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Review

Polymeric Protection for Silver Nanowire-Based Transparent Conductive Electrodes: Performance and Applications

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Abstract: Silver nanowires (AgNWs) are a potential alternative to conventional transparent conductive materials for various applications, such as flexible and transparent electrodes in optoelectronic devices, including touch screens, solar cells, and flexible displays. However, AgNW electrodes face degradation due to environmental factors, electrical instability, and mechanical stress. To overcome these challenges, strategies to protect AgNW-based electrodes via the incorporation of polymeric materials were widely investigated to improve the durability and stability of AgNW-based electrodes. This review paper gives a comprehensive overview of the incorporation of polymeric materials with AgNW electrodes, emphasizing their performance, and applications. We compare the different polymeric materials and their effect on the electrical, optical, and mechanical properties of AgNW electrodes. Furthermore, we evaluate the key factors affecting the choice of protective layers, such as their compatibility with AgNWs, and also we present current challenges and future opportunities for the development of polymeric materials for AgNW electrodes in emerging technologies.

Keywords: silver nanowire; protection layer; electrode; polymer; flexible

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1. Introduction

The demand for advanced transparent conductive materials is increasing as flexible and high-performance electronic devices become more popular [1–8]. Silver nanowires (AgNWs) are one of the most promising candidates to replace the most widely used material, indium tin oxide (ITO) [5–7,9–14]. AgNWs possess a unique amalgamation of attributes, boasting exemplary electrical conductivity, remarkable optical transparency, and innate mechanical flexibility [1,8,15–21]. These distinctive properties render them exceptionally well-suited for a diverse array of applications, spanning from cutting-edge touchscreens to innovative photovoltaic systems, and beyond.

For a substantial duration, ITO has held sway as the predominant transparent conductor, lauded for its formidable combination of high conductivity and exceptional transparency [22]. However, ITO bears significant drawbacks, notably its brittleness, exorbitant production costs, and the scarcity of indium—a pivotal component within its composition. These inherent limitations have galvanized a fervent quest for alternative materials, thrusting AgNWs into the spotlight as a formidable contender.

AgNWs have undeniably had their strengths proven, excelling in the efficient conduction of electricity, often outperforming ITO in this crucial regard [23,24]. Moreover, their nanoscale dimensions, characterized by diameters typically ranging from tens to hundreds of nanometers and lengths extending across several micrometers, endow them with the remarkable ability to intricately weave complex networks [25,26]. These nanowire assemblies not only preserve an elevated level of electrical conductivity but also achieve superlative optical transparency—a prerequisite of paramount importance in applications

where visual quality is of the essence [27,28]. In addition, the inherent flexibility of AgNWs has opened up new possibilities in electronics [29,30]. Devices that can bend, twist, and adapt to different shapes are now possible to be used, thanks to AgNW-based electrodes [27,28,30–33]. The potential of AgNWs as a key component in the field of flexible and stretchable electronics is an exciting prospect.

However, AgNWs have their own challenges that need to be overcome to fully exploit their potential, including their vulnerability to environmental factors such as oxidation and corrosion, which can degrade their performance over time [33,34]. Electrical instability is another issue, manifested in the disruption of electrical paths under mechanical stress or exposure to electric fields, leading to erratic device behavior. The limited mechanical stability of AgNW networks is another obstacle, requiring a delicate balance between flexibility and durability.

To address these formidable challenges, researchers have undertaken their own quest—to reinforce AgNW-based electrodes with protective materials, which can act as a shield against environmental threats, ensuring the long-term stability and reliability of AgNWs [35,36]. They also play an important role in improving the mechanical robustness of AgNW networks, enabling them to endure bending, stretching, and various forms of mechanical stress.

This review paper investigates the domain of polymeric protective materials for AgNW electrodes. We examine the various polymeric materials used to strengthen AgNWs against the challenges of the real world (Figure 1). Through a detailed analysis of protective layers, we aim to reveal their effect on the electrical, optical, and mechanical properties of AgNW-based electrodes. Moreover, we survey the diverse applications of these protected electrodes in different industries and the key factors influencing the choice of protective layers suited to specific use cases. Finally, we look ahead to the future, reflecting on the difficulties that remain and the infinite opportunities that await in the domain of AgNWs and their protection. Their incorporation with protective polymeric materials marks a crucial chapter in the story of AgNWs, one that has the potential to transform the field of transparent conductive materials and redefine the possibilities of modern technology.

