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Silver Nanowire Transparent Conductive Film Prepared by Spin Coating: Correlating Network Morphology with Optical and Electrical Properties

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Abstract: In this study, silver nanowires (AgNWs) were synthesized through the polyol process and subsequently deposited onto glass substrates by a spin-coating technique to fabricate transparent conductive films. The morphology, optical properties, and electrical performance of the resulting films were investigated using scanning electron microscopy (SEM), UV–Vis spectrophotometry, and sheet resistance measurements. SEM observations confirmed the successful formation of AgNWs with an average diameter of 332 nm and a length of 28 µm. After film deposition, the AgNWs formed a dense and interconnected network with average dimensions of 178 nm in diameter and 12 µm in length. Optical characterization revealed a transmittance of 86.6% at 550 nm, indicating high transparency in the visible region. Electrical measurements showed a low sheet resistance of 3.3 Ω/sq, indicating good electrical conductivity of the fabricated film. The observed combination of high transmittance and low sheet resistance is attributed to the interconnected AgNW network morphology, in which numerous nanowire junctions provide effective electron transport pathways while the open regions between neighboring nanowires allow efficient light transmission. This correlation between network morphology and the resulting optical and electrical properties suggests that the fabricated AgNW film possesses characteristics suitable for transparent conductive electrode applications.

Keywords: Silver Nanowires; Transparent Conductive Film; Spin Coating; Polyol Method; Optical Transmittance.

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Introduction

The rapid advancement of optoelectronic devices, including touch screens, organic light-emitting diodes (OLEDs), and solar cells, has greatly increased the need for high-performance transparent conductive films (TCFs). For decades, indium tin oxid**e (ITO)** has been the predominant material in the market because of its outstanding electrical conductivity and high optical transparency. However, several limitations of ITO, including high cost of indium, environmental concerns, susceptibility to cracking under bending stress, and the growing demand for flexible electronic devices, have encouraged the development of alternative transparent conductive materials (Borchloo, Shoja-Razavi, & Naderi-Samani, 2024; J. Li, Luo, & Liu, 2025).

Among the available alternatives, silver nanowires (AgNWs) have gained significant interest because of their high electrical conductivity, strong optical transparency in the visible region, and excellent mechanical flexibility. In addition, AgNWs can be processed through solution-based methods, making them suitable for low-cost and large-area fabrication. Due to their high aspect ratio, AgNWs are able to develop interconnected conductive networks while

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retaining good optical transmittance, making them attractive candidates for transparent electrode applications (Borchloo et al., 2024; H. Ha, Amicucci, Matteini, & Hwang, 2022; Kumar, Shaikh, & Chuang, 2021).

The properties of AgNW-based transparent conductive films are strongly influenced by the synthesis process and film fabrication method. The polyol method is widely recognized as a robust and efficient chemical route for synthesizing high-quality AgNWs. This method generally consists of reducing silver nitrate ($AgNO_3$) with a polyol, commonly ethylene glycol, in the presence of a capping agent such as polyvinylpyrrolidone (PVP) (Salam, Ebrahim, Soliman, & Shokry, 2024). Through the polyol route, AgNWs with high aspect ratios can be consistently produced, which is essential for achieving an effective percolation network at low density. Following synthesis, the deposition process plays an important role in determining the final properties of the film. Several deposition techniques have been employed to fabricate conductive films, including spray coating (Alshammari et al., 2017), rod coating (X. Wang et al., 2024), drop casting (Castillo-López et al., 2024), roll-to-roll printing (Meng et al., 2018), and spin coating (B. Ha & Jo, 2017). Among these methods, spin coating is particularly advantageous for laboratory-scale fabrication due to its ability to produce highly uniform, simple, and reproducible thin films by controlling the rotation speed and solution concentration (J. Li et al., 2025; L. Shi, 2023).

In this study, silver nanowires (AgNWs) were successfully synthesized by the polyol method and subsequently fabricated into transparent conductive films (TCFs) using spin-coating technique. While existing studies often investigated a broad range of synthesis parameters, this work focuses on the morphological arrangement of the nanowire network and its direct correlation with optical transparency and electrical sheet resistance. By analyzing the transition from liquid dispersion to a forest-like network on glass substrates, this study demonstrates a reliable and simple fabrication route to produce high-performance TCFs that are suitable for next-generation optoelectronic applications.

