

A Method for Preparing AgNWs with Accelerated Seed–Wire Conversion Time

Xianjie Tang ¹, Guoyou Gan ^{1,*}, Xianglei Yu ¹ and Junpeng Li ²¹ Faculty of Materials Science and Engineering, Kunming University of Science and Technology, Kunming 650093, China² Sino-Platinum Metals Co., Ltd., Kunming 650101, China

* Correspondence: ganguoyou@kust.edu.cn

Abstract: A synthetic method was developed to produce silver nanowires. The method utilized TBAC (tetrabutylammonium chloride) instead of conventional metal halides as crystal seed additives to obtain purer silver nanowires. Our synthesis strategy relies on accelerating the rate of seed–wire conversion. The method allows for the control of the nanowire aspect ratio by tuning the ratio of Ag⁺ ions to polyvinylpyrrolidone (PVP) monomer units and the molar mass of TBAC. The observed synthesis improvements meet the basic requirements of current industrial manufacturing.

Keywords: polyol synthesis; silver nanowires; tetrabutylammonium chloride; seed–wire conversion

1. Introduction

At present, in many practical applications, it is necessary to attach electronic devices to the surface of organisms to detect movement or their physical condition, such as flexible displays, flexible supercapacitors, electronic skin, and so on [1–19]. In recent years, silver nanowires (AgNWs) have attracted much attention as a one-dimensional (1D) metal nanostructured material and have shown a potential trend to replace conventional electronic materials [20–33]. AgNWs combine high electrical conductivity with low optical extinction in the visible spectrum, making them a flexible component of transparent conductive layers [34–40], strain and pressure sensors [41–43], temperature sensors [44], substrates for surface-enhanced Raman spectroscopy [45,46], and conductive layers in photoelectrodes for solar water splitting [47,48].

AgNWs can be synthesized by various techniques, such as the ultraviolet radiation method, the hydrothermal method, and solution-based synthesis [49–51]. Zhou et al. [52] prepared AgNWs by ultraviolet irradiation. Silver nanowires with a length of 350 nm were obtained by exposing the mixed solution of AgNO₃ and PVA to ultraviolet light for 48 h. The most commonly used method for the preparation of AgNWs is the polyol method. The polyol method uses hot ethylene glycol (EG) to reduce Ag⁺ in the presence of polyvinylpyrrolidone (PVP). EG is also the solvent and sometimes contains small amounts of metal halide ions, such as Cl[−] or Br[−]. This method is popular due to the use of environmentally friendly reactants and relatively mild reaction conditions compared to other pyrolysis methods [53]. This method usually involves a 1–2 h reaction at 170 °C or higher [53–56]. This causes the overall solution to acidify and etch the silver particles at various stages, which leads to the generation of silver nanoparticles. These nanoparticles degrade the electrical and optical properties of AgNW-based devices and must be eliminated by multiple purification steps [35,57–59]. In addition, in order to achieve industrial scale production, a simple synthesis method with fast reaction time is needed to reduce production costs.

According to Matteo Parente et al. [60], it was shown that silver nanowires degrade slowly after their generation as the reaction time increases. The real reducing agents in the reaction system are acetaldehyde and ethanol aldehyde formed by the decomposition



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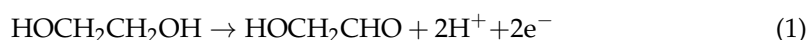
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of ethylene glycol via a high temperature. When acetaldehyde and ethanol aldehyde are in the reaction solution at the same time, the free silver ions in the system are reduced to silver atoms [61,62].



According to Equations (1) and (2), the generation of both reducing agents is accompanied by the acidification of the overall solution, which can lead to the re-etching of the AgNWs to be grown in the grown-up phase into irregularly shaped Ag nanoparticles. It is well known that the synthesis of AgNWs with a low byproduct content depends on a slower nucleation rate as well as a faster seed–wire conversion rate [63]. We speculate that there may be multiple acid etching processes during the reaction.

Figure 1 shows a schematic diagram of the reaction process of silver nanowires. With increasing reaction time, the possibility of fivefold twin seeds being etched rises gradually. In this paper, unlike in previous studies in which metal chlorides were added, the growth step of the reaction process can be accelerated by the addition of TBAC. The acceleration of this step not only makes the twin seeds less susceptible to etching but also accelerates the growth of the twin seeds toward AgNWs.

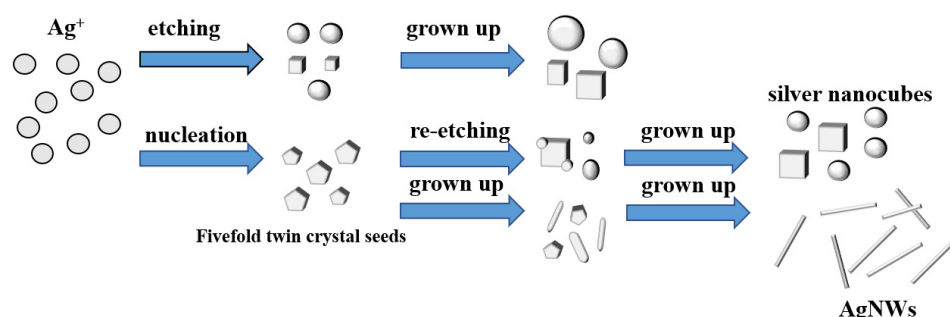


Figure 1. Schematic diagram of the growth mechanism of AgNWs.

The synthesis of AgNWs with the addition of metal halide additives such as NaCl was analyzed by Yamamoto et al. [64] Little has been said about the comparison of the AgNW growth process with organic halide additives and the growth process with metal halide additives. Herein, we present a simple method for the synthesis of AgNWs with dimensions suitable for various applications. In combination with the key factors affecting the polyol method, AgNWs with narrow size distribution and high purity were prepared using the addition of an organic halide. In summary, we propose the use of TBAC to accelerate the rate of seed–wire conversion so that the possibility of the re-etching of AgNWs is greatly reduced. At the initial stage of the reaction, the crystal seeds in the reaction solution using the TBAC additive change to filaments faster. This preparation method meets the basic requirements of current industrial manufacturing.

2. Method

2.1. Chemicals

All the chemicals are used without any purification steps. KCl (>99%), NaCl (>99%), TBAC (>99%), AgNO₃ (>99%), polyvinylpyrrolidone (PVP, 58,000 MW), and ethylene glycol (anhydrous, 99.8%) are purchased from Aladdin.

