Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/135/2025.21082

# *Preparation Methods of Flexible Transparent Conductive Films: Comparison and Evaluation*

**Zhenting Zhao**[1,a,*]

*[1]Jiang Su Tianyi High School, Wuxi, China*
*a. 15861613731@163.com*
**corresponding author*

***Abstract:*** With the development of consumer electronics, transparent conductive films (TCFs) are materials that have become more and more important due to their screen application, and are crucial for the development of the next generation of electronic devices, especially in applications like touchscreens, solar cells, and wearable devices. This paper reviews and compares novel materials and their fabrication methods for TCFs, mainly introducing some substitute materials for traditional brittle and expensive Indium Tin Oxide (ITO). Material like MXene, silver nanowires, carbon nanomaterials, and metal meshes offer enhanced flexibility, conductivity, and transparency. They show a promising future in flexible transparent conductive film applications. However, several challenges remain unsolved in production. In conclusion, while these substitute materials offers light future for flexible transparent conductive films, overcoming scalability, uniformity, and cost challenges is essential for their widespread adoption in consumer electronics. This review highlights the advantages and challenges of these materials and provides their potential for future flexible electronic applications.

***Keywords:*** TCFs, Nanowire, MXene, Carbon, Metal mesh

## 1. Introduction

With the development of consumer electronics, transparent conductive films (TCFs) are materials that have become more and more important due to their screen application, which takes advantage of both transparency and electrical conductivity. This makes them essential in modern electronic devices such as touchscreens, displays, solar cells, and smart devices. For the time being, as the requirement for flexible/wearable devices emerged, flexible TCFs are in great need [1].

In recent years, new materials and new methods of manufacturing flexible TCFs have merged. These new methods enhance both the productivity and the performance of flexible transparent conductive films and motivate the wider application of flexible transparent conductive films. Over recent years, wearable electronics (such as smart watches, health monitoring devices, etc.) have become a popular trend.[2] They change people lives significantly because they are smart and easy to port. Moreover, people are pursuing new materials that are lighter, thinner, and softer since common TCFs could not satisfy all needs. At the same time, the need for high-quality transparent conductive films increases, especially in flexible displays and wearable devices. These new films not only enhance device performance but also provide users with more comfortable and interactive experiences. The rapid growth in the flexible electronic market stimulates innovation in TCFs.

The current widely used TCF material, Indium Tin Oxide (ITO), was considered a suitable material for TCFs due to its high electrical conductivity, high visible light transmission, high mechanical hardness, and good chemical stability [3]. However, there are several problems with the most widely used transparent conductive films like ITO. For example, the material is scarce, the production cost is high and the material is too brittle. Among them, the most severe problem is the lack of flexibility: despite its perfect electrical and optical properties, ITO is brittle. This makes it unsuitable for applications that need flexibility such as foldable phones and wearable electronics. Thus, a new material for manufacturing TCFs with high electrical conductivity, high visible light transmission, and good chemical stability with flexible possibility is needed [4].

Nowadays, many novel methods of manufacturing flexible transparent film have merged. With the development of materials, more flexible conductive materials, such as MXene, Nanowires, carbon nanomaterials, Metal mesh, etc, have been proposed. These new materials are all ideal ingredients for the next generation of flexible transparent conductive films not only due to these materials have many advantages, including high conductivity, excellent flexibility, and good optical transmittance, which are crucial for applications in flexible electronics, wearable, and transparent screens, these materials also enhance both the productivity and the performance of flexible transparent conductive films [5]. Moreover, this motivates the wider application of flexible transparent conductive films. However, despite their potential for future applications, stable and large-scale fabrication of these materials remains challenging. Difficulties such as poor dispersion, difficulty in achieving uniform films, and the complexity of the manufacturing processes limit their widespread use. Scientists need to put more effort into conquering such problems and making the manufacturing of these materials commercially viable. This paper provides a comprehensive discussion of current strategies for producing flexible conductive films. It included a comparison of different material-producing methods and assessments of their advantages and disadvantages in terms of performance, cost-effectiveness, and material properties.

