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Transition Metal Salt Promoted, Green, and High-Yield Synthesis of Silver Nanowires for Flexible Transparent Conductive Electrodes

Sema Sarisozen^{+, [a]} Necip A. Tertemiz^{+, [b]} Tugce A. Arica^{+, [c]} Nahit Polat,^[b]
Coskun Kocabas,^[d, e, f] Fadime M. Balci,^{*[a]} and Sinan Balci^{*[b]}

Silver nanowires (AgNWs) have attracted considerable interest from both academia and industry owing to their excellent electrical, optical, and chemical properties. For large-scale synthesis of AgNWs, the polyol method involving ethylene glycol, a toxic alcohol, has been widely used. We herein report on a facile, green, high yield, transition metal salt promoted, open atmosphere method for the synthesis of high quality AgNWs in a glycerol-water mixture. We have shown that transition metal salts have a strong influence on the morphology of AgNWs. Importantly, in the presence of copper(II) chloride, AgNWs with a high aspect ratio of around 400 (length, 36 μm ; diameter, 90 nm) were obtained. Additionally, for the

first time, we have demonstrated AgNWs based flexible transparent conductive electrodes (TCEs) on poly(sodium 4-styrene-sulfonate) (PSS) treated polyethylene terephthalate (PET) substrate with a sheet resistance of 34 Ω/sq and transmittance of 91 % at 550 nm. The PSS layer on the PET substrate generated a highly hydrophilic surface, which boosts interaction of AgNWs with the PET surface. We envision that our results would play a significant role both in the synthesis of AgNWs with high aspect ratio and also in designing new rigid and flexible TCEs having high transmittance and low sheet resistance for applications especially in printable solar cells, organic light emitting diodes, and high performance flexible electronics.

Introduction

Colloidal metal nanoparticles have received great interests because of their fascinating physical and chemical properties.^[1–3] Especially, noble metal nanoparticles have been attracting a particular interest since they show size, shape, and

morphology dependent optical properties and thus they have found critical applications in a variety of areas^[4,5] such as, plasmon enhanced spectroscopy,^[6] metal enhanced fluorescence,^[7] catalytic selective oxidation of organic compounds,^[8] as well as rigid and flexible optoelectronic devices.^[9] Among the noble metal nanoparticles, silver nanowires^[10] have been intensively studied and they continue to attract significant interest from the scientific and industrial communities due to their promising optoelectronic, electrical, and thermal properties, and also the fact that the bulk silver has the highest electrical and thermal conductivities of all metals.^[11–13] For example, water-processed silver nanowire based transparent conductive electrodes (TCEs) have been successfully fabricated and applied for flexible organic photovoltaics.^[14] In a separate study, silver nanowire based flexible circuit has been fabricated on low cost, rough, and flexible substrates for the purpose of foldable and disposable optoelectronic devices.^[11]

Although, various transparent conductive metal oxides, such as FTO (fluorine doped tin oxide) and ITO (indium tin oxide), have been extensively used for the preparation of TCEs, in recent years, they have been less preferred in flexible and foldable electronic devices because their precursors are less abundant and very expensive, and the conductive layers produced from these metal oxides are very brittle as well. In fact, silver nanowires (AgNWs) are very attractive nanomaterials for the fabrication of flexible TCEs when compared with conductive metal oxides since AgNWs based TCEs display high electrical conductivity with low light absorption as well as they are stretchable.^[15–17] Up until now, various synthetic methods

[a] S. Sarisozen,⁺ Prof. F. M. Balci
Department of Chemistry,
Izmir Institute of Technology,
35430 Izmir, Turkey
E-mail: fadimemert@iyte.edu.tr

[b] N. A. Tertemiz,⁺ N. Polat, Prof. S. Balci
Department of Photonics,
Izmir Institute of Technology,
35430 Izmir, Turkey
E-mail: sinanbalci@iyte.edu.tr


[c] T. A. Arica⁺
Department of Materials Science and Engineering,
Izmir Institute of Technology,
35430 Izmir, Turkey

[d] Prof. C. Kocabas
Department of Materials,
University of Manchester,
Manchester, UK

[e] Prof. C. Kocabas
National Graphene Institute (NGI),
University of Manchester,
Manchester, UK

[f] Prof. C. Kocabas
Henry Royce Institute for Advanced Materials,
University of Manchester,
Manchester, UK

[†] These authors contributed equally to this work.

