Hantang Qin
Department of Industrial and Systems Engineering,
North Carolina State University,
Raleigh, NC 27695-7906
e-mail: hqin@ncsu.edu

Yi Cai
Department of Industrial and Systems Engineering,
North Carolina State University,
Raleigh, NC 27695-7906
e-mail: ycai6@ncsu.edu

Jingyan Dong
Department of Industrial and Systems Engineering,
North Carolina State University,
Raleigh, NC 27695-7906
e-mail: jdong@ncsu.edu

Yuan-Shin Lee[1]
Department of Industrial and Systems Engineering,
North Carolina State University,
Raleigh, NC 27695-7906
e-mail: yslee@ncsu.edu

Direct Printing of Capacitive Touch Sensors on Flexible Substrates by Additive E-Jet Printing With Silver Nanoinks

In this paper, techniques of direct printing of capacitive touch sensors on flexible substrates are presented. Capacitive touch sensors were fabricated by using electrohydrodynamic inkjet (E-jet) printing onto flexible substrates. Touch pad sensors can be achieved with optimized design of silver nanoink tracks. An analytical model was developed to predict touch pad capacitance, and experiments were conducted to study the effects of sensor design (e.g., number of electrodes, electrode length, and electrode distance) on the capacitance of printed coplanar capacitance touch sensors. Details of the fabrication techniques were developed to enable rapid prototype flexible sensors with simple structure and good sensitivity. The presented techniques can be used for the on-demand fabrication of different conductive patterns for flexible electronics with high resolution and good transparency [DOI: 10.1115/1.4034663]

Keywords: rapid prototyping, capacitive touch sensor, flexible substrates, inkjet printing

1 Introduction

Flexible electronics have been rapidly developed in the last few years and have shown a good potential to be the next technology revolution in electronics; similar to the way integrated circuits was in the 1960s. Flexible electronics are not only flexible mechanically but also flexible in functionalities in all kinds of applications, ranging from personal devices (wearable devices [1,2]), electronic memory devices [3] to large area sensors (biomedical sensor arrays [4], solar cells [5,6], flexible displays [7,8]), and radio-frequency identification devices [9]. The flexible electronics began with single-crystalline silicon solar cells used in extraterrestrial satellites back to the 1960s [10,11]. The ultimate goals of flexible electronics are always lightweight, flexible, easy-to-integrate, low-power, and energy independent [12]. Display industry has been driving new development of flexible screens for portable devices. At the same time, chemical and biological sensor arrays are other great opportunities for flexible electronics to be used in human healthcare systems.

Touch sensors have been commercially available for over 30 yr and widely used everywhere, such as touchpad, tactile devices, and fluid detection applications. On the other hand, they are still regarded as new technologies in engineering and business communities with emerging innovation continuing in touch sensor technologies. Touch sensors are based on various techniques, including resistive, capacitive, and infrared sensors. Resistive is one of the oldest types of touch sensors, produced since mid-1970s. They are mostly pressure-sensitive or analogy-resistive film touch panels, which feature a glass screen and a film screen separated by a narrow gap, each with a transparent electrode layer attached. Pressure makes the electrodes in the film touch electrodes on the glass, resulting in the flow of electrical current, where voltage change is detected and contact point is identified. These touch sensors owned the largest market share because of very low cost and ease of implementation despite poor durability and optical performance [13]. Scanning infrared touch sensors are based on the concept of determining position by the interruption of one or more of a series of light beams and thus interrup the excitation of a phototransistor that is illuminated by the beam. If the touch sensor is touched, the infrared light will be blocked and not reach the infrared imaging sensors. For this type of sensor, design cost is high, and initial calibration is difficult and complex [14]. Acoustic touch sensors mainly use surface acoustic wave (SAW), and acoustic pulse recognition (APR) technology, which depend on the propagating mechanical waves on the surface, capturing, and analyzing those waves to determine a touch position. It is difficulty to realize multitouch for acoustic sensors, and it is limited to relative low-resolution applications [15]. Compared to these mechanisms, capacitive sensing represents the second most widely used sensing method. Touch activity is identified by detecting minor changes in electrical charge generated by the contact with a finger. Substrates for capacitive touch sensors may be glass or flexible polymers, or combination of them [16]. The sensors are usually constructed as narrow strips of conductors. Interdigital electrodes are among the most commonly used sensor structures. The change in capacitance caused by proximity of a finger near an intersection is 1 pF or less, and the effect on adjacent electrode may be less than 0.1 pF [17]. Analysis of capacitance changes at or near intersections of electrode reports the touch action if change in capacitance exceeds the system threshold. Capacitive sensors show excellent sensitivity and are unaffected by most contaminations. These advantages have provided particularly attractive options for them to be applied into next generation flexible electronics and in microfluidic devices [18].

