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Beyond Flexibility: Transparent Silver Nanowire Electrodes on Patterned Surfaces for Reconfigurable Devices

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Silver nanowire (AgNW) emerges as a next-generation transparent electrode material, offering enhanced flexibility and ease of fabrication compared to traditional transparent electrode materials, such as metallic oxides. In the previous research, the uniform deposition of AgNWs on flat surfaces is demonstrated, exhibiting high conductivity, flexibility, and excellent transmittance. However, the evolution of nano-electronics technology necessitates the fabrication of transparent electrodes on non-flat surfaces, such as those found in zenithal bistable devices and reconfigurable Fresnel lenses. In this study, a method is proposed to deposit AgNW material on uneven surfaces using the Mylar-bar-coating method, with a polyvinyl chloride (PVC)-based Fresnel lens serving as the target surface. Additionally, the impact of varying AgNW suspension concentrations on transmittance and sheet resistance is investigated. To further reduce sheet resistance, a layer of conductive polymer, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), is deposited on the AgNWs. The measurements reveal that a 2 mg mL^{-1} sample exhibits a sheet resistance of 187.83 W W^{-1} with 87.4% transmittance at 550 nm. After the PEDOT:PSS process, the sheet resistance decreases to 122.84 W W^{-1} with 84.4% transmittance. In this research, a solution is offered for the uniform deposition of AgNWs on patterned surfaces, paving the way for the next generation of optical devices.

1. Introduction

As nanofabrication technology advances, the demand for transparent electrodes in wearable and tunable optical devices is increasing. Traditional transparent electrode materials are metallic oxides, such as indium tin oxide (ITO). ITO exhibits good electrical properties and transparency, which has been widely employed in e-paper, solar cell, and display applications.[1,2] However, due to the physical properties of metallic oxides, ITO is brittle and unsuitable for flexible devices. In addition to that, ITO electrode is costly and requires sophisticated equipment to fabricate. In such cases, conductive nanomaterials like graphene, silver nanowire (AgNW), and carbon nanotube can be used to fabricate transparent and flexible electrodes, which have broad applications in foldable screens and e-skin devices.[3–5] Among these nanomaterials, AgNW offers relatively lower sheet resistance and fabrication costs, making it a popular choice for creating transparent and flexible electrodes.[6,7] In this article, we focus on developing techniques to deposit AgNW on uneven substrate surfaces.

Previous studies have successfully deposited AgNW on flat surfaces using spin coating, drop coating, or spray deposition, etc.[8–11] Different deposition processes result in varying transmittance and sheet resistance values, as shown in **Table 1**.[12,13] Post-processing can further reduce sheet resistance, employing both chemical and physical methods.[12] Chemical methods involve incubating AgNW-coated thin films in hydrogen chloride (HCl) vapor to reduce oxidized surfaces, significantly lowering sheet resistance. Physical methods, such as annealing[8,14] and compression,[15] are the primary post-processes used to achieve reduced sheet resistance.

Existing literature mainly discusses AgNW electrode deposition on flat substrates. However, with the development of nanotechnology, researchers are now exploring the deposition of conductive materials on patterned substrates, such as zenithal bistable devices (ZBDs)[16–18] and reconfigurable Fresnel lenses,[19–21] as shown in **Figure 1**. The metallization processes typically involves evaporation and sputtering using metallic oxide materials, which necessitates professional metallization equipment and increase fabrication costs. Additionally, metallic oxides are fragile, rendering them unsuitable for flexible cells. AgNW, as a more flexible and cost-effective alternative, is a viable substitute for traditional transparent electrode materials. Due

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Table 1. Previous research.

References	Fabrication methods	Purpose	T [%]	R_{sheet}	Post-processing
[8]	Drop coating	Solar cell	84.7	10.3	Annealing
[9]	Transfer process	Percolation network	85	10	Annealing
[11]	Spray deposition	/	90	50	/
[15]	Drop coating	Solar cell	/	8.6	Compression
[34]	Drop coating	Transparent electrodes	95	580	Illumination
[35]	Flood coating	Patterned electrode	87.4	8.2	Repeat coating
[29]	Spin coating	Flexible organic light emitting diode (OLED)	83	12	PEDOT:PSS

