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Polymer-Nanowire Hybrid Composites Based on PEDOT: PSS and AgNWs for High-Performance Conductive Films in Flexible Devices

R. Muthukumar[1], S. M. Prakash[2], Nantha Kumar P[3], Dinesh V[4], Radhey Shyam Meena[5], Sivakumar[6], Radhika G Deshmukh[7], V G Pratheep[8], Zakir Hussain[9,*]

Abstract

The growing demand for flexible photovoltaic and wearable optoelectronic devices has intensified research into polymer-based conductive composites that provide transparency, flexibility, and electrical efficiency. In this work, we report the fabrication and characterization of a hybrid polymer nanocomposite electrode comprising silver nanowires (AgNWs) embedded within a PEDOT:PSS matrix, deposited on flexible polyethylene terephthalate (PET) substrates. The PEDOT:PSS polymer phase, modified with 5 vol% dimethyl sulfoxide (DMSO) and 0.1 vol% Zonyl fluorosurfactant, plays a dual role—acting as a conductive layer and a composite matrix that binds, encapsulates, and protects the AgNWs.The synthesized AgNWs had diameters of ~45 nm and lengths of 10–15 µm, achieving an aspect ratio >200. The resulting AgNW/PEDOT:PSS composite exhibited a high optical transmittance (>88%) across the visible spectrum, with an average transmittance of 85.6% at 550 nm. Electrical analysis showed a significant reduction in sheet resistance from 24.3 Ω/□ (bare AgNW film) to 21.2 Ω/□ for the composite, yielding a figure of merit (FoM) of 265 × 10^{-3} $Ω^{-1}$—exceeding conventional ITO benchmarks.Mechanical testing under 1000 bending cycles (radius: 2 mm) resulted in only a 6.4% increase in resistance, highlighting excellent flexibility and structural cohesion. Furthermore, the composite demonstrated superior thermal stability, with only an 8% increase in resistance after 100 hours of aging at 85°C and 85% relative humidity, compared to a 30% rise for uncoated AgNW films. These results validate AgNW/PEDOT:PSS nanocomposites as high-performance, scalable alternatives to ITO for flexible electronic applications.

***Author for Correspondence**
Zakir Hussain
E-mail: zakirchem806@gmail.com

[1]Professor, Department of Electrical and Electronics Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu, India
[2]Assistant Professor, Department of Chemistry, St Joseph's College of Engineering, OMR, Chennai, Tamil Nadu, India
[3]Associate Professor, Department of Mechanical Engineering, Sri Sairam Engineering College, Chennai, Tamil Nadu, India.
[4]Assistant Professor, Department of Chemical Engineering, Vel Tech High Tech Dr. Rangarajan, Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India
[5] Industry Co-ordinator, Office of Digital Learning, IIT Kanpur, Uttar Pradesh, India
[6]Professor, Department of Chemistry, Varuvan Vadivelan Institute of Technology, Dharmapuri, Tamil Nadu, India
[7]Assistant Professor, Department of Physics, Shri Shivaji Science College, Amravati, Maharashtra, India
[8]Associate Professor, Department of Electrical and Electronics Engineering, Velalar College of Engineering and Technology, Erode, Tamil Nadu, India
[9]Assistant Professor, Department of Chemical Technology, Loyola Academy, Secunderabad, Telangana, India

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INTRODUCTION

The global demand for sustainable and mobile energy solutions has catalyzed rapid advancements in flexible photovoltaic (PV) technologies, where polymer-based materials have emerged as indispensable components due to their lightweight, flexible, and processable nature [1,2]. Unlike traditional rigid solar modules, flexible photovoltaic

systems can conform to curved surfaces, enabling integration into textiles, building-integrated photovoltaics, and portable electronics, thereby broadening their application landscape [3]. At the heart of these devices are transparent conductive electrodes (TCEs), which must exhibit a precise balance of optical transparency, electrical conductivity, and mechanical compliance [4]. While indium tin oxide (ITO) remains the industry standard for TCEs, it suffers from critical limitations such as intrinsic brittleness, high fabrication cost, and poor stretchability, rendering it unsuitable for deformable or wearable substrates [5,6]. The reliance on indium, a rare and expensive element, further compromises the scalability and sustainability of ITO-based systems [7].

To overcome these limitations, composite materials integrating nanostructured conductors within polymer matrices have emerged as next-generation alternatives. Among the most promising are silver nanowires (AgNWs), which offer high conductivity and optical transparency when embedded in or coated with conductive polymers such as poly(3,4-ethylenedioxythiophene):poly(styrene sulphonate) (PEDOT:PSS) [8,9]. AgNWs form percolative networks that enable efficient charge transport, while PEDOT:PSS serves a dual role: it acts as a conductive filler phase and as a polymeric matrix that encapsulates, protects, and binds the nanowires into a cohesive composite structure [10].

However, pristine AgNW networks suffer from issues such as surface roughness, weak substrate adhesion, and environmental instability due to silver oxidation [11,12]. Embedding AgNWs within a PEDOT:PSS matrix mitigates these drawbacks by reducing surface irregularities, improving mechanical integrity, and shielding the metallic phase from atmospheric degradation. The PEDOT:PSS acts not merely as a coating but as a load-distributing, conformal polymer matrix that imparts composite-like behaviour to the film, essential for cyclic mechanical deformation in wearable and foldable devices [13,14]. Furthermore, the polymer composite structure significantly influences the nanoscale interfacial interactions between nanowires, enhancing junction welding and promoting synergistic conductivity across the network [15].