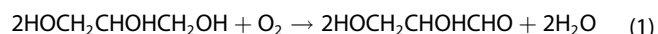
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have been successfully developed for the efficient synthesis of AgNWs under various reaction conditions.^[17–20] Although, in 1989, the polyol synthesis has been originally utilized for the synthesis of micron-sized metal particles by Fievet et al.,^[21] in recent years, it has been extensively employed for the growth of one dimensional silver nanoparticles possessing long length and thin diameter (i.e. high aspect ratio, length to diameter ratio). AgNWs have been synthesized by using a variety of different methods such as electrodeposition in a template,^[6] surfactant templating,^[22] solvothermal synthesis of AgNWs,^[23] porous anodic aluminum oxide template synthesis of AgNWs,^[24] photochemical synthesis of AgNWs within the central channel of self-assembled nanotube of J-aggregated cyanine dyes,^[25] a water-based high-pressure hydrothermal method,^[26] and the widely used polyol route.^[27] Among the synthetic methods, the polyol method is very simple, attractive, and effective in the synthesis of AgNWs with high yield, high aspect ratio, and uniform size. In a typical polyol synthesis of AgNWs, (i) ethylene glycol is used as both a solvent and a reducing agent at elevated temperatures; (ii) AgNO₃ is used as a silver precursor; and (iii) polyvinylpyrrolidone (PVP) is used as a stabilizer for silver nanoparticles. It should be noted that PVP results in one-dimensional growth (elongation) of nanoparticles by interacting with the (100) side surfaces of silver nanoparticles and hence the deposition of silver is mainly preferred to the (111) end surfaces extending in one direction.^[28] In fact, the polyol synthesis of AgNWs in glycerol is more advantages when compared with the polyol synthesis of AgNWs in ethylene glycol.^[29] However, the polyol synthesis of AgNWs in glycerol has not been extensively studied and transition metal salts have not been employed as promoters in the polyol synthesis of AgNWs in glycerol. Herein, we investigate transition metal salts enabled polyol synthesis of silver nanowires in glycerol, which acts both as solvent and reducing agent. Owing to the following main reasons, the use of glycerol is more advantageous in the synthesis of AgNWs: (i) when compared with ethylene glycol, glycerol is a non-toxic, non-volatile, edible, biodegradable, and recyclable substance; (ii) glycerol has three hydroxyl functional groups, which provide stronger reducing power than ethylene glycol; and (iii) due to the high boiling point of glycerol (290 °C) (ethylene glycol has a boiling point of around 200 °C), it is possible to safely carry out reactions at high temperatures. To the best of our knowledge, there has not been any report on the transition metal salts enabled polyol synthesis of silver nanowires in glycerol. Besides, in this study, water has been used as a second solvent to facilitate the preparation of AgNO₃ and PVP solutions since it is not possible to completely dissolve AgNO₃ and PVP in glycerol in the absence of water. We used transition metal salts, such as copper(II) chloride, manganese(II) chloride, iron(III) chloride, cobalt(II) chloride, chromium(III) chloride, and zinc chloride, which serve as oxygen scavengers enabling the polyol synthesis of silver nanowires in ambient air conditions. Importantly, we have found out that silver nanowires synthesized in the presence of copper(II) chloride have a length of around 36 μm and a diameter of around 90 nm, while the reactions by using other transition metal salts have resulted in AgNWs with

an average length of around 10 μm. The synthesized AgNWs have been used for the fabrication of rigid and flexible transparent conducting electrodes, which display very low sheet resistance and high transmittance in the visible spectrum. Different from the previous studies, in this study, we modified the surface of polyethylene terephthalate (PET) substrates with poly(sodium 4-styrenesulfonate)(PSS) polymer and hence we were able to fabricate high performance conducting electrodes on the PSS treated PET substrates. We, for the first time, fabricated AgNWs based flexible transparent conductive electrodes on the PSS treated PET substrates. The flexible AgNWs/PSS/PET substrate has shown a sheet resistance of 34 Ω/sq and a transmittance of 91 % at 550 nm. In fact, the PSS layer on the PET substrate generates a highly hydrophilic surface, which facilitates interaction of AgNWs with the PET surface.

Results and Discussion

Figure 1 shows a schematic representation of transition metal salt promoted polyol synthesis of AgNWs in glycerol. Glycerol, which was used as a polyol compound acts both as a solvent and a reducing agent. AgNO₃, and PVP are the silver precursor, and the stabilizing agent, respectively. Transition metal salts were used as oxygen scavengers or absorbers. The whitish-grey colloidal appearance at the end of the reaction is a very strong indication of the nanowire formation. The length and diameter (i.e. the morphology) of the synthesized AgNWs were carefully determined from electron microscopy investigations. The reaction temperature during the synthesis plays an essential role in the final morphology of the nanowires. We observed that high temperature speeds up the reaction rate. In fact, the reducing capability of glycerol can be attained by converting glycerol to glyceraldehyde at elevated temperatures. It should be notified here that in the reduction of glycerol to glyceraldehyde as shown in reaction (1), we used anhydrous glycerol.



