Low-Cost Fabrication Method for Thin, Flexible, and Transparent Touch Screen Sensors

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This study presents a new fabrication method for touch screen sensors using inexpensive, flexible, and transparent polyethylene terephthalate (PET) films. In the proposed method, a transparent capacitive touch sensor array is implemented with two independent axes of invisible electrodes consisting of indium tin oxide (ITO) patterns and bridge electrodes. A low-cost implementation of the bridge electrodes is achieved by using near-field electrospinning (NFES) method for the conductive lines with linewidth of 3–5 µm. Then, the printed bridge electrode is sintered using green laser without damaging the PET film. It is demonstrated that two transparent electrodes deposited on a single sheet of PET film can detect the touch location by scanning the driving signal while simultaneously measuring the capacitances from the sensing lines connected via bridge electrodes.

Recently, touch screen panels (TSPs) have become essential parts of modern electronics for users to interact with their devices via the displayed contents. When a fingertip or a stylus touches the display, the touch location is detected for further processes. For this reason, TSPs are usually placed in front of, or are integrated into, the display panels and need to be sufficiently transparent to ensure the quality of displayed contents and in order to enhance the user experience. Touch screens can be classified into several types according to their sensing methods and of these, capacitive sensing has been widely used due to its durability, performance, simultaneous multitouch and highly sensitive sensing capabilities. In capacitive sensing, the touch location of the finger or stylus can be determined by scanning for a change in capacitance at each location. Electrode arrays are arranged in two sheets of film with each of the X and Y axes, and these two axes can be used as driving (or transmitter) and sensing (or receiver) electrodes, respectively. Two substrates (or sheets) of driving and sensing electrodes are isolated by a layer of dielectric material, as shown in (Figure 1).

Efforts have been made to integrate two sheets of X and Y electrodes into a single sheet in order to reduce manufacturing costs and the thickness of the touch screen. For this purpose, both driving and sensing electrodes should be fabricated on a single substrate in a process that may require several steps. In the first step, the X and Y electrodes are fabricated such that the Y-axis driving electrode arrays are connected while the X-axis sensing electrode arrays are disconnected as segments, as shown in (Figure 1b). Then, an insulating layer is printed at each intersection position. Finally, a conductive bridge, so called bridge electrode, should be patterned to pass over the insulating layer to connect the sensing electrodes, as shown in (Figure 1c).

For transparent touch sensors, transparent conductive materials such as indium tin oxide (ITO) or aluminum-doped zinc oxide (AZO) have been widely used. In conventional methods, a transparent conductive material should be deposited on a large area first, then a part of the deposited material is removed to obtain the electrode patterns. However, in the case of bridge electrode patterning, a large amount of deposited material should be removed due to the small dimensions of the bridge electrodes, which results in a huge waste of materials. In addition, a low yield can occur due to process difficulties. To overcome such problems, a proper fabrication method should be developed for bridge electrodes, which has been a critical issue for TSP manufacturers. To ensure a transparent touch sensor, printed electrodes should have a width of less than 10 µm in the case where nontransparent materials are used for printing. Several direct patterning methods have been proposed to fabricate the bridge electrode. Schneider et al. implemented...
an electrohydrodynamic printing method to produce patterns with features several micrometers in size. However, the printing speed was very slow from 1–10 µm s⁻¹, and multiple prints were required to achieve proper pattern thickness for the conductivity. As a result, the printing process might not be efficient for mass production. Alternatively, Hong et al.¹² used selective laser sintering to produce fine patterns of about 5 µm and implemented a method to fabricate transparent touch screen sensors. However, it may not be a cost-effective process. For patterning, the whole substrate needs to be coated with conductive materials first. Then, fast laser spot scanning should be used to make fine conductive patterns. The laser absorption layer was shallow, and the final thickness of the patterns was very thin (<200 nm).¹²

In this study, we propose an effective fabrication method for touch screen sensors based using the direct printing method described in Figure 1d and (Movie S1, Supporting Information).

Figure 1. Capacitive touch screen sensors and proposed fabrication process. a) Touch screen sensor with two-sheet films having separate electrode layers. b) Touch screen sensor with driving and sensing electrodes deposited on a single-sheet film with disconnected sensing electrodes. c) Bridge electrodes to connect the sensing electrodes without a short circuit with the driving electrode. d) Proposed direct printing method for invisible electrodes. e) The ITO-patterned PET film used in the demonstration.
120 °C for 10 min. The pads were used to verify the resistance of the printed electrodes after sintering, and to connect to the sensing circuits and driving voltage for the touch sensing demonstration.

