Ascorbic Acid-Assisted One-Step Chemical Reaction To Design an Ultralong Silver Nanowire Structure for a Highly Transparent Flexible Conducting Film

Yuxiu Li, Yao Li, Zhengyang Fan, Hongwei Yang,* Ximin Yuan, and Chuan Wang*

Cite This:ACS Omega 2020, 5, 18458−18464

ABSTRACT: Increasing the length of silver nanowires (AgNWs) has been demonstrated as an effective measure to enhance their optoelectronic properties by reducing light attenuation. Herein, we report a unique modified polyol synthesis of AgNWs with average length as long as ~270 μm in a high yield of ~90%. The synthesis of ultralong AgNWs involves the employment of ascorbic acid in the polyol approach. The strong reducing action of ascorbic acid allows the reduction of silver precursors to occur at a relatively low temperature, wherein the lateral growth of AgNWs is restrained because of efficient surface passivation via the dual function of poly-vinylpyrrolidone and ascorbic acid. The photoelectric properties of the as-synthesized ~270 μm AgNW film show a noteworthy transmittance of 92.61% with a low haze of 1.35% at a sheet resistance of ~322 Ω sq⁻¹. In addition, the AgNW film shows distinguished mechanical property and relatively high electrical stability. The breakthrough in the length confinement of AgNWs is a highly expected step to prepare AgNW films with excellent performance.

1. INTRODUCTION

Transparent conductive films (TCFs), a key component in optoelectronic devices, have been extensively used in displays,¹ touch screens,²,³ solar cells, organic light-emitting diodes,⁴−⁶ smart windows,⁷ sensors,⁸ human–machine interfaces,⁹ and so forth. Indium tin oxide (ITO) is the most common conductive material used in TCFs. However, limited storage of indium and brittle film structure of ITO overshadow its future domination. These limitations caused the scientific community and industry to pay more attention to the alternative materials of ITO, such as silver nanowires (AgNWs),¹⁰−¹² metal nanowire networks,¹³ graphene,¹⁴−¹⁶ conducting polymers,¹⁷ carbon nanotubes,¹⁸,¹⁹ and so forth. Certainly, AgNWs stand out among alternative materials, which have better flexibility and more outstanding photoelectric properties compared with other materials. Undoubtedly, the size of AgNWs is a pivotal structural trait that determines the performance of AgNW films. Specifically, on the basis of percolation theory, longer AgNWs can bring about higher electrical conductivity for a random network at a given material density, which is ideal for flexible films. In addition, longer AgNWs can also help in achieving a better balance between electrical conductivity and optical transmittance, in other words, increasing electrical conductivity without reducing optical transmittance, which is critical for flexible TCFs made of AgNWs.²⁰ Therefore, highly transparent flexible conductive films require longer AgNWs, which pose a severe challenge to the preparation of longer AgNWs.

So far, polyol synthesis is the most popular and effective approach to synthesize AgNWs. Jiu et al.²¹ claimed that the polyol process by adjusting the stirring speed can achieve the synthesis of >60 μm and even 100 μm AgNWs. Araki et al.²² have experimentally shown that ultralong AgNWs with lengths in the range of 20−100 μm have been successfully synthesized by adjusting the reaction temperature and the stirring speed of a one-step polyol process. Andrès et al.²³ have synthesized ultralong AgNWs using a polyol-mediated synthetic procedure with nanowires lengths reaching 195 μm. These AgNW-based TCFs have revealed very promising film properties compared to ITO. Despite this progress, the preparation of AgNWs greater than 200 μm through a traditional polyol process has limited success, and search for a novel modified polyol process capable of controlling the length of AgNWs is still an emerging strategy today.

Herein, we develop a novel modified polyol synthesis to obtain ultralong AgNWs with length ~270 μm and part of them increased to 290 μm and newly find that the addition of ascorbic acid into traditional polyol synthesis can effectively
promote the growth of AgNWs, which is ~2.7 times higher than that without the process of ascorbic acid participation. Also, the possible growth mechanisms of high-yield five-fold twinned pentagonal seeds and ultralong AgNWs were clarified. TCFs fabricated with ultralong AgNWs exhibit a low haze value of 1.35% with a low sheet resistance of ~322 Ω sq⁻¹ at an optical transmittance of 92.61%. More significantly, the film presents excellent stability for electrical property and distinguished mechanical property and shows great potential for use in wearable electronics.

