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Advanced Optics Using Aspherical Elements

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**SPIE
PRESS**

Bellingham, Washington USA

Petitioner has added vertical line numbering to all pages, as well as romanettes to pages (i)-(ii). Otherwise, it leaves the original page numbering.

**MOTOROLA MOBILITY
EXHIBIT 1027**

Library of Congress Cataloging-in-Publication Data

Braunecker, B. (Bernhard)

Advanced optics using aspherical elements / B. Braunecker, R. Hentschel, H. Tiziani.

p. cm.

Includes bibliographical references.

ISBN 978-0-8194-6749-2

1. Aspherical lenses. 2. Optical instruments--Design and construction. I. Hentschel, R. (Rudiger), 1949- II. Tiziani, Hans J. III. Title.

TS517.5.A86B73 2007

681'.423--dc22

2007028838

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

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Web: SPIE.org

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Printed in the United States of America.



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13.11 Aspherical Microlenses Manufactured by Wafer-Based Technology

M. Eisner, R. Völkel, K.J. Weible

13.11.1 Basic assessment of the technology

Microlenses and microlens arrays are used for fiber coupling, collimation, beam shaping, beam homogenizing, wavefront sensing, imaging, and other applications. Different manufacturing techniques, from ion diffusion (GRIN), injection molding, embossing, and grinding, to wafer-based technologies, are suitable and well developed. For the production of high-quality micro-optics, the wafer-based microlens technology is most promising [1–3]. It uses well-established processes from the semiconductor industry like resist coating, lithography, and reactive ion etching. This technology permits the manufacture of microlenses from 10 microns to 2 mm in diameter, and aspherical lens profiles with excellent uniformity and lateral position accuracy in the submicron range. SUSS MicroOptics has successfully established wafer-based manufacturing in 200 mm (8") wafer technology, allowing a maximum array size of 180 mm in diameter (Fig. 13.43c).

Special care has to be taken for the testing of aspherical microlenses. Interferometrical and mechanical profilometers are available. However, due to the small size of the microlens apertures, the accuracy of the measurements is limited by the number of fringes and the accuracy of the sampling. Additionally, diffraction effects might influence the optical properties of refractive microlenses with small F-numbers.

13.11.2 Intended purpose of the technology

Wafer-based microlens manufacturing technology uses standard semiconductor processes and equipment. The semiconductor industry is a frontrunner, with incredible high annual investments in new high-end processing tools and equipment. The micro-optics industry commonly uses equipment that has been optimized by the semiconductor industry some years before. This allows manufacturing and packaging of high-quality micro-optics at reasonable costs. As all processes are based

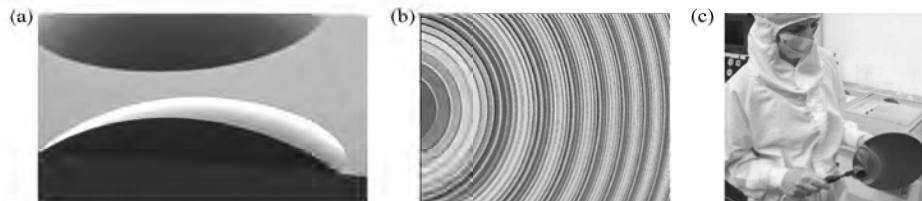


Figure 13.43 (a) Scheme of a refractive microlens (photograph courtesy of J.-C. Roulet); (b) Eight-level diffractive microlens; (c) 8" microlens wafer.

on standard semiconductor technologies, the achieved quality is merely a question of budget and effort to optimize to the very limits.

In contrast to the well-established manufacturing technology, the instruments available for testing of microlenses are still at a low level of development. For interferometrical testing of small microlenses, an interferometer is combined with a microscope to allow sufficient magnification of the observed fringe pattern. For testing of large microlens arrays and a full-wafer mapping, an automated, fast, and precise multi-axis tool is required. Such instruments do not serve much purpose for other tasks than micro-optics testing, and it is not very attractive to develop special equipment for a very limited market. This lack in adequate metrology tools is a severe constraint for the micro-optics industry.

