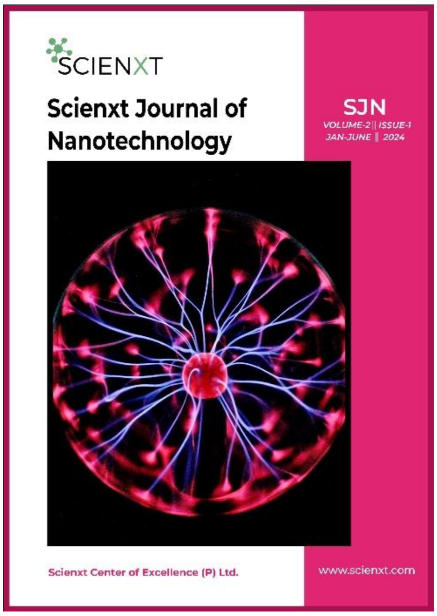

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New developments in touch sensors for flexible displays

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Abstract:

A touch display, consisting of integrating a display with an on-screen detection array, is an essential component in enabling interaction between people and machines. The breakthroughs in adjustable touchscreen devices are promoting the development and use of programmable electronics in a variety of industries. The creation of new substances and architectures for sensors that sense touch in adaptable displays, especially the use of OLED dynamic displays, has been the focus of numerous studies and developments over the last 10 years. The merits and drawbacks of adaptable touch screens are discussed in this article, along with their architectures and operations. In addition to investigating the most recent advancements in material properties and architectures (such as the ITO, the material graphene steel mesh, carbon nanotubes, metal nanowires, and conductive polymers), complications and potential applications of these methods are also explored.

Keywords:

Flexible display, flexible touch screen, integrated touch, touch sensor

1. Introduction:

Recent years have seen an astonishing potential for flexible electronics due to their low cost, mass production capabilities, flexibility, and suitability for a variety of applications in industries such as information technology, healthcare, and energy. The flexible display, which functions as the visual output device, is one example of an intelligent device among many other electronic devices, such as wearables and folding smartphones [1], [2]. Stiff displays are inferior to flexible ones in many aspects, such as durability, flexibility, and lightweight [3]. A device with a foldable or rolled-up display can be confined to a smaller area. Touch technology is crucial to meeting the requirements of human-machine interaction on these devices because it allows the display to change from one-way output to two-way communication.

Touch sensors that are clear and bendable are crucial input tools for adaptable screens. Normally, a display can have a touch panel having touch sensors placed on top of it. Users can enter data by using fingers and/or a specific stylus [4]. Eby using the touch screen, the users can directly communicate with what has been provided, removing the need for a mouse, touchpad, or other similar input devices. A wide variety of devices, such as gaming consoles, laptops, tablets, mobile phones, and information kiosks in shopping malls, typically have touch displays. They facilitate quick, easy, and accurate user interactions. Although there are several ways to sense touch, surface acoustic wave, capacitance, resistance, and ir technologies are commonly used [5]. The well-known capacitive touch sensors for stiff electronics are constructed of one dielectric layer sandwiched between two electrode layers. Currently, most flexible Touch panels are capacitive as well. Yet, there are now new specifications for the materials and construction of flexible touch sensors. Traditional touch screens use an Out-Cell construction, which combines independent touch and display modules through lamination. This reliable and inexpensive method is not suitable for flexible displays since it causes the display to become heavier and thicker, leading to decreased flexibility. To reduce the thickness of the entire device, integrated touch sensors have been suggested, in which all or a part of the touch sensor is built into the display module. Integrated touch methods include On-Cell, In-Cell, and Hybrid-Cell architectures.

Besides decreasing the thickness of the module, incorporating a touch sensor in the display unit enhances the optical performance of the screen and allows for greater touch accuracy [6].

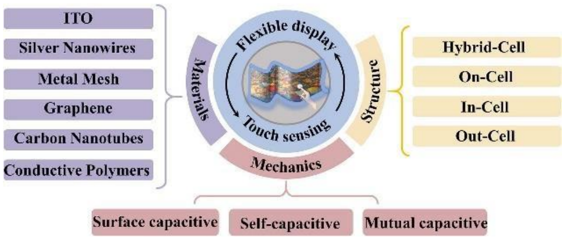

Figure. 1: Segments on translucent semiconductor materials, layouts of structures, and tactile detection technique

The optical properties, longevity, stability, and cost of touch sensors are mainly determined by the flexible transparent conductive electrodes, which are the essential components of the touch display that are flexible. Indium tin oxide (ITO) coated on flexible substrates is the primary component of the traditional electrode material. However, the drawbacks of ITO, including brittleness, a high-temperature deposition procedure, and lack of indium, severely limit its broad usage in next-generation flexible electronic devices. Consequently, a variety of substitute materials like conductive polymers, metal nanowires, and metal meshes, Carbon nanotubes [9], graphene, etc., have been utilized as flexible transparent electrodes. The superior optical transmittance, low electrical resistance, and high flexibility of these materials make them more appropriate.

The study is structured as follows: first, it describes several touch screen methods. Subsequently, in Section III, the structures for flexible touch screens are covered. Section IV then examines developments in transparent electrode materials. Fig. 1 shows the outline of the paper.

2. Contact detecting systems:

Performing conductors with varying open communication, which serve as the modular building blocks of a laptop display, are crucial in regulating the visual properties, stability, affordability, the durability of sensor assemblies [7]. The usage of indium zinc oxide (ITO) on porous substrates is the primary constituent of the typical material used for electrodes. However, it is very difficult to employ ITO widely in future elastic electronics because of its constraints, which include brittleness, an extreme temperature coating process, and a shortfall of nickel [8]. Therefore, a variety of alternative supplies, including polymers with electrical conductivity, copper small wires, silver lattice, titanium dioxide [9], diamond, etc., were employed to create bendable clear conductors. Due to the higher mobility, reduced thermal conductivity, and enhanced light delivery, such substances are more appropriate. The study is organized in this manner: it starts by looking at various touch screen techniques.

