3D Structured Capacitive Sensors

Subjects: Engineering, Electrical & Electronic | Engineering, Mechanical | Nanoscience & Nanotechnology
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Rapid technological advancements have led to increased demands for sensors. Hence, high performance suitable for next-generation technology is required. As sensing technology has numerous applications, various materials and patterning methods are used for sensor fabrication. This affects the characteristics and performance of sensors, and research centered specifically on these patterns is necessary for high integration and high performance of these devices.

Keywords: inkjet printing ; screen printing ; laser patterning ; soft lithography ; 3D sensors ; capacitive sensors

1. Introduction

Various patterning methods can be employed to establish patterns in sensors, and these should be selected in consideration of the characteristics of the materials and substrates [1].

2. Inkjet Printing

Inkjet printing is a widespread technology that directly sprays a target material onto a substrate through a nozzle. This digitally controlled technology is used to perform direct printing that does not require a mask, and the substrate has few restrictions. In addition, many advantages (i.e., high accuracy and repeatability, low costs, and can perform large-area printing) lead this method to be utilized in various fields such as biomedical, energy storage, and electronics [2][3][4]. However, it has issues with throughput, resolution, and positioning accuracy. Moreover, nozzles are clogged when the ink concentration is high, and a coffee-ring effect appears when there is a non-uniform distribution in the pattern; thus, it is crucial to optimize the ink [5][6][7].

Pillai et al. (2023) reported a capacitive sensor capable of detecting polycyclic aromatic hydrocarbons (PAHs), environmental toxicants present in aquatic environments [8]. Silver nano-ink was used as the sensor electrode material, and it was printed on polyethylene terephthalate (PET) using inkjet printing technology. The surface energy and roughness of the substrate were increased using O_2 plasma treatment to improve the adhesion of the ink. The electrode was designed according to the ID pattern with a total area of 316.61 mm^2, the width and length of the fingers were 1.75 mm and 33.3 mm, respectively, and the total number of electrode fingers was eight. The LOD of the sensor for PAHs in aqueous media was 0.05 ng/mL, showing high sensitivity.

In 2022, Mondal et al. studied a transparent wearable tactile-cum-proximity capacitive sensor by utilizing inkjet printing [9]. Thermally deposited aluminum on a PET substrate was used as the electrode for the sensor. After printing polyvinyl alcohol (PVA) in a serpentine pattern using inkjet printing, aluminum was deposited thereon. Subsequently, the PVA was lifted off to fabricate the aluminum into an ID pattern. The pattern was fabricated on a large area of 30 × 30 cm^2, and the distance between the electrode fingers was 300 μm. The fabricated sensor was able to detect non-touch up to 9 cm away from the sensor, while touch detection had a high sensitivity of 1000%.

3. Aerosol Jet Printing

Aerosol jet printing is a recently emerging printing method that is widely used in micro manufacturing, such as microfluidic devices, due to its digitized direct writing, non-contact, and high resolution (≈10 μm) [10][11]. Atomized ink through ultrasound, gas mechanics, and spark discharge flows into carrier gases and is sprayed onto the substrate [12][13]. At this time, clogging of the nozzle can be prevented by flowing the sheath gas together [14].

Fujimoto et al. (2020) reported the production of a capacitive strain sensor using aerosol jet printing [15]. Commercial aerosol jet printing was used (Optomec Aerosol Jet 200), and silver nanoparticle ink was pneumatically atomized and sprayed on a polyimide substrate through a 200 μm nozzle. The pattern was designed in an ID shape, and the finger width, length, and spacing were approximately 70 µm, 15 mm, and 80 µm, respectively. The fabricated strain sensor had initial capacitance values ranging from 42 pF to 15 nF and a gauge factor of 5.2.

4. Screen Printing

Screen printing is used to print a desired pattern using a screen or stencil as a mask. Squeezing is used to pass the ink through the mask and print onto the substrate. It is widely used industrially because of its ability to produce patterns with high resolution and accuracy in a large area at high speed.

Truong et al. (2022) studied a wearable capacitive pressure sensor by using the screen-printing technique [16]. Polyester and cotton fabric were used as substrates, and commercially available silver paste (DM-SIP-2001) was printed in the shape of an ID pattern. The width and length of the electrode fingers were 0.57 mm and 15 mm, respectively, and the gap between the fingers was 0.71 mm. Thereafter, a microporous film consisting of Ecoflex and CNT was coated on the electrode to increase the sensitivity of the sensor. As a result, the sensor could measure up to 400 kPa, and the sensitivity ranged from 0.035 (at 400 kPa) to 0.15 KPa^{-1} (at 50 kPa).

Aeby et al. (2023) produced a renewable and biodegradable humidity sensor using a screen printing method [17]. They printed an ID pattern of electrodes using carbon ink containing graphite flakes and carbon black using a commercial screen printer and polyester mesh. The sensing area was 1 cm^2, the width and gap of the fingers were 200 µm, the length was 10.1 mm, and the number of fingers was 24. Afterwards, egg albumin was drop-cast on the sensing area, which is sensitive to humidity, increasing the sensor's response and recovery speed by about 20 times and achieving a sensitivity of 0.011% RH^{-1}.