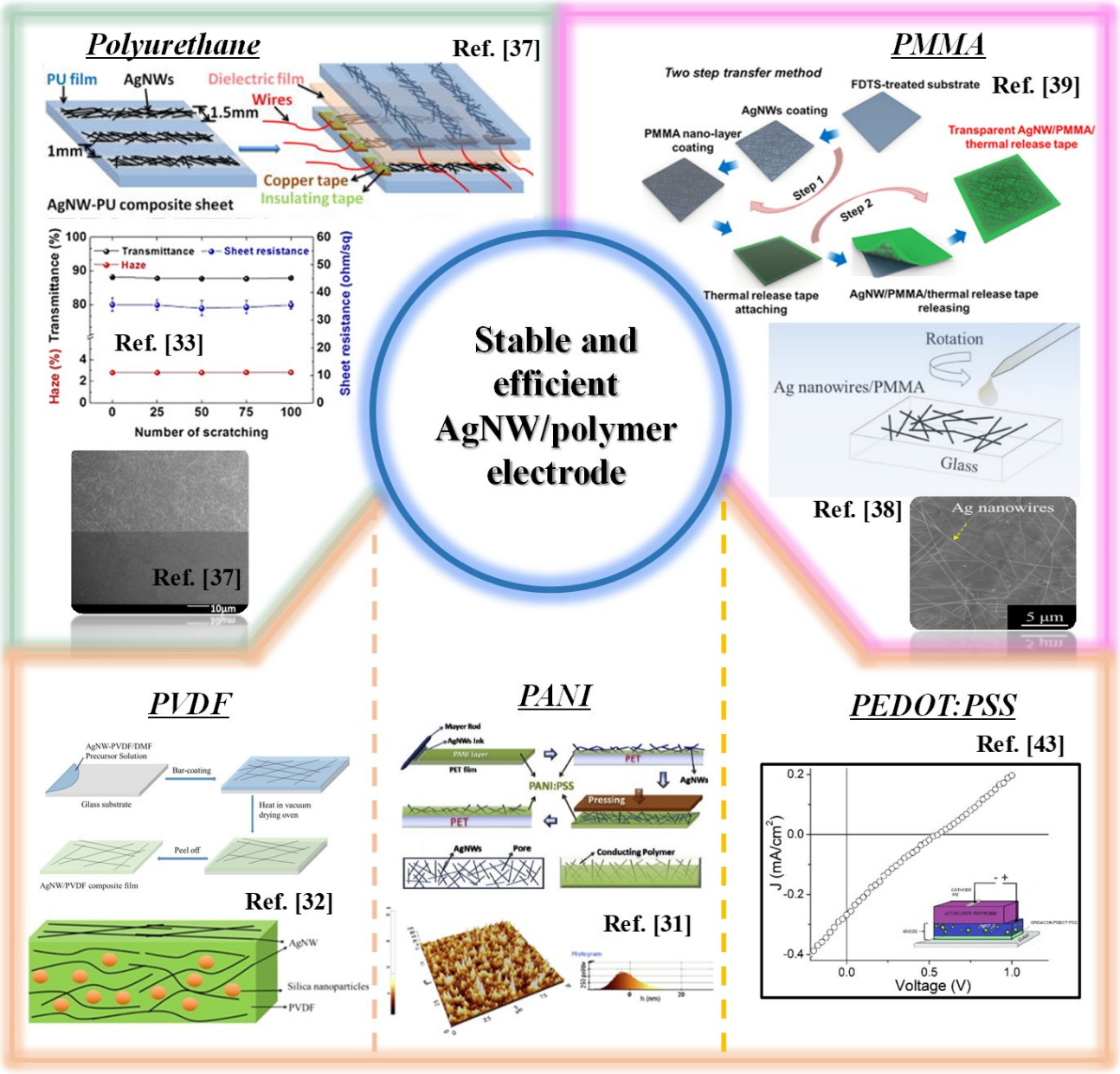

Figure 1. An overview of polymeric materials for AgNWs. Reproduced with permission from refs. [31–33,37–43].

2. Diverse Polymeric Overcoating

Polymeric materials are incorporated with AgNW electrodes using various methods, including spin coating, dip coating, spray coating, and inkjet printing [44–46]. The choice of method depends on the type of polymer, the desired thickness and uniformity of the layer, and compatibility with the substrate and the AgNW network. The details of each polymeric material for changing AgNW properties are discussed in following section. PDMS, as an elastomer, is excellent candidate for stretchable composites. There are numerous works on PDMS, and its applications are also diverse. Due to its exceptional mechanical properties, most of the works are focus on stretchable electrodes, and not on just flexible electrodes or on protection of AgNWs. Therefore, PDMS should be discussed and summarized as a separate review, which will be an interesting topic for future efforts in another review paper.

2.1. Polyurethane (PU)/AgNW

PU, a polymer comprising repeating urethane units characterized by the chemical formula NH_2-CO-O-CH_2, possesses an array of desirable attributes [33,47,48]. The strategic application of PU overcoating onto AgNW transparent electrodes yields multifaceted improvements in the performance and durability of AgNW-based devices, thereby addressing several pertinent challenges [33,47,48]. First, PU can reduce the surface roughness of AgNW electrodes by filling the gaps and smoothing the surface. This can enhance the optical transmittance and reduce the light scattering of the electrodes. Moreover, PU can improve the contact resistance between the AgNWs and the active materials of the devices by forming a uniform interface. This can increase the electrical conductivity and efficiency of the devices. Second, PU can protect AgNWs from external damages caused by mechanical deformation, chemical corrosion, or oxidation. This can increase the durability and reliability of the devices. PU can also prevent electrical shorting problems by isolating the AgNWs from each other and from the environment. This can reduce the power consumption and leakage current of the devices.

PU overcoating has shown to improve the performance and stability of AgNW-based devices without compromising their flexibility and transparency [33,47,48]. In the work by Hwang et al., a layer of PU was applied to AgNW electrodes, and various tests were conducted to assess their stability [33]. The incorporation of PU as an overcoating layer had a profound positive impact on the mechanical stability of AgNW electrodes. Even when subjected to 100 scratches (Figure 2a) and 60 wipes with isopropyl alcohol (IPA) (Figure 2b), the composite electrodes made of PU and AgNWs displayed no deterioration in their optical or electrical characteristics. Moreover, the AgNW electrodes coated with PU demonstrated remarkable reliability, maintaining their resistance even after enduring 300,000 bending cycles (Figure 2d). Additionally, PU served as a protective shield against oxidation for the Ag nanowires; even after exposure for 120 h at 85 °C, the stability of the AgNWs remained intact (Figure 2c). Notably, the application of a PU coating also enhanced the optical transmittance of the AgNW electrodes, as PU possesses a refractive index intermediate between that of air and the substrate. Furthermore, the use of UV-curable PU facilitated a straightforward and precise patterning process. This involved selectively curing the PU through a shadow mask and subsequently removing the AgNWs from the uncured regions by employing sonication in IPA.

Hu et al. presented PU/AgNW composites and used them for touch sensors (Figure 3) [37]. The AgNW electrodes coated with PU exhibited a low sheet resistance of 8 Ω/sq while maintaining a high optical transmittance of 74.6% at a wavelength of 550 nm. The integration of AgNWs into the PU layer resulted in exceptional mechanical stability, with the surface resistance remaining unchanged even after undergoing multiple scotch tape tests. Intriguingly, the PU/AgNW composite electrodes demonstrated a reduction in sheet resistance when subjected to a 60% strain. This phenomenon occurred because the external strain caused the AgNWs to establish tighter contact with each other, thereby reducing the contact resistance between individual AgNWs. Furthermore, the touch panel employing the PU/AgNW composite electrodes exhibited remarkable sensitivity to a pressing force of 30 kPa.

