

# Silver Nanoparticles as Low-Emissivity Coating Materials for Window Glazing Applications

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## ABSTRACT

The potential of silver (Ag) nanoparticles as low-emissivity (low-e) coating materials for window glazing applications has been discussed. Ag nanoparticles were prepared via a wet chemical method and applied on the surface of flat glass through spin coating. A mild heat treatment at 200°C was employed to achieve the low-e effect, which results in a total surface emissivity of about 0.015, compared to about 0.837 of the plain glass substrate. By applying such low-e coatings, the heat loss through a single-glazed window pane could be reduced by about 45% ( $U$ -value from 5.75 to 3.18 W/(m<sup>2</sup>K)).

**Keywords:** Ag nanoparticle, emissivity, glazing

## 1 INTRODUCTION

Reducing the energy loss through the building envelope (e.g., windows, roofs, and walls) is important to increase the energy efficiency of buildings [1]. As a cost-effective technique, low-e coatings have widely been used for such purposes [2]. A low-e coating is essentially a thin film consisting of metal or metallic oxides, which is capable of emitting low levels of radiant thermal energy. Low-e coatings can reflect the radiative thermal energy back into the room in cold weather (or back to the outdoors during warm weather), thereby reducing the radiative heat transfer through the building envelopes. Low-e coatings can be applied in both the transparent (i.e. window glazings) and the opaque (i.e. roofs, walls or floors) parts of the building envelope [3]. Hence, the development of different low-e coating materials to meet the different application requirements is of both scientific and technological interest.

For window glazing applications, low-e coatings are usually prepared via sputtering or chemical vapor deposition [2]. Although these methods can be integrated with the online processes of flat-glass production, the need of high temperature, vacuum, and expensive raw materials may show certain limitations, i.e., with respect to process economics. In this regard, offline coating techniques are very interesting since they may enable more possibilities towards a cost-effective product. For example, metallic

nanoparticles may represent an ideal raw material for low-e coatings [4], because they can be prepared with controllable properties [5] and be readily processed via a number of coating techniques, such as dip coating, spin coating, or inkjet printing [6]. However, to the best of our knowledge, few studies have so far been published to reveal the potential of metallic nanoparticles as low-e coating materials for window glazing applications.

We communicate in this contribution a simple method to achieve low-e coatings by using Ag nanoparticles. A preliminary test shows a total surface emissivity of about 0.015, compared to about 0.837 of the float glass.

## 2 EXPERIMENTAL

Ag nanoparticles were synthesized by a modified polyol process, as reported previously [7]. For a typical synthesis, 10 g polyvinylpyrrolidone (PVP) powder was added into 75 mL ethylene glycol under constant stirring. After the PVP was totally dissolved, 400 mg AgNO<sub>3</sub> was added to the PVP-ethylene glycol solution. Thereafter, the glass beaker that contained the obtained solution was immersed into a preheated oil bath and maintained at 120°C for 1 h. After the synthesis, Ag nanoparticles were separated from the reaction system by centrifugation, and washed twice with acetone and ethanol, respectively. Finally the obtained Ag nanoparticles were dispersed in ethanol to form a colloidal solution (concentration ~ 10 mg/mL).

A spin coating process was performed at 2000 rpm to prepare Ag nanoparticle films on float glass substrates. After being dried naturally in air at room temperature, the coated glass substrates were subject to an annealing treatment at 200°C for 2 hours.

Ag nanoparticles were characterized by using x-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and attenuated total reflectance (ATR) Fourier transform infrared (FTIR) spectroscopy. Optical transmittance spectra of the as-prepared samples were measured on a Perkin Elmer Lambda 1050 UV/Vis/NIR spectrophotometer. Reflectance spectra were measured with a 150 mm integrating sphere reflectance accessory. Reflectance spectra were also measured on a SOC-100 Hemispherical Directional

Reflectometer (HDR) in the wavelength region of 2–25  $\mu\text{m}$ ; Total hemispherical emissivity of the samples was then calculated by integrating the angular reflectance measurement stepwise from  $10^\circ$  to  $80^\circ$  incident angles (12 angles) and calibrated with a standard Au reference.

