Recommended ALD reviews: evolving file

File created 12.10.2019 by Riikka Puurunen. Updates by the creator on the basis of recommendations received.

Introduction

Getting to know a new scientific field often starts by reading review articles. To help newcomers get acquainted with the field of atomic layer deposition (ALD), **this file will contain reading recommendations for review articles on ALD. Public non-anonymous reading recommendation(s) will be accompanied with each review.** In addition to this short list of recommended ALD reviews, a more complete list of reviews on ALD at this link; as of October 30, 2019, that list contains over 200 entries.

Anyone familiar with ALD, is welcome to provide recommendations. Please recommend only articles, which you (or someone too close to you) have not co-authored yourself. Suitable number of recommendations by one person is probably somewhere between one and ten. Please write your recommendation in a polite language and provide your title and affiliation along with the recommendation. Anonymous or offensive recommendations will not be included. Similarly as “comments” in the ALD-history-evolving-file of the Virtual Project on the History of ALD (VPHA), recommendations are to be collected as bullet points under each article, in the order in which they first appeared (new bullets added at the end). Reviews are to be ordered by year, newest first.

All recommendations to be made here shall be provided with the © Authors licence (all rights reserved). Thus, the recommendations may not be copied to other documents without explicit permission by the respective author. Planned later use by the creator of this document includes e.g. open learning materials at Aalto University, to appear later at openlearning.aalto.fi. Those open learning materials are planned to be published with a Creative Commons Byline licence

CC BY 4.0; permission to re-use the recommendations will be separately requested from the authors. Publication of the openlearning.aalto.fi site planned expected for November 29, 2019, along with the event “November Networking - ALD at Aalto University”, https://blogs.aalto.fi/catprofopen/ald-networking-nov-2019.

Riikka Puurunen, Espoo, October 30, 2019
*Closeness note updated by Riikka Puurunen, Espoo, March 29, 2024

Formatting example

Authors,
title,
Journal name in full, volume (year) page-page or article number (pages);
DOI link: Altmetric-link<can be looked up later>

- *“<personal reading recommendation; why this article?>”* Firstname Lastname, title, affiliation

ALD review reading recommendations

Full list of reviews (>200 entries):
https://docs.google.com/spreadsheets/d/1RwwaxQHSGpr3ClquwincqBif1VgVdY9xLdXySJ1maVI/edit?usp=sharing

(Organized newest first)
(Very initial and incomplete list as of 22.1.2020 - note made by Riikka Puurunen)

Recommended reviews published in years 2020 on

M. Weber, N. Boysen, O. Graniel, A. Sekkat, C. Dussarrat, P. Wiff, A. Devi, D. Muñoz-Rojas,
Assessing the Environmental Impact of Atomic Layer Deposition (ALD) Processes and Pathways to Lower It,
ACS Materials Au 3 (2023) 274–298.
https://doi.org/10.1021/acsmaterialsau.3c00002

- *“This perspective first reviews the work done to assess the environmental impact of ALD processes, then interprets how the principles of Green Chemistry relate to ALD, and finally discusses possibilities how to reduce the environmental impact e.g. via optimization. I learnt a lot while reading this paper, for example that some life cycle analysis has already been made for ALD processes (but not much!), not surprisingly mostly for the well-known trimethylaluminium–water process to make aluminium oxide, which has become a “model process of ALD” in some ways. The paper is fluent and a pleasure to read. Clearly, specialists representing different branches of ALD*

(development of metalorganic chemicals, process and reactor development) are on board in the author list, as the views presented cover the field more broadly than a single person's (or research group's) field of expertise would be." Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation written March 29, 2024)

H. H. Sønsteby, A. Yanguas-Gil, J. W. Elam,
Consistency and reproducibility in atomic layer deposition,
Journal of Vacuum Science & Technology A 38 (2020) art. 020804 (17 p).
https://doi.org/10.1116/1.5140603; https://aip.altmetric.com/details/75131095

- *"This article discusses the fundamentals and common misconceptions in ALD (e.g.: When is a process ALD, when not? What is an ALD window?) in order to be able to understand the sources of inconsistency and irreproducibility in experimental results. Examples of processes are given where variation in the growth per cycle (GPC) is reported that is far higher than can be explained by the variation in parameters of tool and measurement set-ups. Separate sections are dedicated to inconsistencies related to precursors (i.e., reactants), substrates and ALD tools. Simulations are included to highlight the effects that can be caused e.g. continuous growth because of upstream leaks, and how the impact depends on the reactivity in the process (reactivity described by a sticking coefficient in irreversible Langmuir adsorption). The article has been written especially for newcomers in the field; I would propose it as a reading recommendation to all, as the critical discussion is a step forward for the field of ALD." Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation written February 23, 2020)*

