

1

Layer-by-Layer Assembly (Putting Molecules to Work)

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1.1

The Whole is More than the Sum of its Parts

The properties of a material arise from the structural arrangement of its constituents and their dynamics.

In nature, a hierarchical organization assures that a required property of a material is realized with a minimum of constituents and a minimum of complexity through processes of evolutionary selection. In the living world functional entities exist on any length scale ranging from atoms to whole organisms, complex properties of “biological materials” such as cellular life emerging at the upper end of the nanoscale (Figure 1.1).

Chemistry, Physics and Materials Science are increasingly approaching maturity on the molecular and macroscopic length scales, shifting importance toward new nanoscale materials and nanoorganized systems. New materials properties, a prerequisite for responding to the emerging problems of the world population, will require materials design at the nanoscale, forcing the development of new multi-material nanocomposites.

In complex systems, new properties appear that are not observed for each individual component. While it is trivial that electrons and nuclei form atoms (sub-Ångstrom scale), that atoms form molecules (Ångstrom scale) or that monomers can be transformed into polymers (early nanometer scale), we are just beginning to explore the potential of supramolecular assemblies of multifunctional objects. Figure 1.1 summarizes how complex materials properties evolve hierarchically over a length scale of several orders of magnitude.

1.2

From Self-Assembly to Directed Assembly

Imagine a self-assembly experiment involving several different chemical species and obtaining equilibrium. Chances are that the result of this experiment will have produced a material with less-than-optimal properties. The generally adopted strategy for improvements is then to re-engineer the chemical structure of the

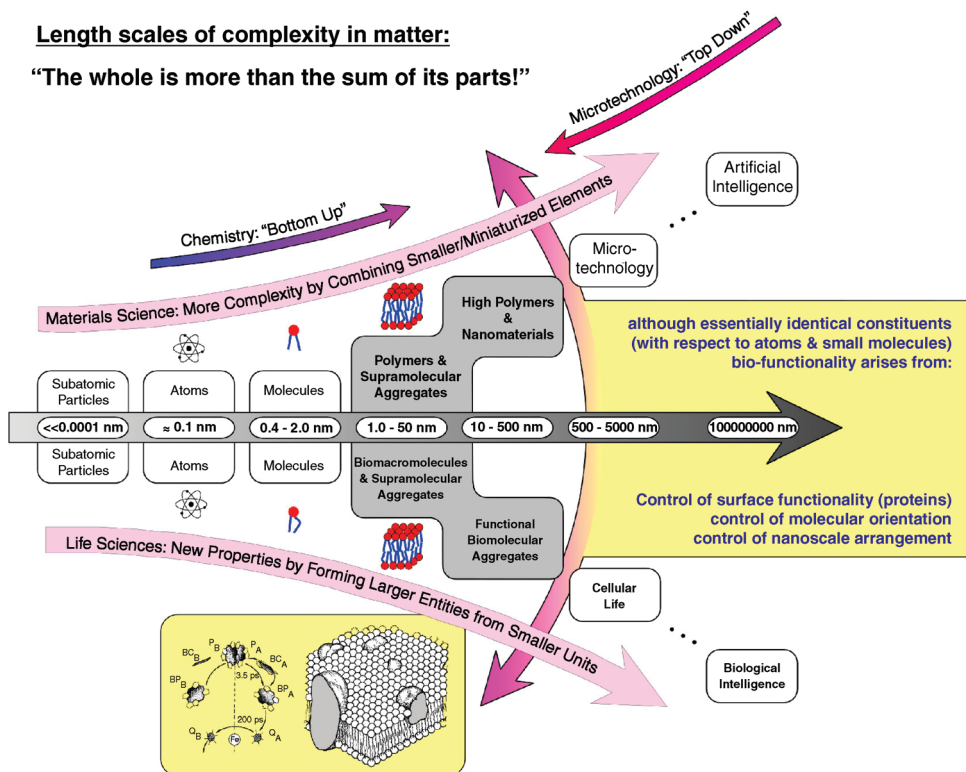
Length scales of complexity in matter:**“The whole is more than the sum of its parts!”**

Figure 1.1 Complexity as a function of length scale. Materials Science is not yet as far advanced as the evolutionary developments present everywhere in nature.

The photosystem is just one example of the precise spatial assembly of a functional molecular machine. The drawing is adapted from [1].

molecules (objects) involved, to test different assembly conditions and to hope for a better outcome in the next experiment. This is a tedious approach as several optimization cycles are frequently required. This approach will necessarily become utterly hopeless when larger numbers of components are being involved and when hierarchically organized materials are targeted.

Another strategy to prepare a desired hierarchically organized composite material is to use an assembly procedure that bypasses equilibrium by trapping every compound kinetically in a predetermined spatial arrangement. At present there are only very few approaches in this direction, likely because as in nature, multiple assembly steps are required to arrive at the desired target structure. Most of the work has been carried out for rather simple cases, for example by assembling different materials with one-dimensional order in a multilayer film. For about 65 years the molecularly controlled fabrication of nanostructured multilayers has been dominated by the conceptually elegant Langmuir–Blodgett (LB) technique, in which monolayers are formed on a water surface [2] and subsequently transferred onto a solid support [3, 4]. The pioneering work on synthetic nanoscale *multicomposites* of organic molecules was carried out by H. Kuhn and colleagues in the late 1960s using

the LB technique [5]. His experiments with donor and acceptor dyes in different layers of LB-films provided direct proof of distance-dependent Förster energy transfer on the nanoscale. These were also the first true nanomanipulations as they allowed mechanical handling of individual molecular layers such as separation and contact formation with Ångstrom precision [6]. Despite being conceptually very elegant, the LB-technique is rather limited with respect to the set of molecular components suitable for LB-deposition, and because molecules are often not firmly trapped and frequently rearrange after or even during deposition.

The so-called layer-by-layer (LbL) deposition technique [1, 7–16] (Figure 1.2) is a more recent approach toward nanoscale multimaterial films that allows one to choose

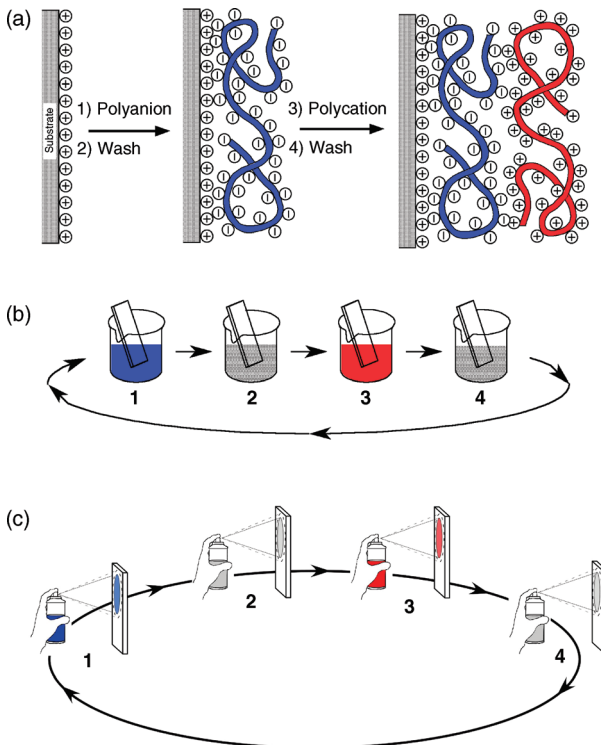


Figure 1.2 (a) Simplified molecular conception of the first two adsorption steps depicting film deposition starting with a positively charged substrate. The polyanion conformation and layer interpenetration are an idealization of the surface charge reversal with each adsorption step which is the base of the electrostatically driven multilayer build-up depicted here. Counterions are omitted for clarity. (b) Schematic of the film deposition process using glass slides and beakers. Steps 1 and 3 represent the adsorption of a polyanion and polycation respectively, and steps 2 and 4 are

washing steps. The four steps are the basic build-up sequence for the simplest film architecture $(A/B)_n$ where n is the number of deposition cycles. The construction of more complex film architectures is trivial and just requires additional beakers and an extended deposition sequence (see Figure 1.3). (c) Instead of bringing the surface into contact with the liquid that contains the adsorbing species by immersion, the liquid is sprayed against the receiving surface onto which the polyelectrolyte multilayer is deposited.

from an unprecedented variety of different components as constituents of the multilayer films and falls into the category of template assisted assembly.