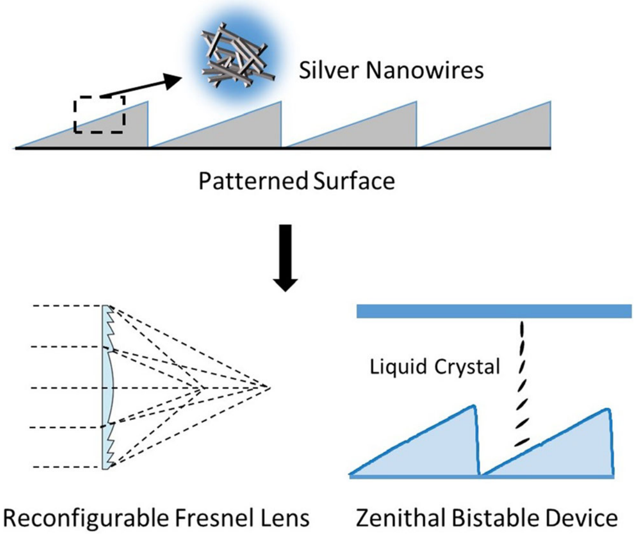

Figure 1. Our concept of depositing silver nanowires (AgNWs) on a patterned surface, as well as two potential applications that involve reconfigurable Fresnel lenses and zenithal bistable devices.

to the complexity of the surface structure, it is difficult to deposit AgNW on Fresnel lenses using traditional methods such as, for example, drop coating and spin coating. One feasible solution is to use the Mylar-bar-coating method. Specifically, Mylar-bar coating is a process to control and apply a precise and uniform thickness of liquid material onto a flexible substrate. The height of the Mylar bar above the substrate is adjustable, which determines the thickness of the coating material. In comparison with other coating methods, Mylar-bar coating is more suitable for depositing AgNWs on patterned surfaces since the gap between the Mylar bar and substrate could be adjusted to ensure the coating material is uniformly distributed on the surface.

In this article, we demonstrate the process of depositing AgNW on patterned surfaces and showcase how varying AgNW suspension concentrations influence transmittance and sheet resistance. We also discuss post-processing techniques to further reduce sheet resistance. Specifically, we use a polyvinyl chloride (PVC)-based Fresnel lens as the target substrate due to its low cost, flexibility, and scalability. Notably, the low melting point of PVC material necessitates temperature control below 50 °C to avoid permanent deformation. The outcomes of our research will contribute significantly to the development of future reconfigurable liquid-crystal technology, including optical switches,[22,23] tunable antennas,[24] adjustable-focus eyewear,[25] and innovative display technologies.[26,27]

2. Methodology

2.1. Fabrication Process

First, the AgNW isopropyl alcohol (IPA) suspension (5 mg mL^{-1}, Sigma-Aldrich) was diluted to concentrations ranging from 1 to 5 mg mL^{-1} using IPA. This step is to prepare different concentrations of AgNW suspensions for electrode fabrication. Using a high concentration of AgNW IPA suspension for electrode fabrication would result in a greater accumulation of silver material per unit area, leading to low sheet resistance but also reduced transmittance. Therefore, five different concentrations of AgNW IPA suspensions were prepared to examine the influence of AgNW suspension concentration on sheet resistance and transmittance.

Second, the substrate (Fresnel lens) was immersed in IPA solvent in an ultrasonic cleaner for 5 min and then dried using a nitrogen flow, as is shown in **Figure 2**a. Notably, the Fresnel lens is made of PVC, which can dissolve in some alcoholic solvents, such as ethanol. Consequently, these materials must be avoided when cleaning samples and diluting AgNW suspension. Following this, two 50 μm spacers of Mylar film were placed at the edge of the cleaned substrate, as shown in Figure 2b. The Mylar film spacer was adhered using optical glue NOA61 and exposed to UV light to cure the glue. This step fixed the spacer and eliminated the gap between the spacer and the patterned substrate. The spacer ensured that each unit area of the substrate received the same volume of material, allowing for a uniform AgNW coating.

Subsequently, the AgNW suspension was dropped onto the edge of the substrate and deposited using the Mylar-bar-coating method, as shown in Figure 2c,d.[28] After deposition, the substrate was baked on a 50 °C hot plate for 5 min to solidify the AgNWs. Finally, the spacers and part of the edges were removed to obtain a uniformly coated area, as shown in Figure 2e,f.

2.2. Post-Processing

As previously mentioned, several post-processing methods can be used to further reduce the sheet resistance of AgNW electrodes. Annealing is an effective post-processing technique aimed at

