Metallurgical and Materials Data 3, no. 4 (2025): 107-114

Publisher: Association of Metallurgical Engineers of Serbia

Metallurgical and Materials Data

www.metall-mater-data.com

Advances in projected capacitive touch panels: innovations in materials and fabrication techniques

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ARTICLE INFORMATION:

https://doi.org/10.56801/MMD60

Received: 23 June 2025
Accepted: 11 August 2025

Type of paper: Review paper

ABSTRACT

Touch panels are one of the most commonly used technologies in a wide range of applications, including mobile phones, tablets, and displays. Among the various types of touch panel sensors, projected capacitive touch panels (PCTPs) are the most popular due to their excellent optical performance, high durability, multi-touch functionality, and precise touch-point detection. A PCTP features a multi-layer structure consisting of two layers of electrode materials and an insulating adhesive layer. The patterning of touch panel conductors significantly impacts the performance, accuracy, and sensitivity of the touch panels. Indium tin oxide (ITO) is the most commonly employed transparent conductive material in touch panel technologies. However, its drawbacks, including the scarcity of indium, elevated cost, and intrinsic mechanical fragility, have been well recognized. Among the alternative materials for replacing ITO, poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS) has emerged as a strong alternative because of its outstanding properties, such as high transparency, excellent conductivity, and mechanical flexibility. The traditional electrode patterning technique for PEDOT:PSS electrodes in touch panel applications is printing, which offers several advantages over conventional methods, including low cost, high accuracy, and rapid processing.

In this study, we review the recent advancements in PEDOT:PSS-based electrode patterning techniques for PCTPs, emphasizing printing technologies such as inkjet printing, screen printing, and other emerging methods. We evaluate their compatibility with PEDOT:PSS, technical challenges, performance metrics, and their role in replacing ITO. The paper also outlines future directions for the development of cost-effective, scalable, and flexible touch panel devices.

Keywords: Projected capacitive touch panels, ITO, flexibility, patterning technique, PEDOT:PSS.

1. Introduction

Touch panel sensors have been widely used in various applications such as smartphones, cameras, tablets, etc.(Seokman Kim, Oh, Yoo, & Cho, 2017; C.-L. Lin et al., 2017; Walker, 2012). Touch panel technologies are based on diverse mechanisms such as resistive(Eaton & Smith, 1997; Ma et al., 2015), surface acoustic wave(Adler & Desmares, 1987; Ma et al., 2015) infrared ray(Han et al., 2011; Ma et al., 2015) , and capacitive(Sunkook Kim et al., 2011; Ma et al., 2015; Walker, 2012). Most of the touch panels have two main parts: touch display and controller. The controller receives the signals to detect the X and Y locations that show the touch point (Zheng, Chen, Wu, Wang, & Wang, 2024; Zuk, Pietrikova, & Vehec, 2018).

Resistive touch panels include two stacked layers of electrodes, produced with conductive materials, and are separated with spacers which are made of dielectric materials. When a touch point is made by the two electrodes' junction at a localized area the electrical current is detected, and the coordination of the touch point is calculated by the controller. However, its drawbacks include mechanical degradation due to exposure of resistive layers to sharp objects, low resolution, and inability to touch several points at the same time (Eaton & Smith, 1997; Sunkook Kim et al., 2011; Walker, 2012). Surface Acoustic Wave touch panel sensors work by using ultrasonic waves to detect touching events. It is made of glass with four receiving and transmitting transducers and four reflector patterns. When a human finger touches the panel, transmitting transducers produce ultrasonic waves that travel over the surface of the panel, are reflected, and are detected by the receiving transducers and then converted to electric signals (Bharadwaj & Sastry, 2014; Walker, 2012). Infrared touch panel sensors are based

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on IR (Infrared Radiation) light beams, which are formed in X and Y directions to create an optical grid across the panel. When an object touches the panel, the invisible beam is interrupted, and a controller determines the position of the touch point (Walker, 2012; Wen, Chen, & Wan, 2024). The drawbacks of the surface acoustic wave and infrared ray touch panels are their premium price, complex structure, and inaccurate answers because of water or contamination (Bharadwaj & Sastry, 2014; Ma et al., 2015).

The quick development of capacitive touch panels (CTPs) is basically attributed to their multi-touch functionality, high-resolution image, very good visibility in sunlight, resistance to moisture, and good mechanical strength (Bharadwaj & Sastry, 2014; Sunkook Kim et al., 2011) . General capacitive touch panel sensors consist of a transparent substrate, conductive layer, and insulating layer. The conductive electrodes cross at right angles (x, horizontal axis, and y, vertical axis). These electrodes are split with a dielectric layer, and capacitors are arranged by the intersections of x and y electrodes. When a human finger is positioned near the junction of x and y electrodes, the capacitance value alters due to the disruption of the electric field in the grid arrangement caused by the finger (H.-M. Lee & Ko, 2024; W. Wu et al., 2024). The electric field lines are transferred to the finger, reducing the capacitance among the electrodes. This reduction of capacitance between two intersecting electrodes is calculated by an electrical sensing circuit. Capacitive touch panels just work with conductive objects, and the minimal resistance of electrodes is preferable to facilitate rapid circuit measurement times and a high signal-to-noise ratio (SNR)(Baxler, 1997; Sunkook Kim et al., 2011; Lim, Park, & Jeong, 2012; Ma et al., 2015). SNR is an industry-standard parameter for evaluating the performance of capacitive touch panel devices. The signal is measured based on the change in mutual capacitance when a conductive object (such as a finger) approaches the surface, while noise is influenced by internal sources (e.g., parasitic capacitance between electrode traces, material inhomogeneities) and external factors (e.g., electromagnetic interference). In capacitive touchscreens, mutual capacitance refers to a configuration where an electric field is formed between intersecting rows and columns of conductive electrodes. When a finger approaches or touches the screen, it disrupts this field, and the change in capacitance is measured at the intersections to detect the precise touch location. Materials with higher conductivity, such as silver nanowires or graphene, can enable faster and more distinct signal changes, thereby enhancing SNR. Additionally, the geometry of the electrode pattern plays a significant role: optimized designs, such as interdigitated or 5-square layouts, promote more uniform electric field distribution and reduce capacitive crosstalk, which helps to further improve SNR. For example, as reported in Lee et al. (J. Display Tech., Vol. 10, No. 5, May 2014), Figure 4(a) and 4(b) illustrate that electrode patterns with a higher density of fringing electric fields (such as the 5-square design) can achieve up to ~5.4% improvement in touch sensitivity compared to conventional interlocking diamond patterns. Overall, both the electrical properties of the materials and the electrode architecture are critical in determining the overall SNR, and thus the performance, of projected capacitive touch panels (J. Lee, Cole, Lai, & Nathan, 2014; Prendergast, December 2011; Walker, 2016). CTPs are divided into two categories: surface capacitive touch panel panels (SCTPs) and projected capacitive touch panels (PCTPs). SCTPs consist of a uniform conductive layer that is deposited on a sheet of glass, and only one side of the glass is coated with a transparent conductor. The conductive layer is connected to pattern electrodes, which are connected to the touch panel flexible tail. When a potential is introduced to the electrodes, the result is a uniform electrostatic field. The controller can determine the touch point indirectly from the change in the capacitance caused by the human finger as measured from the four corners of the panel. PCTPs are made of a matrix of rows and columns of electrodes that are layered on two sheets of glass or films (Hoque, Claros, & Bender, 2024; Palma, Pourjafarian, Steimle, & Cignoni, 2024). It uses a uniform electrostatic field by applying a voltage to the electrodes. When a conductive object encounters the panel, it distorts the field and changes the capacitance. Therefore, the reduction of the capacitance at the touch point is detected by the controller. SCTP is a single-touch technology and is not as robust as PCTP, since the conductive layer is positioned on the upper surface of the glass, covered solely by a protective coating (Barrett & Omote, 2010; Kyoung & Hattori, 2014; Walker, 2012). PCTP has high durability, multi-touch functionality, resistance to environmental conditions, high flexibility in design, and excellent optical properties(Bhalla & Bhalla, 2010; Kyoung & Hattori, 2014).

