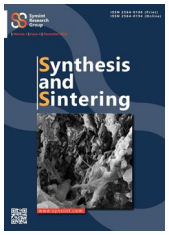
SYNTHESIS AND SINTERING 4 (2024) 256–281

Available online at www.synsint.com

Synthesis and Sintering

ISSN 2564-0186 (Print), **ISSN** 2564-0194 (Online)



Review article

Silver nanowires: recent advances in synthesis, transparent conductive coatings, and EMI shielding applications

Ali Borchloo *, Reza Shoja-Razavi, Hamed Naderi-Samani

Faculty of Materials and Manufacturing Technologies, Malek Ashtar University of Technology, Tehran, Iran

A B S T R A C T

Indium tin oxide (ITO) is a broadly utilized transparent conductor, although it possesses several limitations such as high cost and brittleness. This paper investigates silver nanowires (AgNWs) as suitable alternative materials to ITO due to their improved electrical conductivity, flexibility, and transparency. We investigated several techniques for creating AgNWs, including template, chemical, polyol, and electrochemical approaches. The polyol method is highlighted as very cost-effective and efficient; however, it produces nanoparticle byproducts. We explore changes to the polyol technique that aim to improve yield and purity. The review examines how AgNWs are made, talking about nucleation, phase transitions of silver atoms, and the formation of pentagonal grains. These characteristics show how effectively the polyol approach works for generating high-quality AgNWs on a large scale. We investigated the relationship between AgNW concentration, the additive's characteristics, and the surface tension and viscosity of the resultant ink, with a focus on how these variables influence different coating processes. The study reviews the process of converting AgNWs into conductive inks for use in transparent conductive films (TCFs), with applications including transparent heaters, touch panels, sensors, solar cell electrodes, and electromagnetic interference (EMI) shielding devices. The research overview concludes with a discussion of potential future directions and the promising role of AgNWs in advancing TCF technologies.

KEYWORDS

Silver nanowires
Transparent coatings
Polyol method
Conductive inks
EMI shielding

OPEN ACCESS

1. Introduction

A thin layer of scattered indium tin oxide (ITO) is commonly utilized as a transparent conductor (TC) in touch thin-film solar cells, screens, and organic light-emitting diodes (OLEDs) because of its high transparency (T=95%) [1]. Nevertheless, while ITO's high conductivity makes it suitable for these applications, is not a good choice for transparent and conductive coatings because its disadvantages exceed its advantages; hence, materials with properties better than those of ITO are needed [2, 3, 4].

Recently, various conductive materials, including conductive polymers, graphene, silver nanowires (AgNWs), and carbon nanotubes, have been utilized to create flexible transparent coatings [5]. Owing to their special properties compared to other conductive alternatives, AgNWs are currently considered a promising material for replacing ITO [6, 7]. ITO is costly, fragile, and environmentally hazardous [8]. In contrast, AgNWs offer a cost-effective, scalable alternative with superior flexibility, electrical conductivity, and transparency in the visible spectrum, along with good thermal conductivity [2, 9]. However, ITO growth is impeded by its production, cost, and flexibility restrictions [10]. ITO suffers from limitations in production, cost, and inflexibility, hindering further development [11]. The disadvantages of ITO, such as limited flexibility, brittleness, and cost make AgNWs a more attractive option for transparent electrodes [12].

One-dimensional nanostructures such as wires, rods, and tubes have recently gained great attention owing to their excellent magnetic,

* Corresponding author. *E-mail address:* aliborchloo77@mut.ac.ir (A. Borchloo)

Received 9 September 2024; Received in revised form 4 December 2024; Accepted 9 December 2024.

https://doi.org/10.53063/synsint.2024.44247

thermal, optical, and electrical capabilities, along with a high surface area-to-volume ratio [13, 14, 8–15]. Furthermore, a nanowire structure grows mainly in one direction—the longitudinal direction—while being very limited in the other two directions. Consequently, nanowires are nanostructures that can be produced with small diameters [16, 17, 18, 19].

Fig. 1 shows the rapid rise in publications from Scopus on AgNWs and their use in transparent and conductive coatings. Since 2000, the production of silver nanowires has proliferated.

Due to their transparency, silver nanowires are used in conductive, transparent coatings. While ITO was traditionally used for such coatings, its issues—cost, fragility, and environmental concerns limit its use [20–35]. Since 2000, silver nanowires have emerged as a competitive alternative, offering transparency, electrical conductivity, mechanical stability, flexibility, and low surface resistance, making them a promising replacement for ITO coatings. [36]. Therefore, transparent and flexible conductive layers made of silver nanowires can be considered as a replacement for indium tin oxide coatings [7]. Table 1 lists the names and short forms referenced in this overview are provided in.

Transparent and flexible conductive coatings of AgNWs can be considered as alternatives to ITO coatings. Recently, various techniques, such as chemical [9], polyol [35], electrochemical [18], and template methods [9], have been applied to AgNWs synthesis. Among them, the polyol method has become a widely used approach for synthesizing AgNWs with consistent morphology. The polyol reduction technique has some drawbacks, although it can produce AgNWs with diameters ranging from 30 to 50 nm and an aspect ratio of around 1000 [37–40]. The advantages and disadvantages of using polyol technology to produce silver nanowires are listed in Table 2.

Sun et al.'s [4, 41] development of the polyol synthesis process for AgNWs represented one of the first practical approaches to producing metal nanowires on a large scale. Since then, this method and several modifications have been widely employed to produce AgNWs in large quantities for use as transparent conductive layers. Heated ethylene glycol (EG) was utilized to reduce silver ions in the presence of polyvinyl pyrrolidone (PVP). EG is a polyol, PVP is a polymeric capping agent, and silver nitrate ($AgNO_3$) is a salt precursor for the silver nanowires synthesis. Silver ions are chemically reduced as part of the process while a polymer coating agent is present. Silver nuclei can be formed in the correct shape with the help of a modest amount of appropriate salt. Silver ions are reduced by glycol aldehyde (GA), which is produced from ethylene glycol (EG) [7].

The reaction temperature can influence the growth rate and shape of the AgNWs. Elevated temperatures generally lead to increased growth rates, but may also cause irregular shapes. Studies have demonstrated a significant effect of temperature on AgNWs due to the oxidation of ethylene glycol, which is influenced by temperature and acts as a reducing agent, producing glycolaldehyde. The reduced temperatures do not possess the requisite energy for the anisotropic expansion of the AgNW. Conversely, conducting the synthesis at 170 °C yielded silver nanowires toward the end of the reaction. Mao et al. [31] observed that elevated reaction temperatures reduced the diameter of AgNWs, , and the highest aspect ratio was obtained at 170 °C.

There is an increasing demand for efficient component protection against electromagnetic interference (EMI), a new type of pollution resulting from the expanding use of electronic equipment in a wide range of military, industrial, commercial, and other sectors [42]. Researchers have found that silver-based shielding materials are more flexible and transparent by investigating various materials used in EMI shields. The employment of diverse nanomaterials, particularly one-dimensional nanostructures like nanorods and nanowires, represents the

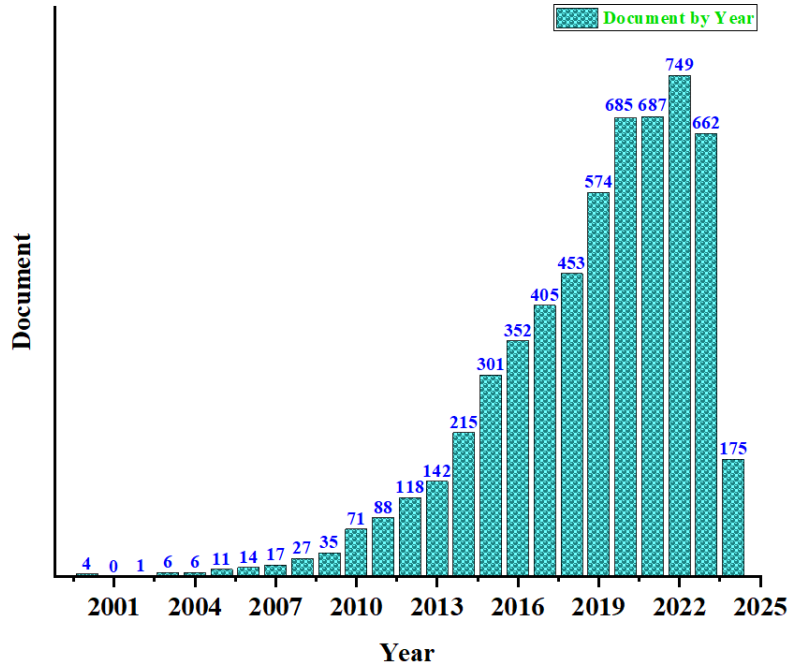


Fig. 1. The Scopus literature search results from various years, focusing on silver nanowires and their application in transparent and conductive coatings as the keyword.

Table 1. Nomenclatures discussed in the current review.

Nomenclature	Full name	Nomenclature	Full name
1D	One-dimensional	TC	Transparent conductor
AgNWs	Ag nanowires	TCF	Transparent conductor film
NW	Nanowire	TCE	Transparent conductor electrode
DI	Deionized	XRD	X-ray diffraction
MTPs	Multiply twinned particles	UV-Vis	Ultraviolet and visible spectroscopy
EG	Ethylene glycol	DRS	Diffuse reflectance spectroscopy
FCC	Face-center-cubic	FT-IR	Fourier-transform infrared spectroscopy
FE-SEM	Field emission scanning electron microscopy	TGA	Thermogravimetric analysis
GA	Glycol aldehyde	DSC	Differential scanning calorimetry
IPA	Isopropyl alcohol	SAED	Selected area electron diffraction
ITO	Indium-tin oxide	TCF	Transparent conductor film
LEDs	Light emitting diodes	PTE	Paint transfer efficiency
LCDs	Liquid crystal displays	RFI	Radio frequency interference
SEM	Scanning electron microscopy	ESD	Electrostatic discharge
PVP	Poly vinyl pyrrolidone	LSPR	Localized surface plasmon resonance
EMI	Electromagnetic interference	TC	Transparent conductor

most compelling and optimal choice for EMI shielding owing to their lightweight properties, high surface-to-volume ratio, and non-corrosive characteristics. Metal-based protective materials have various properties, including high electromagnetic interference protection efficiency [3, 9, 26, 42–44].

Based on our analysis, the transparent and conductive coatings based on silver nanowires and electromagnetic interference shielding discussed in the literature are categorized into three parts: first, the synthesis of silver nanowires and the factors affecting them; second, the investigation of conductive ink production with favorable properties for its coating on the sub-layers; and finally, checking the shielding efficiency of the sub-layer coated with silver nanowires. This review paper investigates the production and synthesis methods of silver nanowires until a conductive and transparent coating that is EMI shielding, is achieved. A road map of this study is shown in Fig. 2.

2. Preparation of AgNWs

There are several methods for preparing AgNWs. Ag^+ ions were deposited onto the (111) plane using a modified polyol method, which produces nanowires [45]. The dual-alcohol method is another technique that may be utilized for controlling the morphology of nanowires [45, 46]. This was achieved by adjusting the temperature of the reaction, the concentration of the control agents, and the rate at which the $AgNO_3$ solution dropped. Additionally, by co-doping silver nanowires and kaolinite nanotubes into silk fibroin and gelatin, electrospinning can be employed to create composite porous fiber films incorporating silver nanowires. Using a different method, materials for carbon nanosphere electrodes containing silver nanowires were prepared by heating, ultrasonication, and polymerization [7, 47].

Reducing silver ions in the presence of a polymer coating agent is how

Table 2. Advantages and disadvantages of using the polyol process to create silver nanowires.

Process name	Advantages	Disadvantages	Ref.
Poly alcohol process (polyol method)	Low cost	Requires relatively high temperature	[26]
	Simple process and no need for complex equipment	Production of nanoparticles as by-products	[30]
	Easy purification, high yields	Extremely sensitive to the concentration of additives	[19]
	Can be conducted in an ambient atmosphere	Relatively long reaction time	[18]
	Ability to adjust reaction conditions and achieve desired morphology	N/A	[39]
	Potential for commercialization	N/A	[18]

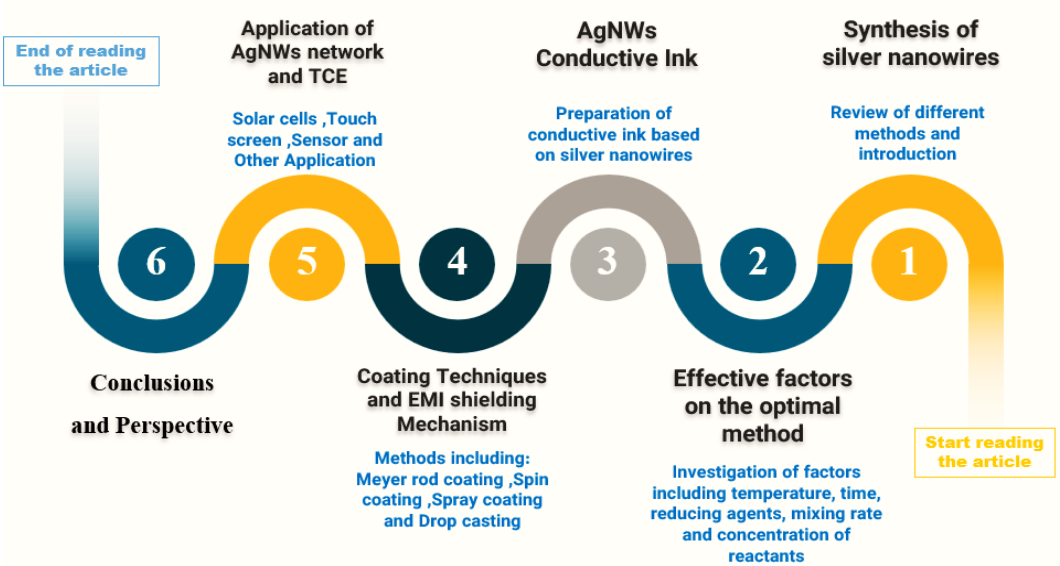


Fig. 2. The roadmap of this article.

silver nanowires are formed [7, 12]. The required form for silver buds can be cultivated using a small amount of sufficient salt. EG functions as a reducing agent and a solvent [7]. Eq. 1 shows that EG is also transformed into glycolaldehyde (GA), the reducing agent of silver ions [29].

$$2HOCH_2CH_2OH + O_2 \xrightarrow{170\ ^\circ C} 2HOCH_2CHO + 2H_2O \quad (1)$$

As a catalyst, use of poly (vinyl pyrrolidone) (PVP), ethylene glycol was used to reduce silver nitrate. According to research by Sun et al., utilizing PVP as a polymer capping agent and placing a seeding step was essential for consistently forming silver nanowires [41]. The polyol process was employed in this method to synthesize AgNWs on a large scale and at a constant diameter [4, 41]. Their studies revealed that the cross-sectional profiles of silver nanowires initially displayed a pentagonal structure along with a twinned crystal arrangement when examined under an electron microscope.

Their studies revealed that the cross-sectional profiles of silver nanowires first showed evidence of a pentagonal structure together with a twinned crystal arrangement when examined under an electron microscope. Furthermore, it was demonstrated that the lateral facets enclosed by the (100) and (111) planes of each nanowire exhibit a notable variance in their responsiveness to molecules and are shielded by the lateral surfaces entirely coated with polyvinylpyrrolidone [4, 16, 41].

The pentagonal structure of AgNWs refers to the formation of five-fold symmetric grains within the nanowires. This unique arrangement affects the material's electronic and mechanical properties. The presence of pentagonal defects can influence the wire's electrical conductivity by creating localized electronic states, potentially causing scattering at these defects and slightly reducing conductivity. However, these structures can also contribute to the mechanical flexibility of the nanowires. The pentagonal shape reduces the brittleness of the nanowires, enabling them to endure deformation without rupture which is crucial for usage in flexible electronics and equipment that require high mechanical stability [7, 47].

This outcome suggests that PVP macromolecules exhibit a more robust interaction with (100) planes of silver than with (111) planes [16, 41]. Based on these observations, they suggested that every silver nanowire began as a multiply twinned silver particle (MTP) assisted by PVP in the early stages of the Ostwald procedure. It should be mentioned that anisotropic growth was sustained through the application of PVP on the (100) orientations, while the (111) orientations remained predominantly uncovered by PVP, rendering them highly reactive [4, 14, 16, 41].

Anisotropic growth refers to the directional growth of AgNWs along a specific axis, leading to structures with a high aspect ratio (length much greater than width). This growth pattern is crucial because it significantly enhances the electrical conductivity of AgNWs. The elongated shape allows for effective electron transport along the nanowire's length, contributing to their high conductivity. Additionally, anisotropic growth enables AgNWs to maintain their flexibility, beneficial for use in flexible and TCFs. The high aspect ratio and aligned structure also improve the mechanical strength of the nanowires, which is beneficial for their integration into electronic devices that require both conductivity and flexibility [4, 16, 41].

In our previous research [1], we were able to synthesize and apply silver nanowires, which are shown in Fig. 3, the stages of doing the work and its step by step. Fig. 3 shows a schematic representation of the process for the synthesis of the silver nanowires (AgNWs) via the polyol technique. Within this image, we identified and incorporated the optimal values based on our study. The selectivity and interactions between polyvinylpyrrolidone (PVP) and different crystallographic levels are also important considerations. A decrease in these elements may increase the anisotropy [12]. However, when PVP and silver nitrate were present in small amounts (less than 1), needle-shaped objects with uneven surfaces were produced. In these cases, PVP will passivate individual nanowires up to the lateral surfaces, but it will be unable to create a continuous layer. As a result, there is little control over how silver nanostructures appear in lateral dimensions [12, 48, 49].

