Abrasion Resistant and Optical Thin Film Coatings for Ophthalmic Lenses

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ABSTRACT

The application of thin films to plastic ophthalmic lens substrates enables attributes such as abrasion resistance and antireflection to be achieved. Surface modification techniques include direct modification of substrates, as well as the application of coatings. A wide variety of abrasion resistant coatings are applied to ophthalmic lenses, generally using solvent based coating processes, whereas antireflection is generally achieved by the physical vapor deposition of multilayer inorganic oxides. However, there is considerable movement in the development of vacuum based hard coatings for and plasma modification of plastic surfaces. One example of a promising fast and high quality coating method for the future is PECVD.

The attributes achieved by surface modification add significant value to an ophthalmic lens product and as such is of fundamental importance to the viability of the ophthalmic lens industry. As part of this paper, the importance of the mechanical characteristics of ophthalmic surfaces will be described, including testing protocols and methodologies.

INTRODUCTION

History of Ophthalmics

Eyeglasses are such an everyday item that we tend to take them for granted. Nearly 160 million Americans wear eyeglasses and about 80 million pairs are purchased each year. The majority of people over the age of 45 require eyeglasses for reading. It is interesting to note that such a mundane product was once the original 'high tech' industry.

During the early part of this century, the greatest advances in ophthalmics were related to new kinds of lens materials. With the expansion of organic and synthetic polymer chemistry in the 20th century, it was soon discovered that optically clear materials could be made from polymers. The logical advantage of plastic over glass was that, theoretically, a lens with similar optics could be made much lighter from plastic materials than glass. Initial attempts at lowering the weight of a given lens were done in the late 1930's using poly methyl methacrylate (PMMA). One major drawback of that material, however, was in its inability to resist scratches.

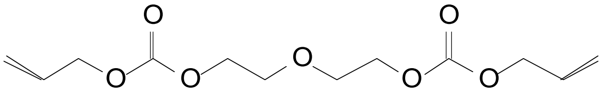

Figure 1: Chemical structure of CR39®, which polymerizes upon addition of a catalyst

The first truly successful plastic lenses were introduced shortly after the second world war. These were made from the thermosetting resin diallyl diglycol dicarbonate, commonly called ADC or CR39® (a registered trademark of PPG), the chemical structure of which is shown in Figure 1. The inherent scratch resistance of this material compared to other plastics at the time, as well as its impact resistance and low density, ensured its commercial success. High index thermoset resins were later introduced to make lenses thinner and lighter, and polycarbonate, a very tough thermoplastic, became widely available by the late 1980s (shown in Figure 2). Other kinds of lens materials have continued to be introduced, although most of these are thermoset (like CR-39) or UV-set resins; polycarbonate remains the only commercially useful ophthalmic thermoplastic.

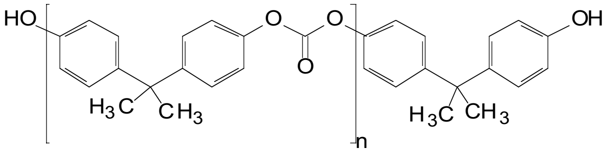

Figure 2: Chemical structure of Polycarbonate

DISCUSSION

Improving Scratch Resistance of Plastic Lenses

Glass lenses are inherently scratch resistant due to the fact that glass is an extended matrix of Si-O linkages, a hard but fairly fragile and brittle material. Plastic is an extended matrix of organic linkages, which can be tough or highly impact resistant, i.e., polycarbonate, but tend to be relatively soft. In order to enjoy the benefits of high impact resistance, while developing a scratch resistant surface, specific thin film coatings have been developed for application to plastic lenses.

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One way to increase the abrasion resistance of a plastic material is to apply a coating that mimics the surface of glass, e.g., SiO_2. Although it is relatively easy to apply a pure SiO_2 coating to a lens surface using physical vapor deposition (PVD) methods, it is sometimes difficult to attain good adhesion to plastic substrates. These difficulties can arise from a number of effects, including thermal damage to the surface, photolytic decomposition of the polymeric surface, and simple poor chemical bonding of the inorganic thin film to the plastic surface.