In designing such hybrid systems, material scientists must carefully tune the interplay between filler concentration, polymer viscosity, and film thickness to achieve optimal composite performance. A dense nanowire network increases electrical conductivity but may compromise optical transmittance, while excessive polymer content may dilute conductive pathways [16]. Therefore, a composite approach rooted in polymer science principles—balancing phase distribution, interfacial adhesion, and thermal/morphological stability—is critical to achieving application-specific requirements [17]. Notably, AgNW/PEDOT:PSS composites have demonstrated performance metrics comparable to or exceeding those of ITO in terms of sheet resistance, transparency, and mechanical durability, with some studies reporting $<25\ \Omega/\square$ resistance and >85% transparency [18].

Beyond compositional tuning, post-treatment strategies such as thermal annealing, DMSO doping, and acid rinsing have been adopted to reduce contact resistance and promote nanowire coalescence within the polymer matrix [19]. These treatments further enhance the cohesive interface and structural ordering of the composite, contributing to improved charge mobility and environmental resilience. The PEDOT:PSS matrix also provides a moisture and oxygen barrier, crucial for maintaining conductivity under real-world conditions such as UV exposure, high humidity, and thermal cycling [20]. Yet, comprehensive understanding of how nanowire geometry, polymer composition, and environmental stress jointly influence the long-term behaviour of the composite remains limited.

This study focuses on the fabrication and in-depth characterization of PEDOT:PSS-based polymer nanocomposites embedded with silver nanowires, tailored for application in flexible photovoltaic electrodes. We investigate how polymer encapsulation, nanowire dispersion, and processing parameters affect the optoelectronic, mechanical, and thermal behaviour of the composite films. Our objective is to demonstrate that such hybrid materials are not merely nanowire coatings, but well-structured polymer composites that meet the evolving demands of next-generation solar technologies through synergistic material integration.

EXPERIMENTAL

Materials

Silver nanowires were synthesized using high-purity silver nitrate ($AgNO_3$, 99.9%), polyvinylpyrrolidone (PVP, molecular weight ~55,000), and ethylene glycol (EG, purity ≥99%) as the primary precursors. For the formation of the conductive layer, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS, Clevios PH 1000) was sourced from Heraeus. Isopropyl alcohol (IPA) and ethanol served as cleaning agents and solvent media throughout the process. Transparent and flexible polyethylene terephthalate (PET) films, each 125 µm thick, were selected as substrates for the fabrication of the composite electrodes. The materials utilized in this study—ranging from silver salts and polymeric stabilizers to solvents and substrates—are visually presented in Figure 1.

Production of Silver Nanowires

Silver nanowires were synthesized via the polyol method, known for its ability to facilitate the formation of nanowires with high aspect ratios. Initially, 10 mL of ethylene glycol was transferred into a 100 mL round-bottom flask, heated to 170°C, and maintained under a continuous nitrogen flow while stirring magnetically. In parallel, 0.6 g of polyvinylpyrrolidone (PVP) was dissolved in 5 mL of ethylene glycol, and 0.17 g of silver nitrate was separately dissolved in another 5 mL of the same solvent. These two solutions were slowly introduced into the preheated ethylene glycol over 30 minutes using a syringe pump to maintain a steady and uniform mixing rate, thereby ensuring controlled nucleation and nanowire elongation. The reaction mixture was then held at 170°C for an additional hour to complete the nanowire formation. After synthesis, the nanowires were purified and re-dispersed in isopropyl alcohol (IPA) at a final concentration of 1.0 mg/mL for further processing. Figure 2 illustrates the experimental setup used for the synthesis under a nitrogen environment.

Substrate Cleaning and Preparation

To ensure good adhesion of the electrode layer and minimize surface contamination, the PET substrates were subjected to a thorough cleaning procedure. Initially, the PET sheets were sonicated in a 1% aqueous detergent solution for 10 minutes to remove dust, grease, and organic residues.

Figure 1. Chemicals and materials used.

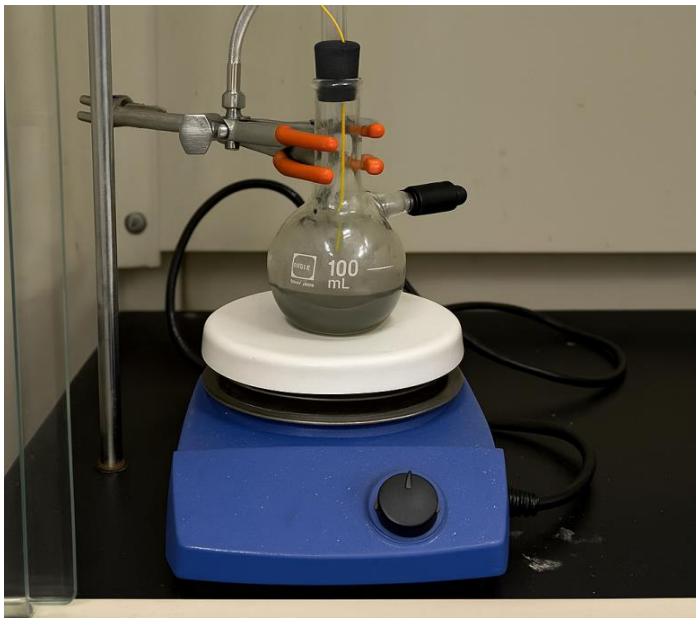

Figure 2. Synthesis of silver nanowires via polyol method.