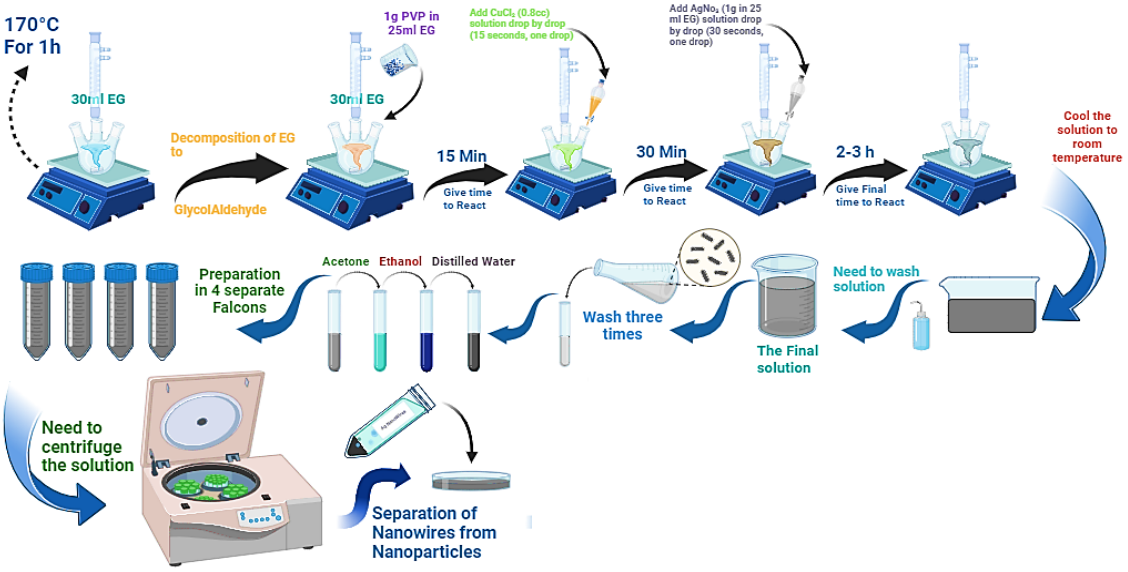


Fig. 3. Schematic from the synthesis of silver nanowires to their washing [1].

To produce longer nanowires, Chu et al. developed a multi-step sequential growth process that uses manufactured nanowires as "cores" [50]. Using this method, researchers have successfully synthesized and cultivated silver nanowires (AgNWs) within a novel growth solution that combines ethylene glycol (EG), silver nitrate ($AgNO_3$), and polyvinylpyrrolidone (PVP). The synthesis process occurred at a temperature of 150 °C, facilitated by a $CuCl_2$-mediated polyol process [50]. Boli et al. studied the purification and synthesis of silver nanowires and found that varying the bromide concentration might regulate the diameter and therefore the optoelectronic performance of nanowires made using polyol synthesis. Additionally, by adding 2.2 mM NaBr to the silver nanowire synthesis, silver nanowires with a diameter of 20 nm and an aspect ratio of up to 2000 were produced [20].

They found that metal nanowire networks outperformed ITO as a solution-coatable alternative. A technique for synthesizing and optimizing AgNWs, when coated with ink, surpassed ITO in performance. However, due to its high transmittance (95%), a thin layer of ITO is still used as a transparent conductor in touch screens, solar cells, and OLEDs [20]. However, the high-conductivity ITO used in these applications is very expensive because of the sluggish coating rates associated with sputtering, a solution-coatable alternative to ITO that can be coated at high speeds and with equivalent performance [20, 51].

Regarding the PVP/$AgNO_3$ molar ratio and PVP molecular weight on silver nanowires produced by the polyol technique, the molar ratios and PVP molecular weight have an impact on the silver nanowire synthesis reaction following Saglam et al (2016). Silver nanowires with the desired shape and high aspect ratio were synthesized using low molecular weight PVP and a low PVP/$AgNO_3$ molar ratio [6, 52, 53]. The chemical reaction of silver chloride, shown in Fig. 4a, illustrates how phase changes in silver atoms, nucleation on surface agents, and pentagonal grain formation are influenced by heterogeneous nucleating agents in the AgCl suspension. Additionally, homogeneous nucleation was employed in an experiment to form AgNWs without using an AgCl solution. Fig. 4a clearly shows that when the AgCl suspension of nucleating agents was not added during homogeneous nucleation, the purity of the AgNWs formed was lower [12].

Silver nanowires are displayed in Fig. 4b at varying magnifications, so that the impact of the aforementioned parameters may be observed. In Fig. 4c, a twinned silver nanoparticle (MTP) produced in the quintuplet range with PVP was transformed into a nanorod. This indicates that the side surfaces are constrained by the (100) direction, whereas the ends of the nanorod terminate in the (111) direction. Dark grey denotes strong interactions between PVP and the (100) direction, whereas light blue denotes weak interactions with (111). Double boundaries that may serve as active sites for adding silver atoms are indicated by the red lines on the end surfaces [4]. One of the five double planes that can act as internal confinement for the evolution of nanorods from the MTP is represented by a red plane. However, Fig. 4b displays a vertical projection on one of the five lateral faces of the nanorod, and the arrows indicate the silver atom emission fluxes [35, 54].

In Fig. 4d, we can see the XRD patterns of the silver nanowires, which have five prominent peaks, and the most common peak is related to the (111) plane. The –C–N– stretching vibration is responsible for the absorption peak shown in Fig. 4e of the FTIR spectrum, which represents AgNWs. The stretching vibrations of C=O (carbonyl group) and C–H are responsible for the peaks at 1659 and 2954 cm^{-1}, respectively [21].

Fig. 4f also displays the results of the TGA examination of the AgNWs in airflow and the graph shows significantly lower weight loss from the starting point to 280 °C. There is further mass loss after 280 °C. The breakdown of PVP's $–CH_3$ side chain is responsible for the weight loss between 280 and 380 °C. PVPs entirely dissolve around 790 °C, as evidenced by the weight loss that occurs mainly from PVP main chain breakdown [21]. Additionally, the percentage of visible light transmission of the samples is displayed in Fig. 4g (ii) and the UV-visible absorption spectra of silver nanowires is shown in Fig. 4g (i) [27].

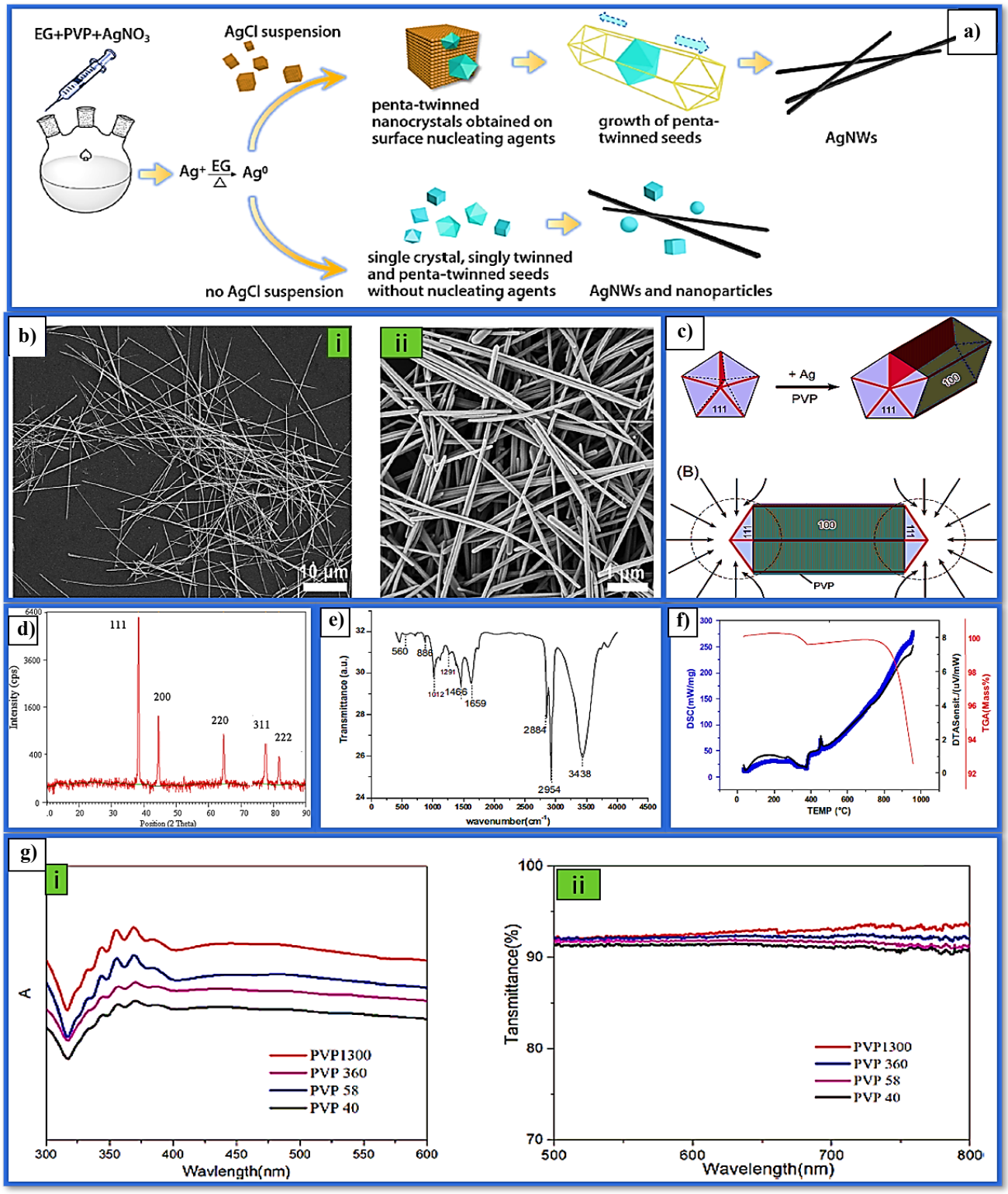


Fig. 4. Schematic of the preparation of silver nanowires. a) AgNWs heterogeneous nucleation growth process by adding AgCl suspension of nucleating agents and AgNWs homogeneous nucleation growth process without nucleating agents [12], b) SEM (i), FE-SEM (ii) images of AgNWs synthesized without AgCl seeds [19], c) Schematic illustration of the proposed mechanism to explain the growth of silver nanowires with a pentagonal cross-section [9], d) xrd patterns of silver nanowires [21], e) FTIR spectrum of silver nanowires [21], f) TGA, DSC and DTA analyzes of silver nanowires [21], and g) UV absorption spectrum i and ii optical transmission of prepared silver nanowire transparent films [27]. Reproduced with permission from Refs. [4, 12, 19, 21, 27].

2.1. Electrochemical method

Electrochemical techniques have been employed to produce silver nanowires. This research suggests an investigation into a distinctive electrochemical approach for manufacturing indium tin oxide nanowires (ITO NWs) decorated with silver nanoparticles, offering a potential pathway for synthesizing silver nanowires.

Yang et al. [11] concluded that indium tin oxide nanowires (ITO NWs) can be synthesized through chemical vapor deposition (CVD) using the vapor-liquid-solid (VLS) mechanism [11]. ITO NWs with 1% and 3% nanoparticles of silver on the surface were fabricated using a unique electrochemical technique. Fig. 5a–d illustrates the methods used to identify ITO NWs: energy dispersive spectroscopy (EDS), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), and X-ray diffraction (XRD). The growth mechanism of ITO NWs was studied using carbothermic reduction to destabilize and evaporate In_2O_3 and SnO_2, the growth mechanism of ITO NWs was studied.

In addition, photoluminescence (PL) and electrical resistance tests were performed to examine the optical, electrical, and structural properties of ITO and Ag-ITO NWs. [11]. To produce nanomaterials, the electrochemical method uses an external electric field and loads to initiate an electrochemical reduction reaction. AgNWs with a particular morphology can be efficiently grown more quickly using both electrochemical and template methods concurrently.

Xu et al. succeeded in producing an array of AgNWs organized by cyclic voltammetry that has a high density and high aspect ratio, using an anodic aluminum oxide (AAO) template in an $AgNO_3$ aqueous solution [55]. The quality of nanowires has increased owing to the use of electrochemical techniques, allowing for controlled size control between 30 nm and 1 µm, and alignment of the nanowires. However, this approach is not practical for mass production because it requires an expensive and intricate hard mold [56].

2.2. Chemical method

The chemical method for synthesizing silver nanowires involves the reduction of silver salts, typically silver nitrate ($AgNO_3$), in a solution with a reducing agent, such as sodium borohydride ($NaBH_4$) or ascorbic acid. The reduction process leads to the formation of silver atoms, which then nucleate and grow into one-dimensional structures, typically in the presence of surfactants or stabilizers to prevent aggregation and control their morphology. This procedure enables the precise control of the size and aspect ratio of the nanowires, but it may face challenges attributed to the purity, uniformity, and scalability of

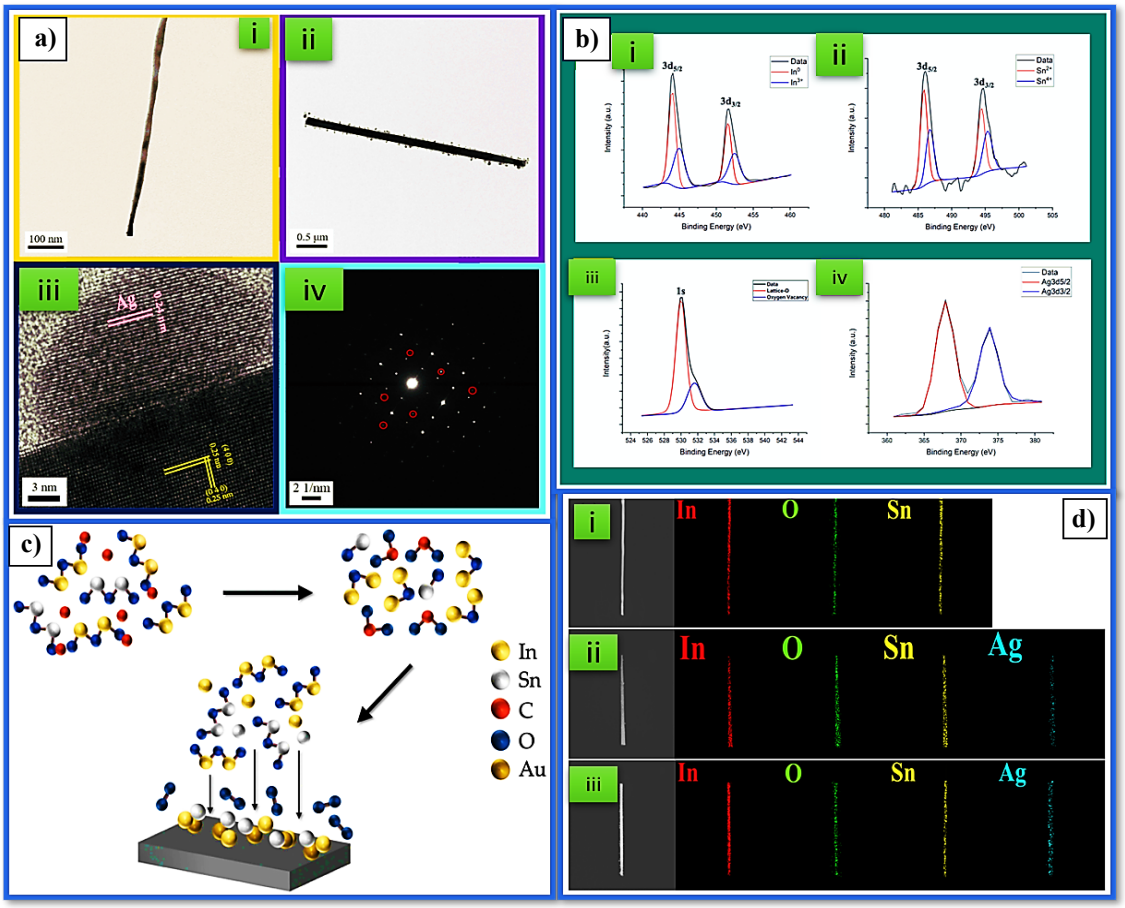


Fig. 5. a) i & ii: TEM images ,iii: HR-TEM image of the Ag-ITO NW, and iv: SAED pattern, b) XPS interpretation of spectra for i: In, ii: Sn, iii: O, and iv: Ag, c) schematic presentation of the growth mechanism of ITO NW, where the reaction follows the VLS route, and d) EDS mapping of the: i) ITO NW, ii) 1 at% Ag-ITO NW, and iii) 3 at% Ag-ITO NW. Reproduced with permission from Ref. [11].

the nanowires, as side reactions can occur. Additionally, the chemical method may not always produce nanowires with the high aspect ratio and quality achievable by other techniques like the polyol process [56]. With the advancement of technology, chemical techniques can now demonstrate their superiority in manufacturing AgNWs without the use of electrochemical methods. The reaction systems of this technique are completed by assuming that a reducing agent, oxidizing agent, and stabilizer are all in the liquid phase with a stabilizer to set the initial state. The term 'chemical method' often refers to chemistry performed in the liquid state. There are cutbacks. AgNWs are challenging to transfer and assemble, but the wet chemical method can produce a high-purity product by modifying the chemical reaction parameters and generating a metal nanomaterial with a specific morphology [57, 58].

2.3. Template method

The template method for synthesizing silver nanowires involves using a template material, typically a porous or fibrous structure, which directs the growth of silver in a specific pattern. Silver ions are reduced onto the template through chemical reduction, electrochemical deposition, or other methods. The template material, which could be an anodized aluminum oxide (AAO) membrane, a polystyrene bead array, or a polymer substrate, serves as a scaffold to guide the growth of the nanowires, resulting in well-aligned, uniform structures. After the deposition, the template is removed, leaving behind the silver nanowires. This method provides excellent control over the morphology and alignment of the nanowires, yielding high-quality products. However, it can be labor-intensive, requires careful control of the template characteristics, and may face limitations in scalability due to the need for template removal and potential defects introduced during the process [23, 34].

The traditional template method starts with the preparation of a particular template, which encourages the development of Ag nanoclusters in a one-dimensional direction following the necessary aspect ratio. Molds can be classified into two categories: soft and hard. The nucleation and synthesis of AgNWs are guided by the hard template approach, which uses materials with nanoscale porosity, such as zeolites, carbon nanotubes, nanoporous polymers, and non-porous silica [23, 34].

Because Ag atoms are transformed into nanowires by the rigid template predesigned structure, this gives the nanowires more control over their size, shape, and overall morphology. The lower yields may result from a substantial loss of nanowires generated during the purification process, despite the simplicity and effectiveness of the method. Soft molding techniques use compounds that dissolve or disperse in solvents. This improves efficiency and scalability because the nanowires produced are easily filtered from the solvent phase. Specifically, the growth of AgNWs is facilitated by the formation of micelles and emulsions through surfactant diffusion in the soft template approach. Proteins and DNA are the most commonly used soft templates [59, 60].