The fabrication methods for flexible electronics are very different from modern semiconductor technologies. Flexible electronics generally have large overall device dimensions and use different types of substrates. This is different from integrated silicon-based chips of modern CMOS technology, which focuses on minimizing area, improving device densities, and reducing sizes. The challenge for modern flexible electronics is to find new solutions for producing large area electronic with full mechanical and electrical

[1]Corresponding author.
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functions while reducing costs. Many research groups are working on alternative fabrication method to replace conventional process such as photolithography and vacuum deposition while meeting high performance, resolution, manufacturing needs, and cost requirements. Among them, additive printing shows its potential to be the best fabrication process for future flexible devices. It can be scaled to very large areas with full microelectronic function. Additive printing is a noncontact jet printing process that is capable of fabricating both silicon-based and polymeric-based thin film transistors and electronic components. However, its feature resolution is limited by the size of droplets, which is typically above 30 μm. Meanwhile, by incorporating it with roll-to-roll fabrication, additive printing can help to reduce process and material cost for flexible electronic fabrication [19–21].

Directly printing approaches, especially those based on inkjet printing in high-resolution fabrication situation, demonstrate attractive features in their application. First, inkjet printing is noncontact, which means any substrates can be processed. Materials can be deposited on planar or curved substrates, as long as there is a stand-off distance between the print head and substrate. Second, inkjet printing is capable of depositing a wide range of materials given appropriate print heads. Third, the printing process is scalable. The use of multiple print heads has been reported to print wider pattern or several materials at the same time [22]. Third, inkjet printing is flexible in position [23]. The location can be changed in real time to ensure high-quality patterns. It also shows potential for mass production and low-cost operation [24]. These features of inkjet printing make it particularly attractive for rapid prototyping of such flexible capacitance sensors.

However, there are still plenty of challenges before inkjet printing can be applied for rapid prototyping of electrical components for flexible electronics. First, most of complex, multifunctional metal or alloy inks have to be characterized before they can be adapted into real applications. Second, there are resolution issues with current inkjet printing methods, and the electrical performance of printed patterns needs to be investigated.

In this paper, new techniques are presented to fabricate integrated capacitance sensors using additive E-jet printing with conductive silver nano-ink. As discussed in the paper, the presented method can be adapted into rapid prototyping of touch pads or microfluid detecting sensors. The interdigital design maximizes the capacitive signals for sensor applications. The over-all performance was characterized using an RC relaxation oscillator circuit. The analysis of electrical performance of parallel coplanar patterns was conducted to test electrical properties of direct printed patterns. The results of experimental tests confirm that capacitive sensors fabricated by the proposed additive E-jet printing could be effective for sensor applications. The proposed additive manufacturing methods and circuit design presented both great resolution and electrical properties. The proposed fabrication technique is capable of rapid prototyping of electronic components for flexible electronic, medical sensors, wearable devices, and radio frequency identification devices.

