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Multimaterial Aerosol Jet Printing of Passive Circuit Elements+

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Abstract

Stable operation of the NanoJet(NJ) [6] aerosol printing technology is enabling for development of printed electronic components. An area of considerable interest for electronic printing is the production of multi-layered, multi-material passive components. To demonstrate the NJ multi-layer, multi-material capability a miniature toroidal inductor structure provided a point of focus for this effort. The toroidal inductor used a planar coil design with a dielectric and core material printed in between the lower and upper halves of the planar coil. The results of this work will be discussed including requirements for successful printing with the multi-layer, multi-material component. Measured device performance of the printed structure will be discussed and compared to predicted values. This results of this work are meant to provide guidance for future work in this area.

Introduction

Printed electronics technology has many advantages over traditional electronics manufacturing, including compatibility with flexible form factors, high throughput and large-area fabrication, and broad materials compatibility [1]. In addition, these technologies can be easily embedded in additive manufacturing process flows, with digital control enabling rapid prototyping and custom fabrication. Aerosol jet printing is attractive in this regard, offering high resolution, broad material compatibility, and versatile digital control. As these technologies advance, more sophisticated multi-layer, multi-material integration becomes possible, with considerable interest for printing of passive electronic components [2-4]. Among electronic circuit components, passive elements such as capacitors and inductors are critical for complex circuit designs, and require integration of multiple materials. Inductors, in particular, are widely used in applications such as signal filtering, and often require a large volume, motivating the development of additive fabrication routes for miniaturized inductors [5]. A basic inductor contains a coil of wire wrapped around a core that stores energy in a magnetic field when current runs through the coil. This stored energy is known as inductance. The inductance, measured in units of henrys, depends on the number of turns in the coil of wire, length of the coil, area of the core (area inside the coil), and permittivity of the material comprising the core. The inductance is directly proportional to the number of turns in the coil, area of the core, and permittivity of the core, and inversely proportional to the length of the coil.

Common shapes for inductors are toroidal and solenoidal. Toroidal inductors are made from disk-like cores and solenoidal inductors are made from solid cylindrical cores, both having wire warped around them to create a magnetic field. Magnetic leaking at the ends of solenoidal designs reduces the inductance, motivating the selection of a toroidal inductor for this research.

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The permittivity and size of an inductor's core strongly influence inductance. In traditional manufacturing of inductors, the area of the core can be manufactured with tight machine or model tolerance, and the permittivity is a material property easily measured from the core material. Achieving the desired area and permittivity is a challenge in additive manufacturing processes. Not all materials are printable, fabricating to precise dimensions can be difficult, and different curing parameters of multi-material parts can damage certain parts and interfaces of the printed structures. A material study for additively manufactured inductors will be the focus of a future paper.

Design

To build a toroidal inductor using an additive manufacturing process, a multi-layer print was designed with two conductive layers of silver ink separated by a core of magnetic or dielectric material. The first layer would be made by printing separate conductive triangle parts in a circle (toroid) with the toolpath shown in Figure 1a. The second layer acts as the core of the inductor, separating the conductive top and bottom layers, with the toolpath shown in Figure 1b. Finally, the third layer, like the first layer, contains silver ink connecting each section of the bottom layer to the adjacent section in the bottom layer to complete the coil like design around the core of the inductor, as shown in Figure 1c. The design dimensions for the inductor specify an inner diameter of 2.875 mm and outer diameter of 9.125 mm. Designed height for layers 1 and 3 is 0.1 mm and 0.5 mm for layer 2 (core).

