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Preparation Methods of Flexible Transparent Conductive Films: Comparison and Evaluation

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Abstract. Indium tin oxide (ITO) has long been the mainstream conductive film in electronic devices, but its inherent defects—such as scarce indium reserves, high brittleness (incompatible with flexible substrates), and high vacuum-dependent preparation costs—have severely limited its application in flexible electronics and large-scale manufacturing. To tackle these challenges, alternative conductive materials, namely MXene, silver nanowires (AgNWs), and metal grids, have garnered widespread research attention. This study systematically analyzes and compares the core properties and intrinsic defects of the three materials. MXene, with its two-dimensional layered structure, delivers excellent electrical conductivity and mechanical flexibility but suffers from poor environmental stability. AgNWs feature high light transmittance and low-cost solution-processable fabrication, yet their tendency to agglomerate and relatively high sheet resistance undermine performance consistency. Metal grids exhibit superior conductivity and long-term stability, while their visible light diffraction and complex patterning processes increase application barriers. Key comparison results of the three materials (including conductivity, flexibility, transmittance, and stability) are summarized in tables. This research aims to provide a practical reference for the selection of conductive materials in different scenarios and offer insights for the optimization of next-generation conductive film technologies.

Keywords: Indium tin oxide, Mxene, Silver nanowire, Metal grid

1. Introduction

With the shift of consumer needs towards flexibility and wearability, products such as foldable smartphones, flexible electronic skins and smart watches have become increasingly popular [1,2]. Along with the development of transparent conducting thin films (TCFs), which serve as the core layer for touch panels, organic light-emitting diodes (OLEDs) displays and organic solar cells, becoming an indispensable component of modern optoelectronic devices [3-6].

Traditional rigid transparent conductive films like ITO, which has a low sheet resistance (Rs) and high optical transmittance (T), have become inadequate to meet the requirement of flexible screens [7,8]. When bent repeatedly on flexible substrates (such as polyimide, PET), it is prone to cracks, resulting in a sharp decline in conductivity [8]. Moreover, the scarcity of indium on earth has also increased the cost of ITO, limiting its application in large-scale flexible electronic devices or even

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replacing ITO by other materials having equivalent properties [9]. Therefore, the new type of flexible transparent conductive film await research to solve these bottlenecks.

In recent years, with the progress of materials, more highly promising alternative materials with flexible advantages have emerged. Titanium carbide MXenes($Ti_3C_2T_x$), silver nanowire (AgNW) and metal grid, owing to their electrical conductivity and tunable properties, are considered ideal candidate materials for next-generation flexible transparent conductive films [10-12]. MXenes, a new class of 2D transition metal carbides and carbonitrides, combining the metallic conductivity, hydrophilic surface and excellent mechanical properties [10]. Silver nanowire TCFs can achieve high scalability, conductivity and tailorable optical properties [11]. Moreover, their preparation process is relatively simple. Metal grid mesh, with its high optical transmittance, superior electrochemical impedance and excellent sheet resistance, are fully biocompatible [7,12]. MXenes easily oxidized in wet air to form TiO_2, leading to performance degradation [10]. Silver nanowires have the problem of morphological instability and corrosion, which affects uniformity an longevity [13]. The complex fabrication of metal grid is time-consuming and costly.

Herein, the aim of this work is to discuss current cases for flexible transparent conductive films. A comparative analysis of the advantages and limitations across various methods was conducted. The specific structure is as follows: In the second part, the typical preparation processes of three types of materials, namely $Ti_3C_2T_x$, silver nanowires, and metal grid, are introduced in detail, including solution methods, physical deposition methods, photolithography methods, etc. In the third part, the performance of films prepared by different methods is quantitatively compared from the dimensions of transmittance, conductivity, flexibility, stability, cost, etc. In the fourth part, the limitations of various methods are analyzed. In the fifth part, the full - text is summarized, and the future development directions and application prospects of flexible transparent conductive films are prospected. Through the above research, it is expected to provide theoretical and practical references for material selection and process improvement of flexible electronic devices.

