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Microscale additive manufacturing and modeling of interdigitated capacitive touch sensors

Md Taibur Rahman[a], Arya Rahimi[b], Subhanshu Gupta[b,*], Rahul Panat[a,*]

[a] School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164, USA
[b] School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164, USA

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ABSTRACT

Touch sensors have created a paradigm shift in the human-machine interaction in modern electronic devices. Several emerging applications require that the sensors conform to curved 3-D surfaces and provide an improved spatial resolution through miniaturized dimensions. The proliferation of sensor applications also requires that the environmental impact from their manufacturing be minimized. This paper demonstrates and characterizes interdigitated capacitive touch sensors manufactured using an Aerosol Jet based additive technique that reduces waste and minimizes the use of harmful chemicals. The sensors are manufactured with the capacitive elements at an in-plane length scale of about 50 μm by 1.5–5 mm, a thickness of 0.5 μm, and a native capacitance of a 1–5 pF. The sensor capacitance variation is within 8% over multiple samples, establishing the repeatability of the Aerosol Jet method. Scanning electron microscopy and atomic force microscopy are used to characterize the sensor electrodes. 3-D electromagnetic simulations are carried out to predict the capacitance of the printed sensors and the electric field distribution. The simulations show a reasonable agreement with the experimental values of the sensors' native capacitance (within 12.5%). The model shows the native capacitance to be relatively insensitive to the thickness of the sensor electrodes, allowing touch sensors to be fabricated with reduced material usage and cost. The model is further used to establish the important sensor dimensions governing its electrical performance. Lastly, electromagnetic field distribution predicted by the model is used to establish the physical range of the touch action to be about a millimeter out of the plane of the sensors for the geometries considered in the current work.

1. Introduction

Wearable 'smart' electronic devices are projected to bring transformative changes to the global economy over the next two decades, with an associated economic value projected to be in the trillions of dollars by 2020 [1,2]. Touch sensors form the most important type of human-machine interaction for such devices with important uses in defense applications, robotics [3], and healthcare [4]. The electronic circuit enabling the touch sensors works largely through detecting the changes in input capacitance by incorporating the distinction between varied stimuli such as stylus, single/double/multiple touch, and touch duration [5]. Although such sensors are already in use, several Internet of Things (IoT) applications have added requirements for size and conformability of the sensors per the location of the sensor circuit. In addition, with an increase in the number of wearable devices, the environmental impact of the manufacturing of its constituents is expected to be significant [6] and requires concerted development of green manufacturing techniques.

To date, several attempts have been made to fabricate low-cost capacitive touch sensors (or touch panels) for various applications. A flexible capacitive sensor with encapsulated liquids as the dielectrics was demonstrated using a MEMS-based manufacturing method [7]. A capacitive touch interface for RFID tags was demonstrated, also using a MEMS-based method [8]. A stretchable capacitive sensor made of thin gold film on silicone rubber was fabricated using photolithography and characterized [9]. A capacitive touch panel using metalized paper was demonstrated with an effective capacitance of about 50 pF [10]. A foldable direct write paper-based capacitive touch pad was developed using inkjet printing of silver nanowires at a feature scale of 500 μm and a capacitance range from 2 to 40 pF [11]. This work [11], however, did not report the resistivity of the sintered nanowires, a criti-

* Corresponding authors.
E-mail addresses: sgupta@eecs.wsu.edu (S. Gupta), rahul.panat@wsu.edu (R. Panat).

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cal parameter for power consumption in IoT devices/applications [12–14].

In contrast to the conventional subtractive or semi-additive MEMS-based fabrication techniques, additive techniques such as Aerosol Jet Method (AJM) [15] are being developed to fabricate passive structures. Such methods avoid creating material waste. The AJM also requires considerably less amounts of environmentally harmful chemicals compared to the MEMS-based techniques. The AJM utilizes a mist of nanoparticle inks directed by a carrier gas to print features at a length scale of 10 μm over a flat or a curved surface and has been used to manufacture solar cells [16,17], electronic interconnects [18], biosensors [19], strain sensors [20,21], and 3-D antenna structures [22]. The maximum particle size in the inks used in the AJM is typically <500 nm [23], with the sintering of the nanoparticles achieved at a temperature significantly lower than the bulk melting point. The conductivity obtained by such methods is about 20–50% of the bulk metal [22]. The AJM has also been shown to allow a standoff height (i.e., vertical distance between the nozzle printing the ink and the substrate) up to 5 mm, enabling electronic circuits on complex 3-D surfaces [22,23].

Although several manufacturing routes have been explored for touch sensors, few if any electromagnetic simulations have been carried out to predict their native capacitance and performance as a function of the sensor electrode morphology, dimension, and the surrounding dielectric medium. Finally, a complete design tool with simulations and predictive modeling integrated with manufacturing could enable rapid prototyping and development of custom-sensors at minimal costs. In addition, the sensor manufacturing variability and its effects on the sensor electrical characteristics have not been reported comprehensively in the literature for additive manufacturing techniques.