This review focuses exclusively on capacitive touch panels utilizing PCTPs. The first section explores the various types of PCTPs and their key features. The second section examines mutual PCTPs, along with their structural designs and electrode patterns. Subsequent sections delve into recent advancements in PCTP materials and the latest technologies for electrode patterning.

2. Projected capacitive touch panel sensors (PCTPs)

Within the diverse kinds of touch panel sensors, projected capacitive touch panel (PCTP) is one of the most important technologies owing to its excellent optical performance, robustness, multi-touch functionality, and high accuracy in determining touch points (Niu et al., 2024; Sakthivelpathi et al., 2024). A general PCTP has a multi-layer structure which consists of a lower layer, an upper layer, and an insulating adhesive layer. The upper and lower layers have multiple conductive strips arranged in parallel patterns in two different directions. There are some electrode patterns for PCTPs as shown in Figure 1 (Bhalla & Bhalla, 2010; Kyoung & Hattori, 2014; L. Lin & Chien, 2012).

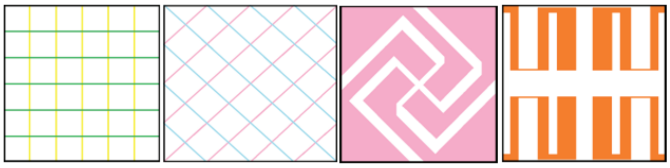

Fig. 1. Some electrode patterns for projected capacitive touch panel sensors. The name of the pattern from the left side to the right side is grid, diamond, interleaved, and angled cross pattern, respectively.

Therefore, a PCTP consists of rows and Vertical arrays of electrode framework composed of a conductive material, which is layered on two sheets of glasses or films. There are two types of PCTP utilizing the capacitive sensing technique: self-capacitive and mutual-capacitive (Aslam, Mittal, & Manglick, 2023; J. Lee et al., 2014). Mutual-capacitive has a capacitor at each intersection of each row (sensing electrodes) and column (driving electrodes). Constant and alternating electric current passes from the driving electrodes. The electrodes on the remaining side are connected to a sensing circuit, termed as sensing electrodes which determine the charge completion in the electronic circuit (J. Lee et al., 2014; Walker, 2012).

Self-capacitive has the same X-Y grid as mutual-capacitive but the columns and rows operate solely. It is based on measuring the capacitance among the finger and sensing electrode or the capacitance of a single electrode to ground (C.-J. Lee et al., 2015). In this case, when a finger is close to the electrode, the human body's capacitance raises the electrode's self-capacitance with the ground. Conversely, in a mutual capacitive when a finger is placed close to the surface of the panel, the human body's capacitance leads to a change in the electrical field thus diminishing the capacitance between the two electrodes (Barrett & Omote, 2010; Kyoung & Hattori, 2014; Walker, 2012). In a self-capacitive, a parasitic capacitance (C_p) is altered with the adjacent ground pattern, and the electric field lines are observable in the region above the panel. When a conductive object enters the region above the panel, it disrupts the electric field lines and effectively introduces finger capacitance (C_f) to the panel. The finger capacitance formed among the finger and the electrode is promptly measured by a controller. In a mutual capacitive touch panel when a finger touches the panel the mutual capacitance (C_m) between the sensing or receiving electrode (RX) and driving or transmitting electrode (TX) is declined, this reduction in capacitance is utilized to detect the touch point(Kyoung & Hattori, 2014). Figure 2 (a and b) show the two various sensing approaches of PCTP namely self and mutual capacitive sensing (Kyoung & Hattori, 2014; Walker, 2012).

The dissimilarity between self and mutual capacitive is the type of electrodes and how the electrodes measure the touch points (Figure 2 (c and d)). In self-capacitive, the electrodes can be placed in a single layer or two layers (Hwang, Cui, Yang, & Kwon, 2010). When electrodes are placed in a single layer, each electrode shows a pair of different touch axes, but when the electrodes are placed in two layers, there is one layer of X electrodes and one layer of Y electrodes, which intersect these two axes and show a special touch point. When the screen is touched with two or more fingers, "ghost" touch points will be identified alongside the actual touch points (ghost points refer to incorrect touches). In multi-touch scenarios, capacitive screens can produce ghost points, which are false touch signals generated when the system misinterprets simultaneous touches as additional, non-existent touch points. These artifacts can significantly affect input accuracy and user experience. Thus, self-capacitive has a lower cost than mutual capacitive; the former is often employed in mobile phones with lower capabilities (Kyoung & Hattori, 2014; Walker, 2012) or as capacitive sensors for applications such as proximity sensing, capacitive switches, and touch pads for notebooks(Baxler, 1997; Kyoung & Hattori, 2014). In contrast, the "intersection" of each electrode in a mutual capacitive is calculated separately; thus, the ghost points do not emerge. Generally, the structure of these panels consists of rows (X) and columns (Y), and the intersection of each X-Y measures the touch point. In other words, the controller measures the capacitance between a single X-electrode and each intersecting Y electrode, this process is repeated until all the X-electrodes have been pushed. Nowadays, due to its capability to accurately operate multiple touch areas, mutual capacitance is favored over self-capacitance in utmost smartphones and tablets. (Table 1) (Bae & Lee, 2015; Kyoung & Hattori, 2014; Walker, 2012).

Table 1. Major differences between self-capacitive and mutual capacitive.

Feature	Self-Capacitive	Mutual-Capacitive
Electrode types	Sensing electrodes but the column and row operate individually	Driving and sensing electrodes in an intersection design
Measurement	Capacitance of a single electrode to ground	Capacitance between electrodes
Sensor behavior	Self-capacitance increases when a finger is near the electrodes and have ghost points in row and column design	Mutual-capacitance initially decreases when a finger approaches the electrodes

An innovative solution to integrate electro-adhesion tactile feedback with projected capacitive touchscreens on mobile terminals using an antimony-doped tin oxide (ATO) coating was developed. The ATO semiconductor layer enables electro-adhesion devices to share the touchscreen's positioning function without interference, offering an effective approach for seamless integration. A voltage model incorporating four impedance types was developed, optimizing ATO impedance within 10^5–10^7 Ω/sq to maintain electro-adhesion force while preserving touchscreen functionality. Using magnetron sputtering, an ATO panel with 5.5 MΩ/sq resistance was fabricated, ensuring safety and performance. Figure 3 (a and b) shows that the ATO panel offers a thinner design than the 3M panel, with a 6 µm insulation layer that enhances tactile feedback stability and reduces driving signals. Its integration with the protective cover glass minimizes overall thickness, preserves screen functionality, and allows low-cost replacement without affecting internal positioning components. The experiments measured electro-adhesion force for two panels at five signal amplitudes, with 16 repetitions each, totaling 160 data sets are shown in Figure 3 (c and d). The 3M panel showed higher electro-adhesion forces compared to the ATO panel. Both followed a square relationship with signal amplitude. Higher amplitudes increase sensitivity but also risk electric shock and breakdown. Experiments on a Microsoft Surface-based prototype demonstrated comparable tactile feedback and positioning performance to conventional devices, albeit at the cost of increased driving voltage. Future improvements include optimizing insulation layer parameters to reduce voltage requirements and adopting closed-loop control to stabilize electro-adhesion force.