2. Case description

2.1. Mxenes

Titanium carbide Mxene is a two-dimensional (2D) transition metal carbide belonging to the MXene family, derived from the phase Ti_3AlC_2 through selective etching of the aluminum (Al) layer has excellent metallic conductivity, high optical transmittance, solution processability, tunable work-function, and hydrophilicity. This makes them suitable for deployment in PV technology. Its layered structure allows bending and folding, critical for flexible devices. While stable at room temperature, prolonged exposure to humidity or high temperatures leads to oxidation. Its 2D layered structure and surface terminations enable diverse applications in energy storage, optoelectronics, and sensing.

2.2. Silver nanowire

Silver nanowire (AgNW) films as a kind of bright flexible transparent conductive material are expected to have the low sheet resistance, the critically high optical transmittance and the wide range haze for different applications, rivaling indium tin oxide (ITO). AgNWs can withstand repeated bending without significant degradation in conductivity. This flexibility makes them suitable for wearable electronics and foldable displays. While AgNWs are susceptible to oxidation and corrosion in harsh environments. AgNWs can be dispersed in polar solvents and processed via spray coating, spin coating, or inkjet printing for large-scale applications.

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2.3. Metal grid

A metal grid is a periodic or quasi-periodic network structure consisting of thin metal lines fabricated on transparent substrates like glass or flexible polymer films like PET. As a promising alternative to ITO in flexible electronics, it enables electron transport via interconnected metal lines while maintaining optical transparency through the large open area between grid lines. It has high electrical conductivity—determined by metal type and grid geometry like line width and pitch. Let alone a critical balance between transparency and conductivity. It also exhibits excellent mechanical flexibility, withstanding repeated bending on flexible substrates without significant conductivity degradation. Its environmental stability can be enhanced via protective coatings. Additionally, it offers good fabrication compatibility, with scalable, cost-effective methods like inkjet printing and roll-to-roll printing enabling large-area, high throughput production.

3. Analysis and challenge

3.1. Mxenes

In general, the $Ti_3C_2T_x$ thin films were fabricated via room-temperature spray coating using delaminated $Ti_3C_2T_x$ (d-$Ti_3C_2T_x$) colloidal solutions, ensuring simplicity and scalability [10]. The d-$Ti_3C_2T_x$ solution (≈3.0 mg mL^{-1}) was prepared by adding 200 mg ground multilayer $Ti_3C_2T_x$ powders to 20 mL deionized water, sonicating for 1h under argon in an ice bath, and centrifuging at 3500 rpm for 1h to collect supernatant with single/few-layer flakes, which TEM confirmed had lateral sizes ranging from hundreds of nanometers to several micrometers. Prior to deposition, Substrates (e.g., glass, flexible polyester) were pretreated: glass substrates, for instance, were sonicated in a 3:1 H_2SO_4/H_2O_2 mixture for 1h, then rinsed with deionized water. For the spray coating process itself, a 0.5 mm-nozzle airbrush was used at a pressure of 80 psi, positioned 30 cm from the substrate, moving at ≈15 cm s^{-1}; each layer was dried immediately with a heat gun after deposition to prevent flake aggregation. Additionally, X-ray diffraction (XRD) patterns confirmed the films contained only $Ti_3C_2T_x$ without any other phases. Scanning electron microscopy (SEM) showed homogeneous, defect-free morphology with flakes aligned parallel to the substrate, forming a compact structure. The structure and manufacturing diagram were showed in Fig.1.

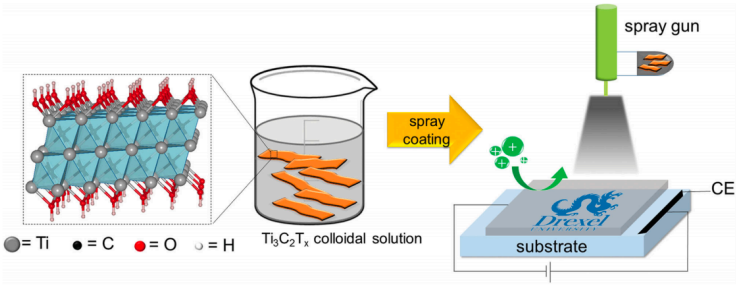


Figure 1. Schematic of Ti3C2Tx film preparation by spray coating [10]

MXenes, a novel class of 2D transition metal carbides and carbonitrides, standing out for their exceptional combination of properties that underscore their potential across diverse applications. Characterized by metallic conductivity, hydrophilic surfaces, and robust mechanical strength, they are particularly well-suited for transparent conductive electrode roles. When processed into thin films via spray coating, these films exhibit favorable optoelectronic characteristics, with