13.11.3 The technology's typical features

Wafer-based manufacturing technology is well suited for microlenses from $10\text{ }\mu\text{m}$ to 2 mm diameter. The microlenses are typically arranged in quadratic or hexagonal arrays. More sophisticated arrangements like Nipkow-discs or a random-like distribution of different microlenses are also possible. The lateral position accuracy depends on the precision of the photomask pattern and is usually better than $\pm 100\text{ nm}$. After manufacturing and testing, the $8''$ wafers are diced to smaller units by using a wafer saw or laser dicing. Dicing marks on the wafer allow a precision for the outer dimensions of better than $\pm 2\text{ }\mu\text{m}$.

The lenses are planoconvex with aspherical lens profiles. The conic constant typically ranges from $k = +10$ to $k = -20$. A diffraction-limited optical performance and excellent array uniformity is achieved.

Wafer-based manufacturing includes a dry-etching step (see Chapter 15 for details), which limits the choice of wafer material for the microlens arrays. The described wafer technology works very well for fused silica, Pyrex (Corning 7740 or Schott BF33), and silicon wafers. Other dry-etchable materials, such as GaAs, GaP, and InP, are possible by using chlorine gases.

For the mounting of microlens arrays, the classical approaches using mounts and holders with springs, rings, balls, or other mechanical supports are well suited. For larger numbers of small microlens arrays, the wafer-based manufacturing technology allows implementation of packaging and alignment strategies from the semiconductor industry. This includes double-sided microlens arrays with a front-to-backside accuracy of $\pm 1\text{ }\mu\text{m}$, alignment marks, aperture or pupil arrays, structured color or dielectric filters, and advanced packaging techniques like wafer-level bonding and flip-chip bonding. For large arrays, special care is necessary to avoid bending of the planar substrates by gravity or stress from the holder.

13.11.4 Description of process

A photoresist layer, typically $1\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$ thick, is spin coated on a wafer. Typical wafer material is fused silica, Pyrex, or silicon. A binary chromium-on-glass

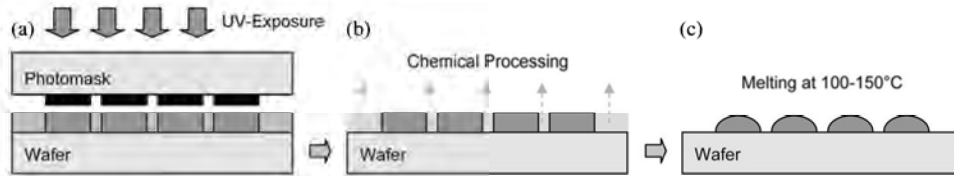


Figure 13.44 Scheme of the fabrication of refractive microlenses in photoresist by the reflow method. (a) Photolithography, (b) developing, and (c) melting of the photoresist structure.

photomask is contact-copied in a mask aligner as shown in Fig. 13.44. The exposed resist is resolved in a standard wet-chemical developing process. The resist structures are now molten at a temperature of 100–150°C on a hot plate or in an oven. Surface tension forms a lens-like drop, the shape of the drop is preserved after cooling and repolymerization of the resist. The remaining resist microlens is typically very close to a spherical lens profile.

Figure 13.45 shows the reactive ion etch (RIE) transfer process of resist microlenses in fused silica. Melted resist lenses are fabricated on a fused silica wafer. The resist shape is transferred in fused silica by RIE. Atoms from the resist surface and the silica are removed simultaneously by energetic ions until the lens shape is completely etched into the substrate. The etch rate of the photoresist and the silica depends strongly on the RIE parameters. A spherical microlens profile will be slightly deformed after the RIE transfer. Usually, the lenses are steeper at the rim and flatter at the vertex. Spherical aberrations are severely enhanced due to the profile change. A profile modification is achieved by changing the etch rate during the RIE step. The resist is etched more quickly at the beginning and more slowly at the end. This procedure also allows precise profile shaping of aspherical microlenses from conic constant $k = +10$ to -20 .