Consequently, silver ions can be reduced to metallic silver by means of aldehyde functional groups (-CHO) available in the glyceraldehydes. We also performed experiments in the presence of trace amount of water in glycerol. Specifically, we intentionally added trace amounts of water to glycerol. However, we observed that the reaction yield was very low, the AgNWs were very short, and large number of silver nanoparticles (by-products) were obtained. By using copper(II) chloride as a transition metal salt promoter, the effect of temperature on the length and diameter of AgNWs was thoroughly investigated. Figure 2 shows SEM images of AgNWs synthesized at 150 °C, 160 °C, and 170 °C for a total reaction time of 120 min. The results shown in Figure 2 suggest that the aspect ratio of AgNWs and the reaction yield are strongly affected by the reaction temperature. It should also be emphasized that AgNWs with ultra-long length and small diameter (high aspect ratio) are always desirable in order to fabricate TCEs with high conductivity and transparency. At

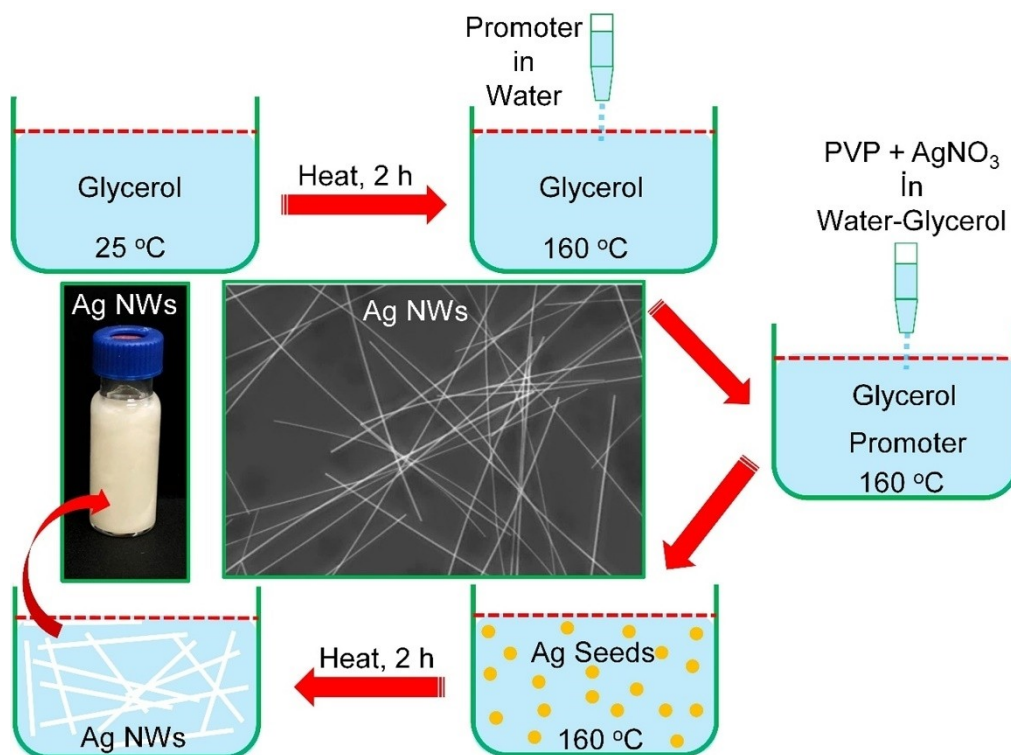


Figure 1. Schematic representation of the green synthesis of silver nanowires (AgNWs). The nanowires were synthesized in glycerol, a polyol compound containing three hydroxyl functional groups (-OH functional groups), which acts both as a solvent and a reducing agent. AgNO_3 , and polyvinylpyrrolidone (PVP) are a silver source, and a stabilizing agent, respectively. The impact of various transition metal salts on the aspect ratio of AgNWs generated via polyol reduction of AgNO_3 was thoroughly investigated. The whitish-grey colloid formed at the end of the polyol reaction is a very strong indication of the nanowire formation. The SEM image in the center of the schematic representation displays a collection of AgNWs on a silicon substrate. The whitish-grey colored glass bottle on the left-hand side of the schematic representation contains the nanowire colloid in isopropanol.