2 Capacitive Touch Sensors

Projected capacitive technology is a technology based on capacitive coupling effect, which can detect anything that is conductive or has different dielectric effects from air [25]. The technology has been widely used in modern touch screens. A basic construction of a typical projected capacitive touch screen includes a top layer touch surface (chemically strengthened cover glass with holes and slots cut into it), optical bonding adhesives, touch sensor arrays (usually a glass separator with indium tin oxide (ITO) deposited on both sides), and the bottom light-emitting diode/light crystal display screen [12], as shown in Fig. 1. Projected capacitive technology provides advantages such as multitouch detection, excellent optical properties, and long life. Projected capacitive touch sensors are easy to integrate into systems to eliminate coordinate drift [26]. Projected capacitive touch sensors can be adapted into both glass and plastic, and flat and curved surface. Most touch applications are immune to chemical attacks and extreme temperatures because sensors are usually sealed by the protection layers.

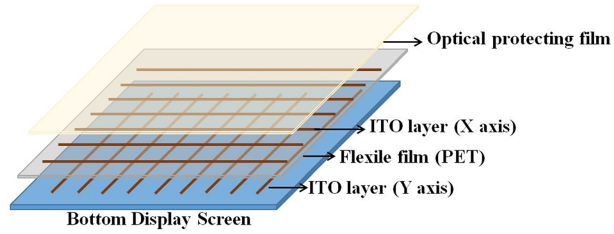

Fig. 1 Schematic of structures in projected capacitive touch screens: row and column stack up layers

Coplanar electrode arrays offer a compact design for capacitive touch sensors. The use of interdigital electrode arrays also helps increase capacitive signals, which is perfect for ultrasmall signal detections. Several research groups have been focused on interdigital sensors consisting of uniform width metallic electrodes [27]. Capacitive sensing is based on the contrast of dielectric property between different phases. In this work, several electrode designs were tested with a range of size, spacing, number of electrode fingers, and curing temperature.

To maximize sensitivity for detection, an effective sensor design and fabrication method is required. The capacitance sensor with single pair of interdigital electrode is shown in Fig. 2. Chen et al. analyzed droplets detection using coplanar capacitance sensors assuming droplets are in direct contact with electrodes [28]. In our case, there is a protecting polypropylene film outside electrodes for protection of electrodes from contaminations. The thickness of polypropylene film is about 40 μm. It is desired to take this into consideration when developing an analytical model of detection.

Chen et al. [28] applied conformal mapping techniques and calculated capacitance created by a single pair of coplanar electrodes in semi-infinite domain with same liquid cover as

$$C = \frac{Q}{2V_0} = \frac{\varepsilon_r \varepsilon_0 l}{\pi} \ln\left\{ \left(1 + \frac{w}{a}\right) + \sqrt{\left(1 + \frac{w}{a}\right)^2 - 1} \right\} \tag{1}$$

where C is the capacitance, ε_r is dielectric constant, ε_0 is the electric constant, l is the length of the electrodes, w is the width of electrodes, and a is half-gap between electrodes. From Eq. (1), the relation suggests that the maximum capacitive signal can be achieved by minimizing electrode gap spacing. The protecting layer, which is polypropylene film, has $\varepsilon_r = 2.2$–2.36. The field lines passing through the cover do not contribute to changes in capacitance detected by sensor

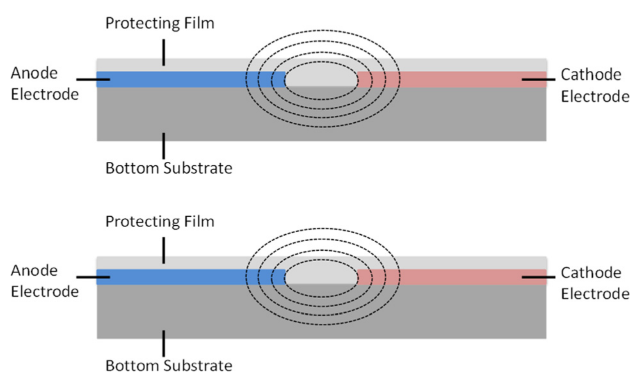

Fig. 2 Working principle of capacitors with single coplanar electrode

$$w_{\mathrm{eff}} = a\left(\sqrt{1+\left(\frac{w}{a}\right)^2}-1\right) \tag{2}$$