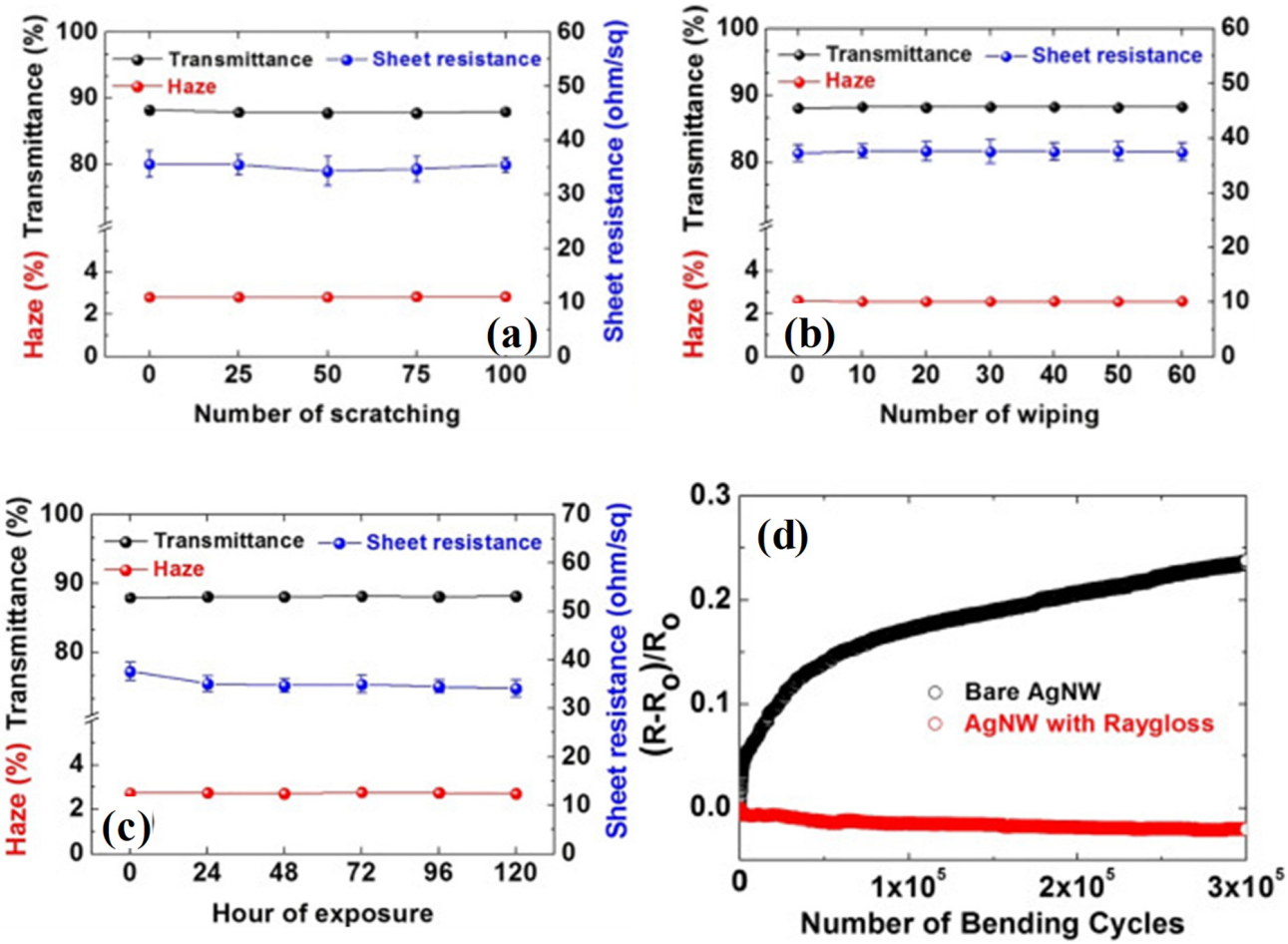

Figure 2. Change in optical transmittance, haze, and sheet resistance as a function of (**a**) the number of scratches made using a pen, (**b**) the number of wipes using IPA, (**c**) the hours of exposure to ambient air at 85 °C, and (**d**) the number of bending cycles of PU coating on the AgNW electrodes. Reproduced with permission from ref. [33].

2.2. Polymethyl Methacrylate (PMMA) on AgNW

PMMA is a polymer that consists of repeating units of methyl methacrylate, which is a chemical compound with the formula $CH_2=C(CH_3)_2$-C(O)-O-CH_2 [38,39,49,50]. PMMA has high transparency, good adhesion, low toxicity, and resistance to heat, moisture, and chemicals [38,39,49,50]. In the work by Sun et al., AgNWs with PMMA were utilized for two specific applications including a thin film heater and surface-enhanced Raman scattering (SERS) detector for biosensors [38]. The process involved dissolving PMMA in tetrahydrofuran (THF), which was then applied through spin-coating onto the AgNW electrodes (Figure 4a). The resulting PMMA/AgNW electrodes exhibited impressive characteristics, boasting a low sheet resistance of 8 Ω/sq alongside a high optical transmittance of approximately 85%. Importantly, these PMMA-coated AgNW electrodes demonstrated exceptional mechanical stability, even when subjected to bending deformations (Figure 4c,d). In the realm of thin film heating, devices employing PMMA/AgNW electrodes showcased robust joule heating performance, emphasizing their practical utility (Figure 4e). Furthermore, these PMMA/AgNW electrodes were effectively employed for the SERS detection of Rhodamine 6G (Rh6G) solutions, underscoring their versatility and efficacy in biosensing applications (Figure 4f).

