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# A hybrid aerodynamic and electrostatic atomization system for enhanced uniformity of thin film

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ABSTRACT

Droplet deposition processes by the mechanisms of either aerodynamics or electrostatic spray have been widely studied in various applications such as aerosol generators, thin film coatings, and nanoparticle formations. Among the current state-of-art methodologies, air spray deposition can produce small-sized droplets without fine control on their sizes and uniformity in deposited thin films. Conventional electrospray depositions, on the other hand, can fabricate thin films with good uniform with a relatively slow deposition speed. In this paper, a hybrid mechanism by means of aerodynamic and electrostatic deposition is investigated and demonstrated to allow high throughput and improved uniformity for thin film depositions. It utilizes both the electrostatic force and aerodynamic force to atomize the liquid and control the droplet spraying process with good stability/repeatability. A uniform thin $TiO_2$ film has been deposited as the demonstration example using this method. The velocities and trajectories of droplets during the deposition process have been characterized under different experimental parameters by using the technique of particle image velocimetry (PIV). This hybrid thin film fabrication method could be applicable in several industrial processes for better uniformity in making transparent electrodes, solar cells, displays, and automobiles.



## 1. Introduction

Over the past decades, a large variety of thin-film deposition methods have been developed for industrial and analytical applications [1–4]. The most common method is based on the physical vapor deposition (PVD), such as sputtering [5] and electron beam evaporation [6] to control the film thickness and roughness under vacuum condition. On the other hand, several solution based deposition methods have been introduced for low cost and large area manufacturing under atmospheric pressure and at room temperature [7–9]. For example, spraying can easily deposit functional materials as droplets by means of single or two-fluid atomization [10], electrospray [11], ultrasonic-spray [12], and pressure-swirl methodologies [13]. The two-fluid atomization spray utilizes a high pressure to break liquid into droplets due to the shear force on the liquid surface [14]. However, this method results in high material loss and low uniformity of thin film due to the drift of droplets under the very complex vortex flows [15,16]. The electrospray method has been introduced for thin film deposition to improve the issues by using the strong electrostatic force to produce ultra-fine droplets [17,18]. Specifically, the meniscus driven outside the nozzle under a strong electrical field is changed to a cone shape (Taylor Cone) and the liquid ligaments can be ejected continuously as fine droplets due to the Rayleigh limit [19]. This method can deposit the uniform thin film with a superior surface roughness. However, the electrospray method has limitation of liquid flow-rate because it is difficult to optimize the stabilities of the process due to the very complex process parameters, including the liquid flow-rate, nozzle geometry, electric field strength, and liquid properties [20]. Various hybrid electrostatic spray methods have been attempted to be applied in the mass production. An air-