In the model, the capacitance must be calculated considering the effect of protecting layer. The total capacitance from single pair of coplanar electrodes can be formulated as follows:

$$C_{\mathrm{air}} = \frac{Q}{2V_0} = \frac{\varepsilon_{\mathrm{air}}\varepsilon_0 l}{\pi}\ln\left\{\left(1+\frac{w}{a}\right)+\sqrt{\left(1+\frac{w}{a}\right)^2-1}\right\} \tag{3}$$

$$C_{\mathrm{film}} = \frac{\varepsilon_{\mathrm{film}}\varepsilon_0 l}{\pi}\ln\left\{\left(1+\frac{w_{\mathrm{eff}}}{a}\right)+\sqrt{\left(1+\frac{w_{\mathrm{eff}}}{a}\right)^2-1}\right\} \tag{4}$$

The effective width w_{eff} is calculated by Eq. (2). Using Eqs. (3) and (4), the capacitance is found as follows:

$$C = C_{\mathrm{air}} + C_{\mathrm{film}} \tag{5}$$

With our design as shown in Fig. 2, assume the number of electrodes for single polarity is N, the total pairs of coplanar electrodes can be considered as $2N-1$. So the total capacitance of printed coplanar electrodes can be estimated as

$$C_{\mathrm{total}} = (2N-1) * C \tag{6}$$

As shown in Fig. 2, when a finger touches the sensor, the finger functions as a media for the system and modifies the electrical field around the sensor to increase total capacitance. Assuming there is an intrinsic frequency of any conducting objects, the system can be modeled as a coplanar capacitance in parallel with finger capacitance. The actual effect from the finger is difficult to model because of variability in electrical properties of human fingers, which may also vary with personal conditions for an individual [29]. As a result, we consider the properties of a finger as a purely dielectric material with relative permittivity to be 60 [30].

3 Materials and Fabrication Process

There are several challenges to fabricate the projected capacitive sensors before they can be used in flexible devices. First, it is relatively expensive in fabrication to build large-area screens for depositing electrodes sensor arrays. Electrodes patterns are most commonly deposited on surfaces by physical vapor deposition, such as electron beam deposition and sputter deposition techniques, which are costly deposition methods that require vacuum. Second, indium tin oxide (ITO) is currently the most popular material as transparent electrodes for optoelectronic devices because of its electrical conductivity and optical transparency. However, indium is a scarce resource on earth, and its mechanical fragility makes it hard to use for flexible electronic devices. As a result, the demand for alternative electrodes that can replace ITO has been critical. Many materials have been introduced, including carbon nanotubes [31–33], graphene [34,35], conducting polymers [36,37], and metal nanoink. Among them, metal nanoink has drawn attention because of several advantages over other materials.

3.1 Nano-Ink Materials. Metals provide excellent conductivity among all other materials at room temperature due to their high free-electron density. At the same time, ultrathin and ultrasmall metal patterns demonstrate decent optical transparency at micro- and nano-scale. Transparent thin metal film and metal grids have been reported as a replacement for ITO in optoelectronic devices in which light must pass through while current or voltage needs to be applied [38,39]. The properties of these transparent metals are extremely important for device performance. For example, the brittleness properties of electrodes are crucial for flexible devices. The optical transparency and electrical resistance are another two important parameters. To achieve the highest performance in optical transparency and resistance, metal-based nanostructures need to be fabricated at microscale while maintain their highest electrical conductivity at room temperature.

In this paper, we used silver nanoink for inkjet printing of electrical patterns. The silver nanoink was purchased from Advanced Nano Products Co., Ltd., Pleasanton, CA. It is composed of silver nanoparticles with 20–35% in weight, triethylene glycol with 65–80% in weight, and other small amounts of surfactants and lubricants to prevent agglomeration of nanoparticles. Silver nanoparticles have diameters below 50 nm, and they are uniformly dispersed in the solvent. The viscosity is 10–18 cP and surface tension is 35–38 dyn/cm. There are two substrates used in the experiments, glass slides (75 mm × 25 mm × 1 mm) and highly insulating polyethylene terephthalate (PET) film, which are widely used for high-density circuit, electronic packaging, and flexible electronics.