The introduction, design and fabrication techniques, analysis of the difficulties, solution, and conclusion are the many sections that make up the structure of the paper. The introduction outlines the fundamental history of flexible electronics and TCFs as well as the shortcomings of the current ITO. The many design and fabrication processes utilized in the production of flexible electronics are connected to design and fabrication methodologies. The conclusion would provide a summary of the entire essay, while the solution discusses the current implementation solutions for flexible transparent conductive films.

## 2. Design and Fabrication

The design of TCFs utilizes various materials and structures to achieve transparency and flexibility. For example, metal meshes and nanowires that are inherently opaque. Scientists make extremely fine line widths to create an illusion of transparency. The spacing between these lines is critical for this effect. By contrast, carbon nanomaterials and MXenes are naturally transparent. This characteristic helps significantly simplify the design process. Flexibility is attained by overlapping the nanostructures of metal meshes, nanowires, or carbon. Additionally, MXenes are flexible, making them one of the best choices for applications that need bending and stretching. The general process of the fabrication of TCFs is almost the same. They usually deposit the materials onto flexible substrates. However, the choice of material can still have a great influence on the performance of the final product. MXene is a type of metal oxynitride. It is known for its high electrical conductivity, mechanical flexibility, and excellent thermal stability. Its surface chemistry makes it easier for MXene to functionalize, enhancing its compatibility with other materials. Nanowires are typically made from metals. They have excellent conductivity. Their flexibility allows them to be widely used in various flexible devices. Carbon nanomaterials are known for their electrical conductivity, lightweight nature, and mechanical strength. These materials are also chemically stable and can be easily processed into various forms. Metal meshes, composed of fine metal wires, have good conductivity and lightweight properties. Their open structure allows for high transparency, which is important in many applications. As a result, careful consideration of the choice of material is necessary in different situations to optimize the performance.

## 3. Analysis and Challenge

### 3.1. MXene

Some researches focused on the new method of using lithium fluoride and hydrochloric acid to synthesize two-dimensional titanium carbide ($Ti_3C_2$), a member of the MXene family. The process involved etching aluminum from titanium aluminum carbide ($Ti_3AlC_2$) to produce a clay-like material. Then it is shaped into flexible films, the fabrication process shown in Figure 1. To evaluate the performance of the produced MXene material various experiments are carried out including tests, for volumetric capacitance cycling stability and rate capability, in applications involving supercapacitors. The results show that the synthesized $Ti_3C_2$ exhibits impressive electrochemical performance.[6] The volumetric capacitances are as high as 900 farads per cubic centimeter. Moreover, the material showcases excellent cycling stability: after 10,000 cycles of charging and discharging, $Ti_3C_2$ still shows high conductivity values which is about 1,500 S/cm. Furthermore, the study investigates the mechanical and conductive properties of FTEs made up of MXene. Compared to conventional materials like PET and ITO which have 0.96GPa and 1.15GPa Young's modulus, the Young's modulus of MXene material is only 0.78GPa the result was shown in Figure 2 [7]. It is relatively small and indicates improved flexibility. These characteristics show that MXene materials such as $Ti_3C_2$ are suitable for energy storage devices, offering both high energy density and reliability. Moreover, $Ti_3C_2T_x$ MXene exhibits a remarkable transparent property (over 83.4% at approximately 6.7 nm thickness). At the wavelength of 550nm, there is a good linear relationship between the transmittance and the surface resistance of the film. It indicates that high transparency and low resistance can be achieved simultaneously [8]. Overall, this method represents the great progress in MXene synthesis. It offers alternatives to traditional methods that are often dangerous and have safety problems. The ability to produce high-quality and scalable MXene materials creates new possibilities for the next generation of energy storage devices. This kind of brand-new method may play a pivotal role in developing more efficient capacitors and batteries, enhancing the performance of portable electronics and electric vehicles in the future.