As seen in Fig. 6a–d, Zhao et al. [61] produced Ag and Au nanowire arrays using a photochemical method and a PVA polymer coating on

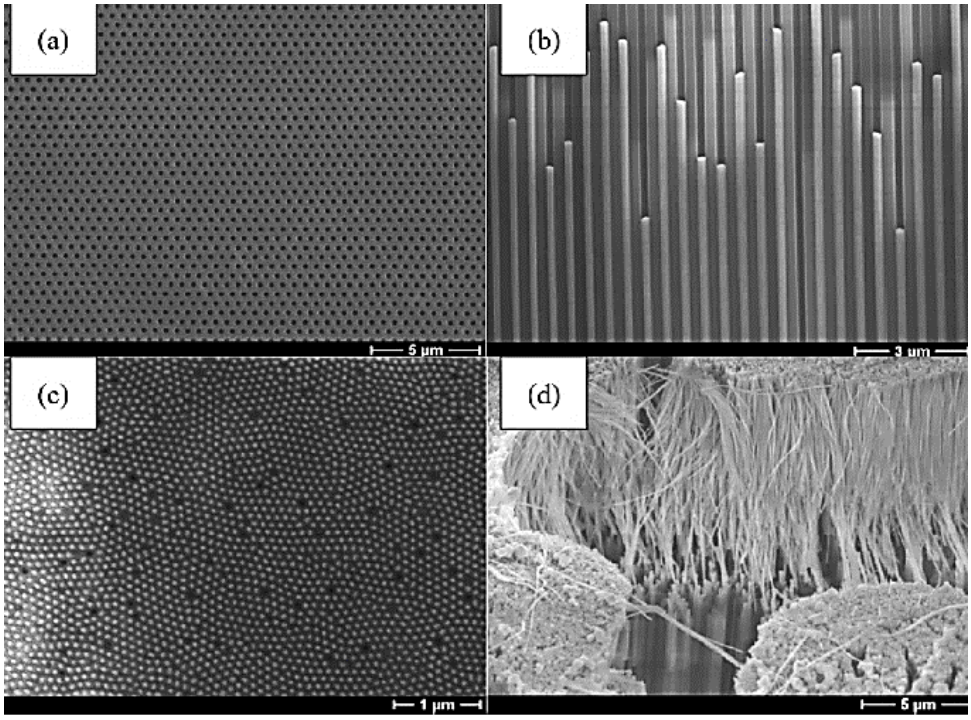


Fig. 6. Diagram illustration of how hard mold porous alumina is used to prepare AgNW. a) Single-domain porous alumina observed with a scanning electron microscope (SEM) showing a pore diameter of 180 nm and an interpore spacing of 500 nm, b) AgNWs infiltrated in a single-domain porous alumina template; patterned AgNWs are seen as brighter bands in the SEM cross-sectional picture, c) AgNW infiltration pattern image in vertical perspective, and d) AgNW with several clusters. Reproduced with permission from Ref. [9].

an anodized porous aluminum mold submerged in an aqueous solution of $HAuCl_4$ and $AgNO_3$ at room temperature [61]. Using the soft template method, template removal is unavoidable, and numerous surface flaws can manifest on AgNW surfaces, thus compromising the overall performance [59].

2.4. Polyol method

Silver nanowires can be synthesized simply and efficiently using polyol synthesis. Researchers have discovered that long-chain PVP can encourage the nanoparticles to organize linearly during the polyol process, lengthening the AgNWs. Moreover, the final product contained many nanoparticles owing to its high KBr content. In addition, the kinetics of the reaction were regulated by adjusting the temperature of the solution and the KBr material. KBr prevents the development of oversized particles and lowers the silver ions concentration in the solution by generating AgBr [42].

The polyol method is the most effective approach for synthesizing high-quality AgNWs on a large scale. This process begins with the reduction of the metal salt with a polyol during the heating phase. In these reactions, poly(vinyl pyrrolidone) (PVP) was employed as a stabilizing agent to prevent the accumulation of AgNPs [49].

Polyol is a standard method for producing AgNWs with optimal shape and improved performance at a lower reaction temperature. The three stages comprise the preparation of AgNWs: nucleation, grain evolution from nucleus to grain, and grain development to nanocrystal. The polyol method for synthesizing the AgNWs is shown in Fig. 7a. $AgNO_3$ is typically used to create seed-based AgNWs, which are normally chosen from Pt or Ag in the presence of PVP, using the polyol method of AgNW preparation [30, 62]. Sun et al. [4] examined the development mechanism of AgNWs and presented a large-scale synthesis method based on a polyol process. Schematic designs of the growth mechanism proposed by Xiang et al. [58] are shown in Fig. 7b & c. During the reduction of $AgNO_3$ with EG, the AgNWs produced by Sun et al.'s research have a conductivity of 0.8×105 S/cm and are controlled at 30–40 nm with a length of up to 50 μm [4].

Among the techniques for creating AgNWs, the polyol method is inexpensive, straightforward, and produces a sizable yield [63]. Mao et al. developed a polyol approach to prepare nanoscale metal particles. During the polyol process, metal colloids are synthesized by warming a polyol solvent in conjunction with a polymer-based coating agent and a precursor salt. Specifically, in the formation of silver nanostructures, ethylene glycol (EG) functions as a polyol, polyvinyl pyrrolidone acts as the capping agent, and silver nitrate is used as the precursor salt [13]. In this process, a polymeric coating agent is present and silver ions undergo chemical reduction. To help grow the necessary form of silver buds, a small amount of salt was added. EG functions as both a reducing agent and solvent [64]. The functionality and shape of the produced AgNWs are influenced by multiple factors. To prevent the quick creation of supersaturated silver, a silver nitrate solution should first be added slowly. Second, the reaction solution should produce twin-propagated particles (MTP) in the shape of decahedrons in the (111) directions. Reducing the additional free energy on the surface directs their creation. Following MTP creation, Ag atoms are drawn to the high local surface energy of the twin orientations, which permits MTPs to grow uniaxially. To promote uniaxial elongation, the PVP protection agent is adsorbed and passivated in the (100) directions, leading to the addition of Ag in the 111 directions [7, 36].

The polymeric agent (PVP), which forms an O-Ag bond with the surface of Ag seeds, causes the Ag seeds to be evenly distributed throughout the reaction solution [65]. The morphology of the AgNWs generated in the polyol process by salt depends on a minimal amount of appropriate salts, including $Fe(NO)_3$, NaCl, CuCl, and $CuCl_2$. Subsequently, the MTPs that were first developed could develop into wires. In terms of cost, throughput, and the possibility of producing nanostructures in large quantities, solution-phase synthesis may be the most efficient. In contrast, the strongly anisotropic crystal structure of solid materials facilitates the formation of homogeneous nanowires up to 50 μm in length from their solutions. However, nearly all metals crystallize in symmetric a cubic lattice, which makes this difficult. Anisotropic restrictions should be used to promote and sustain one-dimensional growth to address this issue, according to research done by Wang et al. One-dimensional growth of nanowires can achieve this [20].

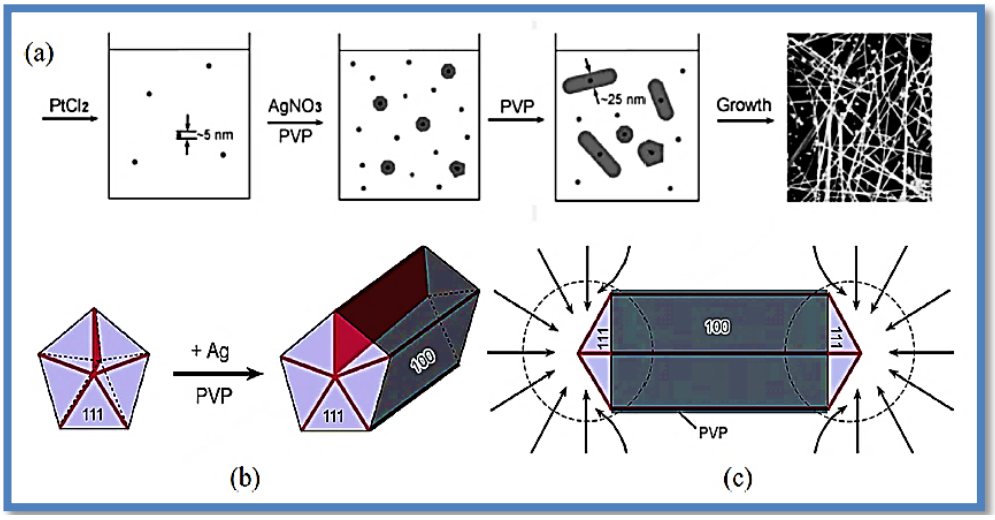


Fig. 7. a) Schematic illustrating the platinum seed polyol process's production of AgNWs [4], b) pentagonal section boundaries. PVP passivated the sidewalls of the nanorods after, and c) dispersed silver atoms to both of their ends [16]. Reproduced with permission from Refs. [4, 16].

The formation of AgNWs is linked to the Ostwald ripening process. When silver nitrate is reduced in the presence of wire-forming agents such as $CuCl_2$ or sodium chloride, silver nanoparticles with a pentahedral shape distribution are produced. This occurs as a result of heterogeneous and homogeneous nucleation within the reaction mixture. The Ostwald ripening technique can then be used in the subsequent stage to manufacture larger AgNPs. Most of the larger silver particles became uniformly sized nanorods or nanowires during the early stages of the ripening process. Subsequently, they can grow into evenly sized nanowires that can reach lengths of up to 50 µm [66, 63, 21]

In various polyol processing investigations, researchers have employed polyvinylpyrrolidone (PVP) as a stabilizer and EG as a regenerator. As a result, the precursors regenerate, and the metal ions change into metal particles [40 ,12]. AgNWs have been successfully generated in multiple studies using silver precursors and ethylene glycol (EG) as the solvent and reducing agent, respectively. The first step in this reaction is the nucleation process, which creates nucleation particles from the precursor in the EG. Ultimately, AgNWs were made from Ag atoms.

For example, Pt atoms become Pt nanoparticles when $PtCl_2$ is reduced using EG solution. These nanoparticles were employed as crystal buds for the growth of silver atoms and heterogeneous nucleation reactions. PVP and silver nitrate were then added to the solution. EG, silver nitrate, and PVP were used as the surfactant, polyol, and salt precursors, respectively. The reduction of silver nitrate resulted in the accumulation and prolonged reaction of the Ag atoms. Ag buds grow because of this interaction, and AgNWs are eventually produced [65, 21].

Fig. 8a presents a schematic illustration of the AgNW synthesis process described by Lahane et al. and Fig. 8b illustrates the AgNW synthesis. Initially, nanocubes of AgBr and AgCl form heterogeneous nuclei. Subsequently, Ag^+ ions were gradually reduced to Ag atoms in the presence of ethylene glycol acting as a reducing agent. This sequence of reactions leads to the seed formation of single-crystal silver and

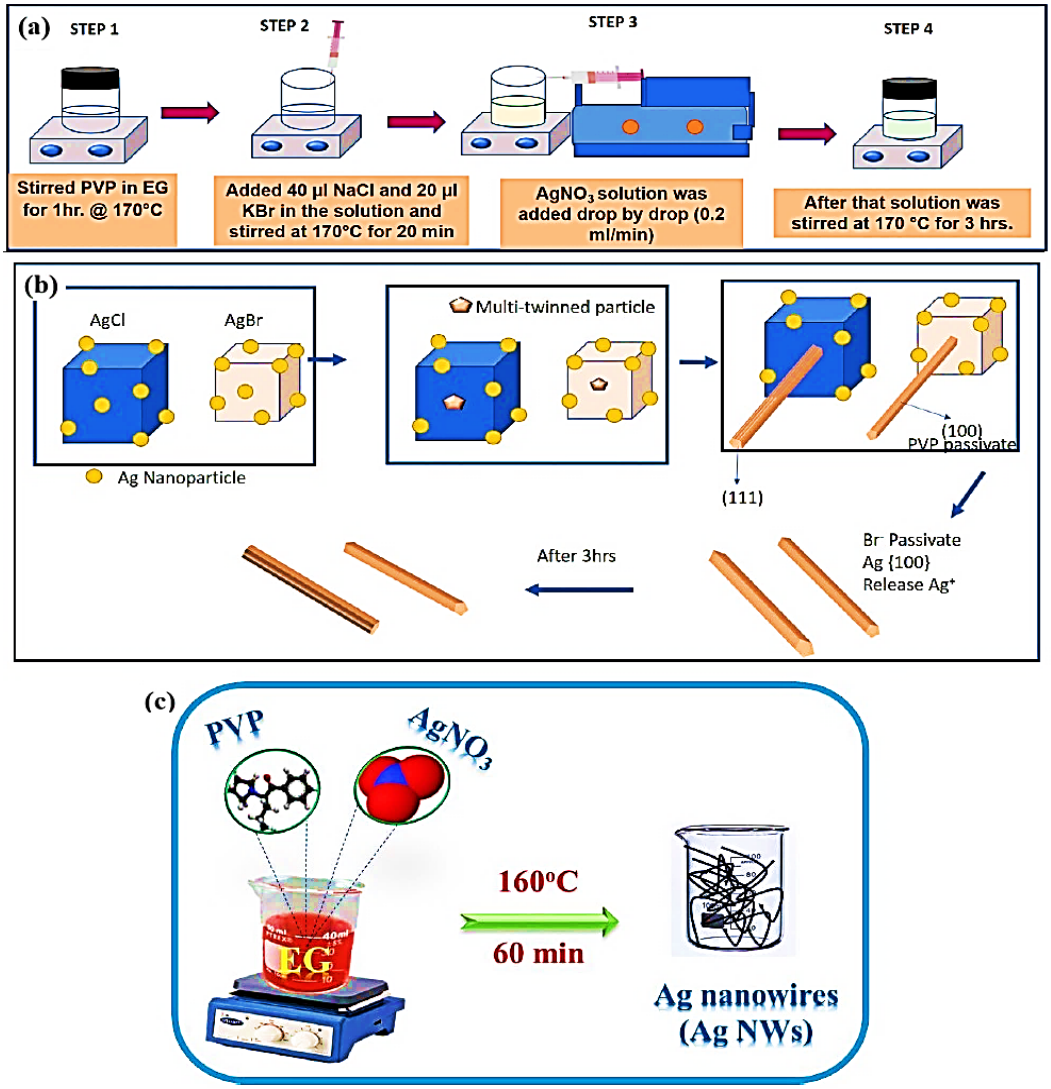


Fig. 8. a) Schematic of experimental process of the AgNWs synthesis, b) mechanism of silver nanowires growth [7], and c) Schematic illustration for the AgNWs synthesis [18]. Reproduced with permission from Refs. [7, 18].

Table 3. Synthesis and characteristics of silver nanowires using the polyol method.

Transparency (%)	Resistance ($\Omega.sq^{-1}$)	Diameter (nm)	Length (nm)	Ref.
88	40	15–30	20	[10]
96	100	100	80–100	[4]
99/1	130	20	40–50	[19]
N/A	N/A	30–50	50	[71]
N/A	N/A	30	50	[72]

multitwinned particles (MTPs) on the nanocubes surfaces of AgBr and AgCl. For the growth of AgNWs, MTPs, and PVP macromolecules functioned as seed and capping agents, respectively. Anisotropic development along the (111) plane in the (110) direction was encouraged during the growth phase by passivation of the (100) facets by PVP. The MTPs continued to expand into the AgNWs as long as Ag^+ ions were added. At the same time, the breakdown of AgBr nanocubes facilitates the steady release of Ag^+ and Br^- ions into the solution, promoting the growth process [7, 67]. In addition, Fig. 8c shows a schematic of the process.

However, research by Sun et al. [16] asserted that $PtCl_2$ or other foreign nuclei are not necessary to synthesize AgNWs. AgNWs can also be formed from Ag atoms by self-assembly. Using this method, Ag atoms can be converted into uniform AgNWs at a rate regulated by chemical solutions. Polyol has emerged as the most common way to synthesize AgNWs owing to its ability to create homogeneous nanowires on a broad scale [16].

Researchers believe that PVP can regulate how quickly the silver structure grows and that sodium chloride or $CuCl_2$ buds in the solution can accelerate the formation of the silver structure [41]. Moon et al. [68] achieved the synthesis of AgNWs with an aspect ratio close to 800 and lengths between 80 and 100 μm [68]. Lee et al. developed ultrathin click nanowires by applying high pressure to the polyol method [69, 70].

Furthermore, Li et al. developed ultra-thin AgNWs with extremely high transmittance and proposed a purification method for AgNWs synthesized via the polyol process [51]. Table 3 presents the results for the AgNWs prepared using the polyal process.

According to the research results, many factors may control the shape of the AgNWs and increase their efficiency. These factors, which are covered in the following order, are the temperature, reactant concentration, reaction time, molar ratio of PVP/($AgNO_3$), reducing agent type, mixing rate, seed particles (seeding agents), and molecular weight of PVP.

Finally, Table 4 summarizes all the methods discussed, along with their respective advantages and disadvantages.

3. Effective factors

3.1. Temperature

The reaction temperature can influence the grain growth rate and the resulting morphology of AgNWs. In general, higher temperatures have a faster growth rate; however, they may also lead to nonuniform shapes. Several studies have demonstrated that AgNWs can be significantly affected by the temperature at which ethylene glycol is converted to glycol aldehyde and used as a reducing agent. Fig. 9a & b shows the effect of temperature on the growth of the AgNWs.

Most of the synthesis reactions in the first step were performed at 160 °C, with a reaction duration of roughly one hour. When the temperature approached 160 °C, the majority of the AgNWs exhibited a sharp drop in length [41]. For example, the researchers found no AgNWs formed in experiments conducted when the temperature was set to 100 °C [16].

At lower temperatures, the anisotropic development of the AgNWs was inhibited by insufficient energy. After the reaction, AgNWs were simultaneously synthesized at a synthesis temperature of 185 °C. Sun et al. [4] demonstrated that when the temperature was 10 °C higher or lower than the preceding temperature, the nanoparticles dramatically transformed into nanowires via the $CuCl_2$-mediated polyol process at 150 °C.

Table 4. Comparison of different synthesis methods for AgNWs, highlighting their respective advantages and disadvantages.