In general there is a significant mismatch between the thermal expansion coefficients of coatings and plastic substrates which can lead to crazing. In order to obtain the scratch resistance of glass while maintaining the flex stability of plastic, some hybrid chemistry is desired, especially as these barrier layers become thicker. Organosiloxane coatings can often perform this duty; they provide organic bonding to the lens substrate while presenting a significant inorganic concentration of SiO_2/organic composite at the lens surface which enables bonding to subsequent inorganic anti-reflection coatings. This underscores an issue which is often overlooked in development of hard coating materials for plastic lenses, and that is primary adhesion of the resin to the lens. It is not acceptable to simply have a good van der Waals interface between the two phases, even though upon application, adhesion may appear excellent. Having a non-bonded or weakly bonded interface will lead to primary interface failure upon subsequent thermal cycling, sometimes with months passing before this event occurs. In order to ensure that the hard coat and substrate remain intimately joined, strong covalent bonding between the two phases needs to exist.

Early coatings produced using organosiloxane/colloidal silica mixtures had excellent abrasion resistance but tended to be brittle[1]. Brittleness of these coatings could be improved by the addition of long chain crosslinking silanes, which increased the organic constituency of the hard coatings[2]. The trade-off in adding these organosilane modifiers was that it made the resultant films again somewhat softer than the original SiO_x matrix of the pure organosiloxane, albeit with much more flex stability. In general, however, the lower the organic content of an organosiloxane, the greater the abrasion resistance.

In some applications it is desirable to coat a lens with an acrylate based coating and perform ultra-violet (UV) curing. Acrylic coatings have the advantage that they can have a higher solids content than siloxanes due to the different active curing chemistries resulting in less shrinkage. Acrylates can also often have good adhesive strength to certain substrates, often due to interpenetration of the organic species into the lens material, or simply to softening of the interface due to solvents in the urethane/acrylate resin system. For example, polycarbonate is difficult to coat with traditional organosiloxane coatings; the interfacial chemistries seem somewhat incompatible. In contrast, acrylate based hard coatings generally adhere very well to these same substrates. The downside is that pure crosslinked acrylates present only an organic surface regardless of curing conditions which can be problematic for subsequent inorganic antireflective film deposition.

A critical issue in the development of any hard coating material is that of optical index matching to the substrate. Without index matching, severe interference fringes can be observed, the severity dependent on a number of issues like film thickness, interface quality, and index mismatch. Since titania has a high optical index of roughly 2.25 (depending on a number of factors), mixing this material as a colloid into a lower index siloxane or organic thin film can give an apparent mixed index material, provided that the colloids themselves are small enough to not be optically active.

Anti-Reflection Coatings

The main reason for adding antireflective (AR) coatings to lenses is to reduce double images (ghost images) and back surface reflections. Double images are produced by internal reflections in the lens while unwanted back surface reflections may lead to the wearer seeing ceiling lights or even his or her own eye on the *inside* portion of the lens. The whole antireflection effect is best observed when wearing uncoated lenses while driving at night or in an environment brightly lit by artificial light sources similar to that found in a usual office space. It is the reduction of double images and back surface reflections that mostly enhances visual acuity; the increase of transmitted light through the lens is a beneficial “by-product” of the AR application.

A standard plastic lens reflects perhaps as much as eight percent (or 4% per surface, varying depending on the index of refraction of the lens itself) of incident light. Adding a fairly simple AR stack to this lens can decrease reflectance to about 1% per surface while increasing transmission through the lens to greater than 98%. Clearly, increasing transmission to this level requires that the AR stack be optically transparent or non-absorbing. Even minor amounts of visible light absorption by the inorganic oxide AR stack will lead to a slightly tinted lens, which partially negates gains in transmitted light, but also is not cosmetically very appealing. However, for reasons already stated, the main purpose of AR coatings is not necessarily to increase transmission. For example, sunlenses in particular have a strong tendency to reflect the wearers eye. Thus, high quality sunlenses, even if mirror coated on the front, almost invariably have an AR coating on the back (inside) surface.