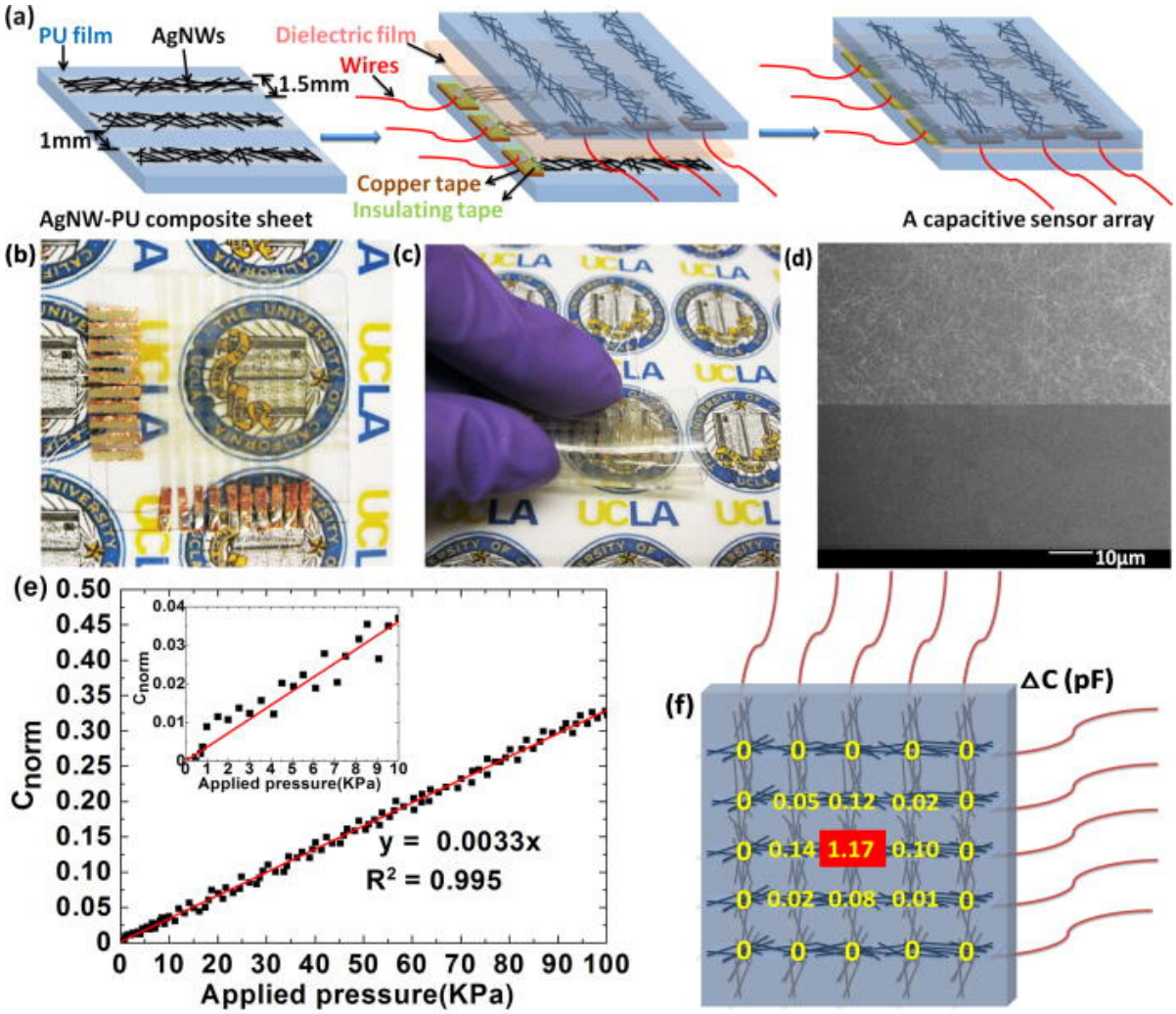

Figure 3. (**a**) A schematic illustration of the fabrication of a transparent capacitive array comprising an acrylic elastomer layer as the dielectric spacer between two transparent AgNW/PU composite electrodes. (**b**) Photograph of a pressure sensor array (10 × 10 pixels), each pixel representing a square area of 1.5 × 1.5 mm^2 separated by 1 mm from other areas. (**c**) Photograph of the sensor array bent at 180°. (**d**) SEM image of a surface area, half of which comprises patterned AgNW/PU electrodes. (**e**) Change in the capacitance, ΔC/C0, of one pixel with transversely applied pressure. (**f**) Mapping of the measured capacitance changes of pixels in the area where a pressure of 30 KPa was applied on the central pixel. Reproduced with permission from ref. [37].

In the work by Kim et al., a transparent quantum dot light-emitting diode (QLED) was demonstrated with PMMA/AgNW electrodes [39]. The PMMA/AgNW electrodes showed good chemical stability without degradation when exposed to ambient air. In addition, a low sheet resistance of 16.1 Ω/sq and a high optical transmittance of approximately ~87% were achieved (Figure 5a). The PMAM/AgNW electrodes, possessing optimized optoelectronic properties (with a figure of merit approximately equal to 3.3 × 10^{-2}), were coated with an ultrathin PMMA nanolayer (Figure 5b). These coated AgNWs were then transferred to QLEDs without causing significant damage to the adjacent active layer (Figure 5c,d). The resulting transparent QLEDs utilizing these transparent top electrodes demonstrated outstanding performance metrics (Figure 5e–g). They achieved a maximum total luminance of 27,310 cd·m^2 and a current efficiency of 45.99 cd·A^{-1}. These QLEDs, fabricated through entirely solution-based processes, create the potential for fabrication through the full roll-to-roll process.

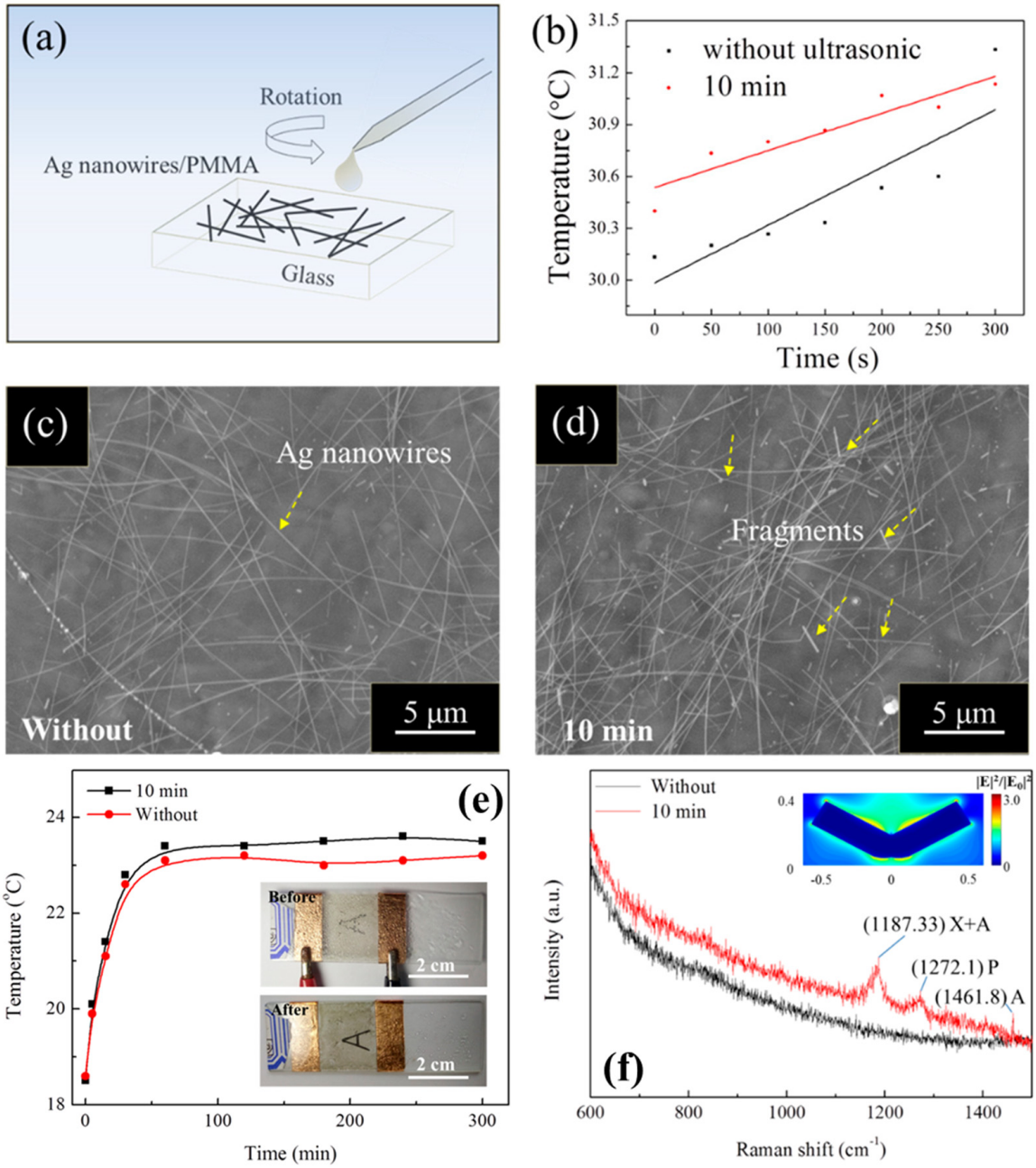

Figure 4. (**a**) A schematic of the structure of PMMA/AgNW electrodes; (**b**) temperature rise in the PMMA/AgNW electrode-based thin film heaters; (**c**,**d**) top views of AgNW electrodes after cyclic bendings without and with PMMA overcoating. Partial fragments of AgNWs are highlighted by yellow dot square frames. (**e**) Temperature increase curves of PMMA/AgNW electrode-based thin film heaters; the inset images are the optical photographs of the defogging process on the Ag-nanowire-based film heater. (**f**) SERS signals of PMMA/AgNW electrodes. Reproduced from ref. [38] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

