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Role of Processing Parameters on Surface and Wetting Properties Controlling the Behaviour of Layer- by-Layer Coated Nanoparticles

by

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Abstract

Wetting phenomena at surfaces and interfaces is an important field of research with numerous commercial applications. As example, superhydrophobic surfaces are used as self-cleaning, antibiofilm forming and antimicrobial materials nowadays. Given the potential impact, creating surfaces with tailored wetting characteristics employing various fabrication techniques is of great interest. One very promising fabrication technique, for creating such materials is the layer-by-layer (LbL) self-assembly. LbL is a versatile technique allowing incorporation of different types of drugs and materials and the ability to coat substrates of complex geometries.

This review summarises recent progress in preparation of Layer-by-layer constructs and a role of surface and wetting parameters in this technique. Effect of various physicochemical properties on LbL construct characteristics also were discussed.

Keywords: nanoparticles, layer-by-layer, wetting, surface properties.

1. Introduction

The aqueous-based layer-by layer (LbL) assembly technique is found to be simple and versatile, thus has been used extensively to fabricate nanostructured materials with precisely tailored properties [1]. An area of active research, exploring the functionalities of LbL films incorporates a broad range of materials (including polymers, nanoparticles, metal ions, lipids, proteins, dye molecules, dendrimers and quantum dots) using various substrates. Assembling these materials are conducted through electrostatic interactions, hydrogen bonding, hydrophobic interactions coordination interactions, covalent bonding, and hydrophobic interactions [1]. Since LbL assembly can be exercised on a wide range of textured and curved surfaces, potential applications for LbL materials are very diverse. Examples include drug delivery [2], antimicrobial coatings [3], self-healing coatings [4], anticorrosion coatings [5], flame-retardant coating [6], superhydrophobic coatings, omniphobic slippery surfaces, light-emitting diodes, electronically conductive films, electrochemically reversible capsules, electrolytes, proton exchange membranes and direct methanol fuel materials, lithium-ion batteries, organic field-effect transistor, electrochemical capacitors as well as photovoltaic and biosensors [1]. Using the bottom-up method, constructing LbL assembly, relies on the spontaneous self-assembly of small molecular components into more complex, larger and functional 2D or 3D structures atom-by-atom or molecule-by-molecule. Bottom-up fabrication methods include Langmuir–Blodgett and self-assembled monolayers. The fabrication is closely packed, well-ordered and organized monolayers, allowing the immobilization of several functional molecules onto surfaces can be applied to both methods. But this will present some drawbacks that limit practical applications. The applicability is limited due to the expensive and specialized instrumentation, the long construction times, and the need for specific and limited molecules, namely, amphiphilic molecules, to prepare the films. The absence of a strong molecular interaction between the film and the solid support (no chemisorption is involved during the formation of the LB films) presents a problem. This is due to its mechanical instability, limiting the stability and robustness of the films under ambient and physiological conditions. Thus, the transfer of the molecules of the film

from the air–water interface to the solid support would be difficult. Thus, the process very slow and limits the incorporation of biological molecules into the films. On a plus side, this method allows the preparation of multilayer films from oriented monolayers. Some of the limitations of SAMs are the instability and lack of robustness of the films under ambient and physiological conditions, the limited loading of biological molecules in the films due to their monolayer nature as well as and the need of specific compounds to be present, including thiols (in the case of noble metals surfaces), silane (for titanium, silicon, and aluminum oxide surfaces), or organic acid (for several metal or metal oxide surfaces) molecules, on the substrate in order to allow the formation of the monolayers [7].

Processing parameters play an important role in determining the organization, layer thickness, and surface properties (roughness, wettability, adhesively, porosity) of multilayer films [8, 9]. In this review, the effects of various processing parameters on these properties will be discussed. Substrate roughness is an important parameter that affects the growth of polyelectrolyte multilayers during LbL process. Trybala *et al.* investigated the adsorption of multilayers made of poly(allylamine hydrochloride) / polysodium 4-styrenesulfonate with or without a polyethyleneimine first layer on various substrates with different roughness and using either polished or unpolished surface (silicon wafer, stainless steel and titanium plates). The build up of layers was higher on unpolished surfaces, for which materials with higher surface roughness, wither they were covered with polyethyleneimine layer or not as confirmed by fluorescent microscopy intensity measurements [8]. The selection of first layer is a way to modify the substrate surface and affects the total mass accumulation and stoichiometry of the deposited polyelectrolyte multilayers [9]. In addition, highly rough heterogenous surfaces affect the process parameters needed for LbL process, e.g. longer immersion and washing times needed to achieve high surface coverage compared to ideal homogenous substrate surface [10].

The LbL assembly coatings of water-soluble polymers or colloidal dispersions, often hydrophilic materials are given focus. These coatings may be superwet through the

introducing roughness and/or low surface energy layers in multiple ways. This technique precisely controls the coating thickness and composition, allowing the creation of “intelligent” systems. As an example, the technique allows the modulating of wettability and advanced functionalities such as water flow guidance. A natural choice for creating surfaces with special wettability, LbL can be used to create nearly any surface texture. Nonetheless, generally there are still several challenges in fabricating superwet coatings with LbL in particular [1].

2. Effects of Physicochemical Properties of Building Blocks on LbL Film

The particulate substrate used for LBL deposition includes titanium oxide (TiO₂), polymer colloid and liposome. These responsive nanoparticles have a configurational design which can be represented by a core-shell architecture formed through self-assembly of amphiphilic copolymers (polymer micelles or vesicles) or surface modification of various particles (inorganic or polymeric) with functional polymers. The self-assembled structures can be stimulated by external stimuli and may induce their reversible or irreversible disintegration, aggregation, swelling and adsorption. The toolbox of responsive colloids includes functional polymers, copolymers and inorganic nanoparticles [11]. The physicochemical properties of the polyelectrolytes play an important role in the assembly process. Some of the most important properties are discussed such as polyelectrolyte charge density, surface activity, wettability and polyion molecular weight.