Method

Materials

The materials used for synthesizing of silver nanowires by the polyol method included silver nitrate ($AgNO_3$, 99%, Merck), polyvinylpyrrolidone (PVP, Mw. 55K g/mol, Sigma-Aldrich), copper (II) chloride dihydride ($CuCl_2.2H_2O$, 99%), ethylene glycol (EG, 99%, Bratachem), and ethanol (EtOH, 98%, Merck)

Synthesis of AgNWs

In this study, silver nanowires (AgNWs) were synthesized using the polyol method. First, A 50 mL PVP (0.45 M) solution in ethylene glycol (EG) was heated at 150 °C under continuous stirring at 260 rpm for 5 minutes under ambient conditions. Then, 140 µL of 0.1 M $CuCl_2 \cdot 2H_2O$ solution was added. Subsequently, the oil bath temperature was decreased to 130 ^oC and the solution was stirred for 45 minutes. After 1 h of stirring process, 12 mL of 0.5 M $AgNO_3$/EG was injected into PVP solution within 20 minutes, and the solution was kept for 2 h at a constant temperature of 130 ^oC. The product AgNWs of this process were chilled in ambient air for 30 min. The obtained suspension was filtered and washed with ethanol by centrifuge treatment at 6000 rpm for 20 min. The washing step was repeated three times to remove residual by-products and impurities. Finally, the purified AgNWs were stored in the vial for the fabrication process.

Preparation of AgNWs-based flexible conducting film

The AgNWs thin film was fabricated using the spin coating technique on a glass substrate measuring (2.5 x 2.5 cm^2). Since a clean surface is essential for the coating process, the glass substrate was washed before being used for fabricating the AgNWs film. The substrate was first soaked in acetone twice, then in detergent water once, followed by another acetone bath twice, and then in ethanol twice. During each soaking step, the substrate was sonicated in an ultrasonic cleaner for 30 minutes. After that, the substrate was dried using a hair dryer and stored in a clean container. The AgNWs solution in ethanol was sonicated for 60 seconds and shaken thoroughly before being spin-coated to prevent local inhomogeneity. The AgNWs solution was then spin-coated onto the substrate at a speed of 1000 rpm for 30 s, and the resulting film was heated at 95^{o}C for 15 min on a hotplate.

Characterization

The morphology of the sample was investigated using a scanning electron microscope (SEM) (JEOL, JSM-6510LA). The optical transmittance of the film was examined using a UV-Vis spectrophotometer (Shimadzu, UV-1700) at wavelength range of 300 nm to 800 nm. The sheet resistance of the AgNWs thin film was measured using a four-point probe technique (Keithley 2401 source meter).

Result and Discussion

Morphology and Size Distribution of AgNWs

The synthesis of silver nanowires (AgNWs) was successfully performed using the polyol method, followed by thin-film deposition on a glass substrate. The morphology of the resulting nanostructures was observed using Scanning Electron Microscopy (SEM) to evaluate the growth of the nanowires both in their initial dispersion and after the film formation process.

As shown in Figure 1(a), the initial AgNW dispersion consists of randomly distributed wire-like nanostructures with an average diameter of approximately 332 nm and an average length of 28 µm. At this stage, the network was not yet interconnected, as the wires remained suspended in the solvent (Kumar et al., 2021; Y. Shi et al., 2019). However, the observed morphology confirmed the successful synthesis of AgNWs through the polyol process.

