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Preparation of silver nanowires and their application in conducting polymer nanocomposites

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HIGHLIGHTS

- Different synthetic techniques for the preparation of AgNWs.
- Effect of various factors on the growth of AgNWs.
- Deposition of AgNWs on conducting polymer by using thin film.
- Improvement of optical and electrical properties of conducting polymers with AgNWs.

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ABSTRACT

Silver nanowires (AgNWs)/conducting polymers based nanocomposites are advanced materials for electrical conductive applications. AgNWs have high electrical conductivity, high surface area and high aspect ratio, which are important for the preparation of AgNWs/conducting polymer nanocomposites by using particularly small amounts of AgNWs as conductive filler. The resultant nanocomposite transparent conductive electrodes play a key role in many optoelectronic devices such as touch screen, liquid crystal display, and solar cell. Thus, we carefully selected such published data which is associated with AgNWs/conducting polymers based nanocomposites. This paper gives a comprehensive review on recent development in the synthetic techniques of AgNWs, factors affecting the growth of AgNWs and their applications in conducting polymer nanocomposites. In addition, the effect of various additives (inorganic anions, transition metal cations and molecular species) on size, shape and aspect ratio (length:-diameter) of AgNWs has been described in detail. Herein, we also focused on various thin film deposition techniques, for the surface modification of AgNWs with conducting polymers for useful applications such as in touch screen, liquid crystal display and solar cell.

1. Introduction

The resistivity and transmittance are usually controlled by the fundamental properties of the material, developing transparent conducting materials (TCMs) with low sheet resistance ($R_S < 10\ \Omega$/sq) and high transmittance (T > 90%) has been a persistent challenge and an active area of research in the field of material science and engineering [1]. Different transparent conductive materials, for example: conducting polymers [2], graphene [3,4], metal nanowire [5,6] and hybrid materials [7,8] have been extensively studied during last decade. Among them conducting polymers (polypyrrole, polythiophene, polyaniline etc.) and noble metals (Ag, Au, Pd and Pt) based nanocomposites are used in producing new material with high conductivity. Among these all noble metals, silver (Ag) is superior in electrical (6.3×10^7 S m^{-1}) and thermal (429 W m^{-1} K^{-1}) conductivities and has the ability to enhance electrical and optical properties of the polymer composites. Due to these superior properties of Ag, silver nanowires (AgNWs) are used as conductive filler and thermal interfacial material in sophisticated

Abbreviations: AgNWs, silver nanowires; PVP, poly(vinyl pyrrolidone); SDS, sodium dodecylsulfonate; PVA, poly(vinyl alcohol); DTDPA, 3,3-dithiodipropionic acid; MTPs, multiple twinned nanoparticles; EG, ethylene glycol; GA, glycolaldehyde; ITO, indium tin oxide; PANI:PSS, polyaniline:polystyrene sulfonate; PEDOT:PSS, Poly(3, 4-ethylene dioxythiophene): poly(styrene sulfonate); MEH-PPV, poly [2-methoxy-5-(2′-ethylhexyloxy)-1, 4-phenylene vinylene].

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nanodevices [9–12]. The combination of AgNWs with conducting polymer matrices to produce nanocomposite materials has got much attention, especially in organic electronics [13].

Different synthetic strategies of AgNWs are flourished in the past decade, their corresponding properties and applications have been extensively studied. The idea of using AgNWs as conductive filler to improve electrical properties of the polymer composites has got much attention both from industrial and academic aspects. These nanocomposites are often used in electronic devices [9,14,15].

Recently, some review articles [16,17] on metal nanowires based transparent and conductive electrodes have been published. Here in this review, we focused our discussion on various synthetic strategies for the synthesis of AgNWs and role of various additives (inorganic anions, metal cations and organic molecular species) on the aspect ratio of AgNWs. Moreover, different methods for the preparation of AgNWs/conducting polymers composite film are reviewed in this article.

2. Synthetic strategies of AgNWs

According to published reports, various strategies for the synthesis of AgNWs have been developed such as, polyol process [18,19], solvothermal method [20,21], ultraviolet irradiation [22], photo-reduction technique, electro-deposition process [23], DNA template method [24], porous material template method [25] and wet chemical method [26].

2.1. Polyol process

Obstacles in the preparation of AgNWs like low yield and disorderness of the morphology were removed by polyol process. The main theme of this process involves the formation of noble metals (Ag, Au, Pt and Pd) nanoparticles by the reduction of noble metal salts by using ethylene glycol (EG) at 160 °C and polymer such as poly(vinyl pyrrolidone) (PVP) to form coordination complex with noble metal ions (Ag, Au, Pd and Pt) and to adsorb selectively onto surfaces of these metals. Many developed forms of polyol process have been reported during the last decade. Different research communities have modified polyol process by using EG and glycerol as solvent and reductant, respectively. It was found that glycerol has strong reducing ability to convert Ag^+ into Ag relative to EG [19,27,28].