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performance metrics that position them as strong alternatives to existing materials. Notably, the films demonstrate impressive flexibility, retaining stable electrical properties even under significant bending, which highlights their suitability for flexible electronic devices. A key advantage lies in the tunability of their optoelectronic properties: chemical or electrochemical intercalation of cations enables adjustments to their optical and electrical behaviors, including reversible changes in UV–visible transmittance—a feature with implications for electrochromic and sensing applications [10]. The study affirms that spray-coated $Ti_3C_2T_x$ thin films hold substantial promise as transparent conductive electrodes in electronics, electrochromic devices, and sensors. The spray coating technique, with its scalability and cost-effectiveness, facilitates large-area fabrication on both rigid and flexible substrates [10].

Despite their promising attributes, MXenes face distinct defects and challenges that hinder their immediate large-scale adoption. Oxidation instability stands as a critical limitation. The material is prone to oxidizing in wet air, forming TiO2 and suffering substantial conductivity loss [10]. This not only degrades long-term performance but also complicates storage and processing, as strict environmental controls (e.g., inert atmospheres) may be required, adding costs and reducing practicality for industrial workflows. Additionally, compared to indium tin oxide (ITO), MXene films still exhibit higher sheet resistance at comparable transmittance, and their figure of merit (FoM) lags behind ITO's benchmarks. This limits their competitiveness in high-performance devices like high-resolution displays, where ultra-low resistance and high transparency are non-negotiable. In analysis, these challenges are not insurmountable but require strategic innovation. Ultimately, MXenes'challenges are rooted in balancing intrinsic material properties with practical fabrication demands.

3.2. Silver nanowire

To fabricate AgNW-based transparent conductive films (TCFs) with tunable optoelectrical properties, AgNWs with three target diameter ranges (~22 nm, ~60 nm, ~107 nm) and corresponding lengths (22.9–80.7 μm) were synthesized via a modified polyol method. For ~22 nm diameter AgNWs: $AgNO_3$ was dissolved in EG under ice bath to prevent premature nucleation, then mixed with NaBr/EG, NaCl/EG, and PVP/EG solutions. The mixture was stirred in a nitrogen-flushed flask, heated to 180 ◦C, cooled to 170 ◦C, and held for 1 h. Shorter AgNWs (~5.9 μm) were obtained by sonicating the as-synthesized product at 100 W for 20 min. For ~60 nm diameter AgNWs: a binary PVP mixture (MW 55,000 + 360,000) was dissolved in EG at 130 ◦C, followed by dropwise addition of $AgNO_3$/EG and $FeCl_3$/EG (1.1 mM) at 140 ◦C, with a 40–55 min reaction duration. For ~107 nm diameter AgNWs: high-MW PVP (1,300,000) was used, and $AgNO_3$/$FeCl_3$ solutions were added over 11 min at 140 ◦C, reacting for 45 min. Purified AgNWs were dispersed in deionized water (1–5 mg/mL) with HPMC and Sago additives to form stable inks. Clean PET substrates were coated with these inks via Mayer rod coating (automatic coater BEVS 1811/2), where wet film thickness (and thus AgNW density) was adjusted by rod type; Coated films were dried at 80 ◦C for 10 min [11].

The optoelectrical properties of AgNW-based transparent conductive films (TCFs) are strongly dependent on the structural parameters of AgNWs, allowing precise tuning for diverse applications. As shown in Fig. 2 Longer AgNWs deliver higher optical transmittance under the same diameter and sheet resistance, while haze shows a clear positive correlation with AgNW diameter, within the 20–100 nm range, thicker AgNWs induce stronger light scattering. AgNW density (adjusted via wet coating thickness) further modulates performance, increasing density reduces sheet resistance via improved inter-nanowire contact but elevates haze. Mechanically, the AgNW TCFs show robust

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flexibility on PET substrates, with no significant degradation in transmittance, haze, sheet resistance, or NUF after 5000 bending cycles at a 1 cm radius, thanks to the inherent flexibility of AgNW networks that resist cracking or delamination. Structural manipulation studies indicate that longer AgNWs boost optical transmittance by reducing the required film coverage for adequate conductivity, while thicker nanowires elevate haze through enhanced light scattering. Thus, long-thick AgNWs suit high-haze applications like solar cells to optimize light trapping.While long-thin ones fit low-haze uses such as touchscreens to ensure display clarity. These films also exhibit excellent bending stability. There is no significant performance loss after 5000 bending cycles, and can achieve a desirable balance of transmittance (>80%), sheet resistance (<75 Ω/sq), and haze (1%–25%), with favorable figure of merit (FoM) values aligning with application-specific needs [11].