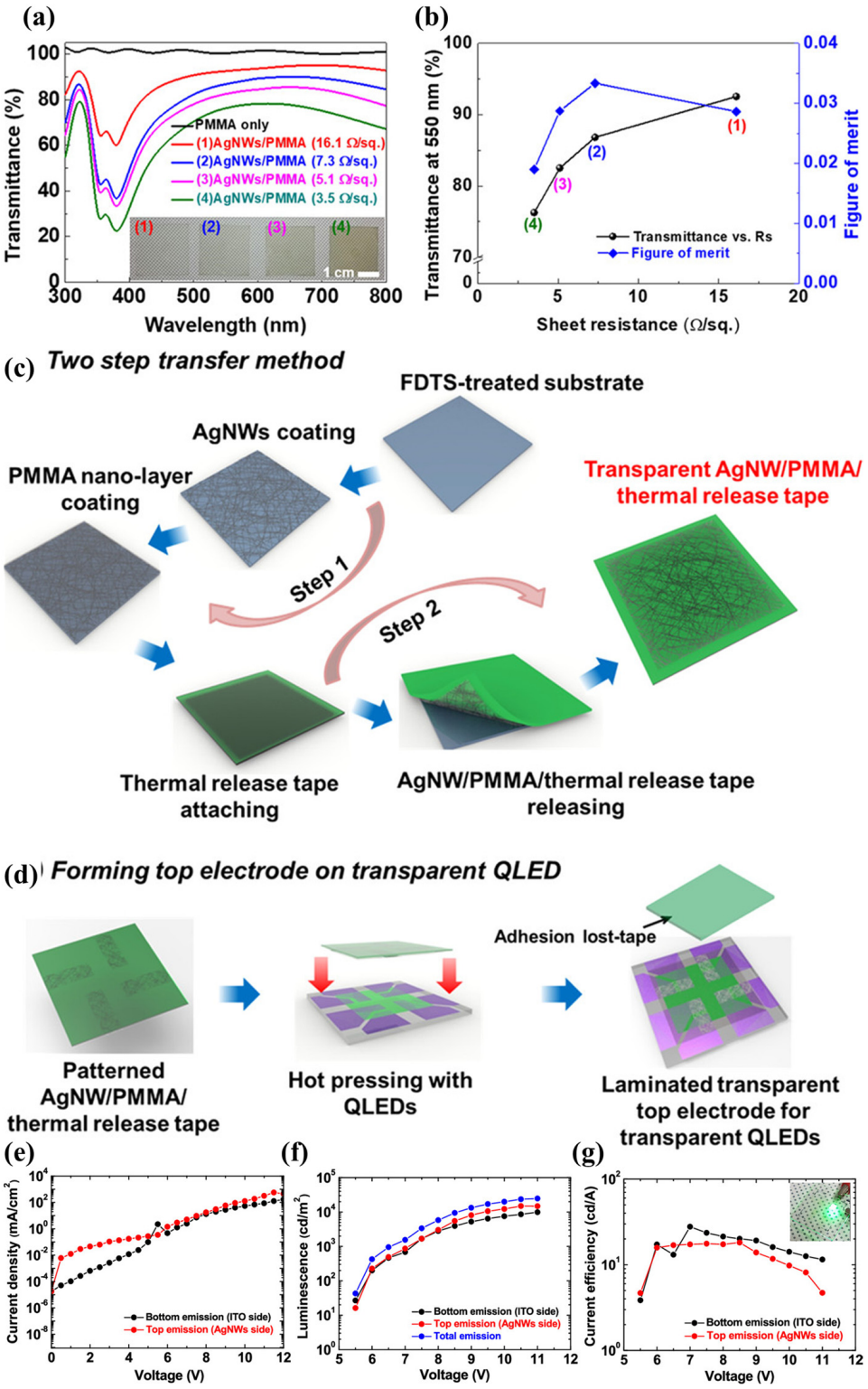

Figure 5. (**a**) UV–vis transmittance spectra of AgNW/PMMA as a function of the number of AgNW coatings (1–4 times). (**b**) Transmittance at 550 nm of (**a**) versus the sheet resistance measured for each sample with the different number of AgNW coatings. Figures of merit were calculated from the transmittance and sheet resistance values and are presented together in (**b**). The numbers in parentheses denote the number of AgNW coatings. Schematic illustrations of (**c**) the AgNW/PMMA TE fabrication process and (**d**) the applications in transparent QLEDs. Performance of the transparent QLEDs with the AgNW/PMMA top electrodes. (**e**) Current density–voltage, (**f**) luminance–voltage, and (**g**) current efficiency characteristics. Reproduced with permission from ref. [39].

2.3. Polyvinylidene Difluoride (PVDF) on AgNW

One of the methods is to use PVDF as an overcoating layer on Ag NWs [32,51–53]. PVDF is a piezoelectric polymer that has good thermal stability, chemical resistance, and mechanical properties [54,55]. Li et al. explored a highly thermally conductive film fabricated using a combination of AgNW and PVDF through a bar coating method (Figure 6a) [32]. The through-plane and in-plane thermal conductivity of the AgNW/PVDF composite film were measured at 0.31 and 1.61 W/mK, respectively, and significantly surpassed those of the pure PVDF film (Figure 6b,c). The experiment demonstrated the successful formation of thermally conductive pathways within the PVDF overcoating due to the incorporation of AgNW. Moreover, it was observed that heat preferentially transferred along these thermally conductive pathways rather than through the PVDF overcoating layer itself (Figure 6d,e).

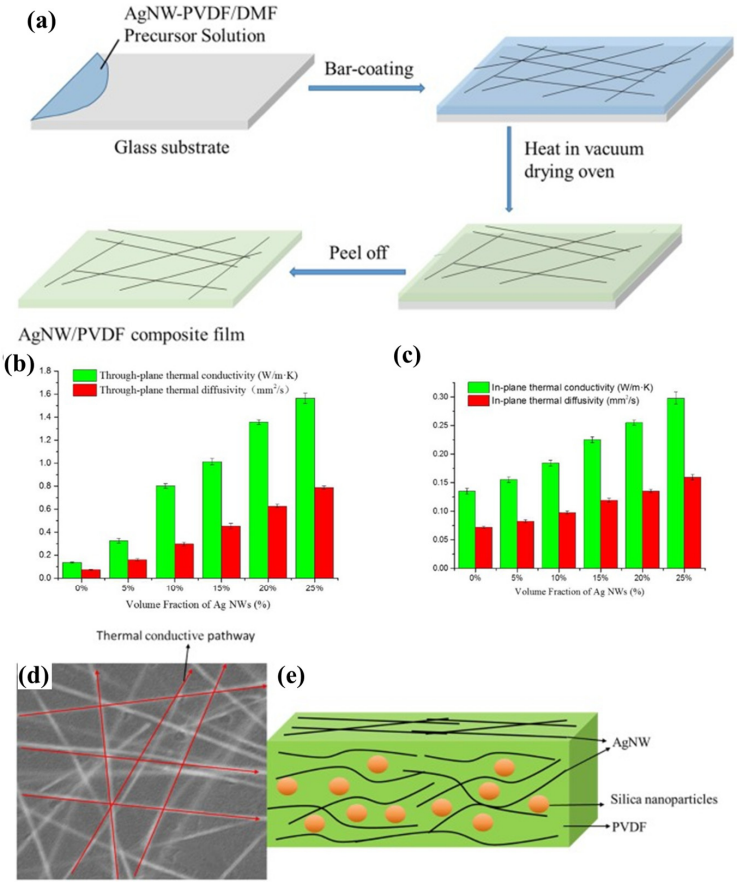

Figure 6. (**a**) Schematic illustration of the fabrication procedure of the AgNW/PVDF composite film. (**b**) Through-plane thermal conductivity and through-plane thermal diffusivity at different volume fractions. (**c**) In-plane thermal conductivity and in-plane thermal diffusivity at different volume fractions. (**d**) SEM image of the AgNW/PVDF composite film forming a thermally conductive pathway. (**e**) Dispersion principle diagram of AgNW in the AgNW/PVDF composite film. Reproduced with permission from ref. [32].