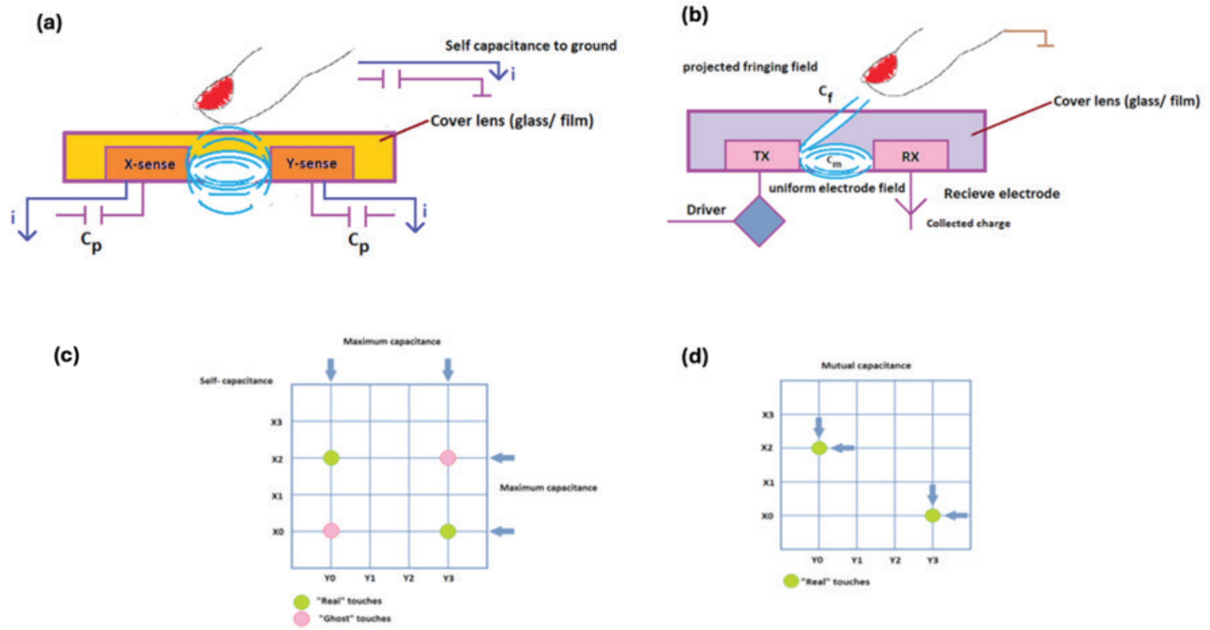

Fig. 2. (a and c) Self-capacitive and (b and d) mutual-capacitive sensing method.

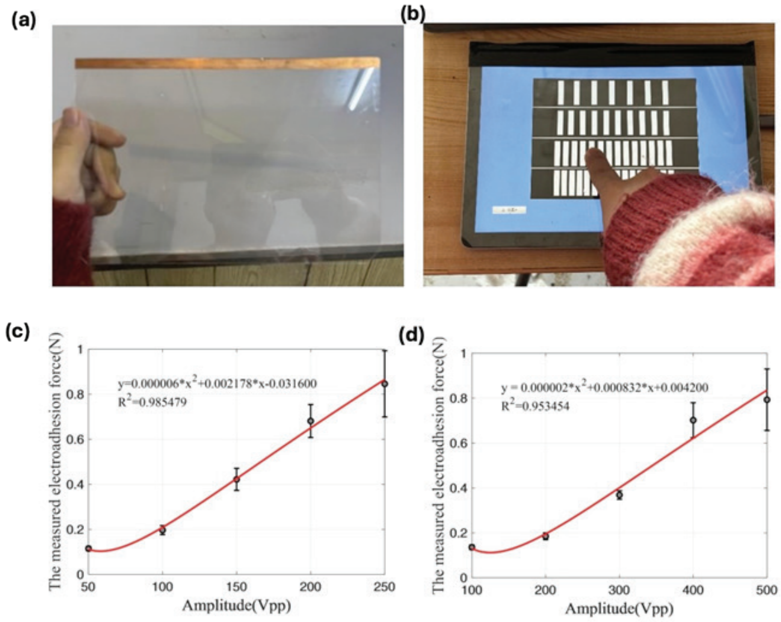

Fig. 3. (a) ATO panel and (b) integrated prototype, measured electro-adhesion forces of the two panels (c) 3M panel and (d) ATO panel (Z. Sun et al., 2024).

This research advances the development of integrated tactile and touch display systems for mobile devices, enhancing user interaction capabilities (Sun, Zhang, & Sun, 2024).

3. Structure of Projected Capacitive Touch Panel Sensors

The different types of projected capacitive touch panels which are made of two glass (plastic) sheets, a cover glass (plastic), and a touch sensor, are shown in Figure 5. In the glass-glass structure (Figure 4a) the total thickness is about 2.2 mm because the thickness of each optical clear adhesive (OCA) layer, glass sheet, and display unit are assumed to be 0.05, 0.55 and 1 mm, respectively. The reflectance of this structure at the air gap is higher which results in poor optical performance (Kyoung & Hattori, 2014; W. Liu, Liu, Yu, Feng, & Guo, 2015; Ruan, Chao, & Chen, 2010). The development of structures based on film substrate instead of glass is recently under investigation. The overall thickness of two films and a single film patterned with one Indium Tin Oxide (ITO) and two ITOs are approximately 2.06 and 1.83 mm (Figure 4b and 4c). The "in-cell" or "one-glass solution" (OGS) is the final structure (Figure 4d). The thickness of this structure is about 1.6 mm and has many advantages including; a thinner and lighter structure, an easy fabrication process, and lower cost (Kyoung & Hattori, 2014; S.-Y. Liu, Li, Wang, Lu, & Shieh, 2015).

The different glass sensor types of projected capacitive touch panels are shown in Figure 4e.

In GG type, sensor patterns X and Y electrodes are placed on each side of the glass. In the GG2 type, sensor patterns are both placed on one side of the glass with bridges that act as dielectric. The G2 type consists of cover glass with ITO electrodes on one side with bridges (S.-H. Lee, An, Hong, & Kwon, 2018; Wen et al., 2024). Figure 4f, indicates the different types of glass and film sensors. In the GFF type, each electrode is placed on one side of the film. In the GF2 type, sensor patterns are placed on each side of the film. The G1F type consists of cover glass with ITO on one side and one ITO film laminated to it and the GF1 type consists of one film with X and Y electrodes on one side of the film with bridges. In film sensors, we can replace the glass on a cover lens with plastic film and produce flexible touch panels ("Capacitive Touch Panel (Touchscreen)/Components ,Global Market: Key Research Findings 2013 ", July 11, 2013; Walker, 2016)

With the extensive use of capacitive touch panels in various applications, there is a big challenge for designers to improve the

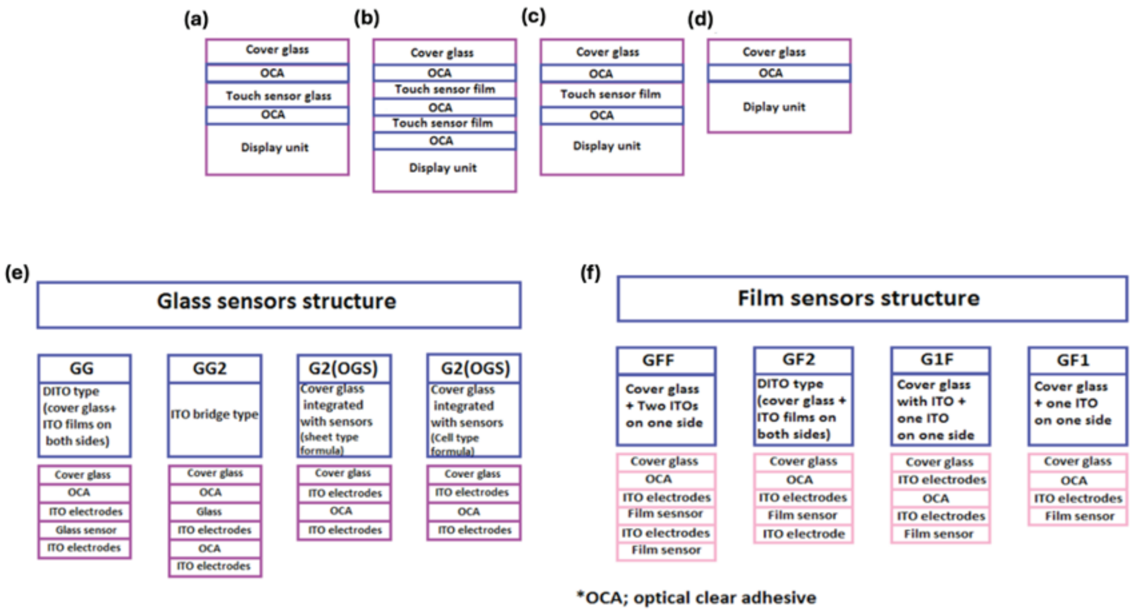

Fig. 4. (a-d) Projected capacitive touch panel structures, e) glass sensor type, f) film sensor type.

accuracy, sensitivity, and durability of touch panels. One area of touch panel designs is the improvement of the geometrical electrode patterning (Akhtar & Kakarala, 2014a, 2014b). Touch panel conductors have several different patterns such as iPhone, diamond and Manhattan, etc. It is difficult to say that one pattern is better than another one because the performance is affected by both the touch panel and electronic equipment together(Barrett & Omote, 2010; Kyoung & Hattori, 2014).