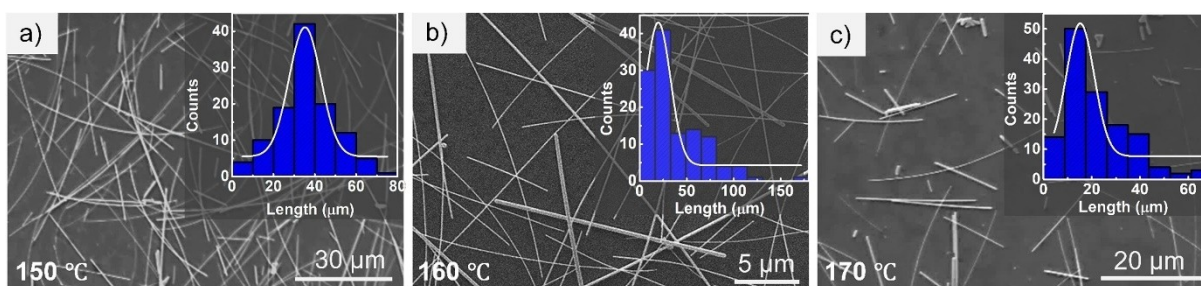


Figure 2. Effect of reaction temperature on the morphology of AgNWs. a) 150 °C, b) 160 °C, and c) 170 °C. The optimum reaction temperature for the polyol synthesis of AgNWs in glycerol was determined to be 160 °C because the highest aspect ratio of AgNWs was obtained at this temperature.

150 °C, the AgNWs were obtained with an average length of around 38 μm , while, at 160 °C and 170 °C, the average lengths of the AgNWs are smaller, 36 μm , and 22 μm , respectively. The average diameters of AgNWs grown at 170 °C, 160 °C, and 150 °C are around 160 nm, 90 nm, and 120 nm, respectively. At 160 °C, the highest aspect ratio of AgNWs was obtained as 400, see also Table S1. Therefore, the optimum reaction temperature for the polyol reaction in glycerol was determined to be 160 °C since the highest aspect ratio and reaction yield were obtained at this temperature. In addition, it should be noted that, in a previous study, glycerol-ethylene glycol mixture was used in

order to completely dissolve PVP (Molecular weight (M_w): 40,000 g/mol) and AgNO_3 and thus AgNWs were successfully synthesized in a Teflon-lined autoclave at a high temperature, 200 °C.^[30] However, in our study, the glycerol-water mixture was used to completely dissolve PVP (M_w : 1,300,000 g/mol) and AgNO_3 and hence AgNWs were synthesized in an oil bath at 160 °C. Noteworthy, in this study, water was used as a second solvent. However, at a high reaction temperature (160 °C), the volume of the glycerol will be nearly constant since the boiling point of glycerol is very high (290 °C) but the volume of water will decrease throughout the reaction.

We now turn our attention to the effect of PVP/AgNO₃ mole ratio on the morphology and aspect ratio of the synthesized AgNWs. It should be noted that in the polyol synthesis of AgNWs, PVP plays an important role in the nanowire synthesis. In fact, PVP results in one-dimensional growth of nanowires by interacting with the (100) side surfaces of nanoparticles and hence the deposition of silver is mainly preferred onto the (111) end surface extending in one direction.^[28] Figure 3 shows SEM images of the AgNWs synthesized at varying PVP/AgNO₃ mole ratios of 4, 6, and 8. Notably, the reaction temperature was maintained at 160 °C for all reactions. The average lengths of the AgNWs for the PVP/AgNO₃ mole ratios of 4, 6, and 8 are 23 μm, 36 μm, and 34 μm, respectively, see also Table S2. The largest average length of AgNWs is obtained when the PVP/AgNO₃ mole ratio is 6. In addition, the average diameters of the AgNWs are 233 nm, 91 nm, and 186 nm for the PVP/AgNO₃ mole ratios of 4, 6, and 8, respectively. The thinnest nanowires were grown by using the PVP/AgNO₃ mole ratio of 6. Furthermore, AgNWs synthesized at 160 °C with the PVP/AgNO₃ mole ratio of 6 were isolated with the highest yield. The highest aspect ratio of around 400 was obtained when the PVP/AgNO₃ mole ratio was 6. It should be noted that when the amount of PVP used in the synthesis is not enough for sufficient passivation of (100) faces of the seed nanoparticles, multi-twinned seed particles can grow on both (111) and (100) faces. When the mole ratio of PVP/AgNO₃ in the reaction mixture is 8, the excess PVP may cover all surfaces of the growing nanoparticles and hence

elongation along (111) faces leading to anisotropic growth may be prevented. Therefore, by utilizing the PVP/AgNO₃ mole ratio of 6, AgNWs were obtained with the highest aspect ratio and yield.

