

Article

Effective Synthesis and Recovery of Silver Nanowires Prepared by Tapered Continuous Flow Reactor for Flexible and Transparent Conducting Electrode

Hyung Duk Yun ¹, Duck Min Seo ^{1,†}, Min Yoeb Lee ^{2,†}, Soon Yong Kwon ^{1,†} and Lee Soon Park ^{1,*}

Received: 30 November 2015; Accepted: 5 January 2016; Published: 8 January 2016

Academic Editor: Hugo F. Lopez

¹ School of Material Science and Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Korea; yun2985@gmail.com (H.D.Y.); seodm@unist.ac.kr (D.M.S.); sykwon@unist.ac.kr (S.Y.K.)

² Department of Polymer Science and Engineering, Kyungpook National University, Daegu 41566, Korea; youp1999@naver.com

* Correspondence: parkls@unist.ac.kr; Tel.: +82-52-217-2349; Fax: +82-52-217-2309

† These authors contributed equally to this work.

Abstract: Silver nanowires (AgNWs) with high aspect ratio were obtained utilizing a tapered tubular reactor by the polyol process. The tapered tubular type flow reactor allowed us to obtain nanowires in high yield without defects that is generally encountered in a closed reactor due to excessive shearing for a long time. After reaction the AgNWs were precipitated in the aqueous solution with the aid of a hydrogen bond breaker and were recovered effectively without using a high-cost centrifugation process. Dispersion of the AgNWs were used to prepare transparent conducting electrode (TCE) films by a spray coating method, which showed 86% transmittance and $90 \Omega\text{sq}^{-1}$ sheet resistance.

Keywords: silver nanowires; transparent conducting electrode; continuous flow reactor; touch screen panel

1. Introduction

Transparent conducting electrodes (TCE) are widely used in touch screen panels (TSP), thin-film solar cells, and transparent/flexible displays. A sputtered film of indium tin oxide (ITO) shows high transmittance (95%T) at low sheet resistance ($50 \Omega\text{sq}^{-1}$) [1]. However, ITO films lack mechanical rigidity especially under bending stress and have limitation in application to large area TSP (over 25 inches) due to the trade-off in high transmittance and low sheet resistance properties. Therefore many new materials are under development including carbon nanotubes [2,3], graphene [4,5], conductive polymers [6,7], and metal nanowires [8–10]. Among these materials one dimension metal nanowires have received great attention due to their potentials in fabricating large area TSPs, thin film solar cells, flexible OLEDs, and transparent displays. Silver nanowires (AgNWs) have been extensively studied during past years. They exhibit high conductivity ($\sim 105 \text{ Scm}^{-1}$) without any detrimental effects to their high transparency (>90%) [11]. Regarding the synthesis of silver nanowires several methods have been reported including hard-template [12,13] and soft template synthesis [14]. Among these synthetic routes, solution phase synthesis by polyol reduction has been the most intensively studied method [15,16]. However high-aspect ratio and rapid synthesis of AgNWs have not been achieved yet. Furthermore the cost of recovery and purification is also very high hindering the wide applications of AgNWs. Herein, we report a novel facile and high-concentration synthesis of AgNW utilizing tapered tubular type continuous flow reactors and a new method for the recovery of AgNW by precipitation method.

2. Experimental Section

2.1. Materials

Ethylene glycol (EG), AgNO₃, NaBr, poly(vinylpyrrolidone) (PVP, $M_W \sim 10,000\text{--}40,000$) and sodium dodecyl sulfate (SDS) were purchased from Sigma Aldrich (St. Louis, Mo, USA). All chemicals were used as received without further purification.

2.2. Synthetic Procedure and Recovery of AgNWs

Silver nanowires were synthesized by polyol process utilizing different type of reactors in this research. In both type closed system, the AgNWs were synthesized in a three-neck round-bottomed flask by dropping method. First poly(vinylpyrrolidone) (PVP, $M_W \sim 40,000$) and sodium dodecyl sulfate (SDS) were dissolved in ethylene glycol (EG) at 75 °C for 12 h. In another beaker was dissolved AgNO₃ powder in EG at room temperature for 6 h. The PVP and SDS in EG solution was poured in a three-neck flask and heated to 160 °C, and AgNO₃ in EG solution was added dropwise for 5 min by using a dropping funnel while stirring with a magnetic bar. For the scale-up of AgNWs synthesis another type of batch reactor, the resin kettle reactor, was used with mechanical stirrer utilizing the same dropwise addition method.

For the high-concentration rapid synthesis of AgNWs the tapered tubular type reactor was used with a mechanical stirrer. Here the PVP/SDS in EG solution was added first in the tapered tubular reactor and then AgNO₃ in EG solution was added dropwise separately, while taking out the AgNW reaction mixture through the bottom outlet of tapered tubular reactor. This type of continuous flow reactor can minimize the destruction or damage of synthesized AgNWs due to high shearing force induced in the closed reactors of three-neck with magnetic stirrer or resin kettle type with mechanical stirrer, enabling high concentration and rapid synthesis of AgNWs.

In the small scale synthesis of AgNWs in three-neck flask and resin kettle, the recovery of AgNWs were carried out by centrifuge. The reaction mixture of AgNWs solution was diluted with a five-fold volume of ethanol and stirred for 30 min and then subjected to centrifuge for 30–60 min at 3000 rpm. After removing the supernatant by siphon, five-fold deionized water was added to the precipitate of AgNWs mixture and subjected to centrifuge to purify the obtained AgNWs.

