ARTICLE IN PRESS

Journal of Aerosol Science xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Numerical investigation for the effect of electro-aerodynamic nanoparticle deposition on the performance of a metal grid type transparent electrode

Ali Mohamadi Nasrabadi, Jungho Hwang[*]

School of Mechanical Engineering Yonsei University, Seoul 120-749, South Korea

ARTICLE INFO

Keywords:
Electro-aerodynamic (EAD)
Grid thickness
Particle deposition
Pitch distance
Transparent electrode

ABSTRACT

Electro-aerodynamic particle jet printing is a method to fabricate transparent electrodes, which have been used in applications such as solar cells, display screens, and touchscreen panels. The desired TE sheet resistance and transmittance are realized by trial and error through repeated printing experiments with different parameters such as nozzle size, nozzle-to-substrate distance, airflow rate, electric field strength, and printing time. Because this trial-and-error approach requires a great deal of time, cost, and effort, we present a numerical approach using computational fluid dynamics to simulate nanoparticle deposition using dynamic mesh. The particle trajectories are studied by considering both momentum and electrical forces simultaneously. After validation of numerical deposition height results with experimental data, we investigate the effects of pitch distance and printing time on sheet resistance and transmittance for a given grid line width. Increasing grid thickness with increasing printing time decreases sheet resistance while transmittance remains constant. Our calculation shows that the sheet resistance for pitch distance of 2000 μm decreased by a factor of approximately 62 after 10 min of printing while the transmittance remained constant.

1. Introduction

Using nanoparticles in electric (Kim & Lee, 2010; Lee et al., 2007), optic (Kim et al., 2009; Park, Park, Park, & Hwang, 2015) and also biological devices (Adam et al., 2013; Shafiee et al., 2013) has increased the requirement of high speed as well as high accurate methods for patterning of nanoparticles with high focusing. One of the applications of focusing nanoparticles is the field of transparent electrodes (TE) (Catrysse & Fan, 2010; Park, Jeong, Kim, & Hwang, 2013). Metal grids with periodic lines has been used to develop transparent electrodes (TE) (Qiu et al., 2015; Yang, Lee, Jang, Byun, & Choa, 2016; Hwang, Jeong, Moon, Chun, & Kim, 2011; Jeong, Kim, & Kim, 2014; Park & Hwang, 2014; Lee, Jin, Cho, Kang, & Kim, 2016). Metal-grid electrodes have become very promising in conjunction with printing technology in terms of product cost, because printing technology helps improve the efficiency of material utilization as well as simplify the process steps for the fabrication of metal-grid TEs.

Optical transmittance and electrical sheet resistance are the two most significant parameters of interest for all TEs, but they are also in constant competition. Ideally, a TE has a low sheet resistance at high optical transmittance. Optical transmittance and electrical sheet resistance depend on the grid line width and the grid pitch (spacing between lines). Increasing the grid pitch for a given line width leads to increased transmittance but also increased sheet resistance. However, increasing grid thickness leads to low sheet resistance without decreasing transmittance (Ghosh, Chen, & Pruneri, 2010).

---

[*] Corresponding author.
E-mail address: hwangjh@yonsei.ac.kr (J. Hwang).

https://doi.org/10.1016/j.jaerosci.2017.12.002
Received 24 August 2017; Received in revised form 18 November 2017; Accepted 6 December 2017
0021-8502/

Please cite this article as: Mohamadi Nasrabadi, A., Journal of Aerosol Science (2017), https://doi.org/10.1016/j.jaerosci.2017.12.002

Ghosh et al. (2010) determined the grid thickness by controlling the thickness of the photoresist within a mask. Parallel printing of nanoparticles (NPs) via electrodynamic focusing charged aerosols is another option for increasing grid thickness. Park et al. (2015) proposed using an electro-aerodynamic (EAD) jet to print nanoparticles (NPs) on a pre-patterned metal grid. The pre-patterned silver grid TE was prepared by using an AC-pulsed voltage for electro-hydrodynamic (EHD) jet printing, which enabled well-controlled drop-on-demand printing of Ag NPs on a PET film. In the EAD jet printing method, electrically charged aerosol particles move through the inner cylinder of a coaxial nozzle, where an external electric field is applied. A sheath airflow passes through the outer cylinder of the nozzle to prevent the particles from digressing from the aerosol stream. These charged and sheathed aerosol particles can achieve a high deposition rate even at lower velocities owing to the force of their electrostatic attraction to the substrate (Park et al., 2013). In Park et al. (2015), Ag NPs of 32 nm in diameter were printed on a metal grid for 3 min. The line width and grid pitch were 18 µm and 500 µm, respectively. They found that the grid thickness increased from 360 nm to 587 nm after 3 min, resulting in decreased TE sheet resistance by a factor of approximately 3.78 while transmittance was kept constant at 84%.