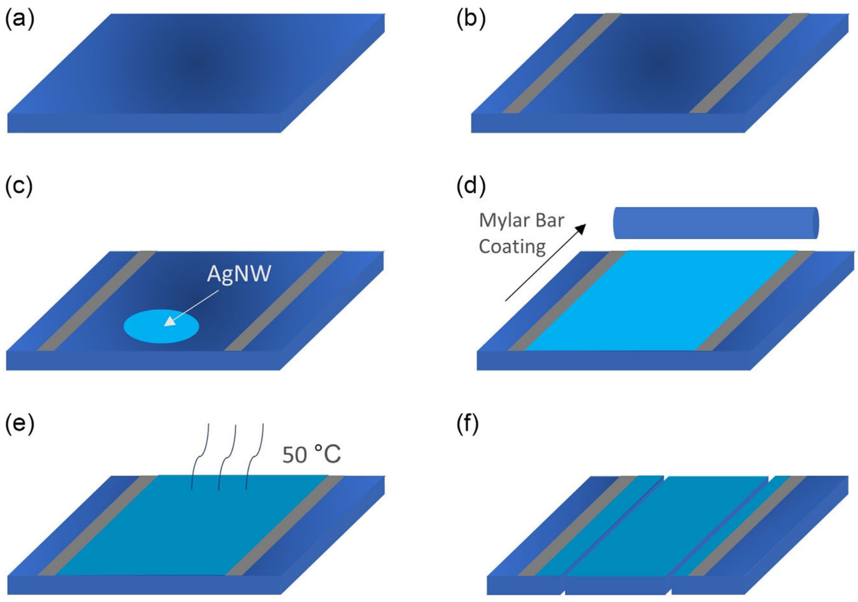

Figure 2. Processes of depositing AgNWs on patterned substrate: a) targeting substrate; b) observing two Mylar film spaces adhesive on two side of the substrate; c) placing one droplet of AgNW material on one side of the sample; d) using Mylar-bar-coating method to uniformly deposit AgNW material; e) heating the substrate on a hot plate at 50° to evaporate isopropyl alcohol; and f) removing spacers and uncoated area.

improving the quality of AgNW deposition by reducing the joint resistance between the nanowires. Typically, AgNWs could be annealed at temperatures ranging from 100 to 150 °C.[29,30] However, due to the low melting point of PVC material, post-processes involving high temperatures are unsuitable for our application. Other high-temperature methods such as plasma and microwave processes can also cause a temperature increase in the substrate, potentially damaging the surface pattern. Moreover, mechanical compression methods were ruled out due to the inherent low rigidity of our PVC substrate. High pressure cannot be applied uniformly across the patterned surface without risking damage to the Fresnel lens pattern. Therefore, chemical processes emerged as the most suitable approach for PVC substrates, which is why we used poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) treatment as a post-processing technique to effectively reduce the sheet resistance.

PEDOT:PSS is a conductive polymer mixture widely used in transparent electrodes and flexible organic devices.[31] Previous research has demonstrated that PEDOT:PSS can reduce joint resistance in AgNW networks and decrease surface roughness by encapsulating AgNWs. In this article, we show that PEDOT:PSS can also improve the conductivity of patterned substrates without affecting their optical properties.[29]

In our experiment, we first deposited AgNWs uniformly onto the substrate. Subsequently, Orgacon S305 (0.54% PEDOT:PSS in H_2O, Sigma-Aldrich) was spin-coated over the AgNW layer at a speed of 1000 rpm, achieving a thickness ranging between 50 and 60 nm.[32] Following practices documented in prior literature, the substrates were then heated on a 50 °C hot plate for 10 min to solidify the polymer. It is important to note that PEDOT:PSS is typically applied from a solution, which requires solvent evaporation for film solidification. High-temperature annealing speeds up this evaporation, enabling the polymer chains to realign and the film to solidify more effectively. This process yields a denser and more ordered structure, thereby boosting electrical conductivity. However, due to our substrate's limitations, we could only solidify the PEDOT:PSS at 50 °C. While this is not the optimal annealing temperature for PEDOT:PSS deposition, the result still showcased commendable conductivity. After solidifying at 50 °C, there was a notable reduction in the sheet resistance of the AgNW. Based on prior research, we understand that increasing the film's thickness by repeating the spin-coating process can further enhance conductivity and smooth the surface. However, this method might also decrease light transmittance and slightly modify the surface pattern, potentially influencing optical properties.

2.3. Characterization

This article focuses on examining how different concentrations of AgNW suspension influence sheet resistance and transmittance. Additionally, we investigate the use of post-processing to further reduce sheet resistance. Sheet resistance was measured using the four-point probe method with a Hall effect measurement system (Nanometrics).[33] Furthermore, transmittance under various light wavelengths was measured using a UV–vis spectrophotometer (Ultrospec 9000). According to these measurements, we determined the relationship between the concentration of AgNW suspension and transmittance. The results also showed how the PEDOT:PSS process reduced both transmittance and sheet resistance.

Moreover, an optical profilometer and stylus profilometer (Bruker) was used to measure surface patterns after deposition.

This step demonstrated that the deposition of AgNW and PEDOT:PSS did not influence the substrate's pattern, ensuring that the optical properties of the Fresnel lens remained unaffected. Additionally, scanning electron microscope (SEM) images were captured before and after the post-process to observe the impact of PEDOT:PSS on AgNWs in reducing sheet resistance. Atomic force microscopy (AFM) was employed to measure surface geometry, illustrating that PEDOT:PSS reduced surface roughness and increased mesh connectivity within the AgNW network.