2.1 Polyelectrolyte Charge Density

Tuning polyelectrolytes is easily done since the linear charge density along weak polyelectrolyte backbones is a function of pH with the electrostatic interaction within

PEMs (polyelectrolyte multilayers) incorporated. These properties of PEM films such as permeability, morphology or wettability could be triggered widely. The outermost polyelectrolyte layer is converted into a non-charged macromolecule, thus creating most hydrophobic surfaces (contact angle (δ) $> 70^\circ$) [12]. The possibility of creating surfaces with water contact angles close to 100° increases when a precursor polycation such as the polycationic precursor to poly(phenylenevinylene) and polyamic acid are used to construct the bilayer. Similar results are obtained when polyaniline is used as the polycation as opposed to poly-(allylamine) which are the general trends essentially independent of the nature of polycationic base layer [13]. The advancing water contact angle contrastingly changes in a dramatic manner when changes occur on the outermost polyanionic layer. It is possible to systematically vary the surface from a completely wettable surface ($\delta < 5^\circ$) to a hydrophobic surface ($\delta = 72^\circ$) using these simple single bilayer combinations. The most wettable surfaces ($\delta < 20^\circ$) are created when the outermost layer is an aliphatic polyacid such as poly-(acrylic acid), whereas aromatic polyacids such poly(styrenesulfonate) and poly(thiophene acetic acid) produce contact angles in the $50\text{-}60^\circ$ range [13].

2.2 Surface Activity

One of the approaches to change the surface chemistry and expand the functionality of PEMs is by incorporating amphiphilic surfactant into PEMs where surfactants are able to diffuse and swell into PEMs. Complexes between polyelectrolytes and surfactants can be formed through electrostatic or secondary interactions during the inter diffusion process, displacing small counterions in the multilayer or even the ion pairs formed between polyelectrolytes. By adding new functionality such as hydrophobicity, the charged surfactant is able to become incorporated into the multilayer especially when this newly incorporated property can be tuned. The surfactant can be incorporated, creating a gradient or switchable wetting (erasable-rewritable) with controlling this inter diffusion procedure. The use of counterion exchange from small counterions to larger surfactant molecules on the top surface of a PEM surface may modify the wettability [14]. Wu *et al* reported the fabrication of fluorine-free self-healing superhydrophobic films by LbL

assembly of poly(sodium 4-styrenesulfonate) (PSS)–1-octadecylamine (ODA) complexes (PSS–ODA) and poly(allylamine hydrochloride) (PAH)–sodium dodecyl sulfonate (SDS) (PAH–SDS) complexes. The wettability of the assembled layers (PSS–ODA/PAH–SDS) depends on the film structure which can be tailored by changing the NaCl concentration in the aqueous dispersions of PSS–ODA complexes and the number of film deposition cycles. The polyelectrolyte-complexed ODA and SDS surfactants migration to the film surface covers the film with hydrophobic alkyl chains to lower its surface energy, which gradually makes the film superhydrophobic in air. The presence of large amounts of surfactants at the film surface give the films the ability for self-healing and restoring the damaged hydrophobicity [15].

2.3 Wettability

The chemical properties on the surface may influence the wetting on a smooth surfaces depends on, but roughness will enhance either hydrophobicity or hydrophilicity. Wetting on smooth and structured surfaces are shown in **Figure 1**. The geometry (hills and valleys) should ensure low contact area between water and the surface (Cassie state instead of Wenzel state) in order to achieve low contact angle hysteresis on a hydrophobic surface. The addition of a nanoparticle is often required to achieve this texture when referring to the context of LbL systems, although there are some exceptions. As the last step, a low surface energy molecule as fluorinated or alkyl silane is also almost always applied to the surface. In this way, water interacts with this chemistry and not with the ionic groups of the PEM that have a much higher affinity for water [16].

In reducing capillary forces that impede fluid flow in confined spaces, superhydrophilic surfaces have potential critical roles. The definition of a superhydrophilic surface is a contact angle of less than 5 degrees, or another definition is that a surface with static water contact angle of less than 10 degrees [17]. Furthermore, surface roughness is important in superhydrophilic wetting behavior, with a limitation that only surfaces with a roughness factor of greater than 1 (defined as the ratio of actual area of the surface to its geometric area) should be described as superhydrophilic. The surface microstructure is the mechanism behind superhydrophilicity while the surface wetting property is a

consequence of water penetrating a roughened or porous surface. The fabrication of superhydrophilic surfaces is based on photoactive materials such as titania that become superhydrophilic after UV irradiation [18].

Inorganic/organic LbL films can achieve superhydrophilicity, including those with inert particles such as silica or silicates or those incorporating photoactive particles such as titania. Generated by LbL, these superhydrophilic surfaces can be made using solid-, spherical-, or disc-like nanoparticles and more complex geometries such as hollow TiO₂ and mesoporous SiO₂ spheres and a number of raspberry- or mulberry-shaped [19].

The wettability of substrate surface can be altered and controlled by sequentially adsorbed polyelectrolyte layers. The change in wettability is effected by a number of factors including the chemical composition of the adsorbed polymer, the hydrophilicity of its functional groups and the level of interpenetration of the outermost layer by segments of the previously adsorbed polymer layer. Thus, it is possible to establish the basic understanding needed to controllably alter surface wettability by monitoring the changes that occur in wettability during the layer-by-layer processing of different polymers. It can also gain fundamentally important information about the level of interlayer interpenetration present in sequentially adsorbed polyelectrolyte layers.

A subject of many review papers, the ability to control wetting at surfaces and interfaces has the potential to impact many areas, especially based on biomimetic strategies. These include using superhydrophobic surfaces for energy saving, reducing frictional energy dissipation at solid–liquid interfaces and creating dropwise condensation to improve heat transfer rates, product lifetimes such as self-cleaning surfaces [20], as well as microfluidics. The superhydrophilic surfaces are vital in antifogging and evaporative cooling [21] while superoleophobic or superoleophilic materials may be of potential use for oil/water separations [1]. Lin *et al* improved the surface wettability of silicone hydrogel contact lenses via LbL assembly technique. The silicon based hydrogel was synthesized by a block copolymer of polydimethylsiloxane (PDMS) and poly (ethylene glycol) methacrylate (PEGMA). Polysaccharide PEMs of chitosan and hyaluronic acid were assembled on the PDMS-PU-PEGMA silicone hydrogel. The contact angle of the

silicone hydrogel decreased with an increase in the number of polyelectrolyte grafting layers [22].