3.2 Fabrication Process. As shown in Fig. 3, a direct E-jet printing system developed at our lab was used in this paper. The E-jet printing system consists of a three-axis stage, a dispensing system with pressure regulator, nozzle, and substrate. The three-axis stage can be programmed to provide relative displacement in X–Y directions between substrates and nozzle, simultaneously controlling plotting speed of nozzle and trajectory of tracks. Note that the fabrication process is capable of on-demand printing multilayers on substrate by programming the movement of the three-axis stage.

Conventional inkjet printing approaches are based on thermal or acoustic formation and ejection of liquid droplets through nozzles [40]. The fabrication processes are successfully applied in electronics, drug delivery systems [41], micromechanical devices [42,43] and other areas. The theoretical maximum resolution using thermal or acoustic application is 20–30 μm, resulted from the fact that the diameters of the droplets are typically bigger than 10 μm [44]. Even though with assistant technique, e.g., by combing lithography into these inkjet printing to confine the liquid flow [45], it remains a challenge for electronics research and industry community to achieve the submicrometer resolution in fabrication process.

In our previous research presented in Refs. [46–48], we have demonstrated applying electrohydrodynamic inkjet printing (E-jet printing) to fabricate sub-20 μm conductive patterns on insulating substrates. In E-jet printing, we applied a voltage between nozzle and substrates. When a liquid is supplied to a sufficiently high electrical potential, the liquid will form a stable cone and emits a jet on its summit. The technique that uses electric fields instead of thermal or acoustic offers some advantages of patterning compared with other direct write technologies. The dimension of the jet generated by E-jet printing is much smaller than the dimension of the nozzle, thus improving the resolution of printed patterns.

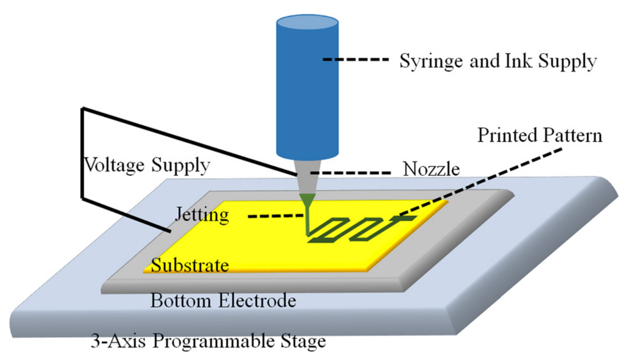

Fig. 3 Fabrication platform for E-jet printing

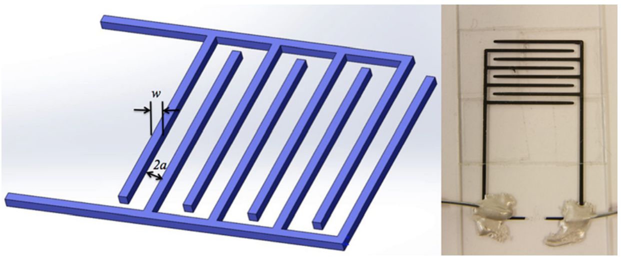

Fig. 4 Schematic view of touch sensor structure and the patterns printed in the lab

Figure 4 shows a schematic view of the touch sensor structure design used in this paper. The design variables include the number of electrodes, electrode length, and electrode distance. The output parameter is capacitance of printed coplanar capacitance touch sensors. A high-resolution prototyping of microelectrodes array on flexible substrate will be demonstrated in Sec. 4.5 to demonstrate the versatility and capability of rapid prototyping using E-jet printing.

