Jet™ (available since 2004) uses a sheath gas as the nozzle, thereby eliminating many of the clogging issues that plague ink-jet, and enabling the use of a much wider variety of materials in the inks. However, the cost of Aerosol Jet™ systems ranges from $295 k to $495 k, making them out of reach for many potential users. In comparison, the Voxel8 (released in 2016), which combines a conventional plastic filament extrusion nozzle with a syringe-based silver ink extruder, is less expensive at $9k for the developer kit [21]. The lateral resolution of the traces that can be printed with the Voxel8 is 250 μm with a recommended pitch of 2 mm [22], and the printer allows pausing of the print to enable manual placement of circuit components. However, as with ink-jet and Aerosol Jet™, the Voxel8 has a limited capability to print freestanding structures in the z-direction, with recommended trace thicknesses <500 μm.

To circumvent the high-cost and limitations of dedicated 3D printed electronic systems using surface direct write processes, there have been efforts to develop post-processing techniques for 3D printed parts to imbue them with the desired electronic properties. Perhaps the most popular of these is electroplating a plastic part, which can be accomplished after an initial metallization with electroless deposition or conductive paint. Swissto12 has used this technique to produce a variety of 3D printed antennas and waveguides, and Yurduseven et al. demonstrated metallization of 3D printed cavity antennas for imaging [23,24]. However, this technique produces chemical waste and it can be difficult to achieve consistent, high-quality results. Wu et al. showed that 3D conductive traces could be created by injecting silver paste into 3D printed channels, and used this process to create passive wireless sensors. However, the filling process had to be repeated five times to fill ∼70% of the channel with paste, and the smallest channel that could be filled was 600 μm.

Freeform 3D printing can make three-dimensional electronic structures, without the requirements of an existing 3D surface or post-processing. For example, syringe-based printing of sheer-thinning silver nanoparticle inks was used to make freestanding, three-dimensional interconnects [17]. However, these inks required sintering at high temperatures (∼250 °C) to become conductive in 30 min. Ladd et al. demonstrated that gallium liquid metal alloys can be extruded from a nozzle to form freestanding, out-of-plane metal structures up to a few millimeters in height that are stabilized by the material's oxide shell [25]. The liquid metal does not require sintering, and can be embedded in PDMS to create stretchable devices, but its liquid nature means that the freestanding structures cannot be used for practical applications. In principle, either sheer-thinning inks or liquid metals can be printed with low-cost (<$200), fused filament fabrication (FFF) 3D printers by replacing the original polymer extruder with a syringe-based extruder consisting of 3D printed parts [26].

In terms of low-cost, accessibility, and ease of use, it would be ideal to create a highly conductive polymer filament that can be used directly with FFF printers to create electronic components and interconnects without the requirement of sintering, electroplating, or any other post-processing. This would allow many people who already own a 3D printer to create their own custom 3D printed electronics. Until recently, however, the only conductive materials that were commercially available for FFF printers were two carbon-based filaments, Black Magic 3D and Proto-pasta, which have a reported volume resistivity of 0.6 Ω cm and 30 Ω cm, respectively. Researchers have shown that similar materials can be used to create resistive flex and touch sensors [27], but these high resistivities are not suitable for use as conductive traces. For example, a 10-cm-long, 2-mm-thick trace made from Black Magic 3D and Proto-pasta would be 150 Ω and 7500 Ω, respectively. Thus, these materials are better suited for printing of resistors rather than interconnects.

Given our lab's previous experience with highly conductive, copper-based nanostructures [28,29], we decided to create a conductive filament that could be used to print electronic components and interconnects with low-cost, FFF-based 3D printers. The resulting copper-based filament, Electrifi, has a resistivity of 0.006 Ω cm and is commercially available [7]. Further details as to how to make a filament with this level of resistivity will be reported elsewhere. Recent reports have demonstrated applications of Electrifi at microwave frequencies, demonstrating the material can be used to 3D print microstrip transmission lines, frequency-diverse metasurface antennas and 3D metamaterial building blocks [30–32]. In this article, we use a combination of commercially available dielectric and conductive filaments to demonstrate the potential for additive manufacturing of basic electronic components and circuits with low-cost FFF technology. Conductive traces, resistors, capacitors and inductors were printed with both single and dual-extrusion. The high conductivity of Electrifi allows for 3D printing of AC radio frequency (RF) circuits, a wireless power transfer circuit, and a high-pass filter. We show Electrifi can be used in conjunction with a dual-material printer to electrically connect standard surface mount components, such as an LED, by printing over the pads of a component embedded in 3D printed plastic. Finally, we demonstrate that Electrifi can be used to 3D print flexible conductive traces, multi-level embedded conductive traces, as well as freestanding, thin-walled structures such as a horn antenna.

2. Methods

2.1. Materials

Hatchbox PLA and ColorFabb bronze-fill PLA were used as dielectric materials. Electrifi (Multi3D LLC), a graphene-based conductive PLA (Black Magic 3D), and a carbon black-based conductive PLA (Proto-pasta) were used as conductive materials. BuildTak and painter's tape were used as build surfaces.

2.2. Fabrication

The prevention of cross contamination during dual-extrusion, i.e., the mixing of two filament materials during printing, is critical to printing electronic components because cross contamination of the conductive material will result in either shorting between conductive traces, or in the interruption of a conductive trace with non-conductive material. Although many printers are available with multiple nozzles, all printers we have tested (Prusa i3, Hictop, CTC 3D, and LulzBot Taz 5) are not able to prevent cross-contamination. Typical multimaterial printers use two separate nozzles at the same z height, but this method leaves the inactive nozzle in a position where it is likely to scrape across the printed surface and cause cross-contamination.

One approach that has been advertised as a way around this issue is to extrude multiple materials through the same nozzle. To change the printed materials with a single extruder, the old filament is programed to retract all the way out of the hotend and a new filament is then fed into the hotend by a separate stepper motor. However, the old material must be cleared out of the noz-