The fabrication of multicomposite films by the LbL procedure means literally the nanoscopic assembly of hundreds of different materials in a single device using environmentally friendly, ultra-low-cost techniques. The materials can be small organic molecules or inorganic compounds, macromolecules including biomacromolecules, such as proteins or DNA or even colloids (metallic or oxidic colloids or latex particles). The choice of different components for LbL-assembly has become so large that the hundreds of different published articles describing that work cannot be meaningfully cited. The positive side of this aspect points to a key strength of LbL-assembly, the preparation of multicomponent nanomaterials. At present most publications in the field describe films composed of only two to five different components, however, the door is wide open for assembling more complex systems. Looking at the complexity of “materials” found in biological systems it seems clear that future LbL-devices will certainly contain more components in better controlled spatial arrangement (barriers, compartments, . . .) with precise response to stimuli (degradation, opening/closing of pores, renewable surfaces, . . .).

The LbL-technique can be applied to solvent accessible surfaces of almost any kind and any shape, the more exotic ones being colloids, fruit, textiles, paper or, even biological cells.

One of the key advantages of LbL-assembly is that LbL-films often display close to identical properties after deposition of the first few layers, even if films are deposited on very different surfaces. This means that it is frequently possible to prepare films for analytical purposes on (e.g., silicon) wafers while the films are put to work on surfaces that prevent thorough physico-chemical characterization (e.g., paper, textiles). Another interesting consequence is that different materials can be equipped with close to identical surface functionalities (e.g., anti-coagulation coatings on different surfaces in contact with blood).

1.3

History and Development of the Layer-by-Layer Assembly Method

It is now a little over 20 years since layer-by-layer assembly was introduced as yet another method to functionalize surfaces and to fabricate thin films. Starting with simple bola-shaped amphiphiles [7] it was quickly extended to simple polyelectrolytes [8] and functional macromolecules including proteins [17, 18] or DNA [19, 20]. Eventually, in 1994, biological nanoparticles [21] and inorganic nanoparticles [22, 23], including magnetic [24] and gold [25] nanoparticles, were added to the list of possible multilayer film constituents. The field took off in the late 1990s, after it became clear that stratified multilayer architectures could be prepared [12, 26, 27] and that multilayer films can also be assembled on non-planar surfaces, namely on microparticles, as first demonstrated by T. Mallouk in 1995 [28] and then brought to a sheer explosion by H. Möhwald and his team a few years later [29, 30]. Polyelectrolyte multilayers were even deposited on nanoparticles [31, 32] a process that was further

enhanced [33, 34] and which led to very interesting and very small multifunctional objects [35, 36]. Today, multilayer films are even prepared on surfaces such as textiles, paper, or on the skin of fruits. Due to its simplicity and the unprecedented choice of different components for polyelectrolyte multilayers and related systems, the method is today well established in materials science and making its way into the life sciences as well. Both developments have led to a solid and continuous growth of this field with no sign of reaching a peak or a plateau yet. In 2010, there were about 1000 articles published in the field.

Looking back at the historic development of this method over the last 20 years is quite interesting. When we started to work on this topic in 1989 (the first graduate student Jong-Dal Hong—now professor in Korea—finished his thesis in 1991) we were not aware of any other previous work on multilayer fabrication using electrostatic interactions. It was only much later that we learned about the work of R. K. Iler of Du Pont de Nemours & Co., on “Multilayers of colloidal particles” that was published in *J. Colloid and Interface Science* already back in 1966 [37]. In the early 1990s, the inversion of the zeta potential of charged colloids after adsorption of an oppositely charged polyelectrolyte had already been experimentally observed, for example, from work in the field of flocculation [38]. However, we were initially not aware of work by C. Gölander *et al.* [39] on “heparin layer formation” through sequential adsorption of a heparin complex and heparin which also demonstrated charge reversal, nor of a proposal of P. Fromherz [40] outlining similar ideas, or work of R. Aksberg *et al.* on the adsorption of a polyanion on cellulosic fibers with pre-adsorbed polycations [41]. We also did not know about a somewhat similar SILAR method (Successive Ionic Layer Adsorption and Reaction) for preparing polycrystalline inorganic films first reported by Nicolau in 1985 [42]. Neither seemed any of these research teams to know about each other.

Nowadays there is even “*unintentional*” use of LbL-assembly principles. Since about 1991 one increasingly finds protocols in biology in which “*two-component coatings*” are used or recommended for certain experiments (e.g., poly-L-lysine or poly-D-lysine and laminin for controlling cell attachment), nobody being aware that they are using layer-by-layer principles for their experiments. Imagine how much such experiments could benefit from knowing what is happening at the molecular scale and how the field of for example cell biology could gain advantage from engineering more suitable coatings for certain experiments. Today, the impetus for improvements in this field is coming from colleagues in the materials sciences (see many chapters in this book) who are addressing cell biology issues by introducing LbL-assembly to the life science community.

By 1988, when I started to work on layer-by-layer assembled films (unfortunately the first attempts during my time as a postdoctoral fellow using 4,4'-terphenyl disulfonic acid failed), the field of thin organic multilayer films was dominated by the so-called Langmuir-Blodgett technique (see above). Already in the early 80s, the field of LB-films had grown so large that the community started a meeting series “International Conference on Langmuir-Blodgett Films” the first of which being held in Durham, England in 1982, followed by meetings in Scenectady (1985) and Göttingen (1987). The meeting in Durham was of particular interest also with respect

to layer-by-layer assembled films. At this meeting G.L. Gaines contributed two important papers “On the history of Langmuir-Blodgett films” [43] and “Deposition of colloidal particles in monolayers and multilayers” [44]. The abstract of his latter contribution reads as follows:

“Preliminary observations are reported on the deposition of alumina, silica, zinc sulfide and gold colloidal particles on solid surfaces. The alumina, which is positively charged, can induce subsequent deposition of the other colloids (which are negative) onto glass, as pointed out by Iler in 1966. However, more uniform, reproducible and rapid deposition occurs on two monolayers of docosylamine sulfate applied to the glass by the Langmuir-Blodgett technique. The zinc sulfide sol, which is not stable to flocculation, deposits as three-dimensional aggregates. The deposition of colloidal gold was followed by optical absorption measurements, and layers containing a substantial fraction of the close-packed limit were obtained.”

So Iler’s early experiments were in fact known to the thin film community in the early 1980s, they were even taken up and presented by one of the leading researchers of the field. With this in mind, one can only conclude that Langmuir-Blodgett films seemed so overwhelmingly promising at that time that the electrostatically driven assembly of inorganic particles must have looked like a scientific dead-end street. In the meantime this has changed, in the recent meetings of this conference series layer-by-layer assembled films have taken an ever growing fraction of the scientific program, due to the growing number of developments and applications.

1.4

LbL-Assembly is the Synthesis of Fuzzy Supramolecular Objects

For most cases a LbL film has a unique layer sequence that is strictly defined by the deposition sequence (Figure 1.3). This indicates that LbL deposition should be considered as an analog to a chemical reaction sequence. While a chemical reaction takes part between different synthons and typically yields a unique molecule after each step of a given synthesis, layer-by-layer deposition involves the adsorption of a single species or mixture in each adsorption step and yields a multilayer film with a defined layer sequence at the end of the film assembly. While molecules are synthesized in several consecutive reaction steps, a multi-composite film is fabricated in several subsequent adsorption steps.