The present work demonstrates and characterizes printed capacitive interdigitated touch sensors using an Aerosol Jet micro-additive manufacturing technique with the native sensor capacitance in the range of 1–5 pF. The manufacturing method is shown to allow sensor feature sizes down to tens of microns, with a capacitance per interdigitated electrode-pair of about 100 fF. Section 2 describes the sensor operating principle, while Section 3 provides a detailed experimental procedure of sensor fabrication by the Aerosol Jet printing. Section 4, along with Supplementary information S1-3, provides details of 3-D electrodynamic model developed to predict the capacitance of the printed sensors. The sensor measurements are described in Section 5, while the results are presented and discussed in Section 6.

2. Sensor operating principle

The schematic of the design and the operating principle of the sensor is shown in Fig. 1. The sensor consists of an interdigitated electrode structure forming the capacitor with the probe pads connected using interconnects (Fig. 1-a). Fig. 1-b, c shows the expected field lines in the untouched state and the schematic of an equivalent electrical circuit, respectively. The coupling between the two sides of the capacitor is expected to occur through air as well as through the glass base. Fig. 1-d, e, shows the expected field-line disruptions (in air) when touched by a thumb and the schematic of its equivalent circuit with the added capacitance, C_{touch} due to the high relative permittivity of the skin/tissue/blood (ε_r), respectively. Note that a thin layer of non-conductive plastic over the sensor prevents the thumb from shorting the capacitor and will be considered in simulations. C_{touch} acts in parallel to the capacitance, C_0, in the untouched state, resulting in the total capacitance, $C_{\mathrm{sensor}} = C_0 + C_{\mathrm{touch}}$. Electromagnetic simulations were developed to determine the field lines outside the sensor plane and determine the field disruption when touched. These simulations also enabled estimating the expected capacitances prior to fabrication.

3. Sensor fabrication

An Aerosol Jet micro-additive manufacturing machine (AJ300, Optomec Inc, Albuquerque, NM, USA) was used to print the electrodes directly onto the glass substrate as shown in Fig. 2 (also see Fig. S1 for a picture of the equipment). An ultrasonic atomizer was used to create the aerosol/mist. The nozzle exit diameter during printing was 150 μm, while the atomizing flow rate and the sheath gas flow rate were maintained at 25 sccm and 50 sccm, respectively. During printing, the standoff distance between the substrate and the nozzle was kept at about 2.8 mm. Note that the optimized parameters such as sheath gas pressure, atomizing pressure and exhaust pressure were suitable for the ink formulation used in the current work but may vary for other inks depending upon their viscosity, particle size and the solvent type.

The electrodes were printed using a silver nanoparticle ink (Perfect-TPS G2, Clariant Group, Frankfurt, Germany) with a viscosity of about 1.5 cP, a particle size of 30–50 nm and a particle loading of 40 ± 2 wt%. A transparent glass slide (Thermo Fisher Scientific, Waltham, MA, USA) was used as the substrate. The substrates were cleaned with DI water followed by isopropyl alcohol. The substrate surface was then further treated with an atmospheric plasma (Atomflo™ 400, Surfx® Technologies LLC, Redondo Beach, CA, USA) at 100 W for 5 min. Before printing the structures, ink material was placed in a tube which was rotated continuously around its axis for 12 h using a tube roller (Scilogex MX-T6-S, Rocky Hill, CT, USA) at about 70 rpm to prevent nanoparticle agglomeration within the ink. The printed material was then sintered at 200 °C for 30 min in a programmable oven (Neytech Vulcan furnace, Model 3-550, Degussa-Ney Dental Inc., Bloomfield, CT, USA) to create conductive electrodes. The electrode resistivity was measured through a 4-Wire method and was about 6.35×10^{-8} Ω-m, or about 5X of the bulk silver and within the range reported in literature for thermally sintered nanoparticles of silver [24]. Three sensors were fabricated for each of the interdigitated region lengths of 1.5, 3, and 5 mm. For the samples with 3 mm interdigitated region length, a sensor with smaller number of electrodes (8) was also fabricated.

4. Sensor simulation methodology

Consistent use of additive printing (e.g. by Aerosol Jet method) will require an accurate and well-modeled parametric library of the different variables involved. Electromagnetic simulations can be used to study the effect of various geometrical and material parameters on the sensor behavior to aid in its design. The simulations can also provide a quantitative picture of the electric field for the sensor geometry to further illustrate its behavior under different conditions. We used the Momentum ADS® and EMPro® software (Keysight®, Santa Rosa, CA, USA) in this work to develop detailed 3D models and simulation structures for the printed touch sensors. A 2D layout was created in Momentum ADS® and then exported to EMPro for simulation with additional 3D components using a frequency-domain finite element method (FEM) solver. The added 3D electromagnetic (EM) components enabled detailed study of the electric fields to understand different aspects of manufacturability and electrical behavior of the printed sensors. Both programs are 3-D planar electromagnetic simulators used for passive circuit analysis with partial differential equation solvers for Maxwell's equations (with boundary conditions prescribed by the users) based on the method of moments [25,26]. Each model took into consideration internal and external parasitics, surface roughness and variations in metal thickness, dielectric constants, and