Antireflection of polymer optics by coating and nano-structuring procedures

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1. Introduction to plastic optics

Injection moulded or hot-embossed polymer optics will replace glass optics whenever improved properties or lower costs can be achieved with the plastic parts. Coatings play an important role in this development [1]. Highly transparent thermoplastic polymers offer significant weight reduction, cost saving and manufacturing advantages for optical components. Optical interference coatings are required to provide a specific optical function within a desired spectral range. The most common applications are antireflection (AR) coatings to increase the transmitted light. Applications for coated transparent plastics are complex formed optical lenses and eye glasses but also display covers for automobile interiors. Especially on eye glasses and display covers multifunctional coatings are required to provide the optical function and to protect the soft surface at the same time. Scratch resistant surfaces with low reflectance can be produced for example by applying the design concept AR-hard® as described in this paper.

If no mechanical protection is required, the generation of sub-wavelength surface structures can be a cost effective alternative to realize antireflective properties. Such structures have been discovered firstly in nature on the cornea of night-flying moths and are called "motheye structures" therefore [2]. A new ion etching procedure to generate an stochastic antireflection structure on poly-methylmethacrylate (PMMA) will be presented here.

2. Technology for coating and ion etching

High vacuum Physical and Chemical Vapour Deposition processes (PVD and CVD) are commonly used for the production of optical interference coatings on glass and other inorganic substrates. Vacuum deposition of optical coatings at low substrate temperature is realizable with Plasma Ion Assisted Deposition- technology (Plasma-IAD) using Leybold APS 904 [3]. A thermally evaporated film is bombarded during its growth with energetic ions emitted by the Advanced Plasma Source (APS) as schematically shown in Figure 1. This results in improved mechanical properties of deposited dielectric films. Applying Plasma-IAD on plastics, the low-pressure plasma can be used in manifold way to modify the polymer surface properties as well as to adjust the mechanical stress of inorganic thin films. The Advanced Plasma Source (APS) of a Leybold box-coater APS904 can also be used to perform the etching procedure on PMMA as described in section 4.

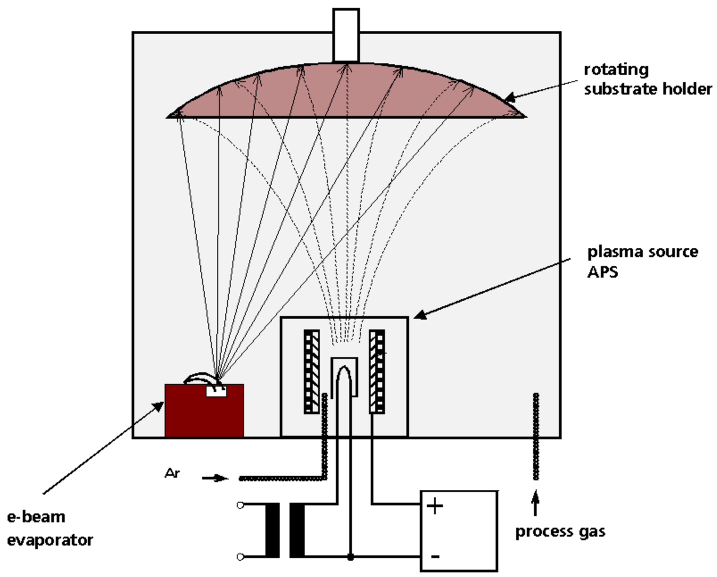

Fig. 1 Plasma-ion assisted deposition using APS904 (Leybold-Optics)

3. Antireflection by deposition of interference coatings

The basic theory to generate antireflective coatings by using the interference effect is well known for many years. Most frequently used broadband AR coatings for the visible spectral range nowadays are adapted from a "quarter-half-quarter" design with the first quarter-wave layer of medium refractive index being replaced in different ways by fractions of high-index and low-index QW layers followed by a 2 QW (half-wave) thick high-index layer and a low-index QW layer on top. Most coatings of that type consist of 4 to 6 layers and are suitable to reduce the residual reflectance of a low index substrate (ns=1.5) to less than 0.5 % in the visible spectral range (420-680 nm). Alternatively, antireflective coatings AR-hard® integrates the antireflection function into a hard layer [4, 5]. The AR-hard® coating is scratch resistant itself because of its high overall thickness. Antireflection coatings of the AR-hard® type can be understood as an arrangement of symmetrical three-layer periods, each of them consisting of a very thin high refractive index layer H in the middle of two thick low refractive index layers L. Figure 2 shows this principle schematically.

