Tutorial

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Coating processes for plastic optics

Abstract: Transparent plastics have been used for optical applications with growing demand. This development is accompanied by a desire for extended surface functionalities. Most important optical surface function is antireflection (AR), which is performed mainly by applying plasma-assisted processes. Critical considerations for coating polymers include interaction with emission from plasma and thermal stress. State-of-the-art vacuum processes for coating on plastic, as well as new results of research and development in the fields of AR design and AR structures will be introduced and discussed.

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1 Introduction

Polymers are lighter than glass and are easy to manufacture [1]. The low weight of polymers was essential for developing plastic eyeglasses. Today, more than 90% of all eyeglasses in developed countries consist of plastic [2]. The use of plastics in automotive applications is also driven by their low weight, which leads to energy savings. The possibility of shaping complicated parts by injection molding and hot embossing is fundamental for low-cost mass production, on the one hand, and for manufacturing multicomponent parts, with new possibilities for design and construction, on the other hand. Injection molded aspherical and freeform lenses are important for many applications. There is an increasing demand for more complex camera systems containing plastic lenses in consumer products like smart phones and for security and automotive devices.

The desire for more complexity and higher quality of devices is accompanied by a desire for extended surface functionalities of plastic optical parts. Antireflection (AR) coatings are the most important optical coatings for plastics. Systems consisting of several lenses cannot be used without excellent AR properties. In addition, broadband AR properties are required for eyeglasses as well as display covers for cars, machine devices, and medical instruments.

Furthermore, coatings can help to overcome or abate the disadvantageous properties of plastics. The main disadvantage of plastics to overcome is their low abrasion and scratch resistance, but properties such as resistance to cleaning reagents and chemicals or easy-to-clean function can also be realized. Such integrated functions, together with the optical function, require intelligent coating solutions that have to be optimized carefully for each application.

One of the first steps in plastic optics development is to choose a suitable plastic material. All aspects of coating must be considered during an early development phase of the product. The optical and mechanical requirements for the surfaces to coat and the later application conditions have to be taken into account to find the most suitable plastic material. This tutorial may help to identify suitable combinations of polymer materials and deposition processes, especially for achieving antireflection properties. The general problems of polymers in vacuum coating processes are discussed to give advice for the development of process parameters and coating designs.

2 Plastic materials for optical applications

The diversity of transparent polymers with regard to chemical composition is very large. Table 1 summarizes some properties of transparent polymers belonging to different polymer classes. All materials are thermoplastics and are, therefore, useful for injection molding and hot embossing. Mainly, thermoplastic polymers are used for precision optical elements. Thermoplastics consist of non-crosslinked chains. They become liquid in the glass

Table 1 Properties of thermoplastics for optical application.

Polymer name	Brand name	n_D (587.6 nm)	Abbe number	Transmittance 3 mm (%)	Density (g/cm³)	Water absorption (%) ISO 62	Deflect. temp. ISO75-2 (°C)	Coating adhesion[a]
PMMA	Plexiglas 6N, 7N, 8N	1.491	58	92	1.19	2.2	85	+
Methylmethacrylate copolymer	Plexiglas HW55	1.51	49	90	1.19	2.2	106	++
Poly(n-methyl methacryl imide)	Pleximid TT70	1.54	43	91	1.21	6	158	++
PC	Makrolon LQ2647	1.585	30	89	1.2	0.4	120	++
PC copolymer	Apec HT9351	1.572	30	88	1.15	0.3	159	+
Cycloolefin copolymer (COP)	Topas 5013	1.533	58	92	1.02	<0.01	123	+++
COP	Zeonex E48R	1.53	56	92	1.01	<0.01	122	+++
COP	Zeonex 480R	1.525	56	92	1.01	<0.01	123	+++
COP	Zeonex F52R	1.535	56	91	1.02	<0.01	144	+++
COP	Zeonor 1020R	1.53	56	92	1.01	<0.01	101	+++
COP	Zeonex 330R	1.509	56	92	0.95	<0.01	110	+
Polyether sulfone	Ultrason E2010	1.65	20	83	1.37	2.2	212	+++
Polyamide	Trogamid CX7323	1.516	45	89	1.02	3.5	122	+++
Polyester	OKP-4	1.607	27	88	1.22	0.15	105	+++

[a]Experimental results: adhesion of AR coatings deposited by PIAD; +++ very good; ++ good with some limitations; + good only by applying special conditions.

transition region and convert into a solid after cooling down. This process is reversible and is a precondition for replication by injection molding. In addition to the main polymer classes shown in Table 1, there are many other compositions, and nearly everyday, new grades conquer the market. This is fantastic, on the one hand, because these materials are normally optimized for a special application or exhibit new combinations of properties. On the other hand, the risk is increasing that proved coating processes cannot be applied successfully to these new materials. Just a slight variation of the chemical structure can change the coatability of a polymer.

Two polymers that have been known and studied for a long time are acrylic [poly(methyl methacrylate) (PMMA) (http://www.plexiglas.de/product/plexiglas/en/Pages/default.aspx)] and polycarbonate (PC, poly-bisphenyl-A-carbonate, i.e., Makrolon®) (http://www.makrolon.de/bms/db-rsc/makroloncmsr6.nsf/id/home_en). A newer class with a growing number of members is the polycycloolefines, which are based on norbornene [3]. Optical-grade polycycloolefines, as well as PMMA and PC, exhibit high transmission without a reasonable absorption loss in the visible range. Figure 1 shows the basic chemical structures of these polymer groups.