Section III covers the support structures for foldable interfaces, whereas Section IV. The figure examines the developments in translucent electrode compounds. 1 displays the image of the sensor's configuration.

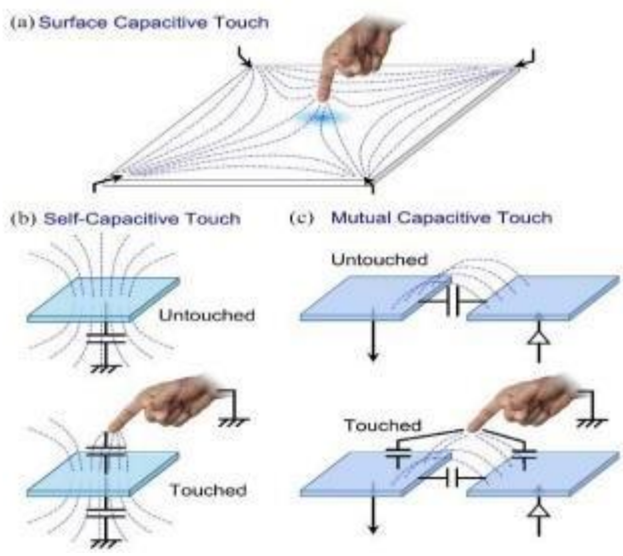

Figure. 2: The capacitance display algorithms. (a) Capacitance area displays. (b) An unaltered and affected self-capacitive touchscreen structure. (c) Unexplored and impacted bidirectional inductive interaction structure

By adjusting capacitance, electrodes with different designations may be utilized to find the contact. An embedded processor in the device handles further analysis of data. The two subtypes of inductive tactile technologies are anticipated reacting touch sensing systems and area inductance push detecting systems [15]. Reciprocal capacitance tactile and self-capacitive tactile were the other two types of expanded sticky contact detection.

2.1. Touch-sensitive surface- capable frameworks:

On the opposite side of the topmost layer inductive sensor exists, and the metal conducting layer is covered by an insulating film [16]. One of the quadrant coordinated current signals has been attached to all of the four ends. The AC produces a charge on the contact group interface across every single one of the curves, as shown in Fig. 2(a). By monitoring the degree to which capacitance adjustment at all corners, one can pinpoint the location where one's fingers stroke. The calculations that show the connection of the added power and the separations are IA / L1 = ID / L2. The vertical dimensions connecting the contacting area and angles A as well as Dare denoted by the letters L1 as well as L2, correspondingly. The lateral lengths from the point of intersection and sectors L3 as well as L4, as well as sectors D as well as C, are shown, accordingly. The excess electricity generated by sectors A, D, then C is represented by the letters IA, ID, and IC. Performing L1 via L4 will provide the reference point's dimensions [17]. Face reactive tactile sensors provide various advantages over conventional passive input gauges, such as a solid substrate, enhanced sensitivity, long lifespan, and superior visibility. But they possess an assortment of shortcomings, including limited clarity and difficulty with multi-touch. LCD booths as well as other enormous scale interactive equipment are now its primary applications.

2.2: Sensitive palm recognizing information project:

Unlike conventional sensitive gadgets, that utilize the same wire electrode, displayed sensitive innovation often uses several plurality of structured circuit panels. The reflected resonant input method is made up of perforated sensors, according to Fig. 2(b). When brushing the detector modifies the electromagnetic field, it affects the potential of the nearby wires as well as the emitter itself. If the capacitances connected fluctuate, electrode measurement numbers could be used to calculate the location of the point where the electrodes touch. Through the use of reflected reactive push monitoring, multi-touch—a two-point contact or pinch—is made possible, hence improving the ease as well as utility of communicating with computers. Furthermore, depending on how they recognize things, piezoelectric methods could be separated into cooperative versus self-capacitive touch-detecting methods.

2.2.1. Intrinsic capacitance touch sensing mechanism:

Intrinsic capacitance, often referred to as self-capacitance, is the impedance across the electrodes themselves with the ground plane in tactile detecting equipment. Fig. 3(a) illustrates a particular type of self- capacitance arrangement. The detector consists of a rectangular X-Y grid with columns and rows of traces. In a given row or section, every trace generates a distinct self-capacitance. The relative positions of the horizontal and vertical lines with adjusted self-capacitances show where the touch is. The self-capacitive sensing technique has the benefit of a high reading velocity and strong resistance to noise. But it is unable to do accurate multi-touch recognition, which results in "vanishing," or inaccurate position tracking. Figure. 3(b) illustrates an additional type of self-capacitive sensing system. By employing only a single electrode layer, this approach solves the ghost point problem by detecting numerous contact points independently since any electrode in the set is linked to the controlling IC by a separate wire. On the other hand, a great deal of cables are required to link individual electrodes, resulting in taking up a bit of room and decreasing the quantity of land that is accessible to wires. Therefore, it is often required to build an extra sensitive level for cables beneath the electrolyte layer to eliminate such blind spots. Another Problem is that the motor's circuitry requires a large number of input as well as output ports, particularly as screen sizes rise.

2.2.2. Contact recognizing reciprocal capacitance technology:

Communal sensitive contact detection depends on the overlapping electromagnetic field created by two neighboring electrodes, as opposed to self- capacitive touch detection. The capacitance amongst both of the electrodes decreases when one of them interacts with the outermost layer of the panel because of a shift in the interaction that occurs at their joint location. The relative positions of each of the nearby electrodes determine the touch point. As can be observed in Figure, the latitudinal neurons are utilized as receiving neurons (Rx) while the long- term row neurons are intended to be transmitter neurons (Tx). As seen in 3(c).