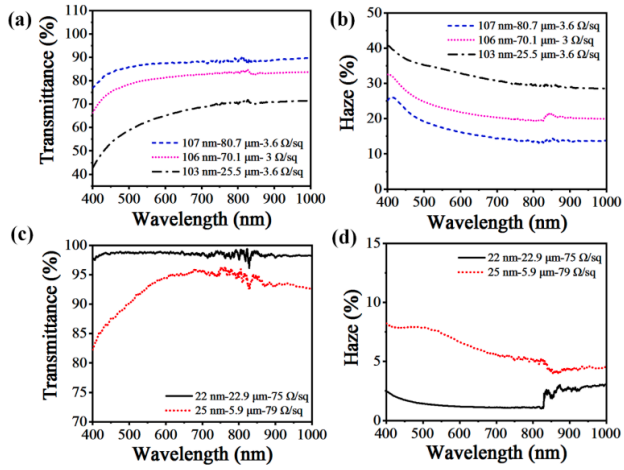


Figure 2. The structural parameters of AgNWs prepared and optoelectrical properties of AgNW TCFs [11]

Silver nanowire transparent conductive films (AgNW TCFs) stand out as promising flexible alternatives to indium tin oxide (ITO), with their optoelectrical properties strongly dictated by structural parameters including diameter, length, aspect ratio, and density. Nevertheless, critical challenges hinder their large-scale commercialization. It is hard to ensure consistent structural uniformity during mass AgNW synthesis, leading to batch-to-batch performance fluctuations. Additionally, long-term environmental stability remain to be improved. If susceptible to oxidation or corrosion, it may lead to a decrease in conductivity over time. Besides, it has insufficient compatibility with existing device manufacturing processes, Which is difficult to be efficiently integrated with various substrates or packaging materials. Practically, the tunability of AgNW structures for targeted optoelectrical demands is a major advantage, but future research should prioritize developing scalable, cost-effective synthesis techniques to maintain structural precision, along with surface modification or composite approaches to boost stability.

3.3. Metal grid

Generally, the preparation method of metal grid is as follow. A polyethylene naphthalate (PEN) substrate was prepared for fabricating the metal grid, it was first cleaned via ultrasonic sonication sequentially in acetone, isopropanol, and distilled water for 30 minutes each, followed by a 20-minute ultraviolet surface treatment to enhance the adhesion between the subsequent ink and the

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substrate. A sacrificial ink was then formulated by blending a positive photoresist with its dedicated thinner at a 1:1 volume ratio using a vortex mixer, yielding a solution with a viscosity of 9.15 cp (measured at 24°C) and a surface tension of 21.62 mN/m. A commercial inkjet printing system fitted with a 19-μm diameter cartridge head was employed to deposit this sacrificial ink into a dot array pattern, with each jetting operation delivering a consistent 10-pl droplet; the nozzle voltage was tuned within the range of 28–31 V and the jetting frequency fixed at 1 kHz. Post-printing, the sample was baked at 110°C for 80 seconds to reinforce the sacrificial layer's bonding to the PEN substrate, then exposed to extreme ultraviolet radiation for 20 seconds. Next, a 100-nm thick aluminum film was deposited across the entire sample, using thermal evaporation. Finally, the sacrificial layer, along with the aluminum film atop it, was removed by immersing the sample in acetone and applying ultrasonic treatment for 20 minutes [14]. The process was shown in Fig. 3.