3.1. iPhone Pattern

The iPhone pattern is the simplest pattern consisting of rows of conductor (ITO) on one side of the glass (film) and columns on the other side (Figure 5a). This pattern has good performance but requires an accurate coordinate for electrodes. Capacitance is measured between neighboring intersection nodes (Barrett & Omote, 2010; Gary L.Barrett).

3.2. Manhattan Pattern

In this pattern, as shown in Figure 5b, X electrodes are patterned as rectangles with the greatest width and positioned below the Y electrodes. The Y electrodes are arranged as narrow vertical lines which reduce and eliminate noise. The rectangular electrode is positioned between the Y electrodes are dummy electrodes. The features of these electrodes include; electrical isolation, little impact on the sensitivity, average transparency, and preventing the ITO pattern from being visible(Hotelling & Land, 2011; Kyoung & Hattori, 2014).

3.3. Diamond Pattern

The most popular electrode structure is an interlocking diamond. The electrode paths are arranged in X and Y directions with a specific angle in a diamond pattern and a small bridge connects the two corners. Diamond rows and columns are the layers of the X electrode and Y electrodes, respectively. These layers are adhered together with a dielectric layer to avoid routing overlap between the horizontal and vertical electrodes. The schematic illustration of this pattern is shown in (Figure 5c) (Barrett & Omote, 2010; Zhan, Wei, Li, Liu, & Chen, 2012).

A capacitive soft sensor that distinguishes shear and normal forces using four deformable capacitors, mimicking skin's deformation, was designed, made of patterned elastomer that enables the sensor to contort and buckle, similar to the way skin behaves (Sarwar et al., 2023). With low cross-talk, it offers a sensitivity of 0.49 kPa for normal and 0.31 kPa for shear forces, 40 μm displacement resolution, and can detect finger proximity up to 15 mm, ideal for humanoid robotics. Figure 6(a-e) exhibits a stress-strain behavior of the sensor with low (E1) and high (E2) modulus at small and large strains. It responds to finger approach and contact by decreasing capacitance, with a 10–12% decrease in light contact. When touched by a plastic object, capacitance increases slightly. The sensor can detect human proximity from a distance of 1.5 cm, which is useful in robotics for delicate interactions and collision warnings. It also responds to normal and shear forces, with capacitance changes reflecting deformation, much like skin. The architecture allows simultaneous detection of both forces. The sensor detects the proximity of a grounded object up to 15 mm, with a maximum capacitance decrease of 14.7% as a finger approaches (Figure 6f). This ability allows anticipation of incoming objects and identification of light touch with minimal force. The sensor can distinguish shear, proximity, and touch simultaneously (Figure 6g) (Sarwar et al., 2023).

4. ITO-replacement materials for projected capacitive touch panel sensors

Optical transparency plays a crucial role in projected capacitive touch panel (PCTP) performance. A transparent conductive material named Indium Tin Oxide (ITO) has a high impact in large-scale production for various optoelectronic applications such as touch panels(L. Hu, Kim, Lee, Peumans, & Cui, 2010; Ma et al., 2015). ITO electrodes for capacitive touch panels are typically fabricated through a lithography patterning method. Lithography is transferring a pattern onto a substrate and photolithography refers to semiconductor lithography. Photolithography is a technique to transfer geometric patterns to a substrate (film or glass) which makes a structure to provide electrical properties for a technological purpose. Photolithography has several steps, including substrate cleaning, barrier and photoresist layer formation, mask alignment, soft-baking, development, exposure, and hard-baking (Figure 7) (S.-Y. Liu et al., 2015; K. Wu et al., 2020).

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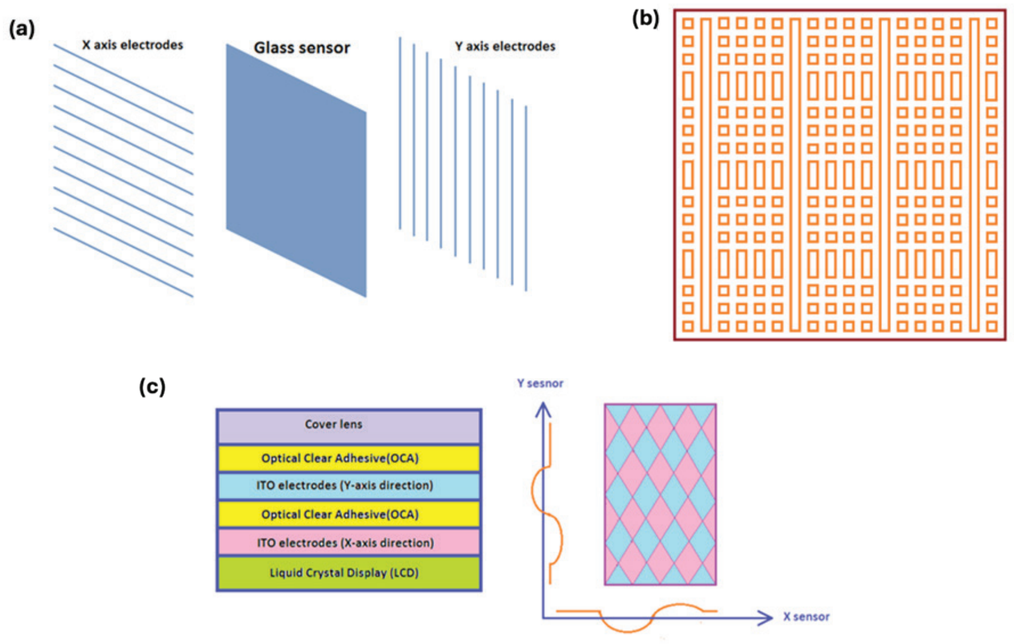

Fig. 5. a) iPhone pattern for touch panel conductor, b) Manhattan structure for electrode patterning in capacitive touch panels, c) The simple structure of projected capacitive touch panels.

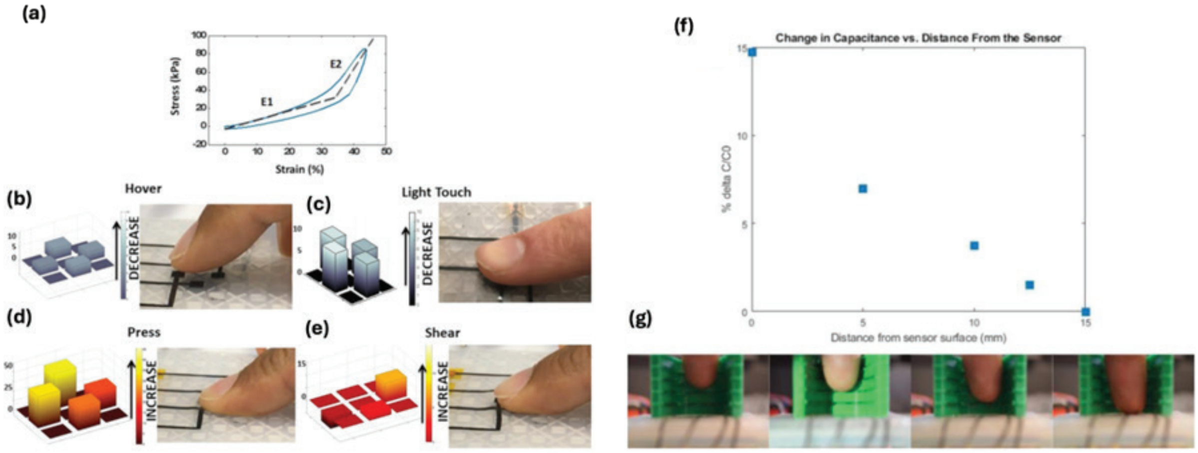

Fig. 6. Response of the sensor to various stimuli. (a) Non-linear elastic response (b) Hovering finger. response (c) Light touch response. (d) Pressure response. (e) Shear. response. Proximity characterization of approaching objects: (f) Taxel capacitive response with a baseline capacitance at 15 mm distance. (g) Finger approaching guide. Reprinted with permission (Sarwar et al., 2023). Copyright 2023, Springer Nature.