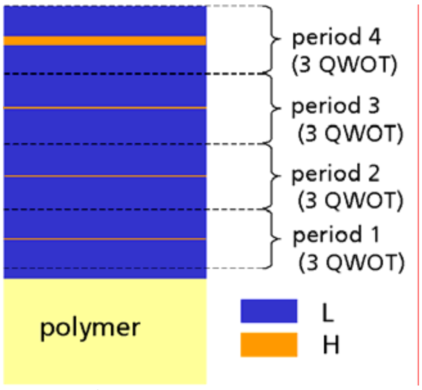

Fig. 2 Schematic of coating design AR-hard®; arrangement of 3-layer periods

Typical layer materials are SiO_2 as a hard oxide with low refractive index and TiO_2 as a high refractive index material. Each of the symmetrical periods with three times the quarter wave optical thickness (3 QWOT) can be represented mathematically by a single equivalent film having an equivalent index n_{eq} that is lower than the index of the low index material L itself used practical for the thin-film combination. The design concept of AR-hard® uses such equivalent layers to build up a layer stack with decreasing equivalent refractive index from the substrate side to the outermost surface. Coatings AR-hard® can also be adjusted for a broader spectral range [6]. Figure 3 shows a display cover with AR-hard®-coating for a Blaupunkt car-navigation system developed in a joint research project supported by the German BMBF (FKZ 03N3118) . The substrate material of this display is polycarbonate Makrolon® (Bayer MaterialScience).

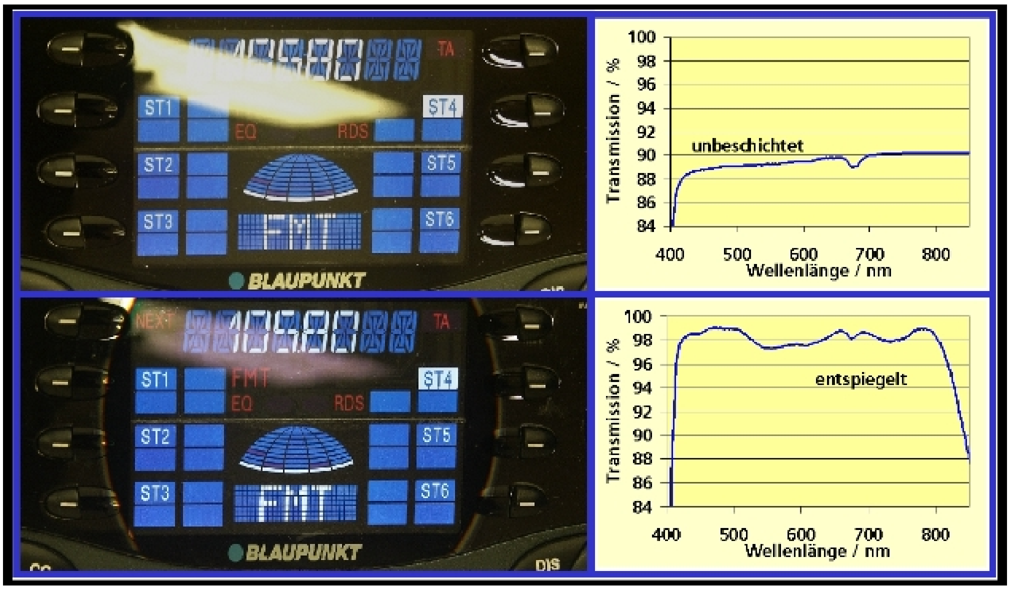

Fig. 3 Display of a car radio for the Blaupunkt company (above: pure surface/ below: anti-reflective coating system AR-hard®)

4. Antireflection by plasma etching of PMMA

Low pressure plasma treatment is a convenient way to activate and clean polymer surfaces before coating. Additionally, several ion bombardment processes on polymers are known that initiate etching processes and change the surface topography. Our investigations show that special ion bombardment conditions applied by the plasma source APS leads to stochastic antireflective structures on acrylic surfaces, so-called "NANO-moth eyes" [7, 8].
From a first very fine-grained structure, larger agglomerates are formed with increasing treatment time. These features are almost uniform in size and are stochastically distributed over the surface (Fig. 4).