The touch sensors are printed by E-jet printing applying a DC voltage of 100 V on PET film. In this paper, the experiments were conducted as follows:

(1) To study the effect of electrode numbers on touch sensor capacitances, the length of each electrodes is printed as $l = 10$ mm, the distance between two adjacent same polarity is printed as $4a = 1.5$ mm, the number of printed electrodes of the same polarity N are 2, 3, 4, 5, and 6.
(2) To study the effect of the length of electrodes on touch sensor capacitances, the number of electrodes N is set as 4, the distance a is set as 1.5 mm, and length l is printed as 5 mm, 7.5 mm, 10 mm, 12.5 mm, and 1.5 mm.
(3) To study the effect of the distance on touch sensor capacitance, the number of electrodes N is set as 4, length l is set as 10 mm, and distance $4a$ is printed as 1 mm, 1.25 mm, 1.5 mm, 1.75 mm, and 2 mm.
(4) To study the sensitivity of printed touch sensor, one set of electrodes was printed with the number of electrodes N set as 4, length l set as 10 mm, and distance $4a$ set as 1 mm. The time constant was measured before and after a finger touched on the sensor.
(5) To demonstrate the capability of E-jet printing as rapid prototyping method, microelectrodes array on PET film was fabricated with high resolution and transparency.

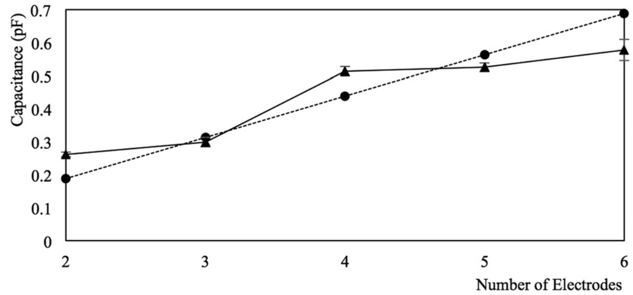

Fig. 6 Effect of number of electrodes on touch sensor capacitance

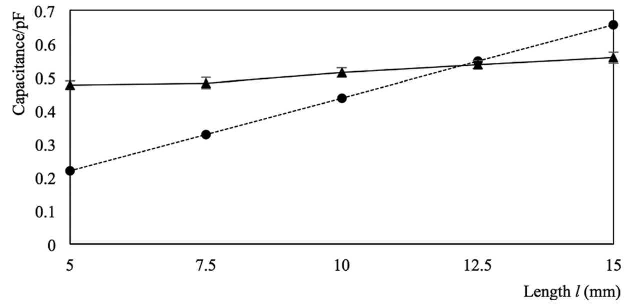

Fig. 7 Effect of length of electrodes on touch sensor capacitance

4 Experimental Results and Discussion

4.1 Sensor Test Circuit Layout. Capacitive touch sensor is a transducer with a touch responsive surface that interacts with electrical signals. It is desirable for the touch sensor to be flexible and provides enough sensitivity to touch. A detector (Arduino Nano ATmega 328) is controlled by microprocessor, providing excitation signals for the sensor and receiving signals from the sensor in response to a touch, converting the received signal into the presence of the touch and communicated with system.

Figure 5 demonstrates sensor circuit layout as an RC-delay circuit. The touch sensor can be represented as capacitance C cascaded with a high-value 1550 kΩ resistor R and a signal generator. The microchip was used to send signals to electrodes and extract time delay signal from the capacitor. The time constant is defined as the time for the voltage to be raised to $1 - 1/e$