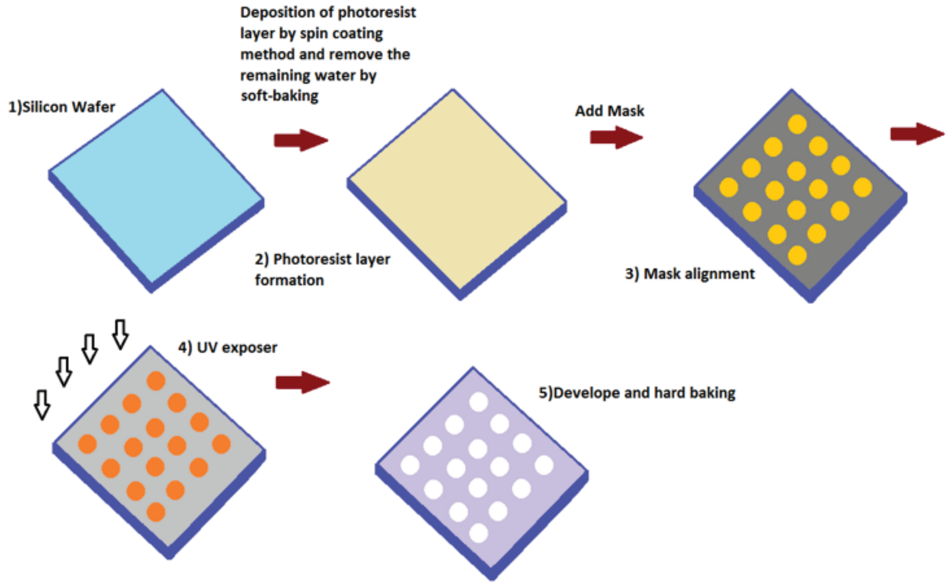

Fig. 7. Lithography electrode patterning process including substrate cleaning, barrier and photoresist layer formation, soft-baking, mask alignment, exposure, development, and hard-baking.

n the photolithography process, the substrate needs to be chemically cleaned because any impurities can affect the adhesion of the patterns. After cleaning, the silicon wafer is applied to the surface to create a barrier layer. After the formation of the silicon layer, a photoresist layer is applied to the surface by a spin coating method (Fried et al., 2015; Luo, Lian, He, & deMello, 2024). The next step is soft-baking which removes the remaining solvents from the photo-resistant coating. The most important step is mask alignment and UV exposure. The pattern is aligned with the substrate. Each mask after the first one must be aligned to the previous pattern and then the photoresist is exposed through the pattern with a high-intensity UV-light. After exposure, the photoresist which is exposed, makes a color change on the substrate. Then, the substrate is immersed in a developer solution, dissolving away the exposed areas of the photoresist layer. The final step is hard-baking, hardening the photoresist layer and improving the adhesion of it to the substrate(X. M. Hu, 2015; Martins, 2013; "Semiconductor Lithography (Photolithography) - The Basic Process," 2006-2017; Singh, Haverinen, Dhagat, & Jabbour, 2010; Waferworld, 2016). The photolithography process has the greatest cost, high waste, and mask requirement, is a time-consuming process, and requires complicated steps in the fabrication process(Ma et al., 2015; Singh et al., 2010; Teichler, Perelaer, & Schubert, 2013).

On the other hand, the noticeable drawbacks of ITO have been acknowledged, including the limited availability of indium, high expense, and its natural mechanical fragility (Ma et al., 2015; Triambulo, Cheong, Lee, Yi, & Park, 2015). ITO-substitute materials can be processed at ambient temperature in a regular atmosphere, eliminating the requirement for vacuum sputtering. Due to the high resolution needed for pattern formation and a huge number of electrode connections that must fit into a confined space, there are at least five alternative ITO materials, such as carbon nanotubes, copper metal mesh, graphene, silver nanowires, and conductive polymers (C. Sun et al., 2024; Walker, 2012). The advantage of metal mesh is very low sheet resistance, so double routing is not necessary and the touch panel sensitivity is better. Other advantages are simple design, short processing time, and low cost. Silver nanowires closely follow metal mesh in rank. The electrical and optical properties namely transmittance and sheet resistance are greatly competitive with ITO(Karagiorgis et al., 2024; Walker, 2012).

The use of carbon-based materials such as graphene, carbon nanotubes (CNT), and conducting polymers such as Poly (3,4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT: PSS) enable the fabrication of flexible electrodes for different applications like sensors, touch panels and flexible displays, etc.(Lipomi et al., 2012; Ma et al., 2015). PEDOT is one of the most successful conductive polymers that is used in most applications. A polyelectrolyte complex can be prepared with PSS, which is a counter-ion. PSS operates as a template for PEDOT to keep it in the dispersed position and make a film. Thermal stability is one of the main advantages of PEDOT: PSS films. Thermal Gravimetric Analysis (TGA) is used to study thermal stability. The data obtained from TGA shows that thermal stability is up to 200 °C. Compared to other conductive polymers, PEDOT has high thermal stability. Like most polymers, UV light can degrade pure PEDOT: PSS films over time which is due to oxidation but can be supported by polymer protective coating. PEDOT: PSS are amorphous films, increasing the concentration of PSS leads to phase separation which affects the mechanical properties of films (Xie, Yang, Zhang, & Zhang, 2015). Since PEDOT: PSS is a polyelectrolyte complex, the drying process is very crucial for the morphology of the film because the morphology determines the ability of the film to transport an electrical current. During the drying process, polar solvents like ethylene glycol (EG) which has a high boiling point, remain in the film longer than water. As a result, the film has a more favorable morphology that facilitates the macroscopic transport of the current(Elschner, Kirchmeyer, Lovenich, Merker, & Reuter, 2010; Lövenich, 2014).

Today, PEDOT: PSS is believed to be a possible material candidate for ITO replacement in a number of applications because it allows the preparation of films with a low sheet resistance. Furthermore, it has unique properties such as high transparency, conductivity, and mechanical flexibility which can be bent without an increase in sheet resistance (Elschner et al., 2010; Lipomi et al., 2012; Ma et al., 2015).

A nanocomposite based on ITO/PEDOT:PSS, which is covered with Ag mesh-like network was developed. A solution-based deposition method, followed by low-temperature plasma annealing, reduced sheet resistance from 7.21 Ω/sq. to 5.05 Ω/sq. while maintaining high transparency (85.17%). A flexible transparent capacitive touch panel was fabricated using an Ag NW-ITO/PEDOT:PSS nanocomposite electrode on a PET substrate (Figure 8). Masking was used for the preparation of the bottom electrode, followed by coating Ag NW and ITO/PEDOT:PSS, with PU as the dielectric layer and Ag nanowire as the top electrode. Encapsulated with PDMS, the device's functionality was confirmed by detecting capacitance changes. The panel indicates a capacitance change of 0.4 ΔC/Co, showcasing the suitability of the Ag NW-ITO/PEDOT:PSS electrode for large-scale touchscreen applications. The Ag NW-ITO/PEDOT:PSS electrode exhibits excellent chemical and mechanical stability. a transparent flexible electrical heater and capacitive touchscreen panel were fabricated by the electrode, demonstrating its potential for various applications. This process offers a cost-effective, scalable solution for transparent conducting flexible thin films in commercial devices (Raman et al., 2021) .