Another key parameter strongly affecting the morphology of the AgNWs is the amount of promoter (CuCl₂) used in the polyol synthesis of nanowires. It should be noted that the reaction temperature was kept constant at 160 °C and also 4 mM CuCl₂ was used as a promoter for the reactions discussed in this section. SEM images of the AgNWs synthesized with varying volume of 4 mM CuCl₂ solution (0.080 mL, 0.160 mL, and 0.240 mL) are shown in Figure 4. The average lengths of the AgNWs obtained from the reaction mixture containing 0.080 mL, 0.160 mL, and 0.240 mL of 4 mM CuCl₂ are 24 μm, 36 μm, and 32 μm, respectively, while the average diameters of AgNWs are 91 nm, 91 nm, and 209 nm, respectively, as also shown in Table S3. The results suggest that the highest aspect ratio of around 400 was obtained from AgNWs synthesized by using 0.160 mL of 4 mM CuCl₂. Furthermore, the reaction yields in the presence of 0.080 mL, and 0.160 mL of 4 mM of CuCl₂ are higher than the reaction yield obtained with 0.240 mL of 4 mM of CuCl₂. Therefore, the optimum transition metal salt promoter amount in the polyol synthesis of AgNWs in glycerol was determined to be 0.160 mL of 4 mM CuCl₂.

Additionally, we have extensively studied the effect of some transition metal salts as promoters on the morphology of AgNWs. The experimental results suggest that in order to synthesize AgNWs in an open atmosphere, transition metal

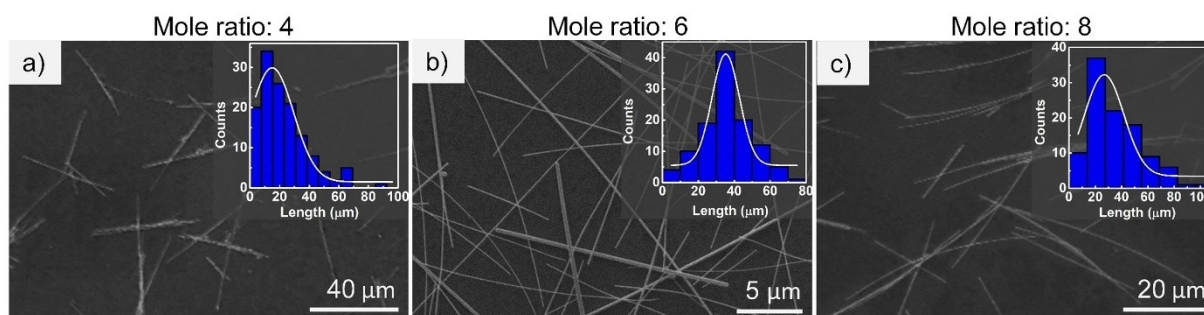


Figure 3. Effect of PVP/AgNO₃ mole ratio on the morphology of AgNWs. The mole ratios of PVP/AgNO₃ are a) 4, b) 6, and c) 8. When the PVP/AgNO₃ mole ratio is 6, the highest aspect ratio and reaction yield of the nanowires are obtained. The reaction temperature was held constant at 160 °C.

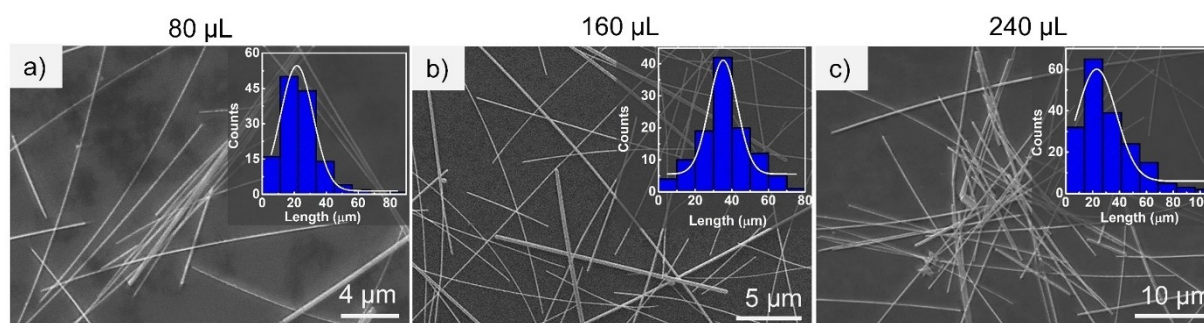


Figure 4. Effect of promoter amount on the morphology of AgNWs. The volume of the promoter (4 mM CuCl₂) is a) 80 μL, b) 160 μL, and c) 240 μL. The optimum volume of the 4 mM CuCl₂ was determined to be 0.160 mL.