Synthesis method	Advantages	Disadvantages	Ref.
Template method	High control over size and shape	Complex and time-consuming process	[59]
	Produces high-quality	Limited scalability	[61]
Chemical method	Simple and cost-effective	Difficult to control morphology	[10]
	Suitable for large-scale production	Requires high temperatures and toxic chemicals	[7]
Polyol method	Low cost and high efficiency	Produces nanoparticle byproducts	[19]
	Scalable and reproducible	Requires precise control of parameters	[72]
Electrochemical method	High reproducibility and control over nanowire growth	Requires complex equipment and high-precision control	[16]
	Can be applied to large areas	Limited to certain substrates	[11]

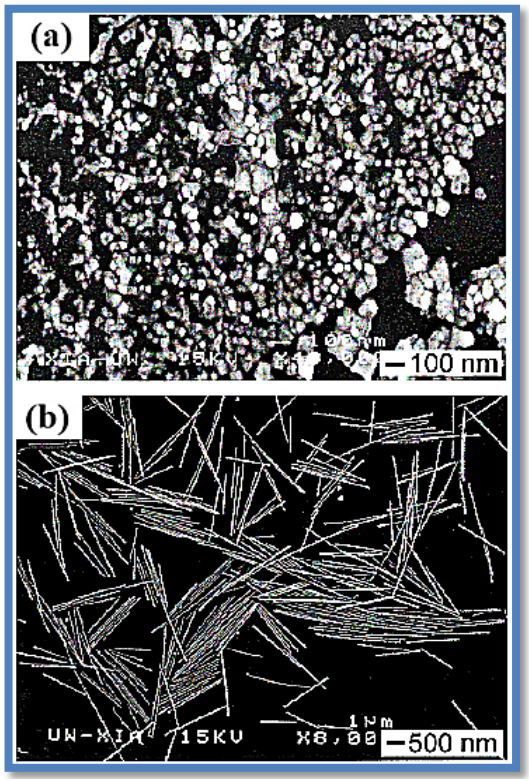


Fig. 9. SEM image of the product at a) 100 °C and b) 185 °C. Reproduced with permission from Ref. [16].

Mao et al. [31] reported that the diameter of the AgNWs decreased with the increasing temperature of the reaction. They also found that AgNWs had the most minor diameter when created at 170 °C. The nanowires did not develop at temperatures below 110 °C. The components produced at 100 °C were consisted of silver nanoparticles of various sizes and morphologies, as demonstrated by the SEM images.

Following the initial formation of the solution at 100 °C, the transformation of specific nanoparticles into nanorods or nanowires occurred when the temperature was maintained at 160 °C for one hour (Fig. 10c). Increasing the temperature is essential for dissolving smaller silver nanoparticles and facilitating the movement of silver atoms across the surfaces of the nanowires. On the other hand, high temperatures promote the silver nanowire formation with a low-aspect-

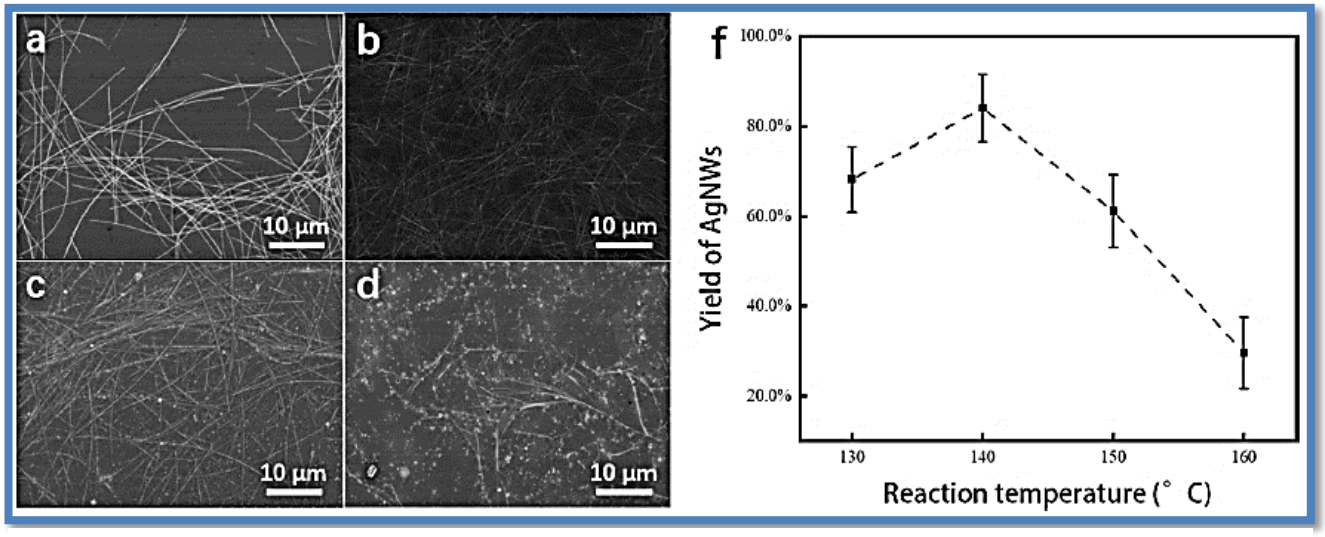


Fig. 10. SEM images of AgNWs obtained at different temperatures: a) 140 °C, b) 130 °C, c) 160 °C, d) 150 °C, and f) yield of AgNWs from different reaction temperatures. Reproduced with permission from Ref. [12].

ratio. Consequently, the activation of different nanostructures required for the isotropic growth of nanowires is prevented by insufficient energy from the relatively low reaction temperatures [6, 53, 68, 73].

Therefore, the reaction temperature is essential for the AgNW formation. Fig. 10a–d displays the SEM images of the AgNWs produced at different temperatures. At 130 °C, lower temperatures were sufficient to produce shorter AgNWs. This is because the extremely low reaction temperature causes the initial buds of the AgNWs to develop quickly. However, as the reaction temperature rose, the quantity of silver nanoparticles gradually increased. This is explained by the significant increase in non-pentaploid buds caused by the Homogeneous nucleation process. These results indicated that 180 °C is the optimal reaction temperature for high-purity AgNWs [19 ,10].

3.2. Concentration of reactants

The concentrations of PVP and $AgNO_3$ can have a significant impact on the size and efficacy of AgNWs. Furthermore, the size and form of the silver nanostructures had a substantial impact on several experimental variables, including the concentrations of $AgNO_3$, PVP, and NaCl. It was discovered that the best conditions for the creation of silver nanorods and nanowires are a low PVP content (50 mM), a medium NaCl concentration (3 mM), and 120-minute heating times [16, 64].

Fig. 11a shows FE-SEM images demonstrating that at higher NaCl concentrations (10 mM), silver chloride particles also occur in Fig. 11b & c in addition to the one-dimensional products (nanorods and nanowires) in Fig. 11a. Fig. 11b illustrates how the concentration affects the AgNW growth. According to research by Li et al. in 2015, the diameter and corresponding optoelectronic properties of silver nanowires synthesized through the polyol method can be fine-tuned by varying the concentration of bromide. Additionally, introducing 2.2 mM NaBr to a suitable silver nanowire precursor can result in the formation of silver nanowires with a diameter of 20 nm and an aspect ratio as high as 2000. They discovered that metal nanowire networks are the best-performing solution-coatable substitutes for ITO and presented a method for producing and refining AgNWs that exceed ITO when coated with conductive ink to create a transparent conductive monolayer [70].

Li et al. observed that the introduction of 1.1 mM NaBr led to a reduction in the nanowires' diameter to an average of 36±7 nm. A further decrease in diameter to 20±2 nm was achieved by incorporating 2.2 mM NaBr. Moreover, an increase in the NaBr concentration to 4.4 mM elevated the nanoparticle density within the final reaction mixture [20].

Additionally, the main products turn into nanoparticles when 8.8 mM NaBr is introduced. They showed that the diameter drop observed with the addition of NaBr is mainly caused by an increase in nucleation that arises from the conversion of Ag^+ to Ag. Furthermore, when the NaBr concentration was raised from zero to 2.2 mM, more nanowires were generated. This increase is primarily attributable to the reduction in the diameter of the reaction and the increase in nanowire production. This demonstrated that the number of nucleations increased with the addition of NaBr.

In recent years, researchers have discovered that very thin nanowires can be produced using the polyol technique because of the concentration of bromide ions. Zhang et al. [30] concluded in their investigation that increasing the concentration of bromide ions can lead to a decrease in the width of AgNWs. In this regard, the TEM pictures of AgNWs produced with varying doses of KBr and NaCl are shown in Fig. 12a–e. More particles were formed as the number of bromide ions increased, whereas the amount of AgNWs gradually decreased. Furthermore, the artificially generated AgNW diameter distribution demonstrated that when KBr grew, the number of very thin nanowires less than 30 nm grew as well [10].

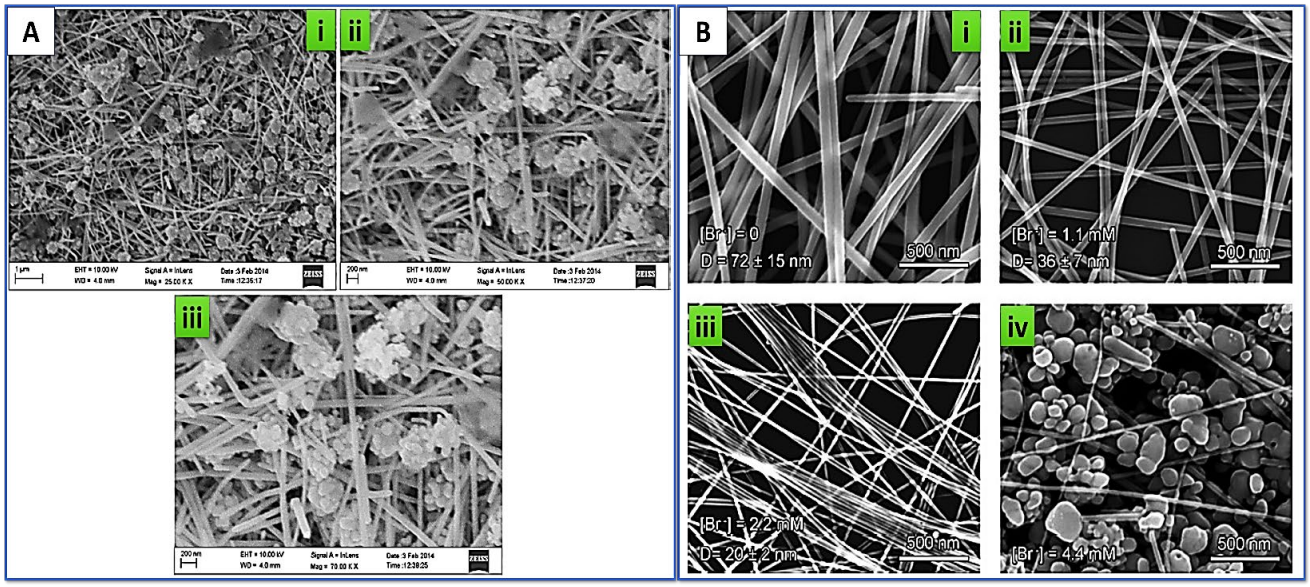


Fig. 11. a) FESEM images of silver nanostructures in NaCl concentration (10 mM) and b) high-resolution SEM images of the purified products obtained at different concentrations of: i) 0 mM NaBr, ii) 1.1 mM, iii) 2.2, and iv) 4.4 mM. Reproduced with permission from Refs. [13, 20].

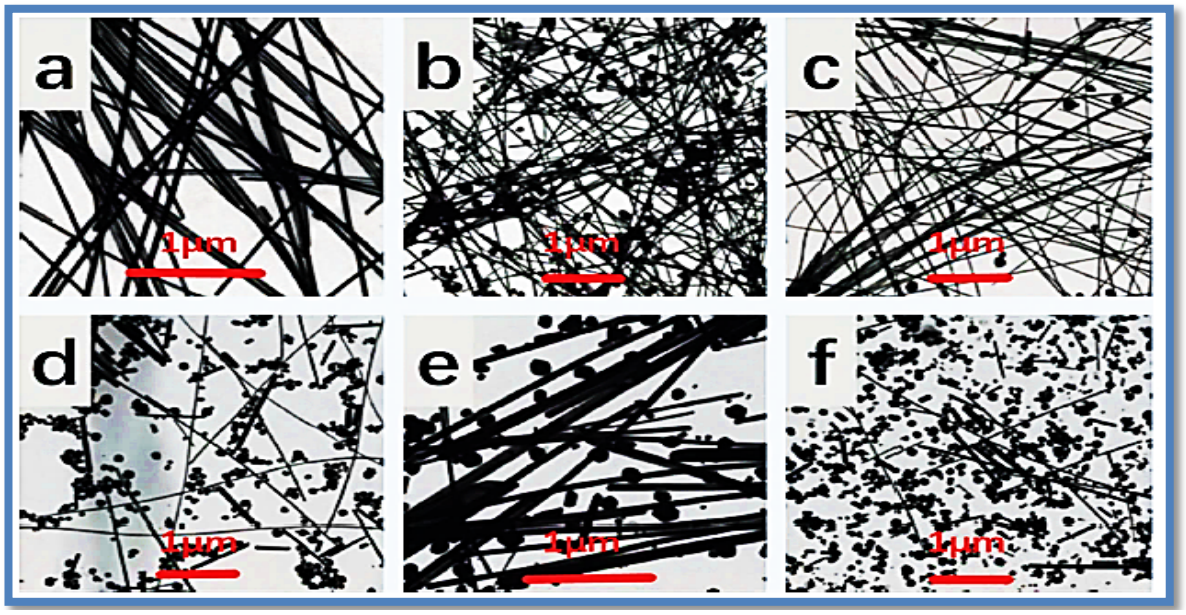


Fig. 12. TEM images of AgNWs synthesized using a) 0.125 mM NaCl, b) 0.1 mM NaCl, c) 0.025 mM KBr, d) 0.041 mM NaCl, e) 0.041 mM KBr, and f) 0.0840 mM KBr. Reproduced with permission from Ref. [67].

3.3. Reaction time

Wei et al. [12] produced high-purity silver nanowires (AgNWs) at different reaction times in one investigation. Different UV-Vis absorption wavelengths allowed for the observation of the AgNW production process. Fig. 13a shows the variable surface plasmon resonance (SPR) wavelengths; which may be related to the varying AgNW diameter and shape resulting from various reaction times [12].

Fig. 13 shows the reactant solution with a broad peak at approximately 423 nm, approximately 10 min after the reaction started. The pentatonic nanoparticle surface tension response in solution was responsible for this peak. Consequently, AgNWs were responsible for the prominent peaks at 374 nm SPR [12]. The size and yield of nanowires are frequently influenced by the reaction periods; longer times lead to more significant sizes and higher yields, but they also encourage the development of contaminants. According to a 2002 study by Sun et al. on the uniform synthesis of silver nanowires, nanowire development increases with reaction time [16].

3.4. Mixing rate

Agitating and blending the solution leads to the creation of silver nanowires with consistent lengths and diameters while minimizing the buildup of silver atoms and clusters. The mixing rate influences the resulting shape and dimensional ratio of the final products in the polyol synthesis of AgNWs [74].

Fig. 14a shows FE-SEM images of the artificial silver nanostructures at various polyol reaction mixing rates. Conducting the reaction at a stirring speed of 300 rpm resulted in the silver nanowires formation, which on average measured about 100 nm in diameter. The fewest nanoparticles were also present in the nanowires. As demonstrated in Fig. 14b, the final manufactured product contains more than just silver nanowires when the mixing rate of the solution is increased.

Additionally, when the polyol reaction was conducted at a high mixing rate (1200 rpm), nanostructures of different sizes and shapes were formed. This 1200 rpm polyol reaction results in final products that blend one-dimensional and zero-dimensional silver nanostructures. Individual silver nanowires range in size and have varying diameters at different points along their lengths, as shown in Fig. 14a. The size of the one-dimensional nanostructures resulting from the high mixing rate is shown in Fig. 14c. According to the picture, it can be seen that the one-dimensional products resulting from this reaction have a length dimension higher than 200 nm and a smaller diameter, Thus, it can be deduced that increasing the mixing rate in the reaction produces a variety of silver morphologies, such as nanowires, nanorods, and quasi-spherical and cubic silver particles of different sizes [9].

3.5. $\frac{PVP}{AgNO_3}$ molar ratio and PVP molecular weight

Additionally, the average diameter of the silver nanowires was influenced by the molar ratio of the polymer (PVP) to the precursor salt ($AgNO_3$). Scientists have shown that when the molar ratio of PVP/$AgNO_3$ drops from 9 to 3, the composition of the product shifts from spherical to nanowire. However, increasing the molar ratio causes undesirable formations in the product [34, 43].

In our previous research, we were able to obtain silver nanowires with different molar ratios, and the silver nanowire synthesis reaction was influenced by the molecular weight and PVP/$AgNO_3$ molar ratio [1]. The Ag-based sample morphology and characteristics depend highly on the preparation parameters, including temperature, PVP chain length, reaction duration, and PVP concentration of the starting materials. According to our study, there was a weak chemical connection between C–N and Ag at the PVP molecular weight contact.