To provide a clearer understanding of the trade-offs between different transparent conductive materials used in projected capacitive touch panels, a comparison table is presented (Table 2). This table summarizes key parameters including optical transmittance, sheet resistance, and mechanical flexibility for widely used materials such as indium tin oxide (ITO), PEDOT:PSS, silver nanowires (AgNWs), graphene, and some hybrid systems. These parameters are critical in determining the suitability of materials for high-performance, flexible touch panel applications.

ITO, while offering low sheet resistance and high transparency, suffers from brittleness and mechanical instability under bending, making it less suitable for flexible electronics. PEDOT:PSS, on the other hand, shows excellent mechanical flexibility but has relatively higher sheet resistance unless optimized through doping or hybridization. AgNWs provide a promising balance between conductivity, transparency, and flexibility, especially when combined with polymer matrices such as PEDOT:PSS. Graphene, particularly in its doped or multilayer forms, demonstrates excellent mechanical properties and decent conductivity, with potential for next-generation flexible and stretchable electronics.

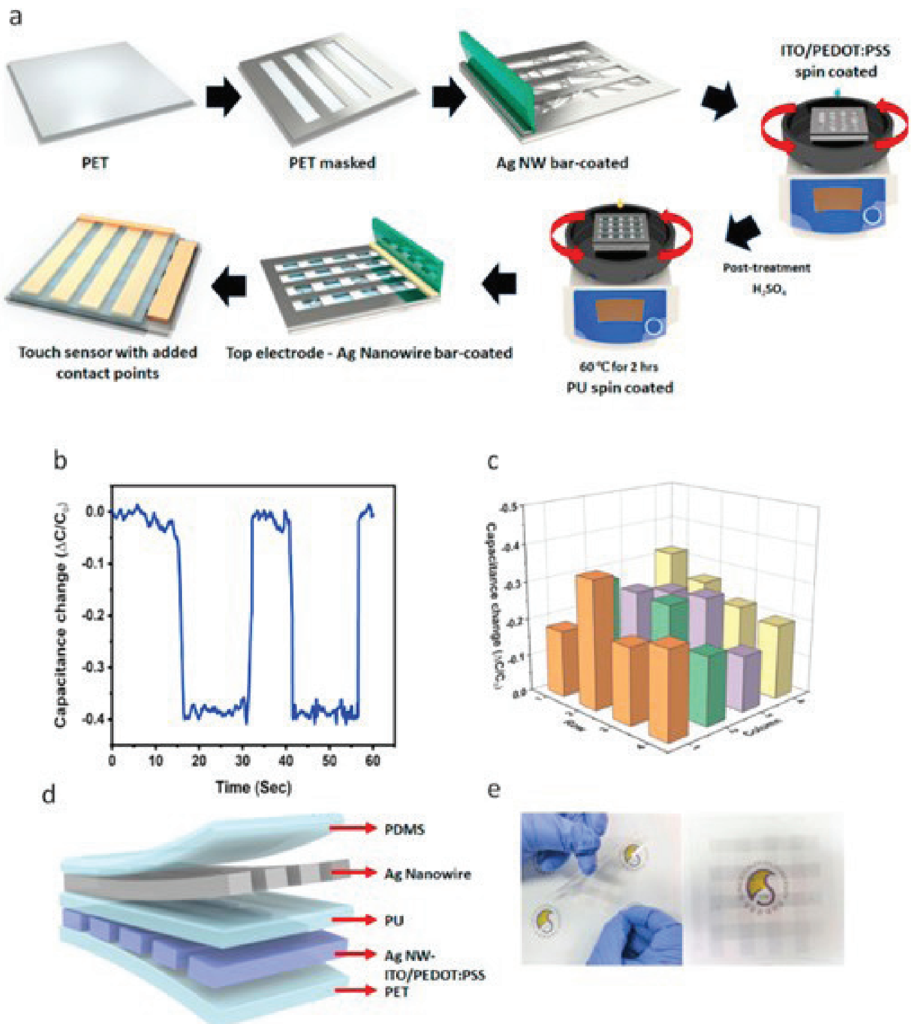

Fig. 8. The optoelectronic properties of the capacitive touch panel include a) fabrication process schematic, b) capacitance change per pixel, c) capacitance change for 16 pixels (10×10 cm), d) layer structure, and e) photograph of the flexible device (Raman et al., 2021).

Table 2. Optoelectrical performance and mechanical flexibility of transparent conductive materials for flexible electronics

Material / System	Transmittance (%)	Sheet Resistance (Ω/sq)	Mechanical Flexibility / Durability	Reference
ITO (flexible on PET/graphene)	~91 % (at 550 nm)	~45 Ω/sq (at 60 nm on graphene/PET)	Moderate: maintained performance under bending radii to ~8 mm, $\Delta R/R_0$ < 5 % over cycles	(S. J. Lee et al., 2017)
PEDOT:PSS (neat film)	~84 %	~122 Ω/sq (after treatment)	Excellent inherent flexibility, stable under bending	(Xia, Yalagala, Karimullah, Heidari, & Ghannam, 2024)
PEDOT:PSS:Ag NW hybrid	~88.7 %	~17–21 Ω/sq	Improved mechanical stability due to composite structure	(Du et al., 2021)
Ag nanowires (pure)	~91–95 %	~6–14 Ω/sq	High flexibility; retains conductivity after repeated bending	(Van De Groep, Spinelli, & Polman, 2012)
AgNWs/rGO or PEDOT:PSS hybrid	~88–92 %	Reduced (~10 Ω/sq or less)	Enhanced robustness and conductivity in hybrids	(Elsokary et al., 2024)
Graphene (CVD/$FeCl_3$ intercalated)	~84–97 %	~8.8 Ω/sq ($FeCl_3$intercalated)	Excellent mechanical resilience; ideal for flexible electronics	(Khrapach et al., 2012)
a-ITO/Ag/c-ITO triple-layer	~88.7–91.4 %	~6.4–13 Ω/sq	Very good flexibility: ΔR ≈2–4 % over 15000–30000 cycles (3 mm radius)	(C.-C. Wu, 2018)

Hybrid structures such as Ag/ITO/Ag and graphene-based composites further enhance performance by combining the strengths of individual materials.

This comparative analysis aids in material selection for capacitive touch panels depending on the desired balance between electrical performance, transparency, and mechanical robustness.

Recent advancements in MXene-based materials have demonstrated their potential in flexible and transparent conductive applications. For instance, Li et al. (2024) (Li et al., 2024) who developed flexible MXene@SWNTs composite films with outstanding flexibility and shielding properties; Liu et al. (2022) (H. Liu et al., 2022) on 3D MXene/Ag nanowires aerogels that improve conductivity and mechanical robustness; Guo et al. (2023) (Guo et al., 2023) who designed $Ti_3C_2T_x$ MXene inks for transparent conductive electrodes; and Xu et al. (2024) (Xu et al., 2024) on multi-scale MXene/Ag nanowire composite foams with highly effective shielding and durability. These additions broaden the scope of the review and present a more comprehensive overview of the state-of-the-art in flexible transparent conductive materials.

5. The most used technologies for electrode patterning

Nowadays, the applicable techniques to deposit electrode materials on both rigid and flexible substrates are inkjet printing, screen printing, gravure printing, lithography, slot die coating, etching, and photoresist coating (Andò et al., 2017; Ma et al., 2015) . The use of printing techniques for electronic applications has several advantages. Printing is fast, has high efficiency and high resolution, low cost and low material consumption, and is also a widely used technique. Among the different printing techniques, inkjet printing is a simple method to create a specific shape and dimension of the conductive material on a substrate and has low wasted materials in the production process. Also, this technology has a growing interest in the possibility of developing low-cost flexible electronic devices. The inkjet materials are in a liquid state where the solute is dissolved in a solvent and these materials can be easily printed in a large area. There are two different categories for Inkjet printing technology; continuous inkjet and drop-on-demand technology(Andò et al., 2017; Cruz, Dias, Viana, & Rocha, 2015; Faller, Mühlbacher-Karrer, & Zangl, 2016b; Martins, 2013; Matic et al., 2014).

