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Review

Excitation by acoustic vibration as an effective tool for improving the characteristics of the solution-processed coatings and thin films

Morteza Eslamian*

University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai, 200240, China
State Key Laboratory for Composite Materials, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

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ABSTRACT

Solution-processed thin films and coatings have received tremendous attention in recent years, as a substitute for vapor-phase grown films, to develop low-cost devices, such as thin film solar cells, displays, sensors, etc. The challenge, however, is to overcome the lack of adequate controllability and reproducibility of solution-processed thin films which inherently contain excessive pinholes and other defects, particularly when processed at low temperatures. In this review, it is substantiated that imposed sound and ultrasound vibrations could result in significant improvements in the nanostructure, uniformity, and functionality of the resulting thin solid films. Using a wealth of information in the fluid dynamics literature, it is demonstrated that the acoustic excitation results in creation of fluid flow, such as streaming, microstreaming, and surface waves, as well as enhanced heat transfer, causing improvement in the quality and characteristics of the thin films prepared by vibration-assisted techniques, even though the vibration tends to destabilize the liquid films. In addition, the pertinent works that have exploited this effect to prepare high performance materials are critically reviewed and the results are discussed and interpreted in the framework of fluid dynamics. A brief review on the effect of imposing other external fields including electric and magnetic fields on the fabrication process and characteristics of the thin films is also provided.

1. Introduction

Thin solid films and some emerging devices incorporating thin solid films, such as thin film transistors and displays, solar cells, organic light emitting diodes (OLED), thermoelectric devices, sensors and actuators, are currently at the forefront of research and development in various areas of nanotechnology and renewable energy [1]. A thin solid film may be processed and deposited from the vapor phase, using physical or chemical vapor deposition or from liquid solutions or colloidal mixtures also in a physical or chemical route, using casting and printing methods [2], such as drop casting, spin coating, blade coating, gravure, slot-die coating, screen-printing, inkjet printing and spray coating, as shown in Fig. 1 [3]. The solution-processed methods are cheaper in terms of capital, energy, and operating costs, and therefore are desirable, but generally suffer from the lack of controllability and reproducibility of the resulting products, which may also contain manufacturing defects in micro- and nano- scales. Addressing and resolving the aforementioned setbacks is a prerequisite for the fabrication of high performance solution-processed thin film devices in a high volume and industrial scale.

From a fluid mechanics point of view, the solution-processed casting and printing methods may be categorized as either those based on immediate formation of a thin liquid film or those based on the formation of many impinged droplets on the substrate. To elaborate, in methods such as spin coating, slot-die coating, and blade coating, a thin liquid film of the solution forms directly, whereas in spray coating and inkjet printing, the impinged droplets may form a continuous liquid film before drying or may dry individually to yield a thin solid film comprised of dried liquid islands that usually overlap with one another. The latter scenario (overlapped dried islands) is hard to control; thus, for obtaining a high quality and uniform thin solid film or coating, particularly an ultrathin film, it is desirable to have a continuous liquid film formed first, followed by a drying stage to yield a defect-free and smooth thin solid film or coating [4].

Most applications, particularly emerging molecular semiconductor thin film devices, require fabricating defect-free, homogenous, and uniform thin solid films for satisfactory performance of the ensuing devices. For this reason, the thin solid films made using well-controlled vapor and vacuum-based methods are currently more desirable than the solution-processed methods, as far as the device performance is

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* Corresponding author at: State Key Laboratory for Composite Materials, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China.
E-mail addresses: Morteza.Eslamian@sjtu.edu.cn, Morteza.Eslamian@gmail.com.

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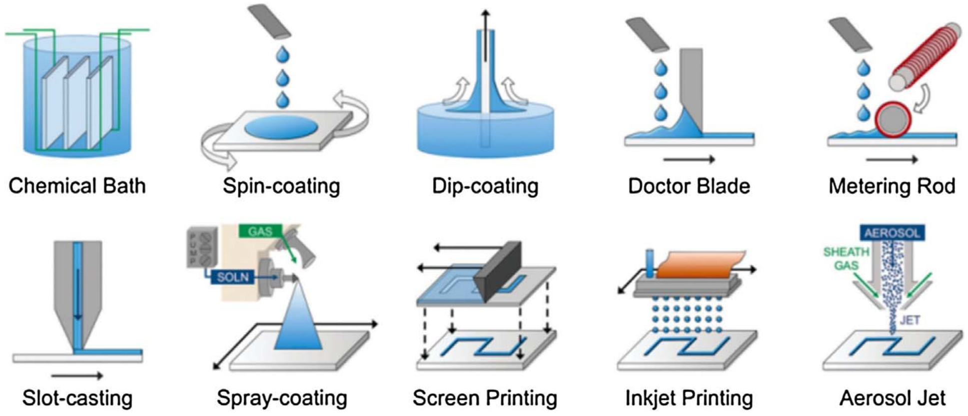

Fig. 1. Some frequently used coating and printing methods in the lab or industry scale. The figure is reproduced from Ref. [3] with permission from the Royal Society of Chemistry.