Before determining each Rx's reaction, the management IC first provides a voltage gradient to each Tx in turn. Before determining each Rx's reaction, the management IC first provides a power supply to all Tx in turn. The matching Tx and Rx combination that correlates to a suppressed answer may be used to determine the locations (X, Y) that the fingers touch. All three share the same circuit structure and electrode sizes. While bilateral sensitive contact technology for sensing can still handle multi-touch detecting, self-capacitance contact sensing tech is quicker and uses less power. Although the sensor Tx serves to convey touch signals, the sensor Rx is utilized to receive calls. Usually, an unobstructed electrical layer is employed. It is necessary to insert an array of isolation signals amid several Tx/Rx impulses. Nowadays, bendable displays are one of the most popular platforms for deploying reactive touch screens. Additional non-traditional methods for bendable touch surface screens are also under research. The highly reactive a-Si: H phototransistor for infrared near connection use in sensors was suggested by Lee et al. In 2015. The device features a straightforward, easy-to-assemble design. Despite its tiny design, the infrared reader doesn't interfere with a display. Although the use of advanced touch detection offers less effect on the sense of sight, it nevertheless presents a natural latency. Additionally, the technique needs a stable setting to operate and is dependent upon light. The cost is increased substantially by the extra board on the device.

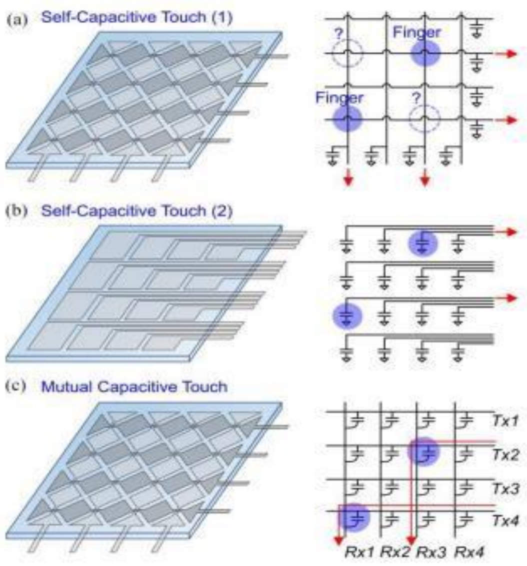

Figure. 3: The three types of reactive feel sensors—self- Capacitive touch (type 1), self-capacitive interaction (type 2), and mutually capacitive touch—have identical circuit designs and cathode configurations

3. Formations:

3.1. Outcell layout:

An adhesive-lamination show element, polaris film, paper shelter, and distinct touch-sensitive panel make up the active- matrix natural light-emitting diode, which or MODERN, bendable touch panel type. A working instance of this structure may be seen in Figure. 4(a). Film-Film, Double- Side ITO, Single-side ITO/bridge interaction organization, and Film2 are the three architectures that are often utilized for Out-Cell detection [24]. Overall Out-Cell screen possesses an established design and tested mechanism as of the present time [25], but more is needed to satisfy its gauge and bendability criteria.

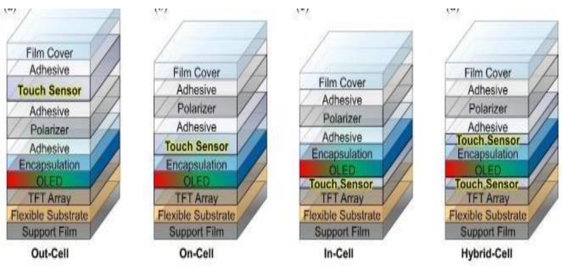

Figure. 4: Touchscreen sensor that is being tested architectures for flexible displays, such as AMOLEDs: There are four types of touch: a hybrid model, in-cell, out- cell, and on-cell. Cellular)

3.2. Sensors incorporated with physical contact:

Due to the ability to drastically cut costs, linked touch sensor equipment has attracted more interest in studies. Reduce the dimensions and height of the component and increase its versatility [26]. The embedded touch screen architectures may be classified as On-Cell, In-Cell, or Hybrid- cell layouts based upon how the boxes were arranged as shown in Figs. 4(b)–(d).

3.2.1. Physical cell:

Using a specific internet, "On-cell touch" integrates artificial light-emitting transistor (AMOLED) active-matrix screens with sensors for touch [27]. As seen in Fig. The touch sensor of the AMOLED is situated above the protective layer enclosing the OLED, as seen in 4(b). A different circuit barrier may be used to bridge the longitude as well as the latitude cathode connection regions, which may be positioned on the same circuit layer or two different conductor surfaces surrounded by a barrier of dielectric [28]. Hsieh et al. [29] reported an On-Cell contact sensor for an IGZO- driven Oled with a high sharpness of 168 PPI as well as an excellent visibility of 45%. Hu et al. [30] suggested a unique circuit design for the On-Cell touch sensor for AMOLED to avoid disruptive noise and drifting ground. The On-Cell construction provides a large, easy-to-use screen area.

3.2.2. Interior touch:

Tactile sensors that are built straight into particles are referred to as "in-cell touch" in contact technology. The term "in-cell design" refers to the arrangement where the touch detector is included in the water- resistant glass panel of the LCD or positioned underneath the protective film of the organic light-emitting diode (Fig. 4(c)). Usually, the patterns from the touch detector and the signaling pixels mix. Producing OLED cells with additional terminals is more challenging. In addition, more sophisticated controlling circuits for the fingertip and display are needed to reduce interference. The standard sensor VCOM in In-Cell is often divided into blocks and used as touch electrodes once more to minimize the total amount of circuit layers. Every block has a touch-detecting signal line attached to it. Therefore, further study is required to reduce parasitic capacitance, disruptive noise, and other issues. Su et al. (2021) demonstrated an enhanced 10.95-a little In-Cell LCD with a 120 Hz rate of refresh by lowering the capacitance that is parasitic in the electrodes. This was achieved by the use of an electronic double-layer framework. To solve the issue of volt drift during the contact detection phase with one another, Shen [32] et al. presented a gate motor circuit with a pair pre-charge arrangement the following year. This circuit greatly decreased threshold voltage drift and increased stability.