2.3. AgNWs-PET Film and Property Measurements

The purified AgNWs (0.05 wt. %) were added into ethanol solvent with 0.25 wt. % ethyl cellulose to make AgNW spray coating solution. The AgNW on polyethylene terephthalate (AgNW-PET) film was obtained by 20 times spray coating of the AgNW coating solution. The size of the AgNWs was measured with SEM (Hitach High-Technologies, Tokyo, Japan), whereas the sheet resistance and transmittance of the AgNW-PET film was analyzed by four-point probe and UV-VIS spectrophotometer (Craic, San Dimas, CA, USA). The crystal structure of AgNW was studied by XRD (Rigaku, Tokyo, Japan) and the stability of AgNW-PET film under flexure stress was examined by a bending test.

3. Results and Discussion

Over the past few years, the polyol process has been the most promising method for preparing AgNWs by using poly(vinylpyrrolidone) (PVP) as the capping agent and ethylene glycol (EG) as the solvent and reducing agent to reduce AgNO₃ into Ag nanowires. In the polyol process, many factors have always affected the yield and morphology of AgNWs, such as additive agents, temperature, stirring speed, ratio of chemicals, reaction times, and injection speed of chemicals.

Although the synthesis of silver nanowires has been studied for many years and a variety of silver nanowires have been synthesized by different methods, continuous flow-type synthesis of high-concentration silver nanowires has rarely been reported. In this work we first examined the optimum chemical and physical condition for the synthesis of AgNWs by the polyol process utilizing closed batch type reactors. Based on this conditions the scale-up of AgNW synthesis was studied and

applied to the synthesis of AgNWs by continuous flow reactions. A new method of recovery and purification of AgNWs was also developed.

3.1. Reaction Parameters of AgNWs Synthesis in Batch Type Closed Reactors

The synthesis of AgNWs is strongly affected by reaction conditions including chemical parameters such as the mole ratio of Ag^+ ion, repeating units/molecular weight of PVP, amount of sodium dodecyl sulfate (SDS) and various seed materials as well as physical parameters such as total solid content and method of addition of reactants, reaction time, method of stirring, structure and speed (rpm) of stirrer, and recovery/purification of AgNW product.

These special features of AgNW synthesis are due to the complex process of AgNW formation including the reduction of Ag^+ ion to Ag metal, seed formation, growth of silver nanometals (both nanowires and nanoparticles) under the capping of PVP, and other soft template materials in addition to the physical factors such as association and sedimentation of silver nanowires under high shearing forces.

In an attempt to separate these complex factors affecting AgNW formation, we first examined the synthesis of AgNWs in the closed reactor system. Here, we used the chemical composition of reactants which could promote a rapid and high-concentration synthesis of AgNW with high aspect ratio and high yield of AgNWs over Ag nanoparticles through the wide search of previously reported papers. In a typical synthesis of AgNWs, 1875 g PVP ($M_W \sim 40,000$) and 0.115 g SDS were dissolved in 20 mL EG by heating at 75 °C for 12 h under moderate stirring with magnetic stirrer. After PVP was dissolved completely, this solution was added in a three-neck flask and heated to 160 °C. Into the PVP/SDS solution was added AgNO_3/EG solution (which was made by dissolving 0.709 g AgNO_3 in 5 mL EG by stirring at room temperature for 6 h) by using dropping funnel over a period of 5 min and then stirred at 250 rpm with magnetic stirrer for certain period of time. After reaction the AgNWs were recovered and purified by centrifugation and subjected to SEM examination.

As for the effect of Ag^+ ion to PVP repeat unit, the mole ratio of 1:4 was found to give high yield of AgNWs as shown in Table 1 and Figure 1. From Figure 1 it was noted that large amount of amorphous Ag particles were observed below the $\text{Ag}^+:\text{PVP}$ repeat unit mole ratio of 1:4 due to insufficient capping of PVP on the growing direction of AgNWs. This result may also be attributed to the change of the total solid content (sum of AgNO_3 , PVP and SDS) in EG solution, showing that the larger the amount of AgNO_3 than the amount of PVP the larger the diameter of the AgNWs synthesized.

The most interesting part of this work was the effect of SDS on the AgNW synthesis and morphology. Previously, many surfactants have been used for the synthesis of AgNWs by the polyol process, for example, anionic surfactant sodium dodecylsulfonate (SDSN) by Tian [17] and cationic surfactant cetyltrimethylammonium bromide (CTAB) by Murphy [18]. They were used to generate either seed for AgNWs or soft capping agent. In our study the PVP was employed as main capping agent and SDS as soft capping agent. However, the small amount of SDS (*ca.* 0.3 mM) increased the reaction rate of Ag^+ reduction substantially; thus, it is suggested that SDS may play the role of phase transfer catalyst to supply Ag^+ ion effectively for reduction and incorporation into AgNW crystal growth.

From Table 1 it is noted that with small amount (0.3 mM) of SDS, the synthesis of AgNWs was almost completed in 5 min after addition of AgNO_3 solution into PVP/SDS solution. This may be the shortest reaction time ever reported in the synthesis of AgNWs so far. The effect of SDS concentration in AgNW synthesis is shown in Table 1 and Figure 2. At 0.24 mM SDS the aggregates of amorphous AgNWs were observed. When concentration of SDS was raised to 0.30 mM high yield of AgNWs was detected. Similarly, at 0.36 mM concentration of SDS the aspect ratio of AgNWs became significantly higher with the rapid supply of Ag^+ ions to the growing AgNW crystals. At higher concentration (0.42–0.48 mM) of SDS an increasing number of amorphous Ag particles were observed due to too rapid a supply of Ag^+ ions to be regularly packed into the AgNW crystal sites.

Table 1. Synthesis of AgNWs in batch type closed reactors.