2.2. Preparation of AgNWs

In a typical synthetic procedure, 0.34 g PVP (40,000 MW) was dissolved into 20 mL ethylene glycol in a 25 mL three-necked round bottom flask, heated to 160 °C, and stirred at 800 rpm. After 10 min, 0.02 g TBAC (0.004 g NaCl, 0.006 g KCl) was added. The reaction

was stirred at 160 °C at 800 rpm and small aliquots (<0.5 mL) were taken periodically, diluted 100-fold in water, and analyzed by optical spectroscopy and electron microscopy. The reaction solution was cooled to room temperature, poured into a centrifuge tube, and diluted with an appropriate amount of acetone. After being completely dispersed, it was centrifuged for 5 min using a bench-top high-speed centrifuge, which was set to 3000 r/min. AgNWs were selected for characterization at different time points, from minute 8 to minute 24. The overall morphology produced significant changes from the twelfth minute onwards. The optimum preparation time was the twenty-fifth minute of the reaction.

2.3. Structural Characterizations

In this paper, extinction spectra are applied as direct illustrations and scanning electron microscope (SEM) analysis is applied as indirect illustrations. Size distributions and yield analyses performed using SEM or TEM pictures are typically based on samples sizes smaller than ~100 nanowires [37,65,66]. This means that, if the spectral information can be correlated to the structure of the wires, a single UV-Vis spectrum measured on a 100×-diluted AgNW solution contains as much information as $\sim 10^{10}$ SEM or TEM pictures [60].

Many unexpected images can be observed under the representation by high magnification images. These, although also appearing on SEM substrates, are best used to demonstrate the presence of morphology, but their use to illustrate the overall morphology is worrying.

3. Results and Discussion

Figure 2a shows the extinction spectra with different crystal additives. This is indicated by the appearance of a sharp peak at 377 nm, which corresponds to the transverse resonance peak of the pentagonally twinned AgNWs. The solution of AgNWs with TBAC corresponds to a relatively lower residual extinction and a narrower absorption peak, indicating that the synthesis has the smallest amount of byproducts.

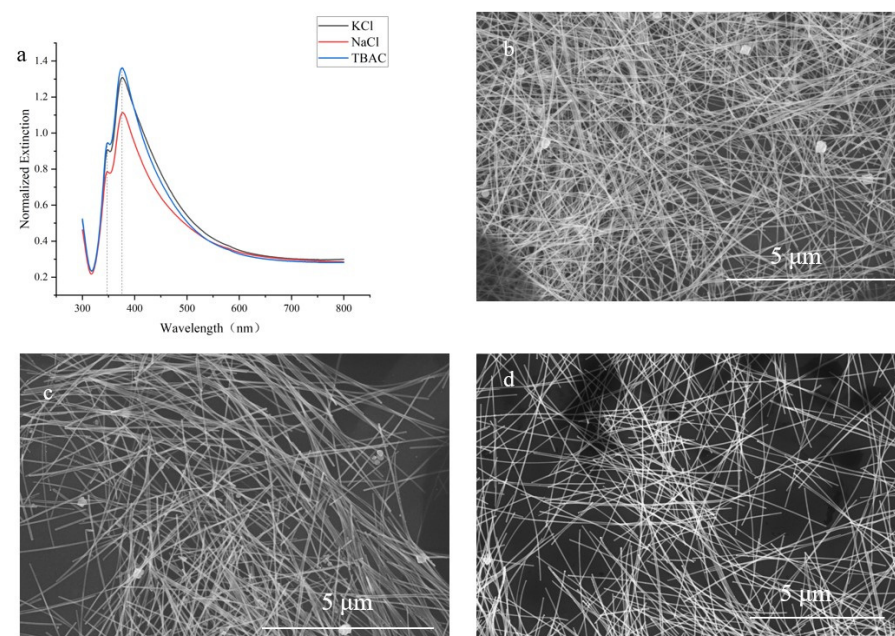


Figure 2. (a) Comparison of the extinction spectra. (b–d) SEM images of the crystal additives KCl, NaCl, and TBAC.

Moreover, the AgNW solution we used to test the extinction spectra was not centrifuged to remove impurities but was made by diluting it 100 times with anhydrous ethanol (analytically pure) immediately after the reaction was completed, so it is more

indicative of the overall morphology. Figure 2b–d show SEM images of the AgNWs generated by the reaction involving KCl, NaCl, and TBAC. Compared with metal halides, the AgNWs generated by TBAC as a crystal seed additive are better dispersed and have fewer impurities.

Figure 3a,b show the extinction spectra of the AgNW solution with the addition of the same concentration of TBAC and NaCl. For the synthesis at 160 °C, during the initial 8 min after the addition of AgNO₃ only Ag nanoparticles are formed, as indicated by the symmetric plasmon resonance peak centered at around 404 nm. Under other identical preparation conditions, the AgNW solution with the addition of TBAC only has the strong transverse resonance peak of AgNWs at 377 nm and the shoulder peak at 350 nm at 12 min, while the AgNW solution with the addition of NaCl at the same time remained as a broad peak near 400 nm, indicating that the seed–wire transition of the AgNW solution with the addition of TBAC was faster, which greatly reduced the seed number, thus reducing the possibility of byproduct generation.