N. E. Richey, C. de Paula, S. F. Bent,
Understanding chemical and physical mechanisms in atomic layer deposition,
Journal of Chemical Physics 152 (2020) art. 040902 (17 p.).
https://doi.org/10.1063/1.5133390; https://aip.altmetric.com/details/74363899

- *"A thorough discussion of the chemical mechanisms that underpin atomic layer deposition, with particular focus on precursor adsorption, film nucleation, surface diffusion, and film growth. It connects work done using a variety of techniques to alter film nucleation and growth--such as beam patterning, surface treatments, nucleation layers, and inhibitors--using the chemical principles that underlie them. Discussion of fundamental models for saturation, nucleation, and diffusion prove particularly useful in explaining and understanding the behaviors occurring in the first stages of ALD that are often glossed over. The perspectives are especially applicable to metal ALD and area-selective ALD studies."* Joel Schneider, MS, Stanford University, Stanford, California, USA

Recommended reviews published in years 2010 to 2019

A. J. Mackus, J. R. Schneider, C. McIsaac, J. G. Baker, S. F. Bent,
Synthesis of Doped, Ternary, and Quaternary Materials by Atomic Layer Deposition: A Review,
Chemistry of Materials 31 (2018) 1142-1183.
https://doi.org/10.1021/acs.chemmater.8b02878; https://acs.altmetric.com/details/52536237

- *"An in-depth review on ALD of multi-component materials. The work provides detailed discussion on different approaches and factors for the deposition of multi-component materials, including choice of precursor, process conditions, phase considerations and more. This review contains a comprehensive summary of all multicomponent materials deposited by ALD, which extends the original work by Puurunen (https://doi.org/10.1063/1.1940727). In addition to reviewing the literature, this paper discusses fundamentals such as nucleation effects, diffusion, persisting surface species and intermixing. Overall, this is a must-read for anyone interested in multicomponent ALD." Camila de Paula, MS, Stanford University, Stanford, California, USA*

A. A. Malygin, A. A. Malkov, E. A. Sosnov,
Structural-dimensional effects and their application in the "core-nanoshell" systems synthesized by the molecular layering,
Russian Chemical Bulletin 66 (2017) 1939-1962.
https://doi.org/10.1007/s11172-017-1971-9; https://springeropen.altmetric.com/details/49680872

- *"A short theoretical introduction into ALD and a number of examples of its practical applications, emanating mainly from the molecular layering (Soviet-Russian) branch. The review features single-cycle depositions, thicker shielding layers, multicomponent functional coatings and applications based on substrate-film interactions."* Ivan Bodalyov, PhD, Saint-Petersburg State Institute of Technology, St Petersburg, Russia

H. Van Bui, F. Grillo, J. R. van Ommen,
Atomic and Molecular Layer Deposition: Off the Beaten Track,
Chemical Communications 53 (2017) 45-71.
http://doi.org/10.1039/C6CC05568K; https://rsc.altmetric.com/details/12677822

- *"An up to date review on ALD and MLD that is extremely comprehensive and goes beyond the usual applications in semiconductors, dealing with surface chemistries, process conditions, and reactor types. This should be required reading, along with the*

other reviews referenced, for all starting out in thin film processing." Michael Nolan, PhD, Tyndall National Institute, UCC, Cork, Ireland

S. D. Elliott, G. Dey, Y. Maimaiti, H. Ablat, E. A. Filatova, G. N. Fomengia,
Modeling mechanism and growth reactions for new nanofabrication processes by atomic layer deposition,
Advanced Materials 28 (2016) 5367-5380.
https://doi.org/10.1002/adma.201504043: https://wiley.altmetric.com/details/4913229
[This article is labelled as a "Progress report"]

- *"First principles modelling of atomic layer deposition using density functional theory (DFT) has been a vital aspect of the development of DFT. This major review reviews not only the important work of Simon's group in modelling of ALD processes for a range of materials, but also the field in general. For anyone starting in ALD who wants to know more about DFT modelling in this area, this review is required reading."* Michael Nolan, PhD, Tyndall National Institute, UCC, Cork, Ireland
- *"In many areas of chemistry and chemical engineering, there is great power in combining theoretical modeling and experimental processes. Experiments are useful in validating modeling methods, and theoretical work can provide useful insight into effective experimental design. This work is a critical part of illustrating this in the field of ALD. Modeling can be extremely useful in ALD, and this review summarizes work on a wide variety of materials ranging from oxides to mixed materials to metals, organics, and silicon compounds. The manuscript also describes a number of the major current challenges in developing modeling approaches for ALD. A very interesting read that describes how useful DFT can be when applied to ALD systems."* Joel Schneider, MS, Stanford University, Stanford, CA, USA

T. Bloberg,
(Invited) Unit Steps of an ALD Half-Cycle,
ECS Transactions 58 (10) (2013) 3.
http://doi.org/10.1149/05810.0003ecst
(Copyright info?)