Sample No.	AgNO ₃ Solution		PVP/SDS Solution				SDS (mM)	Stirrer Speed (rpm)	Reaction Time after Edition of PVP/SDS (min)	Ag:PVP (Mole Ratio)
	AgNO ₃ (g)	EG (mL)	PVP (g)	PVP (M _w)	EG (mL)	SDS (g)				
AgNW-P1	1.875	5	1.875	40,000	20	0.115	0.30	250	5	1:1.5
AgNW-P2	0.937	5	1.875	40,000	20	0.115	0.30	250	5	1:3.0
AgNW-P3	0.703	5	1.875	40,000	20	0.115	0.30	250	5	1:4.0
AgNW-P4	0.469	5	1.875	40,000	20	0.115	0.30	250	5	1:6.0
AgNW-S1	0.703	5	1.875	40,000	20	0.092	0.24	250	5	1:4.0
AgNW-P3	0.703	5	1.875	40,000	20	0.115	0.30	250	5	1:4.0
AgNW-S2	0.703	5	1.875	40,000	20	0.138	0.36	250	5	1:4.0
AgNW-S3	0.703	5	1.875	40,000	20	0.161	0.42	250	5	1:4.0
AgNW-S4	0.703	5	1.875	40,000	20	0.184	0.48	250	5	1:4.0
AgNW-R1	0.703	5	1.875	40,000	20	0.115	0.30	80	5	1:4.0
AgNW-P3	0.703	5	1.875	40,000	20	0.115	0.30	250	5	1:4.0
AgNW-R2	0.703	5	1.875	40,000	20	0.115	0.30	500	5	1:4.0
AgNW-P3	0.703	5	1.875	40,000	20	0.115	0.30	250	5	1:4.0
AgNW-T1	0.703	5	1.875	40,000	20	0.115	0.30	250	10	1:4.0
AgNW-T2	0.703	5	1.875	40,000	20	0.115	0.30	250	15	1:4.0

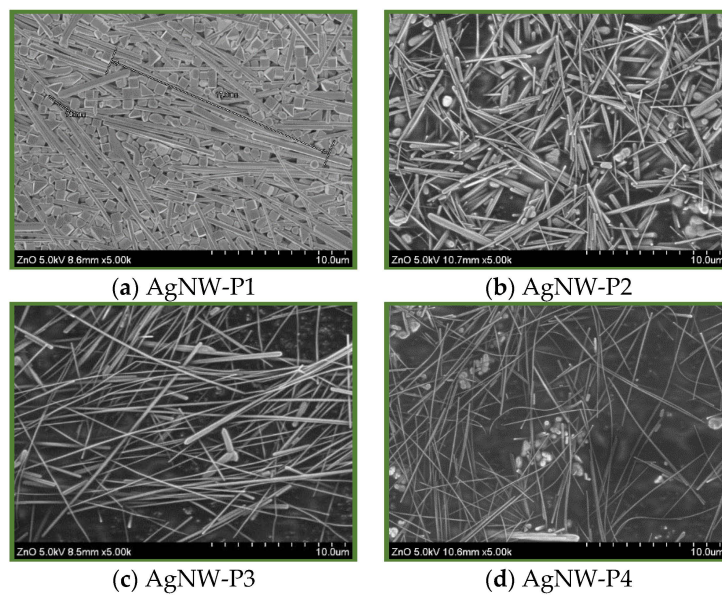


Figure 1. SEM images of AgNWs synthesized by mole ratio of Ag^+ ion:PVP repeat unit, (a) 1:1.5; (b) 1:3.0; (c) 1:4.0; and (d) 1:6.0.

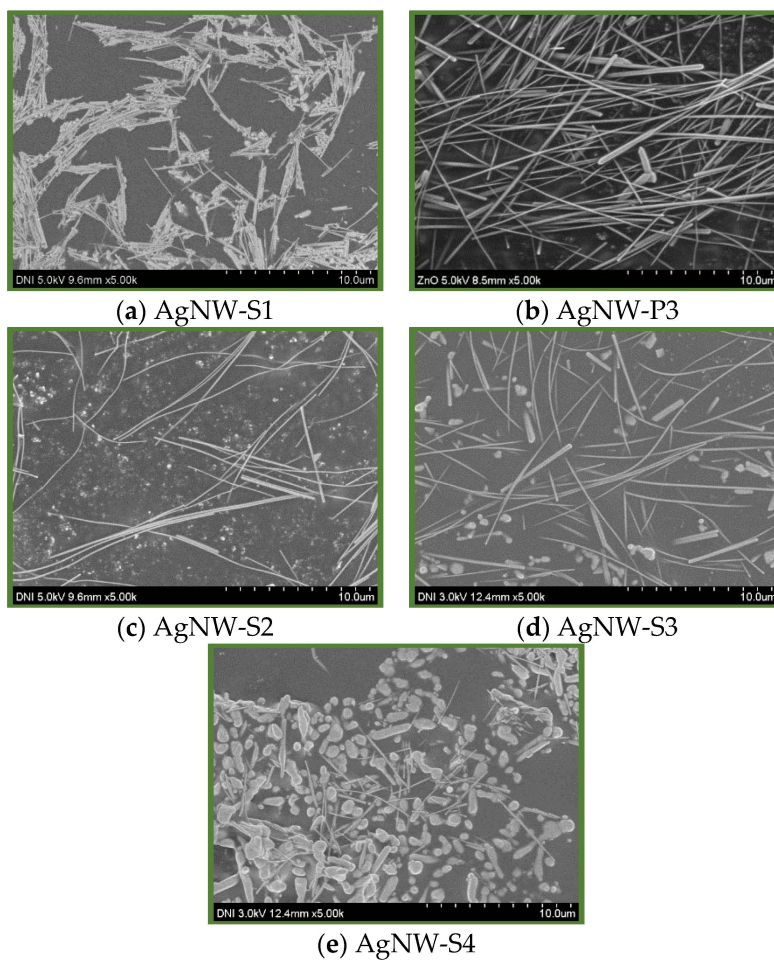


Figure 2. SEM images of AgNWs synthesized by varying the amount of SDS, (a) 0.24; (b) 0.30; (c) 0.36; (d) 0.42; and (e) 0.48 mM.