For the second step, insulating layers were inkjet-printed at the intersection points of the X and Y electrodes by using polyimide (PI, JNC Corp., Japan) ink. Then, the insulating layers printed on the PET film were thermally cured at 100 °C for 10 min in a convection oven. Note that readout pads were used for printing alignment during insulation ink deposition since ITO-patterned X and Y axis electrodes are invisible.

For the third step, we used near-field electrospinning (NFES) to directly print the bridge electrodes over the insulation ink (Section S1, Supporting Information). NFES is a noncontact printing method based on Taylor cone jet produced by electrical field.\[^{[13–15]}\] By using NFES technology, very thin patterns (<10 μm) could be printed using high viscosity ink (>1000 cP).\[^{[13]}\] The use of high-viscosity ink has advantages when low resistance is required for fine patterns.\[^{[11,16,17]}\] NFES has additional advantage of fast printing speed more than 500 mm s\(^{-1}\).\[^{[13]}\] Due to the advantages, NFES has been drawn attention in recent studies.\[^{[14,18]}\] However, on-off control of jet stream has been one of its challenges. As a possible solution for this issue, masking layer could be used in order to avoid printing on unnecessary parts.\[^{[13]}\]

Note that conventional inkjet method cannot be used in our application because it uses low viscosity ink (<20 cP) and the patterns size could be more than dozen micrometers.\[^{[19]}\] Other conventional printing methods using high viscosity ink, such as screen printing and nozzle based dispensing methods, are not suitable for our application due to the large printing feature size more than 100 μm.\[^{[19–22]}\]

In order to implement NFES method for our purpose, the ink is continuously supplied to a nozzle tip by a syringe pump and a high DC voltage is applied to the nozzle holder in order to produce electrical field for jetting. For the conductive ink for NFES, commercially available silver (Ag) nanopaste ink was used and added a high molecular weight polymer (refer to the Experimental Section). The critical printing parameters to obtain the desired printing result were the ink supply flowrate, voltage, and stage motion speed.\[^{[13]}\] A lab-developed printing system was used for the inkjet and NFES printing process. The NFES ink was fed to the nozzle using a syringe pump (Nanojet, Chemyx Inc., USA). The syringe needle with an inner diameter of 100 μm was used to dispense the ink. For patterning using electrospinning, the standoff distance between the nozzle and the substrate was set to 2 mm. Note that the stage motion speed should be sufficiently high during patterning. Due to a high printing speed, the stretchable and continuous jet stream could become thinner and better aligned to the printing direction.\[^{[13]}\]

Our study used a speed of 300 mm s\(^{-1}\) for patterning. Figure 2 shows scanning electron microscopy (SEM) images of the printed bridge electrodes that connect the sensing electrodes over the insulating layer described in (Figure 1c). The printed positions for both the insulation layer and bridge electrodes were well aligned at the intersection of the X and Y-axis ITO electrodes. The printing accuracy was within dozens of micrometers, which is acceptable for our applications (Figure 2b). The width of the printed line was around

![Figure 2. SEM images of the printed bridge electrodes using NFES. a) Nonprinted ITO pattern and b) printed results at the intersection of the sensing and driving electrodes. c) Magnified SEM images of the boundary of the insulating layer. d) Magnified SEM image of the boundary of the pad electrodes. e) Printing behavior on the pad. f) Illustration of printing on a nonflat surface. Printing parameters: ink flowrate of 0.2 μL min\(^{-1}\), printing speed of 300 mm s\(^{-1}\), and driving voltage of 1100 V at the nozzle holder.](image-url)
Among others, the readout pads affected the sintering performance could be different according to the underlying materials, including laser power and laser scanning speed, were not optimal (Sections S2 and S3, Supporting Information). Another difficult issue of light-based sintering is that the insulating layer did not influence the printing results because it was a considerably thin layer of several hundreds of nanometers, and the printed lines could pass over the insulating area easily (Figure 2b,c). On the other hand, the thickness of the readout pads was about 5 µm, which is significantly thicker than the printed line thickness (~1 µm). Nevertheless, the stretchable ink used for NFES can effectively print over nonflat surfaces (Figure 2e). The printability of the NFES on a nonflat surface can be useful when it is used to interconnect various electronics components of different heights.