Polymers belonging to the same classes typically show basic similarities caused by the backbone structure but have special properties caused by additives and larger side-chain modifications. However, the chemical variety within the polymer classes is sometimes hard to recognize from the polymer names. For example, the trade name 'Zeonex' is used for multiple polycycloolefines with

markedly different chemical compositions. Infrared spectroscopy can be used to clarify this (Figure 2). Different numbers and letters behind a trade name indicate, in most cases, only slight chemical modifications by additives (i.e., Makrolon, trade name for PC), which cannot be recognized in the infrared spectrum.

Polymer manufacturers try to modify the materials to obtain higher thermal stability by co-polymerization with additional monomers. For newly developed materials, the properties relevant for coating can hardly be derived from related known materials and should be investigated experimentally. All recommendations regarding coating properties given in Table 1 have been achieved in that way.
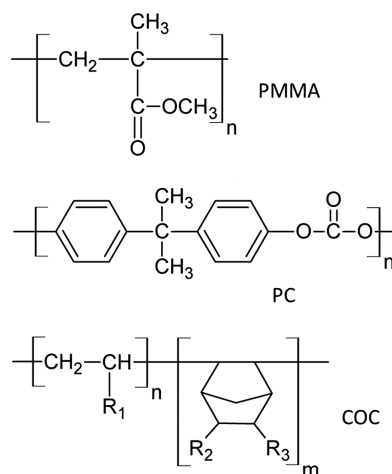

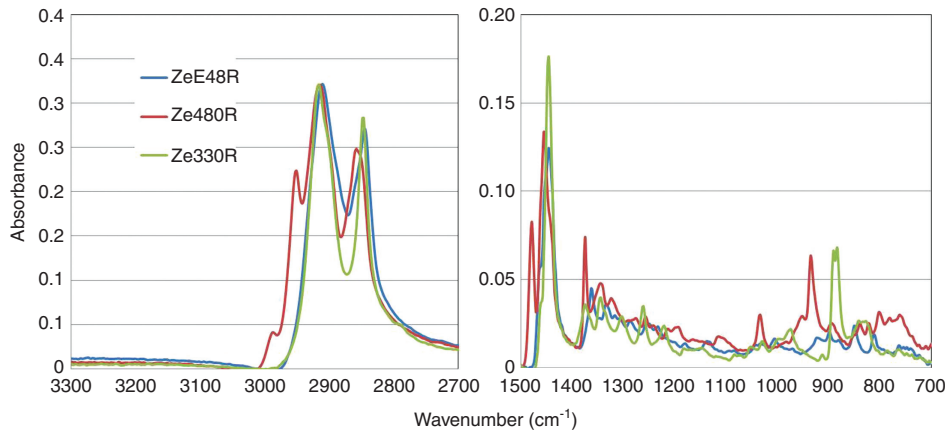**Figure 1** Basic chemical structures of PMMA, PC, and cycloolefine copolymers (COC).

Figure 2 Infrared spectra of several polymers with the same tradename 'Zeonex' illustrating their different chemical compositions.

Besides the thermoplastics, there is a large polymer group of thermosetting polymers, which cannot remold thermally. Prominent examples are the eyeglass material CR-39 [ADC, poly(diethyleneglycol bis(allyl carbonate)] and some high-index poly(thio-urethanes) (http://www.mitsu-ichemicals.com/mr-series.htm). A thermosetting optical element is obtained by mixing and chemically reacting at least two components, mostly inside of a polished form to prepare an optical-grade surface. The other surface has to be shaped and polished afterward because of shrinkage that occurs during the reaction. Researchers are forging ahead with the use of composites with non-thermo plasticity for precision optical elements, mainly for micro-optics. Based on the backbones of thermoplastics, new materials are created using crosslinking reagents and UV irradiation or heat treatment for rigidifying. The most important crosslinked resins are acrylates, epoxides, and urethanes. Again, the behaviors of coatings of these materials cannot be derived from their backbone structures, in general. However, the higher crosslinked state may stabilize the materials, and plasma damage and adhesion problems do not occur very often. Many of these new composites contain siloxane groups. As a rule of thumb, the properties of these materials tend to be more similar to those of inorganic glasses the higher the concentration of siloxane groups is. Hundreds of thermosetting resins have entered the market during the last few years. The characteristics of some of these resins are summarized in (http://www.chemicalbook.com/ProductNameList_30_5100_EN.htm).

3 Plastics in plasma-assisted processes

Optical coatings, for example, antireflection layers, are mainly deposited by vacuum processes (evaporation or sputtering). Modern coating processes typically use low-pressure plasma, which can interact with polymers. The aspects of the coating conditions for coating plastics will be discussed in the next sections.

3.1 Plasma-assisted evaporation

Optical interference coatings require nanometer precision, which can be realized best by vacuum deposition. Coating plastics prohibits, on the other hand, the application of the high-temperature processes that had been used for glass to obtain dense film structures with constant optical properties. Independent from that condition, low-temperature processes are meanwhile in use for glass optics as well. So-called 'ion assistance' or 'plasma assistance' supplies growing films with the energy to achieve a certain grade of densification. For plastics, plasma ion-assisted deposition (PIAD) is the most commonly used technology today. This technology allows long distances between substrates and evaporation sources, in contrast to sputtering techniques where the short distance between target and substrate is dangerous because it can overheat a polymer.