Zhang et al. developed transparent PVDF/AgNW electrodes, where AgNWs were partially embedded in PVDF layers that remarkably enhanced the electrical conductivity and adhesion of AgNWs (Figure 7a) [40]. The conductivity increased by more than two times during the formation of the PVDF/AgNW electrodes (Figure 7b,c). The adhesion of the AgNWs to the substrate was significantly enhanced, while the conductivity was persevered under multiple bending deformations (Figure 7d–f). Antioxidant ability and chemical resistance was also remarkably improved due to the excellent chemical stability of the PVDF substrate and the conductive structure of the PVDF/AgNW electrode. Therefore,

the PVDF/AgNW electrode showed a much slower increase in sheet resistance than that of bare AgNWs during the 30 days of exposure to ambient air (Figure 7g).

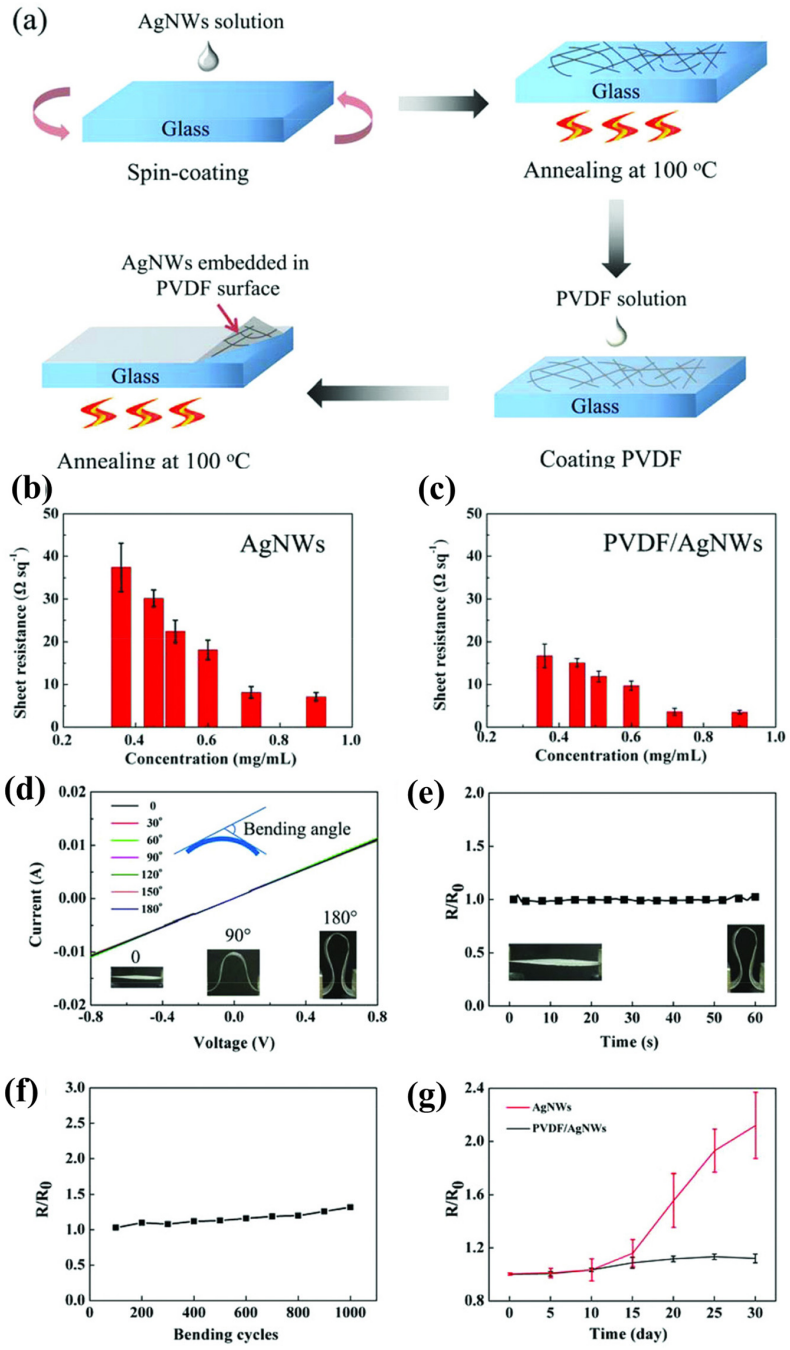

Figure 7. The fabrication and characteristics of PVDF/AgNW electrodes. (**a**) The fabrication of transparent PVDF/AgNW electrodes. (**b**) The sheet resistance of the AgNWs films decreasing with increasing concentrations. (**c**) The sheet resistance of PVDF/AgNW electrodes significantly decreasing by about half compared with that of AgNW films with the same concentrations. Flexibility tests and the long-term stability of the PVDF/AgNW electrodes are shown. The area of the electrode was 3 cm^2 (1 cm × 3 cm). (**d**) *I*–*V* curves of the PVDF/AgNW electrodes bent at different angles. The responses show that the bent electrodes did not change compared with those in the unbent state. (**e**) Dynamical resistance variation in the PVDF/AgNW electrodes with bending angles from 0° to 180° for 60 s. (**f**) The variation in the sheet resistance of the PVDF/AgNW electrodes after repeated bending from 0° to 180° for various cycles. (**g**) The long-term stability of the PVDF/AgNW electrodes after exposure to air for 30 days. Reproduced with permission from ref. [40].

2.4. Polyaniline (PANI)/AgNW

PANI is a conducting polymer renowned for its remarkable electrical and mechanical characteristics [41,56–58]. It can be produced through diverse synthesis methods, including chemical oxidation, electrochemical polymerization, and interfacial polymerization [41,56–58]. Polyaniline exhibits versatility through its existence in distinct oxidation states, namely leucoemeraldine, emeraldine, and pernigraniline, each characterized by unique colors and conductive properties. Moreover, the conductivity and stability of polyaniline can be significantly improved by doping it with acids or bases [41,56–58]. PANI can also improve the adhesion between AgNWs and substrates, and reduce the surface roughness of the electrodes.

Kumar et al. investigated AgNW/PANI transparent electrodes via layer-by-layer coating and mechanical pressing, resulting in excellent surface characteristics (Figure 8a,b) [41]. The empty spaces between the individual AgNWs were filled with a polyaniline:polystyrenesulphonate (PANI:PSS) coating, which reduced the surface roughness of the AgNWs electrode to ~6.5 nm (Figure 8c,d). The transparent composite electrode achieved a reasonable sheet resistance of 25 Ω/sq and a high transmittance of 83.5%, highlighting the enhancement of the conducting properties of AgNWs when incorporated into a composite with PANI:PSS. In the work by Fang et al., AgNW/PANI composite electrodes were fabricated to have a free-standing layer structure [31]. The composite electrode showed a high electrical conductivity (EC) of 5300 S/cm, which is higher than that of bare AgNW electrodes (Figure 8e). The conductivity of the composite electrodes was retained even after cyclic bendings.