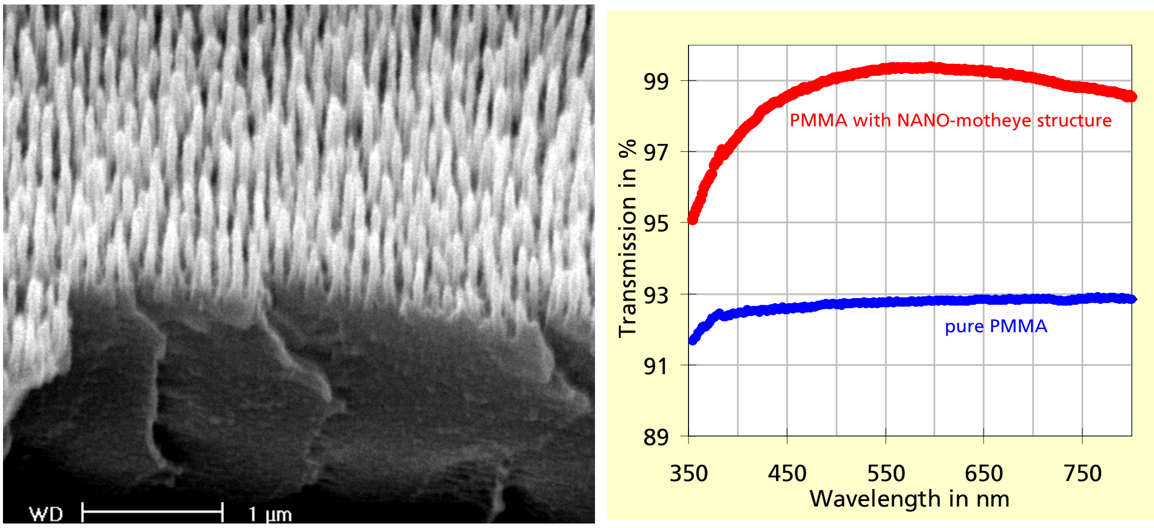

Fig. 4 Scanning electron micrograph of a "NANO-motheye"-structure on PMMA (left) and Transmission of a PMMA sample before and after the plasma etching procedure

The ion energy, the treatment time and the gas composition determine essentially the modification of topography as well as the optical properties. The combination of argon and oxygen in the plasma for a treatment time of several hundred seconds leads to excellent antireflective properties on PMMA surfaces. The aspect ratio of height and diameter of the individual features, which should be at least 2:1, is crucial for the antireflection effect without scattering losses. A special advantage of our "NANO-motheye" structure is the attainable high transmission which is independent from surface geometry.

5. Summary

The replacement of glass by plastic for optical applications is a challenge for modern vacuum and plasma techniques. Antireflection as the most required surface function for plastic optics can be obtained by means of optical interference coatings or surface structures. The low pressure plasma present in modern vacuum processes provides possibilities to activate substrate surfaces, to densify growing layers and to adjust mechanical and thermal film stresses.
Plasma ion-assisted deposition has been found a suitable technology for coating polymers. The design type AR-hard has been used for providing a high abrasion resistance together with an antireflection function of variable bandwidth. In case of PMMA, the plasma degradation processes offer an interesting alternative to achieve antireflective properties. It was shown that, under certain conditions of a plasma ion-etching process, the surface reflection of PMMA decreases significantly. A special advantage of the "NANO-motheye" antireflection structure is the low sensitivity of the antireflective performance to different angles of light incidence. Thus, this procedure should be favourably applied on curved and structured surfaces but only on surfaces that do not have to be touched or cleaned later. Cost-effective mass production may be possible by direct ion etching of small optical parts as well as by replication of the structure onto bigger parts.

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References

[1] U. Schulz, "Review of modern techniques to generate antireflective properties on thermoplastic polymers",Applied Optics 45, 1608-1618 (2006)
[2] S. J. Wilson, M. C. Hutley, "The optical properties of "moth eye" antireflection surfaces", Optica Acta 29, 993-1009 (1982)
[3] S. Pongratz, A. Zöller, "Plasma ion assisted deposition: A promising technique for optical coatings", J. Vac. Sci. Technol. A 10 (4), 1897-1904 (1992)
[4] U. Schulz, U. Schallenberg, N. Kaiser, "Reflection-reducing coating", Patent WO0204374 (2002)
[5] U. Schulz, U.B. Schallenberg, N. Kaiser, "Symmetrical periods in antireflective coatings for plastic optics", Applied Optics 42, 1346-1351 (2003)
[6] U.B. Schallenberg, U. Schulz, N. Kaiser, "Multicycle AR coatings: a theoretical approach", in Advances in Optical Thin Films, N. Kaiser, A. Macleod, C. Amra, eds., Proc. SPIE 5250, 357-366 (2004)
[7] P. Munzert, H. Uhlig, M. Scheler, U. Schulz, N. Kaiser, "Method for reducing boundary surface reflection of plastic substrates ans substrate modified in such manner and use thereof", PCT Patent WO04024805C1, 2004
[8] A. Kaless, U. Schulz, P. Munzert, N. Kaiser, "NANO-motheye antireflection pattern by plasma treatment of polymers", Surf. Coat. Technol. (2005)

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Areas of research and development:
Investigates, designs and develops optical and multifunctional coatings for plastic substrates