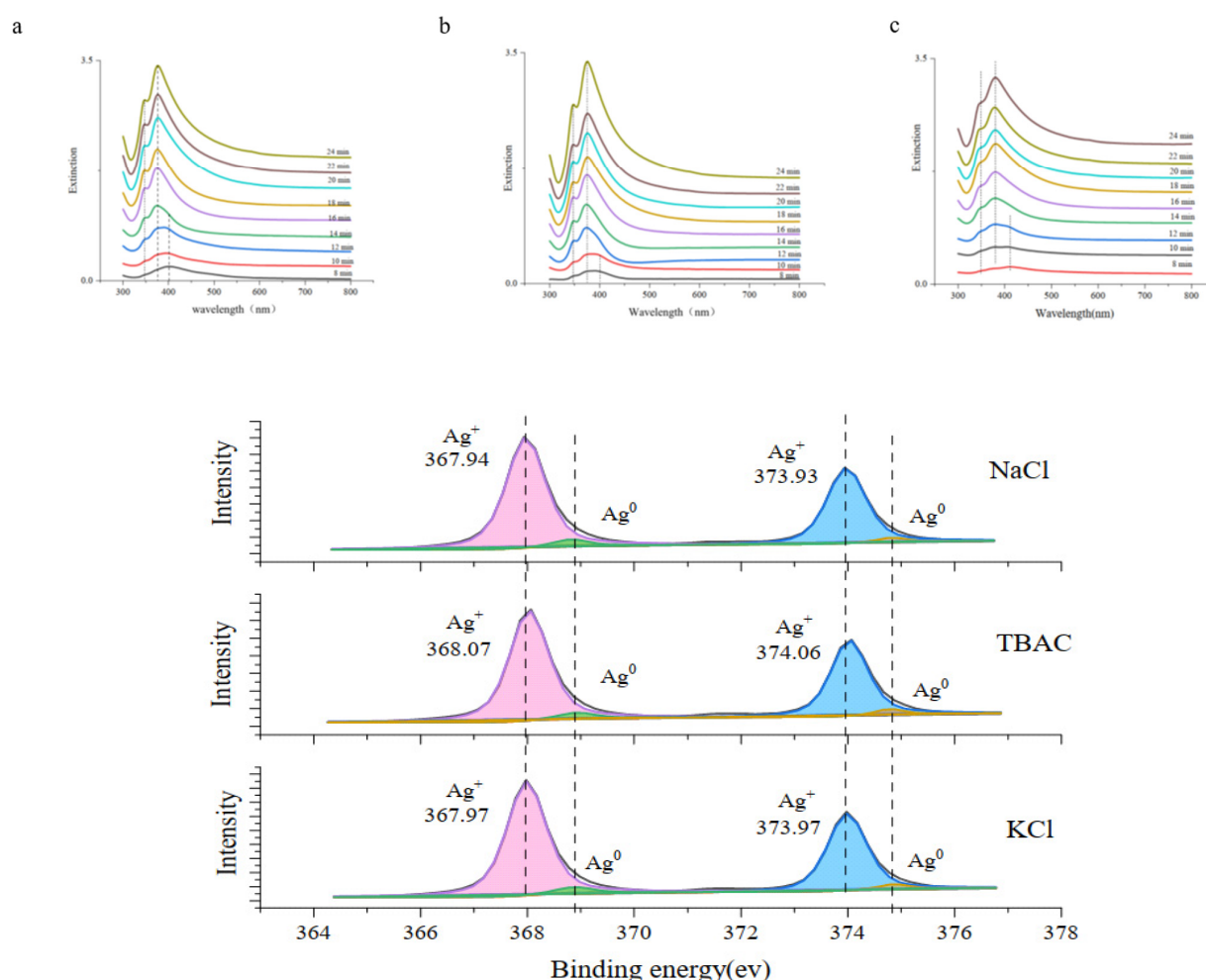


Figure 3. UV extinction spectra of AgNWs prepared under the addition of NaCl (a), TBAC (b) and KCl (c) with time. (d) The XPS spectra under the addition of NaCl, TBAC and KCl in the 10th minute.

The real reducing agents in the reaction system are acetaldehyde and ethanol aldehyde formed by the decomposition of ethylene glycol via a high temperature. When acetaldehyde and ethanol aldehyde are in the reaction solution at the same time, the free silver ions in the system are reduced to silver atoms by the combined effect of these two factors. However, according to Equations (1) and (2), the generation of both reducing agents is accompanied by the acidification of the overall solution, which can lead to the re-etching of the AgNWs to be grown in the grown-up phase into irregularly shaped Ag nanoparticles.

Figure 3c shows the XPS spectra at the 10th minute of the reactions following the addition of NaCl, TBAC and KCl. The average binding energy of Ag^+ is higher and the stability is better after the addition of TBAC compared to NaCl and KCl. Since TBAC is an ionic liquid composed of organic ammonium and halide ions, this ionic liquid can effectively act as a soft template to induce the anisotropic growth of nanostructures due to its unique self-assembled local structure [67,68].

Figure 4a,b can also show this phenomenon, thus illustrating more visually the acidification during the reaction. This also illustrates the need to accelerate the seed–wire conversion at the same time. Figure 4c shows the UV extinction spectra at 25 and 70 min. The figure shows that the absorption peak located near 404 nm broadens and the residual extinction density increases when the solution reacts for up to 70 min, indicating that the AgNWs are etched into irregular silver nanoparticles by continuous acidification. The possibility of AgNWs being re-etched with increasing reaction time is corroborated, corresponding to what is expressed in Figure 1.

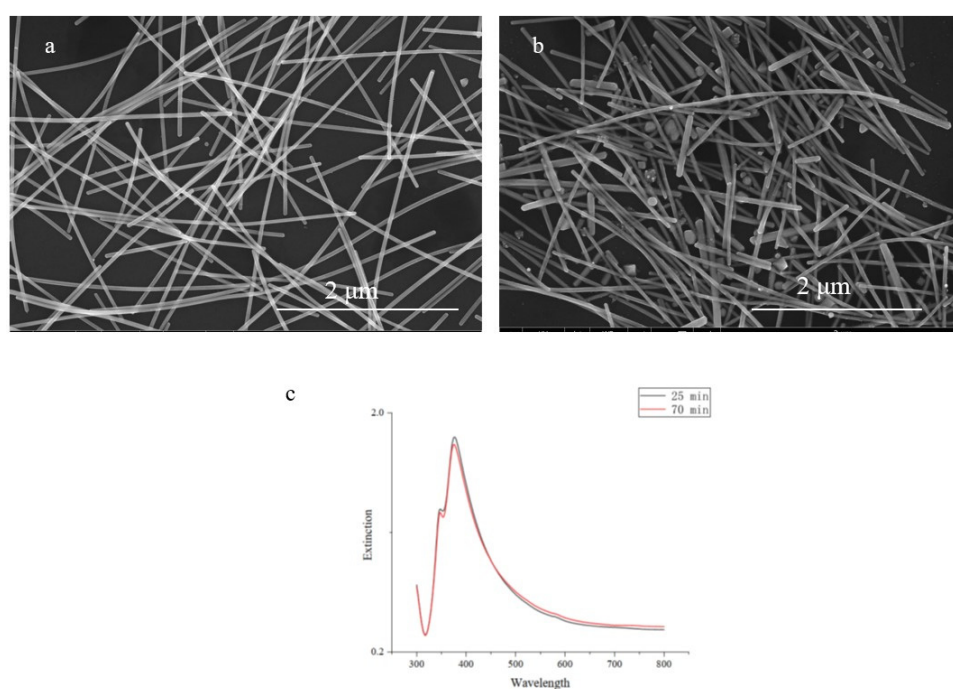


Figure 4. SEM images of AgNWs at 160 °C with TBAC as crystal seed additive at (a) 25 min and (b) 70 min. (c) The extinction spectrum at the above times.