2.4 Solution pH

Factors like pH, electrical potential, ionic strength, and surfactant of the surrounding environment can tune the conformation, ionization and construction of charged polyelectrolyte on the surface, which can be effective external stimuli to control surface wettability. Wettability can be tuned by pH value of the polyelectrolyte assembly solutions when using weak polyelectrolytes, as the charge density of the polyelectrolyte is pH dependent [11]. Creating surfaces capable of switching properties is due to the responsiveness of polyelectrolytes to different conditions. However, under extreme acidic or basic pH conditions, decomposition or reorganization of weak polyelectrolyte assemblies held together via electrostatic interactions, forming porous structures. The films should be at least partially covalently crosslinked to avoid this response. Some authors reported a bell-shaped superhydrophilic-superhydrophobic-superhydrophilic double transformation in response to the increase in the pH value of surrounding solution by covalent surface modification of alkyl, amino and carboxylic acid groups [23].

2.5 Addition of Salt

The surface wettability of sequentially adsorbed polyelectrolyte layers is sensitive to a number of processing factors including the addition of salt to a dipping solution [13]. A previous study indicates that the thickness of the total multilayer on a substrate can be controlled with high precision by adding salt to the aqueous polyion solution¹. At high salt concentration, there could be a chance of precipitation of the polyelectrolyte in the solution preventing them from striking to the oppositely charged interface therefore, limiting the multilayer growth [24,25].

2.6 Polyion molecular weight

The molecular weight of the polyelectrolyte is one of the parameters that affect the growth of multilayers. The film thickness increases with the increase of molecular weight of the polyelectrolytes in the case of linear growth behavior, because of the more coiled polyelectrolyte chains with higher molecular weight [26]. However, the film thickness of the multilayers can be decreased by increasing the molecular weight of the polyelectrolytes in the presence of multilayer diffusion, because the higher the molecular weight the slower the diffusion between deposited layer which adversely affects multilayers growth [27]. Yu *et al* studied the effect of using high or low molecular weight poly(allylamine hydrochloride) (900K or 15K g/mol) and poly(acrylic acid) (225 K or 15K g/mol) on the growth of multilayers. The layers were fabricated by linear and exponential growth regime by varying the pH conditions. In the linear growth regime, high molecular weight polyelectrolytes with low charge density slowed down the adsorption because of suppressed interlayer diffusion, compared to low molecular weight polyelectrolytes at short deposition time (< 5 minutes). However, the effect of molecular weight can be reversed by increasing the deposition time improving the deposition of high molecular weight polyelectrolytes, while low molecular weight polyelectrolyte reaches equilibrium. In the exponential growth regime, the high molecular weight polyelectrolytes suppressed the interlayer diffusion and decreased multilayer thickness regardless of deposition time [28].

3. Effects of Assembly Method on LbL Film

The process of polyelectrolyte multilayer self-assembly usually depends on the electrostatic interaction between the substrate and subsequent layers. The first step is anchoring of the coating material on the surface followed by slow relaxation to form a dense film packed on the surface [29]. Some processing parameters that affect the adsorption steps on LbL assembly are briefly discussed because of their important role in controlling the assembly process, which are deposition technique, adsorption time,

polyion concentration, adsorption kinetics, ion concentration and pH of the medium and temperature.

3.1 Deposition Technique

By using various LbL deposition methods (i.e., dip- and spin-assisted LbL assembly), the surface morphology and the resulting wetting behavior of multilayer films can be controlled. The spin-assisted LbL deposition method had produced thin and uniform multilayer films with low surface roughness; both roughness and water contact angle of spin-assisted films remained constant with the layer pair number, as the result of limited rearrangement and aggregation of complexes within the film during spin deposition. In comparison, dip-assisted multilayer films exhibit a three-dimensional surface texture above a critical number of layer pairs, which was attributed to the migration and aggregation of complexes within the film [8, 21].

Different deposition methods can affect surface morphology and surface-wetting behavior of LbL films. This well-documented finding was reported by Seo *et al* in their study on manipulation of LbL film morphologies via the choice of dip-assisted versus spin-assisted LbL assembly methods using systems containing an amphiphilic hydrogen-bonding polymer. The dip-assisted hydrogen-bonded LbL films consisting of hydrophobically modified poly(ethylene oxide) (HM-PEO, a triblock copolymer consisting of PEO end capped with alkyl groups) and poly(acrylic acid) (PAA) yielded a unique surface morphology, developed above the critical number of layer pairs. The formation and aggregation of HM-PEO micelles within the film was related to the surface structure. The arrangement of polymers at the interface is a kinetic process, which means that these properties would be highly dependent on the assembly technique, where the adsorption under shear at very short times (spin-assisted) may yield completely different growth profiles, surface roughness and water contact angles relative to the processing based on the dip-assisted technique for several minutes per cycle [30].

When hand-dipping versus auto dipping methods are used, significant differences in surface wettability can be observed suggesting that the drying step and different pH

adjustments of the rinsing baths used in the hand-dipping process (pH 2.5 versus 6.0) created a surface layer different from that obtained in the all-wet, auto dipping process. It should be noted that the completely wettable surfaces created via the use of the PAH/PAA bilayer combination (contact angle $< 5^\circ$) exhibit antifogging features. This means that antifogging mirrors and eyeglasses can be created by simply adsorbing a few bilayers of this system onto a surface with PAA as the outermost layer [8].

Only a single bilayer of these sequentially adsorbed polyelectrolytes is needed to effectively modify the surface properties of a non-charged, hydrophilic substrate, while the surface properties can be systematically controlled by changing the nature of the outermost layer. Similar results were obtained with glass slides that have been chemically treated to render their surfaces hydrophobic (contact angle $> 70^\circ$) [13].