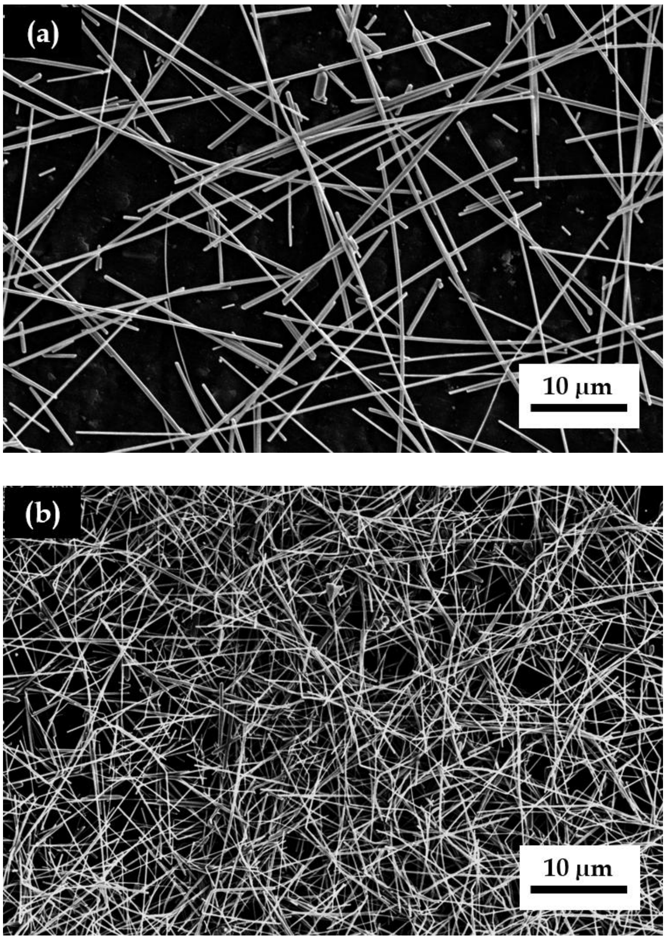

Figure 1. SEM images of (a) AgNWs dispersion and (b) AgNWs film

After deposition onto the glass substrate, the morphology changed noticeably. Figure 1(b) shows that the nanowires became interconnected, forming a dense network with numerous overlapping junctions. Such an arrangement is favorable for the formation of continuous conductive pathways across the film surface (Gerlein, Benavides-Guerrero, & Cloutier, 2021; L. Shi, 2023; Yu et al., 2017). To further examine the morphology of the synthesized and deposited AgNWs, the diameter and length distributions were analyzed and are presented in Fig. 2. Figures 2(a) and 2(b) correspond to the AgNW dispersion, whereas Figures 2(c) and 2(d) represent the deposited film. The AgNWs in the dispersion exhibited average dimensions of approximately 332 nm in diameter and 28 µm in length. After film formation, the average diameter and length were approximately 178 nm and 12 µm, respectively.

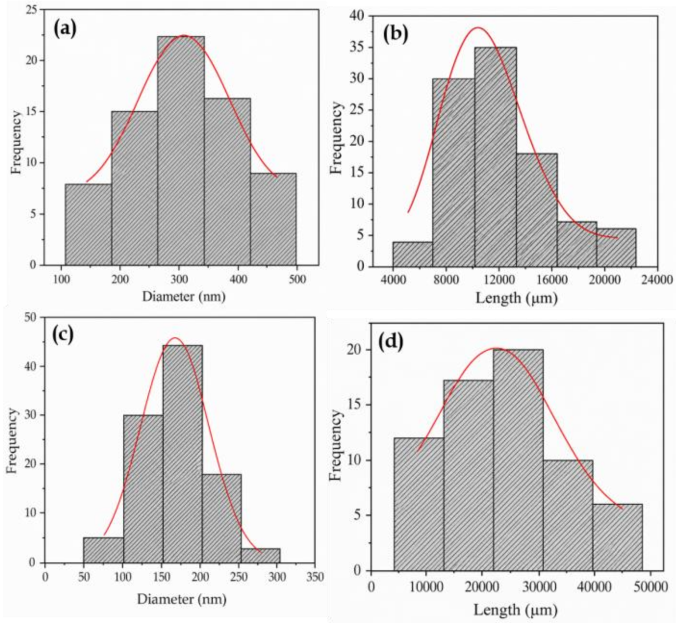

Figure 1. AgNWs size distribution: (a) diameter distribution of AgNWs dispersion, (b) length distribution of AgNWs dispersion, (c) diameter distribution of AgNWs film, and (d) length distribution of AgNWs film

This difference may be associated with the dispersion and homogenization steps before coating, where mechanical agitation and ultrasonication could induce partial fragmentation of long nanowires, leading to a reduction in their apparent length (Y. Wang, Yang, & Du, 2019). In addition, the dense overlapping structure of the deposited network may make dimensional measurements more challenging than those obtained from isolated nanowires in the dispersion. The SEM results confirm that the spin-coating process successfully transformed the dispersed AgNWs into a well-connected nanowire network. The formation of numerous junctions and conductive pathways suggests that the resulting film possesses a morphology suitable for transparent conductive electrode applications (J. Li et al., 2025).

Optical Properties of AgNW Film

The optical properties of the fabricated AgNWs film were analyzed using UV-Vis spectrophotometry. As illustrated in Figure 3, the fabricated film exhibited a relatively stable transmission profile in the visible region, achieving an optical transmittance of 86.6% at a wavelength of 550 nm. This result indicates that the deposited AgNW network maintained a high level of transparency despite forming a continuous conductive layer on the glass substrate. The optical transmittance observed in this study can be attributed to the percolated morphology of the AgNW network, as revealed by SEM analysis.

Although the AgNWs formed an interconnected conductive pathway, substantial open areas remained between neighboring nanowires. These open regions allowed visible light to pass through the film while the nanowires simultaneously provided pathways for electron transport. Similar behavior has been reported for AgNW-based transparent conductive films, where optical transparency is strongly influenced by nanowire density, network coverage, and wire dimensions (Kumar et al., 2021; J. Li et al., 2025). A slight decrease in transmittance was observed in the lower wavelength region. This behavior is commonly attributed to light scattering and plasmonic interactions associated with silver nanostructures, particularly near the ultraviolet region (Hou et al., 2022). As the wavelength increased toward the visible range, the transmittance remained relatively stable, suggesting that the fabricated film possessed good optical uniformity across the measured spectrum.