Other interesting features of AgNWs synthesis in closed reactor (under the reaction condition designated in Table 1) were the reaction time and the stirring speed of magnetic bar. As shown in Figure 3 the morphology of AgNWs was strongly dependent on the speed of magnetic stirrer. At 80 rpm a large amount of amorphous Ag nanoparticles was observed due to the uneven supply of Ag^+ ions to the crystal growth site. At a high stirring speed of 500 rpm the silver nanoparticles instead of AgNWs were mainly observed due to breakdown of the synthesized AgNWs to Ag nanoparticles. This suggests that AgNWs can be destroyed easily by high shearing force exerted by a magnetic stirrer in contact with the bottom of three-neck flask reactors. The effect of reaction time on AgNWs morphology in Figure 3 can also be explained similarly by high shearing forces during an excessive reaction time period.

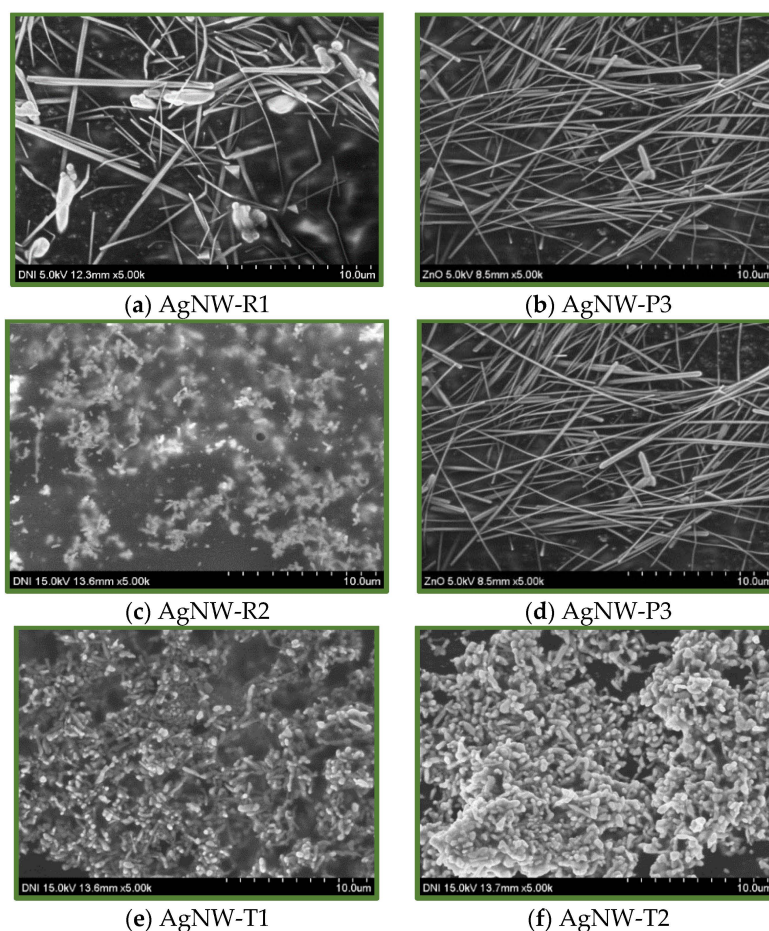


Figure 3. SEM images of AgNWs synthesized by varying magnetic stirrer speed after addition of AgNO_3 in EG solution at (a) 80 rpm; (b) 250 rpm; and (c) 500 rpm and by varying reaction time; (d) 5 min; (e) 10 min; and (f) 15 min.

3.2. Scale-Up and Rapid Synthesis of AgNWs

With the data, obtained in the light of chemical and physical reaction parameters utilizing the small scale three-neck flask synthesis of AgNWs, we tried to scale up the rapid synthesis of AgNWs both in closed and continuous flow type reactors. First the AgNWs were synthesized in a resin kettle type closed reactor with mechanical stirrer instead of magnetic bar stirrer which caused direct contact of AgNWs with the bottom glass of three-neck flask reactor. The reactant materials were increased to eight times as compared to small scale synthesis in three-neck flask and mechanical stirrer with a different impeller structure was used to prepare AgNWs in high concentration at a rapid speed. The composition

and ratios of reactant were kept as close as possible to the three-neck flask reactor while adjusting the chemical and physical reaction parameters in the case of scaling up AgNWs synthesis.