2.5. Poly(3,4-ethylenedioxythiophene) Polystyrene Sulfonate (PEDOT:PSS)/AgNW

PEDOT:PSS enhances the performance and stability of AgNW transparent electrodes [46,59–61]. PEDOT:PSS reduces the contact resistance between individual AgNWs, thereby increasing the overall conductivity of the network [44–46]. In addition, the optical performance of AgNW electrodes can be enhanced by filling the gaps between AgNWs and reducing the light reflection [44–46]. For example, PEDOT:PSS protects AgNWs from oxidation and corrosion by forming a passivation layer that prevents contact between oxygen and water molecules from the surface of the AgNWs [46,59–61]. In addition, the thermal degradation of AgNWs is suppressed by the overcoating acting as a thermal barrier that reduces the heat transfer between AgNWs and the substrate [46,59–61]. However, PEDOT:PSS is susceptible to high temperatures or humidity, resulting in the loss of conductivity or transparency. Therefore, the optimal thickness and composition of PEDOT:PSS overcoatings should be carefully controlled to balance the trade-off between protection and performance.

In the work by He et al., PEDOT:PSS-coated AgNW transparent electrodes were used for a flexible transparent heater [42]. PEDOT:PSS overcoating provides protection via enhancing the adhesion and flexibility of AgNW transparent electrodes, as well as preventing their oxidation and corrosion. Moreover, PEDOT:PSS overcoatings also improve heating efficiency by reducing the contact resistance and noise of AgNW transparent electrodes (Figure 9a,b).

Zappia et al. used PEDOT:PSS-coated AgNW transparent electrodes for perovskite solar cells (PSCs) [43]. PSCs require transparent electrodes that have high conductivity, transparency, work function, and stability. AgNW transparent electrodes meet these requirements, but they need to be compatible with the organic materials and the deposition techniques used in PSCs. PEDOT:PSS overcoating is compatible with the PSC system in that in increases the work function and surface energy of AgNW transparent electrodes, as well as preventing their aggregation or migration during the deposition process. The power conversion efficiency was 25% (Figure 9c). Furthermore, PEDOT:PSS overcoating improves the power conversion efficiency and lifetime of PSCs by enhancing the charge extraction and transport of AgNW transparent electrodes.

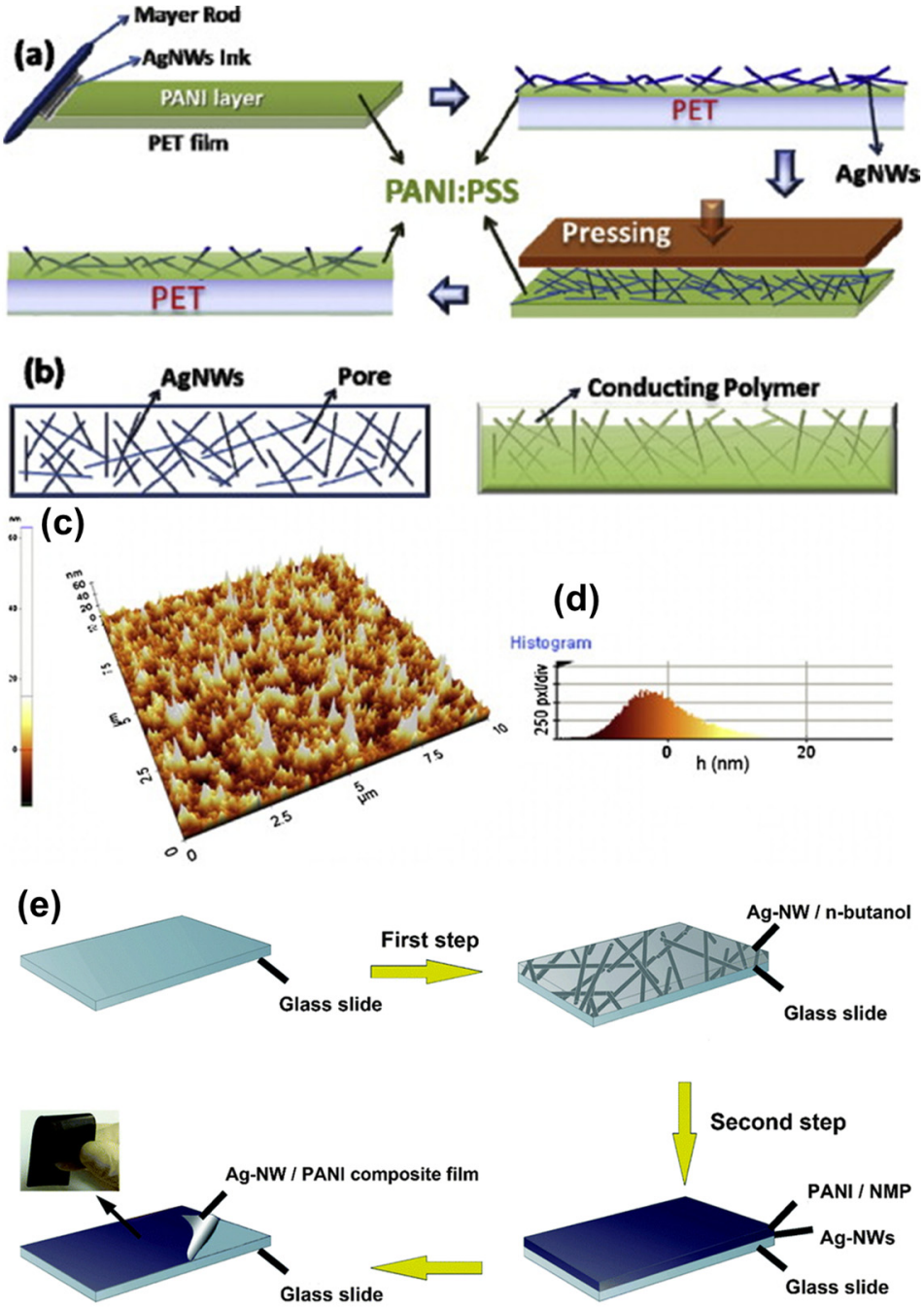

Figure 8. (**a**) Schematic representation of the preparation of the AgNW/PANI:PSS composite transparent conducting film via layer-by-layer coating. (**b**) Filling properties of the conducting film with and without PANI:PSS. (**c**) The AFM image and (**d**) height distribution of the AgNW/PANI transparent electrode after pressing. Reproduced with permission from ref. [41]. (**e**) Schematic showing the preparation of the layer-structured AgNW/PANI composite film. First step: an AgNW dispersion was cast on a glass slide to form a deposition layer; second step: a PANI solution was cast over the AgNW layer; third step: thermal evaporation was conducted and the AgNW/PANI composite film was peeled off from the glass substrate. Reproduced with permission from ref. [31].