Figure 13.46 shows the surface profile of an aspherical microlens with a lens diameter of 1.1 mm, a radius of curvature of 8.85 mm, and a conic constant of $k = -11.75$ measured in a Wyko NT3300 white light profilometer in PSI mode. The microlens surface is measured in reflection. A spherical reference surface is used for calibration. The radius of curvature (ROC) of the reference surface is well known and close to the aspherical microlens surface to be measured. The reference sphere serves to determine the measurement errors due to the interferometer. A file containing these errors is subtracted from each asphere measurement.

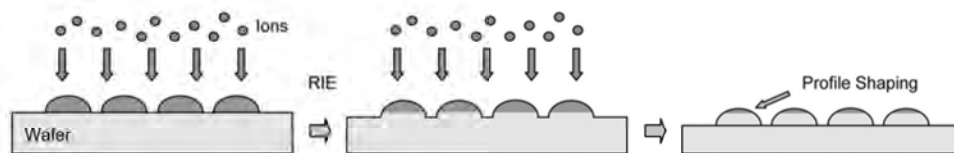


Figure 13.45 Scheme of the reactive ion etching (RIE) transfer process of resist microlenses in fused silica. A correction of the lens slope is obtained by changing the etch rate between the resist and fused silica during the etching process.

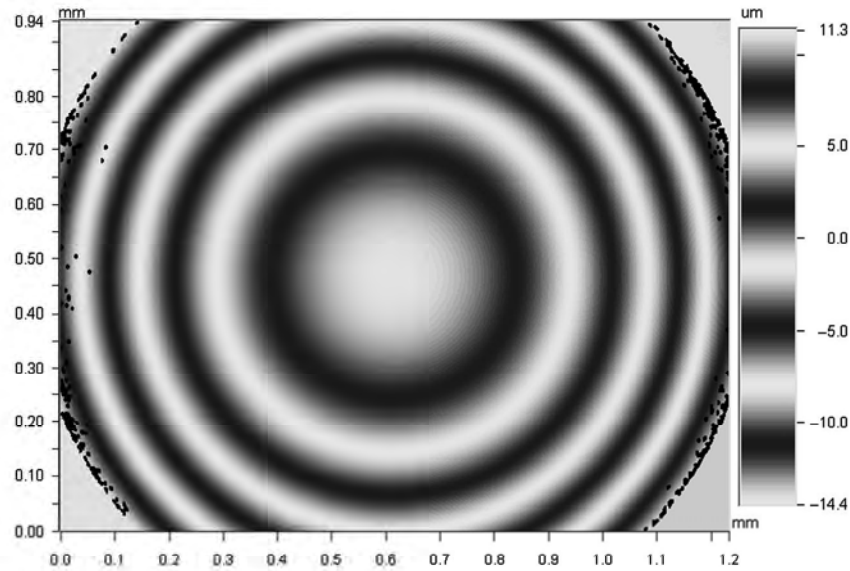


Figure 13.46 Aspherical microlens with lens diameter $\varnothing = 1.1$ mm, ROC = 8.85 mm, and conic constant $k = -11.75$ measured in a Wyko NT3300 white light profilometer in PSI mode.

The aspherical data with the error file subtracted are taken into a fitting routine, and the best-fitting aspherical surface is calculated using the rms deviation as an optimization constraint. Comparison of the measured microlens profile (gray dots)

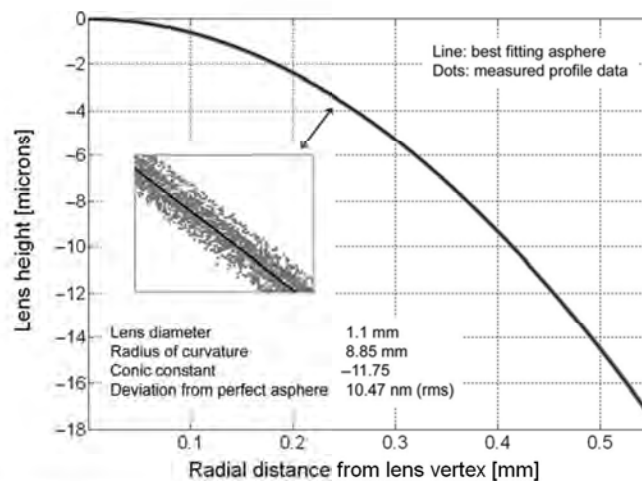


Figure 13.47 Comparison of the measured microlens profile (gray dots) with the best-fitting asphere (solid line). The gray dots represent the polar coordinates of all measured 3D surface data. A deviation from the perfect asphere of ± 10.47 nm (rms) is achieved.