salts are stringently required. In this study, several types of transition metal salts such as CuCl_2 , CoCl_2 , MnCl_2 , CrCl_3 , FeCl_3 , and ZnCl_2 have been investigated as promoters in the polyol synthesis of AgNWs in glycerol, see SEM images in Figure 5. The results presented in Figure 5a indicate that AgNWs synthesized in the presence of CuCl_2 have the longest length. The average lengths of AgNWs in the presence of CoCl_2 , ZnCl_2 , CrCl_3 , FeCl_3 , MnCl_2 , and CuCl_2 , are 7 μm , 10 μm , 10 μm , 11 μm , 12 μm , and, 36 μm , respectively. Concurrently, the average diameters of the AgNWs in the presence of CoCl_2 , ZnCl_2 , CrCl_3 , FeCl_3 , MnCl_2 , and CuCl_2 , are 77 nm, 74 nm, 50 nm, 230 nm, 67 nm, and 91 nm, respectively. Obviously, the thinnest and the most uniform nanowires are grown in the presence of CrCl_3 . Nevertheless, the results suggest that the highest aspect ratio of AgNWs was achieved when CuCl_2 was used as a promoter in the synthesis. Therefore, CuCl_2 was determined to be the optimum transition metal salt promoter in the polyol synthesis of AgNWs in glycerol. It is noteworthy that we have also performed experiments under the optimized reaction conditions without using a transition metal salt promoter in glycerol, however, in these control experiments; we observed large number of Ag nanoparticles and only a few short AgNWs, see Figure S5 for the details. In fact, the halide ions such as Cl^- provided by the dissociation of transition metal salts in water may effectively react with the free silver ions and thus they form AgCl complexes.^[31] Also note that, to be able to synthesize silver nanowires with high yield and high aspect ratio, thermodynamically stable multi-twinned seed nanoparticles, which are provided by the slow and controlled reduction of silver ions, are required.^[13] However, oxygen molecules in air can easily adsorb and dissociate into atomic oxygen on these seed nanoparticle surfaces.^[32] In an open atmosphere synthesis of AgNWs, the atomic oxygen could cover the surface of silver

seed nanoparticles and hence the atomic oxygen block the growth of AgNWs. However, in the presence of transition metal ions during the open atmosphere synthesis of AgNWs, transition metal ions are able to scavenge adsorbed atomic oxygens from the silver seeds and therefore, AgNWs can easily grow in the open atmosphere polyol synthesis of AgNWs.^[13] In our study, the observed different behaviors of several transition metal salts in polyol synthesis of AgNWs may be due to their different oxygen scavenging capability.

In order to determine optimum reaction time and stirring speed, and also understand the growth mechanism of nanowires, the experimental and theoretical extinction spectra of AgNWs were obtained. In fact, the synthesis of AgNWs (performed at 160 °C in the presence of MnCl_2 as a promoter) was serially monitored using broad band absorption spectroscopy by taking samples at the selected times of the reaction. Figure 6a shows the time evolution of the extinction spectra of the reaction mixture. Furthermore, the experimental results were supported by theoretical calculation of a single AgNW suspended in air as indicated in Figure 6b. Note that AgNWs have two main plasmon polariton resonance modes; the longitudinal plasmon polariton mode (along the main axis of the nanowire) and the transverse plasmon polariton mode (in the plane perpendicular to the main axis of the nanowire).^[33] After 5 minutes of the first addition of AgNO_3 , the extinction spectrum shows a resonance peak at around 410 nm, which is most probably due to the localized surface plasmon polariton formation of nearly spherical silver nanoparticles^[34] as also supported by SEM observations. In theoretical calculations shown in Figure 6b, the direction of the electric field or polarization of the incident light is in the direction perpendicular to the main axis of the nanorods. Obviously, as the reaction proceeds, the optical density of AgNWs increases since