The experimental conditions and evaluation of AgNWs synthesized in the batch-type resin kettle reactor with different impeller structure, reaction time, and molecular weight of PVP are shown in Table 2 and Figure 4. As far as the shape of mechanical stirrer is concerned, the denticulated impeller was found to destroy the formed AgNWs faster than the screw type impeller as shown in Figure 4a–f. The denticulated impeller will encounter much more impact with the AgNWs compared to the screw type impeller under high rotating speed. The effect of reaction time in the resin kettle type reactor with mechanical stirrer can also be explained by impact exerted by mechanical stirrer, although the impact to the formed AgNWs will be much lower in the case of screw type impeller. Even with the screw-type impeller the yields of AgNWs were lower than 80% and the ratio of AgNWs to Ag nanoparticles was lower than 80:20. This was considered to be due to the high viscosity of the AgNW reaction mixture with PVP of M_W 40,000. In order to increase the yield and ratio of AgNWs and to decrease the diameter of AgNWs, we reduced the viscosity of reaction medium by decreasing the molecular weight of PVP to 10,000 g/mol. This improved the yield of AgNWs over 90% and the ratio of AgNW to Ag particles to 90:10 ratio. This could be achieved due to the proper transport of Ag^+ ions to the growing AgNWs crystal under reduced reaction medium.

Although the chemical and physical reaction conditions were established through the scale-up of AgNW synthesis in the resin kettle reactor by employing smooth screw type impeller and proper transport of Ag^+ ion to the AgNW crystal growth sites by reducing viscosity of reaction medium, improvement is still needed from the view point of rapid synthesis of AgNWs, minimum damage on the formed AgNWs, and widening of the synthetic process window for the efficient synthesis of desirable AgNW materials.

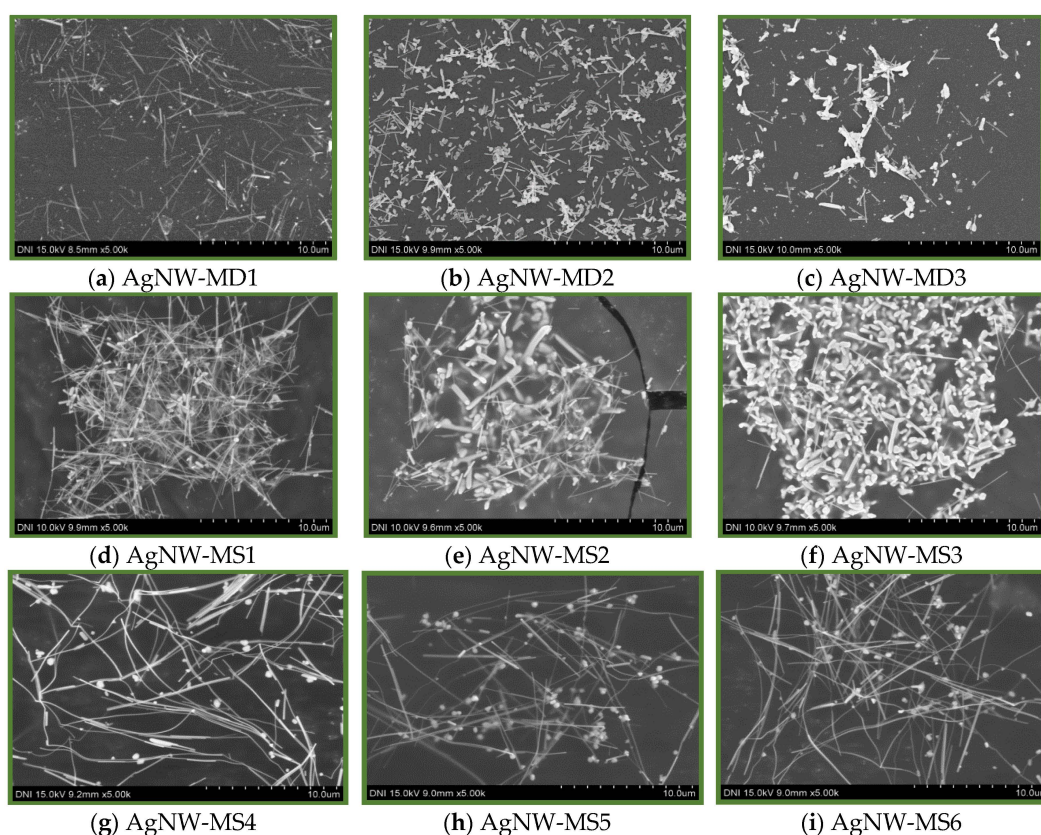


Figure 4. SEM images of AgNWs synthesized by varying impeller structure and reaction times, (a–c) denticulated-type impeller; (d–f) screw-type impeller and PVP M_W 40,000; (g–i) screw-type impeller and PVP M_W 10,000.

Table 2. Synthesis of AgNWs in batch type resin kettle reactors.

Sample No.	AgNO ₃ Solution		PVP/SDS Solution				Stirrer (rpm)	Reaction Time (min)	Impeller Type	Yield (Wire:Particle)
	AgNO ₃ (g)	EG (mL)	PVP (g)	PVP (M _w)	EG (mL)	SDS (g)				
AgNW-MD1	5.624	40	15	40,000	160	0.92	150	5	denticulated	NA
AgNW-MD2	5.624	40	15	40,000	160	0.92	150	10	denticulated	NA
AgNW-MD3	5.624	40	15	40,000	160	0.92	150	15	denticulated	NA
AgNW-MS1	5.624	40	15	40,000	160	0.92	150	5	screw	70.0% (75:25)
AgNW-MS2	5.624	40	15	40,000	160	0.92	150	10	screw	79.4% (80:20)
AgNW-MS3	5.624	40	15	40,000	160	0.92	150	20	screw	45.7% (70:30)
AgNW-MS4	5.624	40	15	10,000	160	0.92	150	5	screw	92.0% (90:10)
AgNW-MS5	5.624	40	15	10,000	160	0.92	150	10	screw	94.0% (90:10)
AgNW-MS6	5.624	40	15	10,000	160	0.92	150	15	screw	94.2% (90:10)