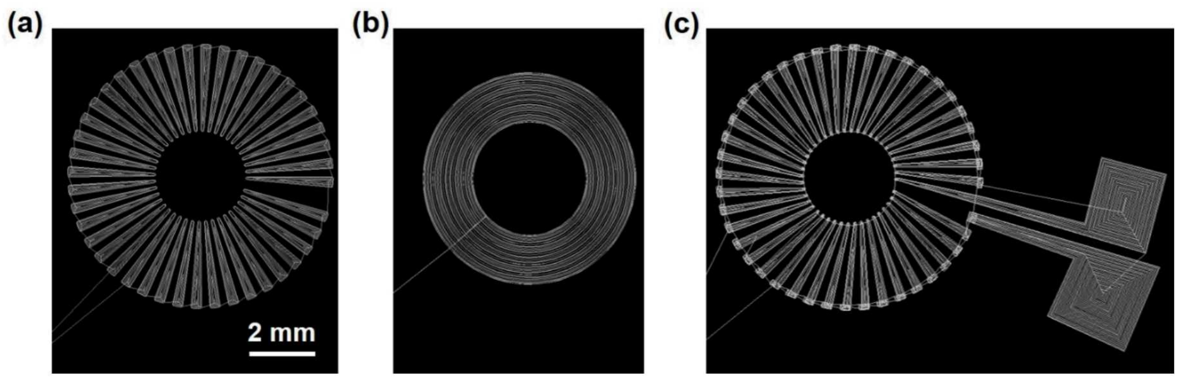

Figure 1. Toolpath drawings for printed layers 1-3 in (a)-(c), respectively.

Device Printing

To create the device, the bottom layer made of silver ink is printed first. The layer of silver was cured at 170 □ on a hot plate for 30 minutes. The second layer for the inductor core was then printed directly on top of layer 1. The material used for the core was a polyimide precursor. This was cured in two steps to prevent cracking, first on a hot plate at 80 □ for an hour followed by 200 □ for 30 minutes. After curing layer 2, the final layer of silver ink was printed to complete the coil of conductive material. This layer was cured with the same parameters as layer 1 to complete the device.

In measuring the final device, it was clear the printed part was significantly smaller than the designed part from which the toolpath was generated. The final measurement of the printed device had an inner diameter of 2.0 mm and outer diameter of 5.90 mm which are both much smaller than the designed 3D model with an inner diameter of 2.875 mm and outer diameter of 9.125 mm. The cause for this size difference wasn't fully understood and would affect inductance of the part. For purposes of this study, the overall size of the part was not a priority and can be studied in later research.

Motor Accuracy Problem

After printing of layer 1 a problem with section sizes (individual triangles) started to occur. Certain regions of the part would have larger sections than others, causing overlapping of sections in regions with larger sections. The larger sections were also not totally infilled due to the larger area in the sections. Figure 2a displays this problem with the regions in the top left and bottom right having sections with much larger area then adjacent sections. Having larger, unfilled sections which overlap would cause shorts and poor conductivity in the inductor, lowering overall inductance.

To find the cause of the print offset in the larger regions, layer 1 was printed in three different ways. First, a print with no adjustments provided a reference for comparison. Second, the X and Y axes where switched on the Flash Cut control box to test the mechanics of the printer. Third, after putting the X and Y axes back to their original position on the control box, the toolpath was rotated 90 degrees to test the software of the printer. In all three prints no differences in defect occurrence was observed in the overall appearance of layer 1. This led to the conclusion that the accuracy of the X and Y motors was a problem. To test this assumption, layer 1 was printed at double its size. When doubled in size, no sections with larger area were observed, fixing the overlap and infill issues and confirming the issue was due to the printer's motor accuracy.

To achieve as-designed prints, we sought ways to improve motor accuracy. The addition of servos to both the X and Y axes motors with a 7:1 turning ratio, thus making the positional motors seven times more accurate, sufficiently solved the sizing issue. After adding servos no sizing issues occurred, giving the required print precision. Figure 2b shows an image of layer 1 at normal size after adding servos to the X and Y axes motors.