with the best-fitting asphere (solid line). The gray dots represent the polar coordinates of all measured 3D surface data (Fig. 13.47). A deviation from the perfect asphere of ± 10.47 nm (rms) is achieved.

13.11.5 Data for aspherical microlenses manufactured by wafer-based technology (Tables 13.54–13.56)

Table 13.54 Typical operation parameters.

Shape accuracy	$< \pm 20$ nm (rms)
Surface roughness	1.1–1.4 nm (rms)
Gradients	
Machinable dimensions	190 mm diameter for 8" wafer technology
Radius	5 μm up to 200 mm

Table 13.55 Cost drivers.

Investment	Cleanroom, process equipment, metrology
Process time	2–3 weeks
Operator	Less important for fully automatic equipment
Tools and supply	Wafer cleaning, resist-coating, photomasks, lithography, RIE, metrology, interferometers, microscope

Table 13.56 Limits of the technology.

Metrology	Diffraction effects and sampling limit the accuracy of profile measurements for small microlens diameters
Geometry	Lens diameters are typically 10 μm to 2 mm Lens sag typically from 100 nm to 100 μm

13.11.6 Conclusions

Aspherical microlens and microlens arrays are key components for medical applications, telecom networks, metrology, laser, and illumination systems. Even though the micro-optics is only a tiny passive component within such complex systems, these components are often very decisive for the overall performance of the system.

The described wafer-based manufacturing technology is well established and controlled. Tools for simulation of microlens arrays within optical design programs and adequate metrology to test and characterize microlens arrays exist, but they are not yet fully developed.

Although the basic principles of aspherical microlenses and microlens arrays are well understood, proper definition and integration in complex optical systems is often very difficult. For a large asphere, the lens material, the ROC, and the

aspherical coefficient k are sufficient to predict optical performance. This is not the case for aspherical microlenses and microlens arrays:

- For microlenses with a low Fresnel number $FN = (\varnothing^2/4\lambda f) \leq 1$, diffraction effects significantly shorten the observed focal length [4].
- Microlenses have a small space-bandwidth product and do not transmit many pixels in an imaging system [5, 6].
- Illuminating a microlens array with a periodic lens pitch with coherent laser light might lead to interference effects in the far-field.

Miniaturization of optics leads to an increase of diffraction effects [7], and array optics suffers from interference. From the first draft of a system to the final acceptance tests, an optical engineer has to understand how the microlens or the microlens array will improve the performance of his optical system and where potential risks lie. If the engineer is not an expert in micro-optics, he needs qualified partners and suppliers who can educate him and provide him with all of the information required to make the right decisions. Only customer education will lead to customer satisfaction [8]. It will be a joint effort of the micro-optics manufacturers, research institutes, and universities [9] to better educate and train the next generations of optical engineers in micro-optics.

13.11.7 Status

The front-running semiconductor industry and the recent progress in micro-technology research and development constantly improve the manufacturing equipment and processing also usable for wafer-based microlens technology. Therefore, further improvement of aspherical microlenses and microlens arrays is merely a financial question. Despite the high initial costs, wafer-based microlens technology is perfectly suited for mass production. No industry has been more successful in cost reduction of highly sophisticated products than the semiconductor industry. So far, micro-optics is still a niche product with small batches of wafers—and is therefore still expensive.

13.11.8 Further reading

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Chapter 15

Coating Technologies

15.1 Coating Design

U. Schallenberg

15.1.1 Basic assessment of the technology

Coating design involves generating the design of an optical coating for a particular application and the conditions of manufacturing. It is part of the manufacturing process of optical coatings itself. It gives the layer sequence for the production run, assists the monitoring of the deposition process during the run, and enables a reverse engineering after the run. It is also particularly part of any R&D in optics in general and goes hand in hand with the optic design itself (Fig. 15.1). Necessarily, it has to use corresponding thin-film design software.