2. RESULTS AND DISCUSSION

The X-ray powder diffraction (XRD) characterization was conducted to elucidate the crystalline nature of the as-synthesized ultralong AgNWs, as shown in Figure 1. Five diffraction peaks from the XRD pattern are observed and indexed to the (111), (200), (220), (311), and (222) reflections of the face-centered cubic Ag crystal [JCPDS no. 99-0094, a = b = c = 4.086 Å, space group Fm3m (225)]. As can be seen from the XRD spectrum, the diffraction peak intensity at (111) is greater than that at (200) by 3.4-fold, which suggests that the as-synthesized AgNWs demonstrate higher aspect ratios. The intensity ratio is in accordance with a preferential growth of AgNWs along the {111} direction. In addition, no other visible peaks are attributed to silver oxide or silver halide. It can be inferred that the AgNWs have been successfully synthesized via an ascorbic acid-assisted one-step chemical reaction with high crystallinity and purity.

To investigate the influence of ascorbic acid in the polyol synthesis process, the AgNW synthesis without ascorbic acid was performed. Figure 2 shows the field emission scanning electron microscopy (FE-SEM) images of the traditional polyol process-synthesized AgNWs. From Figure 2a, it can be seen clearly that the sample is composed of almost uniform wires with an average length of ~100 μm. The more detailed structural features of the AgNWs based on the traditional polyol method are shown in Figure 2b. It can be noticed that the average diameter of AgNWs is close to ~155 nm, which is consistent with the results reported in previous literature studies.

In order to further prove the contribution of ascorbic acid to nanowire growth, the morphology of the as-synthesized AgNWs was observed in the FE-SEM images, as shown in Figure 3. Different from the traditional polyol method, the addition of ascorbic acid can effectively increase the growth of AgNWs. The whole morphology features are shown in Figure 3a. As can be seen from Figure 3a, the length of AgNWs is drastically increased to ~270 μm; a part of the nanowire has a length exceeding 290 μm, which is 2.7 times as long as that prepared without the process of ascorbic acid. In addition, the yield of silver products is over 90%, which is much higher than the traditional method. Figure 3b,c exhibits the magnified FE-SEM images, from which we can observe the AgNWs with homogeneous distribution and high crystallinity. The larger magnified image of AgNWs is displayed in Figure 3d; the average diameter of AgNWs is about 220 nm, and a small change in the diameter indicates that the addition of ascorbic acid has little effect on the AgNW diameter, which attributes to the both-side effects of poly-vinylpyrrolidone (PVP) and ascorbic acid. In addition, a special part is marked by the blue circle, and it can be seen that the formation of a five-fold twinned structure in the tip of AgNWs indicates the existence of a twin-plane structure parallel to the crystal growth direction.

Furthermore, detailed morphology and structure of the as-synthesized ultralong AgNWs were analyzed by transmission electron microscopy (TEM), high-resolution transmission electron microscopy (HRTEM), and fast Fourier transform (FFT) and are displayed in Figure 4. Figure 4a,b shows the low-magnified TEM images of the produced AgNWs. The nanowire has a diameter of ~220 nm, which effectively supports the above-mentioned SEM measurement results. Moreover, it is generally known that a PVP layer remains around the AgNWs, but from Figure 4, the layer is not clearly recognizable anymore, which illustrates that PVP and ascorbic acid were thoroughly removed through the process of washing. The crystal structure of AgNWs was characterized by HRTEM, as indicated in Figure 4c. A twin plane is revealed in parallel to
The addition of ascorbic acid to a traditional polyol process can appreciably increase the length of AgNWs. Figure 4d further indicates the twin crystalline structure of ultralong AgNWs with different magnifications. HRTEM image (c) with the corresponding FFT pattern in (d).

Figure 4. (a,b) TEM images of ultralong AgNWs with different magnifications. HRTEM image (c) with the corresponding FFT pattern in (d).