5.1. Continuous inkjet printing and drop-on-demand method

Ink droplets are formed from a print head nozzle and pass them through an electric field. These droplets which are required for printing are charged by a charge electrode. After that, the droplet passes through an electrostatic field. Some parameters are important for the correct position of a droplet on the substrate including nozzle diameter, ink density, jet velocity, and viscosity. This technique has high speed in printing and can affect material characteristics including; shape, size, and porosity (Figure 9a) (Faller, Mühlbacher-Karrer, & Zangl, 2016a; Martins, 2013). In printed electronics and sensor fabrication, **drop-on-demand (DOD)** inkjet printing is a method where ink droplets are ejected only when required, allowing precise material deposition. This technique enables high-resolution patterning and material efficiency, making it widely used for printing conductive patterns, sensing layers, and even biological components. Over the last two decades drop on demand technology has a rapid growth in the form of inkjet printing. In this technology, the drops which are formed by the creation of a pressure pulse within the print head are ejected (Figure 9b). A heater pad (thermal inkjet) and piezoelectric elements (piezoelectric inkjet) are used to produce a pressure pulse and activate the ejection of fluid(Martins, 2013; Miedl & Tille, 2015).

Graphene-based inks tailored for printed electronics enable transparent, flexible, and environmentally friendly multitouch sensing surfaces. Using carboxymethyl cellulose as a binder, water/alcohol-based inks were optimized for screen-printing. Printed lines achieved 2.4 kΩ resistance with 0.5 mm width and five printing steps. A flexible

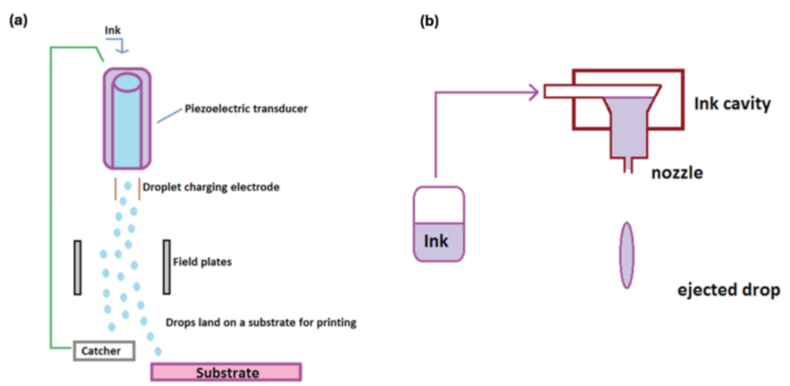

Fig. 9. Schematic diagram of a) continuous inkjet printer, b) drop-on-demand print head.

8” touchscreen (40×28 rows) was developed, integrating electronic circuits and a graphic interface for multitouch detection and writing. Bottom and top electrode resistances were 151 kΩ and 400 kΩ, respectively. This study highlights additive manufacturing’s potential to produce sustainable electronic devices with tailored properties for next-generation applications in sensing and interactive displays (Franco et al., 2021; Kaur & Saxena, 2024).

5.1.1. Thermal inkjet

A thermal inkjet printer consists of an ink cartridge and does not require any bottles of ink or solvents. When an electric flow moves through the resistive layer which is inside of the cartridge, it is rapidly heated up to 300 ⁰C and leads to the boiling of the ink in the chamber, forming bubbles of vapor. After the continuous expansion of the bubbles, ink is driven out of the nozzle to form a droplet. Because of the high temperature and low mechanical strength of the heater layer, other protection layers are used on top of the heater to minimize thermal and mechanical damage(Calvert, 2001; Martins, 2013; Sridhar, Blaudeck, & Baumann, 2011; Wijshoff, 2010). The development of soft electronics is vital for wearable devices, robotics, and human-machine interfaces. A study introduces an inkjet printing method to fabricate polydimethylsiloxane (PDMS)-based soft electronics using a water-soluble polyvinyl alcohol (PVA) substrate. This innovative, additive, and low-cost approach enables the creation of capacitive pressure sensors with mesh-like conductive layers and microstructured dielectrics, eliminating complex processing or hazardous chemicals. The sensors exhibit high sensitivity (4 MPa^{-1}) for low pressures (<1 kPa), detect up to 50 kPa, and maintain excellent repeatability over 2000 cycles with low hysteresis (≤8.5%). The tactile sensing capability was demonstrated by detecting fingertip interactions, showcasing their suitability for applications like e-skin and smart prosthetics. Sensor properties can be easily adjusted by modifying printing parameters or ink composition. This method facilitates scalable, customizable, and cost-effective fabrication of high-performance soft electronics, advancing applications in wearable devices, robotics, and artificial intelligence systems (Mikkonen, Koivikko, Vuorinen, Sariola, & Mäntysalo, 2021).

Another study (Mitra, Mitra, Thalheim, & Zichner, 2024) presents inkjet-printed thermal sensors based on a metal–insulator–metal (MIM) architecture, designed for temperatures ranging from 100 to 300°C. Using conductive silver and hybrid insulator inks, sensors with active areas of 16–36 mm^2 and dielectric layers up to 15 µm thick were fabricated on flexible polyimide substrates. The sensors demonstrated a capacitance change of 20–100 pF and could reliably detect 50°C increments. Optimizing active area and insulator thickness enhanced performance and sensitivity. The MIM device design features a square-shaped top electrode for the active area, extended lengthwise with a conductive track to establish electrical contact during characterization (Figure 10a). MIM device capacitance varied with active area, dielectric thickness, and temperature cycles (Figure 10(b-e)). Devices with a 25 mm^2 area and drop spaces of (15+20) µm showed better stability, with capacitance ranging from 107 pF to 119 pF (±1.5 pF) compared to devices with (20+20) µm drop spaces (154–165 pF, ±2 pF). Larger 36 mm^2 sensors exhibited higher deviations (±18 pF), indicating reduced stability. Smaller sensors showed more reliable performance, while capacitance variations across devices highlighted manufacturing inconsistencies. Sensitivity differences between 150°C and 300°C were marginal, suggesting that thinner dielectric layers improve capacitance but reduce operational stability in larger sensors. The sensors exhibited high repeatability, stability under thermal cycling, and potential for integration into high-temperature applications, such as automotive components and embedded electronics (Mitra et al., 2024).

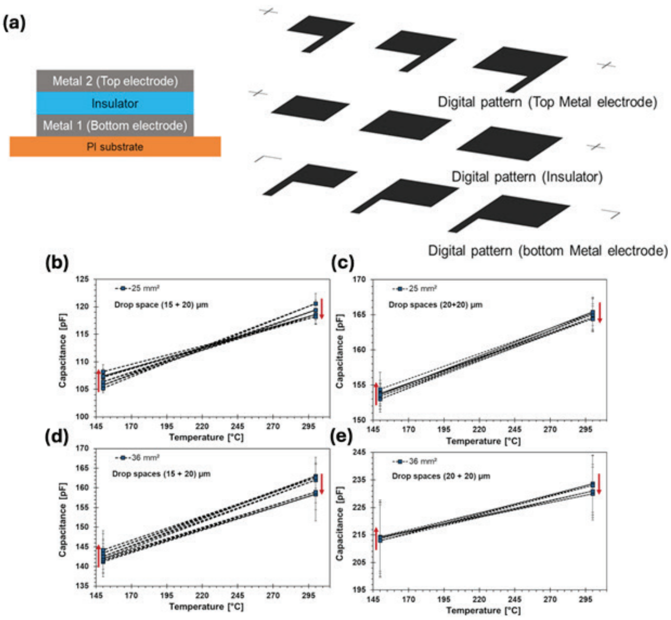

Fig. 10. a) Illustration of MIM device architecture on PI substrate with digital images showing printed structures with varying active areas. Graphs (b–e) depict capacitance changes during thermal cycles (150–300 °C) for 25 mm^2 and 36 mm^2 MIM devices with varying insulator thickness. Reprinted with permission (Mitra et al., 2024). Copyright 2024, Wiley.

