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"Atomic Layer Deposition in Energy Conversion Applications"

Edited by Professor Julien Bachmann (Friedrich-Alexander University of Erlangen-Nürnberg, Erlangen, Germany), Wiley-VCH Verlag GmbH & Co KGaA, Weinheim, Germany, 2017, 312 pages, ISBN: 978-3-527-33912-9, US$190.00, £110.00

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Introduction

"Atomic Layer Deposition in Energy Conversion Applications" is a series of reviews presented as nine chapters that focus on the applications of atomic layer deposition (ALD) for photovoltaics, electrochemical energy storage and photo- and electrochemical devices. These have been edited by Julien Bachmann whose research is based on the fabrication of nanostructured materials and interfaces to study the key mechanisms within energy conversion systems. Developed in the 1970s, ALD is a deposition technique whereby thin-film growth is achieved by alternating the exposure of a substrate surface to pulses of chemical precursors, resulting in the sequential deposition of sub(monolayers). The process has potential application in fields ranging from catalysis to batteries and fuel cells.

The book is organised into five main sections. Part I introduces the concept of ALD and the growth characteristics and conformality of ALD processes. Part II, which comprises three chapters, explores the use of ALD for the preparation of functional layers in commercial solar cells. Part III consists of three chapters where the recent advances in thin-films fabricated by ALD for fuel cells, water-splitting electrocatalysts and lithium-ion batteries are reviewed. The final section is presented in two chapters where an overview of ALD for photoelectrochemical and thermoelectric energy conversion is provided.

Principles of Atomic Layer Deposition

Chapter 1, presented by J. Dendooven and C. Detavernier (Ghent University, Belgium), provides an overview to ALD including the basic principles of the deposition process and the *in situ* characterisation techniques frequently used in ALD research. This chapter will be of particular interest to general readers.

The first section of Chapter 1 describes several advantages that the ALD technique offers over more common deposition methods (for example, chemical vapour deposition (CVD) and physical vapour deposition (PVD)) that are the result of the unique self-saturating nature of the process. Of these are the control of layer thickness at the Ångström level and the ability to deposit conformal coatings onto high aspect ratio (AR) structures with holes, trenches and pores. The essential characteristics of layer-by-layer growth in the ALD process are highlighted as growth per cycle (GPC), saturation, temperature window and linearity, where under ideal conditions ALD is characterised by a linear increase in the amount of deposited material as a function of the number of pump cycles.

In the following section of Chapter 1, the authors discuss the range of *in situ* characterisation techniques that are used to study the growing film during ALD. The most common of these is the quartz crystal microbalance (QCM) which monitors the mass of deposition by measuring a shift in the resonant frequency of an oscillating piezoelectric crystal. Other methods include quadrupole mass spectroscopy (QMS), spectroscopic ellipsometry (SE), optical emission spectroscopy (OES), as well as a variety of X-ray based synchrotron techniques.

The final section of Chapter 1 reviews the conformality of the ALD process. The deposition of ultrathin coatings on the interior of nano-sized pores is explored using both meso- and microporous thin films, where the growth is monitored by the *in situ* techniques described earlier in the chapter.

Applications in Photovoltaics

Part II comprises three chapters where the opportunities for ALD in silicon heterojunction (SHJ) solar cells are explored.

In Chapter 2, B. Macco *et al.* (Eindhoven University of Technology, The Netherlands) investigates the role of ALD Al_2O_3 passivation layers in *p*-type doped SHJ cells. Al_2O_3 nanolayers prepared by ALD have been shown to account for ~1% absolute increase in the conversion efficiency of commercial solar cells. This has been attributed to both the excellent chemical and field-effect passivation offered by the material. However, as the interface properties are strongly dependent on the thickness and processing conditions of the film, there is a balance between achieving complete surface coverage to prevent rapid deterioration and maximising light transmittance through the cell. The optimal thickness of the layer is determined to be >5 nm for plasma ALD and >10 nm for thermal ALD.

Chapter 2 also reviews the preparation of transparent conductive oxides (TCO) by ALD with examples of In_2O_3 and ZnO for the front side and rear side of a SHJ cell, respectively. The physics and requirements of TCOs for SHJ cells are discussed and the advantages of ALD TCOs in high volume manufacturing (HVM) are highlighted. In the later part of the chapter, novel passivating tunnelling contacts and carrier-selective materials based on metal oxides such as MoO_x, WO_x, NiO_x and TiO_x are reviewed.