3.2.3. Hub-cell linkage:

Hybrid-cell contact sensing equipment combines in-cell and on-cell innovations. The Rx is applied and formed on the Amoled enclosing appear, as seen in Fig. 4(d), whereas the hybrid-cell architectural Tx conductors are located in the graphical component. Table. 1.

Table. 1: Summary of the capacitive touch sensor structures

Structure	***Out-cell***	***Integrated touch screen***		
		On-cell	***In-cell***	***Hybrid-cell***
Thin module	*	**	***	**
Image quality	*	**	***	**
Process feasibility	***	**	*	*

TABLE 1. Summary of the Capacitive Touch Sensor Structures

Structure	Out-Cell	Integrated touch screen		
		On-Cell	In-Cell	Hybrid-Cell
Thin module	★	★★	★★★	★★
Image quality	★	★★	★★★	★★
Process feasibility	★★★	★★	★	★

A Brief Description of Sensitive Contact Detection Frameworks: Tx conductors are usually formed on the usual wire layer (VCOM), while Rx wires are made utilizing an extra transparent conductive layer. Furthermore, the hybrid-cell display is unsuitable for devices with short borders as extra fanout sectors are needed to link the Tx and IC on both sides of the edges. A summary of the types of sticky sensory devices is given in Table 1. Classical out- of-cell fingertip detecting is improved, but its image brightness and component bulk are constrained. Though more complex to build, In-Cell has the greatest throughput among incorporated touch-recognizing systems, however, On-Cell is better harmonized overall.

4. Portable electrode services:

Translucent leading needles are essential for numerous flexible photoelectric tools, including interactivity semiconductors and reach displays. Exceptionally responsive and thin sensors must be present to follow the image below, particularly for flexible displays with touchscreens. When put exactly on the edges of the display panel, the sensor's sensitive material has to be able to endure below-freezing temperatures for On-Cell to operate. Additionally, affordable supplies that are ready for production in large quantities are beneficial from the production standpoint. Other adaptable opaque electrode compounds that have been historically used in earlier times to construct flexible responsive touchscreens include metal lattice and metallic nanowires (AgNWs) [35].

4.1. Tin oxide:

Tin oxide, or ITO, is an extremely twisted and heavily plated n-type semiconductor compound that exhibits outstanding photonic and physical features including high transparency, low resistivity, or resistance extraordinary durability against abrasion, and chemical resiliency. The material's electron gap is between 3.5 and 4.3 eV. ITO is now the most widely used opaque sensitive material for electrodes one method that is often employed for overlay ITO on glass as well as malleable plastic boards is the technique of vapor phase casting. ITO is now dealing with several barriers, though: (1) exorbitant costs since indium is scarce; (2) costly deposition processes involving air coating tools.

4.2. Silver small wires:

Silver small wires owing to their remarkable electrical conductivity, and high transmittance, which as well as adaptation, silver tiny wires or AgNWs, have garnered a lot of interest [45]. Silver is an additional powerful metal that, regardless of the worst conditions, has remarkable mechanical features and remarkable chemical reactivity.

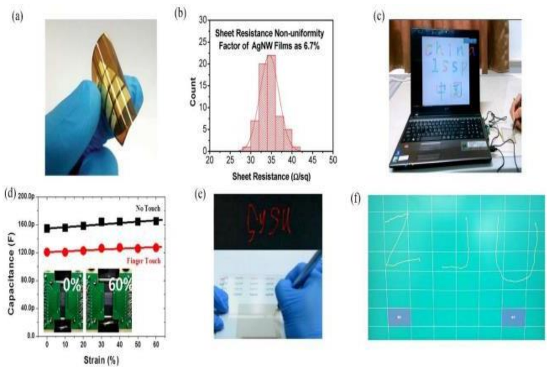

Figure. 5:

Fig. 5: (A) Picture of the ion-plated ITO films-covered bendable MAPBI3 solar cell made of perovskite (b) Fabricated argent nanowire thin sheet resistivity histograms that (c) Input writing technique using uniform AgNW opaque conductive sheets. (d) The capacitance of a single inductive touch sensor changes under stretched strain while contacting (red) and not (black). (f) AgNW's contact panel with multitouch writing capability ("SYSU") is shown. (f) Displaying

the letters "ZJU" on a non-flat substrate using a bending touch display demonstration

These AgNWs have visibility and conductivity characteristics that are equivalent to or even better than the iron oxide films. The homogeneity of the resistance of the sheets is the main hindrance to the actual utilization of AgNWs in opaque copper films. As a result, a lot of work has gone into combining AgNW flicks

4.3. Metal netting:

With its exceptional light including transmittance, relatively low resistance, and remarkable folding versatility, metallic mesh—a micrometer-scale matrix architecture made of connected metal wires—is perfect for flexible electronic devices. Compared to silver tiny wires metal netting offers a better promise for display options due to their increased flexibility and tunable line diameter and depth.

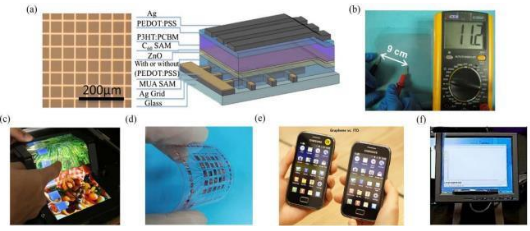

Figure. 6:

Fig. 6. Photographs of the graphite LCD added in a handheld device (left) compared to an ITO-based contact screen The phone (right) a) The material mesh and solar energy cell structure (b) Electrical resistance testing of the PEAN using an ohmmeter for measurement (c) Images about the 8.67-in foldable organic light-emitted diode display with a fingertip sensor (d) The 5 × 5 arrays of the 3DGF/CNT developed relationships strain sensor (e) (F) A full-color LCD incorporated within the Unidym control panel.