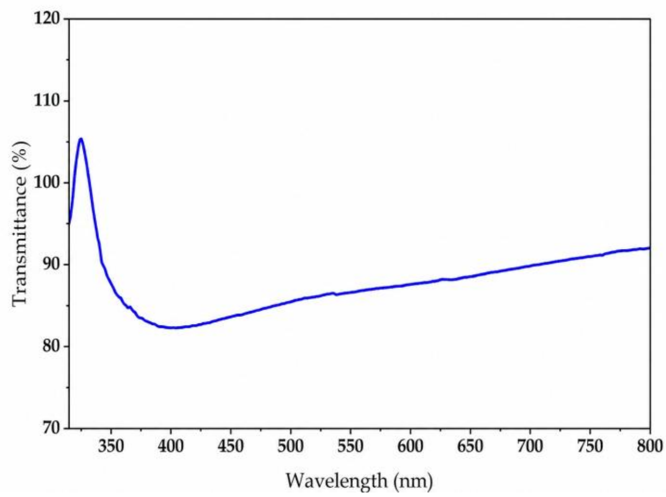

Figure 3. Optical transmittance of AgNWs film

Electrical Properties of AgNW Film

The performance of transparent conductive films is typically evaluated by balancing optical transparency and electrical conductivity. In this study, the fabricated AgNW film exhibited a sheet resistance of 3.3 Ω/sq, indicating the successful formation of a well-connected conductive network across the substrate surface. This result aligns with the SEM observation that numerous overlapping nanowires and interconnected junctions provide continuous pathways for electron transport (Pham et al., 2022).

As the number of conductive junctions increases, electrons can traverse multiple interconnected routes, reducing the film's overall resistance. Similar behavior has been widely reported in AgNW-based transparent conductive electrodes, where conductivity strongly depends on network density and junction quality between adjacent nanowires (Gerlein et al., 2021; L. Shi, 2023; Yu et al., 2017). The relatively low sheet resistance obtained in this work may also be influenced by the post-deposition thermal treatment applied after spin coating.

The thermal treatment likely assisted in the evaporation of residual solvent trapped within the deposited network and improved contact between neighboring nanowires. Previous studies have shown that residual organic species surrounding AgNWs can hinder charge transport across nanowire junctions, whereas thermal treatment facilitates their removal and promotes more efficient electrical pathways within the conductive network (Chen et al., 2026; Xianjie et al., 2025). In addition, the uniform distribution of AgNWs observed in the SEM image suggests that conductive pathways were formed throughout the substrate surface, supporting stable electron transport across the film. The sheet resistance achieved in this study falls within the lower range commonly reported for solution-processed AgNW transparent conductive films. When considered together with the optical transmittance of 86.6%, the fabricated film demonstrates characteristics desirable for transparent conductive electrode applications.

Conclusion

This work demonstrated that a transparent conductive film can be successfully fabricated from silver nanowires synthesized by the polyol method and deposited by spin coating. The resulting film consisted of a well-connected AgNW network that provided good electrical conduction while preserving high transparency in the visible region. An optical transmittance of 86.6% and a sheet resistance of 3.3 Ω/sq were obtained, indicating that the fabricated film achieved a favorable combination of optical and electrical properties. These findings show that the proposed fabrication route is straightforward, reproducible, and suitable for preparing AgNW-based transparent conductive films for transparent electrode applications.

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References

Alshammari, A. S., Sam, F. L. M., Rozanski, L. J., Mills, C. A., Alenezi, M. R., Beliatis, M. J., … Silva, S. R. P. (2017). Controlled growth and spray deposition of silver nanowires for ITO-free, flexible, and high brightness OLEDs. Physica Status Solidi (A) Applications and Materials Science, 214(5). https://doi.org/10.1002/pssa.201600561

Borchloo, A., Shoja-Razavi, R., & Naderi-Samani, H. (2024). Silver nanowires: recent advances in synthesis, transparent conductive coatings, and EMI shielding applications. Synthesis and Sintering, 4(4), 256–281. https://doi.org/10.53063/synsint.2024.44247

Castillo-López, D. N., Gómez-Pavón, L. del C., Gutíerrez-Nava, A., Zaca-Morán, P., Arriaga-Arriaga, C. A., Muñoz-Pacheco, J. M., & Luis-Ramos, A. (2024). Flexible force sensor based on a PVA/AgNWs nanocomposite and cellulose acetate. Sensors, 24(9). https://doi.org/10.3390/s24092819