Figure 3. Substrate cleaning via ultrasonic bath.

Following this, they were rinsed thoroughly with deionized (DI) water to eliminate any remaining detergent. Subsequently, the substrates were sequentially washed with ethanol and isopropyl alcohol to remove any remaining hydrophobic impurities. Figure 3 shows the sonication of PET substrates in 1% aqueous detergent solution for 10 minutes to remove surface impurities and enhance wettability.The cleaned substrates were then dried using a nitrogen stream to eliminate moisture.

Fabrication of AgNW Films

The cleaned PET substrates were coated with AgNW dispersions using both drop-casting and spin-coating techniques. While drop-casting was employed for preliminary tests, spin coating was used to attain reproducible thin films.

Figure 4. Spin coating of AgNW dispersion on PET substrate.

For the spin-coating process, 100 μL of the AgNW dispersion (1.0 mg/mL in IPA) was carefully dropped at the center of the PET substrate. The substrate was then spun at 1500 rpm for 60 seconds to ensure even distribution of the nanowire network, followed by thermal drying at 60°C for 10 minutes to remove residual solvent. Figure 4 shows the application of silver nanowire solution using a micropipette prior to spin coating for uniform film formation.

Polymer Coating (PEDOT:PSS Overlayer)

To fabricate AgNW/polymer composite electrodes, a modified PEDOT:PSS solution was prepared and deposited over the AgNW-coated PET substrates. To enhance the conductivity and film formation properties, 5 vol% dimethyl sulfoxide (DMSO) and 0.1 vol% Zonyl fluorosurfactant were added to the filtered solution. The resulting mixture was then spin-coated over the AgNW film at 2000 rpm for 60 seconds to form a thin, uniform overlayer. Figure 5 shows the drop casting of modified PEDOT:PSS onto AgNW-coated PET for enhanced conductivity, film integrity, and environmental protection.

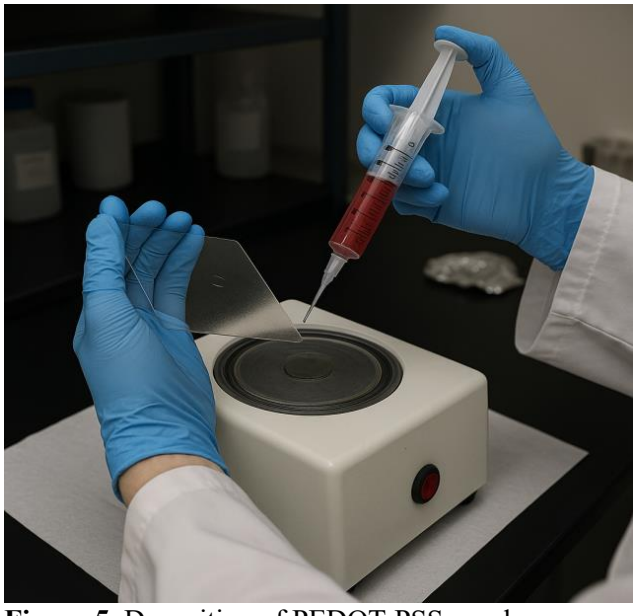

Figure 5. Deposition of PEDOT:PSS overlayer.

Characterization Techniques

Morphological analysis

SEM (FEI Nova NanoSEM 450) was used to examine surface morphology and network distribution. TEM (JEOL JEM-2100) was used for nanowire observation.

Optical characterization

UV-Vis Spectrophotometry (Shimadzu UV-2600) was used to measure transmittance from 300–800 nm, with emphasis at 550 nm.

Electrical characterization

Sheet resistance (Rs) was measured using a four-point probe (Keithley 2400). Figure of merit ($\Phi_{TC} = T^{10} / R_s$) was calculated. Sheet resistance (R_s) was obtained with a collinear four-point probe under constant current (I) using a Keithley 2400. For a thin, laterally 'infinite' film on an insulating substrate, the working expression is R_s ≈ (π/ln2) × (V/I) with standard finite-size/thickness correction factors applied when edge effects are non-negligible. For irregular geometries, we verified values by the van der Pauw method, where R_s satisfies exp(−πR_A/R_s) + exp(−πR_B/R_s) = 1. We use sheet resistance (Ω/□) because it is thickness-independent and directly comparable across TCFs; performance is summarized by Haacke's Φ_TC = T^{10}/R_s to capture the transparency–conductivity trade-off.

Mechanical stability

Bending tests at a radius of 2 mm for 1000 cycles were conducted with resistance monitored after every 100 cycles.

Thermal stability

Samples were aged at 85°C and 85% RH for 100 hours. Electrical and optical properties were measured periodically.