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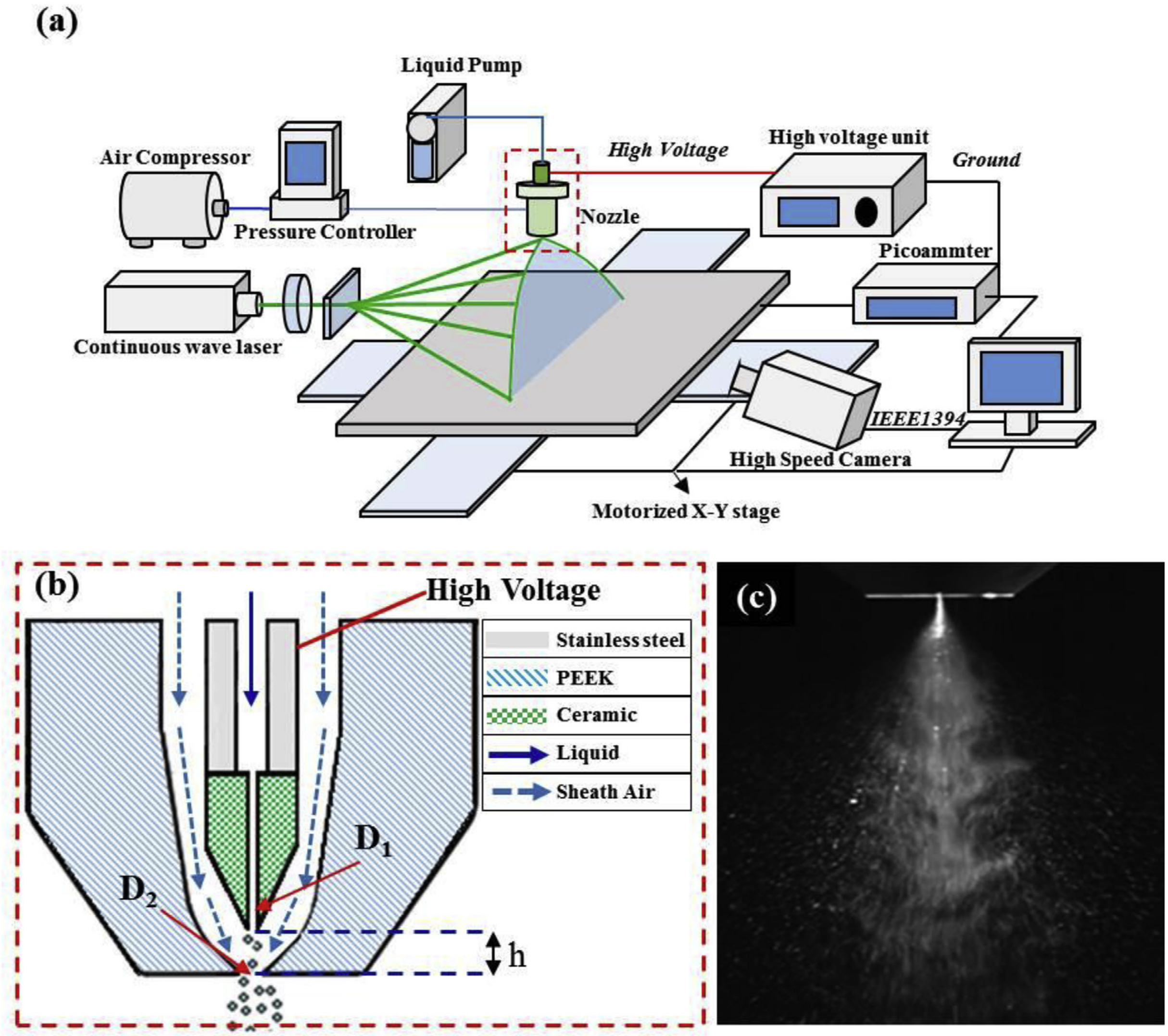


Fig. 1. (a) Experimental setup for the hybrid aerodynamics and electrospray deposition system using liquid solutions with or without nanoparticles. (b) The close-up view showing the nozzle design with an inner electrospray nozzle and an outer air nozzle. (c) A photograph taken by a high-speed camera during the deposition process.

**Table 1**
Specific dimension of Nozzle.

| Nozzle | Outer Diameter (μm) | Inner Diameter (μm) | Material | Gap between Liquid and Gas Nozzle (μm) |
|---|---|---|---|---|
| Liquid Shaft | 3000 | 1000 | Stainless steel | 1000 |
| Liquid Nozzle | 200 | 150 | Ceramic | |
| Gas Nozzle | 20000 | 1000 | Polyether ether keton (PEEK) | |

assisted electrostatic spray method have been developed for industry applications. The air-assisted spraying method with the external electrostatic charging capability can easily control the droplet size and spray velocity and be applied in industrial applications with high liquid flow-rate [21,22]. These studies provided evidence that the uniformity and roughness of thin film could be controlled by hybrid air-assisted electrostatic spray.

Herein, we investigate the thin film deposition with air-assisted electrostatic atomization by applying electric field and air pressure around the liquid nozzle. In order to deposit the uniform thin film, the spraying characteristic including velocity, trajectory, size and current of the electrostatically charged droplets during the spraying process have been analyzed. $TiO_2$ nanoparticles in solvent were deposited to evaluate the morphology by field emission scanning electron microscopy (FE-SEM) (JEOL, JSM-7600F). The $TiO_2$ thin films were fabricated with various spraying conditions and their surface topology was investigated by atomic force microscopy

**Table 2**
Spraying conditions.

| Liquid | Ethanol | | | Water | | |
|---|---|---|---|---|---|---|
| H.V (kV) | 0–20 | | | | | |
| Working Distance (cm) | 10 | | | | | |
| Liquid flow-rate (ml/min) | 3 | | | | | |
| Gas flow-rate (l/min) | 3.1 | 4.4 | 5.1 | 3.1 | 4.4 | 5.1 |
| ALR | 1.6 | 2.3 | 2.6 | 1.3 | 1.7 | 2 |