3. Results and Discussion

Initially, after applying five different concentrations of AgNW suspensions uniformly onto the Fresnel lens using the previously mentioned Mylar-bar-coating method, the transmittance at different wavelengths was measured using UV–vis, as shown in **Figure 3**a. The transmittance significantly decreased as the concentration of AgNW suspension increased. A higher concentration of AgNW suspension resulted in a denser AgNW network, which influenced the transmittance. Subsequently, the transmittance was measured after the PEDOT:PSS process and plotted in Figure 3b. Compared to Figure 3a, the transmittance dropped between 3% and 7% after the process. Notably, samples deposited with higher concentrations of AgNW suspension had denser AgNW networks, which retained more residual PEDOT:PSS material after spin coating, resulting in a larger drop in transmittance.

Moreover, we used the four-point probe method to measure the sheet resistances of five samples for each suspension concentration. The average sheet resistances for these are illustrated in Figure 3c. The data indicated that a suspension with lower concentration led to a sparser AgNW network, resulting in a higher sheet resistance. With the increase in concentration from 1 to 3 mg mL^{-1}, the sheet resistance dropped from 375.75 to 32.64 W sq^{-1}. However, for the samples with concentrations of 4 and 5 mg mL^{-1}, the reduction in sheet resistance was small, moving from 11.09 to 8.02 W sq^{-1}. Upon applying the PEDOT:PSS process, another set of measurements was taken and is also shown in Figure 3c. Relative to the earlier findings, the PEDOT:PSS process brought about a reduction in sheet resistance, demonstrating a more pronounced effect on samples with lower concentrations. For instance, the average sheet resistance for the 1 mg mL^{-1} AgNW samples was originally 373.75 W sq^{-1} and decreased to 231.48 W sq^{-1} post-PEDOT:PSS treatment.