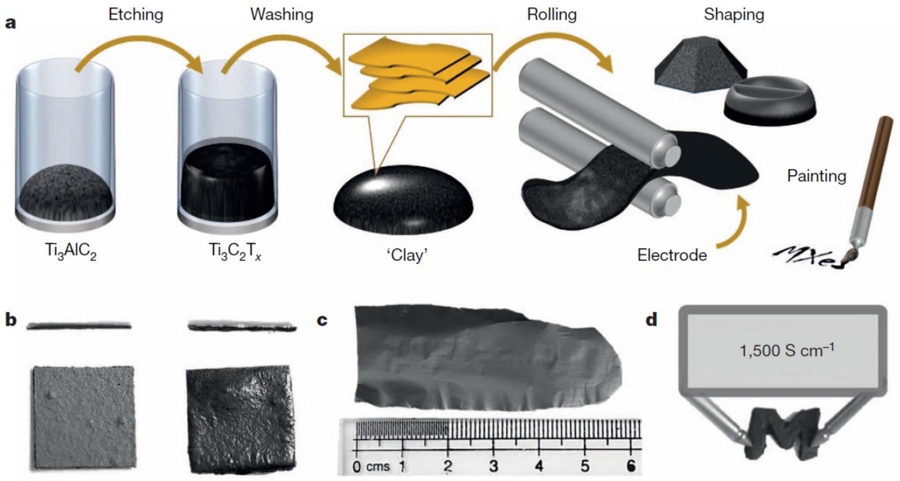

Figure 1: Schematic of MXene clay synthesis and electrode preparation. [6]

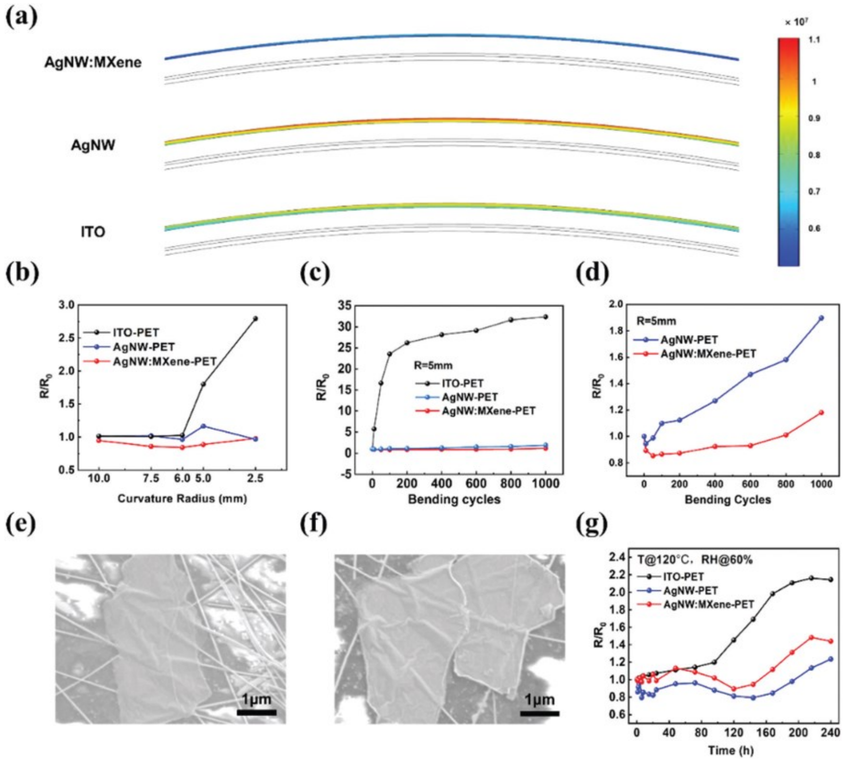

Figure 2: Mechanical and long-term stability of AgNW-MXene FTEs. (a) The finite-element simulation of AgNW:MXene, AgNW, and ITO electrodes. (b) Resistance changes of AgNW-PET, AgNW:MXene and ITO-PET FTEs at various curvature radii (10, 7.5, 6, 5, and 2.5 mm). (c) and (d) Resistance changes of AgNW-PET, ITO-PET, and AgNW:MXene FTEs under a curvature radius of 5 mm versus the bending times. (e) and (f) SEM images of AgNW:MXene FTE before and after the mechanical bending tests with bending 1000 times at a curvature radius of 5 mm. (g) Resistance changes of AgNW-PET, ITO-PET, and AgNW:MXene FTEs versus the store time. The ambient temperature is 120 C and the relative humidity is 60%. [7]