In a SyrusPro (Leybold Optics) PIAD coating chamber, which can be used for coating plastics, the distance between evaporation source and substrate is approximately 70 cm (http://www.leyboldoptics.com/optics/precision-optics/machines/syruspro-family/syruspro-family.html). The schematic assembly is shown in Figure 3.

Oxides are evaporated mostly by an electron beam. In addition to high- and low-index oxide layers, transparent conductive layers and organic hydrophobic layers can be incorporated in multifunctional coatings. During layer deposition, argon ions emitted from the ion source advanced plasma source (APS) are accelerated in the direction of the substrates by a magnetic field. The
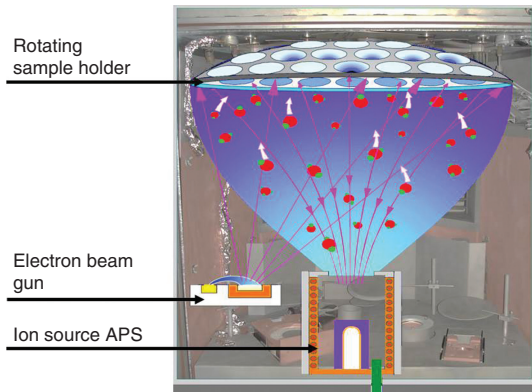
Figure 3 Schematic assembly of a PIAD coating chamber (SyrusPro by Leybold Optics), which can be used for coating plastics. Typical parameter: work pressure: 10^{-2} Pa, gas: Ar, O_2, ion energy 20 eV to 120 eV, ion current density: 0.5 mA/cm^2.

maximum energy of the argon ions can be adjusted in a range from approximately 60 eV up to 150 eV. Atoms of the evaporated material and oxygen added to the process can be exited partly as well. Depending on the ion energy, a densification of the growing film occurs. The adjustment of the densification is very important in the case of coating plastics for several reasons, as explained in the next sections.

3.2 Plasma-polymer interactions

Any contact with plasma can be dangerous for polymers. Photons, electrons, and ions generated by plasma sources and electron beam provide high-enough energy to modify the chemical composition of any organic polymer. Some of the most important mechanisms are shown schematically in Figure 4.

Plasma-polymer interactions have been investigated intensively during the last 20 years to understand plasma activation of polymers and plasma-induced degradation

[4–6]. Low-pressure plasma conditions may cause the breaking of some bonds as well as initiate extensive material loss (etching).

An important reaction mechanism that typically occurs very quickly is the chemical reaction of the activated surface with water molecules from residual gas in the vacuum. The newly formed hydroxyl groups provide a reduced contact angle to water, and the hydrophilic character is often discussed as being useful for enhancing the coating adhesion to oxides and metals [7].

However, bonds of non-crosslinked thermoplastic polymers are sometimes cracked in the same moment, and small organic molecules retain on the surface. These 'weak bonded layers' often reduce the adhesion. In the case of PMMA and other acrylic-containing compounds, the adhesions of all types of coatings are very bad after any arbitrary plasma exposure [8]. In that case especially, the deposition of a first protective layer is helpful. For example, a TiO_2-containing layer (starting with Ti_3O_5 or H4®, Merck KgaA [8]), coating materials deposited by thermal evaporation, can protect the interface from later vacuum ultraviolet radiation (VUV), which is typically emitted by electron beam guns and ion sources.

The reactions, which can occur on PC caused by various plasma treatments and irradiation conditions, have been investigated in detail [9, 10]. Depending on the parameters applied, adhesion loss caused by degradation and also improved adhesion after crosslinking reactions has been found. From our own experience, the best procedure is to forego plasma treatments and start layer systems with a porous silica layer.

Of all polymers, the hydrophobic polycycloolefines can be rapidly activated. Most of them exhibit very good conditions regarding coating adhesion. Polycycloolefines do not contain water and have been coated successfully with several microns thick and highly compacted interference layers [11]. However, an intensive plasma treatment (some minutes) can initiate photo-oxidation of the olefin
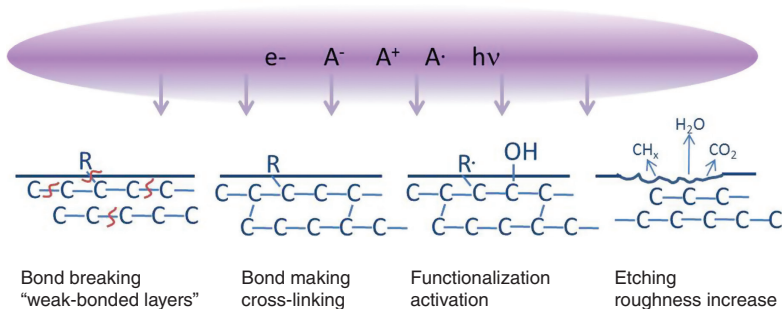

Figure 4 Basic modifications on polymer surfaces by plasma treatment and/or ion bombardment using an inert gas A.

structure, which can progress slowly over months and cause the optical element to appear yellow after a certain time (Figure 5).