If a pitch smaller or larger than 500 µm were used by Park et al. (2015), different TE sheet resistances and transmittances would have been obtained. Similarly, if a printing time longer than 3 min was selected, different TE sheet resistance would be obtained. In EAD jet printing, the desired TE sheet resistance and transmittance are realized by trial and error even for given grid pitch and line width, through repeated printing experiments with different parameters such as nozzle size, nozzle-to-substrate distance, airflow rate, printing time, and electric field intensity. Because this trial-and-error approach requires a great deal of time, cost, and effort, computational fluid dynamics (CFD) can be an effective tool for considering and studying a wide range of these parameters. By using CFD tools in a proper way, it is possible to predict the effect of almost any fluid-involving problems and provide detailed information. In the transport process of charged particles, both aerodynamic and electrical forces play important roles. The motion of the charged particles can be manipulated by the combination of electric and aerodynamic forces, aiming to predict the grid thickness distribution on a grounded substrate to evaluate both sheet resistance and transmittance.

In this study, TE sheet resistance and transmittance of transparent electrodes were calculated for different pitch distances along with different printing times. For each pitch distance, an EAD jet was used to print Ag NPs on pre-patterned Ag grid lines. It was assumed that each pre-patterned Ag-grid line had width of 18 µm and average thickness of 360 nm, which were obtained from experiments by Park et al. (2015). A complete aerosol deposition process was simulated using a commercial CFD code, ANSYS FLUENT v14. The spatial electric field distribution was obtained by solving the Laplace equation. The ANSYS FLUENT original code was extended with several user-defined functions (UDFs) for applying electric force and extracting data to calculate grid thickness variation with printing time.

2. Problem description

The transmittance of a metal (silver in this study) grid is expressed as

$$T_{\mathrm{Ag,grid}} = T_{\mathrm{Bare}} \times (1 - FF) \tag{1}$$

where T_{Bare} is the transmittance of a bare electrode. The filling factor (FF) is defined as

$$FF = \frac{(p \times w) + [(p - w) \times w]}{p^2} \tag{2}$$

where p is the grid pitch, and w is the line width. The sheet resistance is written as (Jang, Kim, & Byun, 2013)

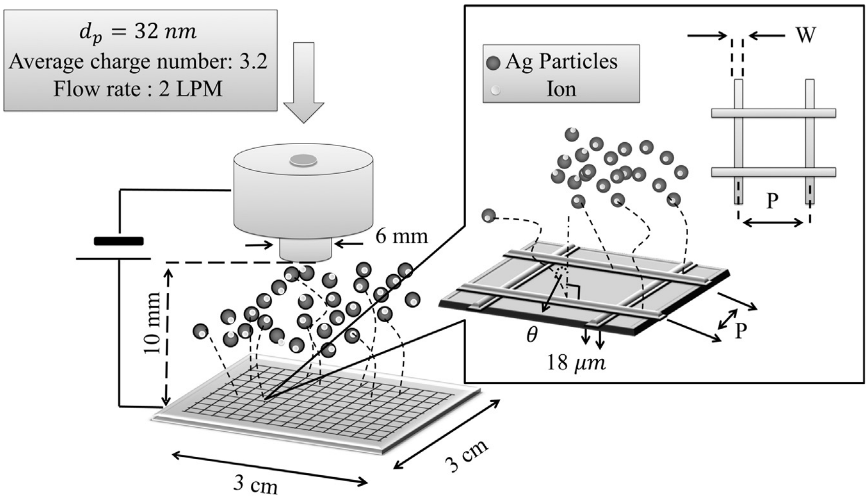

Fig. 1. Schematic of EAD jet printing of Ag nanoparticles on grid-type Ag electrode.