Antireflection is achieved as a direct result of destructive interference of light reflections from interfaces between very thin films deposited on the lens surface which destructively interfere, resulting in a low total reflectance from the coated lens. This is described well in many reference texts[3]; the nature of the AR coatings (interference filters) requires individual layers to be very thin, typically on the order of 10 to 100nm in practice. Controlling the deposition of such thin film structures poses a considerable challenge. Most AR films are composite multiple stacks of optically transparent inorganic materials. Typical materials used in these stacks include TiO_2, ZrO_2, Nb_2O_5, SiO and SiO_2, Al_2O_3, and Ta_2O_5 , in addition to the classical MgF_2, to name a few.

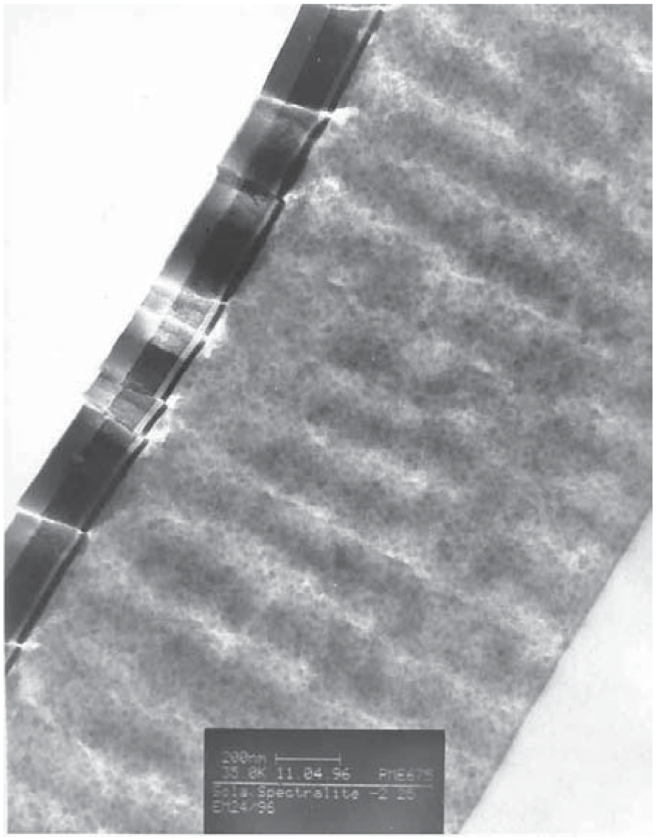

Figure 3: TEM cross section of a resin based hard coating (middle) and anti-reflection thin film (left edge) on a Spectralite™ (a UV-cured polycarbonate material) substrate (right lower corner). [©SOLA - 1999]

Methods of Antireflective Coating Deposition

Anti-Reflection (AR) coatings are generally applied using physical vapor deposition (PVD) which involves either thermally evaporating or sputtering the elements comprising the AR stack, usually in the presence of oxygen. With thermal evaporation, a focused electron beam is used to heat a crucible holding a single compound or element which evaporates from the heat. The crucible then essentially becomes a point source of material vapor. This evaporated material condenses on the lens surface, and when useful for the optical design, is oxidized by a background partial pressure of oxygen. Ion assisted deposition (IAD), is sometimes used to both densify and further oxidize the deposited film. Generally, IAD uses an auxiliary beam of argon ions generated in an ion gun. The argon ions are focused and accelerated towards the substrate surface. The reason that oxidation can be enhanced in an IAD process is that the argon ions can collide with oxygen molecules during transit, transferring their energy and momentum to the oxygen, which subsequently impacts the growing electron beam deposited film[4, 5].

Planar magnetron reactive sputter deposition is another method of physically depositing inorganic materials onto lens surfaces. In contrast to the thermal evaporation point source, the sputter source provides an area source which is ideal for scaling processes to any production volume and or coating/ deposition area. Although sputtering incorporates reasonably complex physics in its application, it is also utilized widely in the deposition of quite a large range of products[6]. An advantage of sputtering over electron beam evaporation is in speed of deposition. Although sputter deposition has been widely practiced in a variety of industries, it has not enjoyed a lot of work in ophthalmic lens coatings. In general, however, reactive sputtering (in contrast to direct dielectric sputtering) has been used when applied to this industry.