Other polymers show adhesion improvement after plasma treatment for a shorter time, but the newly formed bonds are sensitive to hydrolysis, and the adhesion is worse in humid atmosphere. The adhesion of thin films is commonly tested by applying and removing pressure-sensitive tape over cuts made in the film (tape test, see Figure 6). After depositing the first nanometers of a coating, UV radiation may still partly reach the interface. That fact can be critical for later adhesion, as has been found, for example, for PC and PMMA. A useful way to identify an intrinsic adhesion loss (inside the polymer rather than direct in the interface) is to analyze the back of the tape, which was used to remove an inorganic oxide or metallic layer (see Figure 6B). Infrared spectroscopy (in attenuated total reflectance mode) or XPS can be applied to detect organic groups belonging to the polymer. The adhesion loss was extrinsic only if there are no organic groups detectable, and in this case, the polymer should be carefully activated by a short plasma treatment to improve the adhesion.

The direct contact time with emissions from ion sources and electron beam guns should always be as short as possible. However, the specific conditions that are allowed, useful or forbidden, must be determined for each plastic material separately.

3.3 Effects of thin film densification and film stress

The activation of the evaporated material by plasma and the ion bombardment of a growing oxide film determine the densification of the film and all related properties. With higher ion energy and/or ion density, the film density increases [12]. A certain level of densification is necessary to achieve a minimum of mechanical hardness and stability in environmental tests. For example, silica layers deposited cold without any assistance would show a high solubility in water. On glass, it is common to work with a high grade of densification, close to that of the bulk oxide material. Those coatings, therefore, do not absorb water and exhibit a stable refractive index.

On plastic, a high densification of growing oxide layers is dangerous for several reasons.

High densification requires a high ion energy, which could damage the polymer as mentioned above. Another point is the film stress. The growth stress mostly increases to reach high compressive values. Even more important for plastics are thermal stresses. Polymers have high thermal expansion coefficients that are typically more than 10 times those of oxide layers. A high plasma load or high ion assistance energies, together with the evaporation heat of the material, cause an increasing temperature during the deposition process and a high level of thermal stress (Figure 7).

Figure 8 shows the increase in temperature during deposition of a TiO_2 single layer applying an ion assistance energy of 120 eV, whereas the temperature is nearly constant during deposition of SiO_2. The evaporation heat, itself, is different for these materials. Linked to the higher evaporation temperatures, the commonly used high-index materials dominate the temperature increase. Especially for thicker interference coatings, the use of materials with lower heat development, i.e., higher parts of low-index material, should be taken into account. Moreover, if the substrate temperature is rising during coating deposition, the residual stress will be distributed inhomogeneously
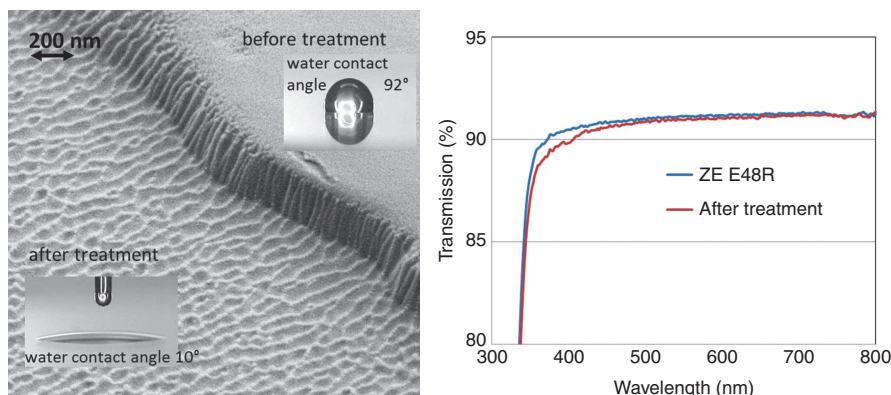

Figure 5 Scanning electron micrograph (SEM) and transmission of ZEONEX E48R before and after plasma exposure and ion bombardment. Optical properties, roughness, and surface energy (water contact angle) are modified (treatment: ion source APS, bias voltage 120 V, 30 sccm Ar/O$_2$, 5×10^{-4} mbar, 300 s).
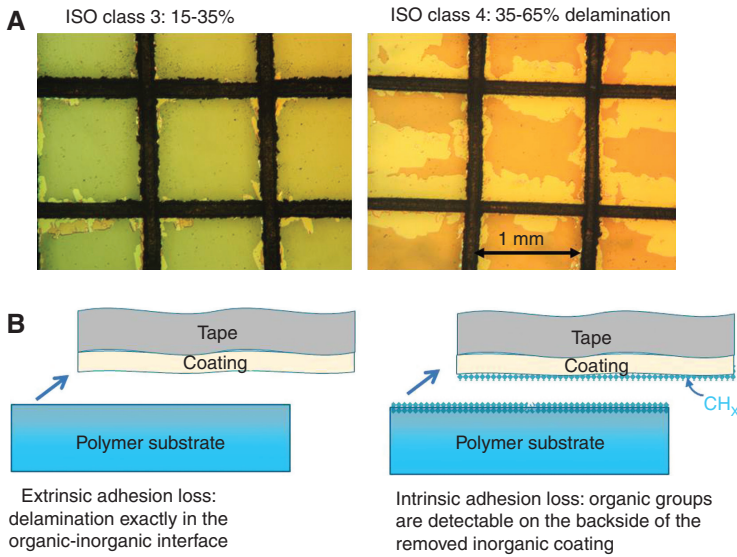
A ISO class 3: 15-35%   ISO class 4: 35-65% delamination

B
Tape
Coating
Polymer substrate

Tape
Coating
CH_x
Polymer substrate

Extrinsic adhesion loss: delamination exactly in the organic-inorganic interface

Intrinsic adhesion loss: organic groups are detectable on the backside of the removed inorganic coating

Figure 6 (A) Examples for adhesion loss after crosscut tape adhesion test (ASTM D3359, DIN ISO 2409), and (B) schematic illustration of intrinsic and extrinsic adhesion loss.