Important parameters such as the thickness and conformation of an adsorbed layer and its level of interpenetration with neighboring layers can vary dramatically when processing conditions are changed. Variations in solution conditions may influence layer thickness and interpenetration. Detailed studies have been carried out on the PAH/PAA bilayer system with particular emphasis on the role that solution pH plays in determining layer thickness and organization. Since PAA (pKa about 4.5) and PAH (pKa about 10) are weak polyelectrolytes with a level of functional group ionization that is highly sensitive to pH, this bilayer combination provides a rich parameter space to explore variations in processing conditions. Guzman *et al.* studied the effect on increasing of ionic strength on the multilayer growth for PSS, and poly(diallyldimethylammonium) chloride, PDADMAC changed the growth regime from linear to non-linear because of the alteration of the ionization of the polyelectrolytes in the presence of different ions in solution. Also the water content of the multilayers were affected, where increasing NaCl concentration decreased the water content, but for films with high number of layers water content stays almost constant with increasing ionic strength [31].

The wetting behavior of water droplets is affected by the contrasting surface morphologies of the dip- and spin-assisted LbL films. The water contact angle of the dip-assisted HM-PEO/PAA LbL films reaches a maximum at an intermediate layer pair number, coinciding with the critical number of layer pairs for surface morphology

development. Then it decreases rapidly as the surface structure is evolved and amplified. In contrast, spin-assisted HM-PEO/PAA LbL films yield a nearly constant water contact angle due to the surface chemical composition and roughness that is uniform independent of layer pair number. The multilayer samples prepared using both the dip- and spin-assisted LbL methods were easily peeled away from any type of substrate to yield free-standing films; spin-assisted LbL films appeared transparent, while dip-assisted LbL films were translucent [30].

Seo *et al.* reported that the wetting behavior for the dip-assisted LbL film of HM-PEO/PAA multilayers above the critical number of layer pairs (i.e., 26 layer pairs) changed drastically: the water contact angle rapidly decreases with the increase in layer pairs. This coincides with the critical number of layer pairs, at which the rough surface structure is developed, indicating that the drastic change in contact angle for the dip-assisted HM-PEO/PAA multilayers is directly related to the surface morphology or roughness. The surface roughness and heterogeneity is documented as having a significant effect on wettability. Above the critical number of layer pairs, the water droplet is wicked (or imbibed) into the rough, hydrophilic surface roughness; amplified with the increase of layer pair number as the surface structure grows. This situation is known as hemiwicking: an intermediate state between spreading and imbibition [30].

Spraying technique is an alternative method for the classical dipping LbL coating technique, where the polyelectrolyte and rinsing solutions are sprayed rather than dipped onto the substrate. The major advantage of using spraying technique is reducing the time needed for multilayer formation. However, time should be allowed between deposited layers for drainage of the solution after each layering step. In a study comparing the multilayers formed by dipping and spraying technique, the multilayers formed by dipping were thicker, denser and less rough than sprayed films with the same number of layers or deposition cycles, as confirmed by neutron and X-ray reflectometric studies [32].

3.2 Adsorption Time

Early studies used short adsorption times (1 min per layer) for material deposition due to the large size of the particles and colloids used, while it was later determined that, for standard immersive LbL assembly with polymers, the substrate should be immersed for more than 12 min for optimal layering [33].

This time requirement for deposition is one of the primary impediments to large-scale, high-throughput use of immersive LbL assembly. To expedite the process, dimethylformamide can be added into the layering solutions, thereby removing the need for rinsing and drying steps, as dewetting leads to both deposition and drying. Additionally, dewetting LbL assembly allows for the deposition of materials not conducive to LbL assembly, such as branched SiO₂ nanowires with a low surface charge and small contact area [33].

3.3 Polyion concentration in the coating solution

The use of concentrated coating solution is needed during LbL multistep coating for maintaining enough concentration of the polyion deposited, which must be kept above a minimum threshold to reverse the charge of previously deposited layer [34]. The threshold is variable from a polyelectrolyte to another and depends on solubility and charge density in the coating solution medium. Jurin *et al.* studied the effect of polyelectrolyte concentration on the deposition of self-assembled multilayers made of poly(3,4-thylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) and poly(diallyldimethylammonium chloride) PDDA for the preparation of conductive thin films. When the polyelectrolyte concentration was below 1 g L⁻¹, no conductive films were obtained even if 50 bilayers were deposited. This suggests not enough PEDOT:PSS complexes incorporated into the film or too thin film [35].

3.4 Adsorption kinetics

Formation of polyelectrolyte multilayers is dependent on the competitive interaction between polyelectrolytes, substrate and the solvent. Initially, adsorption onto the substrate is a first order process because of the presence of many sites for electrostatic interaction. After saturating the anchoring sites on the substrate, a slower process takes

place for the rearrangement of the coated polyelectrolytes from the initial process, which may also result in multilayers growth through the diffusion of additional polyelectrolyte chains. The second rearrangement step gives the establishment of a brush-like polyelectrolyte barrier of the initially absorbed chains that prevents further surface saturation [29]. Liu *et al.* studied the adsorption kinetics for the layering of chitosan and PAA to form a surface grafted polyelectrolyte multilayers, using total internal reflection Raman. The build up of layers showed non-linear growth behavior, with different adsorption kinetics for chitosan and PAA. The protonated form of the low molecular weight PAA diffuses into and out of the layered films during adsorption and rinsing steps. Chitosan showed similar behavior to a lower extent because of higher molecular weight. The non-linear growth is caused by the diffusion of PAA, and also by the island-like morphology showed by atomic force microscopy [36].

3.5 Ion concentration and pH of the medium

Slight alterations in the pH medium or ions can cause drastic changes in the electrostatic charge of the polyelectrolytes involved in LbL assembly process, which is essential for their interactions and multilayers growth [37]. Adding salt ions beyond a certain threshold or concentration can compensate all charges for the polyelectrolyte and substrate forming a coagulated turbid dispersion, where no multilayer growth can be achieved [38]. Similarly, a change in pH of LbL solutions will change the dissociation of the polyelectrolytes and ions, altering the adsorption of multilayers on the substrate. However, the adsorption and layer thickness of strong polyelectrolytes can be adjusted by controlling salt concentration, whereas layers constructed by weak electrolytes can be adjusted by the variations in the solution pH [39]. Guzman *et al.* studied the effect of ionic strength on the assembly of polyelectrolyte multilayers composed of PDDA and PSS, and of PAH and PSS. The increase in ionic strength reduced the charge density for polyelectrolytes, and affected their conformation in solution. For (PAH+PSS)_n, thickness of the deposited multilayers is not affected by the ionic strength. However, for (PDDA+PSS)_n, increasing the ionic strength from 100 mM to 500mM changed the growth in the thickness of multilayers from linear to nonlinear growth [40]. Tang and Besseling reported also the same observation when increasing the ionic strength between

0.5-1 M NaCl in (PDDA+PSS) multilayers, which was explained as absorption of the polyelectrolyte throughout the film, rather than just for adsorption at the outer surface [41].