It is readily accessible on shelves for its adaptability buttons and is economically cheap to create in big quantities. However, there are a few drawbacks to using metal netting. For instance, the substantial dark sequence concentration of the netting reduces the graphical impact of the LCD panel, and the rough texture of the grid restricts the bonds amongst movable parts.

4.4. Graphene:

Graphene constitutes a multifaceted carbon tiny material composed of molecules of carbon-containing sp2-hybridized spaces organized in a rectangular comb lattice. Although the ideal diamond is made up of a single coating of carbon molecules, each atom of carbon that interacts with the surrounding atmosphere can operate as an active location that is responsive to excitation. Because of its significant mobility of electrons (200000 cm2/(Vs)), enormous specific surface area (2360 m2/g), strong conductivity of compact size, beneficial durability, and a connection with large-area adaptive solid supports, graphene is a promising material to use in the fabrication of responsive sensors [56]. Yet attempts to create opaque electrical films utilizing graphene have been hindered by the absence of practical techniques for transferring, manufacturing, along Contaminating graphene at the dimensions and purity required for those purposes.

4.5. Wooden nanotubes:

Carbon nanotubes (CNTs) are one- dimensional carbon allotropies with length- to-diameter ratios (aspect ratios) greater than 1000 [61]. Just one CNT can carry 106 A/cm2 of electrical power and has a movement of around 100,000 cm2/s. Although carbon nanotubes, or CNTs, offer amazing electrical and refractive capabilities, it is still difficult to produce huge quantities of high-quality, inexpensive CNTs. For cost-effective and reliable CNT production, solution-based coatings with spin techniques the wet- pulling method [62] are often used. Hecht et al. [63] created a composite nanotube elastic opaque anode layer with nearly eighty percent brightness and 550 ~/sq of resistance on one side for a four-wire responsive touch panel using Unidym's Carbon solution and a spinning coated method. As observed in Fig. 6(f), a significantly lower interface alongside a flat panel that showed full color was integrated with the flicks. A formed synthetic thin coating of tiny silver particles and multiwalled carbon fiber nanotubes was created by Zhang et al. [64] using a solution technique.

4.6. Bioactive Polymers

Regarding opaque electrically conductive substances composed of various polymer chains, poly(34-ethylene dioxythiophene): poly(styrene sulfonate) (PEDOT: PSS) appears to be an intriguing choice due to its outstanding work function, appropriate conductivity, which ranges a sufficient range of motion, and remarkable openness [66].

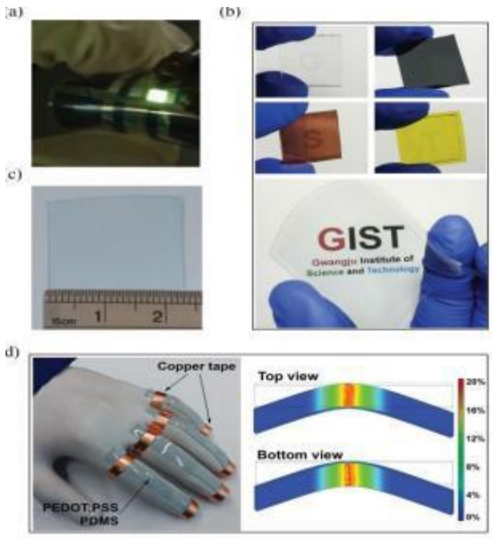

Figure. 7: (a) Picture of light-emitting apparatus using PEDOT: PSS. (b) Pictures of PSS films that have been treated with H2SO4 and applied to a range of surfaces, including silicon chips, glass slides, Cu foil, Kapton tape, and large-area PET foil. (c) A picture of the film's transferring on the PDMS

This type of capacitor, solar cells made of organic materials, and organic diode arrays (OLEDs) represent just among the PEDOT- based electronic gadgets that have displayed extremely promising photographic capabilities. Extensible PEDOT: PSS grid anodes that are which form the basis of organic lamps (OLEDs), provide highly intriguing ITO-free anodes that are for malleable and accessible devices due to their exceptional physicochemical capabilities. Even with the achievement of superior luminous properties, a spin coating is still the foundation of the majority of contemporary industrial operations.

5. Conclusion and outlook:

The creation of versatile displays is being driven by the fast expansion of adaptable electronics, with a focus on specific applications under diverse conditions. That goal has guided research endeavors in the fields of production; detection, and show capabilities. The fast-approaching Internet of Things (IoT) and Industry 4.0 era is expected to drastically change how individuals interact with objects thanks to Movable user interface technology. A brief review of the approach substance of the electrodes and methods employed throughout the current flexible board touch sensor investigation was given in this review. The constraints and potential of proximity sensors in the areas of layout and component depth, budget and fabrication viability, and viewing experience will be examined to inform upcoming studies on flexible panels.

5.1. Configuration and density of modules:

Traditionally, the Out-Cell structure screen has been an independent touch module connected to the display module. Optical transparent adhesive is sometimes used to laminate these two modules together, giving them a total thickness of considerably. This challenge may be handled by integrated touch sensor technologies, such as hybrid-cell, on-cell, and in-cell designs. The total thickness of the module is significantly decreased since the touch and display modules are either fully or partially integrated. Furthermore, flexible touch panels are growing in popularity, and in the future, there will be an increase in the number of smart gadgets that include integrated touch sensors. When it comes to visual effects and module thickness, In-Cell is the finest choice. However, In-Cell has to be incorporated into the pixel circuit and have a special driving integrated circuit (IC) to synchronize the touch and display. Furthermore, in certain designs, the OLED VCOM cathode may be constructed and repurposed as In-Cell touch electrodes, which would increase complexity and decrease yield in the OLED evaporation process. Because of this, On-Cell integrated touch—which is found in most flexible AMOLEDs on the market—is predicted to keep dominating the flexible display market.