Reactive magnetron sputtering incorporates the reaction of the sputtered material upon condensation on the substrate with background gas. In most cases for ophthalmic coatings, this is oxygen. The main reasons for the use of reactive sputtering in AR stack deposition are that metal sputtering is in general much faster than direct dielectric sputtering and that different dielectrics can be produced from a single target by simply changing the background gas. For example, both SiO_2 and SiN_x can be deposited using a silicon target by changing from oxygen to nitrogen as the background gas, respectively. However, due to some implantation of the cathode target material during sputter processes, it is often difficult to attain distinct interfaces when using only a single target to produce two materials, often yielding graded material consisting of oxynitrides.

Complex stack designs incorporating many different metal oxides or nitrides are not very practical since a separate magnetron must be supplied for each element in the stack. Electron beam evaporation does not suffer this drawback since multiple cups filled with different compounds or elements can be rotated into the beam and evaporated as needed to provide complex stacks. Therefore, although an electron beam box coater can provide complex stack designs, reactive sputter tools perhaps offer the best PVD alternative for large volume production at this time.

Test and Qualification Methods for Ophthalmics

Ophthalmic lens coatings are evaluated in four main areas: abrasion resistance; durability; adhesion, and impact resistance. While impact testing and evaluation is exceptionally straight forward, the abrasion resistance, adhesion, and durability analysis is considerably more complicated due to higher level interactions between the three measured characteristics.

A minimum impact resistance of 0.2 joules is required by the FDA for all non-mineral (glass) lenses sold in the United States with higher requirements for safety lenses, depending on lens type and configuration. Impact testing is most often performed by dropping a steel ball of a given diameter from a given height to achieve the requisite impact energy. To pass the base line FDA test the lens must not fracture into two or more pieces on impact.

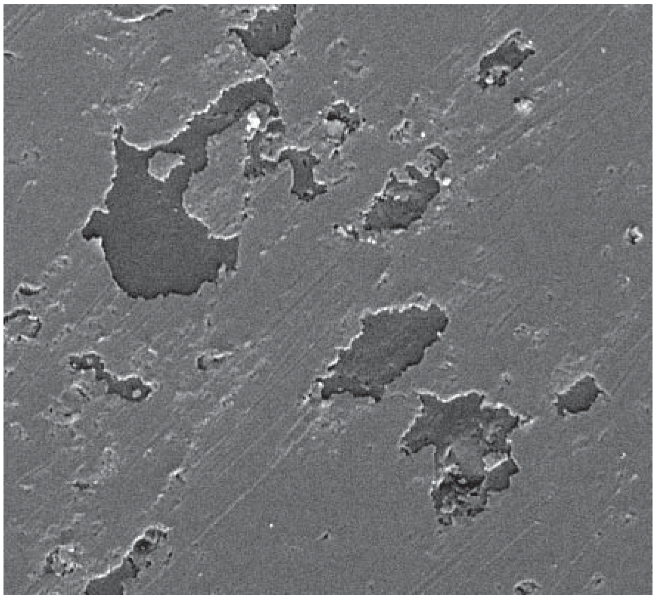

Figure 4: Result of Bayer sand abrasion test. [©SOLA - 1999]

What is generally considered in the industry to be adhesion testing is also very straight forward. The standard adhesion test is a cross hatch/tape pull adhesion test. In this test a 5 by 5 grid of 1 mm squares is cut into the lens surface. Adhesive tape is applied to the lens and pulled off at a 180 degree angle to the surface. The percentage of coating removed is measured. This test is often used in conjunction with other tests as described later.

The abrasion resistance of lens and coating combination is tested in a variety of ways. However, the main techniques generally accepted as industry norms are oscillating sand abrasion or Bayer testing, steel wool abrasion, and tumble abrasion. Bayer testing involves mounting the lens horizontally in a bed or tray of standard abrasive which oscillates a fixed number of times back and forth causing the sand to repeatedly travel across the surface of the lens causing abrasion (see Figure 4). In steel wool testing a steel wool pad is pressed to the surface of the lens with a force applied nearly normal to the surface. The pad is caused to travel across the surface of the lens for a set number of cycles (Figure 5). Tumble testing is performed by placing the lenses to be tested in a drum with paddles along the length of the cylinder along with a variety of abrasive media. The drum is rotated for a specified time and the lens is abraded by the impact of the other lenses and the abrasive media.