After printing, the printed line should be sintered to fuse the Ag nanoparticles and remove some organic additives to achieve proper conductivity. In general, thermal sintering with a hot plate or a convection oven has been used. For instance, the manufacturer of the Ag nanopaste ink recommends that the ink should be sintered at 150 °C or a higher temperature for 30 min. On the other hand, the sintering condition might differ from that of the original Ag paste ink since polymer was added to the Ag nanopaste ink in order to enhance the stretchability of the ink. According to the thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) measurements of the NFES ink (Section S2, Supporting Information), a significant portion of solvents in the ink can be removed at 150 °C. The TGA analysis (Figure S3, Supporting Information) indicates that a high temperature of up to 400 °C may be necessary to remove most organic additives. However, the use of low-cost PET film substrate could limit the use of a direct heat source for sintering. The PET substrate has a glass transition temperature and melting point of about 80 °C, and about 250 °C, respectively. As a result, the PET film could be easily damaged during thermal sintering. The most difficult issue in fabricating fine conductive patterns on PET film is to optimize the sintering conditions without damaging the film.

To solve the sintering issue, we proposed the use of CW green laser with a wavelength of 532 nm (LaserGlow Technologies, Photonic Endeavours Inc., Canada). Laser sintering can minimize the damage to the substrate since it can affect only the irradiated part. By irradiating a focused laser light on the printed lines, heat can be generated only on the surface of the printed lines. Here, the transparent PET film tends to be less affected by the green laser light because most of the laser light is transmitted or reflected on the substrate. Nevertheless, the PET substrates were damaged when the laser sintering parameters, including laser power and laser scanning speed, were not optimal (Sections S2 and S3, Supporting Information). Another difficult issue of light-based sintering is that the sintering performance could be different according to the underlying materials. For example, there are three different underlying materials to sinter the printed bridge electrode: readout pads, insulating layer and ITO patterns on the PET film. Among others, the readout pads affected the sintering performance significantly since the amount of absorbed light could be significantly higher compared to that of the printed lines on a transparent film. Note that the diameter of the focused laser light (~50 µm) was larger than the printed feature size (~4 µm) and much smaller than the size of the readout pads. Another consideration for sintering is that readout pads may have a higher heat transfer capability than another part of the PET film. So, the heat generated on the irradiated part of the readout pads can be transferred to the other nonirradiated part quickly. As a result, we can observe that the degree of damage appears differently according to the path of the laser light. For example, we observed a totally burnt pad at the part where light enters while there was no damage to the middle part of the pads (Figure 3a). Damage on the pads, especially burning at the light entering part, should be avoided to ensure a connection between the printed line and the pad.

To avoid such damage, two options can be considered: 1) reducing the laser power; 2) increasing the laser scanning speed. However, it should be noted that, even in the case using low laser power, cracks in the sintered lines can sometimes be observed near the connection (Figure 3b). Based on our experiments, a laser power from 0.5 to 0.7 W and scanning speed from 20 to 50 mm s⁻¹ should be used for the laser sintering condition (Figure 3c,d).

To evaluate the bridge electrodes after sintering, we measured the resistance between the pads, as shown in (Figure 3e). The measured resistance is almost inversely proportionate to the pattern width, as shown in (Figure 3f). The average of the measured resistances was about 800 Ω in the case of a pattern width of 6 µm, and about 1.1 kΩ in the case of a pattern width of 3–4 µm, which is equivalent to 18 and 24 Ω mm⁻¹, respectively. Note that the pattern width, thickness and underlying materials could influence the sintering process and results. The thickness of the printed lines was in the range from 800 nm to 1 µm depending on the pattern width (Figure 3d).

To demonstrate the touch sensing capability, an array of 4 × 4 transparent electrodes (ITO and printed bridge electrodes) was used for external sensing and driving, as shown in (Figure 4). The patterned substrate was covered with an antifingerprint film (Alubskin, South Korea) to protect the printed lines from direct contact. The fabricated touch screen sensor was sufficiently transparent, and the characters underneath can be read without any nonvisible part (Figure 4a). The sensing circuit and driving signal are connected to the pad electrodes in the X and Y directions, respectively. For the driving signal, an AC voltage (50 kHz, 5 Vpp) was scanned throughout the driving lines (readout pad in the Y direction) applying voltage only one line at a time in a sequential manner. Each time a driving voltage was applied, the capacitances of each cross-section driving Y and all X electrodes were measured simultaneously (Section S4, Supporting Information). To understand the sensitivity of the amplified capacitance, the amplified signal was monitored by using an oscilloscope when the corresponding location was touched by a finger (Figure 4b) and (Movie S2, Supporting Information).
Information). The amplified capacitance signal was about 1 V when the location is touched, and the signal did not show any significant drift and high-frequency noise (Figure 4b and Movie S2, Supporting Information). The capacitance changed due to touching is about 20 pF, which is similar to others’ works.[7,33]

Since the touch sensors were fabricated on a flexible PET film, the touch location can be detected even when the touch screen sensor was bent (Figure 4c) and (Movie S2, Supporting Information).