3.6 Temperature

Temperature of the coating solutions is an easily adjustable parameter for tuning the film thickness by heating or cooling during film preparation. However, assembly of multilayer films is usually carried out at room temperature, and most of the biological application of multilayers occur at 37 °C. Temperature can affect the film growth in various ways depending on the nature of interaction between film polyelectrolyte molecules, whether they are strongly or weakly interact with each other. For strong polyelectrolytes, the build up of film is linear where the strong interaction between polyelectrolytes minimizes diffusion of molecules, while weak polyelectrolytes interaction allow for fast diffusion in the film leading to exponential film growth [42].

Increasing temperature in linearly growing multilayers leads to increased fluidity of the films, switching the growth regime from linear to exponential, as observed in the buildup of polyelectrolyte multilayers consisting of PSS, PDDA, and PAH [43]. Vikulina *et al.* studied the effect of temperature on the film growth of exponentially growing multilayers. Dipping method was used for the assembly of poly(L-lysine)/hyaluronic acid multilayers in the temperature range of 28-85 °C. The mechanism of deposition for the multilayers is diffusion-mediated, where increasing temperature increased the film growth rate because of higher permeable film structure at higher temperatures allowing faster molecules diffusion. The multilayers growth switches from exponential to linear after certain number of deposition steps because of limited diffusion into the film. Increasing temperature shifts the transition point for the growth regime to a higher number of steps, where the growth shifts from exponential to linear [44].

4. Unconventional LbL Assembly

A non-exhaustive list of pertinent examples of how certain types of films and assembly methods that is not typically associated with LbL assembly can be leveraged to assemble multilayer films in unique ways. For example, certain multilayered films, such as coordination-driven films and cellular multilayer films, and certain methods, such as using inkjet deposition, have only recently gained traction in the LbL field and therefore can be considered unconventional. This section focuses on three distinct areas: the first is unconventional assemblies, where examples such as step-by step and coordination-driven multilayer films that have clear similarities to conventional LbL assemblies are highlighted; the second is multilayer film patterning, which can be challenging to achieve for films assembled on the nanoscale; and finally biological assemblies, which are often both patterned films and unconventional assemblies. A unifying theme of unconventional LbL assembly is a move towards control over assemblies at larger and smaller scales than conventional LbL assembly, as it is found in multilayer films of cells and small molecules, respectively [33].

Early studies in multilayer assembly utilized silica particles and colloidal alumina as the layer materials, but when LbL assembly was revitalized in the early 1990s, much of the focus was on polyelectrolytes. Today, a wide range of different materials can be used to form multilayers and this toolbox continues to expand, especially with the advent of new assembly technologies. As the use of LbL assembly, associated materials and relevant techniques continues to expand, the boundaries of what constitutes LbL assembly starts to blur. In this section, examples of innovations in multilayer assemblies and highlight unique properties of these systems are discussed. As mentioned above, these examples are not intended to be comprehensive or fully exhaustive but instead are intended to highlight unconventional assemblies (e.g., metal–organic frameworks and metal–phenolic networks) and unique combinations of building blocks (e.g., inorganic–organic hybrid films, stereo complexed materials and polyelectrolyte complexes).

4.1 Inorganic–Organic Hybrid Assemblies

Inorganic–organic hybrid multilayers can be assembled using so called “cerasomes”, which are organo-alkoxysilane proamphiphiles, prepared under sol–gel reaction conditions, to form a liposomal membrane with a ceramic surface. The ceramic surface supports the liposomal structure and prevents fusion of vesicles, which enables multilayered assemblies to be formed. Alternatively, enzymes can be used as an organic portion, allowing for micro reactors to be assembled with high surface area. Metal–organic hybrids are the constituents of numerous films and constructs, some of which can be used to construct multilayered assemblies. For example, thin films can be formed through the coordination-driven assembly of Fe(III) ions and tannic acid, resulting in so-called metal–phenolic network films. These components can also be used to assemble multilayered films. The coordination process can either be performed in one step by mixing the iron and tannic acid simultaneously, which can then be performed multiple times to form multilayers in 10 nm increments, or instead can be performed in a multistep procedure where the tannic acid is adsorbed to a surface, followed by Fe(III) ions, and the cycle repeated. Interestingly, when comparing metal–polyphenol films made through one-step or multistep assembly, substantial differences can be observed, both in the nature of complexation and in their physicochemical properties such as permeability and stiffness. This demonstrates how the choice of assembly method, even with identical material components, can be used to tune the properties and performance of the resultant films.

4.2 Hydrophobic Interaction-driven LbL Assembly

When the adsorbed molecules are uncharged, the hydrophobic interactions play a major role in the buildup of multilayer films. The fabrication of stable ultrathin films of poly(vinyl alcohol) (PVA) onto a gold substrate by repetitive physical adsorption from aqueous solution and subsequent drying processes can be made as example, as demonstrated by Serizawa *et al* [45]. The presence of NaCl in the aqueous PVA solution releases the water from the hydrated PVA, hence physical adsorption in the fabrication process occurred due to hydrophobic effect. In addition, the thickness of the film was increased by increasing the concentration of NaCl, and no assembly was observed in the absence of NaCl. The authors demonstrated that surface reconstruction on drying

facilitated the adsorption of PVA at the solid–liquid interface as well as the assembled amount of PVA increased with its concentration, when PVA concentration was tested in the range of (0.2-40) mM with 2M NaCl. Also, The film thickness increased with increasing PVA molecular weight when tested in the range of (23000 to 1860000) at a concentration of 20 mM, with NaCl concentration of 2 M at 25 °C [45]. Kotov and coauthors [46] had published a breakthrough paper that addressed the importance of hydrophobic interactions between polyelectrolytes and charged surfaces in the formation of stable layers. They reported the existence of several independent contributions to the Gibbs free energy of adsorption of a positively charged polyelectrolyte to a negatively charged polyelectrolyte surface. This included the removal of the ionic atmosphere around both positively and negatively charged polyelectrolytes, the reorientation of water molecules previously oriented by charged polyelectrolytes, the loss of mobility of the polyelectrolyte chains and the partial removal of the hydration shell around both positively and negatively charged polyelectrolytes. These contributions possess a large component of entropic nature due to the release of water molecules when hydrophobic parts of polyelectrolyte chains establish a contact. Therefore, apart from electrostatics, hydrophobic interactions must be necessarily taken into account when considering LbL multilayer formation, i.e., purely electrostatic interactions do not guarantee the formation of the multilayers [7].