Figure 5 illustrates that the seed–wire conversion is roughly completed at about 12 min under the influence of TBAC, which corresponds to the extinction spectrogram in Figure 3a. In addition, the AgNWs prepared using TBAC as a crystal seed additive maintain a certain degree of dispersion, as can be seen from the graph, which also facilitates the subsequent process of the AgNWs.

The SEM images of the AgNWs with the NaCl addition (Figure 6) show that the seeds grow into the structure of wire-like AgNWs at 16 min and at 12 min; although there are similar wire-like structures, they are basically ungrown crystal seeds. Compared to AgNWs with TBAC, the seed–wire conversion rate was slower and the possibility of generating polymorphic silver particles was increased.

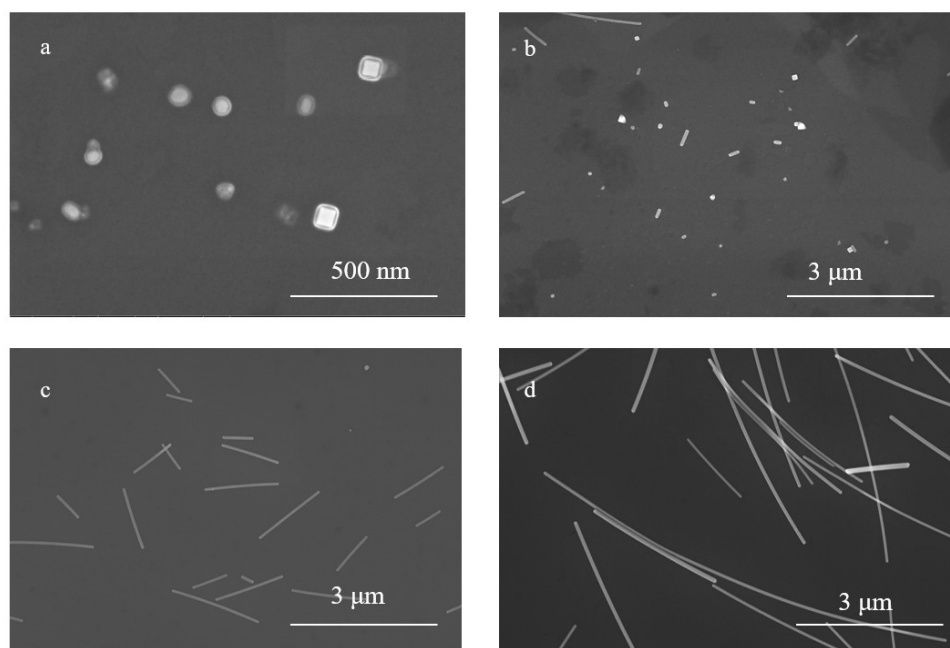


Figure 5. SEM images of AgNWs at 160 °C with TBAC as crystal seed additive at (a) 8 min, (b) 10 min, (c) 12 min, and (d) 14 min.

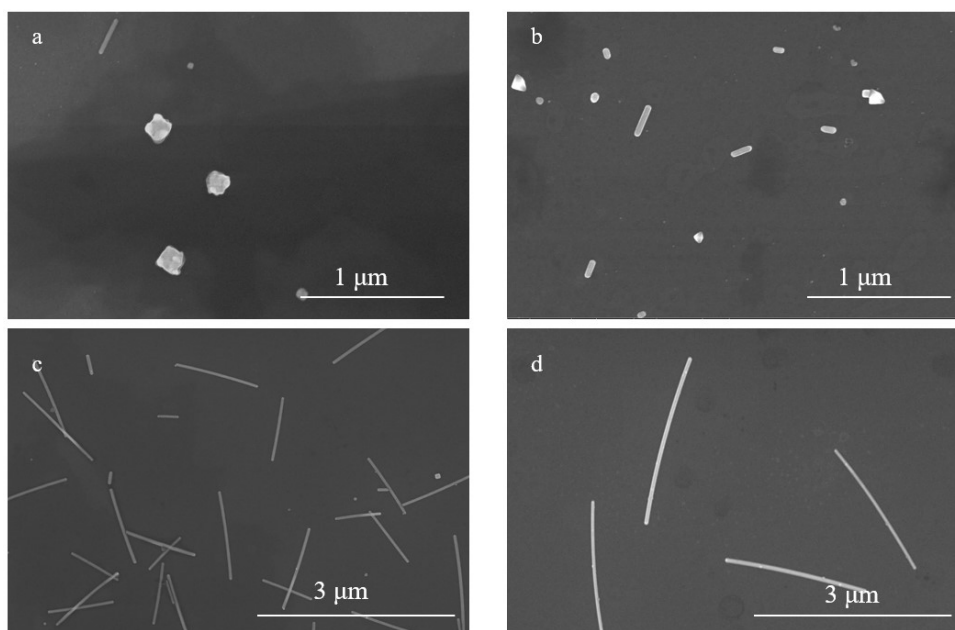


Figure 6. SEM images of AgNWs at 160 °C with NaCl as crystal seed additive at (a) 12 min, (b) 14 min, (c) 16 min, and (d) 18 min.

The mechanism of the involvement of crystal seed additives in the reaction is the self-assembly of surfactants with hydrophilic head groups and hydrophobic tail groups that form wire-like micelles in an aqueous solution. The coordination of the metal ions on the nanoparticle surface by the crystal seed additive inhibits the growth and aggregation of the particles. Moreover, it is apparent that the organohalides control the massive aggregation of twin seeds in the prereaction period, which achieves slow nucleation and fast growth, thus reducing the possibility of silver nanoparticle generation. PVP also induces the anisotropic growth of nanostructures by forming soft stencils [62].

Figure 7 illustrates the fivefold twin seeds structure of AgNWs during the growth phase. Figure 7a shows a high-magnification TEM image of the AgNWs prepared by

adding TBAC. After a simple centrifugal cleaning, the surface of AgNWs was very clean and no organic insulators were adsorbed. This indicates that the AgNWs did not generate a surface coating layer that was difficult to remove after the addition of TBAC.