In summary, we successfully fabricated touch screen sensors by printing bridge electrodes via NFES direct printing on PET film. Most display devices require a human-device interface function. For this, a touch screen sensor can be used to replace other input devices, such as mice or keyboards. With our proposed method, only a single sheet of low-cost PET film is required to fabricate an array of touch sensors. As a result, thinner, more flexible, lower-cost touch screens could be produced. We believe that most display devices will incorporate touch screens as innovating manufacturing methods such as our proposed method meet both the functional and low-cost requirements of today’s mobile devices.

Figure 3. Laser sintering results. a) Sintering with a laser power of 1 W. b) Sintering with a laser power of 0.7 W. c) Sintering with a laser power of 0.5 W. d) Microstructure of the printed line sintered with a laser power of 0.5 W. e) Measurement of a single line of 46 mm in length. f) Measured resistance of the printed line sintered with a laser power of 0.5 W. Laser scanning speed = 20 mm s⁻¹.

Figure 4. Touch screen sensor for demonstration (refer to Section S4 and Movie S2, Supporting Information). a) Transparency demonstration. b) Signal readout during touching on the touch screen sensor. The change of voltage level is about 1 V. c) Sensing demonstration during bending of the touch screen sensor. The touched position is shown in lighter color on the display.
Experimental Section

**NFES Ink Preparation:** For the conductive ink for NFES, commercially available silver (Ag) nanopaste ink (ES-INK, NPK, South Korea) with a particle diameter of around 150 nm was purchased. The paste ink contains 85.5 wt% of Ag nanoparticles and has a typical viscosity of 11200 cPs. To enhance the viscoelasticity of the paste ink, Ag paste ink was mixed with a 3 wt% poly (ethylene oxide) (PEO, Mw = 400 000 g, Sigma-Aldrich, USA) solution. The solvent of the PEO solution was a mixture of ethanol (Duxsan Chemical, South Korea) and distilled water at a 4:1 mass ratio. The Ag paste ink and the prepared PEO solution were mixed at a 5:1 mass ratio using a vortex mixer (VM-96E, Jeio Tech, South Korea) for 30 min to obtain the NFES ink.

**Bridge Electrode Patterning and Sample Preparation:** The transparent driving and sensing electrodes were patterned via dry etching of the ITO-coated PET films (Elecrysta, Nitto Denko Corp., Japan). The readout pads were screen printed using Ag paste (DGP-MS, ANP Co. Ltd., Korea) followed by curing at 120 °C for 10 min. The ITO-patterned PET films with readout pads were prepared and provided by Samsung Electronics. For the insulation layer, polyimide insulation ink (PI, JNC Corp., Japan) was inkjet printed on each intersection of the ITO electrodes in the X and Y directions. After curing the deposited ink, bridge electrodes were printed. For this purpose, NFES ink was fed to a syringe needle with an inner diameter of 100 μm by using a syringe pump (Nanjoit, Chemyx Inc., USA). The stand-off distance between the nozzle and the substrate was set to 2 mm, and the voltage applied to the nozzle was 1 kV. In order to achieve fine and well-aligned patterns, the printing speed was set to 300 mm s⁻¹. In order to obtain a steady-state jet, idle printing was performed for 30 min prior to printing the bridge electrodes. After printing the bridge electrodes, the printed lines were sintered using a green laser with a wavelength of 532 nm (LaserGlow Technologies, Photonic Endeavours Inc., Canada) in a continuous mode with a power of 0.5 W and scanning speed of 20 mm s⁻¹. The patterned sample was covered by an antifingerprint protection film (Alubskin, South Korea).

**Characterization and Verification:** The Ag bridge electrodes were characterized using an optical microscope (Mitutoyo, Japan) and surface profiler (Surfcorder ET200, Kosaka Lab Ltd., Japan). Then, a microstructure analysis was carried out using a high-resolution scanning electron microscope (HRSEM, Mira 2, Tescan, Czech Republic) and a Focused Ion Beam (FIB, Lyra 3, Tescan, Czech Republic). The resistance of the Ag bridge electrode between the pads was measured using a multimeter (Chekman TK-4002, Tae Kwang Electronics, South Korea).

Keywords
capacitive touch panel, laser sintering, near-field electrospinning, PET substrates, transparent flexible electrodes

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