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Fabrication and electrical characterization of multi-layer capacitive touch sensors on flexible substrates by additive e-jet printing

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ABSTRACT

Current consumer electronics, in particular touch displays and flexible electronics, were limited by the properties of existing commercial transparent conductor materials used as electrodes both in flat panel display and capacitive touch sensors. In this paper, an alternative fabrication technique using silver nanoink that can be used for rapid prototyping of high-resolution electrode arrays to replace indium tin oxide (ITO) for flexible electronics was presented. By direct printing silver nanoparticles on flexible substrates, capacitive touch sensors were fabricated onto polyethylene terephthalate (PET) film. Experiments were conducted to study the feasibility of electrohydrodynamic inkjet printing (e-jet printing) of high-resolution electrodes for touch sensors. Sensitivity of sub-20 μm capacitance sensor array was investigated in the study for droplet and humidity detection applications. The rapid prototyping method makes a significant impact in enabling simultaneously (1) customized and flexible touch sensors, (2) cost-effective manufacturing, and (3) high resolution and good sensitivity. The presented techniques can be used for the on-demand fabrication of customized conductive patterns for flexible and wearable electronics.

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]. Display industry has been driving new development of flexible screens for portable devices. Indium tin oxide (ITO) is the current industry standard materials used as transparent conductor electrodes. ITO is a brittle ceramic material which makes it unsuitable for flexible electronics. ITO in most cases is fabricated through a vacuum deposition process. A most distinguishing feature of flexible electronics is the possibility to print or coat the device directly onto thin flexible carrier substrates using roll-to-roll manufacturing or printing methods that enable simple handling and fast processing [10]. The ideal ITO replacement material should be a printable or coatable conductor material. Nanowires and other forms of metal meshes have emerged as ITO replacement materials. On one hand, they offer benefits for large-area flexible displays where conductivity and flexibility of ITO on plastic substrates is an issue. On the other hand, the overall manufacturing cost can be reduced as they all have flexibility in printing or coating.

Touch sensors have been commercially available for over thirty years and widely used everywhere such as touchpad, tactile devices, and fluid detection applications. 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 [11–13]. 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 an object. Substrates for capacitive touch sensors may be glass or flexible polymers, or combination of them [14]. The sensors are usually constructed as narrow strips of conductors. Interdigital electrodes are among the most commonly used

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sensor structures. The change in capacitance caused by proximity of a finger near an intersection is 1pF or less, and the effect on adjacent electrode may be less than 0.1 pF [15]. 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 [16].

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 focus 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 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 flexible devices in prototyping domain. 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 TFTs 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.

Directly printing approaches, especially those based on ink jet printing in high-resolution fabrication situation, demonstrate attractive features in their application. First, inkjet printing is non-contact, 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 [17]. Fourth, inkjet printing is flexible in position. [18] The location can be changed in real time to ensure high quality patterns. It also shows potential for mass production and low cost operation [19]. 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, multi-functional 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, the focus is in device and system integration level to test products from electrohydrodynamic inkjet printing (e-jet printing) on underlying of electrode structure, materials, and fabrication process. The capacitance sensor design, sensitivity, and electrical performance on flexible substrates were investigated in the study. The new techniques was presented to fabricate integrated capacitance sensors using additive e-jet printing with conductive silver nano-ink. With the help of e-jet printing, sub-20 μm features can be on-demand printed on any substrates. The presented method can be adapted into rapid prototyping of touch pads or micro fluid detecting sensors in micro scale. The interdigital design maximizes the capacitive signals for sensor applications in 2D domain. The over-all performance was characterized using an RC relaxation oscillator circuit. The analysis of electrical performance of parallel coplanar patterns and high-resolution pattern was conducted to test electrical properties of direct printed patterns.

The results of experimental tests confirmed that capacitive sensors fabricated by the proposed additive e-jet printing could be effective for sensor applications. The sensors exhibited great stretchability, high sensitivity, and fast response time (~30 ms). Both high resolution and electrical properties were achieved in the work. 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 [20]. 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 deposited on both sides), and the bottom LED/LCD screen [21], as shown in Fig. 1. Projected capacitive technology provides advantages such as multi-touch detection, excellent optical properties, and long life. Projected capacitive touch sensors are easy to integrate into systems to eliminate coordinate drift [22]. 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.

The electrodes are active conductive elements of the sensor. Many electrode patterns can be used to create projected capacitive sensor. The electrode pattern geometries are an important factor in sensitivity and resolution of the sensor. For the projected capacitive touch sensor pattern shown in Fig. 1, the touch sensor arrays are "scanned" in working conditions. Each individual electrode or electrode intersection is measured one-by-one. In a typical scanning for touch sensor arrays, the controller will drive a single column (Y) and then scan every row (X) that intersects with the column. The capacitance value at each X-Y intersection will be measured and compared with initial values to determine location of objects [23]. The process is repeated for every column until the entire pattern is scanned. The columns and rows of touch displays are physically fixed. Since each intersection is responsible for a small area. The capacitive touch sensors are more precise than any other methods. The development of capacitive touch displays has evolved since the past 10 years with patents and introduction of iPhone from Apple in 2007.

The actual functioning area is shown on the right in Fig. 1. The active functioning components are the intersection areas. It can be modeled using the simple capacitor model.

$C = \varepsilon_r \varepsilon_0 A/d$, where C is the capacitance of intersection, ε_0 is permittivity of free space ($8.85^* \, 10^{-12}$ F/m), ε_r is the relative permittivity to space of filling material. The value of capacitance is related to surface area of plates, distance between plates, and materials constant for insulating films. In this design, patterning ITO on glass with line widths of 20 μm and resistivity of 2–6 Ω *μm is commonly accomplished using photolithography. Micro level metal wires (sub-20 μm) can be a good substitute for sputtered ITO in most cases. When it comes to flexible electronics, e.g. pattern on flexible PET film, line width based on screen-printing or laser ablation are typically 100-200 μm. There are increasing demands