### 3.2. Nanowire

Nanowires are the ideal materials for TCF fabrication, Ag and Cu nanowires are more useful due to their high electrical conductivity. The research investigates the fabrication, optical, and electrical performance of transparent conductive films (TCFs) based on silver nanowires (AgNWs). It mainly focuses on the influence of structural parameters—such as diameter, length, aspect ratio, and density—on the TCFs' performance. By the synthesis of different diameters (22 nm, 25 nm, 61 nm, 67 nm, 106 nm, 103 nm, and 107 nm) and lengths varying from 5.9 μm to 80.7 μm, the resulting AgNW TCFs show changeable optical properties, including transmittance and haze. These performances can be controlled by adjusting the thickness of the wet coating, which controls the density of nanowires and the coverage rate of the films [9]. The results show that compared with the AgNWs with similar aspect ratios, as the diameter increases, it leads to higher haze due to increased scattering of light. If the AgNWs have a similar diameter, higher aspect ratios contribute to improved transmittance and figure of merit (FoM) values. The research also manifests that by choosing the proper diameter and aspect ratio, it is possible to tailor the optical properties of AgNW TCFs for specific applications. To be specific, AgNWs with large aspect ratios and low diameters are suitable for application in low-haze, such as touchscreens, while AgNWs with small aspect ratios and large diameters are ideal for high-haze applications like solar cells. [10] The use of finite-difference time-domain (FDTD) simulations further verified these experimental findings. It particularly demonstrates the effect of AgNW diameter on scattering electric field intensity and its influence on haze. The optical properties of the TFCs, including the transmittance greater than 80% at 550nm and the controllable haze between 1% and 25%, make it suitable for a series of optoelectronic applications. Moreover, the AgNW TFCs have excellent bending stabilities. It can maintain the same optical and electrical properties after 5000 bending cycles. Combining high flexibility and low resistance, these films are promising candidates for flexible electronic devices.

In summary, the structural parameters of AgNWs play a crucial role in determining the performance of the TCFs. The ability to change the parameters and assure great performance in both optical and electrical simultaneously makes AgNWs TCFs advanced materials for applications of a variety of optoelectronic and flexible device applications, including solar cells, touchscreens, and light-emitting devices.

### 3.3. Carbon material

The synthesis of high-quality graphene sheets plays a pivotal role in flexible and stretchable transparent conductive electronics (TCEs). Many methods have been developed, including mechanical cleavage, chemical vapor deposition (CVD), liquid-phase exfoliation, and reduction of graphene oxide (GO)[11]. Though mechanical cleavage can produce defect-free monolayers, it is not suitable for production on a large scale. CVD is a bottom-up method that involves the catalytic decomposition of hydrocarbons on metal catalysts like copper or nickel. The advantage is that it can yield high-quality graphene films. By comparison, Liquid-phase exfoliation is a top-down method. It disperses graphene sheets in solvents. It effectively overcomes van der Waals forces between layers. Although scalable, the reduction of GO often introduces defects that can compromise electrical conductivity. The synthesized graphene-based TCEs exhibit remarkable properties and shown in Figure 3: CVD-grown graphene films exhibit excellent conductivity (as low as 8Ω/sq) and high optical transmittance (94% at 550 nm)[12]. It is much better than traditional materials like indium tin oxide (ITO) and carbon nanotubes. The roll-to-roll fabrication enhances scalability. This characteristic ensures uniformity and stability even under mechanical deformation, making these TCEs suitable for wearable electronics. The methods of synthesis of graphene for TCEs are innovative and promising. Although the cost is high and also has a large complexity, the CVD method is still important because it offers superior quality and performance. This is essential for high-quality applications. Liquid-phase exfoliation offers a cost-effective alternative but requires further optimization to improve yield and reduce disadvantages. In general, the development of graphene synthesis methods represents a major improvement in producing high-performance TCEs on an industrial scale. However, there are still a lot of obstacles to overcome. For example, how to reduce the production cost and realize larger graphene sheets.