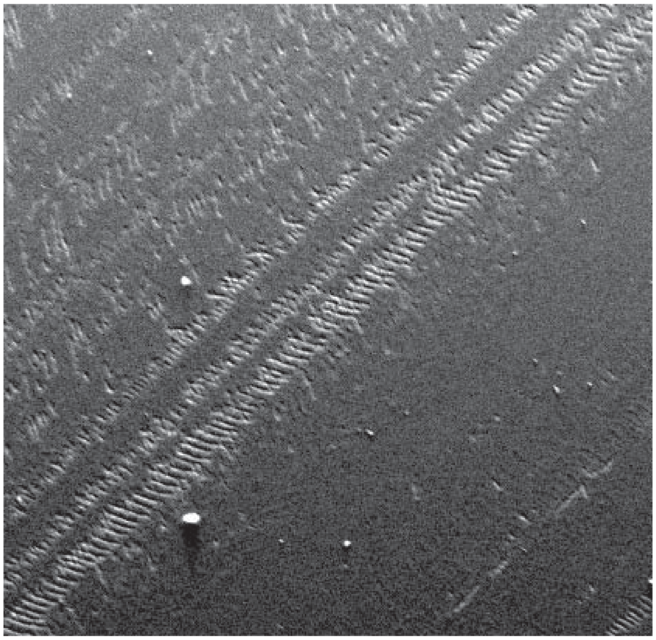

Figure 5. Steel wool abrasion test on plastic lens. [©SOLA - 1999]

The degree of abrasion is typically measured in one or both of two ways. The objective evaluation is a simple measurement of haze change in the lens on abrasion. This can be measured in a number of ways including scatter of a collimated beam to a specific angle or total integrated, haze. In many cases this measurement can be difficult because of the small region abraded and the typical non-uniformity of the abraded region. As a result of these short comings a subjective measurement is also often performed in which the test sample is visually compared to a number of standard samples and ranked.

The interpretation of these results is complicated. A low abrasion result may be the effect of a soft thin film which has been severely scuffed during testing. It may also be the result of poor adhesion between a hard thin film and the substrate, causing significant delamination during testing. Finally it may be the result of a soft or weak substrate which failed during testing causing disruption in the a well adhered and hard thin film. All of these effects, and others, must be considered when performing abrasion evaluation. Additionally, as is shown comparing Figures 4 and 5 with Figure 6 (below), there sometimes is little relationship between "standard" scratch tests and actual wear experience by a customer.

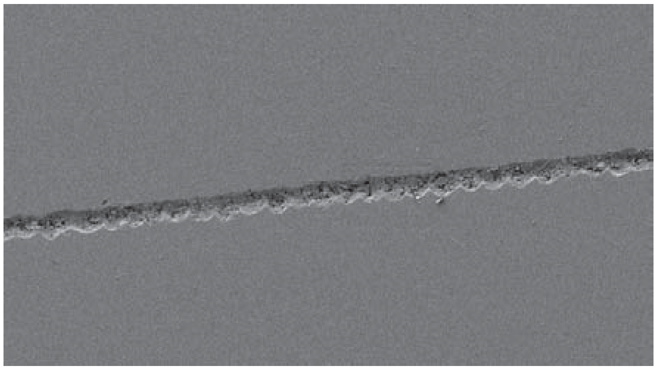

Figure 6: Scratch from a returned customer lens. [©SOLA - 1999]

The final group of testing is durability testing. Laboratory durability testing techniques include repeated immersion in boiling water (deionized or with added dissolved solids), cyclic humidity exposure, dry heat exposure and solvent attack. The films are evaluated for crazing, both intensity and area effected and for delamination. It is not uncommon to perform a cross-hatch adhesion test at the end of the test cycle. These tests are commonly believed to evaluate adhesion, residual stress and film integrity.

The other type of durability testing is the weather and simulated weather testing. In this testing coated lenses are exposed to either the outdoors, often in areas believed to have "aggressive" weather such as the southern Florida coast, or to "artificial weather". The testing can last from between a few days to a few weeks and the lenses are typically evaluated daily. In both types of tests it is common to perform cross-hatch adhesion testing at the end of the test cycle and occasionally during the course of the test.