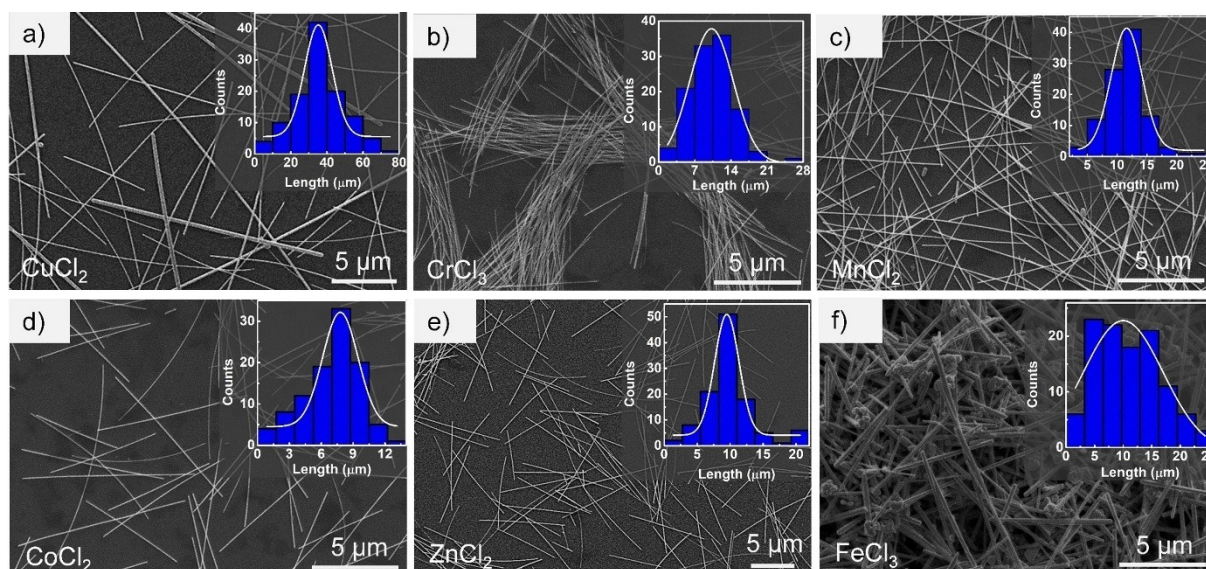


Figure 5. Effect of transition metal salt promoters on the morphology of AgNWs. The promoters used in the synthesis of AgNWs are a) CuCl_2 , b) CrCl_3 , c) MnCl_2 , d) CoCl_2 , e) ZnCl_2 , and f) FeCl_3 . The nanowires synthesized by using CuCl_2 as a promoter exhibit the highest aspect ratio. In fact, in the absence of transition metal salt promoters, only spherical silver nanoparticles, and a few short AgNWs were obtained.

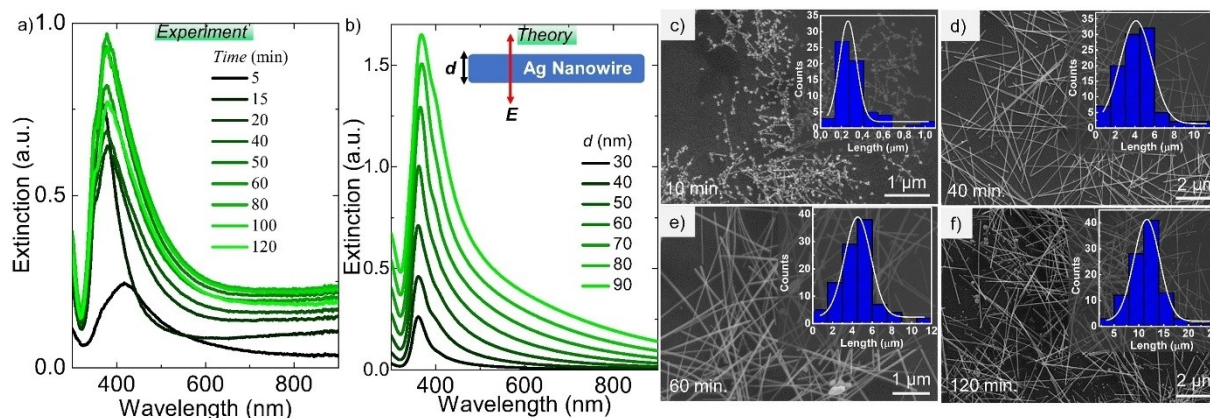


Figure 6. Experimental and theoretical extinction spectra of AgNWs. SEM images of AgNWs at the selected reaction times. (a) UV-vis extinction spectra of the reaction mixtures were acquired during the growth of AgNWs at the selected reaction times (in the presence of MnCl_2). (b) Theoretically calculated extinction spectra of a single AgNW as a function of nanowire diameter. The electric field of the incident light is perpendicular to the nanowire main axis. SEM images of the reaction products taken at the selected reaction times of (c) 10 min, (d) 20 min, (e) 40 min, and (f) 60 min.

the concentration of AgNWs increases with time. The appearance of a sharp extinction peak at around 380 nm is a strong indication of AgNW formation.^[20] In addition, the electron microscopy images of the reaction products were shown in Figure 6c–6f. The results indicate that the nanowire formation starts at around 10 min after the first addition of AgNO_3 to the reaction medium. At the end of the reaction (around 120 min after the first addition of AgNO_3), AgNWs have an average length of 12 μm and an average diameter of 67 nm, whereas the concentration of Ag nanoparticles is significantly reduced. The highest aspect ratio of AgNWs was found to be 170 when the polyol reaction time was 120 min. Therefore, optimum reaction time was determined to be 120 min. We further investigated the effect of stirring speed on the morphology of AgNWs (at 160 °C) by employing 160 μL of 4 mM CuCl_2 as a promoter and a PVP/ AgNO_3 mole ratio of 6. The stirring speed of the reaction mixture was immediately reduced to zero after dropwise addition of PVP/ AgNO_3 mixture. As a result, the AgNWs were obtained with an average length of 59 μm and an average diameter of 134 nm. It is noteworthy that both the length and the diameter of AgNWs increase when the reaction is unstirred since the chance of deposition of silver atoms on the silver nanowires and seed nanoparticles increases.