### 3 RESULTS AND DISCUSSION

In this work, Ag nanoparticles were prepared via a polyol process, as reported previously [7, 8]. The as-synthesized Ag nanoparticles are crystalline and have a face-centered cubic structure (Figure 1a). According to Scherrer's formula [9], crystallite size of the as-prepared Ag nanoparticles is about 47 nm, which also agrees with the subsequent TEM analysis. No XRD reflections related to any silver oxides such as  $\text{Ag}_2\text{O}$  were observed, indicating that Ag nanoparticles are rather stable despite of their small sizes.

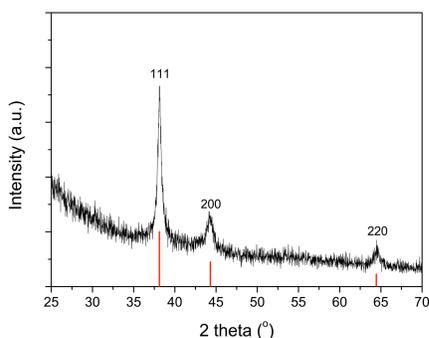


Figure 1: XRD pattern of the as-prepared Ag nanoparticles. The positions and relative intensities of the reflections are indicated at the bottom.

Figure 2a shows a typical TEM image of the as-prepared Ag nanoparticles. The particles are nearly spherical and are polydisperse with a relatively large size range from 20 to 80 nm, with an average diameter of about 50 nm, which is in agreement with the XRD results (Figure 1). Electron diffraction pattern (Figure 2b) shows typical polycrystalline features, indicating that the individual Ag nanoparticle may constitute of several primary particles.

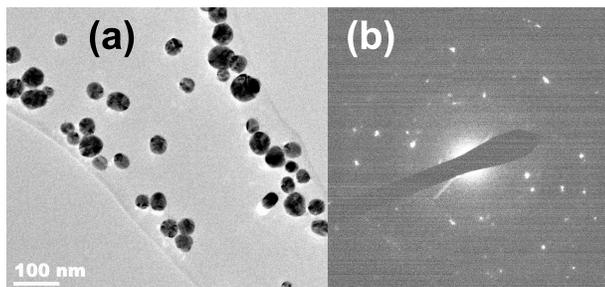


Figure 2: TEM image (a) and electron diffraction pattern (b) of the as-prepared Ag nanoparticles.

It is worth noting that, during the polyol synthesis, PVP has been added as a protective agent to prevent Ag nanoparticles from aggregation [7, 8]; therefore, the surface of the resulting Ag nanoparticles is most likely capped with PVP molecule residuals. For example, as shown in Figure 3a, the FTIR spectrum of the as-prepared Ag nanoparticles exhibit features similar to those of the PVP powders (Figure 3b), apart from the absorptions related to the glass substrate (Figure 3c). The existence of PVP on the surface of Ag nanoparticles increases not only their chemical stability against oxidation (see, e.g, Figure 1), but also workability for thin film processing. For example, the as-prepared Ag nanoparticles can be well dispersed within ethanol to form a stable colloidal suspension with different concentrations (up to 100 mg/mL), which is important for the subsequent spin coating process.

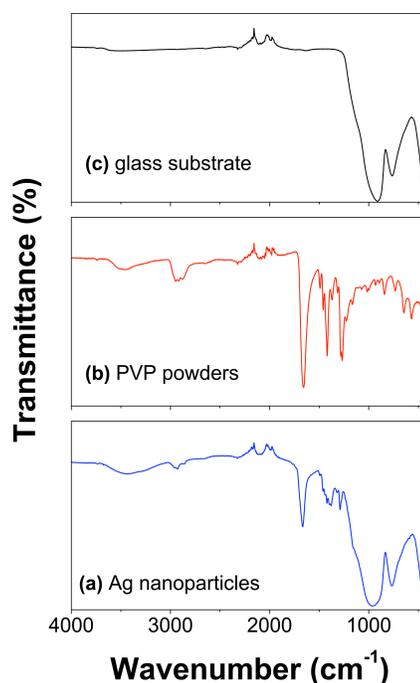


Figure 3: FTIR transmittance spectra of (a) the as-prepared Ag nanoparticles, (b) PVP powders, and (c) glass substrate. The noise around  $2000\text{ cm}^{-1}$  is due to the ATR diamond crystal.