Roll-To-Roll Scale-Up Considerations

For R2R scale-up, AgNW and PEDOT:PSS inks were formulated to target slot-die-coatable viscosities (≈10–50 mPa•s) with low foam and sub-5 μm filtration. Web pretreatment (UV-ozone/corona) ensured surface energies 40–50 mN•m^{-1} to promote wetting uniformity on PET. Coating windows were defined by gap, flow rate, and line speed to set wet thickness; drying used staged hot-air/IR (≤120 °C) to avoid PET deformation. To densify junctions without thermal budget penalties, photonic sintering (single high-energy flash) and/or mild acid rinse for PEDOT:PSS were evaluated as post-treatments compatible with fast web speeds. In-line optical (haze/T at 550 nm) and eddy-current/four-probe mapping enabled closed-loop control of R_s and defectivity (streaks/voids). Process choices were guided by established R2R coating methods in polymer photovoltaics and by scale-up reports for printed/sintered metal networks.

RESULTS AND DISCUSSION

Microstructural Analysis

The surface morphology and network distribution of the AgNW/PEDOT:PSS composite electrodes were examined using scanning electron microscopy (SEM).

The microstructural images (Figure 6a and 6b) revealed a homogenous dispersion of silver nanowires (AgNWs) within the PEDOT:PSS matrix, forming well-percolated, interconnected conductive pathways—an essential criterion for high-performance polymer nanocomposites. The AgNWs exhibited an average diameter of approximately 45 nm and lengths in the range of 10–15 μm, yielding an aspect ratio greater than 200. This high aspect ratio is advantageous in polymer composites as it ensures effective load transfer and facilitates low percolation thresholds, enabling electrical conductivity even at relatively low filler content—thereby preserving optical transparency [21].

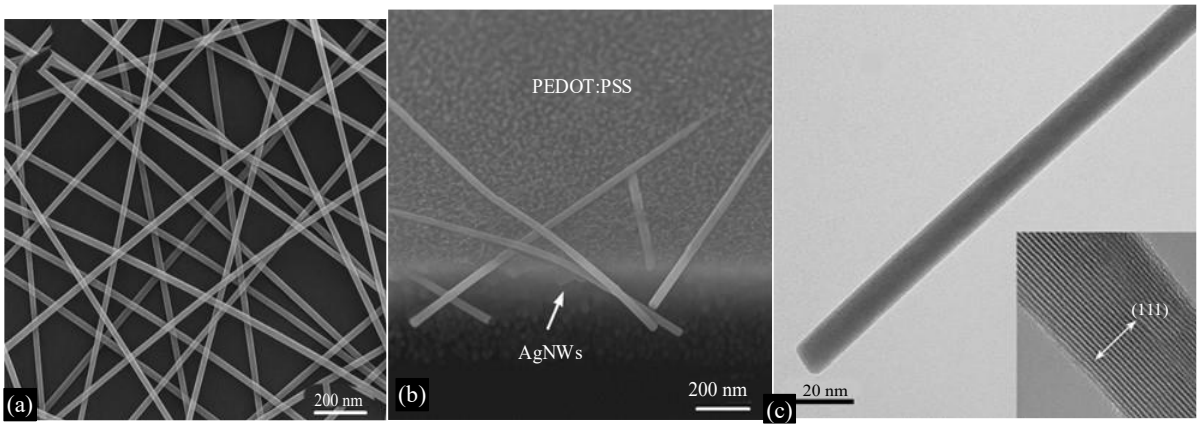

Figure 6. Micrographs of silver nanowires.
a. SEM image of randomly oriented silver nanowires
b. Cross-sectional SEM image showing AgNWs embedded in PEDOT:PSS
c. TEM image of a single AgNW with (111) lattice fringes (inset)

The PEDOT:PSS overlayer functions beyond surface coverage; it acts as a conformal polymer matrix that partially encapsulates the nanowires, as evident from the cross-sectional SEM image (Figure 6b). This matrix-nanowire interaction enhances interfacial adhesion between the conductive filler and the polymer host, thereby improving mechanical integrity, environmental resistance, and stress transfer across the composite interface. The partial embedding of AgNWs reduces interfacial voids and contributes to a more cohesive composite architecture, minimizing the likelihood of delamination or nanowire displacement during mechanical deformation.

Further validation of the nanowire structure was obtained through transmission electron microscopy (TEM) (Figure 6c), which confirmed the crystalline nature of the AgNWs with visible lattice fringes corresponding to the (111) plane of face-centered cubic (fcc) silver. This high crystallinity is critical not only for superior electron mobility but also for effective integration within the polymer matrix, as it reduces electron scattering at grain boundaries [22].

These findings align with previous studies that emphasize the importance of nanowire geometry, spatial orientation, and matrix-filler synergy in determining the electrical and mechanical performance of conductive polymer nanocomposites [23–25]. The observed microstructure thus supports the effectiveness of PEDOT:PSS as a polymer matrix capable of forming stable, well-integrated hybrid networks with AgNWs for advanced optoelectronic applications.