Therefore, it can be concluded that both the molar ratio and molecular weight influence the process and must be controlled and optimized. SEM images of samples based on silver nanowires

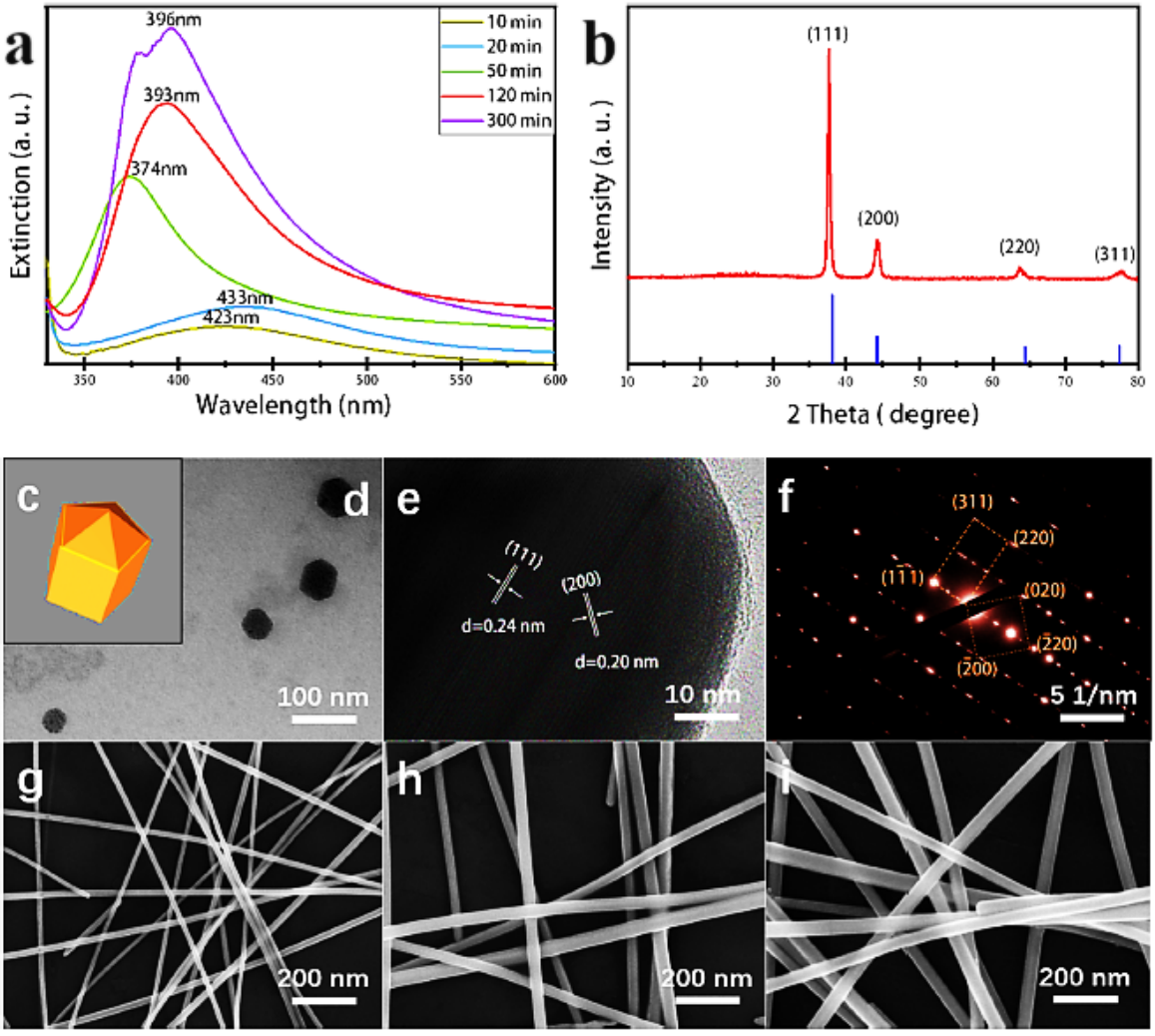


Fig. 13. a) UV-vis absorption spectra of AgNWs at different reaction stages, b) XRD spectrum of AgNWs, c) geometrical simulation graphics of quintuple twin nanoparticles, d) TEM image of nanoparticles obtained at 10 min reaction time, e) HRTEM image of AgNWs, f) SAED pattern of AgNWs, g–i) SEM images of AgNWs obtained at different times (g: 50 min, h: 120 min, and i: 300 min). Reproduced with permission from Ref. [12].

fabricated using the polyol method which involves reducing Ag ions with glycerol in the presence of PVP and NaCl are displayed in Fig. 15. Silver nanowires were abundant in the SEM images of the prepared samples, along with nanowires, nanorods, and nanocubes. It is clear how the AgNW form is influenced by the molar ratio of PVP to $AgNO_3$ [7, 12].

The presence of silver nanowires including some silver nanoparticles was observed in Fig. 15a & d at molar ratios of 1.5 and 3. The nanowires became more pseudo-cubic as the molar ratio increased (Fig. 15c). The nanocubes are visible at a molar ratio of 5. As a result, the crucial molar ratio of PVP to $AgNO_3$ in this reaction system to synthesize AgNWs is approximately 1.5, as specified in the publications [1].

Furthermore, the final product morphology was significantly influenced by the length of the PVP chain. Although 40,000 wt% PVP was utilized in the synthesis, more nanowires were generated than 360,000 wt% PVP. Instead of producing nanowires, the solution formed nanoparticles when high-molecular weight PVP was introduced. One can observe nanowires and a small number of nanocubes from Fig. 15e–g, respectively. The nanowires are presented clearly in Fig. 15h. The presence of silver nanoparticles indicates that not all nanoparticles are transformed into nanowires during synthesis [1].

The shape of silver nanowires is primarily influenced by the molecular weight of polyvinylpyrrolidone (PVP) and the molar ratio of PVP to silver nitrate ($AgNO_3$). Additionally, when the PVP to $AgNO_3$ ratio was relatively high, a dense PVP coating on all surfaces of the nanowire buds led to an isotropic growth mode. Furthermore, the low PVP to $AgNO_3$ ratio lowers the coverage of each nanowire's side surfaces and its quickly expanding end surfaces. Furthermore, the lateral growth of the nanowires causes them to grow longer on one side and more significant in diameter due to lateral growth, making the partial PVP coating on the lateral surfaces unable to passivate these surfaces [18, 66].

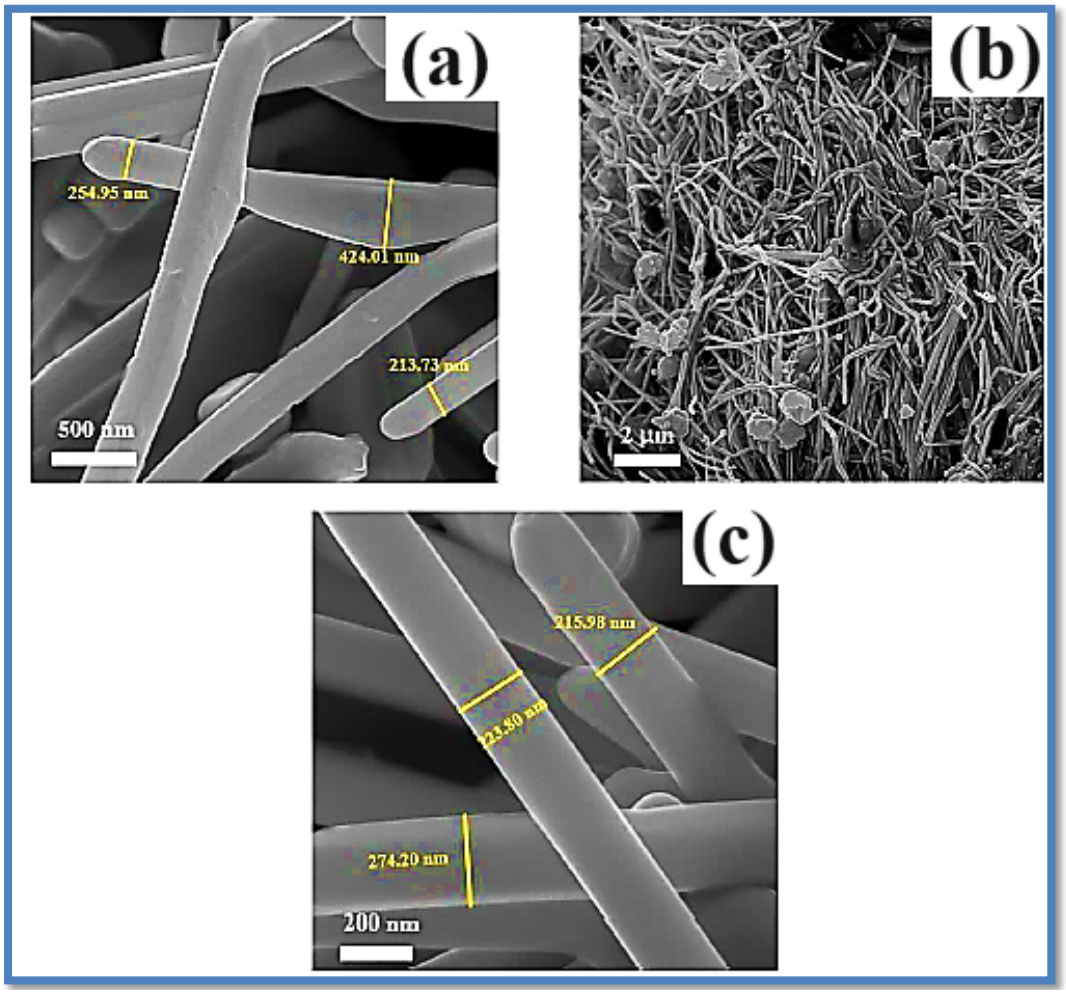


Fig. 14. FE-SEM images of silver nanostructures synthesized under different mixing rates at a) 300 rpm, b & c) 1200 rpm. Reproduced with permission. from Ref. [9].

4. AgNWs conductive ink

Numerous techniques have emerged for creating silver nanowires (AgNWs), which can be broadly categorized into four groups: template, electrochemical, chemical, and polyol methods. Despite these advancements, achieving large-scale AgNWs with predictable shapes remains challenging. This limitation hinders the development of AgNW-based flexible transparent conductive films (FTCF) [37, 50, 60].

Conductive ink is the principal material used in the printing technology. The quality of the flexible transparent conductive film (FTCF) is significantly affected by its efficacy. Solvents, functional additives, adhesive agents, and conductive fillers are essential components of conductive inks [27, 35, 37, 50, 60]. Functional additives encompass a range of components, including surfactants, dispersion stabilizers, humectants, pH adjusters, defoamers, and leveling agents. When it comes to FTCF, silver nanostructured conductive inks predominantly utilize either silver nanoparticles (AgNPs) or silver nanowires (AgNWs), sometimes in combination with graphene or highly conductive polymers [7, 27, 35, 40, 47, 60].

The mass of AgNWs had a significant impact on the conductivity of the printed FTCFs. A higher AgNW mass concentration often translates into more vital conductivity. Furthermore, alcohol or water are commonly utilized as solvents for AgNW conductive inks, as they are both hydrophilic and cannot effectively bind with non-hydrophilic substrates. Consequently, substrate treatment is required to produce FTCF [24, 50].

In addition to using a single solvent, two solvents with varying boiling points were combined to diminish the surface tension. Li et al. [25] N-methyl pyrrolidone, ethylene glycol, glycerol, and N-methyl pyrrolidone in a 1:2 to 1:4 volume ratio: The ratio of glycerol and ethylene glycol was determined to be 5 to 7.

Silver nanowire (AgNW) ink production is relatively simple. Usually, AgNWs are added directly to a solvent, well-mixed, and then mixed well with the appropriate adhesive and additive [56]. However, AgNWs typically precipitate and clump together in the ink under normal circumstances. Scientists have been using various techniques to improve the stability of AgNW inks. Binders modify the viscosity and surface tension of the ink in addition to increasing the adhesion of the AgNWs to the substrate to enhance compatibility during printing. Furthermore, AgNPs or AgNWs are dispersed using surfactants, which

improve the wettability and durability of the ink. In addition, a leveling agent was applied to improve ink flow [18].

Some researchers [75, 76] developed a stable and long-lasting silver ink with an adhesive composed of hydroxyethyl cellulose, a formic acid-reducing agent, and an isopropanolamine silver complex. The ink was used to produce flexible electrodes. Li et al. [77] utilized ultralong silver nanowires (AgNWs) as conductive components. They developed a straightforward formulation and successfully fabricated flexible transparent conductive films (FTCF) with remarkable properties. These films demonstrated excellent mechanical stability, conductivity, and light transmittance of approximately 80% on a screen-printed, flexible polyethylene terephthalate substrate.

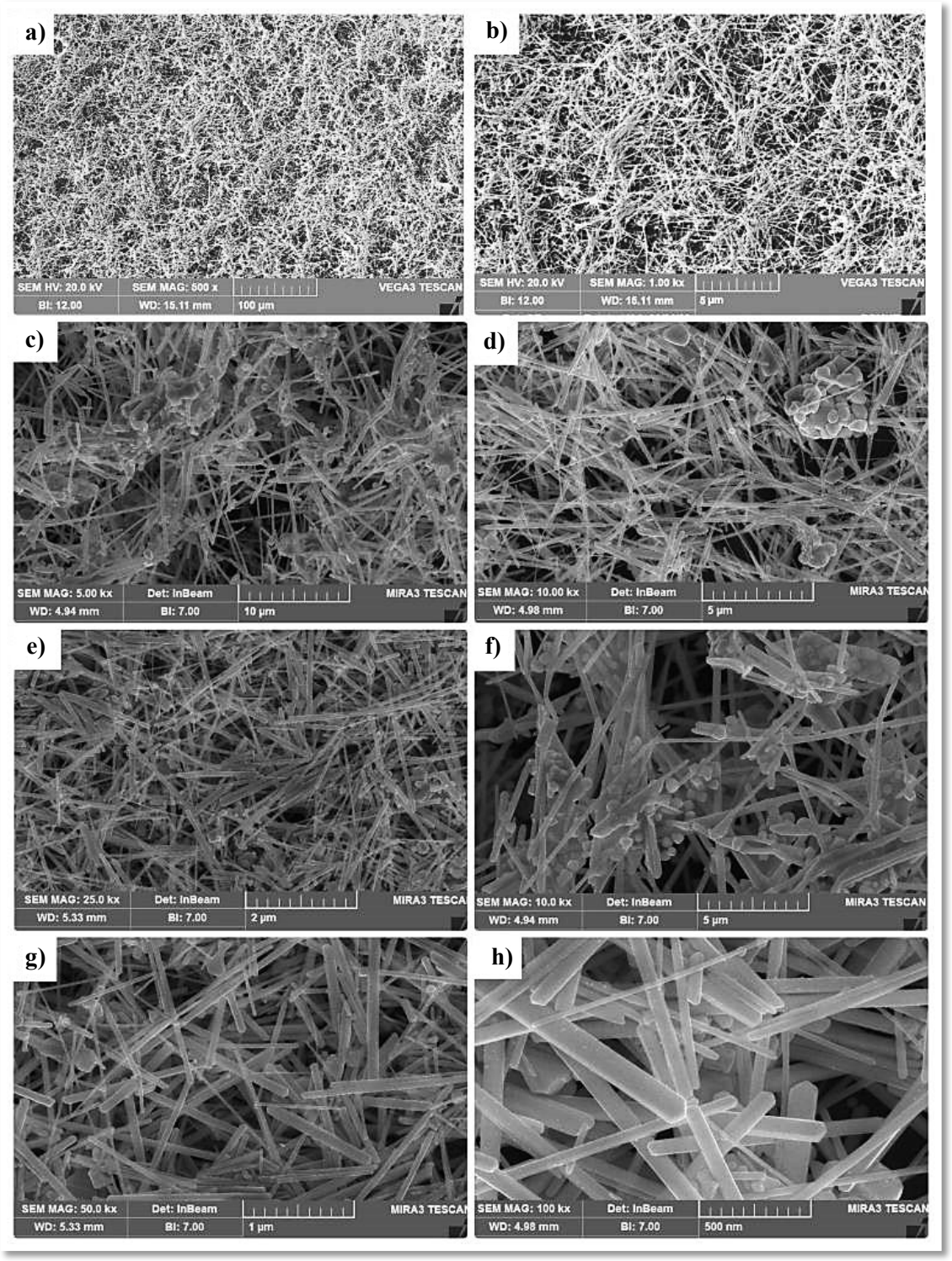


Fig. 15. a & b) SEM images and c–h) FE-SEM images of silver nanowires using different molar ratios [1].

It is well known that the concentration and characteristics of silver nanowires (AgNWs) and other additives are intimately linked to the ink's viscosity and surface tension. The uneven forces acting on the surface atoms give rise to surface tension, which has a significant impact on the printability and precision of ink patterns [78]. Unlike the atoms within an object, surface atoms exhibit scattering and mutual attraction. For instance, weightless droplets readily coalesce into spherical shapes. Marangoni flow occurs when liquid droplets on a surface migrate from regions of lower surface tension to those of higher surface tension, driven by the variance in surface tension [43]. The unique loop patterns observed in both screen and inkjet printing are caused by this phenomenon [77].

5. Coating techniques

The generation of thin layers frequently requires coating technology. AgNW dispersion solutions are typically evenly sprayed, poured, or scratched onto substrate surfaces to create conductive AgNW films. Subsequently, the solvent was removed. A conductive channel was generated on the substrate by the AgNW network formed after coating. We discuss layer homogeneity, electrical conductivity, and transparency because these are frequently the results of different coating techniques.

5.1. Meyer rod coating

A bar cover with a Mayer rod, which is a metal rod wrapped around metal wires, is known as a Mayer rod cover. The AgNW solution was applied to the substrate surface during the Meyer rod coating process, and the surplus solution was subsequently filtered using a Meyer rod (Fig. 2a). The conductivity and transparency of the AgNW film were determined by its thickness, which can be controlled by varying the diameter of the metal wires around the rod [75].

AgNW electrodes were created by Hu et al. using the Meyer rod coating method (Fig. 2b) [79]. The polyethylene terephthalate (PET) substrates were initially covered with AgNW ink using a Meyer rod. AgNWs were consistently produced on PET surfaces after drying using an infrared laser. Subsequently, a Teflon layer with a thickness of 20 nm was affixed to the AgNW film surface to safeguard the electrodes. Compared to ITO, the electrodes exhibited higher transmittance and conductivity [79].

5.2. Spin coating

Spin coating is the standard technique used at testing facilities to create thin layers. Centrifugal force was used in the spin coating process to produce a uniform film on a spinning platform. After the volatile solvent evaporated during the rotating operation, the coating was still present. One advantage of spin coating is the timely and reliable production of thin films. However, the difficulty in controlling thickness and material loss during rotation makes it challenging to adapt to large-scale industrial manufacturing. Lee et al. integrated AgNWs into the graphene surface using spin coating technology, which significantly increased the electrical and thermal conductivities of the material. AgNWs were similar to bridges in that they were able to successfully resolve the transfer of electron/phonon energy carriers among polycrystalline organisms [80].

To achieve spin-coating deposition, the solution droplets were sprayed onto a flat substrate that was vacuum-sucked. The droplets were then distributed into a film under centrifugal force via rapid spinning. The thickness of the film depends on both the spin rate and solution concentration. Usually, after spin coating, an annealing procedure is used to improve the film characteristics, such as reducing the sheet resistance and increasing the light transmittance [23].