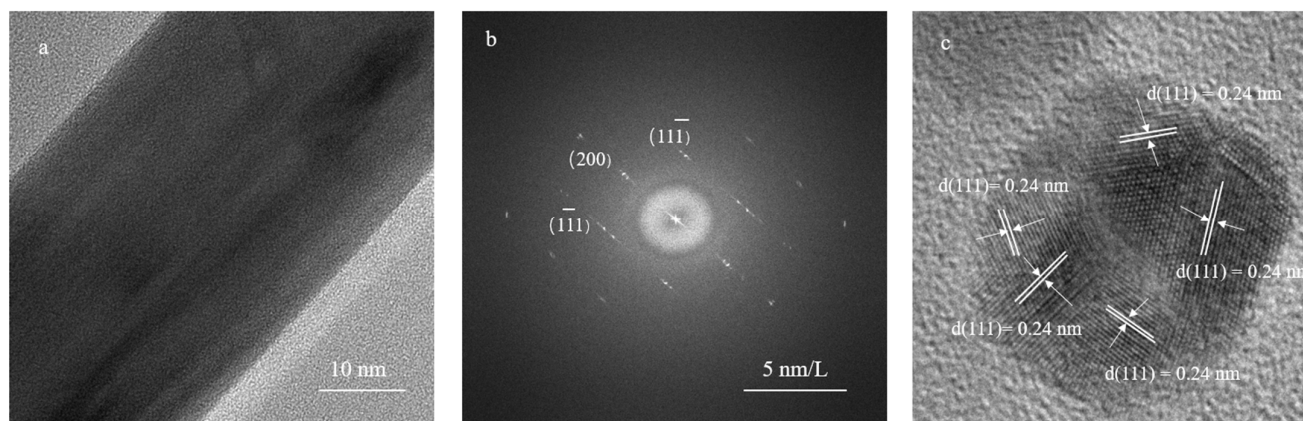


Figure 7. (a) A selected transmission electron microscope image. (b) A SAED image of region (a). (c) An image of a twinned crystal species in the prereaction period.

Figure 7c shows a high-resolution transmission electron microscopy (HRTEM) image extracted from one side of the AgNWs that shows the single crystallinity of the unilateral surface with two directions of stripe spacing corresponding to the (111) crystal plane, indicating the growth direction in the [110] direction. The corresponding selected-area electron diffraction (SAED) pattern taken from an individual nanowire is shown in Figure 7b. Each AgNW was a twin structure, and the twin face was the (111) plane. The results are consistent with the reported articles [69].

4. Conclusions

In this work, AgNWs were prepared by a modified conventional polyol method, and surface pure AgNWs were obtained with a simple post-treatment process. We discussed the idea of adding TBAC to speed up the seed–wire conversion and reduce re-etching. In summary, we propose the use of TBAC to accelerate the rate of seed–wire conversion so that the possibility of the re-etching of AgNWs is greatly reduced. Compared to the conventional polyol method, this method is additive, fast, and efficient in generating silver nanowires, saving time and costs, and reducing the environmental impact of long preparation and postprocessing times, which is in line with the requirements of modern industrial production. This provides a new idea for the subsequent industrial mass production of AgNWs.

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References

1. Hua, Q.; Sun, J.; Liu, H.; Bao, R.; Yu, R.; Zhai, J.; Pan, C.; Wang, Z.L. Skin-inspired highly stretchable and conformable matrix networks for multifunctional sensing. *Nat. Commun.* **2018**, *9*, 244. [[CrossRef](#)] [[PubMed](#)]
2. Huang, H.; Han, L.; Wang, Y.; Yang, Z.; Zhu, F.; Xu, M. Tunable thermal-response shape memory bio-polymer hydrogels as body motion sensors. *Eng. Sci.* **2019**, *9*, 60–67. [[CrossRef](#)]

