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Hybrid nanomaterials through molecular and atomic layer deposition: Top down, bottom up, and in-between approaches to new materials

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A B S T R A C T

The ability to produce or alter materials to obtain drastically different or improved properties has been the driving goal of materials science since its inception. Combining multiple elements, compounds, or materials while maintaining the beneficial aspects of each constituent is a complex problem often involving highly interdisciplinary research. Hybrid materials, i.e. materials that incorporate organic and inorganic parts, have become popular in a variety of fields. Though not entirely new, the modern embodiment of hybrid materials has led to a large variety of new materials and techniques to produce them. One of the most recent being combination of atomic layer deposition (ALD), which produces inorganic materials, and molecular layer deposition (MLD), which produces organic materials. Furthermore, a variation on these techniques, commonly referred to as infiltration, has allowed for the modification of a variety of natural and synthetic polymers with surprising results related to their bulk mechanical properties. In this review three approaches are taken. First, hybrid materials through bottom-up combinations of ALD and MLD are reviewed, focusing on the process and properties of the resulting materials. Second, the modification of biomaterials through coating is discussed, and finally the relatively new concept of vapor phase infiltration is considered as a new and unique method to produce hybrid materials from a top down perspective.

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1. Introduction to hybrid materials

Hybrid materials comprise essential building blocks that enable the functioning of the world as we know it. One prominent example is bone, which is composed of collagen as the bioorganic component and calcium based minerals as the inorganic component. Such combinations of dissimilar materials can have completely different characteristics resulting in a hybrid with – as in the case of bone – mechanical properties significantly superior to the properties of the individual components. This example is one among millions that nature has developed through evolution as a response to specific environmental pressures. Evolutionary pressure, however, is not the only motivation to bring about hybrid materials. As early as the 9th century the Mayans were using a pigment, contemporarily referred to as "Maya Blue," for their paintings, which was extraordinarily resistant to weathering, thus allowing their survival until the present [1]. The pigment was composed of indigo, prepared from local plants, and palygorskite, a magnesium aluminum phyllosilicate found in the local clay, the combination being a hybrid material with an amazing resistance to bleaching [2].

Current developments in materials science also aim at trying to merge physical and/or chemical characteristics of individual components into a balanced intermediate but rather do so through controlled synthesis techniques developed by modern science. The term 'hybrid,' however, can have a variety of meanings and can depend on the field of research. The modern usage began in the 1980s when soft-chemistry techniques capable of producing inorganic materials at low temperature were first developed [3]. In principle, however, modern hybrid materials date back to the beginning of the industrial era when inorganic pigments ($PbCrO_4$, $PbCO_3$, TiO_2, etc.) were suspended in solvents for paints; and minerals, clays, and talcs were mixed with early polymers [4]. Since then the concept of 'hybrid' has permeated many areas of research. Reference to hybrid materials, hybrid devices, and/or hybrid methods exists in almost all branches of materials science and the associated crossover fields, i.e. chemistry, physics, biochemistry, etc. and can often refer to any material or concept that combines something not normally in that field. More commonly, and for the sake of this review, it refers to the combination of organic and inorganic materials as found in solar cells [5], polymers composites [6], thermoplastic polymers [7], metal–organic frameworks (MOFs) [8], catalysis [9], and/or devices and applications in optics [3], electronics [10], energy storage, environmental biology, and medicine [11].