Issues Surrounding Vacuum Thin Film Deposition on Polymer Surfaces

There are a couple of specific issues surrounding vacuum thin film deposition on either hard coatings or on polymer substrates themselves. It has been of general experience with ophthalmic laboratory coating professionals that e-beam deposition on hard coated plastic substrates can vary dramatically, empirically depending on whether the hard coating was a thermally cured polysiloxane or a UV cured urethane/acrylate coating; thermal coatings result in better adhesion. Sputter deposited films exhibit even more extreme preference for adhesion to thermally cured coatings. Arguments can be made that the energetics of deposition between an ion-assisted e-beam system and a sputter system are not all that dissimilar (at the lens surface), and therefore the differences in adhesion to UV cured coatings between these two deposition processes is confusing. Sputter deposition of AR on UV cured acrylate coatings has historically been highly problematic, generally leading to outdoor weather failures after short term apparent good surface adhesion. To get past this issue, a number of AR laboratories generically overcoat factory applied hard coatings with known thermal cure coatings to avoid returns due to adhesion failure. There are however, some fundamental reasons why differences in adhesion are observed for various materials.

The historic and empirical evidence of differences in adhesion or deposition ease between box coaters and sputter systems can be viewed fairly rationally. If one considers that there are no large substantive differences in the actual deposition physics/chemistry between IAD box coaters and sputter systems, one is left with few arguments explaining thin film quality differences between the two processes. Both sputter and e-beam deposition processes occur at roughly the same pressures, deposited material temperature, and electronic state (all ground-state neutral species). The main substantive difference is that sputter cathodes intrinsically emit tremendous amounts of vacuum UV as compared to an e-beam deposition process. Whereas an e-beam gun produces a white light point source of energy, the sputter cathode produces high energy light in relatively close proximity to the lens surface due to excited state transitions and energy transfer. Only the ion gun in an IAD assisted electron beam deposition system emits substantial UV, and again that is a point source quite some distance from the lens surfaces.

Workers at Ecole Polytechnique Montreal have characterized the vacuum UV wavelengths and flux in vacuum plasma discharges and have found exceptional amounts of deep UV[7]. In particular, the hydrogen vacuum UV lines below 160nm would be particularly damaging to polymeric substrates. However, the oxygen typically used in sputter systems perhaps attenuates this high energy light somewhat.

Argon in the system (as the excitation gas for the cathodes) has primary vacuum UV emissions below 160nm, ironically due to energy transfer from excited state argon metastables to hydrogen (from water and the lens material), as well as higher energy emissions at 104.8 and 106.6 nm[8]. These are highly energetic photons which could conceivably damage conjugated organic systems - like acrylate polymers and optical polycarbonates[9]. The penetration depth of photons at these wavelengths in polymer systems is roughly 20 - 80nm[7]. It should also be noted that, due to the pressures typically used in sputter deposition systems, that the near region of all gaseous species will likely be saturated as excited state species, although this somewhat depends on the power being used. Saturation of the gas phase excited states simply means that there is little background ground-state gas phase molecules to attenuate any transition state UV emission. Therefore, the UV flux to the surface should be high indeed.

This effect could conceivably be tested by using the methods developed at Montreal[7]. It would be expected that UV damage might efficiently cross link and oxidize the near surface of, for example, an acrylate leading to good adhesion to subsequent SiO_2 thin films. However, it would also be expected that this cross linking reaction could be a concerted one, where bond breaking occurs with VUV photons and cross linking reactions occur with lower energy UV coupled with oxygen insertion. If this were the case, one would expect cohesive failure of the polymer *underneath* the deposited SiO_2 thin film and within the polymer bulk (Figure 7)[10].