The characteristic results of the ultralong AgNWs grown through the ascorbic acid-assisted polyol process indicate that each nanowire has grown from five-fold twinned particles with the assistance of ascorbic acid and PVP, and the possible formation mechanism is illustrated in Figure 6. Ascorbic acid plays a key part in the control of the number of five-fold twinned structures and the length of AgNWs. In the initial step, AgNO₃ reacts with NaCl and produces AgCl. It can be used to reduce free silver ion (Ag⁺) concentration in the solution of the initial formative Ag seed stage and can provide attachment sites for reductive Ag, which provide convenient conditions for further growth of AgNWs. Because of poor solubility of AgCl at high temperatures, the reduction rate of Ag⁺ and the formation rate of Ag crystals are slow, which is conducive to the formation of thermodynamically stable five-fold multiple twinned structures (MTPs). Especially, in the whole process, AgCl constantly and gradually releases Ag⁺ into the solution; these released Ag⁺ ions can continuously provide the source of silver for MTPs. Meanwhile, the strong reducing action of Vc allows the reduction of AgNO₃ to Ag⁰. It is believed that Ag nanoparticles are formed in the next step to serve as seeds to stimulate their enlargement into Ag clusters. On the basis of the surface free energy minimization principle, the Ag clusters tend to generate five-fold MTPs. The two processes provide more five-fold multiple twinned particles for the growth of AgNWs compared to the traditional polyol process. Once the five-fold multiple twinned particles are formed, more Ag⁰ formed from reduction condense and crystallize on the twin boundaries of the five-fold multiple twinned particles because of the high surface energies of the twin boundaries. The selective deposition of Ag⁰ causes the uniaxial elongation of five-fold multiple twinned particles into wire-shaped nanostructures under the confinement of twin planes. The formed {110} facets are passivated by chemical interactions with the oxygen atoms of PVP and Vc. In comparison, the interaction between PVP, Vc, and the {111} facets will be much weaker to enable the two ends of the nanowire to grow continuously. As a result, high yield and ultralong AgNWs were obtained by the modified polyol process.

Comparatively, transmittance could be increased in the visible region using ultralong AgNWs compared to typical short nanowires while maintaining high electrical conductivity. The ultralong AgNWs tend to set up a more sparse and effective percolation network that increases light transmission and decreases sheet resistance through providing a longer percolation path by reducing wire–wire junctions. This mechanism for high transmission and low sheet resistance caused by ultralong AgNWs is schematically represented in the inset of Figure 7a. The photoelectric properties of TCFs fabricated by using ultralong AgNWs were performed, and their corresponding results are shown in Figure 7. The as-fabricated flexible TCF shows a 92.61% optical transmittance with 1.35% haze (see Figure 7a). Meanwhile, the sheet resistance of the film is represented in Figure 7b, which exhibits a sheet resistance of ~322 Ω sq⁻¹. The excellent

Figure 5. UV–vis absorption spectra of ultralong AgNWs taken from the final product.
photoelectric properties compete with those of the previous literature.\textsuperscript{31}

From the viewpoint of practical applications, flexible TCFs are supposed to possess excellent electrical stability for a long term. To verify the electrical stability of the conductive films based on ultralong AgNWs, the sheet resistance was tested for 120 days, as shown in Figure 8. It can be found that the sheet resistance increases nearly linearly with the increase in exposure days. The linear dependence is depicted as follows

\[ y = 316.49 + 0.19 \times x \]  \hspace{1cm} (1)

where \( y \) is defined as the sheet resistance, and \( x \) is defined as the days. The sheet resistance exhibits the slower-growing tendency on further increasing the days, and the line slopes upward slightly with a slope of just 0.19, suggesting that the as-fabricated flexible TCF surely possesses good long-term stability; such an outstanding stability also demonstrates potential applications in optoelectronic devices.

Bending strength is one important parameter which can be used to evaluate the reversibility of the flexible AgNW film; one sheet resistance was measured under every 50 bendings, and the bending was applied down to 2 mm bending radius, the schematic diagram of which is shown in the inset of Figure 9. It is evident that there is no significant change in the sheet resistance even after 500 bending cycles. The linear dependence of the sheet resistances on the bending cycles was also

\[ y = 323.38 + 0.09 \times x \]

Figure 6. Schematic illustration of the proposed formation process of the ultralong AgNWs.

Figure 7. Optoelectronic performance of the as-fabricated ultralong AgNW TCF. (a) Transmittance and haze test picture; the inset shows the distribution of longer AgNWs and shorter AgNWs in PET for exhibiting the influence on optoelectronic performances and (b) sheet resistance test picture.

Figure 8. Stable sheet resistance of the as-fabricated ultralong AgNW TCF tested for up 120 days.