3. Zhao, L.; Tallman, T.; Lin, G. Spatial damage characterization in self-sensing materials via neural network-aided electrical impedance tomography: A computational study. *ES Mater. Manuf.* **2021**, *12*, 78–88.
4. Dong, Q.; Wang, X.; Liu, H.; Ryu, H.; Zhao, J.; Li, B.; Lei, Y. Heterogeneous iridium oxide/gold nanocluster for non-enzymatic glucose sensing and pH probing. *Eng. Sci.* **2019**, *8*, 46–53. [[CrossRef](#)]
5. Padvi, M.N.; Moholkar, A.V.; Prasad, S.R.; Prasad, N.R. A critical review on design and development of gas sensing materials. *Eng. Sci.* **2021**, *15*, 20–37. [[CrossRef](#)]
6. Lu, Y.; Yu, G.; Wei, X.; Zhan, C.; Jeon, J.; Wang, X.; Jeffries, C.; Guo, Z.; Wei, S.; Wujcik, E.K. Fabric/multi-walled carbon nanotube sensor for portable on-site copper detection in water. *Adv. Compos. Hybrid Mater.* **2019**, *2*, 711–719. [[CrossRef](#)]
7. Wei, H.; Li, A.; Kong, D.; Li, Z.; Cui, D.; Li, T.; Dong, B.; Guo, Z. Polypyrrole/reduced graphene aerogel film for wearable piezoresistive sensors with high sensing performances. *Adv. Compos. Hybrid Mater.* **2021**, *4*, 86–95. [[CrossRef](#)]
8. Jayachandiran, J.; Arivanandhan, M.; Padmaraj, O.; Jayavel, R.; Nedumaran, D. Investigation on ozone-sensing characteristics of surface sensitive hybrid rGO/WO₃ nanocomposite films at ambient temperature. *Adv. Compos. Hybrid Mater.* **2020**, *3*, 16–30. [[CrossRef](#)]
9. Patil, S.S.; Bhat, T.S.; Teli, A.M.; Beknalkar, S.A.; Dhavale, S.B.; Faras, M.M.; Karanjkar, M.M.; Patil, P.S. Hybrid solid state supercapacitors (HSSC's) for high energy & power density: An overview. *Eng. Sci.* **2020**, *12*, 38–51.
10. Cai, J.; Xu, W.; Liu, Y.; Zhu, Z.; Liu, G.; Ding, W.; Wang, G.; Wang, H.; Luo, Y. Robust construction of flexible bacterial Cellulose@Ni(OH)₂ paper: Toward high capacitance and sensitive H₂O₂ detection. *Eng. Sci.* **2019**, *5*, 21–29. [[CrossRef](#)]
11. Nie, R.; Wang, Q.; Sun, P.; Wang, R.; Yuan, Q.; Wang, X. Pulsed laser deposition of NiSe₂ film on carbon nanotubes for high-performance supercapacitor. *Eng. Sci.* **2019**, *6*, 22–29. [[CrossRef](#)]
12. Dong, H.; Li, Y.; Chai, H.; Cao, Y.; Chen, X. Hydrothermal synthesis of CuCo₂S₄ nano-structure and N-doped graphene for high-performance aqueous asymmetric supercapacitors. *ES Energy Environ.* **2019**, *4*, 19–26.
13. Sayyed, S.G.; Mahadik, M.A.; Shaikh, A.V.; Jang, J.S.; Pathan, H.M. Nano-metal oxide based supercapacitor via electrochemical deposition. *ES Energy Environ.* **2019**, *3*, 25–44. [[CrossRef](#)]
14. Rehman, S.U.; Ahmed, R.; Ma, K.; Xu, S.; Tao, T.; Aslam, M.A.; Amir, M.; Wang, J. Composite of strip-shaped ZIF-67 with polypyrrole: A conductive polymer-MOF electrode system for stable and high specific capacitance. *Eng. Sci.* **2021**, *13*, 71–78. [[CrossRef](#)]
15. Li, X.; Zhao, W.; Yin, R.; Huang, X.; Qian, L. A highly porous polyaniline-graphene composite used for electrochemical supercapacitors. *Eng. Sci.* **2018**, *3*, 89–95. [[CrossRef](#)]
16. Wang, X.; Zeng, X.; Cao, D. Biomass-derived nitrogen-doped porous carbons (NPC) and NPC/polyaniline composites as high performance supercapacitor materials. *Eng. Sci.* **2018**, *1*, 55–63. [[CrossRef](#)]
17. Li, G.; Ji, Y.; Zuo, D.; Xu, J.; Zhang, H. Carbon electrodes with double conductive networks for high-performance electrical double-layer capacitors. *Adv. Compos. Hybrid Mater.* **2019**, *2*, 456–461. [[CrossRef](#)]
18. Xiao, L.; Qi, H.; Qu, K.; Shi, C.; Cheng, Y.; Sun, Z.; Yuan, B.; Huang, Z.; Pan, D.; Guo, Z. Layer-by-layer assembled freestanding and flexible nanocellulose/porous Co₃O₄ polyhedron hybrid film as supercapacitor electrodes. *Adv. Compos. Hybrid Mater.* **2021**, *4*, 306–316. [[CrossRef](#)]
19. Koo, J.H.; Kim, D.C.; Shim, H.J.; Kim, T.; Kim, D. Flexible and stretchable smart display: Materials, fabrication, device design, and system integration. *Adv. Funct. Mater.* **2018**, *28*, 1801834. [[CrossRef](#)]
20. Ovid'Ko, I.A.; Valiev, R.Z.; Zhu, Y.T. Review on superior strength and enhanced ductility of metallic nanomaterials. *Prog. Mater. Sci.* **2018**, *94*, 462–540. [[CrossRef](#)]
21. Cao, Y.; Ni, S.; Liao, X.; Song, M.; Zhu, Y. Structural evolutions of metallic materials processed by severe plastic deformation. *Mat. Sci. Eng. R* **2018**, *133*, 1–59. [[CrossRef](#)]
22. Alawi, O.A.; Sidik, N.A.C.; Xian, H.W.; Kean, T.H.; Kazi, S.N. Thermal conductivity and viscosity models of metallic oxides nanofluids. *Int. J. Heat Mass Transf.* **2018**, *116*, 1314–1325. [[CrossRef](#)]
23. Zhou, G.; Shan, Y.; Hu, Y.; Xu, X.; Long, L.; Zhang, J.; Dai, J.; Guo, J.; Shen, J.; Li, S.; et al. Half-metallic carbon nitride nanosheets with micro grid mode resonance structure for efficient photocatalytic hydrogen evolution. *Nat. Commun.* **2018**, *9*, 3366. [[CrossRef](#)] [[PubMed](#)]
24. Xie, F.; Liu, T.; Xie, L.; Sun, X.; Luo, Y. Metallic nickel nitride nanosheet: An efficient catalyst electrode for sensitive and selective non-enzymatic glucose sensing. *Sens. Actuators B Chem.* **2018**, *255*, 2794–2799. [[CrossRef](#)]
25. Wei, Q.; Xiong, F.; Tan, S.; Huang, L.; Lan, E.H.; Dunn, B.; Mai, L. Porous one-dimensional nanomaterials: Design, fabrication and applications in electrochemical energy storage. *Adv. Mater.* **2017**, *29*, 1602300. [[CrossRef](#)]
26. Ge, M.; Li, Q.; Cao, C.; Huang, J.; Li, S.; Zhang, S.; Chen, Z.; Zhang, K.; Al-Deyab, S.S.; Lai, Y. One-dimensional TiO₂ nanotube photocatalysts for solar water splitting. *Adv. Sci.* **2017**, *4*, 1600152. [[CrossRef](#)] [[PubMed](#)]
27. Zhang, G.; Xiao, X.; Li, B.; Gu, P.; Xue, H.; Pang, H. Transition metal oxides with one-dimensional/one-dimensional-analogue nanostructures for advanced supercapacitors. *J. Mater. Chem.* **2017**, *5*, 8155–8186. [[CrossRef](#)]
28. Wang, C.; Kaneti, Y.V.; Bando, Y.; Lin, J.; Liu, C.; Li, J.; Yamauchi, Y. Metal-organic framework-derived one-dimensional porous or hollow carbon-based nanofibers for energy storage and conversion. *Mater. Horiz.* **2018**, *5*, 394–407. [[CrossRef](#)]
29. Gong, S.; Cheng, W. One-dimensional nanomaterials for soft electronics. *Adv. Electron. Mater.* **2017**, *3*, 1600314. [[CrossRef](#)]