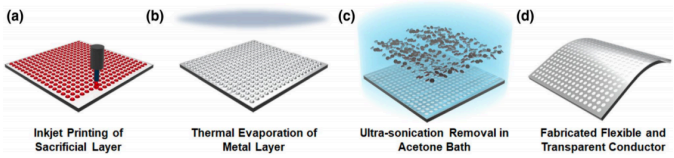


Figure 3. Schematic illustration for the fabrication procedure of a transparent electrode with a negative pattern of an inkjet-printed dot array. (a) PR ink-jet printing on the glass; (b) thermal evaporation of aluminum; (c) the removal of the printed PR array; (d) the metal grid electrode [14]

The metal grid transparent electrodes demonstrate outstanding comprehensive performance. Optically, they feature a broad and uniform transmittance spectrum that covers the UV region. when the drop spacing is 75 μm, the triangular array achieves a maximum transmittance of 81.4% and the square array 74.4%, showing better UV transmittance than commercial ITO which absorbs UV light [14]. Electrically, there is a trade-off between transmittance and conductivity. Smaller drop spacing reduces aluminum areal density, boosting transmittance but increasing sheet resistance, yet their figure-of-merit (FoM) is comparable to that of materials like ITO, CNTs, PEDOT:PSS, and graphene, especially at over 80% transmittance [14]. Mechanically, they exhibit excellent flexibility and stability, with resistance changing by less than 1% after 7000 bending cycles and maintaining stability even at a 1 mm bending radius, outperforming flexible ITO/PEN electrodes [14]. The fabrication process is simple and low-cost, using inkjet-printed photoresist as a sacrificial layer with thermal evaporation and aluminum instead of noble metals to cut material expenses. A resistive touch screen panel (TSP) made with these electrodes can accurately detect touch positions, proving practical application value. Though the electrode's roughness may limit its use in stacked thin-film devices, the process allows a wide range of choices for sacrificial layer and metal film materials.

While the metal grid electrodes demonstrated notable advantages, they still face several non-negligible challenges. One major challenge of the metal grid electrodes lies in their surface roughness, which can induce electrical non-uniformity and even leakage current in stacked thin-film devices, as the uneven film topology disrupts the stable operation of layered device structures. Another key limitation stems from process constraints on drop spacing. when the spacing is less than 75 μm, printed droplets tend to merge, preventing further reduction to optimize transmittance and conductivity [14]. Additionally, compared with commercial indium tin oxide (ITO), the metal grids show slightly lower transmittance in the visible spectrum. Furthermore, while the fabrication process offers broad material choices, it still has compatibility limitations—for example, aluminum films thicker than 100 nm cannot form clear patterns, due to failure to break along the sacrificial layer's topography, restricting the tuning of electrical conductivity [14]. From my perspective, these

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challenges do not negate the application potential of metal grid electrodes, but rather clarify the key directions and priorities for subsequent research.

4. Summary and suggestion

MXenes have emerged as a highly promising candidate for flexible transparent conductive films (TCFs), attributed to their remarkable combination of high intrinsic conductivity, high optical transmittance across the visible spectrum, and excellent solution processability. These unique properties enable their facile large-area deposition through techniques like spin-coating or inkjet printing, thus opening up exciting avenues in applications such as flexible solar cells, transparent touchscreens, and wearable bioelectronics. However, their inherent susceptibility to oxidation, especially under ambient conditions with moisture and oxygen, leads to a rapid degradation of electrical and optical properties, coupled with poor long-term stability and relatively higher sheet resistance compared to conventional indium tin oxide (ITO) [10]. To surmount these critical challenges, it is essential to develop multifaceted strategies: first, implementing effective oxidation-resistant measures such as atomic layer deposition (ALD) of ultrathin protective layers or chemical passivation via surface functional groups to inhibit redox reactions [15]. Second, optimizing the synthesis routes, including tuning the etching conditions and post-treatment processes, to refine the crystal structure and reduce interflake resistance, thereby lowering the sheet resistance [16]. Moreover, integrating MXenes with other functional nanomaterials like carbon nanotubes or conductive polymers to form hybrid composites can synergistically enhance their stability and electrical performance, paving the way for their practical implementation in next-generation flexible electronics [17].