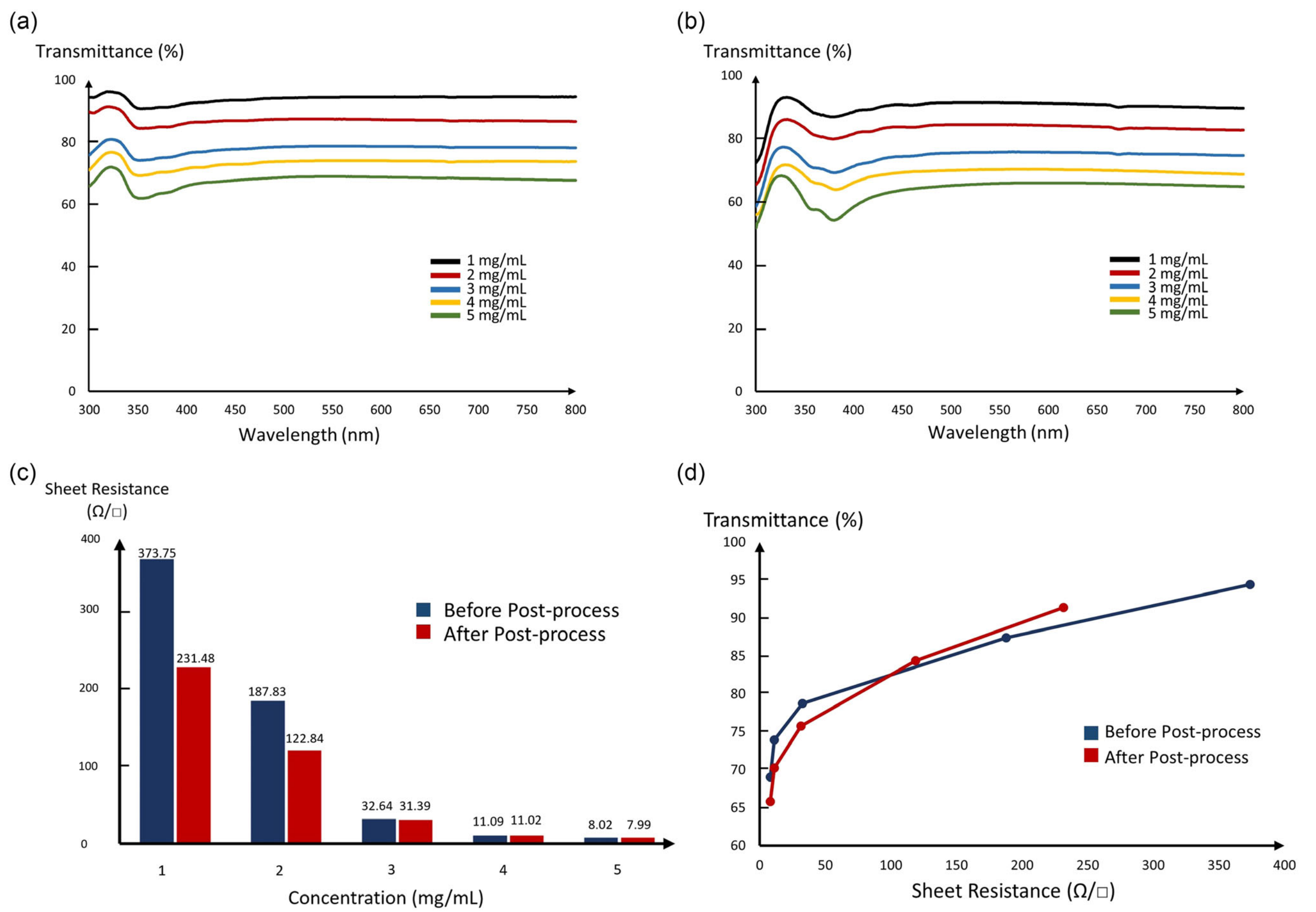

Figure 3. a) Transmittance of samples coated by different concentration of AgNW suspension before PEDOT:PSS process. b) The transmittance after PEDOT:PSS process. c) Sheet resistance of samples coated by different concentration of AgNW suspension before and after PEDOT:PSS process. d) The relationship between sheet resistance and transmittance at 550 nm.

However, for denser AgNW samples, particularly those above 3 mg mL^{-1}, the influence of the PEDOT:PSS process on sheet resistance was minimal. The underlying reason for this observation is linked to the structure of high-density AgNW samples, since they possess a greater number of crossing junctions within their networks. These junction resistances are connected in parallel, meaning high-density AgNW samples are less affected by junction resistance compared to their low-density counterparts. Since PEDOT:PSS primarily acts to reduce junction resistance, it naturally has a more significant impact on reducing sheet resistance in samples with a lower density of AgNWs.

According to Figure 3a–c, the relationship between transmittance and sheet resistance for different AgNW concentration samples can be determined. As shown in Figure 3d, an intersection point occurs between the two curves at around 103 W sq^{-1}. For samples with a target sheet resistance above 103 W sq^{-1}, the PEDOT:PSS process could help achieve higher transmittance. However, for samples requiring sheet resistance no greater than that, the PEDOT:PSS process is not ideal, as it might result in lower transmittance. In our case, the AgNW electrode on the patterned surface is intended for reconfigurable liquid-crystal devices, where sheet resistance within the range of hundreds of W sq^{-1} is desirable.

To better understand the substrate's behavior, SEM images were captured before and after the PEDOT:PSS process, as shown in **Figure 4**. Prior to the application of PEDOT:PSS, the AgNW material was uniformly distributed across the substrate, resulting in nanowires that overlapped to create a well-connected AgNW network. The SEM images confirm both the

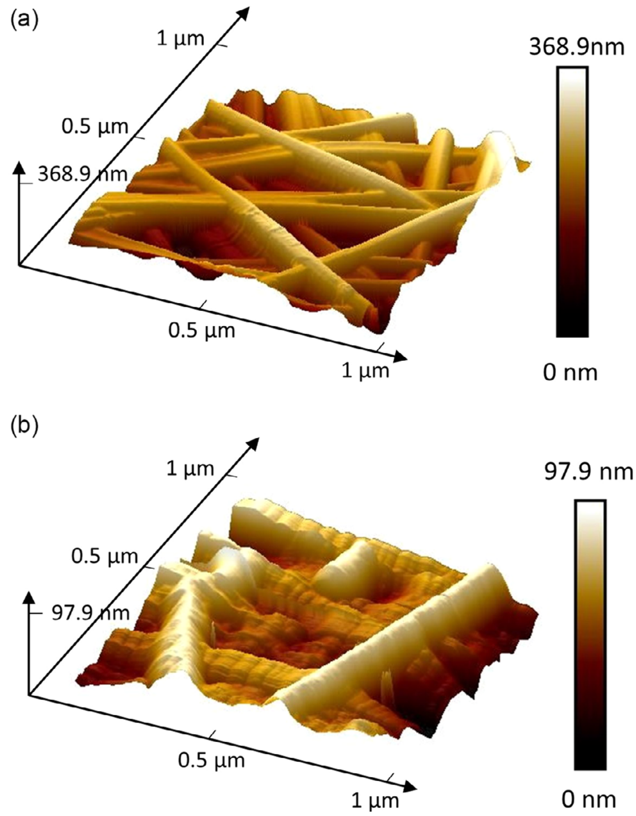

Figure 5. a) The 3 mg mL^{-1} sample before PEDOT:PSS process and b) after process.