4.3 Hydrogen Bond-facilitated LbL Assembly

The integration of amphiphilic blocks copolymer micelles; serving as vehicles for drugs to be incorporated in LbL films is an approach that enables the incorporation of hydrophobic drugs. Other methods of embedding hydrophobic drugs within multilayer thin films such as cyclodextrins, amphiphilic polysaccharides, and liposomes. This micellar encapsulation method would provide a general approach, since amphiphilic block copolymers can spontaneously self-assemble in water to encapsulate hydrophobic drugs. These polymeric micelles have been extensively utilized to provide a highly versatile nanometer-sized delivery platform for drugs, proteins, DNA, and personal care products. The integration of block copolymer micelles into LbL films has been previously reported, relying either on covalent linkages or on the electrostatic interactions between the polyelectrolyte and the micellar corona block. The first example of

polymeric micelles incorporated into LbL films are based on hydrogen bonding, without the use of charged polyelectrolyte [47].

The integration of amphiphilic block copolymer micelles as nanometer-sized vehicles for hydrophobic drugs within LbL films are presented using alternating hydrogen bond interactions as the driving force for assembly (**Figure 2**). This enables the incorporation of drugs and pH-sensitive release. The film was constructed based on the hydrogen bonding between PAA as an H-bond donor and biodegradable poly(ethylene oxide)-block-poly(-caprolactone) micelles as the H-bond acceptor when assembled under acidic conditions [47].

4.4 LbL Assembly Driven by Charge-Transfer Interactions

The alternate adsorption of two types of nonionic molecules, which present electron-accepting and electron-donating groups, respectively, in the side chains can result in the growth of multilayer films. The advantage of using Charge -Transfer interactions is that the films can be prepared in organic solvents, which considerably increases the possibility of incorporating hydrophobic functional groups in the films and has the potential for making nanostructured films based on organic materials. This in turn can be used in developing interesting materials for applications in electronics, photonics and optics devices [7].

4.5 LbL Assembly via Host–Guest Interactions

Based on highly selective and specific host– guest interactions, multilayer assemblies can also be fabricated using the LbL assembly approach. This can be done by exploring the strong interactions between host (e.g., cyclodextrins, cucurbiturils, calixarenes, pillararenes, crown ethers, porphyrins) and guest (e.g., ferrocene, adamantane, azobenzene) molecules. Some researchers revealed that the synergistic effect of LbL assembly and host–guest interactions could be used to build up multilayer films based on water-soluble calixarenes (cavity shaped cyclic molecules made up of benzene units) and lipophilic dyes [7]. Simultaneously, Anzai *et al* [48] unveiled the possibility of fabricating sensing devices by forming LbL polymer films via strong host–guest

interactions between a neutral β -cyclodextrin dimer and positively charged ferrocene-appended poly(allylamine hydrochloride).

4.6 LbL Assembly Driven by Biologically Specific Interactions

Biologically specific interactions have high steric demand that is composed of many different molecular interactions, such as electrostatic and hydrophobic interactions, and hydrogen bonding. This ensures high specificity and functionality to the target molecules. This type of intermolecular interaction has appeared over the years, such as avidin–biotin, antibody– antigen, and lectin–carbohydrate interactions, as well as DNA hybridization [7].

4.6.1 Avidin–Biotin Interactions to Build Up and Grow Multilayer Assemblies

The first example of LbL assembly was driven by biologically specific interactions employed the well-known avidin–biotin pair interaction. Müller *et al.* reported the assembly of protein multilayers was induced by specific molecular recognition. The authors mimicked the assembly of proteins by using streptavidin as a docking matrix [49]. Decher *et al.* [24] had described the immobilization of multilayers of biological molecules (such as polyelectrolytes, proteins, or DNA) in their native state via biologically specific recognition. A well-established biotin–streptavidin system was used to construct such multilayers. Later, Anzai and Nishimura [48] revealed the formation of multilayer films based on the alternate deposition of avidin and biotin-labeled polymers (polyethyleneimine or polyamidoamine dendrimer) and demonstrated that the multilayer structure of such films depended on the molecular geometry of the polymers: globular polymer polyamidoamine provides a monolayer deposition of avidin, while the avidin multilayer is formed by the deposition with randomly branched polymer polyethyleneimine. While Spaeth *et al.* [50] prepared protein multilayer systems by alternate deposition of a biotin conjugated with bovine serum albumin and polymerized streptavidin on hydrophobic silica surfaces, as confirmed by ellipsometry measurements (350-750 nm). Up to 20 alternating incubations were prepared on the surface of a biotin–protein conjugate and polymerized streptavidin. The build up of layers were reproducible

with a thickness increase of about 18.75nm per incubation, and protein mass deposition of 4.74 ng/mm².

4.6.2 Antibody–Antigen Interactions to Build Up and Grow Multilayer Assemblies

The focus had been on the fabrication of multilayer assemblies through antibody– antigen specific interactions. Bourdillon *et al* [51,52] had reported antibody–antigen specific interactions to successfully build up multilayers of GOx onto a glassy carbon electrode, as well as to fully preserve the catalytic activity of the enzymes and improve their stability against denaturation. In addition, Zhou *et al* [53] had reported that the antigen binding affinity on antibody immobilized CHT/ALG multilayer film can be tailored by the assembly pH. The increase of the assembly pH of alginate had led to a decrease of the antigen binding affinity. These highly specific interactions are particularly important for the design of biosensors, immunosensors, and immunoassays with enhanced detection capabilities [54].