- *"This invited contribution offers a unique chemical engineering perspective to an ALD (half-)cycle, from reactant delivery to considering the square wave partial pressure pulse (idealized, never in reality followed) and the purge. Experience speaks here; the paper has been written by an industry professional. I especially appreciate the practical engineering mindset to see the big picture by using order-or-magnitude estimations for unknowns, including the notion that growth per cycle in ALD usually corresponds to less than five metal atoms adsorbed per square nanometre." Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation written March 29, 2024)*

T. Hatanpää, M. Ritala, M. Leskelä,
Precursors as enablers of ALD technology: Contributions from University of Helsinki,
Coordination Chemistry Reviews,
257 (2013) 3297–3322.
https://doi.org/10.1016/j.ccr.2013.07.002; <no Altmetric info as of 15.1.2020>

- *"Invited review on ALD metal reactant (here: "precursor") development made at the University of Helsinki, Finland. The authors are world-leading experts on the topic and have decades of experience. Contains overview of ligand types used, and then describes in separate sections metal reactant development for alkaline earth metals, Group 4 metals (Ti, Zr, Hf), Group 15 & 16 elements, and Pt group metals. Cites 262 references, mostly scientific articles from own group (this limitation of scope is clear from the title and introduction). A pleasure to read and a definite recommendation to newbies and more seasoned scientists interested in details of and trends in ALD chemistries and how metal reactant development is made. (Introduction to the thematic journal issue in which this review was published: https://doi.org/10.1016/j.ccr.2013.08.006)"* Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation dated January 15, 2020)

G. N. Parsons, J. W. Elam, S. M. George, S. Haukka, H. Jeon, W. M. M. Kessels, M. Leskelä, P. Poodt, M. Ritala, S. M. Rossnagel,
History of atomic layer deposition and its relationship with the American Vacuum Society,
Journal of Vacuum Science & Technology A 31 (2013) 050818.
http://doi.org/10.1116/1.4816548; https://aip.altmetric.com/details/4118299
(Correction) **Erratum: "History of atomic layer deposition and its relationship with the American Vacuum Society" [J. Vac. Sci. Technol. A 31, 050818 (2013)]**
Journal of Vacuum Science & Technology A 38, 037001 (2020);
https://doi.org/10.1116/6.0000143

- *"I think this is a good first general read to understand what is ALD and the possibilities that it brings. Moreover, ALD had different names during his history and in early publication, this paper makes most of the clarification needed. It's the first paper I usually send it to new students in our group."* Emanuele Sortino, MSc, CU Boulder, Colorado, USA
- *Analysis of "Erratum: "History of atomic layer deposition and its relationship with the American Vacuum Society" [J. Vac. Sci. Technol. A 31, 050818 (2013)]", dated 9.6.2020, by Riikka Puurunen: http://aldhistory.blogspot.com/2020/06/analysis-of-erratum-jvsta-history-of-ALD-and-relationship-AVS.html*

S. D. Elliott,
Atomic Scale Simulation of ALD Chemistry,

Semiconductor Science and Technology 27 (2012) 074008.
http://dx.doi.org/10.1088/0268-1242/27/7/074008; https://iop.altmetric.com/details/3024137

- *"This is a nice review of some early work in first principles DFT modelling of atomic layer deposition processes up to 2012. Gives a readable and clear overview of the role of modelling in ALD processing".* Michael Nolan, PhD, Tyndall National Institute, UCC, Cork, Ireland

S. M. George,
Atomic Layer Deposition: An Overview,
Chemical Reviews 110 (2010) 111-131.
https://doi.org/10.1021/cr900056b; https://acs.altmetric.com/details/3348730