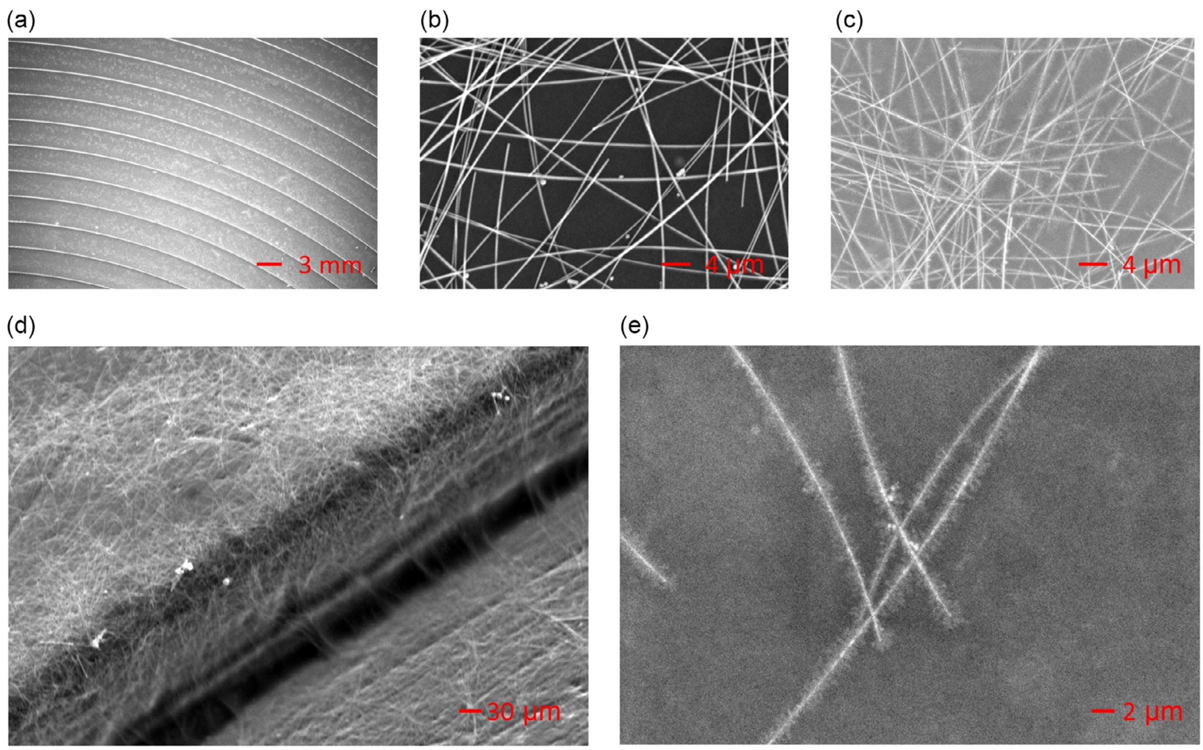

Figure 4. a) Low-magnification scanning electron microscope image of Fresnel lens structure. b) AgNWs network on flat area before PEDOT:PSS process. c) AgNWs network on flat area after PEDOT:PSS process. d) AgNWs network on patterned area. e) AgNWs encapsulated by PEDOT:PSS.

uniformity and connectivity of the AgNW layer, in both flat and corner regions of the substrate. Moreover, the images show that a higher concentration of AgNW suspension leads to a denser network, but leads to reduced light transmission. Following the deposition of the PEDOT:PSS layer, the SEM images showed that the AgNWs were encapsulated by this conductive polymer. This encapsulation lowered the overall resistance of the AgNW network, thereby contributing to a subsequent reduction in sheet resistance.

In addition to reducing sheet resistance, PEDOT:PSS can also decrease surface roughness, which can be beneficial when fabricating liquid-crystal cells with the substrate. A rough surface has an anchoring effect on liquid-crystal molecules, which can cause light distortion. In **Figure 5**, AFM images were taken to demonstrate that the PEDOT:PSS process can reduce surface roughness. Figure 5a,b was captured before and after the post-process for a 3 mg mL^{-1} sample, where the surface roughness decreased significantly after the process. The height difference of the surface was 368.9 nm before the PEDOT:PSS process and dropped to 97.9 nm afterward.

Furthermore, a Dektak profilometer was used to measure the geometry of an uncoated Fresnel lens, as shown in **Figure 6**a. This surface structure enables the Fresnel lens to focus light and magnify objects. To ensure that the optical properties of the substrate are not affected by the coated layers, the surface geometry of samples was measured by profilometers before and after deposition, as demonstrated in Figure 6b. Compared to the non-coated sample, the patterns on coated substrates were slightly rounded at the corners, but the rest of the area maintained its structure. This result confirms that the substrate is still functional and that the processes do not affect its optical properties.

