Sensors and Actuators A 222 (2015) 1–7

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Development and performance test of a ZnO nanowire charger for measurements of nano-aerosol particles

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ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
16 November 2014
Accepted 18 November 2014
Available online 26 November 2014

Keywords:
ZnO nanowire
Charger
Corona discharge
Aerosol
Nanoparticle

ABSTRACT

The most efficient and widely used technique for monitoring aerosol particles is essentially an electrical method. For the development of any miniaturized aerosol classifier based on electrical techniques the miniaturized aerosol charger must provide a sufficient and stable charging efficiency. We designed and fabricated a ZnO nanowire charger (4 cm length × 2 cm width × 1 cm height) and then carried out an aerosol particle charging performance test. To test the electrical characteristics of this charger, corona currents were measured according to various applied voltages to determine the maximum stable ion number concentration. The average particle charge and wall loss of the charger were evaluated with monodispersed NaCl aerosol particles with diameters of 15–80 nm. The particle charge and wall loss were also obtained utilizing FLUENT (version 6.3), a commercial computational fluid dynamics (CFD) software, with an external user-defined function (UDF) code, by solving equations for the electric field, flow field, and particle trajectories. The measured data for particle loss and particle charge were in good agreement with the results calculated by FLUENT.

1. Introduction

The potential benefits of nanotechnology for society are well-recognized, but there is also increasing awareness about uncertainties concerning the risk of released nanoparticles (<100 nm) to the environment and human health [1]. In this regard, questions have been posed by stakeholders in the nanotech industry and by several societal organizations, notably workers' unions, and governmental agencies [2]. Of particular importance is the potential health hazard to employees of the nanomaterials industry where products are made containing engineered nanoparticles. Depending on their size and chemical nature, exposure to nanoparticles through inhalation can be hazardous because of their ability to reach and deposit in the deep alveolar region of the lung from which they may subsequently enter the systemic circulation [3,4]. Studies of engineered nanoparticles demonstrated their ability to cross the blood–brain and blood–testis barriers as well as the nuclear membrane within cells, although human health effects remain unknown [1,5–7]. The currently recommended safety policy is precautionary, and aims to minimize exposure in general; it advocates *in situ* control by monitoring workplace pollution level and personal exposure to ultrafine particles [1].

The most efficient and widely used technique for monitoring aerosol particles is essentially an electrical method. One of the most important processes in electrical aerosol measurement is aerosol particle charging. The purpose of the particle charging is to impose a known net charge distribution on the aerosol particles, since particle size distribution is commonly determined through the electrical mobility classification. High charging efficiency of aerosol particles results in high sensitivity of measurement [8,9].

Attempts have also been made to implement aerosol particle charging in the form of a miniaturized aerosol classifier for applications requiring spatially distributed measurement, or monitoring particle exposure at the personal level. To achieve a quantitative particle size distribution, aerosol particles must be electrically charged to a well-defined charge distribution prior to electrical-mobility classification. Thus, a miniaturized aerosol charger providing a sufficient and stable charging efficiency is an essential component in the development of any miniaturized aerosol classifier based on electrical techniques [10,11].

In this study, we designed and fabricated a ZnO nanowire charger for aerosol particle charging. Owing to their unique semiconducting properties, ZnO nanowires have been suggested

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http://dx.doi.org/10.1016/j.sna.2014.11.009
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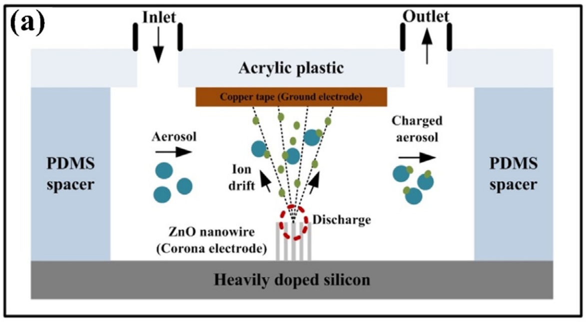
as an effective and reliable electron-emitting source [12]. Chen et al. [13] used ZnO nanowires to generate ions, and indicated that using nanowires to generate ions is more effective than using single or multiple micron-sized rod(s). The ion generating capacity of a nanowire design exceeds that of a normal ion generator and the emitted voltage is much lower [13].