Figure 4a shows the SEM image of the as-synthesized Ag nanoparticle film, which is relatively dense and has a thickness of about 400 nm. After the annealing treatment at  $200^\circ\text{C}$  for 2 hours, a dense-porous transformation has been observed for the Ag nanoparticle film (Figure 4b), which can be attributed to the melting and growth of Ag nanoparticles. It is worth noting that small nanoparticles usually have a lower melting temperature than that of the corresponding bulk counterpart due to the size effect [10].

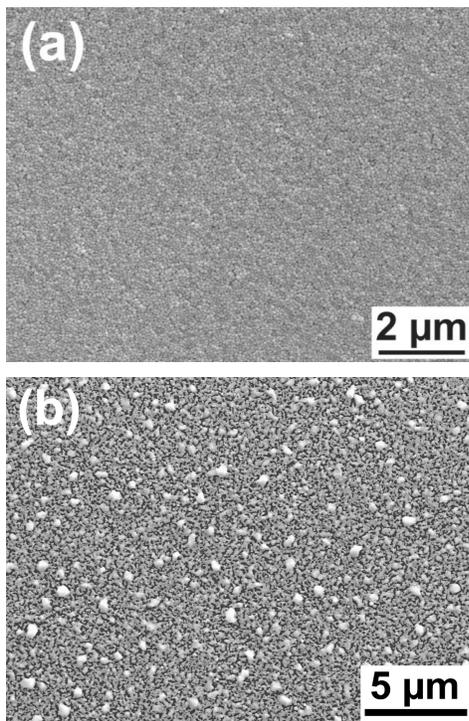


Figure 4: SEM images of Ag nanoparticles before (a) and after (b) the annealing treatment at 200°C.

Figure 5 shows the transmittance spectra of the obtained samples. The original Ag nanoparticle film is relative dense and shows a limited visible transparency of about 1% at 510 nm (Figure 5a). The transmission band at about 1200 nm is probably related to the absorbed PVP molecules. For example, this band disappears after the annealing treatment (Figure 5b). Moreover, the visible transparency of the Ag nanoparticle film increases to about 35% at 510 nm after the annealing treatment. This can be attributed to the dense-porous transformation (Figure 4) and the removal of surface-absorbed PVP molecules. The absorption peak at about 352 nm is related to the surface plasmon resonance (SPR) band of Ag [11, 12].

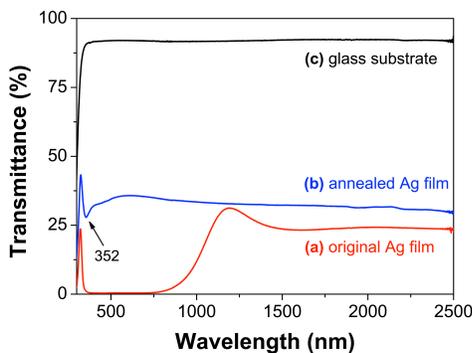


Figure 5: Transmittance of the Ag nanoparticle films before (a) and after (b) the annealing treatment at 200°C. Glass substrate (c) is also measured for comparison.

Reflectance spectra of the obtained samples were also measured, Figure 6. It is found that, compared to the plain glass, Ag nanoparticle-coated glass substrates are highly reflective. For example, the glass substrate has a reflectance of about 8% at 510 nm; in contrast, the as-prepared Ag nanoparticle film shows a higher reflectance of about 44% at 510 nm, which increases further to about 73% after the annealing treatment. Obviously, applying Ag nanoparticles on the glass surface may have the potential to achieve the low-e effect.