The reagents in classic synthesis are typically molecules, in layer-by-layer deposition they can be chosen from a wide range of materials. While today most of the multilayer films have been fabricated using mainly electrostatic attraction as the driving force for multilayer build-up, this is by no means a prerequisite. There are many other interactions that have successfully been used for multilayer deposition including: donor/acceptor interactions, hydrogen bridging, adsorption/drying cycles, covalent bonds, stereocomplex formation or specific recognition.

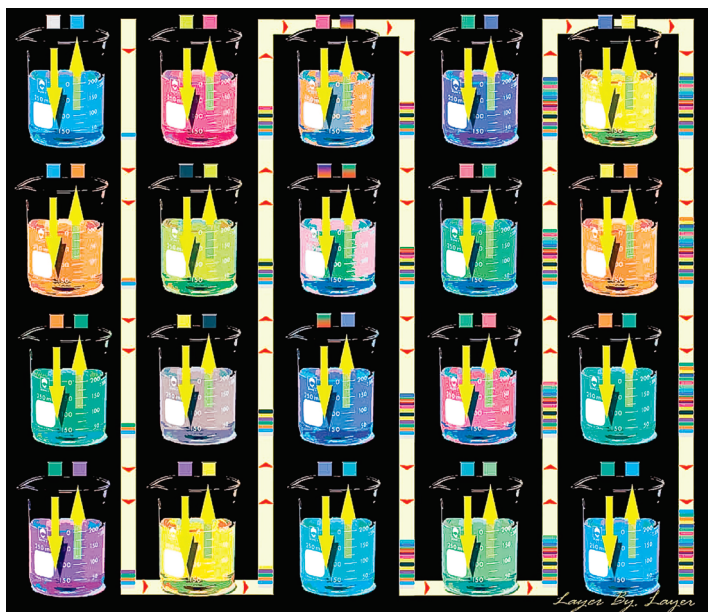


Figure 1.3 An artists rendition of layer-by-layer multicomponent film with a defined layer assembly has recently appeared on the cover of a review published by K. Ariga *et al.* [45]. It nicely depicts that the architecture of a sequence conveniently depends on the sequence of immersions in different beakers containing the different species.

In general one needs just any interaction (this may be one or several different interactions) between two species “reagents” in order to incorporate them into a multilayer film. The interaction can easily be tested in solution prior to carrying out the deposition if both film constituents are soluble in the same solvent. When both solutions are mixed and flocculation occurs it is a good sign that multilayer fabrication will be possible. However this is only a very crude test for the “complementarity” of different compounds, multilayer formation may also be possible in the absence of flocculation.

It is possible to coat almost any solvent-accessible surface starting with nanoparticles or nanochannels up to the inside of tubings, or even objects with a surface of several square meters. Like a chemical reaction, the precise structure of each layer and the properties of the whole film depend on a set of control parameters, such as concentration, adsorption times, ionic strength, pH or temperature, but in general the processing window is rather broad.

1.5 Reproducibility and Choice of Deposition Conditions

The question of reproducibility arises immediately when we draw the analogy between a chemical reaction and layer-by-layer adsorption. On first sight one may

say that molecules are unique species and multilayer films are “only” fuzzy supramolecular objects. This is essentially the same argument that has downgraded for years macromolecular chemistry in comparison to organic chemistry. Today it is generally accepted that “ill-defined” macromolecules are also unique species that can indeed be well described by distributions and average properties like polydispersity or degree of polymerization. The situation is similar for multilayer films as they are characterized by a sequence of layers in which each layer has its individual structure and properties (Figure 1.3). While the sequence of layers is as strict as the arrangement of atoms in a molecule, the properties of each layer can only be described as an average over a certain area or over a certain distance along the layer normal. The most obvious property of an individual layer is its thickness, which is dependent on the nature of the underlying surface and on the deposition conditions. Parameters presumed to be important with respect to the underlying surface are, for example, nature and density of charged groups, their local mobility (in the case of a polymeric surface), and the surface roughness. Other important parameters are: solvent, concentration of adsorbing species, adsorption time, temperature, nature and concentration of added salt, rinsing time, humidity of the surrounding air, drying, agitation during adsorption or rinsing, dipping speed, and so forth. Typically, polymer and salt concentrations and deposition times are well described in the literature, however, some teams have already seen reproducibility issues when trying in colder weather to repeat results obtained during a hot summer.

How do we choose the right deposition conditions? This is not an easy question, because experimental constraints are very different for different investigations or applications. Film parameters, such as target thickness, target roughness, target functionalities, must be decided and are the result of an optimized deposition procedure. However, there are some guiding principles for polyelectrolyte multilayer deposition:

- 1) Longer adsorption times lead to more reproducible results. Everybody is aware that the plateau of adsorption is reached as a function of the concentration of the adsorbing component and of the adsorption time. While concentrations are easy to reproduce with little error, it is much more difficult to reproduce adsorption times in the range of seconds, especially if far from the plateau of adsorption or if adsorbing onto large or irregular shaped objects. Even a small difference in the adsorption times may lead to a large difference in the adsorbed mass in the initial phase of adsorption, whereas even a much larger difference in the adsorption time will lead only to a small difference in the adsorbed mass close to the plateau of adsorption. Adsorption kinetics are conveniently followed *in situ* for example, by quartz crystal microbalance (Figure 1.6).
- 2) The rinsing volume is important for avoiding cross-contamination of deposition solutions. While many multilayer films grow well even without rinsing, one should carefully calculate the required rinsing volumes to avoid cross-contaminations in the case of LbL-assembly by “dipping”. Of course this is only relevant when the rinsing solution is in a beaker into which the substrate is immersed (e.g., “dipping robot”). When the substrate is withdrawn from a deposition solution a thin film of the deposition solution will adhere to its surface, the

volume of the adhering liquid can be estimated from the surface area of the immersed object, assuming a thickness of the adhering liquid film of a few microns. The dilution factor of the first rinsing bath is calculated by dividing the volume of the first rinsing bath by the estimated volume of the adhering liquid. Each further rinsing bath will increase the dilution factor correspondingly. The number and volume of the rinsing baths should be chosen such that the overall dilution factor is at least $1:10^6$, otherwise the liquid adhering on the surface of the substrate will contaminate the following deposition solution. *Cross-contamination and the depletion of the concentration of the adsorbing molecules are frequently underestimated, especially with large surface areas and with a large number of deposited layers.*

- 3) The surface coverage of functional groups is a key parameter for reproducibility. While most LbL-films show linear growth, which is likely associated with densities of functional groups that are independent of the layer number, this is not always the case. Superlinear growth may result from increasing surface coverage (or densities) of functional groups (or from the reservoir effect brought about by molecules diffusing into the whole film) and sub-linear growth results from decreasing densities of functional groups which will finally lead to stagnation of layer growth. In general, stagnation of layer growth is more likely with molecules or objects that possess only few functional groups, especially when the adsorbed geometries permit orientation of all functional groups toward the surface. For molecules with a large number of functional groups (i.e., high degree of polymerization) such unfavorable orientations for layer growth are much less likely. However, reproducible layer-by-layer assembly can be performed even with molecules containing only two functional groups (e.g., [7, 46]).

While the LbL-technique works generally very well due to the fact that the processing window is rather large, it is highly recommended to keep the deposition conditions as constant as possible in order to get highly reproducible results. If this is done rigorously, one obtains films composed of tens of layers whose thickness for example, differs by about 1%.

When comparing data, one should not overlook that one must not only maintain exactly the deposition conditions, but also the conditions under which the measurements were taken. Figure 1.4 shows an example of how the film thickness of a (PSS/PAH)₈ multilayer film, for which both polyions were deposited from solutions containing 2 M sodium chloride, depends on the temperature and on the relative humidity at the time of the measurement [47].