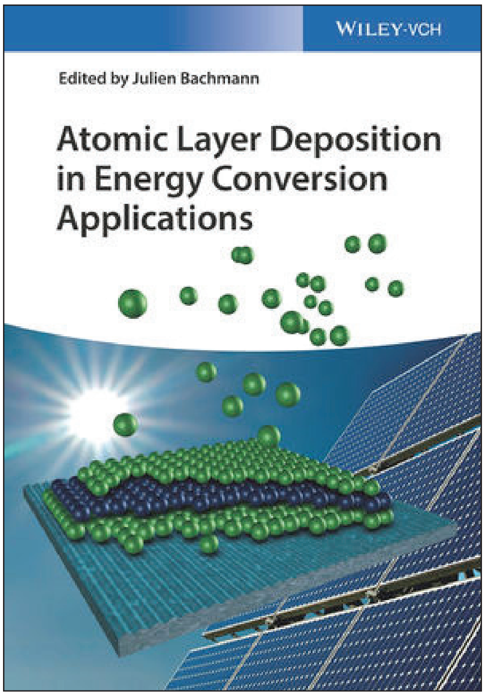
The author concludes that the precise control of film growth and film composition offered by ALD render it a very promising deposition method of functional layers for a variety of materials in HVM. The success of the ALD Al_2O_3 passivating layer over the last few years has resulted in the development of high-throughput reactors which are capable of meeting industrial demands. In addition, other materials prepared by ALD for the passivation of Si have been explored including HfO_2, SiO_2 and Ga_2O_3.

Chapter 3 focuses on the use of ALD for light absorption. In this chapter, A. Martinson (Argonne National Laboratory, USA) discusses each of the key sources of major solar light absorption deficiencies: reflectivity, indirect semiconductor band gaps and transmission of photons with energy less than that of the band gap. The author follows by describing the unique characteristics that make ALD favourable for the preparation of solar absorbing materials. Of these is the ability of ALD to orthogonalise light harvesting and charge extraction. The conformal coating ability of ALD means that ultrathin films can be arranged in high density parallel to the direction of illumination. This unusual configuration allows for greater light absorption from ever-thinner absorber films. In the later part of the chapter Martinson reviews a variety of absorbing metal oxides and metal chalcogenides that can be grown by ALD, ranging from $CuInS_2$ to Bi_2S_3. This chapter is particularly useful to both the general reader and those beginning research in the field as it provides a general overview of the light absorbing process in photovoltaic devices in addition to recent advances in ALD solar absorbers.

In the final chapter of Part II, Guerra-Nuñez *et al.* (EMPA, Swiss Federal Laboratories for Materials Science and Technology, Switzerland; ETH Zürich, Nanoscience for Energy Technology and Sustainability, Switzerland) present the most relevant research on ultrathin films of metal oxides deposited onto nanostructured surfaces by ALD. These films are designed to engineer the interfaces within photovoltaic devices such as dye-sensitised solar cells (DSSC), quantum-dot-sensitised solar cells (QDSSC), colloidal quantum-dot solar cells (CQDSC), organic solar cells, perovskite solar cells and photoelectrochemical cells for water splitting, with the purpose of minimising recombination losses. The review mostly focuses on the application of ALD in DSSCs, investigating the use of both TiO_2 as a compact layer at the TCO/metal oxide interface and Al_2O_3 as a blocking layer at the metal oxide/absorber interface. It is concluded a 5–10 nm thick amorphous TiO_2 film that is both uniform and pinhole-free is the optimal configuration to block the back transfer of electrons to the hole-transport material (HTM). Increasing the thickness and crystallinity of the TiO_2 film reduces the light transmittance and efficiency of blocking properties due to the presence of grain boundaries, and thus reduces the power conversion efficiency (PCE). In the later parts of the chapter, examples where ALD has been used to deposit blocking films directly onto nanotubes/nanowires in DSSCs and in water-splitting devices are briefly discussed.

Conclusions

The book is intended to provide an overview of the opportunities offered by ALD in the energy conversion field and the requirements for it to become a promising candidate in high volume manufacturing. It should therefore be of interest to general researchers within the semiconducting industry as well as ALD specialists.



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The Reviewer

Sabrina Elix joined Johnson Matthey in 2017. She is currently a Process Development Chemist at Johnson Matthey, Royston, UK. Her work focuses on the scale-up and process optimisation of new catalyst products for the company's worldwide manufacturing facilities.