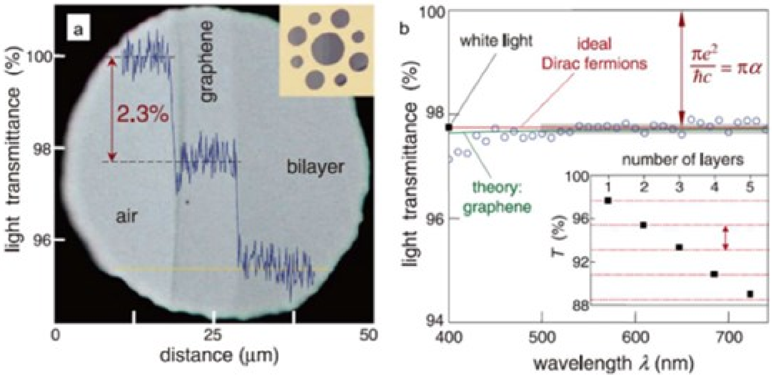

Figure 3: (a) Photograph of a 50-um aperture partially covered by single-layer graphene and bilayer sheets. (b) Transmittance spectrum of single-layer graphene [12].

### 3.4. Metal Mesh

In general, the production of metal mesh transparent films, especially ITO/Au grid hybrid transparent films, follows a well-established process, including photolithography, sputter deposition, and etching. The transparent films are made by patterning ITO islands on a flexible PET film. Then, the deposition of gold (Au) grids is used to create transparent conductive paths. The grid's structure typically has a width of 10 µm and pitches of 80 µm. This ensures that the structure is invisible to human eyes and keeps excellent conductivity at the same time. This method increases the flexibility of the machine, optical transparency, and electrochemical performance, making it suitable for all kinds of optoelectronic applications, such as bio-interfaces and electrophysiology.

As shown in Figure 4. The main advantages of metal mesh transparent films include high optical transmittance, good electrical conductivity, and excellent mechanical flexibility. For example, the hybrid ITO/Au structure exhibits a transmittance of 81%, sheet resistance of 14.1 Ω sq−1, and low impedance. This property makes it a candidate for transparent films. Moreover, the transparent films show an imposing mechanical stability. The performance of metal mesh remains stable after 5000 times of bending. These properties are crucial in applications that need flexibility and transparency, such as in wearable and implantable sensors [13].

However, the technology does have some remaining problems. The trade-off between optical transparency and electrochemical performance must be carefully considered because increasing the transparency by reducing the mesh density will also lead to a smaller effective recording area and eventually do harm to the electrochemical behavior. Despite this, the hybrid of ITO/Au mesh offers a balanced solution, optimizing both transparency and performance. The biocompatibility of these transparent films, demonstrated through histology studies, further supports their possibility for in vivo applications. Overall, the ITO/Au metal mesh hybrid transparent films have a promising application in flexible, high-performance electronic devices.

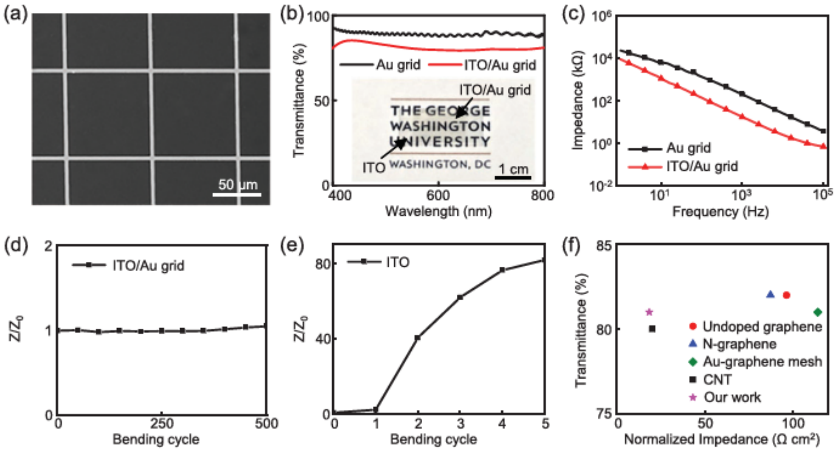

Figure 4: a) SEM image of the new ITO/Au grid. Scale bar, 50 um. b) Transmission spectra of an Au grid and an ITO/Au grid. (Inset) optical image of the ITO/Au grid film on a logo of George Washington University. Scale bar, 1 cm. c) Impedance plots of Au grid and ITO/Au grid microelectrodes, respectively. Variation of impedance versus bending cycle for d) ITO/Au grid and e) ITO microelectrode films. The bending radius is 5 mm. Zo is the impedance before bending whereas Z represents the impedance at a specific bending cycle. f) Comparison of transmittance versus normalized impedance of our ITO/Au grid hybrid microelectrodes compared with other reported representative transparent microelectrodes with transmittance ⩾80% for electrophysiology [13].