15.1.2 Intended purpose of the technology

Optical coatings consist of thin films of different materials and thicknesses. Thin films are deposited onto a substrate, and the optical application of such a coating is based on the interference effect of light within the thin films and between the ambient media. The propagation of light as an electromagnetic wave is described by Maxwell's equations. Under defined conditions, there are solutions that describe the interference effect exactly. Various recurrent calculating techniques exist to evaluate the effect of optical coatings, but the most versatile method is based on the matrix formulation of Maxwell's equations. Each individual thin film is described by a characteristic matrix including refractive index, extinction coefficient, and physical thickness of the film in dependence on the wavelength of light. The optical coating is described by the product of all the characteristic matrices and the vector whose elements depend on the refractive index of the substrate.

There are only less explicit equations to obtain the reflectance, transmittance, absorptance, and phase changes on reflection or transmission of an optical coating,

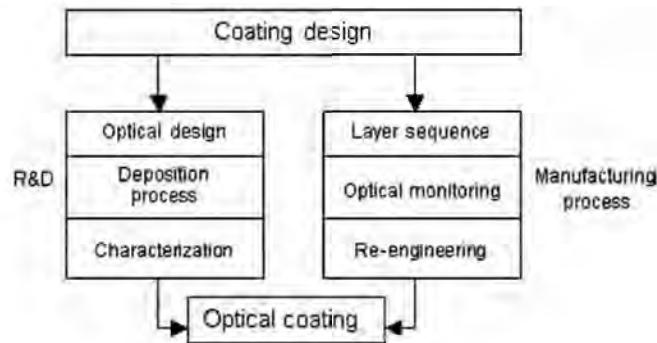


Figure 15.1 Coating design as basis of both the R&D process and the manufacturing process of an optical coating.

and computer programs are needed to perform these evaluations. In this sense, coating design is strongly connected with progress in computer hardware and software. It is not necessary to develop a corresponding program if someone is interested in performing coating design, because a lot of commercial thin-film design software exists. However, computer-assisted coating design does not reduce the need for comprehensive knowledge, skill, and experience in thin-film optics—both in theory and in practice.

15.1.3 The technology's typical features

Coating design creates a sequence of layers or thin films. It is possible to use the same coating design for different coatings (e.g., at different applications by changing the angle of incidence) in different spectral regions by changing the materials, and with different parameters by using higher orders of phase thickness. On the other hand, the same application can require different designs if different substrates or different manufacturing methods are used.

Based on the intended optical application, coating design distinguishes coating types with respect to the beams created by the coating and the energy balance regarding reflection, transmission, absorption, and scattered loss (Fig. 15.2). If only the transmitted beam is used, the coating is called a “filter,” if only the reflected beam is used, the coating is called a “mirror,” and if only the absorption within the coating is used, the coating is called an “absorber.” If both the transmitted and the reflected beam are used, the coating is called a “beam splitter”: Splitting into different spectral regions gives a “dichroic” (filter or mirror), splitting into different polarization states gives a “polarizer,” and splitting into beams with different phases gives a “phase shifter.” The scattered loss both in reflection and in transmission has a negligible value in most cases.

In many optical applications, there is an undesired reflected beam, which can be reduced using an “AR coating” (antireflecting). An “attenuator” changes the ratio of intensity from a reflected to a transmitted beam. A “nonpolarizing beam splitter” shows no polarization effect of the reflected or transmitted beam. In general, the

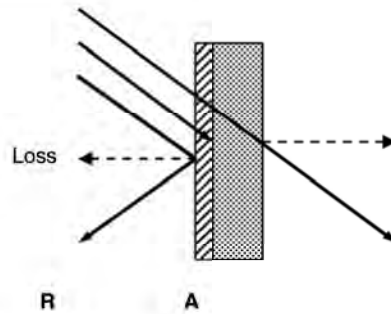


Figure 15.2 Schematic diagram of beam splitting in reflection R, transmission T, and absorption A, and stray light losses at an optical coating (hatched) on a transparent substrate (dotted).

term “filter” is also used for the optical coating itself, often completed to the term “interference filter.”