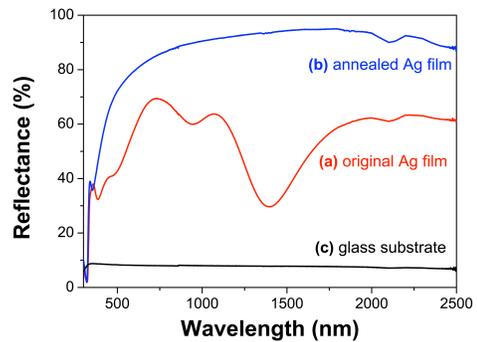


Figure 6: Reflectance of the Ag nanoparticle films before (a) and after (b) the annealing treatment at 200°C. Glass substrate (c) is also measured for comparison.

Figure 7 shows the reflectance spectra of the obtained samples, which are measured in the wavelength region of 2–25 μm in order to calculate the surface emissivity. Interestingly, compared to the plain glass substrate, the original Ag nanoparticle film does not show a significant improvement with respect to the low-e effect [7]. For example, the glass substrate has a total emissivity of about 0.837. After applying the Ag nanoparticles, the obtained sample shows a slightly lower surface emissivity of about 0.793 (Figure 7a). The low-e effect has only been achieved after the annealing treatment (Figure 7b), which results in an emissivity value of about 0.015.

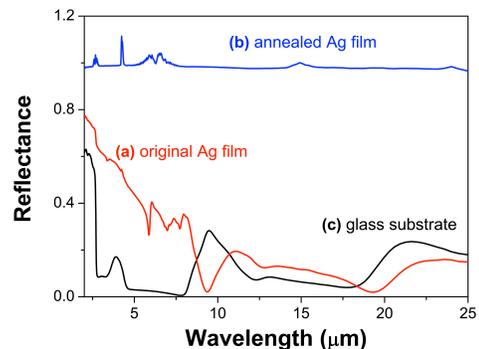


Figure 7: Reflectance of the Ag nanoparticle films before (a) and after (b) the annealing treatment at 200°C. Only the reflectance spectra measured at an angle of 10° are shown. Glass substrate (c) is also measured for comparison.

The low-e effect achieved with the Ag nanoparticle system is interesting and potentially useful. For example, by applying such a coating system,  $U$ -value (heat transfer coefficient) of a single-paned glazing unit can be reduced from 5.75 to 3.18 W/(m<sup>2</sup>K), indicating about 45% reduction on heat loss through a single-glazed window pane. For the most used double-glazed window, a ~ 48% reduction of the heat loss can be reached. Therefore, these low-e coatings can contribute to a large energy saving potential in the building sector [3]. Although the cost issue of Ag nanoparticles may have to be addressed [7], it seems very promising since a highly valuable property can be imparted at relatively low additive ratios and the material cost will decrease as they are produced in larger quantities [13].

Further investigations are still required for improving the Ag nanoparticle films and for a comprehensive understanding on the involved mechanisms. For example, the absence of low-e effect in the original Ag nanoparticle films (Figure 7a) is most likely related to the surface-absorbed PVP molecules, which forms an insulating layer and blocks the electrical conduction between Ag nanoparticles. An effective method for the removal of PVP molecules appears to be required to examine the proposed hypothesis; moreover, the annealing treatment may have certain limitations with respect to soft, organic substrates. In addition, for the practical application as low-e coatings in the building sector, the durability issue of Ag nanoparticle films is important to address [3].

## 4 CONCLUSIONS

Ag nanoparticles with typical diameters of about 50 nm have been synthesized by using a wet chemical method. These prefabricated Ag nanoparticles show a promising potential as low-e coating materials for window glazing applications. The as-prepared Ag nanoparticles can be readily deposited on flat glass through spin coating. A mild heat treatment at 200°C has been used to remove the surface absorbed organic molecules to achieve the low-e effect. A total surface emissivity of about 0.015 has been obtained, compared to about 0.837 for the plain glass substrate. By application of such low-e coatings, the heat loss through a double-glazed window could be reduced by about 48%. Further investigations are still required for an improved understanding on the involved mechanisms.

## ACKNOWLEDGEMENT

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