Often it is said that polyelectrolyte multilayer films are independent of the underlying substrate. This is an oversimplified statement, of course there is a dependence on the underlying surface, as stated above. However, since polyanion and polycation adsorption is often repeated consecutively, each polyanion adsorbs onto a polycation covered surface and vice versa. This means that, after a few layers, the structure and properties of each layer are often governed by the choice of the respective polyanion/polycation pair and by the deposition conditions, and that the influence of the substrate is typically lost after a few deposition cycles.

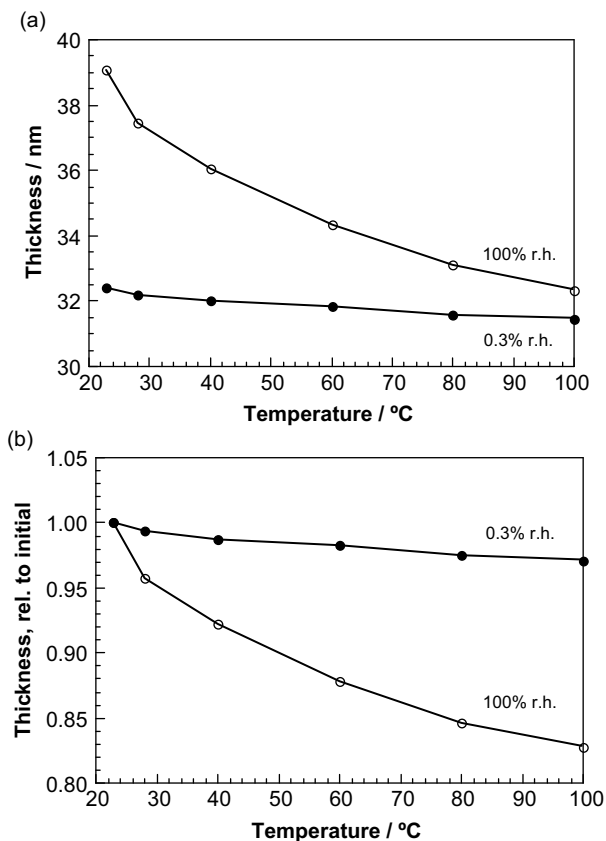


Figure 1.4 (a) Film thickness of the same multilayer specimen as a function of temperature and of relative humidity (r.h.). The differences in thickness at identical temperatures are entirely due to a difference in water content within the film and not to a negative thermal expansion coefficient. This difference becomes less pronounced at elevated

temperature, when the water is driven out of the film. (b) The same data as in (a), but represented normalized with respect to the initial film thickness. It becomes obvious that even small differences in temperature or humidity can easily account for changes in film thickness of the order of 5–10% depending on the swellability of the film.

1.6 Monitoring Multilayer Build-up

The easiest way to follow multilayer build-up is probably by UV/Vis spectroscopy which works for all colored materials. Figure 1.5 is an example for poly(styrene sulfonate)/poly(allyl amine) (PSS/PAH)_n films [8] which constitute probably the best characterized system as of today.

Equivalent to measuring the optical absorbance, one can also determine the film thickness by ellipsometry or X-ray reflectometry. These characterization methods are straightforward and widely available, but they require interruption of the deposition

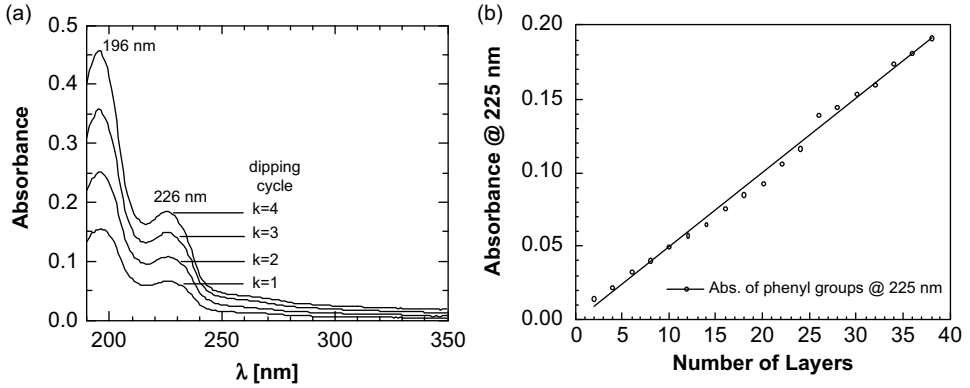


Figure 1.5 (a) UV/Vis spectra taken after different numbers of adsorption cycles (k) during the preparation of a PSS/PAH multilayer. The bands at 195 nm and 226 nm originate from the aromatic chromophore of the styrene monomer unit of PSS. The absorbance increases regularly with the number of PSS layers. (b) Plot of the absorbance of the PSS band at 225 nm

versus the number of layers deposited. The numerical fit to the data (solid line) shows that the increase of absorbance per layer is constant. The absorbance per layer is less than in (a) because the salt concentration in the deposition solutions was different. The slight deviation from a straight increase after 26 layers is due to the interruption of the deposition overnight.

process for taking the measurement. Not only are the measurements an interruption, they also have to be taken in the dry which may not be desirable in some cases.

In-situ methods are available for samples that cannot be dried. Depending on their time resolution, such methods also allow one to follow the kinetics of adsorption (Figure 1.6) and/or multilayer reorganization. Besides measurements of the zeta potential (Figure 1.7) and results obtained by quartz crystal microbalance (Figure 1.6), typical *in-situ* methods include surface plasmon spectroscopy, OWLS (optical waveguide lightmode spectroscopy), optical reflectometry in stagnation point flow cells, scanning angle reflectometry (SAR), *in-situ* ellipsometry, *in-situ* AFM, attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), surface forces measurements, X-ray and neutron reflectometry or second harmonic generation (SHG). Quartz crystal microbalance is ideally suited for screening the adsorption kinetics for new components and for optimizing the adsorption conditions.

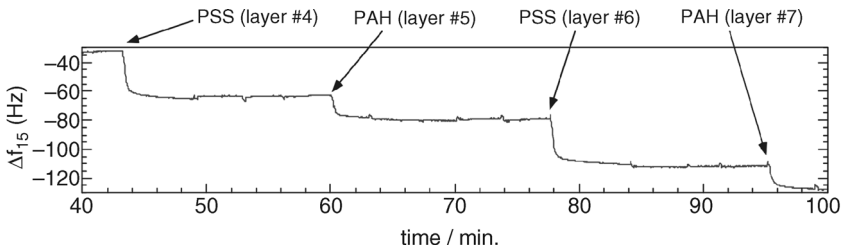


Figure 1.6 Continuous QCM-trace of the third harmonic at 15 MHz (raw data) during the deposition of PSS (large displacements) and PAH (small displacements) during 4 arbitrary adsorption steps (layer numbers 4, 5, 6 and 7) of a longer deposition sequence.

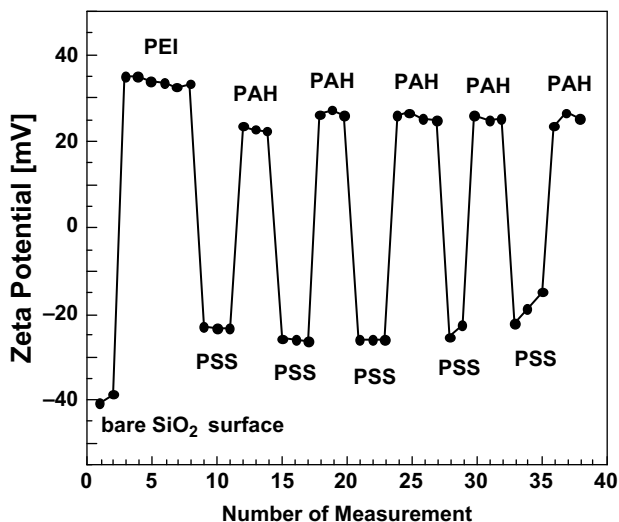


Figure 1.7 Streaming potential measurement showing the surface charge reversal during multilayer buildup *in situ*. The first layer was poly(ethylene imine) (PEI) followed by 5 deposition cycles PSS and PAH [48].