Figure 9. Sheet resistance change measurements during 500 bending cycles (2 mm bending radius) for an as-fabricated ultralong AgNW TCF. The inset shows the bent state of the ultralong AgNW TCF.
investigated, and the tested data in the range from 50 to 500 bending cycles are fitted as follows

\[ y = 3.2335 + 0.09 \times x \]  

(2)

where \( y \) is the sheet resistance, and \( x \) is the bending cycle times. The slope of these data is only 0.09. The electrical property of conductive films did not deteriorate over mechanical stress and remained at a relatively stable value. This implies that the ultralong AgNW flexible film possesses superior reliability under mechanical stress, which matches the previous literature.\(^\text{32}\) The remarkable bending strength of as-fabricated flexible TCFs is attributed to the following reasons. On the one hand, the AgNWs with five-fold MTPs are known to have an excellent yield strength and size-dependent elastic property.\(^\text{33−35}\) On the other hand, the longer AgNW percolation network could more effectively accommodate deformation without any significant degradation of conductivity by changing the network shapes. The longer AgNW percolation network could bend more easily than the shorter AgNW percolation network under the same stress.

### 3. CONCLUSIONS

In conclusion, we developed a novel synthesis method to increase the length of AgNWs from \( \sim \)100 to \( \sim \)270 \( \mu \)m by adding an external reducing agent, ascorbic acid, into a traditional polyol approach. The XRD, FE-SEM, TEM, and UV−vis were performed to follow the growth of AgNWs for gaining a deeper understanding of the role of ascorbic acid. Ultralong AgNW synthesis involves the use of ascorbic acid that allows the reduction of silver precursorsto occur, simultaneously with the reduction of ethylene glycol (EG), while the lateral growth of AgNWs is restrained because of surface passivation derived from the PVP and ascorbic acid. More significantly, the as-synthesized \( \sim \)270 \( \mu \)m nanowires reveal a sheet resistance \( \sim \)322 \( \Omega \) sq\(^{-1}\) at a transmittance of 92.61% with a haze factor of 1.35%. Highly transparent and flexible ultralong AgNW networks also show remarkable superiority in mechanical compliance. The ascorbic acid-modified polyol process exemplifies the potential of polyhydroxy compounds in making advanced AgNWs with enhanced performance.

### 4. EXPERIMENTAL SECTION

#### 4.1. Materials

The following chemicals, solvents, and materials were used to prepare AgNWs, AgNW ink, and AgNW-based TCFs, which all were analytical grade reagents and used as received without any further purification. Silver nitrate (AgNO\(_3\) ≥99.8%, Strem Chemicals), ascorbic acid (V\(_c\) ≥99.7%, Sinopharm), PVP (\( M_w \approx 1,300,000\), Aldrich), sodium chloride (NaCl, ≥99.5%, Sinopharm), EG (≥99.0%, Sinopharm), hydroxyethyl cellulose (HEC, Dow-QP-100MH), ethanol (\( C_2H_5OH \), ≥99.0%, Xilong Chemicals), and polyethylene glycol terephthalate (PET, Yingshang Electronic Material) were all purchased from commercial sources. Deionized water was obtained through a purification system with a resistivity of 18.2 M\( \Omega \) cm.

#### 4.2. Ultralong AgNW Preparation

The synthesis of ultralong AgNWs was realized using an ascorbic acid-assisted one-step chemical reaction. In brief, 3.15 g of AgNO\(_3\) and 4.5 g of PVP were dissolved in an EG solution of 200 mL to form a homogeneous solution under vigorous stirring for 3 h at room temperature. Then, 0.001 g of NaCl and 0.02 g of ascorbic acid were added into the above-mentioned solution, yielding a clear and dark brown solution after 10 min of magnetic stirring. The beaker filled with mixture solution was subsequently placed into an electric constant temperature drying oven at 100 °C for 24 h. After the chemical reaction was completed, the off-white AgNWs were collected by centrifugation at 3800 rpm for 10 min and washed thoroughly with absolute ethyl alcohol and deionized water for three times to remove EG and PVP and then redispersed with deionized water. Specifically, a traditional polyol process without ascorbic acid also was implemented as a comparison experiment.