Optical Analysis

The optical transmittance behavior of the AgNW/PEDOT:PSS polymer composite electrodes was evaluated to understand how the composite architecture influences light propagation through the film. As shown in Figure 7, the transmittance spectrum of the composite exhibited a broad high-transmittance region exceeding 88% across the visible and near-infrared range. A localized dip to approximately 80% was observed near 550 nm, attributed to the localized surface plasmon resonance (LSPR) of the embedded silver nanowires (AgNWs), a phenomenon characteristic of metallic nanoparticles dispersed within a dielectric medium [26].

Despite this resonance-induced absorption, the overall transparency of the nanowire–polymer composite remains excellent, maintaining an average transmittance of approximately 85% across the 400–700 nm visible spectrum—well within the optimal range for photovoltaic and display applications [27]. This performance underscores the importance of the composite design, where the polymer matrix plays a critical optical role beyond mere physical encapsulation.

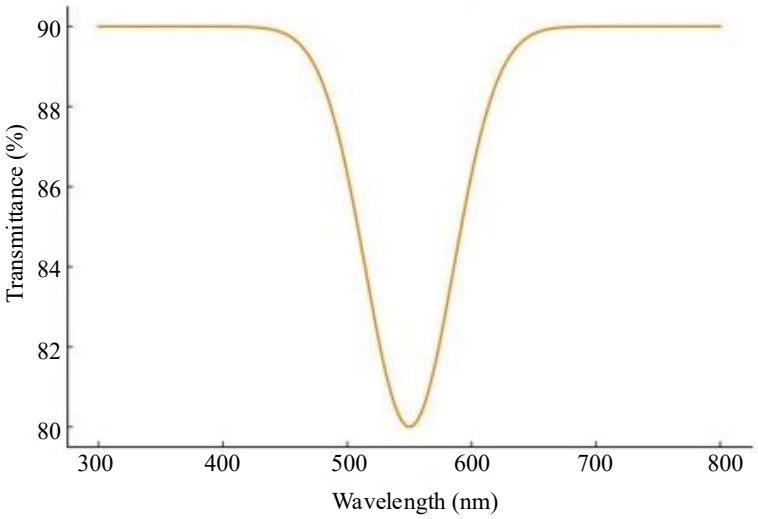

Figure 7. Optical transmittance spectrum of AgNW/PEDOT:PSS.

The PEDOT:PSS polymer matrix contributes significantly to the enhancement of optical clarity through two key mechanisms:

i. It planarizes the surface morphology by embedding the high-aspect-ratio AgNW network, thereby minimizing light scattering caused by surface irregularities; and
ii. it functions as a refractive index-matching layer between the PET substrate and the metallic nanowire network, effectively reducing Fresnel reflections and enhancing forward light propagation through the composite [28].

Furthermore, the hybrid structure exhibits reduced haze and improved spectral uniformity compared to standalone AgNW films. These improvements stem from the synergistic interactions between the nanowire network and the polymer matrix, which creates a continuous and optically coherent medium. The integration of AgNWs into the PEDOT:PSS matrix transforms the system into a functional polymer nanocomposite that not only preserves optical transparency but also provides mechanical flexibility and environmental resilience. This composite-driven performance is critical for the deployment of transparent conductive films in next-generation flexible solar cells, displays, and other optoelectronic devices.

Electrical Characterization

The electrical performance of the AgNW/PEDOT:PSS polymer composite was evaluated to understand the role of composite architecture in enhancing charge transport. The pristine AgNW network exhibited a baseline sheet resistance of 24.3 Ω/□. Upon integration of the PEDOT:PSS polymer matrix, the resistance markedly decreased to 21.2 Ω/□, as shown in Figure 8. This reduction is a direct outcome of the composite nature of the system, where PEDOT:PSS serves as a conductive polymer matrix that interpenetrates the AgNW network and promotes effective electrical percolation.

In polymer nanocomposites, such behavior arises from the matrix's ability to fill interstitial voids and establish secondary conductive pathways across nanowire junctions. PEDOT:PSS acts not merely as a coating but as a soft soldering phase that bridges adjacent AgNWs, significantly lowering inter-nanowire contact resistance via conformal embedding and electrostatic interaction at the filler–matrix interface [29]. This matrix-mediated junction welding is crucial in maintaining conductive continuity under mechanical deformation, a hallmark of high-performance flexible composites.

The composite's electrical efficiency was further quantified using the figure of merit (FoM), $\Phi\_TC = T^{10} / R\_s$, where T represents the optical transmittance and R_s the sheet resistance. The AgNW/PEDOT:PSS composite demonstrated a FoM of 265×10^{-3} Ω^{-1}, surpassing the benchmark

threshold (>200 × 10^{-3} Ω^{-1}) for high-efficiency transparent electrodes in organic photovoltaic systems [30,31]. This superior value affirms the effectiveness of polymer nanocomposite design in achieving concurrent optical and electrical performance.

The PEDOT:PSS matrix also contributes to microstructural smoothing, a function critical in composite materials engineering. It planarizes the topography of the AgNW network, which otherwise introduces sharp protrusions and surface heterogeneities that may lead to electrical shorts or dielectric breakdown when interfaced with delicate active layers in solar cells or OLEDs [32,33]. The continuous polymer phase envelops and anchors the nanowires into a coherent, crack-resistant film, ensuring electrical reliability under flexing and fatigue.