[13]. The layers near the substrate are subjected to the highest level of thermal tensile stress during film deposition, while the last layers receive a high level of compressive stress after venting and cooling to room temperature. Therefore, coatings on plastics may show both tensile and compressive cracking after deposition or environmental testing. Figure 9 shows the appearance of typical cracking caused by tensile and compressive stress.
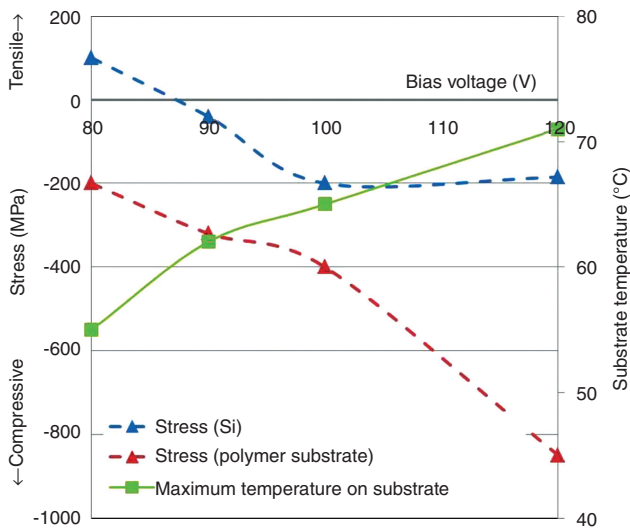
The inhomogeneity of the thermal stress distribution can be minimized by heating the substrates carefully before starting the layer deposition process, but it is not easy to hold the temperature constant. On the other hand, a higher level of compressive stress should be preferred if the coated parts must work later at an elevated temperature. Tensile stress at an elevated temperature typically causes cracking, and the coating and can then no longer be used. High compressive stress is critical if the adhesion is not perfect, and the coating tends to peel off. Only in such a case is typical compressive stress cracking observed.
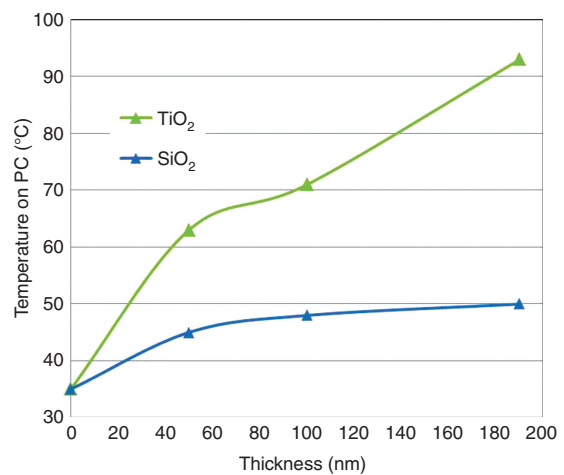

Figure 7 Residual stress of TiO_2 layers (thickness 100 nm) depending on the bias voltage applied during PIAD process. The growth stress (measured on silicon substrate) raises moderately with increasing bias voltage, while the total stress on the polymer substrate is receiving very high values because of the predominating thermal stress.

Figure 8 Temperature change of a polycarbonate surface during ion-assisted deposition of TiO_2 and SiO_2 single layers (PIAD process bias voltage 120 V). The evaporation heat has a more significant influence on the substrate temperature than the ion assistance energy.
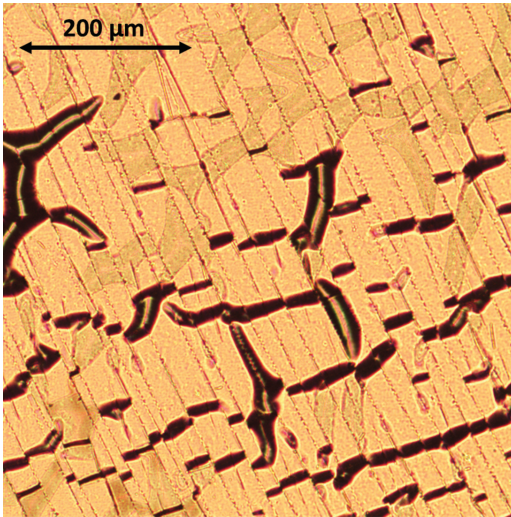
Figure 9 Tensile and compressive stress cracking can occur at the same time on a coated polymer. Tensile cracking (parallel lines or grid of lines) is often caused by heating effects. Compressive stress relaxation of oxide coatings can result in flared and crinkled crack structures if the adhesion is insufficient.