A prerequisite, however, is that the multilayer being deposited should be rather rigid in order to evaluate frequency displacements as adsorbed mass using the Sauerbrey equation. If the multilayer has to be treated as a viscous film, a more sophisticated QCM instrument and data evaluation is needed. The data in Figure 1.6 on the consecutive deposition of poly(styrene sulfonate) (PSS) and poly(allyl amine) (PAH) were taken with a so-called QCM-D instrument, that also registers viscoelastic components of adsorbed films (data not shown). It is seen nicely that adsorption kinetics are rather fast (about 1–2 minutes per layer), that the thickness of each monolayer is autolimited (plateau) and that there is no visible desorption after rinsing (plateau). In this plateau region the QCM cell was rinsed three times for each adsorption step, once with the solution containing the respective polyion and twice with the buffer in which the polyions were dissolved. Please also note that there is a fast and a slow component in data like that shown in Figure 1.6 and that the structure and properties of a multilayer assembly may depend on processes occurring after the rapid adsorption step. Figure 1.6 arbitrarily shows the adsorption of layer numbers 4, 5, 6 and 7 out of a longer deposition sequence. The diagram shows that the film build-up is very regular.

In the early days of layer-by-layer assembly, there was just the idea of layer build-up driven by electrostatics, the surface potential of polyelectrolyte covered surfaces was only discussed to some extent, mostly in colloid science. In the meantime several Zeta potential measurements have been published, the diagram shown in Figure 1.7 results from a measurement using a quartz capillary that was carried out in collaboration with the groups of P. Schaaf and J. C. Voegel [48]. It demonstrates nicely that the adsorption of each polyelectrolyte layer leads to an overcompensation of the previous surface charge, just as we had assumed earlier on and schematically

drawn in illustrations such as Figure 1.2. However, newer data suggest that the alternation of the zeta potential may not be a strict prerequisite for layer-by-layer assembly (see further down).

The theoretical description of polyelectrolyte complex formation including polyelectrolyte multilayers has considerably progressed recently [49]. However, measurements such as shown in Figure 1.7 are not a proof that multilayer build-up is entirely driven by electrostatic attraction (incoming layer) and electrostatic repulsion (auto-limitation to a single layer). Such measurements only show that there is a contribution of electrostatics in the case of multilayer build-up using positively and negatively charged components. Note that the release of the counterions also plays an important role as a driving force of layer-by-layer assembly. Depending on the chemical nature of the polyions and/or colloids employed for deposition, the importance of the electrostatic contribution should vary and other interactions, such as van der Waals, hydrogen bonding or charge transfer may more or less be involved as well.

A rather curious case turned up recently, when we studied the deposition of poly (sodium phosphate) (PSP) with a much longer polycation, poly(allylamine hydrochloride) (PAH) [50]. Despite the fact that both components form a polyelectrolyte complex in bulk, it is *very* difficult to prepare polyelectrolyte multilayers from these constituents. We finally succeeded by using spray assembly, but it turned out that multilayer growth depends strongly on the polymer concentrations, on the pH and on the ionic strength, even the growth regime can change as a function of these parameters. Most interestingly, in the case of linear growth at 10^{-4} M concentrations of PAH and PSP at pH 6.7 and in 0.15 M NaCl the zeta potential does not alternate between positive and negative when changing from polycation to polyanion. While the zeta potential starts out at +60 mV, it decreases to 0 mV during the deposition of the first 75 “layers” then becoming negative, finally stabilizing at -20 mV for layer numbers of 150 and above. The decline is not smooth, consecutively adsorbed layers lead to a difference in the surface potential of about 10 mV, but a classic alternation is not observed [50]. At present this behavior is not understood.

1.7

Spray- and Spin-Assisted Multilayer Assembly

In a variation to the deposition by adsorption from solution, the application of layers by spraying was introduced by L. Winterton [51] and J. Schlenoff [52] and the use of spin-coaters was demonstrated by J.-D. Hong [53, 54] and also by H.-L. Wang [55, 56]. Both spraying and spin coating have the advantage that only small amounts of liquids are needed to coat large surface areas. More importantly, both techniques can lead to an enormous gain in deposition speed. We have recently shown that this reduction in deposition speed by spray-assisted assembly [15] does lead to well ordered LbL-films [16] and does not lead to a degradation of the nanostratification of such spray-assembled films (Figure 1.8).

Again, this underlines that the deposition conditions play an important role with respect to the final film characteristics. Spraying and spin coating extend the

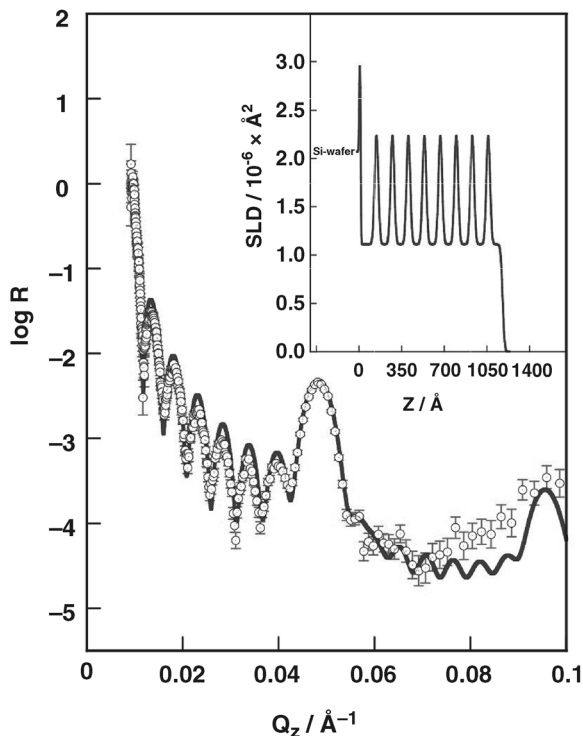


Figure 1.8 Neutron reflectometry data of spray-assembled LbL-films of Si/SiO₂/PEI/[(PSSH₇/PAH)₄/(PSSd₇/PAH)₁]₈/(PSSH₇/PAH)₄. The data points are raw data, the solid line is the expected trace for

the scattering length densities displayed in the inset [16]. As previously reported, spray-assembled films were found to be thinner than films assembled by dipping.

parameter space of LbL-deposition even further. It is to be expected, however, that both methods will contribute to the general acceptance of the LbL-technology.

1.8

Recent Developments

1.8.1

Self-patterning LbL-Films

While the patterning of LbL-films has already been described using classic micro- and nanostructuring techniques, polyelectrolyte multilayers are typically fairly smooth structures. In some cases, especially after changing the pH or the ionic strength, some surface corrugations were observed (sometimes in the context of changing the porosity of the film), but the controlled preparation of nanoscale surface patterns of polyelectrolyte multilayer films is hard to achieve.