In this study, for the first time (to our knowledge), a ZnO nanowire was applied to a charger for particle charging. The charger was fabricated using a hydrothermal method to achieve growth of the ZnO nanowire. To test the electrical characteristics of our ZnO nanowire charger, corona currents for various applied voltages were measured by an electrometer. Ion concentration was estimated from the current data. Using a condensation particle counter (CPC, model 3022, TSI), we then measured particle losses in the charger by determining the number concentrations of classified NaCl aerosol particles at the exit of the charger, under various experimental conditions. The particle charge and wall loss were also obtained utilizing FLUENT (version 6.3), a commercial computational fluid dynamics (CFD) software, with an external user-defined function (UDF) code, by solving equations for the electric field, flow field, and particle trajectories. The experimental results of the particle charge and particle wall loss were compared with those calculated using FLUENT.

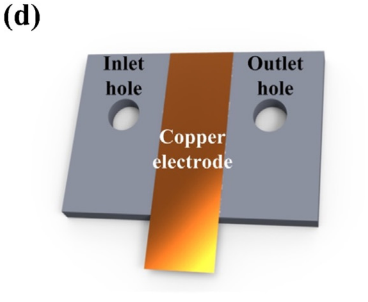
2. Materials and methods

2.1. Fabrication of the charger

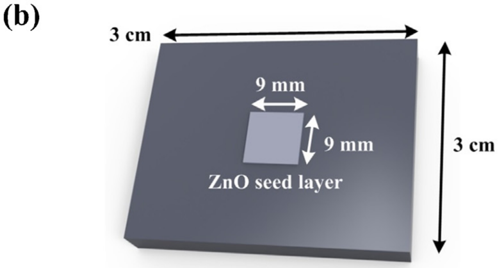
The cross-sectional schematic of the fabricated ZnO nanowire charger is shown in Fig. 1a. If a high positive DC voltage is applied to a discharged nanowire, corona discharge occurs. This discharge results in the production of positive gaseous ions. The particles entrained by carrier air are expected to be positively charged due to the collision of the particles with migrated positive ions. A heavily doped silicon substrate (3 cm × 3 cm) was used for the bottom plate of the ZnO nanowire charger. A 70-nm-thick ZnO seed layer was deposited on the silicon substrate by e-beam evaporation through a shadow mask of 9 mm × 9 mm (Fig. 1b). A 200 × 200 array of circles of 5 μm in diameter was arranged on a deposited area with a center-to-center distance of 10 μm between the neighboring circles. The shadow mask was fabricated on a 20-μm-thick device layer of a silicon-on-insulator (SOI) wafer by lithographically patterning and deep reactive ion etching (DRIE) of silicon. ZnO nanowires were synthesized with a hydrothermal method [14]. The 400 mL of aqueous solution containing 2.96 g of zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$; Sigma–Aldrich) and 1.44 g of hexamethylenetetramine ($(CH_2)_6N_4$, Sigma–Aldrich) was prepared in a quartz beaker. The Si substrate with the ZnO seed layer deposited



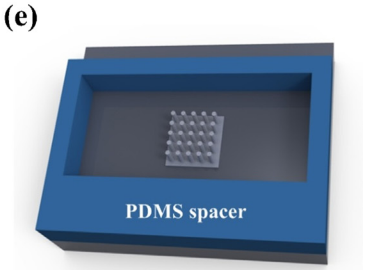
Cross-sectional schematic of fabricated unipolar charger



Top electrode on acrylic plastic

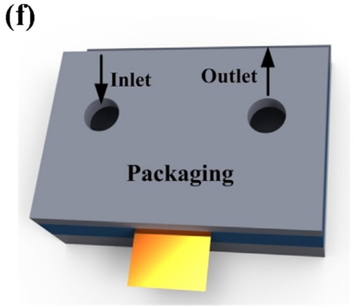


ZnO seed layer deposition through shadow mask



Fluidic channel defined by PDMS spacer

ZnO nanowire synthesis by hydrothermal method



Final packaging

Fig. 1. Cross-sectional schematic of the fabricated ZnO nanowire charger.