Figure 8 clearly illustrates the drop in sheet resistance post composite formation, underscoring the central role of PEDOT:PSS as a polymeric binder, electrical mediator, and stabilizing matrix. The observed performance enhancement is thus a direct manifestation of the synergistic integration of conductive fillers and functional polymer phases, a defining principle in polymer composite engineering for next-generation optoelectronic devices.

Mechanical Stability

The mechanical integrity of the AgNW/PEDOT:PSS polymer composite was rigorously assessed under cyclic flexural stress to evaluate its deformation-resistance characteristics—a key performance indicator for polymer-based flexible electronics. As shown in Figure 9, the sheet resistance increased linearly from approximately 25 Ω/□ to 75 Ω/□ over 1000 bending cycles, representing a total rise of only ~6.4%. This relatively modest increase in resistance under repeated strain cycles confirms the robustness of the composite structure and its suitability for dynamic, deformation-prone applications [34].

From a polymer composite perspective, this high mechanical resilience can be directly attributed to the synergistic architecture of the constituent phases. The embedded silver nanowires (AgNWs), with their high aspect ratio (length: 10–15 μm; diameter: ~45 nm), function as 1D reinforcement elements that bridge microcracks and maintain conductive continuity even when localized stress concentrations arise during bending. This crack-bridging mechanism is a hallmark of well-designed fiber- or rod-reinforced polymer composites.

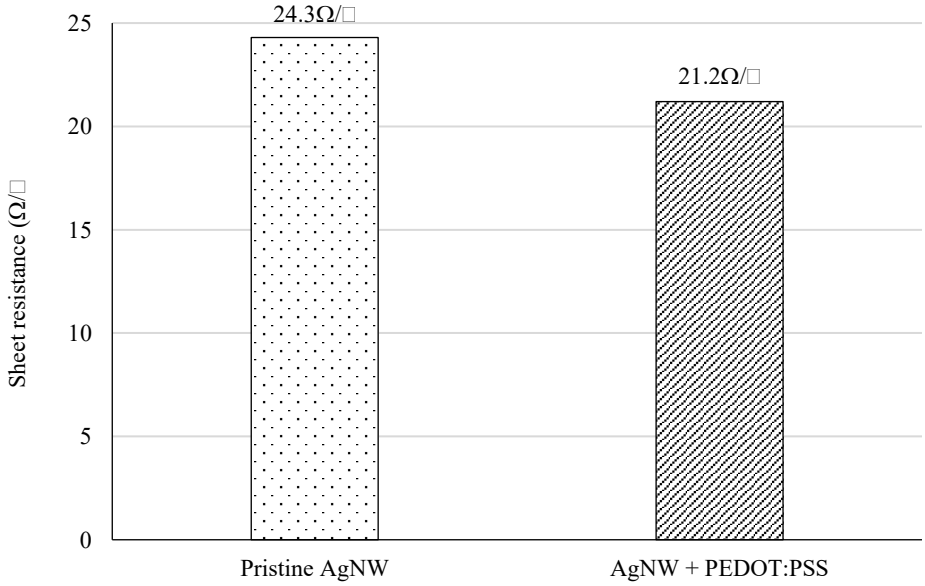

Figure 8. Comparison of sheet resistance.

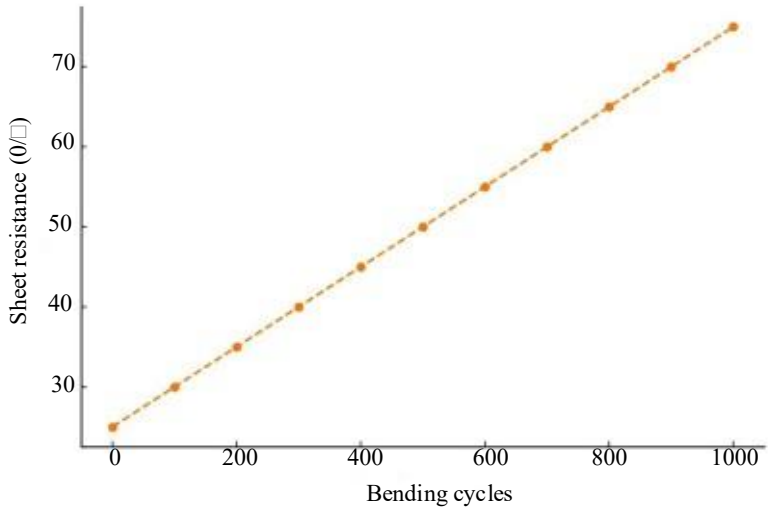

Figure 9. Sheet resistance vs. bending cycles.

Meanwhile, the PEDOT:PSS phase functions as a compliant polymer matrix that distributes mechanical stress evenly across the embedded nanowire network. Its viscoelastic nature enables the composite to undergo strain without initiating microstructural delamination or brittle failure. The polymer encapsulation layer also prevents nanowire dislocation and interfacial debonding by promoting strong interfacial adhesion, a critical criterion for maintaining electrical pathways under mechanical load [35].

Furthermore, the flexible matrix effectively absorbs cyclic strain energy, reducing the likelihood of fatigue failure—a significant advantage over conventional inorganic TCEs like ITO, which tend to exhibit catastrophic fracture and electrical failure within fewer than 100 bending cycles due to their brittle ceramic nature [36]. Unlike ITO, which lacks a matrix phase capable of mechanical stress dissipation, the AgNW/PEDOT:PSS composite leverages the matrix–filler synergy to create a strain-tolerant, conductive, and mechanically stable electrode film.