We next discuss the fabrication of rigid and flexible TCEs from the synthesized AgNWs in glycerol. The rigid TCEs were fabricated by spin coating of AgNWs dispersed in isopropanol onto the glass substrates. The fabricated rigid TCEs from the diluted and concentrated solutions of AgNWs have sheet resistance values as 50 Ω/sq , and 26 Ω/sq and transmittance values as 89.75%, and 83.25%, respectively, see Supporting Information for the details. The sheet resistance and transparency of the TCEs fabricated in this study are comparable to the sheet resistance and transmittance values of the TCEs demonstrated in previous studies, for example, a AgNW network showed a sheet resistance of 40 Ω/sq and an optical transmittance of 88%.^[35] However, the rigid TCEs fabricated in this study have lower sheet resistance and higher optical

transmittance values than the widely used TCEs based on ITO, which has a sheet resistance of 59.85 Ω/sq and an optical transmittance of 80.2%.^[36] Furthermore, we fabricated flexible TCEs on a surface treated PET substrate, which was modified by using 5% PSS in water. In a previous study, polydopamine layer on an elastomeric substrate generated a highly hydrophilic surface and increased the interaction between the AgNWs and the elastomeric substrate.^[14] Specifically, in this study, 35 μL of 5% PSS was placed on a glass substrate and the prepared PET substrate was placed on the PSS solution. The PSS droplet was dried by heating at 90 °C on a hot plate. We speculate that the interaction between the PET substrate and PSS is Van der Waals interactions. Therefore, the surface treatment makes PET surface hydrophilic and increases interaction between the AgNWs and PET surface. Subsequently, the AgNWs were spin coated on the PSS modified PET substrate. It should be noted that the contact resistance between the AgNWs has been the main reason for having large sheet resistance of AgNW networks and therefore, in previous studies, several techniques including mechanical pressing, thermal annealing, and also plasmonic welding have been proposed and performed in order to decrease the sheet resistance of the AgNW networks.^[37] In this study, we used both thermal annealing and mechanical pressing by hot laminating nanowire networks. The sheet resistance of the AgNW network decreased from 126 Ω/sq to 34 Ω/sq after hot laminating, see Supporting Information. In addition, the bending measurements show that the sheet resistance of the AgNW networks on the PSS modified PET substrate does not change significantly after 1000 cycles, which implies that the fabricated flexible TCEs can be used in flexible and foldable electronics.

Conclusions

In conclusion, for the first time, we have demonstrated a facile, green, high yield, transition metal salt promoted, and open atmosphere method for the synthesis of high quality AgNWs in

an environmentally benign solvent, a glycerol-water mixture, and additionally, AgNWs based flexible TCEs on PSS treated PET substrate. We have shown that presence of various transition metal salts has a strong influence on the shape and size of the AgNWs produced by the polyol reduction of AgNO₃. In fact, in the presence of transition metal salts, AgNWs were preferentially formed by keeping the surface of silver seeds free of adsorbed oxygen, and thus enabling the growth of silver nanoparticles in one direction. We have extensively studied the effect of several reaction parameters such as temperature, mole ratio of PVP/AgNO₃, type of promoter, amount of promoter, reaction time, and stirring on the morphology of silver nanowires. Under the optimized reaction conditions, AgNWs with a high aspect ratio of more than around 400 were obtained by using copper(II) chloride as a promoter. Additionally, the extinction spectra of AgNWs were corroborated by theoretical calculation of extinction spectra of a single AgNW. Besides, the synthesized AgNWs have been used for fabrication of flexible TCE on PSS treated PET substrates. The PSS layer on the PET substrate indeed generates highly hydrophilic surface, which boosts interaction of AgNWs with the PET surface. We envision that our results would play a significant role both in the synthesis of AgNWs with high aspect ratio and also in designing new rigid and flexible TCEs having high transmittance and low sheet resistance for applications especially in printable solar cells, organic light emitting diodes, and high performance flexible electronics.³⁸

Supporting Information Summary

The detailed experimental section including materials, synthesis of AgNWs, purification of AgNWs, characterization of AgNWs, and transparent electrode fabrication; SEM images; additional figures and tables; optical properties of AgNWs based flexible transparent conductive electrodes are all available in the Supporting Information.

Acknowledgements

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: Colloids · Flexible TCEs · Polyol synthesis · Silver nanowires · Transition metals

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