Wang et al. used the spin-coating method to sequentially deposit AgNWs and Fe_3O_4/PVP on a PET film to produce a robust EMI shielding layer. The AgNW/PET films treated with Fe_3O_4/PVP have approximately 90% transparency at 550 nm, which is slightly less than the 92.4% transparency of pure AgNW/PET film. The SE value of the AgNW/PET film modified by Fe_3O_4/PVP was 1.37 times higher in the X-band, reaching as high as 24.3 dB. This can be explained by the fact that the high permeability of Fe_3O_4 particles significantly reduces the absorption loss of electromagnetic energy [81].

Moreover, the shielding effectiveness (SE) and electrical conductivity of the unaltered AgNW/PET films significantly decreased after 800 bends and ten tape applications. In contrast, the performance of the AgNW/PET films enhanced with Fe_3O_4/PVP remains almost unchanged after an identical series of treatments. This implies that the flexibility of the AgNW and substrate adhesion were improved by the Fe_3O_4/PVP layer [81]. In conclusion, spin coating is one of the most prevalent and effective methods for depositing uniform thin films onto smooth substrates, owing to its solution-based approach. Using centrifugal force and rapid rotation, the substrate was coated with the solution throughout its entire surface. The smooth substrate surface was cleared of extra material. The viscosity, rotation time, and speed of the solution affect the thickness of the thin coating that is deposited [75].

5.3. Spray coating

Spray coating, utilizing a device that operates on compressed air like an airbrush or spray gun, is a straightforward, swift, dependable, cost-effective, and adaptable method for depositing a conductive film onto a surface without needing elevated temperatures [37].

The spray coating technique is versatile, suitable for various surfaces, rigid or pliable, and accommodates all shapes, not just flat ones. Achieving a uniform thin film via this method critically depends on the fine-tuning of the spray pressure. The sprayed material can dry more quickly if the substrate is heated throughout the process. To remove any remaining solvent after deposition, the thin film was washed with water or acid [42]. In 1910, a thermal spray coating method was developed in Switzerland. The coating material was fed using this approach in both wire and powder form. The wire-type coating substance takes the shape of a wire or wire. Gas sprays because of the high pressure and speed towards this part [47]. In both of these methods, the coating is done in a closed chamber, so there will be a limit on the size of the parts.

After dropping inks on various sub-layers, further coating techniques such as screen coating [49], inkjet printing [78], immersion coating, and vacuum filtering [23], are used. Typically, thermal sintering is required for post-printing to produce a pattern with high conductivity [82–87]. An alternative to current sintering processes is to be compatible with typical flexible and elastic substrates, as well as to reduce the production cost and process time.

6. EMI shielding mechanism and its measurement techniques

Electromagnetic waves are energy sources that travel through space and matter. However, in materials with lower electrical conductivity, the number of constituent atoms decreases. As a result, the levels corresponding to these atoms also decrease, allowing a small number of electrons to pass through them more easily.

There is a direct relationship between the protection of electromagnetic waves by a material and its conductivity. EM waves can pass through materials with low conductivity but are reflected or absorbed by materials with high conductivity [86]. Generally, metals are the most effective EMI shielding materials; however, they are heavy and expensive. Because Ag has a higher electron density ρ(r) than other metals, it is an effective reflector of SE^2 (dB) electromagnetic waves. The morphology, size, and conductivity of AgNWs can affect the protection of electromagnetic waves. In contrast, AgNWs with smaller diameters are expected to show a higher protective effect owing to the increased surface-to-volume ratio [5].

Electromagnetic interference (EMI) is a common phenomenon in which an external source of electromagnetic radiation disrupts the operation of electronic devices. This interference can cause devices to malfunction, leading to data loss or even hardware damage. To address this, various EMI-shielding techniques have been developed. One of these techniques involves the use of transparent and conductive coatings on the glass surfaces. These covers perform two tasks simultaneously. First, they allow the transmission of light, maintain the transparency of glass, and simultaneously create a barrier against EMI. Transparent conductive coatings are used in various applications, particularly against multiple types of disturbances, including EMI and radio frequency interference (RFI), industrial displays, military displays, military controls and equipment, aircraft shields, and equipment where electromagnetic waves are used [5, 48, 74, 86].

Meng et al. [73] produced silver nanowires and coated them on a glass substrate. In the best-case scenario, they achieved 92% transparency and 40 dB protective efficiency. They first created silver nanowires using the polyol approach and then used the spray coating method to produce a 53% transmission transparency for the samples in question. Furthermore, after sintering, the interconnected AgNW network efficiently facilitates electron flow and lowers electrical resistance; their optimal sample had an electrical resistance of 4.6 Ω/sq^{-1} [86]. It can be seen in Fig. 16a the transparency of light transmission of six samples coated with silver nanowires. In addition, in Fig. 16b, one can see the sample of the coated glass.

On the other hand, when an electromagnetic wave hits the sample, three states occur for it, as shown in Fig. 17, where the first state may be absorbed by the sample, as shown by SE_A. Second, the electromagnetic wave may hit the sample and reflect it, which is the best and most ideal state possible, as represented by SE_R. Thirdly, it may pass through the sample, which is the most destructive state possible, and a symbol for it is not considered.

These researchers used the electrical resistance of the sample to obtain the EMI shielding efficiency, which is shown in Fig. 18. In addition, these researchers calculated the protection efficiency in terms of dB using equations 2 to 7, as shown in Fig. 18. First, the electrical resistance of each coated sample obtained in Eq. 2 is input into a Siemens unit:

$$r_f = \frac{2}{\pi} \times \sqrt{\frac{\frac{1}{\mu_r}}{(\varepsilon_r \times \sigma \times f)}} \tag{2}$$

$$s/m = \frac{1}{\Omega/m} \tag{3}$$

where r_f is the surface depth of the electromagnetic wave input (m), f is the electromagnetic radiation frequency (Hz), μ_r is the relative permeability of AgNWs, ε_r is the relative permeability of silver nanowires, and σ is the conductivity (S/m). In addition, the relative permeability of silver is μ_r=1.00001. That is, silver has few magnetic properties and is considered a diamagnetic material [5, 86].

In other words, silver does not have a strong magnetic field by itself, but can be magnetized by placing it in a strong external magnetic field. ε_r is also one for silver nanowires because the relative permeability of silver nanowires depends on the diameter of the nanowires and the frequency of the electromagnetic wave. Now, having r_f and the mentioned values and placing them in Eq. 2, according to Eq. 4, we will put the obtained r_f and we will have:

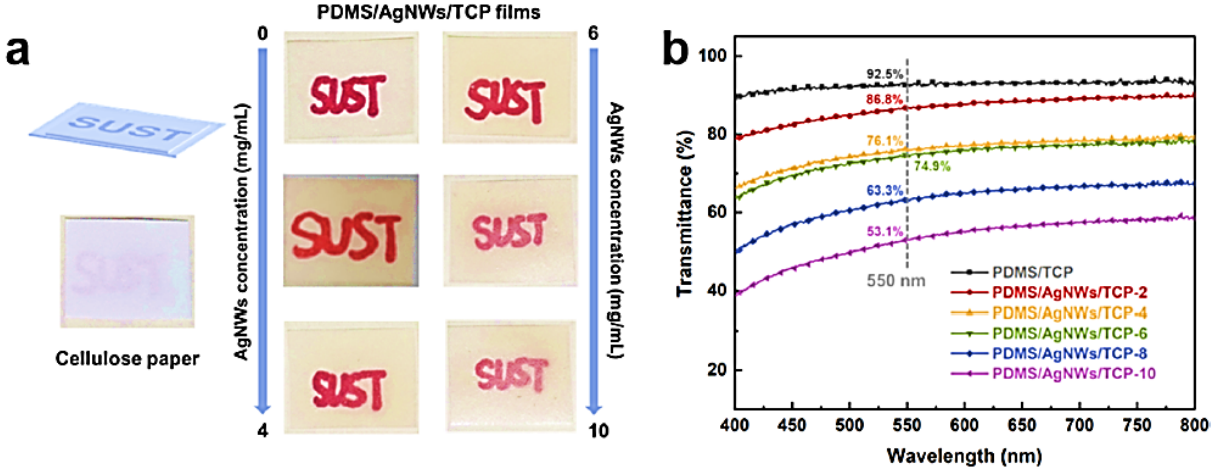


Fig. 16. a) Transparency of light transmission spectrum of six samples coated with silver nanowires and b) coated glass samples. With permission from Elsevier B. V. [86].

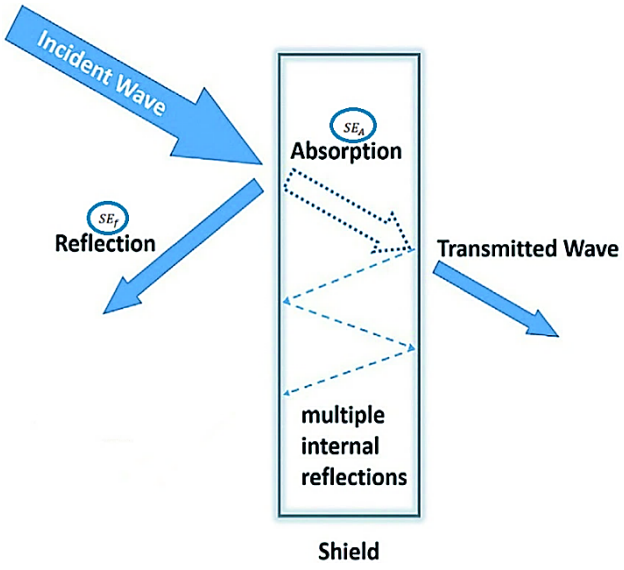


Fig. 17. EMI shielding mechanism. Reproduced with permission from Ref. [5].

$$SE = 20 \times \log(1 - \frac{r_f}{r_o}) \quad (4)$$

Put the obtained SE in Eq. 6 to obtain SE_T. In addition, by inserting Eq. 4 into Eq. 7, SE_T is obtained.

$$SE_T = SE_A + SE_R \quad (5)$$

$$SE_T = 10 \times \log(\frac{1}{SE^2}) \quad (6)$$

$$SE_T = 10 \times \log(\frac{1}{SE^2}) = X \text{ dB} \quad (7)$$

7. Application of AgNWs network

AgNWs have already found practical applications in various commercial products due to their excellent transparency, electrical conductivity, and flexibility. One notable example is the use of AgNWs in TCFs, which are crucial for touchscreens, solar cells, and OLED displays. Companies like Cambrios Technologies and Silver Grains have successfully developed AgNW-based TCFs, offering a cost-effective and scalable alternative to ITO. These films provide high

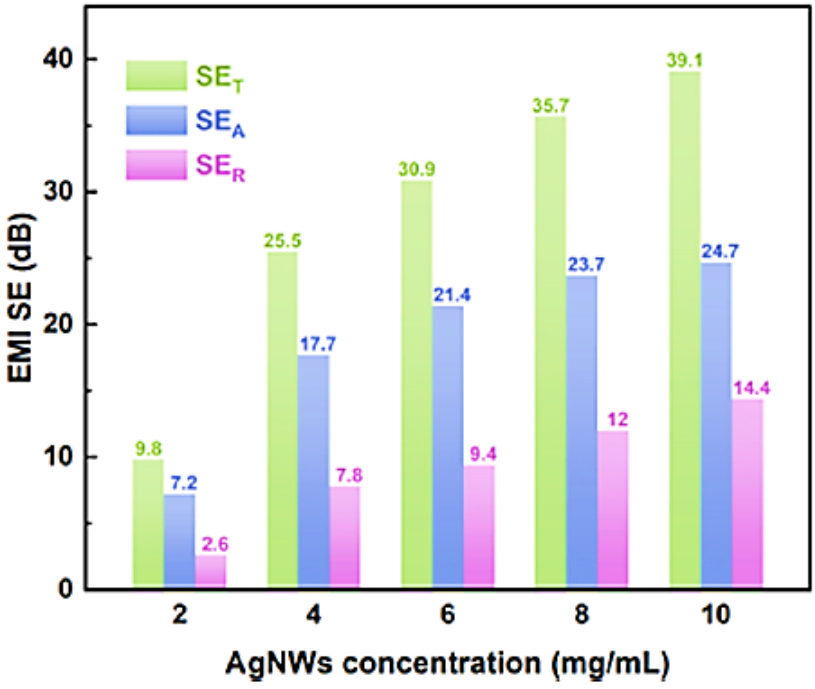


Fig. 18. Protective efficiency of samples coated with AgNWs in dB with different concentrations. With permission from Elsevier B. V. [86].

electrical conductivity, flexibility, and optical transparency, making them ideal for use in flexible and foldable electronics [86].

In addition to TCFs, AgNWs are also increasingly employed in EMI shielding applications for consumer electronics and automotive industries. AgNW-based coatings are being integrated into smart windows and automotive electronics to provide efficient EMI protection while maintaining the transparency of the materials. For example, Corning has developed AgNW-based EMI shielding solutions for next-generation automotive glass, ensuring high shielding effectiveness without compromising visibility or aesthetic quality [9].

Furthermore, AgNWs have shown promise in wearable electronics, where their flexibility and conductivity make them suitable for use in smart textiles and health-monitoring devices. Companies like FlexEnable and Imec are exploring AgNW-based materials for integration into stretchable electronics that can be worn comfortably on the body while maintaining high performance [8].

7.1. Solar cells

FTCF is applied to a wide range of electrical equipment, including transparent heaters, touch screens, sensors, and the bottom and top electrodes of solar cells. We provide an overview and an analysis of these applications.

In recent decades, solar cells have garnered considerable attention in the energy and materials industries. Key performance indicators typically include fill factor, open-circuit voltage, short-circuit current, and power conversion efficiency. The clarity and charge collection capabilities of pliable, transparent electrodes significantly influence the photoelectric conversion efficiency of solar cells. Although indium is a costly and rare metal, it is commonly used as a transparent electrode. Compared with indium, lead poses a lower risk [9, 43, 66].

Researchers will identify affordable and non-toxic compounds that can partially replace ITO by combining a variety of variables. AgNWs exhibit light-solid transmittance and conductivity on flexible substrates and are simple to produce. For this reason, AgNWs are often considered in the design of transparent solar cell electrodes [9].

Improving the light transmittance is also crucial. Fewer photons are dispersed or absorbed when AgNWs have a smaller diameter because there is a decreased chance of photons meeting the AgNWs. Furthermore, the light transmittance was influenced by the placement of nanowires on the substrate. The concentration of conductive nanowires in a given area has a reciprocal relationship with light transmission. As the proportion of AgNWs by mass increases, there is a corresponding gradual reduction in light transmission. To enhance visibility, one could consider adding an eagle-eye pattern or an anti-reflective layer to the surface [9, 44, 87].

7.2. Touch screen

Touch panels represent an innovative computer input technology that significantly enhances daily life. Although exploring AgNWs within touch panels is not as extensive as their use in solar cells, heaters, and optoelectronic devices, it remains an area with considerable promise. The benefits of employing AgNWs in touch panels include high transparency, superior conductivity, expansive dimensions, affordability, and remarkable flexibility. Crafting small-scale AgNW touch panels in a research setting is a simple process. Presently, the focus of research has shifted towards developing touch panels with AgNWs that are both large-scale and high-performing. However, one challenge facing such devices, especially those in prolonged use, is the propensity for crack formation [11, 12, 45, 46].

For example, Yang et al. [82] created a 7×7 cm² transparent touchscreen using the Mayer rod coating method. In this setup, AgNW/PEDOT: PSS served as the upper and lower electrodes. Additionally, the FTCF was engineered to have a sheet resistance of 12 $\Omega \cdot sq^{-1}$ and transparency of 96% at a wavelength of 550 nm. The touchscreen operated effectively after 2000 cycles on an uneven surface, 24 hours of continuous use, 100 cycles of friction, or 5000 bends. The primary research goal in this area is to enhance mechanical durability rather than focusing on optoelectronic applications or solar cell technology.

Huang et al. [3] produced a transparent conductive film embedded with AgNWs-FTCF using RTR slit die coating followed by calendering techniques. This film was then utilized in a resistive touchscreen, as illustrated in Fig. 19a–c. AgNWs are a suitable material for touch panel preparation because of their exceptional light transmittance. Because the light transmittance of a touch screen directly affects its appearance, controlling it is essential. For the AgNW film to have the best anti-vertigo effect, the haze value must also be as low as practical.

7.3. Sensor

Typically, nearly all sensors share the following five attributes: exceptional mechanical strength, robustness, elevated sensitivity, rapid responsiveness, and brief intervals for recovery. Among the metal nanowires, AgNWs stand out as the most conducive in terms of both heat and electricity, and they display remarkable resilience against both oxidation and corrosion. Even when subjected to bending, rolling, or twisting, AgNWs maintain excellent conductivity because of their significant aspect ratio. Consequently, AgNWs have been extensively studied for their application in various sensor technologies [75].

AgNWs have been employed in the development of strain sensors owing to their superior conductive properties. These sensors can gauge

Fig. 19. a) AgNW-SiO_2-based touch panel, b) writing on the touch panel, and c) letters written. Reprinted with permission from Ref. [8].

various physical quantities such as force, torque, pressure, acceleration, and mass. Zhang et al. [83], engineered a networked configuration of AgNW/MWCNT/TPU fibers within a polyurethane (PU) material. Furthermore, they ingeniously fabricated a strain sensor with a diameter of millimeters from fibers, which is notable for its high sensitivity and elasticity.

Peng et al. [85] reported a novel form of weight strain fabric sensor that blends capacitance and piezo-resistance processes, displaying a two-dimensional resistance change diagram that can monitor the object's weight and shape. The sensor was highly scalable. Zhu et al. [86] created a susceptible and stretchable millimeter-diameter fiber strain sensor by integrating AgNWs into polyurethane (PU) fibers via the capillary approach. Consequently, Peng et al. [85], developed a highly scalable sensor that combines piezo-resistance and capacitance mechanisms and can detect numerous forces simultaneously.

For industrial applications, the stability of such devices is as important as their photoelectric performance. Few studies have been conducted on the stability of electronic devices, although many technologies have been successful in recent years. However, the aging process of transparent electrodes in multiple settings has not been well studied, and an efficient protective layer has not yet been developed. AgNW devices are vulnerable to corrosion and failure in high-temperature and biased service environments. Ensuring that AgNW electrodes function well for an extended time is crucial for optoelectronic devices.

7.4. Electromagnetic shielding

Conductive films that are transparent and offer robust EMI shielding properties can be used in communication devices, LCDs, and viewing ports. Owing to their extremely high aspect ratio, which is essential for forming a conductive grid with minimal filler usage, AgNW is the optimal choice for fulfilling the demands of transparent EMI shielding substances [23].