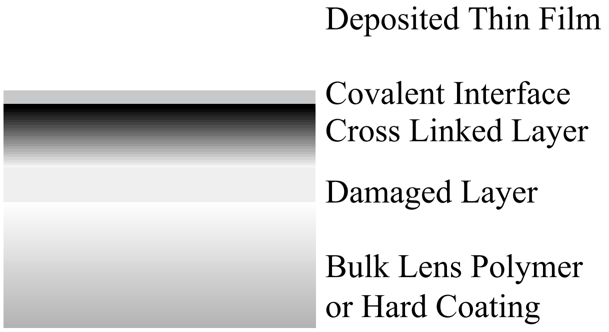

Figure 7: Conceptual diagram of "interphase" structure of a plastic surface after exposure to vacuum UV photons and subsequent thin film deposition. [After Wertheimer, et al[7]]

Alternative Methods of Thin Film Deposition

There have been recent development in the application of hard coatings to ophthalmic lenses using plasma enhanced chemical vapor deposition (PECVD), Diamonex being probably the best known example of a company practicing this technology[11]. In contrast to this limited focus on plasma systems in our particular industry, PECVD technologies are widely practiced in the semiconductor industry[5,12,13]. PECVD essentially constitutes the excitation of a source gas in a plasma, which leads to polymerization, condensation, and/or deposition of gas phase reaction products onto a substrate surface. Various plasma excitation sources have been used for PECVD in semiconductors including high density plasma sources (ECR, ICP, etc.), microwave sources, linear ion gun systems, and diode discharge systems. Typically, the high density systems are used as downstream excitation sources due to their very high efficiency in fully cracking all molecular species into reactive radicals or metastable species. Other systems use dual frequency to employ both the advantages of high cracking efficiencies in high density plasmas coupled with directed energy flux with low frequency (i.e., 40KHz) diode or parallel plate discharge systems[13].

The main advantage of deposition from a plasma excited gas phase rather than thermal excitation, at least from the perspective of ophthalmic coatings on plastic lenses, is that the plasma excitation allows deposition to occur at relatively low temperatures (i.e., <100°C)[11]. This is likely also its main disadvantage since higher temperatures will lead potentially to higher precursor surface mobility, thermal energy to better complete certain reaction chemistries, and faster kinetics. However, high temperatures can not be tolerated by most ophthalmic polymer systems.

Although pure silica coatings can be applied to a lens substrate by PECVD, just as with evaporative SiO_2 coatings, they tend to craze or delaminate when subjected to mechanical and thermal stresses due to differences in the thermal coefficients of expansion between the inorganic SiO_2 and the organic substrate[14]. By changing the gas feedstock and dynamically modifying plasma parameters as a coating is applied, a transition from an interfacial "organic" material to an abrasion resistant "inorganic" material can be achieved[15].

Organosilica precursors, silicon containing chemicals which can be reactively converted to $R\text{-}SiO_x$ (where R = any organic functionality), are used to form organosiloxane type networks. A variety of these organo-silica precursors are used including trimethyl silane [$(CH_3)_3SiH$] (or TMS), vinyl trimethyl silane [$CH_2{=}CHSi(CH_3)_3$] (or VTMS), hexamethyl disilane [$(CH_3)_3Si\text{-}Si(CH_3)_3$], tetramethyl disiloxane [$(CH_3)_2HSi\text{-}O\text{-}SiH(CH_3)_2$] (or TMDSO), and hexamethyl disiloxane [$(CH_3)_3Si\text{-}O\text{-}Si(CH_3)_3$] (or HMDSO)[16,17,18,19]. Precursors which more completely convert to SiO_x in a PECVD environment are generally of the class of silicon alkoxides, such as tetra-ethoxy silicon, more commonly known as tetraethyl ortho silicate (TEOS). Reaction of these silicon alkoxides with oxygen, other oxidizers like N_2O, or even water vapor converts the precursor into SiO_x.

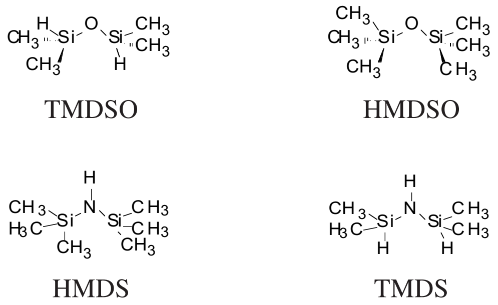
TMDSO
HMDSO
HMDS
TMDS

Figure 8: Structures of some common CVD SiO_2 precursor materials.