4. Application

The thermal properties of AgNW-based transparent heaters were explored due to their outstanding electrical conductivity, mechanical flexibility, and thermal conductivity. Therefore, we showcase an application where an AgNW-coated Fresnel lens serves as a transparent heater. Fresnel lenses are prominently used in optical devices such as projectors and augmented reality (AR) glasses. The primary function of this heater is to remove moisture on the Fresnel lens during its operation, ensuring optimal image quality. Infrared thermal images of the newly prepared heater, presented in **Figure 7**a, were taken at varying voltages, from 500 mV to 3 V. These images revealed that the heater's temperature spans between 25 and 55 °C, rising exponentially in line with an increase in voltage. This behavior is mainly attributed to the Joule effect within the AgNWs. However, it is important to note that the unique shape and design of the Fresnel lens might introduce distortions affecting

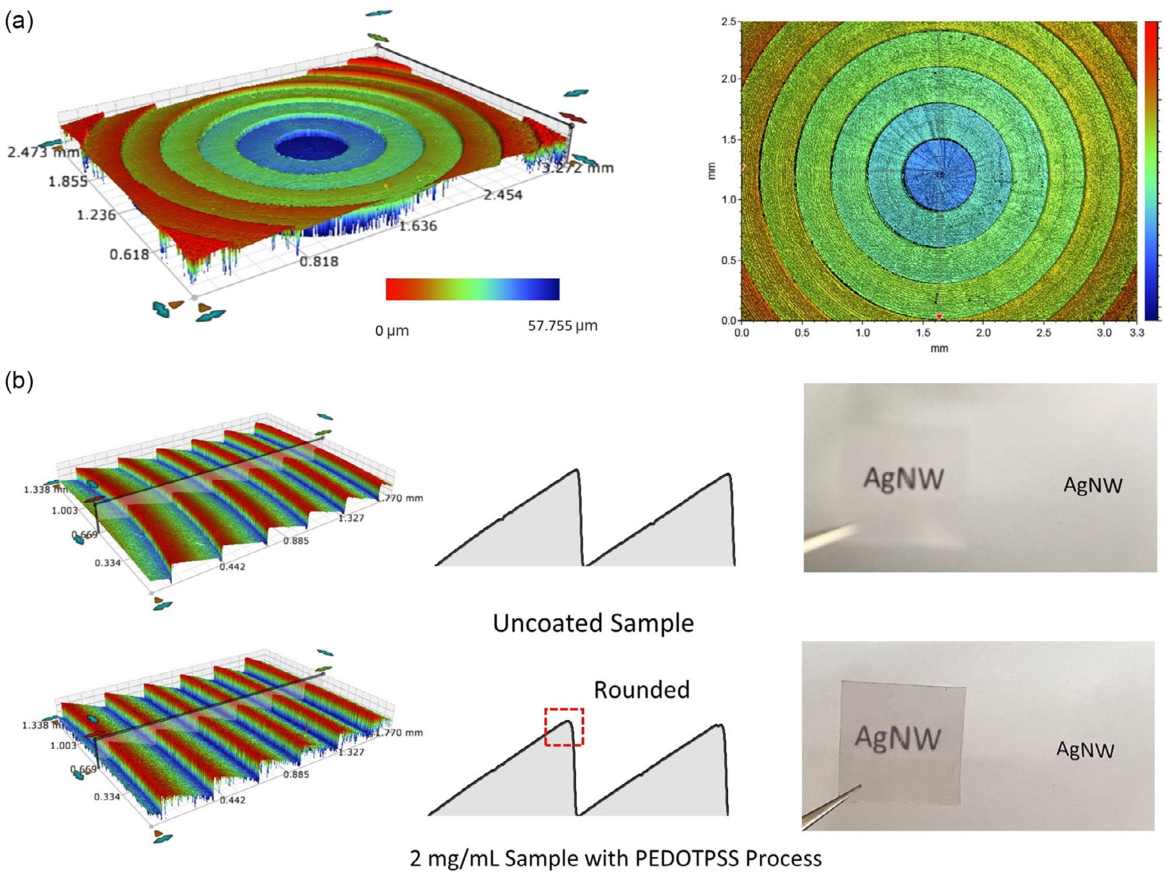

Figure 6. a) The basic structure of an uncoated Fresnel lens; b) comparison between an uncoated sample and 2 mg mL^{-1} sample.