30. Tian, W.; Hu, H.; Wang, Y.; Li, P.; Liu, J.; Liu, J.; Wang, X.; Xu, X.; Li, Z.; Zhao, Q.; et al. Metal-organic frameworks mediated synthesis of one-dimensional molybdenum-based/carbon composites for enhanced lithium storage. *ACS Nano* **2018**, *12*, 1990–2000. [\[CrossRef\]](#)
31. Seok, I.; Al-Hossain, A.A.; Waliullah, M.; Ryu, J.E. Fabrication of nano-patterned arrays using pulsed light technique. *Eng. Sci.* **2019**, *7*, 59–64. [\[CrossRef\]](#)
32. Ul-Islam, M.U.; Ali, J.; Khan, W.; Haider, A.; Shah, N.; Ahmad, M.W.; Ullah, M.W.; Yang, G. Fast 4-nitrophenol reduction using gelatin hydrogel containing silver nanoparticles. *Eng. Sci.* **2019**, *8*, 19–24. [\[CrossRef\]](#)
33. Yu, J.; Sun, L. Facile one-pot synthesis of silver nanoparticles supported on α -zirconium phosphate single-layer nanosheets. *ES Mater. Manuf.* **2019**, *5*, 24–28.
34. Garnett, E.C.; Cai, W.; Cha, J.J.; Mahmood, F.; Connor, S.T.; Greyson Christoforo, M.; Cui, Y.; McGehee, M.D.; Brongersma, M.L. Self-Limited Plasmonic Welding of Silver Nanowire Junctions. *Nat. Mater.* **2012**, *11*, 241–249. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Zhang, P.; Wyman, I.; Hu, J.; Lin, S.; Zhong, Z.; Tu, Y.; Huang, Z.; Wei, Y. Silver Nanowires: Synthesis Technologies, Growth Mechanism and Multifunctional Applications. *Mater. Sci. Eng.* **2017**, *223*, 1–23. [\[CrossRef\]](#)
36. Langley, D.; Giusti, G.; Mayousse, C.; Celle, C.; Bellet, D.; Simonato, J.-P. Flexible Transparent Conductive Materials Based on Silver Nanowire Networks: A Review. *Nanotechnology* **2013**, *24*, 452001. [\[CrossRef\]](#)
37. Hu, L.; Kim, H.S.; Lee, J.Y.; Peumans, P.; Cui, Y. Scalable Coating and Properties of Transparent, Flexible, Silver Nanowire Electrodes. *ACS Nano* **2010**, *4*, 2955–2963. [\[CrossRef\]](#)
38. Kang, B.M.; Xu, T.; Park, H.J.; Luo, X.; Guo, L.J. Efficiency Enhancement of Organic Solar Cells Using Transparent Plasmonic Ag Nanowire Electrodes. *Adv. Mater.* **2010**, *22*, 4378–4383. [\[CrossRef\]](#)
39. Van Hoof, N.; Parente, M.; Baldi, A.; Rivas, J.G. Terahertz TimeDomain Spectroscopy and Near-Field Microscopy of Transparent Silver Nanowire Networks. *Adv. Opt. Mater.* **2020**, *8*, 1900790. [\[CrossRef\]](#)
40. Zhang, L.; Jiang, F.; Wu, B.; Lv, C.; Wu, M. A one-step synthesis of ultra-long silver nanowires with ultra-high aspect ratio above 2000 and its application in flexible transparent conductive electrodes. *Nanotechnology* **2021**, *32*, 105710. [\[CrossRef\]](#)
41. Yao, S.; Zhu, Y. Wearable Multifunctional Sensors Using Printed Stretchable Conductors Made of Silver Nanowires. *Nanoscale* **2014**, *6*, 2345–2352. [\[CrossRef\]](#)
42. Hu, W.; Niu, X.; Zhao, R.; Pei, Q. Elastomeric Transparent Capacitive Sensors Based on an Interpenetrating Composite of Silver Nanowires and Polyurethane. *Appl. Phys. Lett.* **2013**, *102*, 083303. [\[CrossRef\]](#)
43. Wang, J.; Jiu, J.; Nogi, M.; Sugahara, T.; Nagao, S.; Koga, H.; He, P.; Suganuma, K. A Highly Sensitive and Flexible Pressure Sensor with Electrodes and Elastomeric Interlayer Containing Silver Nanowires. *Nanoscale* **2015**, *7*, 2926–2932. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Lu, Y.; Wang, M.T.; Hao, C.J.; Zhao, Z.Q.; Yao, J.Q. Temperature Sensing Using Photonic Crystal Fiber Filled With Silver Nanowires and Liquid. *IEEE Photonics J.* **2014**, *6*, 1. [\[CrossRef\]](#)
45. Tao, A.; Kim, F.; Hess, C.; Goldberger, J.; He, R.; Sun, Y.; Xia, Y.; Yang, P. Langmuir-Blodgett Silver Nanowire Monolayers for Molecular Sensing Using Surface-Enhanced Raman Spectroscopy. *Nano Lett.* **2003**, *3*, 1229–1233. [\[CrossRef\]](#)
46. Fahad, S.; Yu, H.; Wang, L.; Wang, Y.; Ali, T.E.M.; Amin, B.U.; Naveed, K.U.R.; Khan, R.U.; Mehmood, S.; Haq, F.; et al. Synthesis of corrugated surface AgNWs and their applications in surface enhanced Raman spectroscopy. *CrystEngComm* **2020**, *22*, 2183–2196. [\[CrossRef\]](#)
47. Maijenburg, A.W.; Veerbeek, J.; De Putter, R.; Veldhuis, S.A.; Zoontjes, M.G.C.; Mul, G.; Montero-Moreno, J.M.; Nielsch, K.; Schafer, H.; Steinhart, M.; et al. Electrochemical Synthesis of Coaxial TiO₂-Ag Nanowires and Their Application in Photocatalytic Water Splitting. *J. Mater. Chem. A* **2014**, *2*, 2648–2656. [\[CrossRef\]](#)
48. Reddy, I.N.; Reddy, C.V.; Sreedhar, A.; Cho, M.; Kim, D.; Shim, J. Effect of Plasmonic Ag Nanowires on the Photocatalytic Activity of Cu Doped Fe₂O₃ Nanostructures Photoanodes for Superior Photoelectrochemical Water Splitting Applications. *J. Electroanal. Chem.* **2019**, *842*, 146–160. [\[CrossRef\]](#)
49. Liu, L.; He, C.; Li, J.; Guo, J.; Yang, D.; Wei, J. Green synthesis of silver nanowires via ultraviolet irradiation catalyzed by phosphomolybdic acid and their antibacterial properties. *New J. Chem.* **2013**, *37*, 2179–2185. [\[CrossRef\]](#)
50. Xu, J.; Hu, J.; Peng, C.; Liu, H.; Hu, Y. A simple approach to the synthesis of silver nanowires by hydrothermal process in the presence of gemini surfactant. *J. Colloid Interface Sci.* **2006**, *298*, 689–693. [\[CrossRef\]](#)
51. Liu, R.; Wong, F.; Duan, W.; Sen, A. Synthesis and characterization of silver halide nanowires. *Polyhedron* **2014**, *84*, 192–196. [\[CrossRef\]](#)
52. Zhou, Y.; Yu, S.H.; Wang, C.Y.; Li, X.G.; Zhu, Y.R.; Chen, Z.Y. A Novel Ultraviolet Irradiation Photoreduction Technique for the Preparation of Single-Crystal Ag Nanorods and Ag Dendrites. *Adv. Mater.* **1999**, *11*, 850–852. [\[CrossRef\]](#)
53. Castro, K.B.; Cooper, J.B. Single-pot two-temperature synthesis of high aspect ratio silver nanowires with narrow size distribution. *Inorg. Chim. Acta* **2020**, *507*, 119569. [\[CrossRef\]](#)
54. Lee, J.H.; Lee, P.; Lee, D.; Lee, S.S.; Ko, S.H. Large-Scale Synthesis and Characterization of Very Long Silver Nanowires via Successive Multistep Growth. *Cryst. Growth Des.* **2012**, *12*, 5598–5605. [\[CrossRef\]](#)
55. Zhan, K.; Su, R.; Bai, S.; Yu, Z.; Cheng, N.; Wang, C.; Xu, S.; Liu, W.; Guo, S.; Zhao, X.-Z. One-pot stirring-free synthesis of silver nanowires with tunable lengths and diameters via a Fe³⁺ & Cl[−] co-mediated polyol method and their application as transparent conductive films. *Nanoscale* **2016**, *8*, 18121–18133.
56. Chen, Y.-C.; Hsu, J.-H.; Lin, Y.-G.; Hsu, Y.-K. Silver nanowires on coffee filter as dual sensing functionality for efficient and low-cost SERS substrate and electrochemical detection. *Sens. Actuators B* **2017**, *245*, 189–195. [\[CrossRef\]](#)