- *"This world's most cited ALD review, based on a one-day course on ALD by Prof. George for AVS, self-evidently belongs in the list of recommended reviews for newcomers. The review discusses, mainly on the basis of own data, the trimethylaluminium (TMA) water ALD process to grow aluminium oxide as a model system of ALD (Section 2), and contrasts other, non-ideal processes with this "ideal" model system (Section 13.1). The review overviews many types of ALD process and reactor concepts, such as thermal and plasma ALD, various metal ALD chemistries, low-temperature ALD, ALD on particles, polymer MLD, and area-selective ALD. (The review does not discuss the two independent discoveries of ALD.) Interestingly from my personal viewpoint, the review uses several terms, "growth rate", "growth per cycle" and "growth rate per cycle" interchangeably to describe the characteristic quantity obtained in an ALD cycle. Overall, this is a clearly written and pleasant-to-read review by a leading scientist in the field, which I warmly recommend to anyone who wishes to familiarize oneself with the field."* Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation dated November 18-19, 2019)
- *"This is one of the comprehensive ALD reviews that I always point new students towards in order to help them start gaining an understanding of ALD and how it works. The review is quite accessible and covers a breadth of topics, including various processes as case studies, reactor design, plasma chemistry, thermal chemistry, and substrate effects. It provides a good overview of the field that I would recommend to anyone getting started in ALD or who wants to learn more."* Joel Schneider, MS, Stanford University, Stanford, California, USA

Recommended reviews published in years 2000 to 2009

R. L. Puurunen
Surface chemistry of atomic layer deposition: A case study for the trimethylaluminum/water process

Journal of Applied Physics 97 (2005) 121301;
https://doi.org/10.1063/1.1940727; https://aip.altmetric.com/details/2113654

- *"I think this review is indispensable for researchers in the ALD field, both for beginners and cracks.*
  It starts with acknowledging that ALD was separately invented in the USSR ("molecular layering") and in Finland ("atomic layer epitaxy"). It then gives the famous overview of reported ALD processes using the periodic table. Next, it discusses in a systematic way a number of the key concepts in ALD, such as self-limiting behaviour, chemisorption, growth per cycle, etc. Subsequently, it illustrates these concepts using the well-know TMA-water reaction. Moreover, it very clearly discusses some misconceptions in the ALD literature; this is also an extremely useful part of the paper." Ruud van Ommen, PhD, Professor in Chemical Engineering, Delft University of Technology
- *"This is a foundational review that began the tabulation of ALD processes in literature, a practice which has been continued, built upon, and extended into new areas by numerous works since. This manuscript stresses the importance of collecting the existing ALD processes knowledge into centralized locations, an idea that has proven indispensable in my own work. This review also provides useful historical perspectives on the development of the field, and analyzes the mechanisms and practices of ALD through the lens of the trimethylaluminum/water ALD process. The perspectives on ALD development, fundamental physicochemical concepts, and common misconceptions are extremely useful in understanding what makes an effective ALD process."* Joel Schneider, MS, Stanford University, Stanford, California, USA

Recommended reviews published before year 2000

T. Suntola,
Atomic Layer Epitaxy,
Materials Science Reports 4 (1989) 261–312.
https://doi.org/10.1016/S0920-2307(89)80006-4

- *"This is the main review article written by the Finnish inventor of ALD (then called atomic layer epitaxy), Tuomo Suntola. It is a great overview of the early works, including a summary of who was working with ALD in those times (note: Suntola was not yet aware of the other branch of ALD, under the name Molecular Layering). Among others, the ALD window concept had been developed (by Suntola) by this time (notes of tracing back the origin of this concept in ALD History Blog)." Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation written March 29, 2024)*

C. Goodman, M. Pessa
Atomic Layer Epitaxy,
Journal of Applied Physics 60 (1986) R65–R82.

https://doi.org/10.1063/1.337344

- *"This is the first review on atomic layer epitaxy / atomic layer deposition fully written by authors other than the original inventor (Suntola). Prof. Pessa was the first academic collaborator of Suntola, working at Tampere University of Technology with molecular beam epitaxy type systems (more in the "Suntola story", https://doi.org/10.1002/cvde.201402012). This review offers a valuable perspective to the early ALD work, and it is also interesting to read what the authors thought of the future, in those days. Important quote from the abstract: "There is no growth rate in ALE as in other crystal growth processes." — Side note: this review defined the end year (1986) for documenting the "early" ALD activities in the Virtual Project on the History of ALD (VPHA), which I coordinated from 2013 on and which is phasing out since February 2022 (VPHA website at http://vph-ald.com will be outlived by the related blog at http://aldhistory.blogspot.fi; some materials also to be accessed at http://openlearning.aalto.fi → ALD)." Dr. Riikka Puurunen, Associate Professor (Catalysis Science and Technology), Aalto University School of Chemical Engineering, Finland (recommendation written March 29, 2024)*