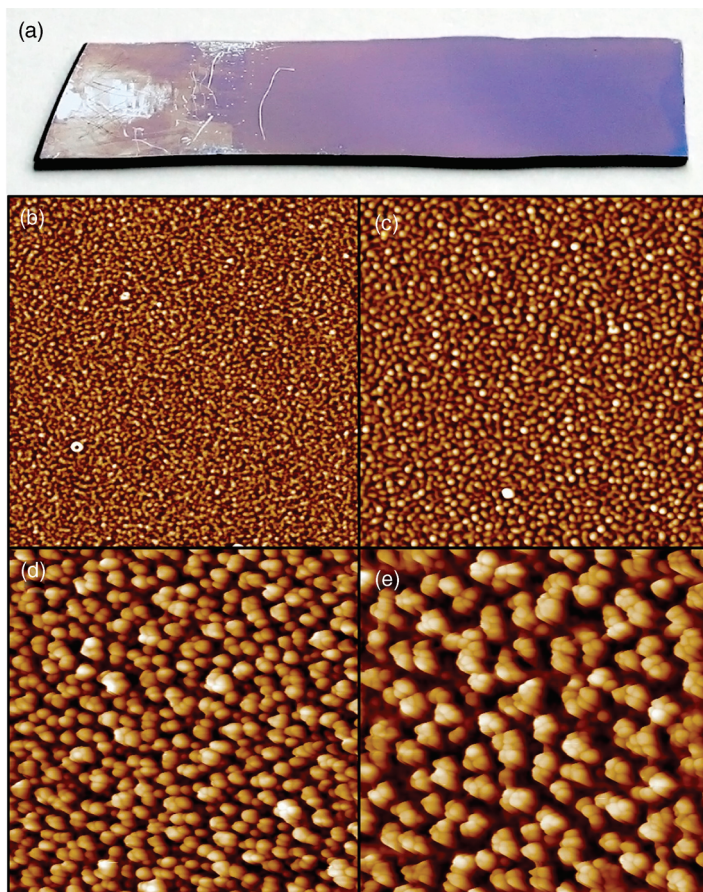


Figure 1.9 Photographic image of a $(\text{PSP}/\text{PAH})_n$ “film” with $n = 75$ on a silicon wafer (a) and AFM topographic images with $n = 3$ (b), $n = 10$ (c), $n = 30$ (d) and $n = 55$ (e), the dimensions of each image being 2×2 microns. Quantitative evaluation shows that the surface roughness of the “films” scales linearly with the “film” thickness [50].

It turns out that the poly(sodium phosphate)/poly(allylamine hydrochloride) system mentioned above allows one to precisely control the feature size of nanoscale surface patterns in LbL-assembled deposits (Figure 1.9) [50].

1.8.2

Deposition of LbL-Films on Very Small Particles

While LbL-assembly is easy to envision on macroscopic objects, it is much more difficult to imagine how very small objects that cannot be handled individually can be coated. In the case of very small objects it is required to bring the objects in question in contact with an oppositely charged macromolecule in the same solution, a situation that is well known as a classic condition for bridging flocculation. Such

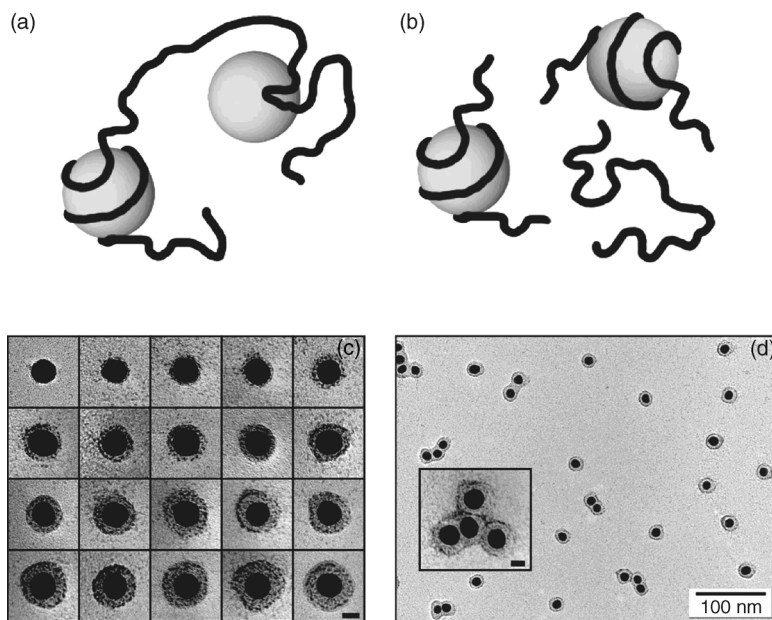


Figure 1.10 (a,b) Schematic showing bridging flocculation of two nanoparticles connected by a single chain of a long polymer (a) and two nanoparticles wrapped individually with short polymers that are in stoichiometric excess (b) [34]. (c,d) Electron microscopic images of a $(\text{PAH/PSS})_n$ film stepwise assembled around gold nanoparticles with a diameter of 13 nm (c). The scale bar is 10 nm. (d) is an electron micrograph of a suspension of particles coated

with 13 layers that demonstrates that the majority of particles are individually dispersed [33]. This is very important for therapeutic applications (e.g., [36]) where precise particle diameters are required for passive tissue targeting which is proposed for tumor therapy by extravasation of nanoparticles through increased permeability of the tumor vasculature and ineffective lymphatic drainage (EPR effect) [57].

investigations were started in 1995 by T. Mallouk, who LbL-assembled redox-active components in an onion-like fashion around Cab-O-Sil SiO_2 particles [28]. In 1998 the team around H. Möhwald prepared the first micron-sized hollow spheres, a procedure that was termed “colloidal templating” [29, 30] and that rapidly then developed a dynamic of its own (several chapters in this book). A little bit later the team of F. Caruso coated gold nanoparticles with LbL-films [31, 32]. Avoiding bridging flocculation in coating nanoparticles with oppositely charged polyelectrolytes turned out to be a very difficult task when assembling larger numbers of layers on nanoscale particles [33, 34]. Figure 1.10 shows the deposition of a total of 20 polyelectrolyte layers on gold nanoparticles with a size of 13 nm and that these particles remain predominantly individually dispersed. These experiments led later to the proof of a well ordered layer structure even around small particles through distance dependent quenching of fluorescence [35], and to the potential application of such particles as multifunctional therapeutic agents [36]. We were in fact able to prepare for the first time nanoparticles equipped with dual functionality: capable of releasing a cytotoxic drug and stealthy toward THP-1 cells.

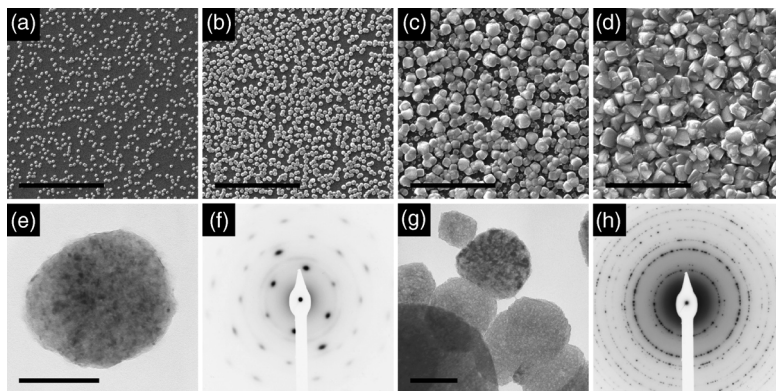


Figure 1.11 Top view scanning electron micrographs of films composed of CaF_2 (a–d) at various stages of film growth. The numbers of spray cycles for each sample are as follows: 3 (a), 10 (b), 50 (c) and 200 (d). The scale bar represents $10\ \mu\text{m}$. Electron micrographs and

diffraction patterns were obtained by transmission electron microscopy from CaF_2 crystals after one spraying cycle (e, f) and three spraying cycles (g, h). The scale bars represent 100 nm for image e and 200 nm for image g) [58].

1.8.3

Purely Inorganic LbL-“Films”

Very recently we opened the field toward another important class of LbL-assembled films. Based on the alternate spraying of complementary inorganic salt solutions against a receiving surface we described the formation of purely inorganic films (“precipitation coating”) [58]. The method applies whenever the solubility of the deposited material is smaller than that of the salts in the solutions of the reactants. The film thickness is controlled from nanometers to hundreds of micrometers simply by varying the number of spraying steps; 200 spray cycles, corresponding to less than 15 min deposition time, yield films with thicknesses exceeding one micrometer and reaching tens of micrometers in some cases.