Therefore, we designed a tapered tubular type reactor for the continuous flow reaction for the synthesis of AgNWs with minimal damage after formation of AgNWs. The schematic illustration of continuous flow reaction system is shown in Figure 5. In this continuous flow system, the distance ratio of L1 to L2 is kept at 80:20 which will allow synthesized AgNWs to sit at the bottom of the tubular reactor thus preventing a damage from shearing force. The reaction condition were adjusted according to the AgNWs synthetic data in Table 2 except the addition of 0.01 mM of NaBr into PVP/SDS in EG solution for the facile seeding of AgNWs growth. First the tubular reactor was filled with PVP/SDS in EG solution including NaBr seeding agent and then heated to 160 °C followed by dropwise addition of AgNO₃ in EG solution into the tapered tubular reactor with a slow rotation of mechanical stirrer with screw impeller. Secondly, after confirming the formation of AgNWs from the initial turbidity of the reaction medium, the reaction mixture in the bottom part of tapered reactor was taken out by opening the valve and then collected in the recovering vessel. The yield and ratio of the AgNWs to Ag nanoparticles were over 90% and 90:10, respectively. The average diameter of the AgNWs was about 88 nm and length of the AgNW was in the range of 30–80 μm as shown in Figure 6.

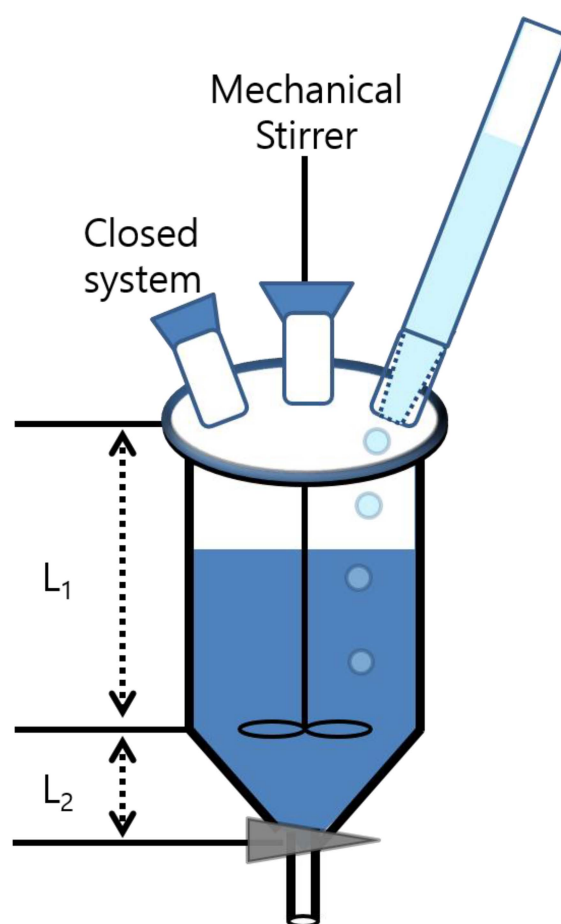


Figure 5. Schematic image of tapered tubular type reactor for continuous flow reaction of AgNWs.

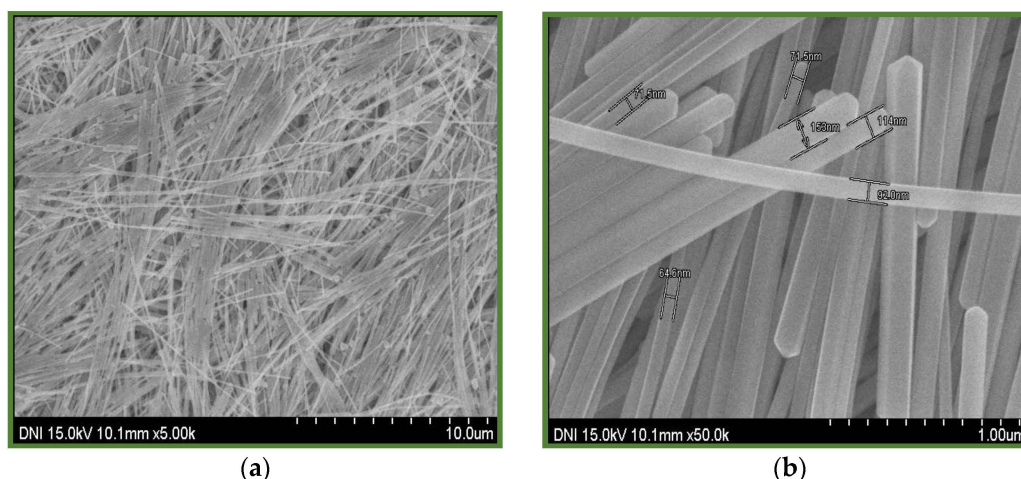


Figure 6. SEM images of AgNWs synthesized by continuous flow reaction of AgNWs utilizing tapered tubular type reactor: (a) low; (b) high resolution.

3.3. Recovery and Purification of AgNWs and Properties of AgNW-PET Film

The recovery of the AgNWs has usually been carried out by centrifugation and repeated washing with DI water or ethanol. We first tried to get information on the solvent through the centrifuge experiments with AgNWs reaction mixture obtained as shown in Table 3. The reaction mixture of AgNWs solution (1–3 mL) was diluted to 50 mL with aqueous solution containing NaCl or urea as a hydrogen bonding breaker and then subjected to centrifuge at 3000 rpm for 30–60 min, followed by removal of supernatant by siphon apparatus. The purification of recovered AgNWs was conducted by repeated centrifugation with DI water three times. The recovery data of AgNW in Table 3 shows that 25% NaCl aqueous solution is an effective solvent for recovering AgNWs from the reaction mixture. Although urea is known as an efficient hydrogen bond breaker, the 25 wt. % NaCl aqueous solution performed better in reducing the high viscosity of the EG solution due to the salting out effect [19].