## 4. Summary

The 4 types of materials which used to fabricated flexible TCFs were compared and summarized in Table 1. Listed as follow:

### 4.1. MXene

Advantages: MXene materials exhibit excellent electrochemical properties. This makes them ideal choices for energy storage applications. It has volumetric capacitances up to 900 F/cm³. Moreover, they possess perfect cycling stability. Undergoing 10,000 times of charging and discharging processes, MXene materials can still maintain high conductivity (1,500S/cm). Its mechanical flexibility (0.78 GPa demonstrated by Young's modulus) is lower than that of conventional materials like PET and Ito. This incredibly enhances its suitability for flexible thin electrodes (FTEs). This synthesis method addresses safety concerns. At the same time, it also achieves the large-scale production of MXene films, paving the way for advanced supercapacitors, batteries, and portable electronics.

Disadvantages: Despite the relatively low Young's modulus of MXene materials, MXene materials might compromise structural integrity under certain mechanical stresses compared to more rigid materials. Mxene materials also exhibit low conductivity which prohibits some further utilize of them in electronic devices. Moreover, although the synthesis method reduces the risk, it still involves chemical complexities and scalability challenges. How to ensure the same quality remains the main problem in the wide use of MXene FTEs.

### 4.2. Nanowires

Advantages: The silver nanowire-based transparent conductive films offer excellent optical and electrical properties. The AgNW can be changed according to its radius and aspect ratios. This helps us optimize its performance in different cases. They also possess high transmittance (greater than 80% at 550 nm) and controllable haze (ranging from 1% to 25%). These properties make them ideal for optoelectronic devices such as touchscreens and solar cells. Moreover, AgNW exhibits impressive bending stability. In the experiment, they can maintain their optical and electrical properties even after 5000 times of bending cycles. This makes them highly flexible and suitable for wearable and flexible electronic devices. The ability to control the key structure parameters like diameter, length, and aspect ratio allows precise adjusting of optical and electrical properties, offering flexibility for different applications.

Disadvantages: The main disadvantage of AgNW-based TCFs is how to balance the transmittance and haze. As the diameter of AgNW enhances, the light scattering increases, which leads to higher haze and reduced clarity. This is not good in certain applications. What’s more, it is challenging to achieve uniformity in AgNW deposition. Although the AgNW-based film is flexible, its stability under long-term continuous mechanical stress is a concern. Moreover, the scalability of the fabrication process remains a challenge.

### 4.3. Carbon Nanomaterials

Advantages: The Graphene-based transparent conductive electronics attract much attention due to their excellent conductivity, transmittance (up to 94% at 550 nm), and mechanical flexibility. Chemical vapor deposition (CVD) makes it possible to produce high-quality graphene films that have low resistance (as low as 8Ω/sq). Moreover, these materials showcase superior mechanical deformation properties. This ensures its stable performance for wearable electronic devices. Compared to traditional materials like indium tin oxide (ITO), graphene exhibits better flexibility and conductivity, making it an ideal choice for flexible and stretchable devices.

Disadvantages: Although graphene possesses an excellent performance, it also has some disadvantages that can’t be ignored. For example, its fabrication process is complex, especially CVD. This kind of method needs an expansive catalyst and precise control for the growing conditions. These limit the cost-benefit effects of large-scale production and lead to a high production cost. Some cheaper methods have been developed such as liquid-phase exfoliation. However, these methods have lower productivity and do harm to the conductivity of the material. Moreover, it is still a challenge to produce large-area graphene sheets. Many obstacles like how to achieve uniformity on a large scale and lower cost remain unsolved. This limits the wide application of graphene in flexible electronics.