These findings underscore the material's behaviour not merely as a conductive film but as a structurally optimized polymer nanocomposite, wherein both filler geometry and matrix compliance jointly determine mechanical performance. The minimal resistance change over extensive cyclic deformation demonstrates that the AgNW/PEDOT:PSS composite fulfills essential mechanical reliability criteria for wearable photovoltaics, foldable electronics, and other applications requiring enduring electrical functionality under dynamic mechanical stress.

Under cyclic bending, failure in bare AgNW networks initiates at high-curvature regions by junction sliding/scission and wire–substrate debonding; oxidation accelerates contact resistance growth. The PEDOT:PSS matrix redistributes strain (viscoelastic dissipation), anchors junctions ('soft-solder' wetting of overlaps), and encapsulates AgNWs against moisture/oxygen ingress—thereby suppressing percolation-path loss. Literature shows large gains in fatigue life for polymer-passivated AgNWs and PFI-modified PEDOT:PSS electrodes compared with unprotected networks or brittle ITO

Thermal Stability

The thermal and environmental durability of the AgNW/PEDOT:PSS polymer composite was assessed under accelerated aging conditions to evaluate its structural-electrical integrity—a key performance metric for any polymer nanocomposite intended for long-term optoelectronic deployment. As illustrated in Figure 10, the bare AgNW film exhibited a pronounced increase in normalized resistance from 1.00 to 1.30 after 100 hours at 85°C and 85% relative humidity, indicating a 30% degradation in conductivity. This degradation arises from the absence of a stabilizing matrix phase, leading to direct exposure of AgNWs to oxidative agents, which induces Ag_2O formation, interfacial delamination from the PET substrate, and eventual disintegration of the percolative conductive network.

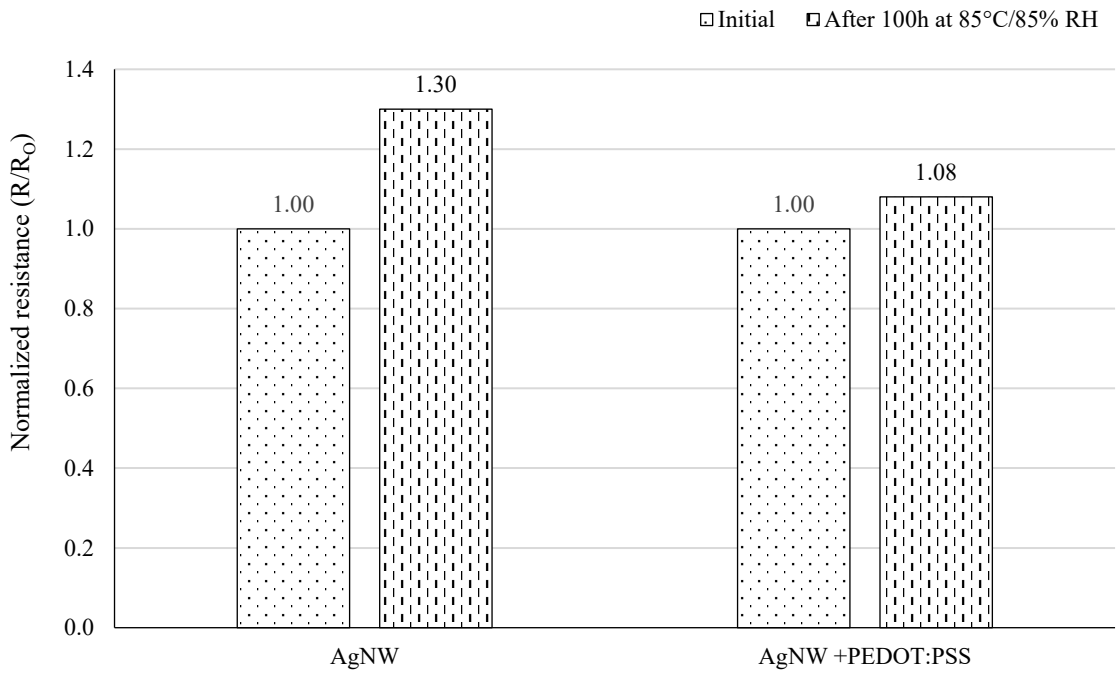

Figure 10. Comparison of thermal stability.

In sharp contrast, the AgNW/PEDOT:PSS polymer composite electrode showed only a marginal resistance increase from 1.00 to 1.08—equating to an 8% rise—demonstrating the thermal and environmental shielding capacity of the polymer matrix. The PEDOT:PSS acts as an encapsulating continuous phase, serving multiple composite-specific roles: it inhibits oxygen diffusion, limits moisture penetration, and mechanically stabilizes the embedded nanowires under thermal stress. This matrix–filler interaction is a fundamental tenet of composite design, wherein the polymeric phase buffers the conductive filler against ambient degradative forces [37].