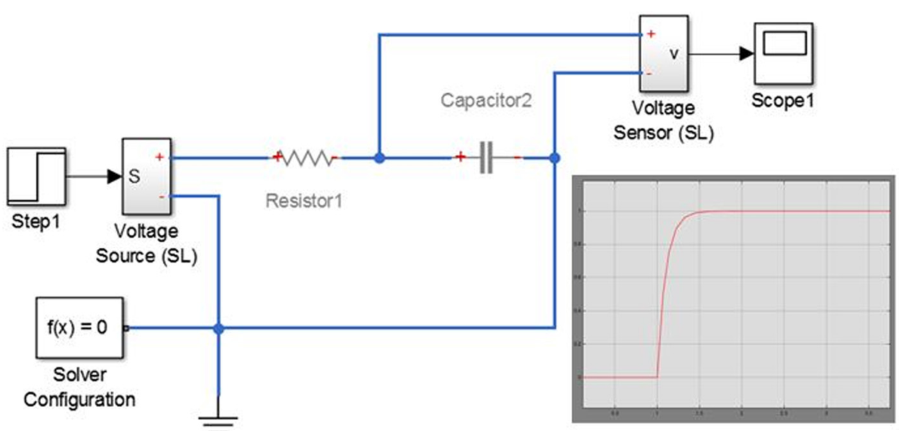

Fig. 5 Schematic of capacitive touch sensor test system

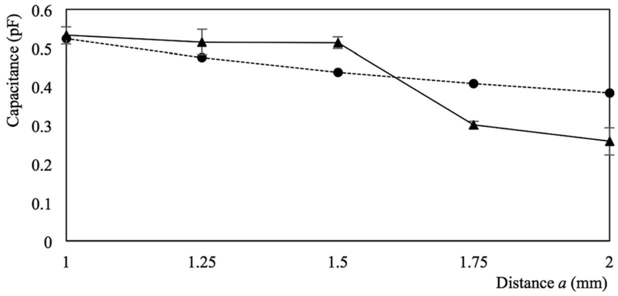

Fig. 8 Effect of distance between electrodes on touch sensor capacitance

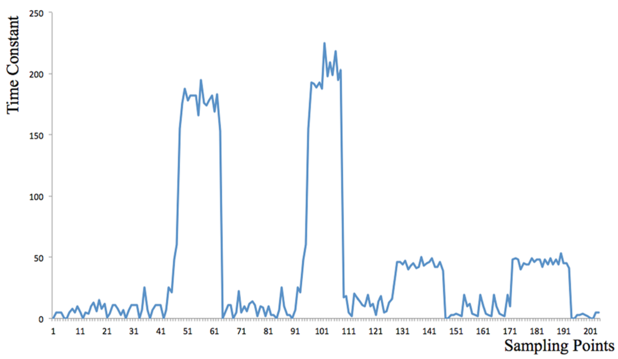

Fig. 9 Response time with finger touch/not touch the sensor

or 63.21% of the maximum value. The applied signal is shown to the right of the circuits.

Based on Kirchhoff's current law, we can calculate the capacitance of a printed touch sensor as

$$C * \frac{dv}{dt} + \frac{V}{R} = 0 \tag{7}$$

$$V_c(t) = V\left(1 - e^{-\frac{t}{RC}}\right) \tag{8}$$

$$C_{\text{sensor}} = \frac{\tau}{R} \tag{9}$$

where C is the capacitance, $R = 1550\ \text{k}\Omega$, and τ is the time for the voltage to be 63.21% of the maximum value of input voltage.

4.2 Effect of Number of Electrodes on Capacitance. The effect of number of electrodes on touch sensor capacitance was investigated in the study. As shown in Fig. 6, the capacitance of printed sensor was increased with increased active number of electrodes. The calculated results based on the model in Sec. 2 are the dotted line in the figure. The results indicated the overall trending and value of printed touch sensor match the proposed model.

The capacitance of a coplanar comblike touch sensor is proportional to the number of electrodes. As a result, for a fixed area, active greater number of electrodes will result in better electrical performance. That is the reason it is desirable to improve the resolution of printed electrodes. We can have more active number of electrodes on the touch area if we can further reduce the dimension of each electrode.

4.3 Effects of Length and Distance on Capacitance. Figure 7 and Fig. 8 demonstrate the effect of length and distance between electrodes on touch sensor capacitance. The dashed line was the calculated capacitance value based on our mathematical model. The experimental results matched the predicted value. With increased distance, the capacitance of printed patterns will be decreased. This is due to the fact that with larger gap between adjacent electrodes, the coupling effect between them will be weaker because air has much larger permittivity.