CaF_2 films constitute a case in which the individual crystals are monocrySTALLINE and form a film in which they grow together with an increasing number of spraying cycles, finally forming a quite dense film with few pores (Figure 1.11). Other inorganic materials yield different structures and morphologies. The approach is also compatible with conventional layer-by-layer assembly and permits the fabrication of multimaterial sandwich-like coatings. This solution-based spray-assembly process is similar to the so-called SILAR method for preparing polycrystalline inorganic films which was first reported by Nicolau in 1985 [42]. The obvious advantage of a spray process over immersion is that it can easily be adapted to different surfaces without needing large baths for large objects. Evidently then, the spray-assembly of complementary species also reduces the risk for cross-contamination as baths are not being used.

1.9

Final Remarks

It has been a pleasure to see Layer-by-Layer assembly grow to the state it has reached today. The chapters that follow in the new edition of this book are a very clear indication that LbL-assembly has reached a certain maturity (despite quite a few remaining open questions) and that a new area has begun in which polyelectrolyte multilayers are more and more being used as materials or in devices that can frequently not be prepared otherwise. In comparison with the first edition, the book has grown in volume since many new fields of application have been “popping up”. Instead of giving a detailed overview of the field, as was my intention in my chapter in the first edition of this book, I wanted to focus on presenting the guiding principles of layer-by-layer assembly and also on its historical context (as far as I am aware of it) and on the development of the technique.

Last year we had the occasion to organize at our institute the international LbL-Symposium 2011: “20 Years Layer-by-Layer Assembly: New Frontiers for Fundamental Science and for Applications”. While over 160 participants attended the meeting (see Figure 1.12), the tight agendas of today caused some invitations for presentations to be declined as was unfortunately also the case with some invitations for chapters in the second edition of this book. Nevertheless, during this meeting a phrase was coined by Helmut Ringsdorf who expressed his amazement about the exceptional development of the field. In the context



Figure 1.12 Conference photograph taken on occasion of the international LbL-Symposium 2011: “20 Years Layer-by-Layer Assembly: New Frontiers for Fundamental Science and for Applications”, that was held March 10–12, 2011 in our institute in Strasbourg, France.

of delivering his presentation with the title: “Art is I – Science is We” he remarked that Layer-by-Layer assembly benefitted strongly in its development from a unique community that distinguishes itself from others through “*Competitive Collaboration*”.

References

- 1 Decher, G. (1996) Layered nanoarchitectures via directed assembly of anionic and cationic molecules, in *Templating, Self-Assembly and Self-Organization* (eds J.-P. Sauvage and M.W. Hosseini), Pergamon Press, Oxford, pp. 507–528.
- 2 Langmuir, I. and Blodgett, K.B. (1935) Über einige neue methoden zur untersuchung von monomolekularen Filmen. *Kolloid-Z.*, **73**, 257–263.
- 3 Blodgett, K.B. (1934) Monomolecular films of fatty acids on glass. *J. Am. Chem. Soc.*, **56**, 495.
- 4 Blodgett, K.B. and Langmuir, I. (1937) Build-up films of barium stearate and their optical properties. *Phys. Rev.*, **51**, 964–982.
- 5 Kuhn, H. and Möbius, D. (1971) Systems of Monomolecular Layers—Assembling and Physico-Chemical Behavior. *Angew. Chem. Int. Ed.*, **10**, 920–637.
- 6 Inacker, O., Kuhn, H., Möbius, D., and Debuch, G. (1976) Manipulation in molecular dimensions. *Z. Phys. Chem. Neue Folge*, **101**, 337–360.
- 7 Decher, G. and Hong, J.-D. (1991) Buildup of ultrathin multilayer films by a self-assembly process: I. Consecutive adsorption of anionic and cationic bipolar amphiphiles. *Makromol. Chem., Macromol. Symp.*, **46**, 321–327.
- 8 Decher, G., Hong, J.-D., and Schmitt, J. (1992) Buildup of ultrathin multilayer films by a self-assembly process: III. Consecutively alternating adsorption of anionic and cationic polyelectrolytes on charged surfaces. *Thin Solid Films*, **210/211**, 831–835.
- 9 Decher, G., Eßler, F., Hong, J.-D., Lowack, K., Schmitt, J., and Lvov, Y. (1993) Layer-by-layer adsorbed films of polyelectrolytes, proteins or DNA. *Polymer Preprints*, **34**, 745.
- 10 Schmitt, J., Grunewald, T., Decher, G., Pershan, P.S., Kjaer, K., and Losche, M. (1993) Internal structure of Layer-by-layer adsorbed polyelectrolyte films - a neutron and X-ray reflectivity study. *Macromolecules*, **26**, 7058–7063.
- 11 Decher, G. (1996) Multilayer films (polyelectrolytes), in *The Polymeric Materials Encyclopedia: Synthesis, Properties, and Applications* (ed. J.C. Salamone), CRC Press Inc., Boca Raton, pp. 4540–4546.
- 12 Decher, G. (1997) Fuzzy nanoassemblies: Toward layered polymeric multicomposites. *Science*, **277**, 1232–1237.
- 13 Decher, G., Eckle, M., Schmitt, J., and Struth, B. (1998) Layer-by-layer assembled multicomposite films. *Curr. Opin. Colloid Interface Sci.*, **3**, 32–39.
- 14 Losche, M., Schmitt, J., Decher, G., Bouwman, W.G., and Kjaer, K. (1998) Detailed structure of molecularly thin polyelectrolyte multilayer films on solid substrates as revealed by neutron reflectometry. *Macromolecules*, **31**, 8893–8906.
- 15 Izquierdo, A., Ono, S.S., Voegel, J.C., Schaaf, P., and Decher, G. (2005) Dipping versus spraying: Exploring the deposition conditions for speeding up layer-by-layer assembly. *Langmuir*, **21**, 7558–7567.
- 16 Felix, O., Zheng, Z.Q., Cousin, F., and Decher, G. (2009) Are sprayed LbL-films stratified? A first assessment of the nanostructure of spray-assembled multilayers by neutron reflectometry. *C. R. Chim.*, **12**, 225–234.
- 17 Decher, G., Lehr, B., Lowack, K., Lvov, Y., and Schmitt, J. (1994) New nanocomposite films for biosensors - layer-by-layer adsorbed films of polyelectrolytes, proteins or DNA. *Biosens. Bioelectron.*, **9**, 677–684.

