ALD on high aspect ratio and nanostructured materials: from fundamentals to economics

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The ability to conformally coat high aspect ratio and nanostructured substrates over large substrate areas is one of atomic layer deposition's enabling capabilities. From the coating of trenches and vias to the extreme case of polymer infiltration, there are numerous examples in the literature illustrating how ALD's self-limited behavior can enable new architectures and applications. In this tutorial I will focus on the fundamental aspects of the coating of high surface area materials, and in particular how the surface chemistry affects the dynamics of infiltration, scale up, and tradeoff between throughput and precursor utilization. After a brief introduction summarizing experimental approaches for both growth and characterization techniques and some conventional and extreme applications, I will explore the impact that shape, pore size, the overall microstructure of nanostructured substrates, and precursor-surface interaction have on an ideal ALD process. The impact of these parameters can be codified in a few compact expressions that help us visualize and explore the scalability of a given ALD process. I will then move on to consider how other aspects of the surface chemistry, such the presence of surface recombination or deactivation pathways, ligand-surface interactions, and non self-limited and soft-saturating components affect conformality. I will also look at the coating of nanostructured materials from a reactor scale perspective, exploring through simple models and experimental observations how precursor transport is disrupted by the presence of high surface area substrates in both cross flow and static dose configurations, two of the most common experimental approaches. I will then conclude with an overview of experimental challenges and gaps in our understanding that, if solved, could help accelerate the development of novel processes involving high aspect ratio and nanostructured substrates.