4.6.3 DNA Hybridization to Assemble and Grow Multilayer Assemblies

The highly biocompatible and biodegradable DNA has been widely used as an attractive building block for the generation of smart responsive materials for biomedical, therapeutics, diagnostic, and biosensing applications for the past few decades. This biopolymer has been predominantly incorporated into LbL films via electrostatic interactions, being used as an anionic polyelectrolyte assembled with polycations. The incorporation of DNA multilayers into LbL assembled films can also be achieved via biologically specific interactions such as through DNA hybridization, that allows the assembly of species displaying the same charge. This specific interaction, which is based on hydrogen bonding, exploits the high specific interaction between complementary DNA base pairs, enabling the design and engineering of the composition and structure of DNA-based multilayer films [7].

4.7 LbL Assembly through Coordination Chemistry Interactions

Coordination chemistry interactions are strong molecular interactions established between a wide variety of metal ions and organic ligands that enable the design and

preparation of novel, well-ordered, highly oriented, versatile and robust 2D functional multilayer thin films and even 3D nano architectures comprising of several materials, such as organic polymers, activated carbon, metal oxides, metal nitrides, zeolites and advanced inorganic–organic hybrid polymeric films, which include metal– organic frameworks. For example, organic–inorganic hybrid microcapsules for efficient enzyme immobilization have been prepared through the metal–organic coordination based LbL assembly. Such materials, which have widespread applications in sensing, separation, porous smart membranes, catalysis, drug/gene delivery, optoelectronics, luminescence, energy and gas adsorption as well as storage, can be grown by two main strategies: the solution-based LbL growth methods and the vapor-based LbL growth methods.

4.8 Solution-based LbL Growth Methods

Solution-based LbL methods can achieve precisely tailored surfaces with a variety of functionalities by pre-functionalization of different substrates (e.g., Au, Si, SiO₂, glass). For example, with thiol or organosilane molecules, the creation of self-assembled monolayers (SAMs) incorporating OH-, COOH-, or N-functional end-groups are enabled. Then, the surfaces functionalized with these organic linkers, which present several accessible functionalities and long range 2D order, direct the orientation, nucleation, structure, stability and the quality of further deposited thin films. The preparation and growth of LbL coordination multilayers through solution-based methods requires the pre-functionalization of the substrate surface with organic linkers, such as SAMs. A well-defined control over the surface properties is required in the functionalization of the substrate surface with organic SAMs requires and limits the whole assembly process to suitable substrates for deposition of densely packed, well-ordered, oriented and high-quality SAMs. Moreover, the formation of pinhole-free films, i.e., films cannot be ensured without defects even when using appropriate substrates for accurate deposition of SAMs because the substrate is not atomically flat all over the entire surface. Thus, other strategies focusing on vapor-based LbL growth methods, such as atomic layer deposition (ALD) and molecular layer deposition (MLD), have emerged to solve some of these problems [7].

4.9 Vapor-based LbL Growth Methods

For the last two decades, several approaches that had focused on vapor based LbL growth methods, such as ALD (atomic layer deposition) and MLD (molecular layer deposition), have appeared as very promising ways to chemically deposit multilayer thin films in a LbL fashion for a variety of applications such as low leakage dielectric films, transparent conductive coatings, and diffusion barrier coatings. Both emerging dry methods are based on sequential self-limiting surface reactions between different precursor molecules in order to grow pinhole-free, high-quality, uniformed and conformal LbL thin films with precise layer control on high-aspect-ratio structures and porous materials. These strategies provide an unprecedented level of control over the chemical composition, structure, conformation and film [7].

4.10 LbL Assembly via Stereocomplexation

The stepwise stereo complex assembly enables the preparation of stable, highly ordered molecularly regulated polymeric structures with great potential for applications in polymer surface chemistry and biomedicine. These stereo complexes are the result of combinations of structurally well-defined synthetic polymers in certain solvents and are fabricated through weak van der Waals interactions between the polymers. This emerging driving force includes not only specific interactions between polymers but also their structural rearrangements at the film surface. Although the association of structurally regulated synthetic polymers into stereo complexes has been extensively reported in the literature, very few researchers had focused on the stepwise stereo complex assembly of such structurally well-defined synthetic polymers on a substrate. The stereocomplex assembly of polymer complexes, such as poly-(methacrylates) and enantiomeric poly(lactides), onto a substrate was a subject of attention recently [7, 55].

5. Conclusion

Titanium (IV) oxide, polymer colloid and liposome are the major core substrate for LbL deposition. The physicochemical properties of building blocks including the density of polyelectrolyte charge, surface activity, solution pH, and the amount of salt in solution influence the characteristics of LbL film. Also, different deposition methods can affect the film surface morphology and surface-wetting behavior and for optimal layering the

substrate should be immersed for more than 12 min. Additionally, conventional LbL assembly methods impact the film properties in unique ways.

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7. References

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8. Appendix: List of acronyms

layer-by-layer (LbL)
as atomic layer deposition (ALD)
hydrophobically modified poly(ethylene oxide) (HM-PEO)
molecular layer deposition (MLD)
poly (ethylene glycol) methacrylate (PEGMA)
poly(3,4-thylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS)
poly(acrylic acid) (PAA)
poly(allylamine hydrochloride) (PAH)–sodium dodecyl sulfonate (SDS) (PAH–SDS)
poly(diallyldimethylammonium chloride) (PDDA)
poly(sodium 4-styrenesulfonate) (PSS)–1-octadecylamine (ODA) complexes (PSS–ODA)
poly(vinyl alcohol) (PVA)
polydimethylsiloxane (PDMS)
polyelectrolyte multilayers (PEMs)
self-assembled monolayers (SAMs)