The polyol method is a well-liked method for the synthesis of AgNWs. This method is based on temperature dependent oxidation of EG to glycolaldehyde (GA), which causes reduction of noble metal ion to zero valent state. These concepts elaborate the mechanistic detail that the polyol method can be used to generate AgNWs with well-controlled shapes [18,19,28]. Skrabalak et al., found that on heating EG at 150 °C in the presence of air, GA was obtained, which was dominant reductant moiety for the synthesis of silver nanostructures. The reaction format for reduction of EG and formation of GA is shown in Scheme 1 [29].

For solution-phase synthesis of AgNWs, several factors [30–32] were investigated that influence on the kinetics of oxidation reaction. Solution-phase synthesis involves the use of soft templates or capping agents which play key role for the synthesis of AgNWs. Different varieties of stabilizing polymers like PVP, sodium dodecylsulfonate (SDS), vitamin B_2, poly(vinyl alcohol) (PVA), dextrin, poly(methyl vinyl ether) were used for the synthesis of colloidal nanomaterials (AgNWs). According to published reports, the degree of polymerization and the concentration of these stabilizing polymers greatly influenced by the size distribution of colloidal nanomaterial. Among these stabilizing agents, PVP was proved as best stabilizing agent in polyol synthesis due to its high degree of polymerization (3240) and ability to support the growth of different shaped nanostructures [33].

The function of PVP is to form coordination complex with Ag ions and to adsorb selectively on facets of Ag multiple twinned nanoparticles (MTPs). Due to the presence of N–C=O group in PVP, binding capacity to the surface of Ag particle increases. The interaction between Ag crystals and N–C=O group of PVP decreases the growth of crystal {100} facet comparatively with {111} facets [18,34,35]. Furthermore, it was found that Ag nanowires have pentagonal cross sectional shape, along with 5-folds twinned crystalline structure. Due to high difference in energy of side surfaces {100} facets and end surfaces {111} facets, there is a great difference of reactivity between {100} facets and {111} facets of AgNWs [36]. Consequently, side surface was completely blocked with PVP and the ends surface was partially blocked with PVP. These investigations show that the PVP macromolecules interact more strongly with{100} facets of Ag than {111} facet of Ag. These evidences strongly emphasize that AgNWs produced from MTPs at the early stage of Ostwald ripening process. Proper concentration of PVP and MTPs, both play key role in the growth of 1-D AgNWs with pentagonal cross section as illustrated in Fig. 1.

$$HOCH_2CH_2OH \xrightarrow{\Delta} CH_3CHO + H_2O$$

$$2Ag^+ + 2CH_3CHO \longrightarrow 2CH_3COOH + 2Ag^0$$

$$2HOCH_2CH_2OH + O_2 \xrightarrow{\Delta} 2HOCH_2CHO + 2H_2O$$

Scheme 1. Catalytic oxidation of EG to GA and reduction of silver ions [29].

2.1.1. Factors affecting the growth of AgNWs during polyol process

Soft solution phase synthesis of AgNWs involves three major steps: nucleation (involving the reduction of metal ion to zero valent atom), seeding (involving the development from nuclei to seed) and finally growth mechanism step (involving the development from seed to nanostructures). By changing thermodynamic

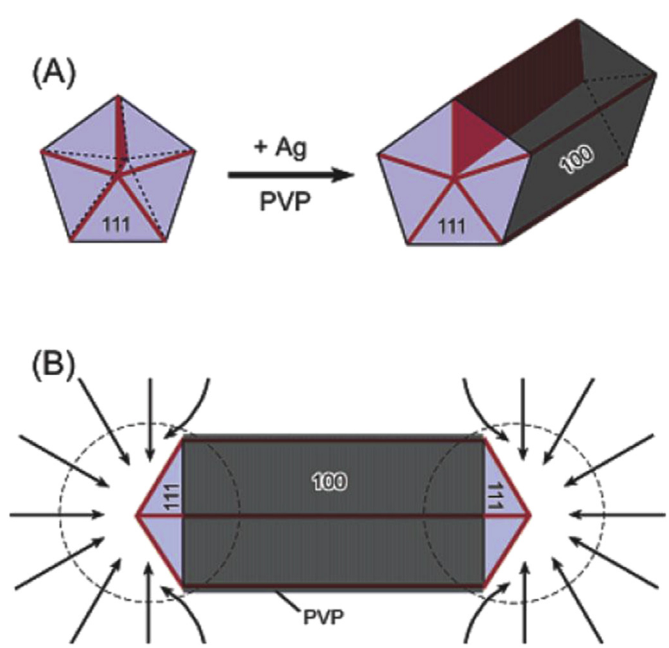

Fig. 1. Growth mechanism of silver nanorod from MTPs. Adapted with permission from reference [19].