5.2. Visual quality:

Commonly available, fairly cheap raw materials such as oxides, silver, and copper may be used to create metal mesh. However, the touch patterns that are now being produced often have a metal mesh line width greater than 5 μm due to technological restrictions. Furthermore, the moiré interference waves would be quite visible at high pixel densities. Therefore, unless the problems with line width and resistance are addressed, metal mesh could no longer be appropriate for very high- resolution displays. AgNW patterns with Line widths as small as 50 nm may be created on flexible surfaces using techniques like laser-assisted printing [72]. This means that when applying the patterns on screens with different pixel densities and sizes, moiré effects are not necessary. AgNWs also exhibit less resistance change and a smaller bending radius when bent in comparison to metal mesh films. AgNWs are scattered randomly, which results in a large degree of diffuse reflection in their films. This diffuse reflection must be controlled since it blurs the picture.

6. References:

(1) C. Wang et al., “User-interactive electronic skin for instantaneous pressure visualization,” Nature Mater., vol. 12, no. 10, pp. 899–904, Oct. 2013.

(2) D.-H. Kim et al., “Epidermal electronics,” Science, vol. 333, pp. 838–843, 2011.

(3) P. Drzaic et al., “44.3L: A printed and Rollable Bistable electronic display,” Int. Symp. Dig. Tech. Papers, vol. 29, no. 1, 1998, Art. No. 1131.

(4) G. Walker, “A review of technologies for sensing contact location on the surface of a display: Review of touch technologies,” J. Soc. Inf. Display, vol. 20, no. 8, pp. 413–440, Aug. 2012.

(5) Z. Zhao, K. Liu, Y. Liu, Y. Guo, and Y. Liu, “Intrinsically flexible displays: Key materials and devices,” Nat. Sci. Rev., vol. 9, no. 6, Jun. 2022, Art. no. nwac090.

(6) Y.-K. Choi et al., “An integrated LDI with readout function for touch-sensor-embedded display panels,” in Proc. IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers, 2007, pp. 134–135.

(7) P. Sun, C. Ma, Y. Chen, and H. Liu, “Flexible conducting composite film with reversible in- plane folding–unfolding property,” Adv. Sci., vol. 8, no. 20, Oct. 2021, Art. No. 2102314.

(8) P. Lee et al., “Highly stretchable and highly conductive metal electrode by very long metal nanowire percolation network,” Adv. Mater., vol. 24, no. 25, pp. 3326–3332, Jul. 2012.

(9) R. V. Salvatierra, C. E. Cava, L. S. Roman, and A. J. G. Zarbin, “ITOfree and flexible organic photovoltaic device based on high transparent and conductive polyaniline/carbon nanotube thin films,” Adv. Funct. Mater. vol. 23, no. 12, pp. 1490–1499, Mar. 2013.

(10) B.-J. Kim, M. A. Mastro, J. Hite, C. R. Eddy, and J. Kim, “Transparent conductive graphene electrode in GaN-based ultra-violet light- emitting diodes,” Opt. Exp., vol. 18, no. 22, pp. 23030–23034, Oct. 2010.

(11) H. Eom et al., “Ag@ni core-shell nanowire network for robust transparent electrodes against oxidation and sulfurization,” Small, vol. 10, no. 20, pp. 4171–4181, Jun. 2014.

(12) S. Lee, D. R. Mason, S. In, and N. Park, “Embedding metal electrodes in thick active layers for ITO-free plasmonic organic solar cells with improved performance,” Opt. Exp., vol. 22, no. S4, pp. A1145–A1152, Jun. 2014.

(13) B. Park and H. G. Jeon, “Spontaneous buckling in flexible organic light-emitting devices for enhanced light extraction,” Opt. Exp., vol. 19, no. S5, pp. A1117–A1125, Sep. 2011.

(14) Y.-S. Jang, K.-U. Gwak, S.-S. Lee, S.-G. Lee, J.-H. Kim, and H.-S. Oh, “P-181: A charge-share-based relative read-out circuit for capacitance sensing,” Int. Symp. Dig. Tech.

Papers, vol. 41, no. 1, pp. 1937–1939, 2010.

(15) H. Nam, K.-H. Seol, J. Lee, H. Cho, and S. W. Jung, "Review of capacitive touchscreen technologies: Overview, research trends, and machine learning approaches," Sensors, vol. 21, no. 14, Jul. 2021, Art. No. 4776.

(16) K. Kyoung, K. Yuge, and R. Hattori, "Single layered and one-side wired capacitive touch panel using transient electrical response," in Proc. 18th Int. Display Workshops, 2011, pp. 1341–1344.

(17) J. Yanase, K. Takatori, and H. Asada, "60.3L: Late-newspaper: Algorithm for recognizing pinch gestures on surface-capacitive touch screens," Symp. Dig. Tech. Papers, vol. 46, no. 1, pp. 899–902, Jun. 2015.

(18) G. Barrett and R. Omote, "Projected-capacitive touch technology," J. Inf. Display, vol. 26, no. 3, pp. 16–21, Mar. 2010.

(19) J.-Y. Ruan, P. C.-P. Chao, and W.-D. Chen, "A multi-touch interface circuit for a large-sized capacitive touch panel," in Proc. IEEE Sensors, 2010, pp. 309–314.

(20) S. Takamatsu, "Fabric touch sensors using projected self-capacitive touch technique," Sensors Mater., vol. 25, no. 9, pp. 627–634, Jan. 2013.