5. Laser Patterning

Laser ablation, or laser patterning, produces patterns by inducing phenomena such as sintering, evaporation, melting, and solidification. It utilizes thermal energy and irradiates a laser beam on a sample. Owing to high-density energy being exposed to a local area, sample damage, such as cracks, distortion, and burning, may occur. Therefore, optimization of process parameters related to the laser energy density, such as the laser-spot size, power, speed, and frequency, is required [18][19]. It is a preferred patterning technique because it does not require a mask and is highly accurate and productive.

Wagh et al. (2022) explored a microfluidic taste sensor by using laser ablation [20]. A polyimide film was used as a substrate, and graphene was partially developed by irradiating a CO_2 laser (1.95 W, 2.5 cm/s). Laser-induced graphene (LIG) was printed in an ID pattern and used as an electrode. The width of the electrode finger and the gap between the fingers were 0.8 mm and 0.4 mm, respectively. Five analytes, namely sucrose (sweet), citric acid (sour), guanosine monophosphate (umami), sodium chloride (salty), and L-tryptophan (bitter), were prepared at 1–1000 ppm each. Their lower limits were 2.92, 5.205, 2.45, 17.11, and 4.89 µM, respectively.

Yagati et al. (2020) also fabricated LIG into an ID pattern and used it in a biosensor for thrombin detection [21]. LIG was patterned with a polyimide substrate as a precursor and an ID pattern with a finger width and gap of 200 µm and 45 µm thickness. The sensor had an analysis range from 0.01 nM to 1000 nM and a low LOD of 0.12 pM due to the high porosity of LIG, and also had excellent repeatability and long-term stability (over 7 days at 4 °C). Furthermore, the sensitivity of the LIG electrode may improve due to changes in the dielectric constant as aptamer antigens are labeled.

In 2023, Cui et al. showed a flexible LM-based humidity sensor using laser ablation [22]. After spray-coating the LM onto a polyimide film, a UV laser (6.8 J/cm^2) was irradiated to rupture the oxide skin of the LM nanoparticles to form a conductive network (resistivity of approximately 0.19 Ω·cm). The conductive path was printed in an ID pattern, and the number of electrode fingers was six. When the relative humidity changed from 30% to 90%, the highest capacitance change value was 142.4%, which was observed when the finger width was 1.5 mm and the length was 11 mm.

6. Soft Lithography

Soft lithography is a technique used to fabricate structures or patterns using elastomeric stamps (e.g., PDMS or Ecoflex) with a patterned surface. Using elastomeric stamps, various sub-techniques, such as microcontact printing, replica molding, and micro transfer molding, can be applied [23]. Soft lithography is a promising fabrication technology due to its low cost and easy process; however, its repeatability is low, and distortion may occur due to deformation of the elastomeric stamp (i.e., pairing, sagging, swelling, or shrinking) [24].

Zhang et al. (2022) studied an LM-based capacitive strain sensor, which was fabricated via soft lithography [25]. An ID-pattern-engraved PDMS was obtained by hardening the PDMS precursor in a pre-prepared mold. At this time, the electrode finger width, gap, and length of the pattern were 50 μm, 200 μm, and 1 cm, respectively. The PDMS microchannel was covered with another flat PDMS layer using O_2 plasma treatment, and then the channel was filled with LM. The fabricated LM-based sensor could be stretched up to 100% due to the material characteristics, and the repeatability gauge factor was −0.3.

Meanwhile, Joo et al. (2022) studied the fabrication of capacitive touch sensors using intaglio contact printing, a type of soft lithography technique [26]. For this purpose, CNTs were mixed with paraffin to make a slurry in a form suitable for intaglio space on PDMS stamps. The CNT composite filled in the intaglio of the ID pattern was transferred to various substrates and used to produce a capacitive touch sensor. At this time, ID patterns with finger widths of 125, 75, and 50 μm were prepared in the same area, and the number of fingers increased to 24, 40, and 60 as the width decreased. Based on Equation (2), it was shown that resolution and sensitivity increased as the pattern width decreased.

7. Advantages and Drawbacks

The major advantages and drawbacks of the patterning technologies reviewed (i.e., inkjet printing, screen printing, laser patterning, and soft lithography) are briefly summarized in **Table 1**.

Table 1. Summary of patterning methods with major advantages and drawbacks.

Method	Advantages	Drawbacks	Ref.	Resolution	Applications
Inkjet printing	**No mask required** **Large-area printing possible** **Low cost**	**Nozzle clogging** **Low resolution** **Low positioning accuracy**	[4][5][6]	**300 μm** [9]	**Wearable tactile sensors**
Aerosol jet printing	**High repeatability** **Non-contact with substrate** **High resolution** **No mask required**	**Low throughput** **Low consistency** **Low reproducibility** **Cumbersome optimization**	[9]	**70 μm** [15]	**Strain sensors**
Screen printing	**High throughput** **High precision** **High resolution** **Low cost** **Large-area printing possible**	**Mask required**	[26]	**570 μm** [16] **200 μm** [17]	**Wearable pressure sensors** **Humidity sensors**
Laser patterning	**No mask required** **High precision** **Large-area printing possible** **High productivity** **Cost effective**	**Damage to materials and substrates**	[17][18][27]	**800 μm** [20] **200 μm** [21] **1.5 mm** [22]	**Microfluidic taste sensors** **Biosensors (Thrombin detection)** **Humidity sensors**
Soft lithography	**Simple process** **Low cost**	**Distortion or damage of elastomeric stamp** **Low repeatability**	[23]	**50 μm** [25] **50 μm** [26]	**Strain sensors** **Touch sensors**

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