57. Mayousse, C.; Celle, C.; Moreau, E.; Mainguet, J.F.; Carella, A.; Simonato, J.P. Improvements in Purification of Silver Nanowires by Decantation and Fabrication of Flexible Transparent Electrodes. Application to Capacitive Touch Sensors. *Nanotechnology* **2013**, *24*, 215501. [[CrossRef](#)]
58. Li, B.; Ye, S.; Stewart, I.E.; Alvarez, S.; Wiley, B.J. Synthesis and Purification of Silver Nanowires to Make Conducting Films with a Transmittance of 99%. *Nano Lett.* **2015**, *15*, 6722–6726. [[CrossRef](#)]
59. Wan, M.; Tao, J.; Jia, D.; Chu, X.; Li, S.; Ji, S.; Ye, C. High-Purity Very Thin Silver Nanowires Obtained by Ostwald Ripening-Driven Coarsening and Sedimentation of Nanoparticles. *CrystEngComm* **2018**, *20*, 2834–2840. [[CrossRef](#)]
60. Parente, M.; van Helvert, M.; Haman, R.F.; Verbroekken, R.; Sinha, R.; Bieberle-Hütter, A.; Baldi, A. Simple and Fast High-Yield Synthesis of Silver Nanowires. *Nano Lett.* **2020**, *20*, 5759–5764. [[CrossRef](#)]
61. Fan, Y.; Han, D.; Song, Z.; Sun, Z.; Dong, X.; Niu, L. Regulations of silver halide nanostructure and composites on photocatalysis. *Adv. Compos. Hybrid Mater.* **2018**, *1*, 269–299. [[CrossRef](#)]
62. Welch, D.A.; Woehl, T.J.; Park, C.; Faller, R.; Evans, J.E.; Browning, N. Understanding the Role of Solvation Forces on the Preferential Attachment of Nanoparticles in Liquid. *ACS Nano* **2016**, *10*, 181–187. [[CrossRef](#)]
63. Wang, T.; Antonietti, M.; Cölfen, H. Calcite mesocrystals: “Morphing” crystals by a polyelectrolyte. *Chem.—Eur. J.* **2006**, *12*, 5722–5730. [[CrossRef](#)]
64. Yamamoto, E.G.; Dantas, M.P.; Yamanishi, G.; Soares, F.B.; Urbano, A.; Lourenço, S.A.; Cava, C.E. Silver nanowire synthesis analyzing NaCl, CuCl₂, and NaBr as halide salt with additional thermal, acid, and solvent post-treatments for transparent and flexible electrode applications. *Appl. Nanotechnol.* **2022**, *12*, 205–213. [[CrossRef](#)]
65. Ran, Y.; He, W.; Wang, K.; Ji, S.; Ye, C. A One-Step Route to Ag Nanowires with a Diameter below 40 nm and an Aspect Ratio above 1000. *Chem. Commun.* **2014**, *50*, 14877–14880. [[CrossRef](#)]
66. Qian, F.; Lan, P.C.; Freyman, M.C.; Chen, W.; Kou, T.; Olson, T.Y.; Zhu, C.; Worsley, M.A.; Duoss, E.B.; Spadaccini, C.M.; et al. Ultralight Conductive Silver Nanowire Aerogels. *Nano Lett.* **2017**, *17*, 7171–7176. [[CrossRef](#)] [[PubMed](#)]
67. Kim, T.Y.; Kim, W.J.; Hong, S.H.; Kim, J.E.; Suh, K.S. Ionic-liquid-assisted formation of silver nanowires. *Angew. Chem. Int. Ed.* **2009**, *48*, 3806–3809. [[CrossRef](#)]
68. Wang, Y.; Yang, H.J. Synthesis of CoPt nanorods in ionic liquids. *Am. Chem. Soc.* **2005**, *127*, 5316–5317. [[CrossRef](#)] [[PubMed](#)]
69. Fahad, S.; Yu, H.; Wang, L.; Zain-ul-Abdin; Haroon, M.; Ullah, R.S.; Nazir, A.; Naveed, K.; Elshaarani, T.; Khan, A. Recent progress in the synthesis of silver nanowires and their role as conducting materials. *J. Mater. Sci.* **2019**, *54*, 997–1035. [[CrossRef](#)]

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