Indeed, there have been disclosures regarding certain see-through films made of AgNPs or polymers, and the processes entailed in crafting these products have been comprehensively delineated in the preceding sections. Consequently, it is advisable to concentrate on the interplay between transparency and shielding effectiveness (SE) in future discussions, as shown in Fig. 20.

Numerous investigators have focused on the design and fabrication of AgNW layers on transparent polymer sheets, such as PMMA, polyethylene terephthalate (PET), polyvinyl alcohol (PVA), and polydimethylsiloxane (PDMS). The shielding effectiveness (SE) of these films, which had an impressive light transmission rate of 480%, ranged from 20 to 40 dB. Films that offer high SE and high transparency are rarely encountered [17]. The reason for this is that coatings containing high mass densities of silver have excellent shielding performance but frequently prevent light dispersion, and lower transmission. Therefore, creating materials with exceptional SE and ultrahigh transparency is a significant concern and a focus of current research. The prospective applications of electronic sensor skins with EM shielding properties in robotics, wearable electronics, artificial intelligence, and electronic skins have garnered significant interest. Zhu et al. [86] are motivated by the natural qualities of human skin. Electronic sensor shell design and production with EMI shielding capabilities. [11, 23, 25, 48].

Deformable EMI shielding materials are required to construct intricate conformal structures that can react to external stimuli. Consequently, conductive shape memory polymers have gained more attention in the design of EMI shielding composites because of their capacity to change shape in response to various environmental stimuli, including heat, electricity, light, magnetism, and pH. Furthermore, conductive shape memory polymers can regulate EMI shielding switches for emergency shutdown and EM signal reception [11, 12, 23, 46, 49].

7.5. Emerging trends in EMI shielding technologies

Recent attempts have led to significant progress in the development of advanced materials for EMI shielding. Traditional materials like metal foils and coatings are being replaced by more flexible, lightweight, and efficient alternatives. One promising trend is the use of nanomaterial-based composites, which combine materials like AgNWs, carbon nanotubes, and graphene with polymers to enhance both shielding performance and mechanical properties. These composites offer superior flexibility, transparency, and conductivity compared to conventional materials, making them suitable for applications in wearable devices, flexible electronics, and transparent conductive films [17].

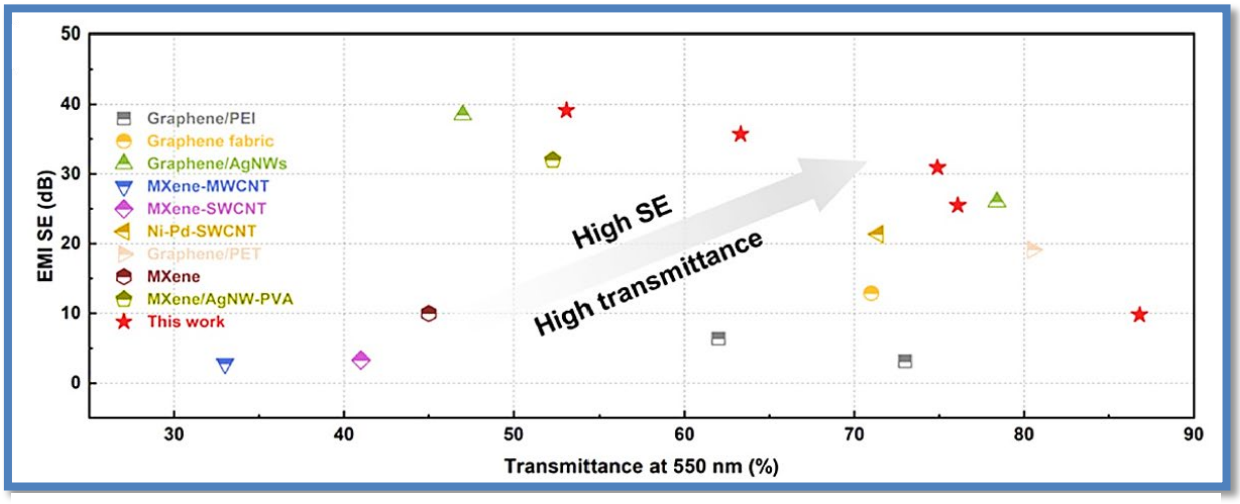


Fig. 20. SET was recorded for all samples in the X-band (8–12 GHz). Reprinted with permission from Ref. [86]. (Copyright 2024 American Chemical Society).

Another emerging trend is the advancements of conductive polymers for EMI shielding usages. These materials, often combined with nanomaterials such as AgNWs, are gaining attention due to their lightweight nature, cost-effectiveness, and potential for easy processing. Conductive polymers can be tailored for specific applications, such as integration into flexible substrates or coatings for electronic devices. This has opened up new possibilities for EMI shielding in compact and flexible devices, as well as in industries requiring lightweight yet efficient shielding materials, such as automotive and aerospace [38, 84].

In addition to improving performance, there is a growing emphasis on the environmental sustainability of EMI shielding materials. As electronic waste continues to rise, researchers are focusing on developing biodegradable and recyclable materials that do not compromise shielding effectiveness. Innovations in green materials including biodegradable polymers and bio-based composites are being explored as potential alternatives to traditional EMI shielding materials. These materials not only address environmental concerns but also support the growing demand for sustainable solutions in the electronics industry. The continued optimization of AgNWs for EMI shielding, combined with these emerging trends, could significantly impact future developments in the field [42, 49, 74].

7.6. Other application

Silver nanowires (AgNWs) have emerged as a class of highly flexible materials because of their unique optical, electrical, and antibacterial features. Numerous uses of AgNWs across a range of scientific and technological domains are covered in this study. For conductive applications, including touch screens, organic light-emitting diodes (OLEDs), and solar cells, transparent conductive films (TCFs) on AgNWs present a solid substitute for conventional indium tin oxide (ITO) on TCFs. They are ideal for next-generation optoelectronic devices because of their good flexibility, electrical conductivity, and excellent transparency in the visible range. AgNW networks, which have efficient charge transport capabilities, can be integrated into various electronic components for high-performance electronics. Printing applications for high-density connection circuit boards and flexible electronics [12, 23, 25, 45, 46, 48, 86].

Optical modulators, biosensors, and medical imaging are enabled by optical applications such as surface plasmon resonance (SPR), in which light contact with AgNWs stimulates local surface plasmons [40]. AgNWs are appealing to various sensing platforms because of their ability to adjust the shape and size to tailor the surface plasmon resonance frequency. AgNWs can be added to solar cells in optical applications to enhance light absorption and scattering and, improve the device efficiency [42, 49, 74]. Furthermore, optical limiters made of them can be employed to shield delicate detectors from intense light, owing to their plasmonic qualities. AgNWs are a viable option for creating antibacterial surfaces because of the intrinsic antimicrobial characteristics of Ag, which are helpful in antibacterial applications, including biocidal materials. They can be added to textiles, wound dressings, and medical devices to fight bacterial growth and heal wounds [38].

Because antimicrobial coatings such as AgNWs can eliminate a wide variety of microorganisms, they can be used in paints, coatings, and filters to clean air and water [47]. Additionally, AgNWs show good catalytic activity for a variety of reactions in other developing applications like catalysis, which makes them appealing for usage in fuel cells and chemical sensors [24, 44]. Electrical conductivity can be produced in textile technology, for example, by incorporating AgNWs into fabrics for applications such as electromagnetic shielding and wearable electronics.

8. Conclusions and perspective

Since silver nanowires (AgNWs) have better electrical conductivity, flexibility, and transparency than indium tin oxide (ITO), they are becoming a more viable option for a variety of applications. This review has examined various synthesis techniques for AgNWs, each with unique benefits and downsides depending on the intended application. The polyol method, for instance, has been recognized as a low-cost way for generating AgNWs on a wide scale, despite difficulties in controlling shape and eliminating byproducts.

ITO is frequently used because of its transparency in solar cells and touch screens; however, it has drawbacks, including brittleness and high cost, that make better substitutes necessary. AgNWs, with their distinctive one-dimensional structure, have attracted attention for their potential to outperform ITO in electrical and optical applications. Despite several disadvantages, the polyol reduction technique is still a popular way to synthesize AgNWs because of its ease of use and scalability.

Despite their numerous advantages, silver nanowires (AgNWs) face certain limitations that may hinder their widespread adoption in some applications. One of the primary challenges is their chemical stability. AgNWs are prone to oxidation when exposed to humidity, air, or corrosive environments, which can significantly degrade their electrical conductivity and optical transparency over time. This issue is particularly concerning in outdoor or high-humidity conditions, where protective measures such as encapsulation or passivation layers are often required. While research on surface coatings and alloying strategies shows promise in improving stability, these solutions can increase production complexity and cost.

Another limitation is the heat resistance of AgNWs. Unlike materials like indium tin oxide (ITO), which can maintain performance at elevated temperatures, AgNWs may suffer from thermal degradation or structural changes when subjected to high temperatures. This characteristic limits their suitability for applications involving high thermal loads, such as certain types of solar cells or transparent heaters. Efforts to address this issue include the development of hybrid nanocomposites and the integration of AgNWs with thermally stable materials, but these approaches require further exploration to achieve optimal performance without compromising other desirable properties.

The study emphasizes the increasing demand for flexible, transparent materials, particularly in the context of electromagnetic interference (EMI) shielding, where AgNWs show considerable promise. Their ability to offer protection while maintaining transparency makes them a strong candidate for various applications. However, the formulation of AgNW-based conductive inks requires careful optimization, as factors such as surface tension, viscosity, and the characteristics of additives are crucial for achieving optimal coating performance.

Several coating processes, including Mayer rod coating, have been evaluated for their ability to produce homogeneous layers with high electrical conductivity and transparency. These methods are vital in advancing modern electronics, where AgNWs can be integrated into devices such as transparent heaters, touchscreens, sensors, and solar

cell electrodes. While AgNWs' applications in EMI shielding are promising, their role in emerging fields like robotics and wearable electronics further highlights their versatility.

The research underscores the importance of improving the synthesis, characterization, and application of AgNWs to advance transparent conductive films and other cutting-edge technologies. AgNWs, with superior electrical, optical, and mechanical properties, are increasingly seen as a viable replacement for materials like ITO in various electronic applications. This study provides valuable insights into the most effective AgNW synthesis methods, particularly the polyol method, which stands out for its scalability and efficiency. Moreover, AgNW-based conductive inks have been developed for use in diverse coating processes, showcasing their potential for the mass production of high-performance transparent electrodes. Furthermore, the report emphasizes the expanding role of AgNWs in emerging domains like flexible electronics, electromagnetic interference (EMI) shielding, and sophisticated sensing technology. The results of this work contribute significantly to the field, offering a strong foundation for future innovations and practical applications of AgNWs in the evolving landscape of electronic and optoelectronic devices.

CRediT authorship contribution statement

Ali Borchloo: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing original draft, Writing – review & editing.

Reza Shoja-Razavi: Data curation, Funding acquisition, Project administration, Validation, Visualization, Writing – review & editing.

Hamed Naderi-Samani: Data curation, Funding acquisition, Project administration, Validation, Visualization, Writing – review & editing.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding and acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] A. Borchloo, R. Shoja-Razavi, H. Naderi-Samani, Synthesis and characterization of silver nanowires with high aspect ratio for transparent coating applications, Synth. Sinter. 4 (2024) 167–190. https://doi.org/10.53063/synsint.2024.43236.

[2] J. Krantz, M. Richter, S. Spallek, E. Spiecker, C.J. Brabec, Solution-Processed Metallic Nanowire Electrodes as Indium Tin Oxide Replacement for Thin-Film Solar Cells, Adv. Funct. Mater. 21 (2011) 4784–4787. https://doi.org/10.1002/adfm.201100457.

[3] S. Huang, Q. Zhang, F. Yang, D. Thrithamarassery Gangadharan, P. Li, et al., A facile way for scalable fabrication of silver nanowire network electrodes for high-performance and foldable smart windows, J. Mater. Chem. A. 8 (2020) 8620–8628. https://doi.org/10.1039/c9ta14030a.

[4] Y. Sun, Y. Xia, Large-Scale Synthesis of Uniform Silver Nanowires Through a Soft, Self-Seeding, Polyol Process, Adv. Mater. 14 (2002) 833. https://doi.org/10.1002/1521-4095(20020605)14:11%3C833::aid-adma833%3E3.0.co;2-k.

[5] W. Tsou, S.-M. Kao, Overview of EMI Development, English as a Medium of Instruction in Higher Education, Springer, Singapore. (2017) 3–18. https://doi.org/10.1007/978-981-10-4645-2_1.

[6] M.K. Francis, B.K. Sahu, P.B. Bhargav, B.C.N. Ahmed, A. Das, S. Dhara, Ag nanowires based SERS substrates with very high enhancement factor, Phys. E: Low-Dimens. Syst. Nanostructures. 137 (2022) 115080. https://doi.org/10.1016/j.physe.2021.115080.

[7] T.K. Lahane, J. Agrawal, V. Singh, Optimization of polyol synthesized silver nanowires for transparent conducting electrodes application, Mater. Today. 59 (2022) 257–263. https://doi.org/10.1016/j.matpr.2021.11.108.

[8] H. Jeong, S. Park, J. Lee, P. Won, S. Ko, D. Lee, Fabrication of Transparent Conductive Film with Flexible Silver Nanowires Using Roll-to-Roll Slot-Die Coating and Calendering and Its Application to Resistive Touch Panel, Adv. Electron. Mater. 4 (2018) 1800243. https://doi.org/10.1002/aelm.201800243.

[9] D. Tan, C. Jiang, Q. Li, S. Bi, J. Song, Silver nanowire networks with preparations and applications: a review, J. Mater. Sci: Mater. Electron. 31 (2020) 15669–15696. https://doi.org/10.1007/s10854-020-04131-x.

[10] J. Kwon, Y.D. Suh, J. Lee, P. Lee, S. Han, et al., Recent progress in silver nanowire-based flexible/wearable optoelectronics, J. Mater. Chem. C. 6 (2018) 7445–7461. https://doi.org/10.1039/c8tc01024b.

[11] S.-M. Yang, H.-K. Yen, K.-C. Lu, Synthesis, and Characterization of Indium Tin Oxide Nanowires with Surface Modification of Silver Nanoparticles by Electrochemical Method, Nanomaterials. 12 (2022) 897. https://doi.org/10.3390/nano12060897.

[12] J. Wei, X. Li, F. Bian, J. Zeng, J. Hu, et al., Synthesis of high purity silver nanowires through a silver chloride-mediated polyol method, Inorg. Chem. Commun. 146 (2022) 110164. https://doi.org/10.1016/j.inoche.2022.110164.

[13] B. Wiley, Y. Sun, Y. Xia, Synthesis of Silver Nanostructures with Controlled Shapes and Properties, Accounts of Chemical Research. 40 (2007) 1067–1076. https://doi.org/10.1021/ar7000974.

[14] J.-J. Zhu, Q.-F. Qiu, H. Wang, J.-R. Zhang, J.-M. Zhu, Z.-Q. Chen, Synthesis of silver nanowires by a sonoelectrochemical method, Inorg. Chem. Commun. 5 (2002) 242–244. https://doi.org/10.1016/s1387-7003(02)00351-9.

[15] J. Choi, G. Sauer, K. Nielsch, R.B. Wehrspohn, U. Gösele, Hexagonally Arranged Monodisperse Silver Nanowires with Adjustable Diameter and High Aspect Ratio, Chem Mater. 15 (2003) 776–779. https://doi.org/10.1021/cm0208758.

[16] Y. Sun, Y. Yin, B.T. Mayers, T. Herricks, Y. Xia, Uniform Silver Nanowires Synthesis by Reducing AgNO3 with Ethylene Glycol in the Presence of Seeds and Poly(Vinyl Pyrrolidone), Chem Mater. 14 (2002) 4736–4745. https://doi.org/10.1021/cm020587b.

[17] C.-C. Huang, S. Gupta, C.-Y. Lo, N.-H. Tai, Highly transparent and excellent electromagnetic interference shielding hybrid films composed of sliver-grid/(silver nanowires and reduced graphene oxide), Mater. Lett. 253 (2019) 152–155. https://doi.org/10.1016/j.matlet.2019.06.058.

[18] S. Subburaj, B. Arumugam, S.M. Chen, T.W. Chen, A. Seetharam, S.K. Ramaraj, Polyol synthesis of Ag Nanowires as an electrochemical sensor for the quantification of Carcinogenic Hydrazine, Int. J. Electrochem. Sci. 16 (2021) 210773. https://doi.org/10.20964/2021.07.74.

[19] H. Wang, Y. Wang, X. Chen, Synthesis of uniform silver nanowires from AgCl seeds for transparent conductive films via spin-coating at variable spin-speed, Colloids Surf. A: Physicochem. Eng. Asp. 565 (2019) 154–161. https://doi.org/10.1016/j.colsurfa.2018.11.050.