4.4 Effects of Finger Touch on Capacitance. We sampled the time constant with/without finger on the touch sensor to test its sensitivity for interaction with human fingers. Figure 9 shows response time with two finger touches and two without touches in 200 sampling points. As we can see, there is a significant difference with/without finger on the touch sensor in terms of response time. The touch response can be further applied into electrical system design and circuit design. Our proposed touch sensor can be further applied into touch screens, medical devices, etc.

4.5 Rapid Prototyping of Microelectrodes Array. We printed microelectrodes array on PET film using the additive E-jet printing to demonstrate the capability and versatility of our proposed rapid prototyping method. As shown in Fig. 10, we successfully printed high-resolution microelectrodes array with dimension as small as 15 μm. The patterns also demonstrated excellent transparency and flexibility on PET film using silver nanoink. The device we fabricated can be further applied for microcapacitor, inducer, or as electrodes array for flexible displays.

The rapid prototyping methods presented in the paper can also be adapted for curved substrates, which have advantages over traditional lithography methods. With metal ink used in the presented process, it can potentially be a good replacement for the traditional ITO film in current flexible display technologies.

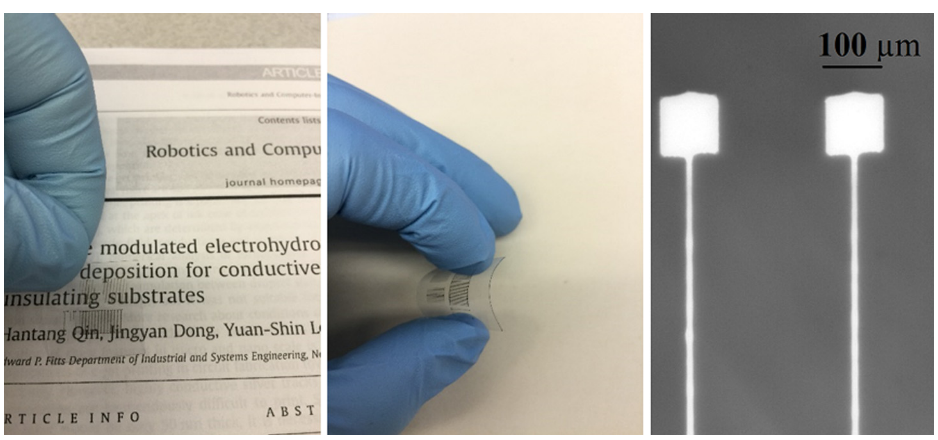

Fig. 10 Printed microelectrodes array on PET film with good transparency, flexibility, and high resolution

5 Conclusions

In this paper, we investigated the feasibility of rapid prototyping of capacitive touch sensor on flexible substrates based on E-jet printing using silver nanoink. An improved mathematical model on our coplanar touch sensor design was developed to calculate the capacitance of printed sensor closely approximated measured values. We successfully fabricated touch sensors using comblike interdigital structure. The effect of the design parameters, including the number of active electrodes, length of electrodes, and distance between electrodes, were investigated in the study. With increasing number of electrodes, active length, and smaller distance, the capacitance will increase, thus providing better sensing performance. Finally, we demonstrated rapid prototyping of sub-20 μm microelectrodes arrays using silver nanoink on PET film.

The successfully developed rapid prototyping method shows several distinct advantages and benefit to the community. It fills the gap between flexible electronics and rapid prototyping using metal ink. The touch sensor demonstrated in the paper can be used as an alternative to fragile ITO film used in current touch display. The overall process is low cost, flexible, and avoid vacuum processing environment. The presented touch sensor and its rapid prototyping method can be further applied in medical and display applications, and it is also capable of on-demand prototyping of any conductive patterns in flexible electronic manufacturing.

Acknowledgment

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Nomenclature

a = half-gap between electrodes
C = capacitance
C_{air} = air capacitance
C_{film} = film capacitance
C_{sensor} = sensor capacitance
C_{total} = total capacitance
l = length of electrodes
N = number of electrodes for single polarity
R = resistance
V = voltage
w = width of electrodes
w_{eff} = effective width of electrodes
ε_r = dielectric constant
ε_0 = electric constant
τ = time constant of RC circuit

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