Nanowires, particularly those composed of metals (e.g., silver) or metal oxides (e.g., ZnO, In_2O_3), stand out as attractive building blocks for flexible TCFs, owing to their outstanding flexibility that allows conformal integration with curved surfaces, low-cost fabrication routes compatible with roll-to-roll manufacturing, and a superb transmittance-conductivity balance that meets the dual requirements of optical clarity and electrical performance [11]. Such merits make them highly suitable for cost-sensitive applications like flexible displays, wearable health monitors, and RFID tags. Nevertheless, they face notable drawbacks: high contact resistance arising from the inherent junctions between nanowires, agglomeration during processing that deteriorates both conductivity and transmittance, and limited mechanical durability under repeated bending or stretching cycles. To address these issues, a series of targeted approaches should be pursued: developing novel dispersion agents or surface modification techniques like ligand exchange or plasma treatment) to ensure uniform dispersion of nanowires and minimize agglomeration [18]. Additionally, engineering the nanowire network architecture—such as introducing hierarchical structures or incorporating conductive adhesives at the junctions—can effectively reduce contact resistance [19]. For enhancing mechanical durability, embedding nanowires into flexible polymer matrices with optimized interfacial bonding can significantly improve fatigue resistance, as evidenced by maintaining stable performance over thousands of bending cycles [20]. Furthermore, exploring alloyed or core-shell nanowire structures can impart additional functionalities, broadening their application scope in advanced flexible electronics [21].

Metal grid flexible TCFs showcase unparalleled advantages, including ultra-high conductivity that ensures minimal power dissipation, robust stability against environmental fluctuations (e.g., temperature, humidity), and precise patterning capability that enables the fabrication of intricate device architectures, making them indispensable in high-performance applications like flexible OLED displays, transparent heaters, and high-frequency RF devices [14]. Despite these strengths,

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their complex fabrication process, optical defects such as visible grid lines that compromise visual clarity, and flexibility limitation due to the inherent brittleness of most metals pose substantial hurdles to widespread adoption. To tackle these limitations, several strategic improvements are warranted: developing simplified and scalable fabrication methodologies, such as advanced nanoimprint lithography with high-throughput capabilities or self-assembly techniques that eliminate the need for complex masks, to reduce manufacturing costs and increase production efficiency [22]. In terms of optical optimization, refining the grid geometry—such as reducing line width to the sub-micron scale, optimizing grid pitch, or adopting fractal-like designs—can effectively mitigate optical diffraction and minimize perceptible grid lines, thereby enhancing visual transparency [23]. For boosting flexibility, exploring ductile metal materials (e.g., copper alloys or silver nanowire composites) or designing hybrid structures that integrate metal grids with elastic polymer substrates can significantly improve bending and stretching tolerance [24]. Those information were concluded and shown in Table. 1.

Table 1. Comparation of various flexible transparent conductive films

Type	advantages	disadvantages
MXenes	-high intrinsic conductivity -high optical transmittance -excellent solution processability	-Oxidation -poor long-term stability -relatively higher sheet resistance
Nanowires	-outstanding flexibility -low-cost fabrication -superb transmittance-conductivity balance	-high contact resistance -agglomeration -limited mechanical durability
metal grid	-ultra-high conductivity -robust stability -precise patterning	-complex fabrication -optical defects -flexibility limitation

5. Conclusion

This study systematically analyzes and compares the core properties, advantages, and inherent limitations of three typical transparent conductive materials: MXene, AgNWs, and metal grids, aiming to provide a comprehensive reference for their selection in practical applications. Each material exhibits distinct strengths in key performance metrics. MXene stands out for its excellent electrical conductivity, mechanical flexibility, and facile solution-processability, making it ideal for flexible electronic devices. However, its poor long-term stability under light and moisture remains a critical bottleneck. AgNWs balance high transparency and conductivity well, with low fabrication costs, but they suffer from uneven film formation (e.g., nanowire aggregation) and potential oxidation, which degrades performance over time. Metal grids offer ultra-high electrical conductivity and outstanding environmental stability, yet their optical diffraction at grid edges reduces transparency at small line widths, and complex patterning processes increase manufacturing difficulty. The comparative analysis confirms that no single material dominates all application scenarios. MXene is most suitable for flexible, short-term-use electronics like wearable sensors where flexibility and processability are prioritized. AgNWs are preferred for cost-sensitive, large-area devices like touchscreens that require a balance of transparency and conductivity. Metal grids excel in high-stability, high-conductivity applications like solar cells where long-term performance is critical. Overall, the selection of these TCMs should be tailored to specific application requirements, and future research should focus on addressing each material's inherent defects to expand their practical utility.

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