(21) Y.-Y. Tang, C.-C. Lai, and C.-C. Lin, "17-1: Self-capacitive touch sensor design for OLED on-cell touch," Symp. Dig. Tech. Papers, vol. 53, no. 1, pp. 178–181, Jun. 2022.

(22) A. Wagner and G. Kaindl, "WireTouch: An open multi-touch tracker based on mutual capacitance sensing," Zenodo, pp. 1–9, Sep. 2016.

(23) Y. Lee et al., "An α-Si: H thin-film phototransistor for a near-infrared touch sensor," IEEE Electron. Device Lett. vol. 36, no. 1, pp. 41–43, Jan. 2015.

(24) S. Shi et al., "Current situation and development of touch sensor technology used in flexible AMOLED display," Chin. J. Liq. Cryst., vol. 37, no. 4, pp. 459–466, 2022.

(25) T.-Y. Ku et al., "Design and implement the readout circuit of an incell high-resolution capacitive touch panel," in Proc. ASME Conf. Inf. Storage Process. Syst., 2017, pp. 1–3, Paper V001T09A001.

(26) G. Walker and M. Fihn, "LCD in-cell touch," J. Inf. Display, vol. 26, no. 3, pp. 8–14, Mar. 2010.

(27) C.-C. Lee, J.-C. Ho, K.-J. Chen, M.-H. Yeh, Y.-Z. Lee, and J. Chen, "Highly flexible

AMOLED integrated with ultrathin on-cell touch panel," in Proc. IEEE Photon. Conf., 2016, pp. 665–666.

(28) J. Kang et al., "P-142: On the equivalent circuit models of flexible AMOLED on-cell touch panels," Int. Symp. Dig. Tech. Papers, vol. 50, no. 1, pp. 1759–1762, Jun. 2019.

(29) H.-H. Hsieh et al., "49.2: Invited paper: A transparent AMOLED with on-cell touch function driven by IGZO thin-film transistors," Int. Symp. Dig. Tech. Papers, vol. 42, no. 1, pp. 714–717, Jun. 2011.

(30) W. Hu et al., "P-218: Late-news-poster: On the scalability of on-cell touch for flexible AMOLED," Int. Symp. Dig. Tech. Papers, vol. 51, no. 1, pp. 1871–1874, Aug. 2020.

(31) C.-Y. Su et al., "P-1.1: A 10.95" high transparent 120 Hz IGZO in-cell touch LCD with a stylus pen," Int. Symp. Dig. Tech. Papers, vol. 52, no. S2, pp. 685–687, Aug. 2021.

(32) S. Shen, C. Liao, J. Yang, and S. Zhang, "A gate driver circuit with the two-stage precharge Structure for in-cell touch panels," Sci. Sin. Inf., vol. 51, no. 6, Jun. 2021, Art. no. 1030.

(33) N. M. Nair, I. Khanra, D. Ray, and P. Swaminathan, "Silver nanowire-based printable electrothermochromic ink for flexible touch display applications," ACS Appl. Mater. Interfaces, vol. 13, no. 29, pp. 34550–34560, Jul. 2021.

(34) J. Lee, P. Lee, H. Lee, D. Lee, S. S. Lee, and S. H. Ko, "Very long ag nanowire synthesis and its application in a highly transparent, conductive and flexible metal electrode touch panel," Nanoscale, vol. 4, no. 20, pp. 6408–6414, 2012.

(35) A. R. Madaria, A. Kumar, and C. Zhou, "Large scale, highly conductive and patterned transparent films of silver nanowires on arbitrary substrates and their application in touch screens," Nanotechnology, vol. 22, no. 24, Jun. 2011, Art. No. 245201.

(36) Y.-M. Choi, K.-Y. Kim, E. Lee, and T.-M. Lee, "16.2: Reverse-offset printed single-layer metal-mesh touch screen panel," Int. Symp. Dig. Tech. Papers, vol. 45, no. 1, pp. 197–199, Jun. 2014.

(37) E.-S. Choi, M.-H. Jeong, K. W. Choi, C. Lim, and S.-B. Lee, "Flexible and transparent touch sensor using single-wall carbon nanotube thin films," in Proc. 3rd Int. Nanoelectron. Conf., Jan. 2010, pp. 718–719.

(38) S. Chun, Y. Kim, H. Jung, and W. Park, "A flexible graphene touch sensor in the general human touch range," Appl. Phys. Lett., vol. 105, no. 4, Jul. 2014, Art. No. 041907.

(39) J. Lee, G. Kim, D.-K. Shin, and J. Park, "Solution-processed resistive pressure sensors based on sandwich structures using silver nanowires and conductive polymer," IEEE Sensors J., vol. 18, no. 24, pp. 9919–9924, Dec. 2018.

(40) A. V. Mudryi, A. V. Ivaniukovich, and A. G. Ulyashin, "Deposition by magnetron sputtering and characterization of indium tin oxide thin films," Thin Solid Films, vol. 515, no. 16, pp. 6489–6492, Jun. 2007.

(41) P. Kuang et al., "A new architecture for transparent electrodes: Relieving the trade-off between electrical conductivity and optical transmittance," Adv. Mater., vol. 23, no. 21, pp. 2469–2473, Jun. 2011.

(42) J. Song et al., "Wearable force touch sensor array using a flexible and transparent electrode," Adv. Funct. Mater. vol. 27, no. 6, Feb. 2017, Art. No. 1605286.

(43) D. Park, W. Park, J. Song, and S. S. Kim, "High- performance ITO thin films for on-cell touch sensor of foldable OLED displays," J. Inf. Display, vol. 23, no. 1, pp. 77–85, Jan. 2022.

(44) J.-H. Kim et al., "Flexible ITO films with atomically flat surfaces for high-performance Flexible perovskite solar cells," Nanoscale, vol. 10, no. 44, pp. 20587–20598, 2018.