Chen, J., Fan, J., Yang, A., Rahaman, M. Z., Mei, T., Ma, X., … Lin, C. H. (2026, February 1). Metal nanowires for flexible and wearable sensors: synthesis, processing, and device applications. Advanced Sensor Research, Vol. 5. Wiley-VCH Verlag. https://doi.org/10.1002/adsr.202500164

Gerlein, L. F., Benavides-Guerrero, J. A., & Cloutier, S. G. (2021). High-performance silver nanowires transparent conductive electrodes fabricated using manufacturing-ready high-speed photonic sinterization solutions. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-03528-w

Ha, B., & Jo, S. (2017). Hybrid Ag nanowire transparent conductive electrodes with randomly oriented and grid-patterned Ag nanowire networks. Scientific Reports, 7(1). https://doi.org/10.1038/s41598-017-11964-w

Ha, H., Amicucci, C., Matteini, P., & Hwang, B. (2022, September 1). Mini review of synthesis strategies of silver nanowires and their applications. Colloids and Interface Science Communications, Vol. 50. Elsevier B.V. https://doi.org/10.1016/j.colcom.2022.100663

Hou, S., Liu, J., Shi, F., Zhao, G. X., Tan, J. W., & Wang, G. (2022, March 10). Recent advances in silver nanowires electrodes for flexible organic/perovskite light-emitting diodes. Frontiers in Chemistry, Vol. 10. Frontiers Media S.A. https://doi.org/10.3389/fchem.2022.864186

Kumar, A., Shaikh, M. O., & Chuang, C. H. (2021, March 1). Silver nanowire synthesis and strategies for fabricating transparent conducting electrodes. Nanomaterials, Vol. 11, pp. 1–51. MDPI AG. https://doi.org/10.3390/nano11030693

Li, J., Luo, J., & Liu, Y. (2025, July 1). Recent advances in silver nanowire-based transparent conductive films: from synthesis to applications. Coatings, Vol. 15. Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/coatings15070858

Meng, X., Hu, X., Yang, X., Yin, J., Wang, Q., Huang, L., … Chen, Y. (2018). Roll-to-roll printing of meter-scale composite transparent electrodes with optimized mechanical and optical properties for photoelectronics. ACS Applied Materials and Interfaces, 10(10), 8917–8925. https://doi.org/10.1021/acsami.8b00093

Pham, S. H., Ferri, A., Da Costa, A., Mohan, M. M. S., Tran, V. D., Nguyen, D. C., … Leclère, P. (2022). Nanoscale electrical investigation of transparent conductive electrodes based on silver nanowire network. Advanced Materials Interfaces, 9(18). https://doi.org/https://doi.org/10.1002/admi.202200019

Salam, A. A., Ebrahim, S., Soliman, M., & Shokry, A. (2024). Preparation of silver nanowires with controlled parameters for conductive transparent electrodes. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-70789-6

Shi, L. (2023). Flexible transparent silver nanowires conductive films fabricated with spin-coating method. Micro and Nano Letters, 18(1). https://doi.org/10.1049/mna2.12151

Shi, Y., He, L., Deng, Q., Liu, Q., Li, L., Wang, W., … Liu, R. (2019, May 1). Synthesis and applications of silver nanowires for transparent conductive films. Micromachines, Vol. 10. MDPI AG. https://doi.org/10.3390/mi10050330

Wang, X., Song, C., Wang, Y., Feng, S., Xu, D., Hao, T., & Xu, H. (2024). Flexible transparent films of oriented silver nanowires for a stretchable strain sensor. Materials, 17(16). https://doi.org/10.3390/ma17164059

Wang, Y., Yang, X., & Du, D. (2019). Silver nanowires from sonication-induced scission. Micromachines, 10(1). https://doi.org/10.3390/mi10010029

Xianjie, T., Guoyou, G., Shouzhi, C., Xianglei, Y., Zhuo, Q., & Junpeng, L. (2025). Synthesis and sintering of AgNWs@PVP core-shell structures for improved transparent electrodes. RSC

Advances, 15(8), 6162–6170. https://doi.org/10.1039/d4ra08659g

Yu, Y., Shen, W., Li, F., Fang, X., Duan, H., Xu, F., … Song, W. (2017). Solution-processed multifunctional transparent conductive films based on long silver nanowires/polyimide structure with highly thermostable and antibacterial properties. RSC Advances, 7(46), 28670–28676. https://doi.org/10.1039/c7ra04569g