15.1.4 Description of process

Optical coating design uses a special notation to define the coatings themselves. The different materials used for the coatings are named by capitals A, B, C, and so on. Because most optical coatings consist only of two different materials, one with a high refractive index and the other with a low refractive index, the capitals H and L are used for two-material coatings. The thickness of each individual film is given by its optical thickness or its absolute physical thickness.

Usually, the optical thickness is normalized with respect to a reference wavelength in a fraction of $1/4$. A layer with an optical thickness of exactly $1/4$ of the reference wavelength is called a quarter-wave layer (QWL) having a normalized optical thickness of 1. A two-material sequence of QWLs gives the basic design of most optical coatings.

Often, a group of two or more layers are repeated within the coating, which is schematically given by a sequence in brackets with an exponent announcing the number of repetitions. The notation itself starts with an abbreviation for the substrate and ends with a term indicating the incident medium, for example

$$\text{BK7}(0.5\text{L } 1\text{H } 2\text{L } 1\text{H } 0.5\text{L})^{21}\text{air.}$$

The individual films within the coating are counted, starting at the substrate or starting with the first film deposited onto the substrate, respectively, or they are counted starting at the incident media with the layer that sees the incoming beam at first.

15.1.4.1 Packages of thin-film design software

Coating design needs thin-film design software consisting of packages for input, analysis, refinement, synthesis, and manufacture assistance (Fig. 15.3). There are

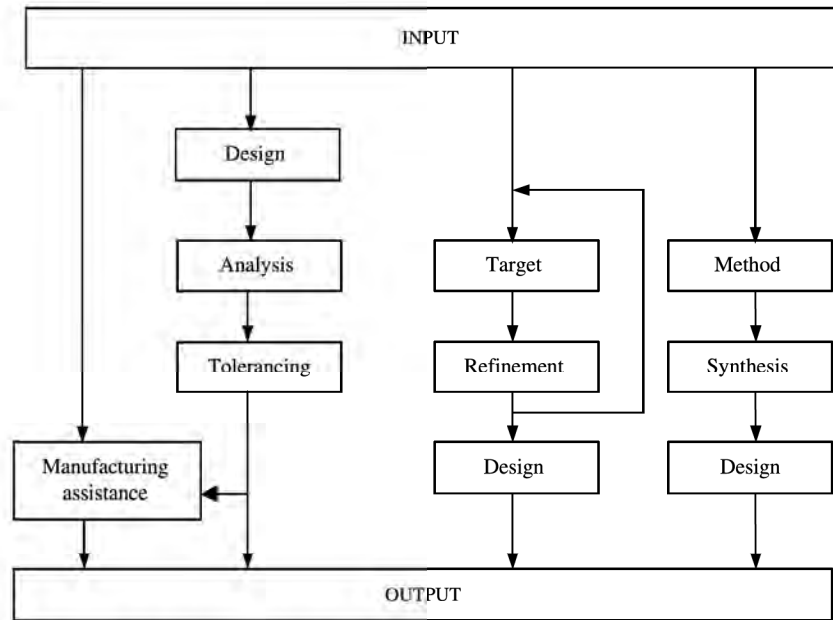


Figure 15.3 Flowchart of different ways of using thin-film software tools.

different ways of using the diverse software tools. Which tool is used for which task depends usually on the requirements for the coating design and the familiarity of the designer with the program.

15.1.4.2 Input

The input is given by the environment, the design itself, and the material definition including index extraction. The environment refers to the refractive index of the incident medium and substrate, a wavelength-dependent illumination or detector, and the angle of incidence of the incoming beam. The design itself is prompt, as an alphanumeric string considering the corresponding notation rules and the defined materials. The design program converts the string into the layer sequence, and a refractive index versus thickness plot illustrates the index profile.

Material definition is a database of materials suitable for use as thin films in an optical coating. Each material is defined by its refractive index as a complex value, with a real part as the refractive index itself and an imaginary part as the extinction coefficient. Usually, the given complex refractive index is listed in its wavelength dependence. The material data files are included in the material software package, or they can be called from the software or the material vendor.