concerned. The downside, however, is the high cost of the vapor phase methods which limits their applications. To alleviate difficulties associated with solution-processed methods, i.e., to eliminate pinholes, restore crystallinity, suppress surface dewetting, and to improve the film nanostructure, various in-situ or post treatment methods are currently employed, most of which are centered about chemical and thermal treatments, as well as interface engineering. Such methods are quite effective, but usually energy intensive, tedious, may need high process temperatures (not compatible with flexible substrates and organic materials), or are environmentally disfavored. This paper focuses on a less-studied but effective thin film and coating treatment method, i.e., treatment using external acoustic excitation of the substrate and the film during or after deposition, while the film has not dried or formed yet. This method usually excites the film by one or a combination of the following mechanisms, including but not limited to imparting energy to the film, exerting forces on the bulk or some components of the solution, creating microstreaming mixing motion in the film and generating surface waves.

While this work focuses on thin films, it is noted that excitation by acoustic vibrations is common to bulk liquid solutions, as well. For instance, ultrasound has conventional and proven industrial applications for cleaning purposes, nondestructive testing, imaging or sonography, and sonochemistry. Acoustic waves may be generated by various vibration sources, such as loudspeakers and piezoelectric transducers. The acoustic waves propagate in the surrounding medium via various configurations, as depicted in Fig. 2. In some cases such as sonochemistry for materials synthesis (Fig. 2a), an ultrasonic probe is immersed into a liquid solution container, in which case the ultrasonic waves propagate in the liquid, where the wave intensity decreases with the distance from the probe. In some other cases, the acoustic source may be outside of the liquid, in which case the waves will be transferred to the liquid via another medium, such as air (Fig. 2b). In the particular case of thin liquids films, the liquid film may be excited by a piezoelectric ceramic that vibrates the substrate from below (Fig. 2c), or surface acoustic waves (SAW) may be generated on a piezoelectric substrate using interdigitated transducers (IDT). The SAWs then propagate parallel to the surface and may interfere with droplets or thin liquid films (Fig. 2d).

Following the foregoing discussion on the importance of obtaining defect-free solution-processed thin films using low-cost mechanical methods rather than expensive chemical and thermal treatments, this paper focuses on the feasibility of using sound and ultrasound vibrations for treatment of thin films and coatings. The rest of this paper is organized as follows. In Section 2, fundamentals of vibration and propagation of acoustic waves in liquids is considered. Section 3 is devoted to fundamentals of hydrodynamics and evaporation of thin liquid films excited by acoustic vibration under various configurations, such as excitation by SAWs and substrate vibration imposed on the substrate from below. Section 4 reviews the literature on the applications of acoustic waves for the synthesis of powders and thin films. While not the main focus of this work, to gain more insight, in Section 5, a mini review on the works that have used electric and magnetic fields for the treatment of thin films is provided. The paper ends with concluding remarks and research directions in Section 6. This paper is

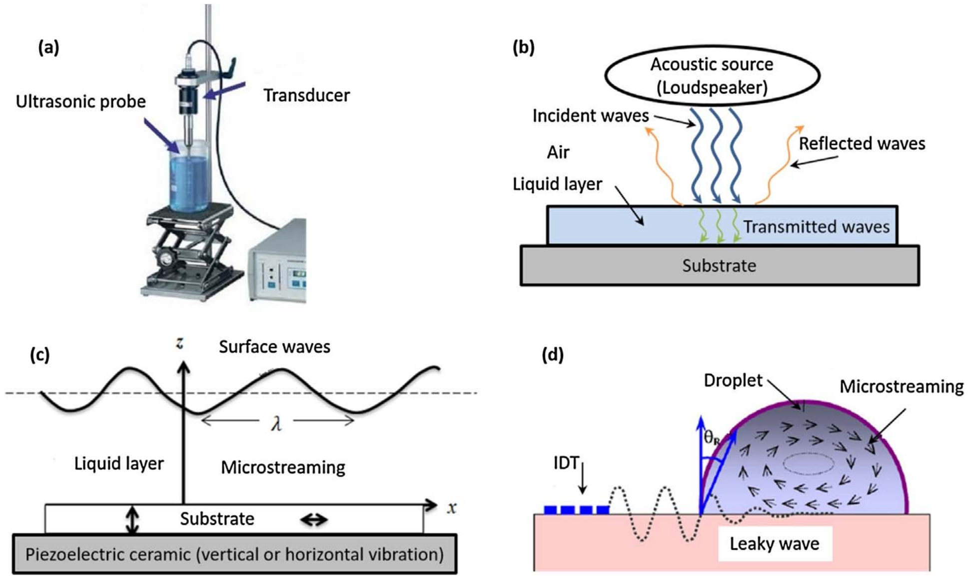

Fig. 2. Various configurations for the generation and propagation of acoustic waves in liquids. (a) Sonochemistry for materials synthesis; (b) acoustic wave generation in air and its propagation in air and liquid; (c) liquid film on a substrate excited by vibrations from beneath; (d) surface acoustic wave (SAW) generated by an interdigitated transducer (IDT) on a piezoelectric ceramic and its interaction with a droplet.