(45) M. Layani, A. Kamyshny, and S. Magdassi, "Transparent conductors composed of nanomaterials," Nanoscale, vol. 6, no. 11, pp. 5581–5591, 2014.

(46) Y. Jia, C. Chen, D. Jia, S. Li, S. Ji, and C. Yet, "Silver nanowire transparent conductive films with high uniformity fabricated via a dynamic heating method," ACS Appl. Mater. Interfaces, vol. 8, no. 15, pp. 9865–9871, Apr. 2016.

(47) T. Y. Choi et al., "Stretchable, transparent, and stretch-unresponsive capacitive touch sensor array with selectively patterned silver nanowires/reduced graphene oxide electrodes," ACS Appl. Mater. Interfaces, vol. 9, no. 21, pp. 18022–18030, May 2017.

(48) G.-S. Liu et al., "Fabrication of embedded silver nanowires on arbitrary substrates with enhanced stability via chemisorbed alkanethiolate," ACS Appl. Mater. Interfaces, vol. 9, no. 17, pp. 15130–15138, May 2017.

(49) H. Yang, S. Bai, T. Chen, Y. Zhang, H. Wang, and X. Guo, "Facile fabrication of large-scale silver nanowire-PEDOT: PSS composite flexible transparent electrodes for flexible touch panels," Mater. Res. Exp., vol. 6, no. 8, May 2019, Art. No. 086315.

(50) M. Azani, A. Hassanpour, and T. Torres, "Benefits, problems, and solutions of silver

nanowire transparent conductive electrodes in indium tin oxide (ITO)-free flexible solar cells," Adv. Energy Mater., vol. 10, no. 48, Dec. 2020, Art. No. 2002536.

(51) H. Wu et al., "A transparent electrode based on a metal nanotrough network," Nature Nanotechnol., vol. 8, no. 6, pp. 421–425, Jun. 2013.

(52) J. Zou, H.-L. Yip, S. K. Hau, and A. K.-Y. Jen, "Metal grid/conducting polymer hybrid transparent electrode for inverted polymer solar cells," Appl. Phys. Lett., vol. 96, no. 20, May 2010, Art. No. 203301.

(53) L. Zhou et al., "High-performance flexible organic light-emitting diodes using embedded silver network transparent electrodes," ACS Nano, vol. 8, no. 12, pp. 12796–12805, Dec. 2014.

(54) K. Watanabe et al., "A foldable OLED display with an in-cell touch sensor having embedded metal-mesh electrodes: Foldable OLED display with in-cell touch sensor," J. Soc. Inf. Display, vol. 24, no. 1, pp. 12–20, Jan. 2016.

(55) S. Hong et al., "Nonvacuum, maskless fabrication of a flexible metal grid transparent conductor by low-temperature selective laser sintering of nanoparticle ink," ACS Nano, vol. 7, no. 6, pp. 5024–5031, Jun. 2013.

(56) A. K. Geim, "Graphene: Status and prospects," Science, vol. 324, no. 5934, pp. 1530–1534, Jun. 2009.

(57) M. Savchak et al., "Highly conductive and transparent reduced graphene oxide nanoscale films via thermal conversion of polymer- encapsulated graphene oxide sheets," ACS Appl. Mater. Interfaces, vol. 10, no. 4, pp. 3975–3985, Jan. 2018.

(58) Y. Cai et al., "Extraordinarily stretchable all- carbon collaborative nanoarchitectures for epidermal sensors," Adv. Mater., vol. 29, no. 31, Aug. 2017, Art. No. 1606411.

(59) J. Ryu et al., "Fast synthesis of high- performance graphene films by hydrogen-free rapid thermal chemical vapor deposition," ACS Nano, vol. 8, no. 1, pp. 950–956, Jan. 2014.

(60) S. Bae et al., "Roll-to-roll production of 30-inch graphene films for transparent electrodes," Nature Nanotechnol., vol. 5, no. 8, pp. 574–578, Aug. 2010.

(61) X.-M. Liu et al., "Carbon nanotube (CNT) - based composites as electrode material for rechargeable Li-ion batteries: A review," Compos Sci. Technol., vol. 72, no. 2, pp. 121–144, Jan. 2012.

(62) L. Liu et al., “Aligned, high-density semiconducting carbon nanotube arrays for high-performance electronics,” Science, vol. 368, no. 6493, pp. 850–856, May 2020.

(63) D. S. Hecht et al., “Carbon-nanotube film on plastic as a transparent electrode for resistive touch screens,” J. Soc. Inf. Display, vol. 17, no. 11, pp. 941–946, 2009.

(64) Y. Zhang et al., “Efficient semi-transparent organic solar cells with high color rendering index enabled by self-assembled and knitted AgNPs/wants transparent top electrode via solution process,” Adv. Opt. Mater., vol. 9, no. 8, Apr. 2021, Art. No. 2002108.

(65) E.-S. Choi, M.-H. Jeong, K. W. Choi, C. Lim, and S.-B. Lee, “Flexible and transparent touch sensor using single-wall carbon nanotube thin films,” in Proc. 3rd Int. Nanoelectronics Conf., Jan. 2010, pp. 718–719.

(66) A. Vacca et al., “Preparation and characterization of transparent and flexible PEDOT: PSS/PANI electrodes by ink-jet printing and electropolymerization,” RSC Adv., vol. 5, no. 97, pp. 79600–79606, 2015.

(67) S. Cha, E. Lee, and G. Cho, “Fabrication of poly (3,4ethylenedioxythiophene): Poly (styrene sulfonate)/poly (vinylidene fluoride) nanofiber- web-based transparent conducting electrodes for dye-sensitized photovoltaic textiles,” ACS Appl. Mater. Interfaces, vol. 13, no. 24, pp. 28855–28863, Jun. 2021.