## 4.4. Metal Mesh

Advantages: Metal mesh transparent films, especially ITO/Au mixed transparent films take advantage of optical transparency, conductivity, and mechanical flexibility. To be specific, the transmittance is about 81%, and sheet resistance is as low as 14.1 Ω sq−1. ITO/Au hybrid structure also exhibits impressive mechanical stability and remains its property after 5000 bending cycles. Additionally, their biocompatibility supports potential use in vivo applications, such as in medical implants and electrophysiology.

Disadvantages: One of the main challenges of metal mesh transparent films is the trade-off between transparency and electrochemical performance. Reducing the mesh density to increase the transparency will lessen the effective recording area as a result. This issue needs to be carefully dealt with to achieve optical performance. Moreover, the production process is complicated. Precisely controlling the photolithography, sputter deposition, and etching process is the key to ensuring consistent quality. Although the hybrid ITO/Au structure is promising, it still needs further improvements in scalability and cost-effectiveness before widespread use in flexible electronic devices.

Table 1: Comparison of various materials for flexible TCFs.

| method | Advantages | Disadvantages |
|---|---|---|
| MXene | -Excellent electrochemical properties<br>-High cycling stability<br>-Good mechanical flexibility<br>-Suitable for FTEs<br>-Addresses safety concerns and supports large-scale production. | -Low Young's modulus limits structural integrity<br>-Low conductivity<br>-Chemical complexity and scalability issues<br>-Consistency in quality remains a challenge |
| Nanowire | -Excellent optical and electrical properties<br>-Impressive bending stability<br>-Flexibility in adjusting key structural parameters<br>-Ideal for optoelectronic devices | -Balancing transmittance and haze is difficult--Challenges in achieving uniformity<br>-Short stability under mechanical stress<br>-Scalability remains a challenge |
| Carbon material | -Excellent conductivity and high transmittance<br>-Superior mechanical flexibility and deformation properties<br>- Low resistance<br>-Better flexibility and conductivity<br>-Ideal for flexible and stretchable electronics. | -Complex fabrication process (CVD) with high production costs.<br>-Difficulty in producing large-area graphene sheets with uniformity.<br>-High cost limits widespread use. |

Table 1: (continued).

| | | |
|---|---|---|
| Metal mesh | -High optical transparency and low sheet resistance<br>-Excellent mechanical stability<br>-Biocompatible, suitable for medical and in vivo applications.<br>- Offers a hybrid structure combining optical transparency, conductivity, and flexibility. | -Trade-off between transparency and electrochemical performance; reducing mesh density reduces effective area.<br>-Complex production process<br>- Scalability and cost-effectiveness need improvement for widespread use. |

## 5. Conclusion

Flexible transparent conductive films (TCFs) show a promise for variety of applications in the future, including flexible electronics, wearable devices, and optical utilizations. Although Indium Tin Oxide (ITO) remains a widely used material for high conductivity and high transparency applications, its brittleness and high production cost stop it from further applications in flexible materials. As a result, new materials such as MXene, nanowires, carbon nanomaterials, and metal meshes have been developed. Each of them has its specific advantages. MXene-based films are known for their excellent electrochemical performance. They are mainly used in energy storage devices, offering high performance and safety. However, they still face problems ensuring the same quality under production and addressing their limited structural integrity under stress. Similarly, silver nanowire films offer high optical transmittance and excellent bending stability. This makes them an ideal choice for flexible electronics. However, balancing the transmittance and haze for them could be hard. Graphene has superior conductivity and mechanical flexibility. It exhibits high performance in TCFs, especially wearable electronic devices. However, the complex and expansive production progress is challenging and prohibits its large-scale production. Metal mesh combines high transmittance with mechanical flexibility. It shows possible use in applications that require both transparency and conductivity. Still, achieving optimal performance while minimizing the trade-off between transparency and electrochemical performance remains a key challenge.

In conclusion, while these substitute materials offers light future for flexible transparent conductive films, overcoming scalability, uniformity, and cost challenges is essential for their widespread adoption in consumer electronics.