[20] B. Li, S. Ye, I.E. Stewart, S. Alvarez, B.J. Wiley, Synthesis and Purification of Silver Nanowires To Make Conducting Films with a

Transmittance of 99%, Nano Lett. 15 (2015) 6722–6726. https://doi.org/10.1021/acs.nanolett.5b02582.
[21] D. Kumar, Kavita, K. Singh, V. Verma, H.S. Bhatti, Microwave-assisted synthesis and characterization of silver nanowires by polyol process, Appl. Nanosci. 5 (2014) 881–890. https://doi.org/10.1007/s13204-014-0386-2.
[22] J.W. Park, D.K. Shin, J. Ahn, J.Y. Lee, Thermal property of transparent silver nanowire films, Semicond. Sci. Technol. 29 (2013) 015002–015002. https://doi.org/10.1088/0268-1242/29/1/015002.
[23] Y. Zhan, C. Santillo, Y. Meng, M. Lavorgna, Recent advances and perspectives on silver-based polymer composites for electromagnetic interference shielding, J. Mater. Chem. C. 11 (2023) 859–892. https://doi.org/10.1039/d2tc03821h.
[24] L. Zhang, T. Song, L.-X. Shi, N. Wen, Z. Wu, et al., Recent progress for silver nanowires conducting film for flexible electronics, J. Nanostructure Chem. 11 (2021) 323–341. https://doi.org/10.1007/s40097-021-00436-3.
[25] H. Li, Q. Chen, G. Zhang, Z. Zhang, J. Fang, et al., Stable, highly conductive and orthogonal silver nanowire networks via zwitterionic treatment, J. Mater. Chem. A. 11 (2022) 158–166. https://doi.org/10.1039/D2TA07406K.
[26] Y. Zhu, Y. Deng, P. Yi, L. Peng, X. Lai, Z. Lin, Flexible Transparent Electrodes Based on Silver Nanowires: Material Synthesis, Fabrication, Performance, and Applications, Adv. Mater. Technol. 4 (2019) 1900413. https://doi.org/10.1002/admt.201900413.
[27] Y. Guo, Y. Hu, X. Luo, S. Lin, J. Hu, Y. Liu, Investigation into the role of poly(vinylpyrrolidone) in the growth of high aspect ratio silver nanowires, Inorg. Chem. Commun. 128 (2021) 108558. https://doi.org/10.1016/j.inoche.2021.108558.
[28] S. Fahad, H. Yu, L. Wang, Y. Wang, T. Lin, et al., Synthesis of AgNWs Using High Molecular Weight PVP As a Capping Agent and Their Application in Conductive Thin Films, J. Electron. Mater. 50 (2021) 2789–2799. https://doi.org/10.1007/s11664-021-08770-6.
[29] S. Fahad, H. Yu, L. Wang, N. Zain-ul-Abdin, M. Haroon, et al., Recent progress in the synthesis of silver nanowires and their role as conducting materials, J. Mater. Sci. 54 (2018) 997–1035. https://doi.org/10.1007/s10853-018-2994-9.
[30] P. Zhang, I. Wyman, J. Hu, S. Lin, Z. Zhong, et al., Silver nanowires: Synthesis technologies, growth mechanism, and multifunctional applications, Mater. Sci. Eng: B. 223 (2017) 1–23. https://doi.org/10.1016/j.mseb.2017.05.002.
[31] H. Mao, J. Feng, X. Ma, C. Wu, X. Zhao, One-dimensional silver nanowires synthesized by self-seeding polyol process, J. Nanoparticle Res. 14 (2012) 887. https://doi.org/10.1007/s11051-012-0887-4.
[32] A.B.V. Kiran Kumar, C. wan Bae, L. Piao, S.-H. Kim, Silver nanowire-based flexible electrodes with improved properties: High conductivity, transparency, adhesion, and low haze, Mater. Res. Bull. 48 (2013) 2944–2949. https://doi.org/10.1016/j.materresbull.2013.04.035.
[33] G. Zhu, D. Chen, Solvothermal fabrication of uniform silver nanowires, J. Mater. Sci: Mater. Electron. 23 (2012) 2035–2041. https://doi.org/10.1007/s10854-012-0699-4.
[34] D. Fu, R. Yang, Y. Wang, R. Wang, F. Hua, Silver nanowire synthesis and applications in composites: progress and prospects, Adv. Mater. Technol. 7 (2022) 2200027. https://doi.org/10.1002/admt.202200027.
[35] J. Junaidi, M. Wahyudi Saputra, R. Marjunus, S. Sembiring, S. Hadi, The Quenching and Sonication Effect on the Mechanical Strength of Silver Nanowires Synthesized Using the Polyol Method, Molecules. 26 (2021) 2167–2167. https://doi.org/10.3390/molecules26082167.
[36] Y. Won, A. Kim, W. Yang, S. Jeong, J. Moon, A highly stretchable, helical copper nanowire conductor exhibiting a stretchability of 700%, NPG Asia Mater. 6 (2014) e132–e132. https://doi.org/10.1038/am.2014.88.
[37] X. Feng, X. Wang, B. Zhang, J. Gu, C. Xu, S. Zhang, Flexible transparent conductive films based on silver nanowires by ultrasonic spraying process, J. Mater. Sci.: Mater. Electron. 33 (2022) 25939–25949. https://doi.org/10.1007/s10854-022-09284-5.
[38] C. Vitelaru, A.C. Parau, M. Dinu, I. Pana, L.R. Constantin, et al., Transparent Silver Coatings with Copper Addition for Improved Conductivity by Combined DCMS and HiPIMS Process, Metals. 12 (2022) 1264. https://doi.org/10.3390/met12081264.
[39] S. Ye, A.R. Rathmell, Z. Chen, I. Stewart, B.J. Wiley, Metal Nanowire Networks: The Next Generation of Transparent Conductors, Adv. Mater. 26 (2014) 6670–6687. https://doi.org/10.1002/adma.201402710.
[40] T. Muhmood, F. Ahmad, X. Hu, X. Yang, Silver nanowires: a focused review of their synthesis, properties, and major factors limiting their commercialization, Nano Futures. 6 (2022) 032006–032006. https://doi.org/10.1088/2399-1984/ac8388.
[41] Y. Sun, B. Gates, B. Mayers, Y. Xia, Crystalline Silver Nanowires by Soft Solution Processing, Nano Lett. 2 (2002) 165–168. https://doi.org/10.1021/nl010093y.
[42] R. Sahoo, S. Ramaprabhu, S. Venkatachalam, Silver Nanowires Coated Nitrocellulose Paper for High-Efficiency Electromagnetic Interference Shielding, ACS Omega. 7 (2022) 41426–41436. https://doi.org/10.1021/acsomega.2c05204.
[43] X. Wu, Z. Zhou, Y. Wang, J. Li, Syntheses of Silver Nanowires Ink and Printable Flexible Transparent Conductive Film: A Review, Coatings. 10 (2020) 865. https://doi.org/10.3390/coatings10090865.
[44] D. Tan, C. Jiang, Q. Li, S. Bi, X. Wang, J. Song, Development and current situation of flexible and transparent EM shielding materials, J. Mater. Sci: Mater. Electron. 32 (2021) 25603–25630. https://doi.org/10.1007/s10854-021-05409-4.
[45] S. Wang, H. Liu, Y. Pan, F. Xie, Y. Zhang, et al., Performance Enhancement of Silver Nanowire-Based Transparent Electrodes by Ultraviolet Irradiation, Nanomaterials. 12 (2022) 2956–2956. https://doi.org/10.3390/nano12172956.
[46] R. Wang, S. Xiong, Preparation and optical properties of AgNWs/WO3:Eu3+ composite film, J. Mater. Sci. 57 (2022) 20210–20223. https://doi.org/10.1007/s10853-022-07912-3.
[47] A. Kumar, M. Kumar, M.S. Goyat, D.K. Avasthi, A review of the latest developments in the production and applications of Ag-nanowires as transparent electrodes, Mater. Today Commun. 33 (2022) 104433. https://doi.org/10.1016/j.mtcomm.2022.104433.
[48] H. Ha, J.Y. Cheong, T.G. Yun, B. Hwang, Polymeric Protection for Silver Nanowire-Based Transparent Conductive Electrodes: Performance and Applications, Inorganics. 11 (2023) 409–409. https://doi.org/10.3390/inorganics11100409.
[49] M. Vaseem, Z. Akhter, W. Li, E. Yarali, T.D. Anthopoulos, A. Shamim, High-conductivity screen-printable silver nanowire Ink for optically transparent flexible radio frequency electronics, Flex. Print. Electron. 7 (2022) 044001. https://doi.org/10.1088/2058-8585/ac97a4.
[50] S.B. Chu, D. Ko, J. Jung, S. Jo, D.C. Hyun, et al., Characterization of silver nanowire-based transparent electrodes obtained using different drying methods, Nanomaterials. 12 (2022) 461. https://doi.org/10.3390/nano12030461.
[51] S. Lee, S. Shin, S. Lee, J. Seo, J. Lee, et al., Ag Nanowire Reinforced Highly Stretchable Conductive Fibers for Wearable Electronics, Adv. Funct. Mater. 25 (2015) 3114–3121. https://doi.org/10.1002/adfm.201500628.
[52] H. Sim, S. Bok, B. Kim, M. Kim, G. Lim, et al., Organic-Stabilizer-Free Polyol Synthesis of Silver Nanowires for Electrode Applications, Angew. Chem. Int. Ed. 55 (2016) 11814–11818. https://doi.org/10.1002/anie.201604980.
[53] A.-T. Pham, X.-Q. Nguyen, D.-H. Tran, V.N. Phan, T.-T. Duong, D.-C. Nguyen, Enhancement of the electrical properties of silver nanowire transparent conductive electrodes by atomic layer deposition coating with zinc oxide, Nanotechnology. 27 (2016) 335202–335202. https://doi.org/10.1088/0957-4484/27/33/335202.
[54] C. Amicucci, H. Ha, P. Matteini, B. Hwang, Facile fabrication of silver-nanowire-based chips using dry-film photoresist for wearable

optical detection, Fash. Text. 9 (2022) 20. https://doi.org/10.1186/s40691-022-00297-6.
[55] X.J. Xu, G.T. Fei, X.W. Wang, Z. Jin, W.H. Yu, L.D. Zhang, Synthetic control of large-area, ordered silver nanowires with different diameters, Mater. Lett. 61 (2007) 19–22. https://doi.org/10.1016/j.matlet.2006.03.143.
[56] J.H. Park, G.-T. Hwang, S. Kim, J. Seo, H.-J. Park, et al., Flash-Induced Self-Limited Plasmonic Welding of Silver Nanowire Network for Transparent Flexible Energy Harvester, Adv. Mater. 29 (2016) 1603473. https://doi.org/10.1002/adma.201603473.
[57] J. Weigang, Z. Xiaohong, W. Shikang, Wet Chemical Synthesis of Ag Nanowires Array at Room Temperature, Chem. Lett. 34 (2005) 510–511. https://doi.org/10.1246/cl.2005.510.
[58] X.-Z. Xiang, W.-Y. Gong, M.-S. Kuang, L. Wang, Progress in application and preparation of silver nanowires, Rare Met. 35 (2016) 289–298. https://doi.org/10.1007/s12598-016-0695-6.
[59] W. Li, H. Zhang, S. Shi, J. Xu, X. Qin, et al., Recent progress in silver nanowire networks for flexible organic electronics, J. Mater. Chem. C. 8 (2020) 4636–4674. https://doi.org/10.1039/c9tc06865a.
[60] C. Ma, Y.-F. Liu, Y.-G. Bi, X.-L. Zhang, D. Yin, et al., Recent progress in post-treatment of silver nanowire electrodes for optoelectronic device applications, Nanoscale. 13 (2021) 12423–12437. https://doi.org/10.1039/d1nr02917g.
[61] W.-B. Zhao, J.-J. Zhu, H.-Y. Chen, Photochemical synthesis of Au and Ag nanowires on a porous aluminum oxide template, J. Cryst. Growth. 258 (2003) 176–180. https://doi.org/10.1016/s0022-0248(03)01504-5.
[62] Y. Sun, Silver nanowires – unique templates for functional nanostructures, Nanoscale. 2 (2010) 1626. https://doi.org/10.1039/c0nr00258e.
[63] S. Hemmati, D.P. Barkey, N. Gupta, R. Banfield, Synthesis and Characterization of Silver Nanowire Suspensions for Printable Conductive Media, ECS J. Solid State Sci. Technol. 4 (2015) P3075–P3079. https://doi.org/10.1149/2.0121504jss.
[64] K.E. Korte, S.E. Skrabalak, Y. Xia, Rapid synthesis of silver nanowires through a CuCl- or CuCl2-mediated polyol process, J. Mater. Chem. 18 (2008) 437–441. https://doi.org/10.1039/b714072j.
[65] M.R. Johan, N.A.K. Aznan, S.T. Yee, I.H. Ho, S.W. Ooi, et al., Synthesis and Growth Mechanism of Silver Nanowires through Different Mediated Agents (CuCl2and NaCl) Polyol Process, J. Nanomater. 2014 (2014) 1–7. https://doi.org/10.1155/2014/105454.
[66] R. Karimi-Chaleshtori, A.H. Nassajpour-Esfahani, M.R. Saeri, P. Rezai, A. Doostmohammadi, Silver nanowire-embedded PDMS with high electrical conductivity: nanowires synthesis, composite processing and electrical analysis, Mater. Today Chem. 21 (2021) 100496. https://doi.org/10.1016/j.mtchem.2021.100496.
[67] P. Zhang, Y. Wei, M. Ou, Z. Huang, S. Lin, et al., Behind the role of bromide ions in the synthesis of ultrathin silver nanowires, Mater. Lett. 213 (2018) 23–26. https://doi.org/10.1016/j.matlet.2017.10.128.
[68] H. Moon, P. Won, S.Y. Lee, S.H. Ko, Low-haze, annealing-free, very long Ag nanowire synthesis and its application in a flexible transparent touch panel, Nanotechnology. 27 (2016) 295201–295201. https://doi.org/10.1088/0957-4484/27/29/295201.
[69] E.-J. Lee, M.-H. Chang, Y.-S. Kim, J.-Y. Kim, High-pressure polyol synthesis of ultrathin silver nanowires: Electrical and optical properties, APL Mater. 1 (2013) 042118. https://doi.org/10.1063/1.4826154.
[70] K.K. Caswell, C.M. Bender, C.J. Murphy, Seedless, Surfactantless Wet Chemical Synthesis of Silver Nanowires, Nano Lett. 3 (2003) 667–669. https://doi.org/10.1021/nl0341178.
[71] S. Ayyappan, Nanoparticles of nickel and silver produced by the polyol reduction of the metal salts intercalated in montmorillonite, Solid State Ion. 84 (1996) 271–281. https://doi.org/10.1016/0167-2738(96)00021-5.
[72] J. Xu, J. Hu, C. Peng, H. Liu, Y. Hu, A simple approach to the synthesis of silver nanowires by the hydrothermal process in the presence of Gemini surfactant, J. Colloid. Interface Sci. 298 (2006) 689–693. https://doi.org/10.1016/j.jcis.2005.12.047.
[73] L.-Y. Meng, B. Wang, M.-G. Ma, K.-L. Lin, The progress of microwave-assisted hydrothermal method in the synthesis of functional nanomaterials, Mater. Today Chem. 1–2 (2016) 63–83. https://doi.org/10.1016/j.mtchem.2016.11.003.
[74] M. Mustaqim Rosli, A. Aziz, A. Umar, M. Nurdin, A. Ali Umar, Propylene Glycol Directed Synthesis of Silver Nanowires for Transparent Conducting Electrode Application, J. Electron. Mater. 51 (2022) 5150–5158. https://doi.org/10.1007/s11664-022-09762-w.
[75] H. Abbasi, M. Antunes, J.I. Velasco, Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding, Prog. Mater. Sci. 103 (2019) 319–373. https://doi.org/10.1016/j.pmatsci.2019.02.003.
[76] Y. Mou, C.H. Chen, H. Wang, Q. Sun, J. Liu, Y. Peng, Facile preparation of stable reactive silver ink for highly conductive and flexible electrodes, Appl. Surf. Sci. 475 (2019) 75–82. https://doi.org/10.1016/j.apsusc.2018.12.261.
[77] D. Li, X. Liu, X. Chen, W. Lai, W. Huang, A Simple Strategy towards Highly Conductive Silver-Nanowire Inks for Screen-Printed Flexible Transparent Conductive Films and Wearable Energy-Storage Devices, Adv. Mater. Technol. 4 (2019) 1900196. https://doi.org/10.1002/admt.201900196.
[78] Q. Huang, K.N. Al-Milaji, H. Zhao, Inkjet Printing of Silver Nanowires for Stretchable Heaters, ACS Appl. Nano Mater. 1 (2018) 4528–4536. https://doi.org/10.1021/acsanm.8b00830.
[79] L. Hu, H.S. Kim, J.-Y. Lee, P. Peumans, Y. Cui, Scalable Coating and Properties of Transparent, Flexible, Silver Nanowire Electrodes, ACS Nano. 4 (2010) 2955–2963. https://doi.org/10.1021/nn1005232.
[80] W. Lee, K.D. Kihm, W. Lee, P. Won, S. Han, et al., Boosted thermal conductance of polycrystalline graphene by spin-coated silver nanowires, Int. J. Heat Mass Transf. 134 (2019) 547–553. https://doi.org/10.1016/j.ijheatmasstransfer.2019.01.052.
[81] Z. Wang, B. Jiao, Y. Qing, H. Nan, L. Huang, et al., Flexible and transparent ferroferric oxide-modified silver nanowire film for efficient electromagnetic interference shielding, ACS Appl. Mater. Interfaces. 12 (2019) 2826–2834. https://doi.org/10.1021/acsami.9b17513.
[82] H. Yang, S. Bai, T. Chen, Y. Zhang, H. Wang, X. Guo, Facile fabrication of large-scale silver nanowire-PEDOT: PSS composite flexible transparent electrodes for flexible touch panels, Mater. Res. Express. 6 (2019) 086315. https://doi.org/10.1088/2053-1591/ab20d5.
[83] S. Zhang, Z. He, G. Zhou, B.-M. Jung, T.-H. Kim, et al., High conductive free-written thermoplastic polyurethane composite fibers utilized as weight-strain sensors, Compos. Sci. Technol. 189 (2020) 108011. https://doi.org/10.1016/j.compscitech.2020.108011.
[84] G.-J. Zhu, P.-G. Ren, H. Guo, Y.-L. Jin, D.-X. Yan, Z.-M. Li, Highly Sensitive and Stretchable Polyurethane Fiber Strain Sensors with Embedded Silver Nanowires, ACS Appl. Mater. Interfaces. 11 (2019) 23649–23658. https://doi.org/10.1021/acsami.9b08611.
[85] S. Peng, S. Wu, Y. Yu, B. Xia, N.H. Lovell, C.H. Wang, Multimodal Capacitive and Piezoresistive Sensor for Simultaneous Measurement of Multiple Forces, ACS Appl. Mater. Interfaces. 12 (2020) 22179–22190. https://doi.org/10.1021/acsami.0c04448.
[86] M. Zhu, X. Yan, X. Li, L. Dai, J. Guo, et al., Flexible, Transparent, and Hazy Composite Cellulosic Film with Interconnected Silver Nanowire Networks for EMI Shielding and Joule Heating, ACS Appl. Mater. Interfaces. 14 (2022) 45697–45706. https://doi.org/10.1021/acsami.2c13035.
[87] A. Kumar, M.O. Shaikh, C.-H. Chuang, Silver nanowire synthesis and strategies for fabricating transparent conducting electrodes, Nanomaterials. 11 (2021) 693. https://doi.org/10.3390/nano11030693.