Table 3. Search of recovery solvent for AgNWs from AgNW/EG reaction mixture.

Solvent for Centrifuge	AgNW Solution (mL)	Centrifuge Composition	Rotation Speed 3000 rpm		
			30 min	60 min	
H ₂ O	1	Ag solution 1 g + H ₂ O 49 g	X	X	
NaCl	20%	1	Ag solution 1 g + NaCl(aq) 49 g	O	
		2	Ag solution 2 g + NaCl(aq) 48 g	X	O
		3	Ag solution 3 g + NaCl(aq) 47 g	X	X
NaCl	25%	1	Ag solution 1 g + NaCl(aq) 49 g	O	
		2	Ag solution 2 g + NaCl(aq) 48 g	O	
		3	Ag solution 3 g + NaCl(aq) 47 g	X	O
Urea	20%	1	Ag solution 1 g + Urea(aq) 49 g	X	O
		2	Ag solution 1 g + Urea(aq) 48 g	X	O
		3	Ag solution 3 g + Urea(aq) 47 g	X	X

The efficiency of recovering solvent was examined further with the AgNWs reaction mixture obtained by batch type resin kettle reactor. As shown in Table 4 the 25% NaCl aqueous solution could separate AgNWs in 10 wt. % AgNWs mixture after 50 min centrifugation (80.2% yield) and 4 wt. % AgNWs mixture after 30 min centrifugation (87.7% yield), both at 3000 rpm speed.

Table 4. Recovery of AgNWs from AgNW/EG reaction mixture with centrifuge condition.

Solvent for Centrifuge	AgNW Solution (mL)	Centrifuge Composition	Centrifuge Time (min)	Yield (%)
NaCl 20%	1	AgNW solution 1 g + NaCl(aq) 49 g	30 min	76.2%
	2	AgNW solution 1 g + NaCl(aq) 48 g	30 min	70.2%
	3	AgNW solution 3 g + NaCl(aq) 47 g	50 min	76.9%
NaCl 25%	1	AgNW solution 1 g + NaCl(aq) 49 g	10 min	69.7%
	2	AgNW solution 2 g + NaCl(aq) 48 g	10 min	80.3%
	2	AgNW solution 2 g + NaCl(aq) 48 g	20 min	79.6%
	2	AgNW solution 2 g + NaCl(aq) 48 g	30 min	87.7%
	3	AgNW solution 3 g + NaCl(aq) 47 g	30 min	72.6%
	5	AgNW solution 5 g + NaCl(aq) 45 g	50 min	80.2%

In order to further decrease the recovery cost of AgNWs, precipitation method instead of centrifugation was tried as shown in Table 5. For this purpose the AgNWs reaction mixture obtained from the tapered tubular flow reactor was used, since the precipitation of the AgNWs reaction product can be directly poured into the precipitation tank. This process can reduce both the electrical power and the centrifuge manipulation cost.

After selecting 25% NaCl aqueous solution as precipitation solvent, recovery of AgNWs from the reaction mixture was conducted by natural sedimentation process. The AgNWs reaction mixtures were prepared by the tapered tubular reactor with reactant composition of 40 g PVP ($M_W \sim 40,000$) in 200 mL EG and 10.14 g AgNO₃ in 50 mL EG solutions. A part of the AgNWs reaction product (25 mL) was diluted with 5000 g of 25 wt. % NaCl aqueous solution and stood still for 6 h. After siphoning of supernatant the precipitated AgNWs was purified by washing with DI water three times.

When the composition of AgNWs reactants was 40 g PVP ($M_W \sim 40,000$) in 300 mL EG and 10.14 g AgNO₃ in 50 mL EG, the precipitation was observed at 4000 g of 25 wt. % aqueous solution as precipitating solvent, while 40 g PVP ($M_W \sim 10,000$) in 200 mL EG and 10.14 g AgNO₃ in 50 mL EG the precipitation occurred at 2000 g of 25 wt. % NaCl aqueous solution. These could be due to the reduced viscosity in the precipitating AgNWs from the reaction mixture. These data indicate that the natural precipitation method is both efficient and cost effective for the recovery of AgNWs.

Table 5. Recovery of AgNWs from AgNW/EG reaction mixture by continuous flow reactor.

Reaction Condition for Synthesis of AgNWs With Tapered Tubular Reactor										Recovery of AgNWs	
AgNO ₃ Solution		PVP Solution					Temp (°C)	rpm	Reaction Time (min)	25 wt. % NaCl aq. Solution (g)	Precipitation Yield (%) (Wire:Particle)
AgNO ₃ (g)	EG (mL)	PVP (g)	PVP (M_W)	EG (mL)	SDS (g)	NaBr (mM)					
10.14	50	40.0	40,000	200	1.5	0.05	160	100	10	5000	72.7 (85:15)
10.14	50	40.0	40,000	300	1.5	0.05	160	100	10	4000	77.1 (90:10)
10.14	50	40.0	10,000	200	1.5	0.05	160	100	10	2000	89.9 (90:10)

After purification the AgNWs obtained from the tapered tubular type method was used to make spray coating solution. The AgNW/ethanol solution (0.5 wt. %) was diluted to tenfold (0.05 wt. %) by mixing with ethanol solvent with 0.25 wt. % ethyl cellulose ($M_W \sim 80,000$) as viscosifying agent. The AgNW/ethanol coating solution was used for the spray coating of AgNWs on top of the optical-grade PET film. The transmittance and sheet resistance of the AgNW-PET film was 86% and 90 Ωsq^{-1} , respectively with 20 times spray coating as shown in Figure 7, which is suitable for the application of touch screen panel (TSP) fabrication.