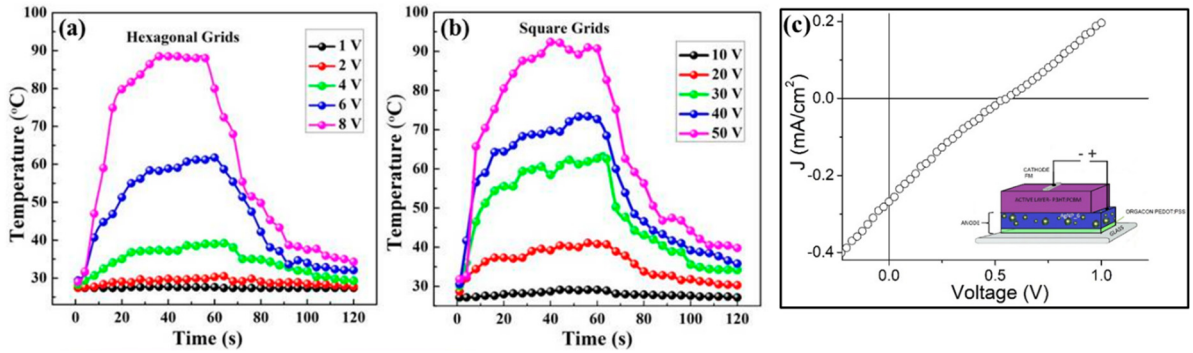

Figure 9. Evolution of generated temperature of the AgNW/PEDOT:PSS composite film with a (**a**) hexagonal pattern at varied voltages from 1 to 8 V, and (**b**) with a square pattern at varied voltages from 10 to 50 V [42]. Reproduced from ref. [42] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License. (**c**) J–V curve for the solar cell using AgNW/PEDOT:PSS composites, the configuration of which is sketched in the inset [43]. Reproduced from ref. [43] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

2.6. Polyimide (PI)/AgNW

Another important polymer material for the protection of AgNW is PI as it has high thermal and mechanical stabilities [62–64]. For example, Ghosh et al. presented a transparent conductor (TC) that consists of AgNWs embedded in a thin PI film (5 μm thick) [62]. The PI/AgNW TC showed outstanding optical transparency in the visible range, exceeding that of indium tin oxide (ITO) with more than 90% transmission. At the same time, it has a similar electrical sheet resistance of only 15 ohms per square. The PI film had two functions; it protected the AgNWs from environmental factors such as oxygen and moisture, and it supported the AgNW network mechanically. The TC showed excellent mechanical stability under bending with a radius of just 1 mm without any problems of adhesion. Moreover, this TC reduces the initial roughness of the AgNWs by about 15 times. In the work by Huang et al., PI/AgNW was also explored for a thin film heater [63]. The resistance of the PI/AgNW electrode under bending was excellent, showing no significant change even after 1000 outer bends. This amazing performance was due to the effective embedding of the AgNW network within the transparent PI film. The surface of PI/AgNW was very smooth (Rrms < 1 nm), and showed the electrode's resistance to oxidation and moisture, making it more durable. Wang et al. also presented PI/AgNW electrodes, wiere AgNWs were partially embedded in PI films [64]. The PI/AgNW electrodes exhibited exceptional performance across various parameters, including a low sheet resistance of ~12.7 Ω/sq, high optical transmittance of ~86.3%, and low RMS value of ~0.32 nm. Furthermore, they showed excellent stability when subjected to thermal, mechanical, and solution-based conditions.

3. Challenges and Future Perspectives

Polymeric materials applied to AgNW electrodes face several challenges and future prospects. One of the most significant challenges is ensuring scalability for mass production. To achieve this, researchers are optimizing deposition techniques such as roll-to-roll coating and inkjet printing to deliver uniform polymeric layers efficiently. The integration of these layers into emerging technologies such as foldable displays poses unique challenges, calling for materials that seamlessly combine robustness with flexibility. Ongoing research investigates advanced organic–inorganic composites and innovative manufacturing methods to address this challenge.

Long-term stability and reliability are paramount concerns, driving the establishment of standardized testing protocols, accelerated aging studies, and predictive models to ensure durability against environmental factors. Additionally, in an era prioritizing environmental sustainability, the assessment of the ecological footprint of polymeric materials is becoming

indispensable. Researchers are spurring research into eco-friendly materials, sustainable fabrication techniques, and strategies for recycling and reusing AgNW electrodes with polymeric materials to minimize waste and environmental impacts.

4. Summary

AgNWs are susceptible to environmental factors such as oxidation and corrosion, which limit their long-term performance. Furthermore, electrical instability can manifest when they are subjected to mechanical stress and electric fields, resulting in unpredictable device behavior. The delicate balance between flexibility and durability also introduces a significant hurdle in the realization of robust AgNW networks.

To overcome these challenges, protective layers have emerged as indispensable preservers of AgNW-based electrodes. These layers serve as shields against environmental threats, ensuring the durability and stability of AgNWs even in the harshest conditions. Simultaneously, they fortify the mechanical integrity of AgNW networks, enabling them to withstand the rigors of flexibility and mechanical stress.

This review paper systematically examines various polymeric materials and their influence on the electrical, optical, and mechanical properties of AgNW-based electrodes. Table 1 provides the overview of various polymeric materials for AgNW electrodes. The paper also reviews the applications of these protected electrodes in different fields and demonstrates their adaptability and importance in various domains. Moreover, the paper clarifies the key factors that determine the choice of protective layers according to specific application needs.

Table 1. Summary of various polymeric materials for AgNW electrodes.

Polymeric Materials	Conductivity	Optical Transmittance	Mechanical Stability	Chemical Stability	Applications	Refs.
PU	~50 Ω/sq	~88%	Excellent	Excellent	Transparent electrode	[33]
	~8 Ω/sq	~74.6%	Excellent	N/A	Touch panel	[37]
PMMA	~8 Ω/sq	~85%	Excellent	N/A	Thin film heater/SERS detector	[38]
	~16.1 Ω/sq	~87%	Excellent	Excellent	QLED	[39]
PVDF	~8 Ω/sq	N/A	N/A	Excellent	Thermal conduction	[32]
	~5 Ω/sq	~73%	Excellent	Excellent	Touch sensor	[40]
PANI	~25 Ω/sq	~83.5%	N/A	Excellent	Solar cells	[41]
	~5300 S/cm	N/A	Excellent	N/A	EMI shielding	[31]
PEDOT:PSS	~2.3 Ω/sq	~70.5%	N/A	Excellent	Thin film heater	[42]
	~12 Ω/sq	~80%	N/A	N/A	Solar cells	[43]

As transparent conductive materials are advancing rapidly, the incorporation of protective materials is an essential step to enhance the performance and durability of AgNWs. These materials and their protection methods offer great potential and opportunities for various applications. However, there are still challenges and open questions that need to be addressed, and the research on AgNWs and their protection is ongoing, driven by the continuous pursuit of innovation and the exploration of the diverse possibilities in the dynamic field of AgNWs and their protection.

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