- 18 Lvov, Y., Ariga, K., and Kunitake, T. (1994) Layer-by-layer assembly of alternate protein polyanion ultrathin films. *Chem. Lett.*, 2323–2326.
- 19 Lvov, Y., Decher, G., and Sukhorukov, G. (1993) Assembly of thin films by means of successive deposition of alternate layers of DNA and poly(allylamine). *Macromolecules*, **26**, 5396–5399.
- 20 Sukhorukov, G.B., Möhwald, H., Decher, G., and Lvov, Y.M. (1996) Assembly of polyelectrolyte multilayer films by consecutively alternating adsorption of polynucleotides and polycations. *Thin Solid Films*, **284/285**, 220–223.
- 21 Lvov, Y., Haas, H., Decher, G., Möhwald, H., Michailov, A., Mtchedlishvili, B., Morgunova, E., and Vainshtain, B. (1994) Successive deposition of alternate layers of polyelectrolytes and a charged virus. *Langmuir*, **10**, 4232–4236.
- 22 Kleinfeld, E.R. and Ferguson, G.S. (1994) Stepwise formation of multilayered nanostructural films from macromolecular precursors. *Science*, **265**, 370–373.
- 23 Keller, S.W., Kim, H.-N., and Mallouk, T.E. (1994) Layer-by-layer assembly of intercalation compounds and heterostructures on surfaces: Towards molecular “beaker” epitaxy. *J. Am. Chem. Soc.*, **116**, 8817–8818.
- 24 Kotov, N.A., Dékány, I., and Fendler, J.H. (1995) Layer-by-layer self-assembly of polyelectrolyte-semiconductor nanoparticle composite films. *J. Phys. Chem.*, **99**, 13065–13069.
- 25 Schmitt, J., Decher, G., Dressik, W.J., Brandow, S.L., Geer, R.E., Shashidhar, R., and Calvert, J.M. (1997) Metal nanoparticle/polymer superlattice films: Fabrication and control of layer structure. *Adv. Mater.*, **9**, 61–65.
- 26 Schmitt, J., Grünewald, T., Kjær, K., Pershan, P., Decher, G., and Lösche, M. (1993) The internal structure of Layer-by-layer adsorbed polyelectrolyte films: A neutron and X-ray reflectivity study. *Macromolecules*, **26**, 7058–7063.
- 27 Lösche, M., Schmitt, J., Decher, G., Bouwman, W.G., and Kjær, K. (1998) Detailed structure of molecularly thin polyelectrolyte multilayer films on solid substrates as revealed by neutron reflectometry. *Macromolecules*, **31**, 8893–8906.
- 28 Keller, S.W., Johnson, S.A., Brigham, E.S., Yonemoto, E.H., and Mallouk, T.E. (1995) Photoinduced charge separation in multilayer thin films grown by sequential adsorption of polyelectrolytes. *J. Am. Chem. Soc.*, **117**, 12879–12880.
- 29 Caruso, F., Caruso, R.A., and Möhwald, H. (1998) Nanoengineering of inorganic and hybrid hollow spheres by colloidal templating. *Science*, **282**, 1111–1114.
- 30 Donath, E., Sukhorukov, G.B., Caruso, F., Davis, S.A., and Möhwald, H. (1998) Novel hollow polymer shells by colloid-templated assembly of polyelectrolytes. *Angew. Chem. Int. Ed.*, **37**, 2202–2205.
- 31 Gittins, D.I. and Caruso, F. (2000) Multilayered polymer nanocapsules derived from gold nanoparticle templates. *Adv. Mater.*, **12**, 1947.
- 32 Gittins, D.I. and Caruso, F. (2001) Tailoring the polyelectrolyte coating of metal nanoparticles. *J. Phys. Chem. B*, **105**, 6846–6852.
- 33 Schneider, G. and Decher, G. (2004) From functional core/shell nanoparticles prepared via layer-by-layer deposition to empty nanospheres. *Nano Lett.*, **4**, 1833–1839.
- 34 Schneider, G. and Decher, G. (2008) Functional core/shell nanoparticles via layer-by-layer assembly. investigation of the experimental parameters for controlling particle aggregation and for enhancing dispersion stability. *Langmuir*, **24**, 1778–1789.
- 35 Schneider, G., Decher, G., Nerambourg, N., Praho, R., Werts, M.H.V., and Blanchard-Desce, M. (2006) Distance-dependent fluorescence quenching on gold nanoparticles ensheathed with layer-by-layer assembled polyelectrolytes. *Nano Lett.*, **6**, 530–536.
- 36 Schneider, G.F., Subr, V., Ulbrich, K., and Decher, G. (2009) Multifunctional cytotoxic stealth nanoparticles. A model approach with potential for cancer therapy. *Nano Lett.*, **9**, 636–642.

- 37 Iler, R.K. (1966) Multilayers of colloidal particles. *J. Colloid Interface Sci.*, **21**, 569–594.
- 38 Ries, H.E. and Meyers, B.L. (1971) Microelectrophoresis and electron-microscope studies with polymeric flocculants. *J. Appl. Polym. Sci.*, **15**, 2023–2034.
- 39 Gölander, C.-G., Arwin, H., Eriksson, J.C., Lundstrom, I., and Larsson, R. (1982) Heparin surface film formation through adsorption of colloidal particles studied by ellipsometry and scanning electron microscopy. *Colloids Surf.*, **5**, 1–16.
- 40 Fromherz, P. (1980) Assembling proteins at lipid monolayers, in *Electron Microscopy at Molecular Dimensions* (eds W. Baumeister and W. Vogell), Springer Verlag, Berlin, Heidelberg, pp. 338–349.
- 41 Aksberg, R. and Ödberg, L. (1990) Adsorption of an anionic polyacrylamide on cellulosic fibers with pre-adsorbed cationic polyelectrolytes. *Nord. Pulp Pap. Res. J.*, **5**, 168–171.
- 42 Nicolau, Y.F. (1985) Solution deposition of thin solid compound films by a successive ionic-layer adsorption and reaction process. *Appl. Surf. Sci.*, **22-3**, 1061–1074.
- 43 Gaines, G.L. (1983) On the history of Langmuir-Blodgett films. *Thin Solid Films*, **99**, R9–R13.
- 44 Gaines, G.L. (1983) Deposition of colloidal particles in monolayers and multilayers. *Thin Solid Films*, **99**, 243–248.
- 45 Ariga, K., Hill, J.P., and Ji, Q.M. (2007) Layer-by-layer assembly as a versatile bottom-up nanofabrication technique for exploratory research and realistic application. *PCCP Phys. Chem. Chem. Phys.*, **9**, 2319–2340.
- 46 Gill, R., Mazhar, M., Félix, O., and Decher, G. (2010) Covalent Layer-by-layer assembly and solvent memory of multilayer films from homobifunctional poly(dimethoxysilane). *Angew. Chem. Int. Ed.*, **49**, 6116–6119.
- 47 Decher, G. and Schlenoff, J.B. (eds) (2003) *Multilayer Thin Films: Sequential Assembly of Nanocomposite Materials*, Wiley-VCH, Weinheim.
- 48 Ladam, G., Schaad, P., Voegel, J.C., Schaaf, P., Decher, G., and Cuisinier, F. (2000) In-situ determination of the structural properties of initially deposited polyelectrolyte multilayers. *Langmuir*, **16**, 1249–1255.
- 49 Gucht, J.v.d., Spruijt, E., Lemmers, M., and Stuart, M.A.C. (2011) Polyelectrolyte complexes: Bulk phases and colloidal systems. *J. Colloid Interface Sci.*, **361**, 407–422.
- 50 Cini, N., Tulun, T., Decher, G., and Ball, V. (2010) Step-by-step assembly of self-patterning polyelectrolyte films violating (almost) all rules of layer-by-layer deposition. *J. Am. Chem. Soc.*, **132**, 8264–8265.
- 51 Winterton, L., Vogt, J., Lally, J., and Stockinger, F. (1999) Coating of polymers, Novartis AG, World Patent WO9935520.
- 52 Schlenoff, J.B., Dubas, S.T., and Farhat, T. (2000) Sprayed polyelectrolyte multilayers. *Langmuir*, **16**, 9968–9969.
- 53 Cho, J., Char, K., Hong, J.D., and Lee, K.B. (2001) Fabrication of highly ordered multilayer films using a spin self-assembly method. *Adv. Mater.*, **13**, 1076.
- 54 Lee, S.S., Hong, J.D., Kim, C.H., Kim, K., Koo, J.P., and Lee, K.B. (2001) Layer-by-layer deposited multilayer assemblies of ionene-type polyelectrolytes based on the spin-coating method. *Macromolecules*, **34**, 5358–5360.
- 55 Chiarelli, P.A., Johal, M.S., Casson, J.L., Roberts, J.B., Robinson, J.M., and Wang, H.L. (2001) Controlled fabrication of polyelectrolyte multilayer thin films using spin-assembly. *Adv. Mater.*, **13**, 1167.
- 56 Chiarelli, P.A., Johal, M.S., Holmes, D.J., Casson, J.L., Robinson, J.M., and Wang, H.L. (2002) Polyelectrolyte spin-assembly. *Langmuir*, **18**, 168–173.
- 57 Peer, D., Karp, J.M., Hong, S., Farokhzad, O.C., Margalit, R., and Langer, R. (2007) Nanocarriers as an emerging platform for cancer therapy. *Nature Nanotechnol.*, **2**, 751–760.
- 58 Popa, G., Boulmedais, F., Zhao, P., Hemmerle, J., Vidal, L., Mathieu, E., Felix, O., Schaaf, P., Decher, G., and Voegel, J.C. (2010) Nanoscale precipitation coating: The deposition of inorganic films through step-by-step spray-assembly. *ACS Nano*, **4**, 4792–4798.