#### 4.3. Ink Preparation

The AgNW ink was prepared by mixing the AgNW solution (AgNW concentration is 5 mg mL\(^{-1}\) in deionized water) and HEC solution. The AgNWs used have an average length of \( \sim \)270 \( \mu \)m and an average diameter of \( \sim \)200 nm. The viscosity of HEC powder is 100,000 mPa s. The HEC powder was first dissolved in deionized water to form a HEC solution and then is mixed with AgNWs and stirred for 30 min to obtain AgNW ink with an AgNW weight ratio of 0.7% and a HEC weight ratio of 0.8%. Figure 10 shows the as-prepared ultralong AgNW conductive ink; the AgNW ink appeared light silver, as shown in Figure 10b. HEC was added to the ink to tune the viscosity and impart rheological property, which results in a good printing property for AgNW ink.

#### 4.4. AgNW-Based TCF Coating and Curing

To fabricate the AgNW-based TCF, PET was used as substrate. The prepared AgNW ink was coated on a PET substrate using a bar coater, as shown in Figure 10a. In this coating process, the PET substrate was confined under a coated bar, and the AgNW ink was pipetted from the beaker and transferred to PET along the edge of bar. When the bar coater was turned on, a uniform film was formed on PET as the bar moves. Coating parameters are as follows: a bar diameter of 15 \( \mu \)m and coating speed varies from 10 to 300 mm s\(^{-1}\) for various applications. The coated AgNW film was subsequently dried in an oven at 130 °C for 30 min to improve wire−wire connection. The optical photograph of the as-prepared film is shown in Figure 10c, as can be seen from the photograph; the AgNW-based TCF maintains high transmittance and good flexibility.
4.5. Characterization. The phase identification of the as-synthesized ultralong AgNWs was performed using a Rigaku D/Max-3B XRD with Cu Kα irradiation ($\lambda = 1.54056$ Å), where the diffracted X-ray intensities were recorded as a function of $2\theta$. The product was scanned from 20 to 90° ($2\theta$) in steps of 0.02°. The FE-SEM images were recorded using a FEI-Versa3D instrument type. The as-synthesized AgNWs were deposited on a silicon wafer for FE-SEM measurements. TEM was carried out using a Zeiss EM 912 Ω instrument operating at 120 KV. A Philips CM200-FFG microscope with a voltage of 200 KV was used to observe the images of HRTEM and FFT. The AgNWs were deposited on a lacy carbon-coated Cu grid for TEM measurements. The absorption wavelength of the ultralong AgNWs was analyzed using a UV–vis spectrophotometer (PERSEE Genera TU-1901). The optical transmittance and haze photographs of AgNW-based TCFs were recorded with a SGW-820 transmittance and haze analyzer. The sheet resistance of AgNW-based TCFs was measured by an EC-80P noncontact resistivity tester. The tape adherence of AgNW-based TCFs was recorded with a SGW-820 transmittance and haze analyzer. The absorption wavelength of the ultralong AgNWs was analyzed using a UV–vis spectrophotometer (PERSEE Genera TU-1901). The optical transmittance and haze photographs of AgNW-based TCFs were recorded with a SGW-820 transmittance and haze analyzer.

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (grant no. 21761016), the Young and Middle-aged Academic and Technical Leaders Reserve Talents Program of Yunnan Province (grant no. 2017HB060), the Applied Basic Research Foundation of Yunnan Province (grant no. 2017FB142), and the Major R&D Project of Yunnan Province (grant no. 20182E001).