Another critical property caused by high densification is the high barrier for penetrating water that is typical for dense oxide layers. This has to be taken into account for polymers that contain a reasonable amount of water (the typical range is 0.1–5%). The specific value is dependent on the environmental conditions, and all changes occur slowly (Figure 10). If a coating is obstructing water vapor diffusion (i.e., if the temperature is rising), the water vapor pressure will increase inside of the polymer, and water starts to diffuse through the small defects that always exist in coatings. In consequence, the polymer swells along the defects, and the deformations become considerable – often visible to the human eye. Therefore,
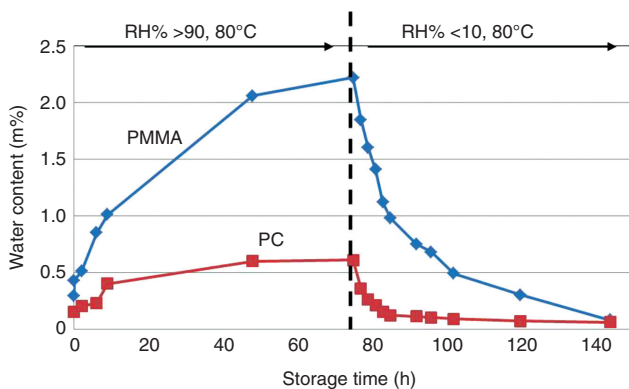
it is important for a water-containing polymer to be able to breathe, which limits the grade of densification. The application of ion assistance of oxide films on plastics is a compromise for all these reasons. Fluctuations of the optical constants caused by the incomplete densification have to be taken into account already for developing suitable coating designs.

4 Antireflection properties

In most optical systems, the light reflected by surfaces would cause significant transmission loss, reduced contrast, and ghost images. Therefore, the antireflection function is the most fundamental property to provide for plastic optics. General aspects of polymer surface modifications and the design and deposition of optical coatings will be explained for the example of antireflection in the next section.

4.1 Interference coatings

Polymers that do not tend to have problems with adhesion may be coated by applying an antireflective coatings as commonly used on glass. Usually, the classical broadband AR coating for the visible spectral range consists of four layers of low-index (L) and high-index (H) (e.g., four-layer design and reflectance shown in Figure 11). The overall
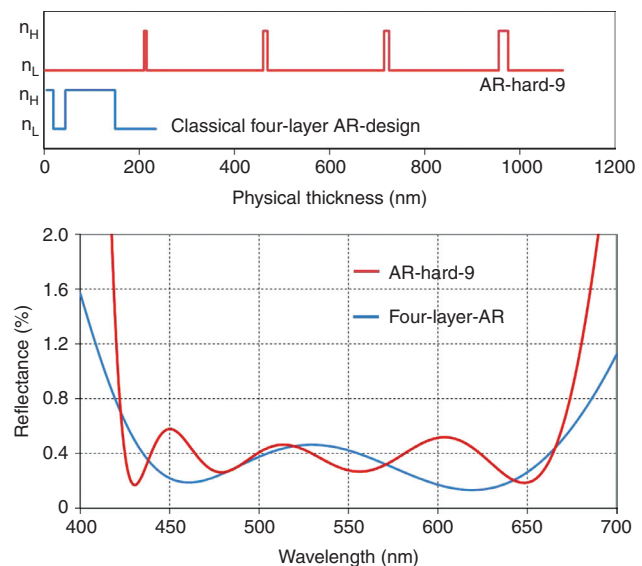

Figure 11 Refractive index profiles and reflectance spectra of AR-hard design (nine layers) compared to a commonly used four-layer design calculated for substrate refractive index 1.53.

Figure 10 Moisture absorption of PMMA and PC during wet storage and during drying at 80°C.

physical thickness is about 180–300 nm [about four in terms of quarter-wave optical thickness (QW)] [14]. SiO_2 or MgF_2 are used as low-index (L) material, and one of various oxides that have a refractive index in the range from 2.0 to 2.5 (for example, TiO_2, Ta_2O_5, HfO_2, ZrO_2, or Nb_2O_5) can be chosen as high-index (H) material. The simplest useful variation for plastic substrates is to apply an additional silica or alumina layer with low or middle density as a starting layer. These materials are known to bond better than others to activated polymer surfaces and make the coating more resistant in environmental tests. Those antireflective designs, with a thickness up to 300 nm, have been applied with good success, i.e., on polycycloolefines. They are also used on all hard coated plastics that have a lacquer as the first hard layer that interfaces with the antireflection coating. Siloxane lacquers are commonly used, for example, on eyeglasses to improve their scratch resistance. Wet chemical hard coatings are also applied in combination with UV-protective layers on PC for outdoor applications [15].

For most thermoplastics, the development of specific coating designs and attention to the deposition parameters is recommended. The following may help in choosing suitable conditions:

– Fluoride coatings tend to show tensile growth stress. On plastics, this would increase crack formation and propagation. Fluoride coating materials including MgF_2 should, therefore, not be used.
– Coating designs must take into account the fluctuations of the refractive index caused by insufficient densification.
– Materials with photocatalytic activity (e.g., TiO_2) must not be used in direct contact with a plastic substrate.
– An essential improvement of surface hardness of a plastic material is possible by applying a coating with a total thickness in the range of several microns. The high total thickness always opens extended possibilities to realize an optical function such as antireflection or filter functions, in addition to the improved abrasion resistance provided.
– In coating designs for plastics with low heat distortion temperatures (e.g., acrylic), the proportion of high-index material should be reduced in favor of the low-index silica to minimize the temperature increase during the evaporation process.
– Coatings for water-containing polymers should not have a high barrier for water vapor penetration. Metallic layers are also not recommended on those substrates, to avoid a swelling in changing environments.