Further enhancement in environmental resilience is imparted by the incorporation of Zonyl fluorosurfactant into the PEDOT:PSS formulation, which introduces hydrophobic characteristics to the composite matrix. This significantly reduces the moisture diffusion coefficient within the polymer phase, decreasing water uptake and thereby preventing hydrolytic and oxidative reactions at the AgNW surface [38]. The result is a hybrid system where the polymer matrix not only mediates electrical performance but also governs environmental shielding, reflecting an ideal structure–property balance for harsh operational environments.

These results underscore the importance of matrix encapsulation and interfacial stability in polymer nanocomposites subjected to thermal and humidity cycling. The AgNW/PEDOT:PSS composite structure demonstrates that thoughtful polymer phase engineering—including additives, crosslinking, and hydrophobic modification—can dramatically improve the long-term functionality of conductive films. As Figure 10 clearly illustrates, the comparative stability between the unprotected AgNW film and the matrix-stabilized composite highlights the critical synergistic role of the polymer matrix in preserving filler conductivity and network morphology under aggressive environmental exposure [39, 40].

Therefore, this study establishes AgNW/PEDOT:PSS composites not just as flexible transparent conductors, but as thermo-environmentally engineered polymer composites optimized for real-world photovoltaic and optoelectronic applications where durability, flexibility, and environmental resistance are non-negotiable.

Scalability and Industrial Relevance of R2R-Compatible Processing

The proposed R2R-compatible formulation and processing window (Section 2.6) directly address the scalability gap for AgNW/PEDOT:PSS composites. High-aspect-ratio nanowires at optimized viscosity enable sub-10 Ω/□ sheet resistance with >85% transmittance at minimal silver loading, reducing material cost. UV–ozone surface treatment and in-line optical/electrical mapping facilitate defect suppression (<2% area affected) over meter-scale webs. Photonic sintering offers junction densification within milliseconds, avoiding PET distortion and enabling line speeds above 10 $m \cdot min^{-1}$. These process choices align with best practices in polymer photovoltaics manufacturing and could lower per-unit electrode cost by >30% compared to batch spin-coating, making the hybrid film competitive for flexible electronics and photovoltaic modules.

End-of-life management of AgNW/PEDOT:PSS/PET is non-trivial because metallic nanowires are intimately embedded in a hydrophilic polyelectrolyte matrix on a thermoplastic substrate. Straightforward options are: (a) aqueous detachment of non-crosslinked PEDOT:PSS (PSS-rich dispersions) aided by ultrasonication; (b) mild base/alcoholic rinses to weaken PEDOT:PSS-substrate adhesion; followed by (c) selective Ag leaching (e.g., dilute HNO_3 to Ag^+) and metal recovery by precipitation/electrowinning. Where PEDOT:PSS has been crosslinked for durability, solvents are less effective and chemical stripping increases. The PET base can then enter mechanical recycling or chemical depolymerization (glycolysis/methanolysis) streams. Key challenges include preventing Ag nanoparticle release, minimizing NOx from acid leaching, and avoiding surfactant contamination of wastewater. Design-for-recycling measures include using water-removable adhesion promoters, limiting crosslink density, specifying longer AgNWs (lower mass per sheet at fixed R_s), and labelling laminates for EoL separation.

CONCLUSION

This study provides a comprehensive investigation into AgNW/PEDOT:PSS-based polymer nanocomposites, emphasizing their potential as multifunctional transparent conductive films for flexible photovoltaics and optoelectronic systems. By treating the system not merely as a coated nanowire network but as a structurally integrated polymer composite, this work highlights the pivotal role of the PEDOT:PSS matrix in governing the overall material performance. The key findings from this composite-centric approach are summarized below:

Matrix-mediated conductivity

The PEDOT:PSS polymer phase acts as an electrically active continuous matrix that bridges nanowire junctions, effectively reducing interfacial contact resistance. This composite synergy led to a low sheet resistance of 21.2 Ω/□ and a high figure of merit ($\Phi\_TC = 265 \times 10^{-3}\ \Omega^{-1}$), exceeding conventional TCE benchmarks.

Optical-morphological integration

The composite maintained an average transmittance above 85% in the visible range. The polymer matrix facilitated refractive index matching and surface planarization, both crucial for optical clarity in polymer composites.

Mechanical reliability through matrix–filler synergy

The composite sustained mechanical cycling over 1000 bending cycles with only a 6.4% increase in resistance. This robustness results from the stress-dissipating PEDOT:PSS matrix and the crack-bridging behavior of the embedded high-aspect-ratio AgNWs, a textbook example of filler-reinforced composite mechanics.

Environmental durability by polymer encapsulation

Under 85°C/85% RH for 100 hours, the composite showed only an 8% rise in resistance, compared to 30% for uncoated AgNWs. This confirms the matrix's role in forming a moisture- and oxygen-resistant barrier, stabilizing the filler network under harsh climatic conditions.

Scalable composite processing

The solution-processable nature of both the polymer and filler phases enables cost-effective fabrication using roll-to-roll techniques on flexible substrates—hallmarks of industrially viable polymer composites.

In summary, this work establishes AgNW/PEDOT:PSS as a true multifunctional polymer composite, where the interplay between the conductive filler network and the polymer matrix yields a high-performance, flexible, and environmentally resilient material platform. This composite approach is foundational to the design of next-generation electrodes for wearable photovoltaics and flexible electronics.

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