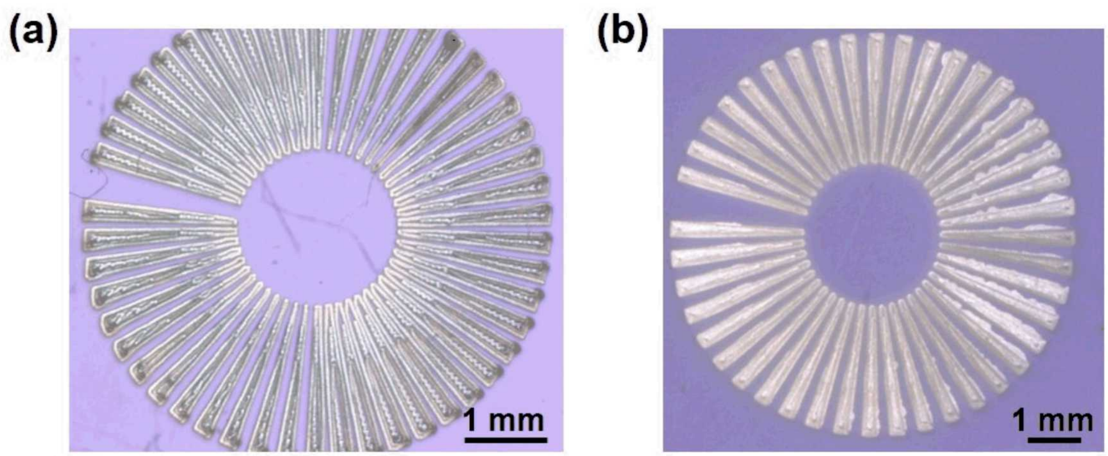

Figure 2. Layer 1 print before (a) and after (b) adding servos to the X and Y motor axes.

Optimized Results

For printing of this device, a multistep process was applied as discussed earlier in this paper. In printing all three layers of this device, registration of the patterns and substrate is a critical factor. Due to different home positions for layer 1 and layer 2, alignment was done manually by using a Marshall compact 2MP HD-SDI camera, which could lead to misalignment and part failure. For future prints, an alignment camera will be used in order to improve section registration. Prints of layers 1-3 after curing can be seen in Figures 3a-c, respectively.

Results of optimized prints with recorded inductance will be here. Then comparing of results to expected values and traditionally manufactured inductors. Along with how inductance changed based on different parameters during printing and curing.

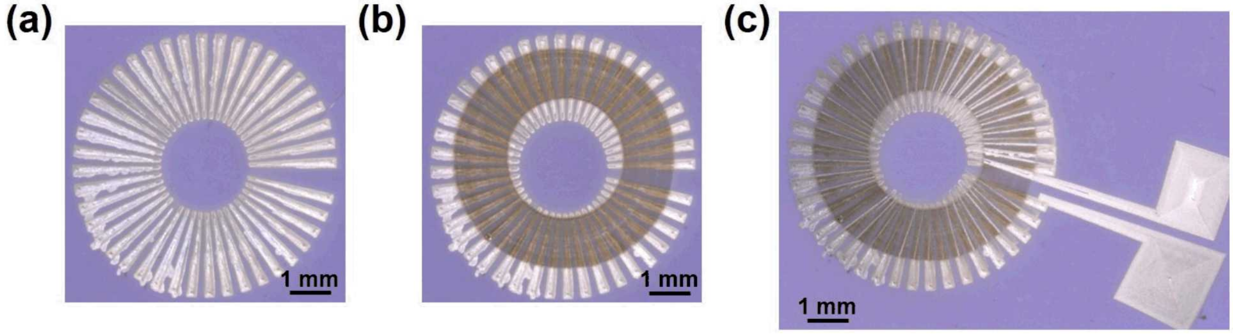

Figure 3. Inductor following printing of layers 1-3 in (a)-(c), respectively.

Future Work

For future additive manufacturing of inductors, testing other designs, materials, and manufacturing techniques will be undertaken to improve inductor performance. For simple solutions to improve inductance, research is ongoing in improving the area of the core, materials with high permittivity for the core, and raising the number of turns per length of the coil. Other additive manufacturing designs for the inductor will also be studied. Alternative approaches, such as a disk-like core with a conductive coil printed directly on the core, will be optimized and tested. Completing this research will further the multi-material fabrication of integrated systems, allowing smaller and more easily incorporated electronics components.

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