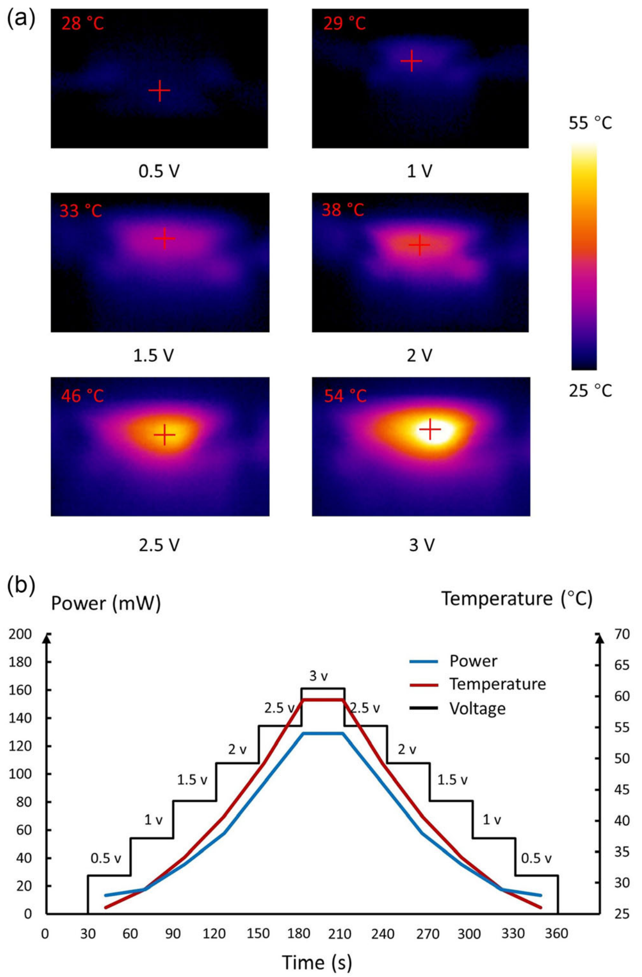

Figure 7. a) Thermal profile images corresponding to the 0.5–3 V insteps of 0.5 V using infrared camera with the scale bar on the right. b) Heating cycles from 0.5 to 3 V, and 30 s for each step.

infrared radiation distribution. Such distortions can potentially influence the accuracy of temperature distribution measurements, which might be the reason behind the observed uneven heat distribution shown in Figure 7a. Additionally, cyclic tests were conducted to assess the stability of the transparent electrode. These tests revealed commendable cyclic stability, maintaining consistent values as depicted in Figure 7b. Given their capability to provide a uniform temperature distribution and proven cyclic stability, such heaters may be useful in diverse applications, including defogging Fresnel lenses in projectors or in solar collectors. AgNW-based transparent electrodes on patterned surfaces hold significant potential for the future of reconfigurable optical devices. Examples include tunable focus lenses and ZBD. Continued research in this direction is likely to lead to further developments in this field.

5. Conclusion

In this article, we proposed a method to deposit AgNW material on patterned surfaces and studied how different concentrations of AgNW suspension influence transmittance and sheet resistance. First, different concentrations of AgNW suspension were uniformly deposited on PVC-based Fresnel lenses. Second, transmittance and sheet resistance were measured before any post-processing. Samples deposited with 1 mg mL^{-1} suspension had an average sheet resistance of 373.75 W sq^{-1} and transmittance of around 94% at 550 nm, while the 5 mg mL^{-1} samples had a sheet resistance of 8.02 and transmittance of 69% at 550 nm. Afterward, the PEDOT:PSS process was investigated to reduce sheet resistance. According to our measurements, sheet resistance dropped significantly among the 1 and 2 mg mL^{-1} samples, from 373.75 to 231.48 and 187.83 to 188.84 W sq^{-1}, respectively. However, for low-sheet-resistance samples, such as those deposited with suspensions over 3 mg mL^{-1}, the PEDOT:PSS process had a limited effect on further reducing sheet resistance. Our analysis indicates that the PEDOT:PSS process could benefit plate electrodes with target sheet resistance above 103 W sq^{-1}. In our case, this work targets reconfigurable liquid-crystal lenses and ZBD devices. According to previous studies, researchers have shown that substrates with sheet resistance ranging from 21.3 to 650 W sq^{-1} exhibit similar performance when switching a basic liquid-crystal cell. Thus, the PEDOT:PSS process could be beneficial for AgNW transparent electrodes in these futuristic liquid-crystal devices.

Compared to previous research on flat surfaces, this work has relatively higher sheet resistance for the same transmittance, which is due to the properties of the substrate. Any post-processing that introduces heat compression to the surface might damage the pattern. Therefore, only limited post-processing methods are suitable for this substrate. However, PVC substrates offer advantages such as low cost, ease of fabrication, and resizability. This work presents a feasible solution for depositing nanowires on patterned surfaces. Future research could further improve the method by investigating other post-processing techniques to enhance sheet resistance without affecting the transmittance of the substrate.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

flexible substrates, Fresnel lenses, silver nanowires, transparent electrodes

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