■ REFERENCES

(1) Su, Y. C.; Chiou, C. C.; Marinova, V.; Lin, S. H.; Bozhinov, N.; Blagoev, B.; Babeva, T.; Hsu, K. Y.; Dimitrov, D. Z. Atomic layer deposition prepared Al-doped ZnO for liquid crystal displays applications. Opt. Quant. Electron 2018, 50, 205.
(2) Chu, X.; Tao, J.; Li, S.; Ji, S.; Ye, C. Sandwich-structured silver nanowire transparent conductive films with 3H hardness and robust flexibility for potential applications in curved touch screens. Nanomaterials 2019, 9, S57.
(3) Mohchizuki, T.; Takigami, Y.; Kondo, T.; Okuzaki, H. Fabrication of flexible transparent electrodes using PEDOT:PSS and application to resistive touch screen panels. J. Appl. Polym. Sci. 2018, 135, 45972.
(4) Park, I.-J.; Kim, T. I.; Yoon, T.; Kang, S.; Cho, H.; Choi, N. S.; Lee, J.-I.; Kim, T.-S.; Choi, S.-Y. Flexible and transparent graphene electrode architecture with selective defect decoration for organic light-emitting diodes. Adv. Funct. Mater. 2018, 28, 1704435.
(5) Yeh, T.-H.; Lee, C.-C.; Shih, C.-J.; Kumar, G.; Biring, S.; Liu, S.-W. Vacuum-deposited MoO3/Ag/WO3 multilayered electrodes for highly efficient transparent and inverted organic light-emitting diodes. Org. Electron. 2018, 59, 266–271.
(6) Tseng, J.-Y.; Lee, L.; Huang, Y.-C.; Chang, J.-H.; Su, T.-Y.; Shih, Y.-C.; Lin, H.-W.; Chuhe, Y.-L. Pressure welding of silver nanowires networks at room temperature as transparent electrodes for efficient organic light-emitting diodes. Small 2018, 14, 180541.
(7) Mallikarjuna, K.; Kim, H. Highly transparent conductive reduced graphene oxide/silver nanowires/silver grid electrodes for low-voltage electrochromic smart windows. ACS Appl. Mater. Interfaces 2019, 11, 1969–1978.
(8) Oh, J.-W.; Heo, J.; Kim, T. H. An electrochemically modulated single-walled carbon nanotube network for the development of a transparent flexible sensor for dopamine. Sensor Actuat. B: Chem. 2018, 267, 438–447.
(9) Dong, W.; Zhu, C.; Hu, W.; Xiao, L.; Huang, Y. A. Stretchable human-machine interface based on skin-conformal sEMG electrodes with self-similar geometry. J. Semicond. 2018, 39, 014001.
(10) Lian, L.; Xi, X.; Dong, D.; He, G. Highly conductive silver nanowire transparent electrode by selective welding for organic light-emitting diode. Org. Electron. 2018, 60, 9–15.
(11) Zhang, K.; Li, J.; Fang, Y.; Luo, B.; Zhang, Y.; Li, Y.; Zhou, J.; Hu, B. Unraveling the solvent induced welding of silver nanowires for high performance flexible transparent electrodes. Nanoscale 2018, 10, 12981–12990.
(12) Niu, Z.; Cui, F.; Kuttnner, E.; Xie, C.; Chen, H.; Sun, Y.; Dehestani, A.; Schierle-Arndt, K.; Yang, P. Synthesis of silver nanowires with reduced diameters using benzoin-derived radicals to make transparent conductors with high transparency and low haze. Nano Lett. 2018, 18, 5329–5334.
(13) Yang, J.; Bao, C.; Zhu, K.; Yu, T.; Xu, Q. High-performance transparent conducting metal network electrodes for perovskite photodetectors. ACS Appl. Mater. Interfaces 2018, 10, 1998–2003.
(14) Shin, D. H.; Seo, S. W.; Kim, J. M.; Lee, H. S.; Choi, S.-H. Graphene transparent conductive electrodes doped with graphene quantum dots-mixed silver nanowires for highly-flexible organic solar cells. J. Alloy. Compd. 2018, 744, 1–6.
(15) Chen, Y.; Fu, X.-Y.; Yue, Y.-Y.; Zhang, N.; Feng, J.; Sun, H.-B. Flexible and transparent supercapacitor based on ultrathin Au/graphene composite. Appl. Surf. Sci. 2019, 467–468, 104–111.
(16) Yuhang, W.; Wu, L. Y.; Liu, G. D.; Liu, L. X. Non-destructive photovoltaic reading of interface type memristors using graphene as transparent electrode. J. Alloy. Compd. 2018, 740, 273–277.

(17) Zhao, P.; Tang, Q.; Zhao, X.; Tong, Y.; Liu, Y. Highly stable and flexible transparent conductive polymer electrode patterns for large-scale organic transistors. J. Colloid Interf. Sci. 2018, 520, 58–63.

(18) Jeon, I.; Delacou, C.; Okada, H.; Morse, G. E.; Han, T.-H.; Sato, Y.; Anisimov, A.; Suenaga, K.; Kauppinen, E. I.; Maruyama, S.; Matsuo, Y. Polymeric acid-doped transparent carbon nanobute electrodes for organic solar cells with the longest doping durability. J. Mater. Chem. A 2018, 6, 14553–14559.