## References

[1] *Chen, L., Liang, S., Liu, Y., & Zhang, L. (2021). Additive manufacturing of metallic lattice structures: Unconstrained design, accurate fabrication, fascinated performances, and challenges. Materials Science and Engineering R Reports, 146, 100648. https://doi.org/10.1016/j.mser.2021.100648*

[2] *Won, D., Bang, J., Choi, S. H., Pyun, K. R., Jeong, S., Lee, Y., & Ko, S. H. (2023). Transparent Electronics for wearable electronics application. Chemical Reviews, 123(16), 9982–10078. https://doi.org/10.1021/acs.chemrev.3c00139.*

[3] *8.Aydın, E. B., & Sezgintürk, M. K. (2017). Indium tin oxide (ITO): A promising material in biosensing technology. TrAC Trends in Analytical Chemistry, 97, 309–315. https://doi.org/10.1016/j.trac.2017.09.021*

[4] *9.Wang, T., Lu, K., Xu, Z., Lin, Z., Ning, H., Qiu, T., Yang, Z., Zheng, H., Yao, R., & Peng, J. (2021). Recent developments in flexible transparent electrode. Crystals, 11(5), 511. https://doi.org/10.3390/cryst11050511*

[5] *10.Wang, T., Lu, K., Xu, Z., Lin, Z., Ning, H., Qiu, T., Yang, Z., Zheng, H., Yao, R., & Peng, J. (2021). Recent developments in flexible transparent electrode. Crystals, 11(5), 511. https://doi.org/10.3390/cryst11050511Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A. N., ... & Polosukhin, I. (2017). Attention Is All You Need.(Nips), 2017. arXiv preprint arXiv:1706.03762, 10, S0140525X16001837.*

[6] *Ghidiu, M., Lukatskaya, M. R., Zhao, M.-Q., Gogotsi, Y., & Barsoum, M. W. (2014). Conductive two-dimensional titanium carbide 'clay' with high volumetric capacitance. Nature, 516(7529), 78-81. https://doi.org/10.1038/nature13970*

*[7] Chen, W., Zhang, R., Yang, X., Wang, H., Yang, H., Hu, X., & Zhang, S. (2022). A 1D:2D structured AgNW: MXene composite transparent electrode with high mechanical robustness for flexible photovoltaics. Journal of Materials Chemistry C, 10(25), 8625–8632. https://doi.org/10.1039/d2tc01178f*

*[8] Guo, T., Zhou, D., Deng, S., Jafarpour, M., Avaro, J., Neels, A., Heier, J., & Zhang, C. (2023). Rational design of* $TI_3C_2T_X$ *MXENE inks for conductive, transparent films. ACS Nano, 17(4), 3737–3749. https://doi.org/10.1021/acsnano.2c11180*

*[9] Chen, C., Zhao, Y., Wei, W., Tao, J., Lei, G., Jia, D., Wan, M., Li, S., Ji, S., & Ye, C. (2017). Fabrication of silver nanowire transparent conductive films with an ultra-low haze and ultra-high uniformity and their application in transparent electronics. Journal of Materials Chemistry C, 5(9), 2240–2246. https://doi.org/10.1039/c6tc05455b*

*[10] Im, H., Jin, J., Ko, J., Lee, J., Lee, J., & Bae, B. (2013). Flexible transparent conducting composite films using a monolithically embedded AgNW electrode with robust performance stability. Nanoscale, 6(2), 711–715. https://doi.org/10.1039/c3nr05348b*

*[11] Dasari, B. L., Nouri, J. M., Brabazon, D., & Naher, S. (2017). Graphene and derivatives – Synthesis techniques, properties and their energy applications. Energy, 140, 766–778. https://doi.org/10.1016/j.energy.2017.08.048*

*[12] Miao, J., & Fan, T. (2023). Flexible and stretchable transparent conductive graphene-based electrodes for emerging wearable electronics. Carbon, 202, 495–527. https://doi.org/10.1016/j.carbon.2022.11.018*

*[13] Chen, Z., Yin, R. T., Obaid, S. N., Tian, J., Chen, S. W., Miniovich, A. N., Boyajian, N., Efimov, I. R., & Lu, L. (2020). Flexible and transparent Metal Oxide/Metal Grid hybrid interfaces for electrophysiology and optogenetics. Advanced Materials Technologies, 5(8). https://doi.org/10.1002/admt.202000322*