– Coating design and material selection should take into account the requirements for further functionalities, such as UV protection, antistatic properties, or cleanability.

For plastic substrates, in particular, the multifunctional coating design AR-hard was developed [16, 17]. The concept is to use very thin high-index layers imbedded in thicker silica layers to hold the process temperature at a low level. The basic design contains symmetrical periods LHL with a thickness of three quarter waves each as shown schematically in Figures 11 and 12. The sequences of these stacks can be arranged to realize a broadband antireflection function. With a total thickness of up to 3 microns, an improved scratch resistance can be achieved.

A special abrasion-resistant antireflection coating was developed for PC [18]. Generally, the coating adhesion on PC drops if UV radiation (e.g., sunlight) reaches the substrate to coating interface. Therefore, the coating must block the dangerous wavelength range below 400 nm. A modified AR-hard design exhibits high reflection in the range from 350 nm to 400 nm, but this design absorbs all wavelengths below 350 nm by using TiO_2 as the high-index material. The reflection spectrum is shown in Figure 13.

4.2 Effective media

Alternatively to interference layers, low-index gradient layers and nanostructured surfaces are suitable for
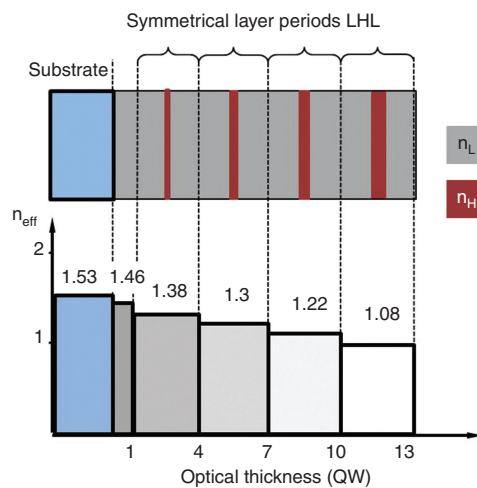

Figure 12 Basic design AR-hard consisting of symmetrical layer periods LHL of low index (n_L) and high index (n_H) layers period. The symmetrical layer sequences with optical thickness of three quarter-waves (QW) provide low effective refractive indices (n_{eff}) to realize the antireflective performance.
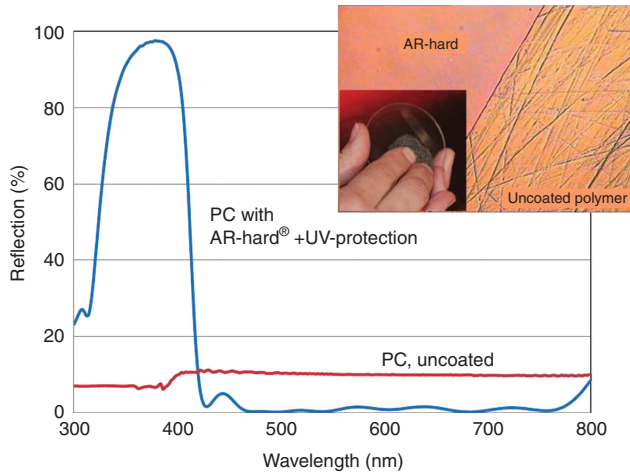
Figure 13 Measured reflection of a polycarbonate sheet coated on both sides. The modified AR-hard coating is exhibiting high reflection in the range from 350 nm to 400 nm and very low reflection in the visible spectral range. The about 1.5-µm thick coating provides an improved scratch resistance.

providing antireflective properties on glass and plastics. Nanostructures with antireflective character were discovered first on the eyes of night-flying insects and are, thus, often called 'moth-eye structures' [19]. While compact low-index materials exhibit minimum refractive indices of 1.46 (SiO_2) or 1.37 (MgF_2), effective media for antireflection should have a lower effective index. Effective media materials are mixtures of a bulk material with air, which is introduced in pores or open structures. Favored optical properties are obtained, especially if the effective index n_{eff} is gradually dropped from the substrate index to that of air [20, 21]. This principle is shown in Figure 14.

Polymers can be molded and etched easily. They are, therefore, particularly suitable for producing nanostructured surfaces exhibiting an antireflection effect. However, it is difficult to obtain very deep structures with the low feature size required to avoid scattering. The
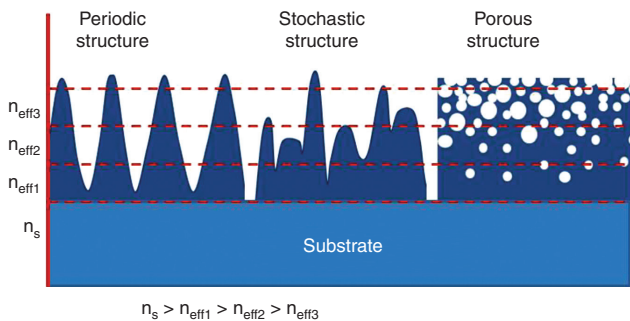
feature size must be only a fraction of the lowest wavelength addressed. Most structures produced by replication are limited to an aspect ratio (structure depth divided by period) of approximately one, which is sufficient for the visible spectral range. An overview of technologies used to produce antireflective nanostructures (not only for plastics) is given in reference [22]. The production of master structures by holographic procedures has been commercialized for the replication of plastic parts [23]. Nano-imprinting is useful for small optical parts, including micro lenses. In this technique, structures are embossed in a liquid polymer or in a composite material and, in a next step, are hardened in the mold by UV radiation [24].