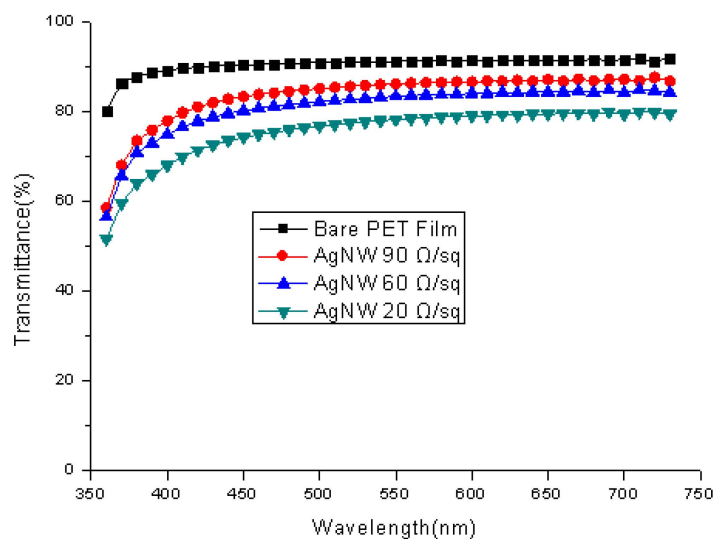


Figure 7. Transmittance and sheet resistance of AgNW-PET film made by spray coating.

The SEM image of the AgNW-PET film and XRD peak of AgNWs are shown in Figure 8 in which the crystal lattice constant of AgNWs was 4.088 Å exhibiting face-centered cubic crystal structure of silver. The bending test of AgNW-PET and ITO-PET film shows that the former is stable up to 10,000 bending stress while the latter shows rapid increase of sheet resistance from 8000 bending motions suggesting that AgNW-PET film can be used in the fabrication of flexible TSP and flexible display substrate.

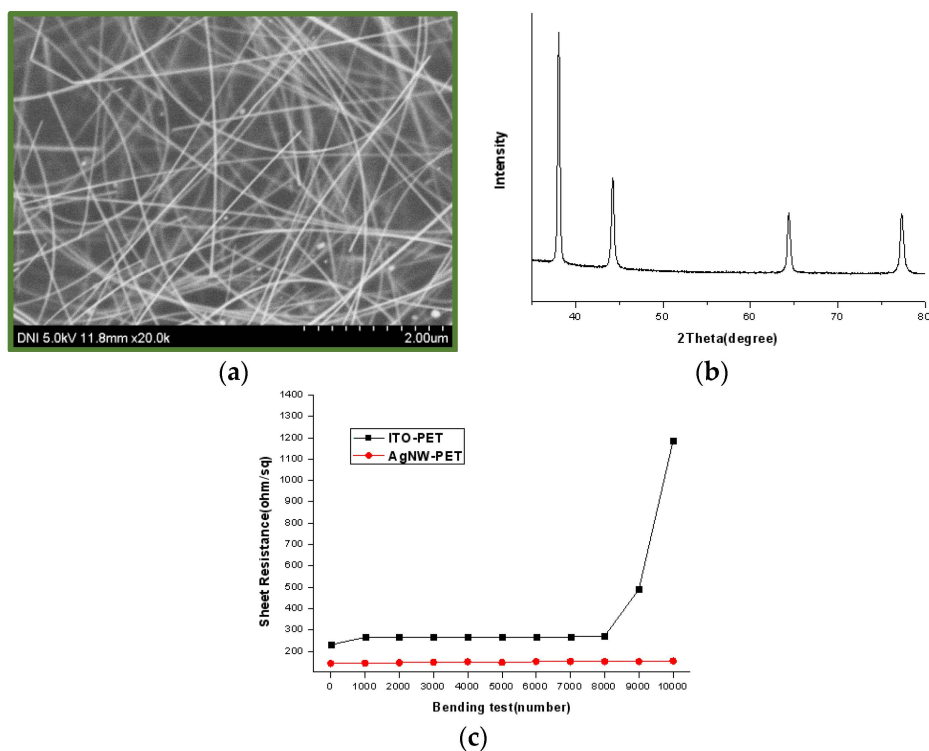


Figure 8. (a) SEM image of AgNW-PET film; (b) XRD peak of AgNW; and (c) bending test of AgNW-PET film.

4. Conclusions

Silver nanowires (AgNWs) were synthesized by the polyol process with high yield and high aspect ratio utilizing a tapered tubular continuous flow reactor. The synthesized AgNWs exhibited less defects in morphology of AgNWs which are commonly caused by excessive shearing for long time in the closed reactor. After reaction the AgNWs were precipitated in the aqueous solution with the aid of hydrogen bond breaker and could be recovered effectively without using high cost centrifugation process. Dispersion of the AgNWs were used to prepare a transparent conducting electrode (TCE) films by spray coating method which showed 86% transmittance and $90 \Omega\text{sq}^{-1}$ sheet resistance applicable to touch screen panel fabrication.

Acknowledgments: This work was supported by the 2014 Research Fund(1.140056.01) of UNIST(Ulsan National Institute of Science and Technology).

Author Contributions: H. D. Yun, D. M. Seo and M. Y. Lee contributed to the synthesis of AgNWs and S. Y. Kwon to the analysis of AgNWs.

Conflicts of Interest: The authors declare no conflict of interest.

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