(19) Tonkikh, A. A.; Tsebro, V. I.; Obraztsova, E. A.; Rybkovskiy, D. V.; Orekhov, A. S.; Kondrashov, I. I.; Kauppinen, E. I.; Chuvilin, A. L.; Obraztsova, E. D. Films of filled single-wall carbon nanotubes as a new material for high-performance air-sustainable transparent conductive electrodes operating in a wide spectral range. Nanoscale 2019, 11, 6755–6765.

(20) Cui, Z.; Han, Y.; Huang, Q.; Dong, J.; Zhu, Y. Electro-hydrodynamic printing of silver nanowires for flexible and stretchable electronics. Nanoscale 2018, 10, 6806–6811.

(21) Jiu, J.; Araki, T.; Wang, J.; Nogi, M.; Sugahara, T.; Nagao, S.; Koga, H.; Suganuma, K.; Nakazawa, E.; Hara, M.; Uchida, H.; Shinozaki, K. Facile synthesis of very-long silver nanowires for transparent electrodes. J. Mater. Chem. A 2014, 2, 6326–6330.

(22) Araki, T.; Jiu, J.; Nogi, M.; Koga, H.; Nagao, S.; Sugahara, T.; Suganuma, K. Low haze transparent electrodes and highly conducting air dried films with ultra-long silver nanowires synthesized by one-step polyol method. Nano Res. 2014, 7, 236–245.

(23) Andrés, L. J.; Menendez, M. F.; Gomez, D.; Martinez, A. L.; Bristow, N.; Kettle, J. P.; Menendez, A.; Ruiz, B. Rapid synthesis of ultra-long silver nanowires for tailor-made transparent conductive electrodes: proof of concept in organic solar cells. Nanotechnology 2015, 26, 265201.

(24) Ji, D.; Wang, Y.; Chen, S.; Zhang, Y.; Li, L.; Ding, W.; Wei, Z. Nitrogen-doped graphene wrapped around silver nanowires for enhanced catalysis in oxygen reduction reaction. J. Solid State Electr. 2018, 22, 2287–2296.

(25) Peng, P.; Hu, A.; Huang, H.; Gerlich, A. P.; Zhao, B.; Zhou, Y. N. Room-temperature pressureless bonding with silver nanowire paste: towards organic electronic and heat-sensitive functional devices packaging. J. Mater. Chem. A 2012, 22, 12997–13001.

(26) Peng, P.; Huang, H.; Hu, A.; Gerlich, A. P.; Zhou, Y. N. Functionalization of silver nanowire surfaces with copper oxide for surface-enhanced raman spectroscopic bio-sensing. J. Mater. Chem. 2012, 22, 15495–15499.

(27) Zeng, L.; Zhao, T. S.; An, L. A high-performance supportless silver nanowire catalyst for anion exchange membrane fuel cells. J. Mater. Chem. A 2015, 3, 1410–1416.

(28) Luo, M.; Huang, H. W.; Choi, S.; Zhang, C.; Silva, R. R. D.; Peng, H. C.; Li, Z. Y.; Liu, J. Y.; He, Z. K.; Xia, Y. N. Facile synthesis of Ag nanorods with no Plasmon resonance peak in the visible region by using Pd decahedra of 16 nm in size as seeds. ACS Nano 2015, 9, 10523–10532.

(29) Sun, Y.; Mayers, B.; Herricks, T.; Xia, Y. Polyl synthesis of uniform silver nanowires: a plausible growth mechanism and the supporting evidence. Nano Lett. 2003, 3, 955–960.

(30) Bari, B.; Lee, J.; Jang, T.; Won, P.; Ko, S. H.; Alamgir, K.; Aashad, M.; Guo, L. J. Simple hydrothermal synthesis of very-long and thin silver nanowires and their application in high quality transparent electrodes. J. Mater. Chem. A 2016, 4, 11365–11371.

(31) Kiran Kumar, A. B. V.; wan Bae, C.; Piao, L.; Kim, S.-H. Silver nanowire based flexible electrodes with improved properties: High conductivity, transparency, adhesion and low haze. Mater. Res. Bull. 2013, 48, 2944–2949.

(32) Chen, S.-P.; Liao, Y.-C. Highly stretchable and conductive silver nanowire thin films formed by soldering nanomesh junctions. Phys. Chem. Chem. Phys. 2014, 16, 19856–19860.