5.1.2. Piezoelectric inkjet

When an electric field is applied, piezoelectric elements undergo distortion, creating a pressure pulse that is propagated between nozzles and the chamber which causes an ink droplet to be ejected from the nozzle under the action of gravity and air resistance onto the substrate. The size and the velocity of the ejected droplet are dependent on the applied voltage and the ink viscosity(Martins, 2013; Singh et al., 2010).

6. Future Opportunities and Challenges

Projective Capacitor Touch Panels (PCTPs) have become the preferred technology for various electronic devices such as smartphones, tablets, interactive displays, etc. Demanding quality touch interfaces, along with advances in physics and manufacturing techniques, PCTP has entered into modern electronic applications. Future research has the potential to drive further innovation in productivity, efficiency, and scalability. But even though it is widely accepted, there are still many challenges that need to be addressed to unlock its full potential.

One promising opportunity for the future of PCTP is electronic advancements. Traditional indium tin oxide (ITO) is a transparent conductive material widely used in touch screen applications. There is mechanical fragility, high cost, and scarcity of the rare material indium. As a result, researchers are looking for alternative materials that replace ITO to maintain or improve touchscreen functionality. One substance that is a strong candidate for emergence is Poly(3,4-ethylenedioxythiophene): Poly(styrenesulfonate) (PEDOT:PSS). PEDOT:PSS is an organic conductor that exhibits unique properties such as good transparency high electrical conductivity and mechanical flexibility This makes it an ideal material for flexible and durable touchscreen electrodes. Integrating PEDOT:PSS into touchscreens is ideal for developing cost-effective, high-performance devices that use rare and less expensive materials. Another important area of promise for the future of PCTP is continued improvements in the manufacturing techniques used to pattern the electrodes. Traditional methods such as sputtering and evaporation are the standard for ITO deposition but are limited by factors such as high energy consumption, complexity, and cost, and with printing techniques, there are significant advantages in terms of scalability, cost-effectiveness, and ease of use. These methods allow the direct deposition of conductive materials on various surfaces. This may be important in developing large-area, flexible, and low-cost touch screens. Even a new model to improve opportunities resulted in wide use in various industries such as automotive, and health care. and industrial control.

The shift to printed electronics and the use of alternative conductive materials such as PEDOT:PSS also offers the possibility of developing flexible, bendable, and even stretchable touchscreens. This is due to the increasing demand for wearable devices and flexible electronics. A surface that deserves a flexible touchscreen has the potential to revolutionize the way users interact with devices. Because it can be integrated into a variety of products, such as smart clothing, health care sensors, and wearable displays. The need for continuous innovation in the physical sciences to protect the future especially in the development of flexible conductive materials such as PEDOT:PSS, which can display consistent electrical properties under various mechanical deformations such as bending, stretching, and twisting. Additionally, the demand for increased functionality and features in touch screens creates opportunities and challenges. For example, the increase in multi-touch functionality and gesture recognition means that touch screens need to offer higher resolutions. Faster response time and greater sensitivity are the innovations to improving these aspects, especially by optimizing the electrode design and modeling techniques. By increasing the number of electrodes and fine-tuning the configuration, researchers may be able to develop touch screens that are more precise and accurate. This makes for a more complex and intuitive user interface.

Even though there are many opportunities, there are several challenges that need to be addressed to realize the full potential of PCTP. One key concern is the scalability of alternative materials such as PEDOT:PSS for large-scale production. Although the material looks promising at the laboratory scale, converting it to mass production remains a major challenge. The ability of PEDOT:PSS to print and pattern large surfaces uniformly without compromising its electrical and mechanical properties will be critical to the success of these materials in commercial applications. Moreover, under Real-world conditions, such as exposure to humidity, UV radiation, and mechanical stress, PEDOT:PSS-based electrodes are carefully examined for their long-term stability and reliability. Ensuring that these materials maintain their effectiveness over time will be critical for their widespread adoption. Another challenge is to optimize the compatibility of PEDOT:PSS with existing manufacturing processes. Although printing technologies such as inkjet printing and screen printing have many advantages, these technologies may not be fully compatible with today's high-throughput production lines for touch screens. Combining these new manufacturing techniques with established production processes without affecting the overall efficiency and value of production is considered. Any changes in the printing process, such as inconsistencies in material deposition or alignment, can lead to performance issues such as decreased sensitivity or accuracy and therefore developing reliable quality control methods.

The environmental impact of the materials and processes used to produce PCTP is another area that needs attention. This is due to increasing concerns about sustainability and environmental responsibility. It is therefore important to consider the life cycle of materials used in touch screens, although PEDOT:PSS has advantages over ITO in terms of cost and resource availability, the environmental impact and disposal at the end of the product's life must also be considered. Additionally, reducing energy use and carbon dioxide emissions associated with touch screen production will be critical in aligning the industry with global sustainability targets. Moreover, the increasing convergence of different technologies will shape the future of PCTP, integrating touch panels with emerging technologies such as augmented reality (AR), virtual reality (VR), and the Internet of Things (IoT) will open up new opportunities for interactive and immersive experiences. As these technologies advance and user interactions become more complex and dynamic, touch the screen to meet your needs. This may include developing touch screens that respond to touch, pressure sensitivity, and increased exposure, which can further improve the user experience. Additionally, integrating touch screens with IoT devices that require connectivity, low power consumption, and the compact form factor will drive innovation in touchscreen electrode design.

7. Conclusion

Recently, projected capacitive touch panels (PCTPs) are one of the most promising technologies in most applications such as mobile phones, displays, tablets, etc. The most important advantages of this technology are multi-touch functionality, low cost, high durability, high sensitivity, and excellent optical performance. Today, the most commonly used electrode pattern for PCTPs is an interlocking diamond but there is an increasing demand for different electrode designs which improve spatial accuracy, resistance to noise, and touch sensitivity. Low electrical resistance and optical transparency of electrodes are essential to have a high signal-to-noise ratio and good display performance. Indium Tin Oxide (ITO) is a transparent conductive material that has been widely used in many optoelectronic applications. ITO electrodes are produced using a lithography patterning process, and it has inherent disadvantages including the greatest cost, high waste, mask requirement, and complex fabrication process. Among different materials for ITO replacement, Poly (3,4 ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT: PSS) is a good candidate because it has unique properties such as high transparency, conductivity, and mechanical flexibility. PEDOT: PSS is a transparent conductive polymer that can be applied as a conductor material in flexible electronics, touch panels, light-emitting diodes (LEDs), and other electronic applications. The most commonly used electrode patterning technique for PEDOT: PSS electrodes in touch panel applications is ink-jet printing which has several advantages including low cost, high accuracy, and high speed in processing. However, despite significant progress, there are still some research gaps and industrial challenges that must be addressed to facilitate broader commercial adoption. For example, PEDOT: PSS exhibits environmental instability, particularly in humid conditions, and its long-term performance needs improvement. Additionally, the ink-jet printing process must be further optimized to ensure uniform, high-resolution patterning over large areas, which is essential for industrial-scale production. Also, more research is needed to develop novel electrode structures and hybrid materials that enhance mechanical robustness, signal integrity, and long-term durability under repeated touch cycles.

Therefore, the reviewed literature highlights that while PEDOT:PSS offers significant advantages over ITO—such as flexibility, transparency, and processing ease—several limitations remain, including environmental sensitivity and printing challenges. Future research directions should prioritize enhancing PEDOT:PSS environmental stability, innovating hybrid electrode materials, and refining scalable printing technologies to meet industrial production requirements. These developments are vital for advancing PEDOT: PSS as a viable, cost-effective alternative for next-generation flexible and wearable touch panels.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no conflict of interest.

Author Contributions

SA: Conceptualization, Investigation, Writing – Original Draft.
MM: Supervision, Writing – Review & Editing.

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