Antireflective structures can also be generated by etching surfaces in an oxygen-containing plasma. This can be performed by using an ion source, as commonly used for ion assistance deposition [25]. On some polymers, suitable nanostructures grow in a self-organized manner within a few minutes. Figure 15 shows the optical performance of PMMA before and after plasma treatment. A broadband antireflective effect appearing at light incidence angles up to 60° has also been achieved. Nearly all polymers can be structured, and the morphology and properties of structures can be adjusted in a broad range [26, 27] (Figure 16). The method is also suitable for processing optical surfaces with complicated geometries, such as Fresnel lenses. Nanostructured polymer surfaces offer an advantage in terms of temperature stability because they are not influenced by thermal stress.

Another technique used to produce effective media on glass or plastic is the wet-chemical deposition of porous layers. Mixtures containing polymer particles with different solubilities are deposited on the substrate in the first
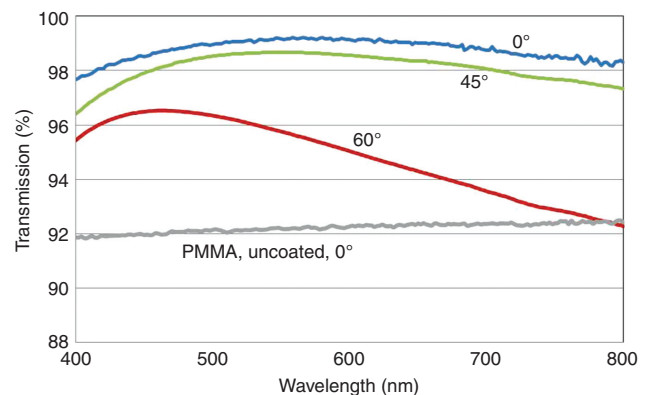

Figure 14 Schematic figure of different surface structures exhibiting a low effective refractive index for antireflection.

Figure 15 Transmission of PMMA with plasma-etched nanostructure on both sides. The transmission was increased in a broad spectral range and for light incidence angles up to 60°.
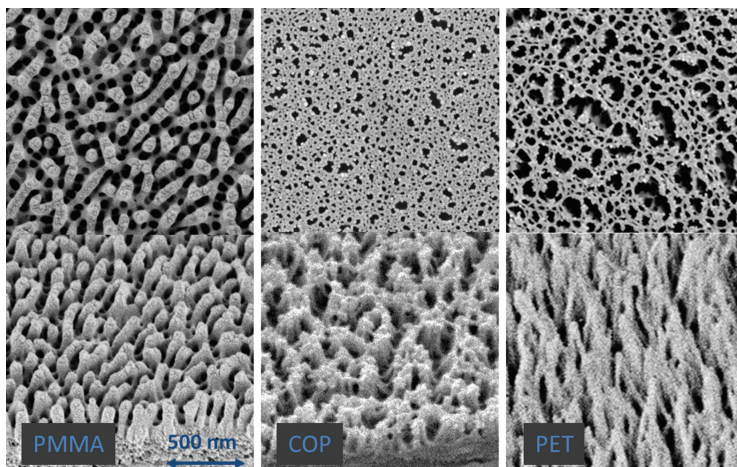
Figure 16 SEM images of antireflective nanostructures on PMMA, Zeonex E48R (COP), and polyethylene terephthalate (PET). Upper row: top-view, lower row: sample 45° inclined.

step. During immersion in a solvent, one of the components is removed to obtain holes [28, 29].

In summary, during the last few years, a growing number of procedures to create antireflective layers with low effective index have been described in the scientific literature and in patents. However, the application of these technologies to the production of plastic optics seems to have stagnated. All of these surfaces have a limited mechanical stability, which limits applications of unprotected areas. Moreover, only coatings exhibiting gradient character are much better regarding optical properties than interference layers [30].

5 Summary and outlook

Polymers are a growing and complex material group. New developments for optical applications with capability and requirements for mass production occur consecutively. They include, for example, medical and bio-photonic parts, smart phone cameras, and displays for all types of devices. The essential advantage for manufacturing is enabling the cost-effective production of complicated optical parts. However, polymers have a versatile chemical composition that is sensitive to energetic radiation. Therefore, the vacuum deposition of polymer optical parts requires adapted processes, coating designs, and deposition parameters. Common antireflective coatings are deposited mainly by evaporation processes. Some coating processes for selected polymers and applications are easily controllable and are currently successfully applied in industry. Extreme application conditions, e.g., automotive specifications or outdoor conditions, are still challenging. However, research and development of new processes is in progress in many places around the world.

While injection molding is a good base for cost-effective production, it seems difficult to establish cost-effective coating procedures for bigger parts, such as car interiors. Evaporation processes are normally carried out in batch processes with limited size; thus, the costs rise extremely quickly for larger coating areas. New coating procedures are needed to solve this problem.

The development of antireflective procedures to realize effective media with low indices and especially with gradient character is a fast-growing field of research. It is foreseeable that those procedures will be integrated in production if the optical properties, especially on curved lenses and for wide-angle applications, exceed the possibilities of conventional antireflective coatings.

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