In doing PECVD, or plasma activated CVD (PACVD), there are a number of factors which need to be considered which complicate the issues of deposition. These include precursor delivery systems, gas flow dynamics, deposition uniformity, reaction kinetics versus reaction thermodynamics, adsorption versus desorption kinetics, parasitic reactions (wall effects and collisional parasitic reactions between molecules), and likely other issues. These must be evaluated concomitantly since all are coupled. For example, providing relatively uniform flow dynamics in a CVD reactor should lead to good surface deposition uniformity. However, it's not quite as simple as this since, in looking at gas flow dynamics one must also consider chemical *reaction* dynamics simultaneously; one must factor changing gas phase concentrations of reactive species along a dominant flow line due to removal of that precursor from the system via deposition. In other words, the precursor providing active deposition of SiO_2 is dynamically being depleted as the flow proceeds over the lens surface. Additionally, depending on system pressure, there is also a trade-off between gas phase diffusion versus bulk flow.

With regard to bulk flow and precursor depletion, one way to accommodate the latter is to inject the precursors radially at the edge of the lens and pump from the middle. This way, as depletion increases, the actual area on which one must deposit material is simultaneously being reduced. A balance can be reached, although then a third issue must be considered, that being diffusion across the static boundary layer over the surface as well as within the reactor system itself. This diffusive boundary layer depth is affected by operating pressure; the lower the pressure, the bigger the apparent "boundary" layer. In considering these three variables, there has been a presumption that the deposition thermodynamics are favorable, the sticking coefficient of a precursor or reaction fragment on the lens surface is not an issue, and that the actual reaction kinetics are faster than *desorption* kinetics[20]. Generally, a balance must be struck between all these factors, and in most cases in this author's experience, common ground in which active high quality deposition (or desorption) can take place is difficult to find[21].

In considering flow dynamics versus diffusion, dropping the pressure should generally improve uniformity, although deposition rates will be sacrificed if this is done. Raising the pressure will increase rate, but then flow dynamics take on an exceptionally important role. The difficult part is that one is also battling reaction kinetics, so one must be continually concerned about mean free path issues and the reaction probability cross section of excited state oxygen, argon, ammonia or other excitation gases with for example, HMDSO and HMDS precursors. There needs to be sufficient collisions of the chemical precursor with oxygen to cause a partial fragmentation (or addition of oxygen into the molecule to make a disilyl-peroxide), and this needs to take place close enough to a surface (the lens) so that a collisional condensation reaction can occur. The downside is that if this "activated" precursor remains in the gas phase too long without colliding with a surface on which to condense, it will likely parasitically collide with a similar intermediate and oligomerize resulting in particle formation or significant wall deposition.

Higher index material can also be deposited by CVD or PECVD[22,23]. Titania can be readily deposited from $TiCl_4$ or *tetrakis*-isopropoxy Titanium, or TIP.

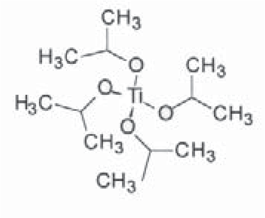

Figure 9: Structure of a common "non-hazardous" titanium CVD precursor, Titanium *tetra*-isopropoxide, or TIP.

Although titanium tetrachloride likely will deposit "cleaner" TiO_2, simply because no carbon exists within its chemical structure, TIP is sometimes used since it has no corrosive byproducts. Most certainly, almost all promising metal oxides and/or metal nitrides can be deposited from chemical precursors. Additionally, it is quite conceivable that mixed metal-silicates can be readily grown by mixing the precursors either in the CVD reactor chamber or in a mixing manifold prior to, for example, a plasma discharge. The only real limitation is that of precursor flow to the deposition system in amounts which afford economic deposition rates. In the semiconductor industry, limitations in volatility of the precursors has been overcome by using direct liquid injection systems, injecting either liquid precursor, or the precursor in a suitable delivery solvent. Since most reactors run slightly "hot", and are at low pressure, instantaneous volatilization occurs. Additionally, activated processes crack even aerosols into molecular constituents quite quickly. So the challenge is an engineering one, and not necessarily all related to intrinsic chemistry.

CONCLUSIONS

Although commercially performed on a large scale, coating plastic ophthalmic lenses is far from trivial. There are unique considerations one must overcome to deposit high quality scratch resistant and optical thin films on plastic. However, even with these difficulties, novel methods of coating hold promise for the future, including activated chemical vapor deposition processes.

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