9. Figures

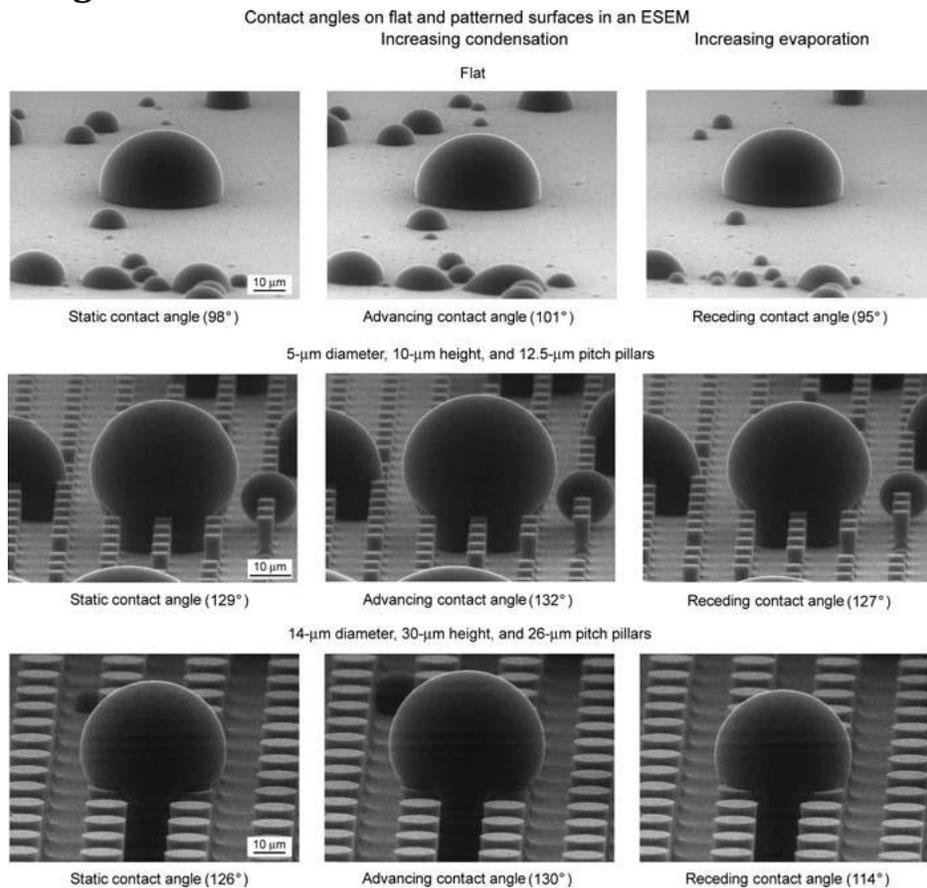


Figure 1

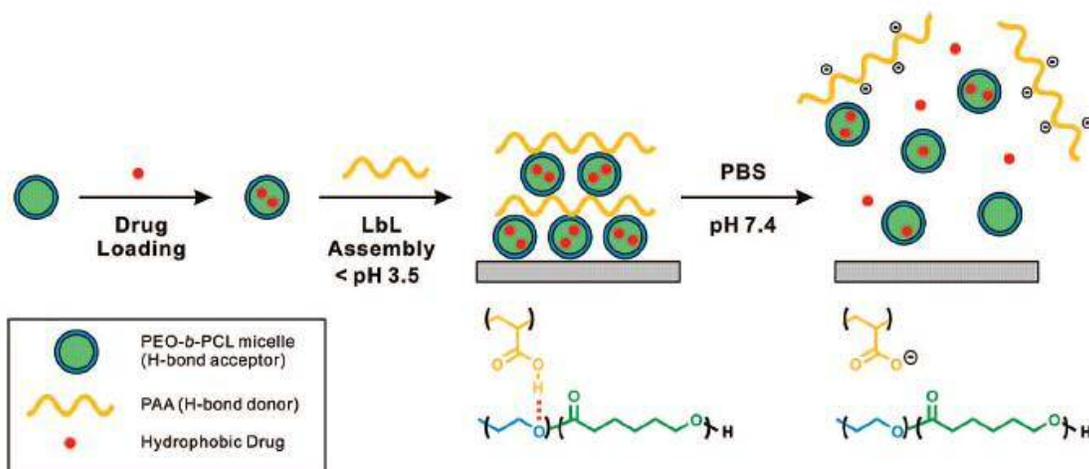


Figure 2

10. Figure captions

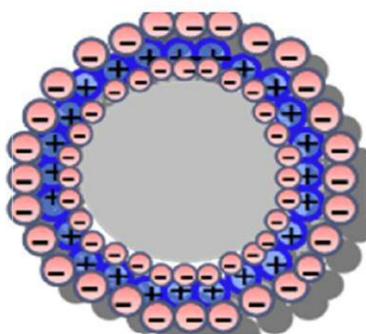
Figure 1. Microdroplets on flat and two-patterned Si surfaces coated with PF3 using ESEM. Second set of images were taken during increasing condensation, and the third set of images were taken during increasing evaporation. Static contact angle was measured when the droplet was stable. Advancing contact angle was measured after increasing condensation by decreasing the temperature of the cooling stage. Receding contact angle was measured after decreasing evaporation by increasing the temperature of the cooling stage. (Reprinted with permission from {Y. C. Jung & B. Bhushan. (2008). Wetting behaviour during evaporation and condensation of water microdroplets on superhydrophobic patterned surfaces. *Journal of Microscopy*, Vol. 229 (1), pp. 127–140}. Copyright {2017} John Wiley and Sons).

Figure 2. Schematic representation of hydrogen-bonding layer-by-layer assembly of block copolymer micelles for hydrophobic drug delivery vehicles from surfaces (Reprinted with permission from {Kim, B., Park, S. and Hammond, P. (2008). Hydrogen-Bonding Layer-by-Layer-Assembled Biodegradable Polymeric Micelles as Drug Delivery Vehicles from Surfaces. *ACS Nano*, 2(2), pp.386-392}. Copyright {2017} American Chemical Society).

Physicochemical Properties of LbL Building Blocks



Polyelectrolyte charge density; Surface activity; Wettability, pH solution, Salt addition



LbL assembly methods and adsorption time



Hydrophobic, Hydrogen-Bond, Host-Guest, Charge-Transfer, Coordination Chemistry and Biologically specific interactions



Tailored Wettability and Surface properties of coated materials

Graphical abstract

Highlights

- Layer-by-layer (LbL) is a versatile coating technique allowing encapsulation of any drugs and materials on complex geometry surfaces.
- LbL allows the modulating of wettability and advanced functionalities of surfaces.
- Processing parameters play an important role determining surface properties of LbL films.
- Physicochemical properties of building blocks influence the characteristics of LbL films.
- Different LbL deposition methods affect the film surface morphology and surface-wetting behaviour.