15.1.4.3 Analysis

The analysis program performs evaluations based only on the given design, with the design parameters of layer number, layer type, and layer thickness. Analysis is

used to check a design under different parameter values or different environments, to refer or to compare designs of a database or a reference, or to modify designs by material substitution.

Because different coatings are possible for the same application, a method to select an optimal design solution is to analyze the design performance if small errors in thickness or refractive index are created. The checked errors have their origin in tolerances of thickness and refractive index during the manufacturing process, which gives this analysis tool the name “tolerancing.” Multiple numerical simulations of the design performance can be performed using a random error generator or using schematic deviations. Finally, a worst-case consideration indicates error values that yield a coating out of the target design.

15.1.4.4 Refinement

To obtain a desired coating performance, a target has to be defined. A broad range of performance values can be used as targets simultaneously, for example, reflectance versus wavelength and versus angle of incidence. The refinement program modifies a given design in its layer sequence and in the thickness of each individual layer to reach the targets as well as possible. Also, the refractive index of each layer material can be used as a refinement variable. Constraints can be defined concerning the layer thickness, layer number, and available refractive indices. A merit function is used to drive the changes in the refinement parameters and to indicate when a satisfactory solution has been reached.

The refinement program itself uses known optimization procedures similar to those that have been developed for the solution of general engineering problems. Because there is no one optimization method that works best on all problems, the coating designer can choose different procedures for different problems, but usually this has to be done with the aid of his own experience. The final value of the merit function, and the process time to get this value, may be parameters to select good start designs and optimal refinement algorithms for further design works.

15.1.4.5 Synthesis

Because the refinement program only varies given variables of the design, the result of refinement depends strongly on the start design. To overcome this problem, there is a synthesis program to find a design that matches the specified performance only when target and constraints are given. Synthesis creates an optimal design by adding layer by layer into the design, and thickness and refractive indices of the layers are so refined.

There are various methods of synthesis implemented in most of the thin-film software, such as comprehensive search, gradual evolution, needle technique, minus-filter approach, flip-flop design, and inverse Fourier transformation. In contrast to refinement procedures, thin-film syntheses do not require specific starting

designs and were developed solely for solving thin-film problems. However, synthesis requires special practices in handling of the different methods, because different problems are best solved by different methods. Furthermore, different synthesis methods yield different types of solutions to the same problem, and particular attention has to be paid to the creation of the targets.

15.1.4.6 Manufacturing assistance

Special thin-film software tools have the ability to guide the designer through the manufacturing process depending on the method of thickness monitoring and the deposition process used. Monitoring methods are based directly on the change in transmittance or reflectance of a coated substrate. Different direct optical monitoring techniques exist in which light of only one wavelength, several optimum wavelengths, or a whole spectral range are used. For each method, calculations can be performed that assist in determining the exact point where the deposition of individual layers should be terminated.

A more satisfactory approach is to use real-time design analysis. If the individual layers are measured for thickness and refractive index during the deposition process, it seems possible to adjust the thickness of the remaining layers of the coating if any error at an individual layer is indicated by the monitoring system. Such a completely automatic coating process is not yet implemented in a commercially available coating plant, but it is in development and demonstrates the future in thin-film manufacturing.

If the coating is manufactured, a re-engineering program based on the refinement program can be used to identify real errors in thickness and refractive index made during the manufacturing process. This gives feedback for the evaluation, both of the chosen design and the quality of the manufacturing process used.

15.1.4.7 Output

Output of the program tools take the form of different plots as spectral characteristics (e.g., reflectance or transmittance versus wavelength with angle of incidence as a parameter), as angle characteristics (e.g., transmitted or reflected phases versus angle of incidence with wavelength as parameter), or as thickness characteristics (e.g., transmittance or absorptance versus physical thickness with wavelength and angle of incidence as parameters). Some applications require an analysis of color in reflection or transmission under a given illumination. The CIE color specification system and common illuminations are implemented in any analysis program, and different chromaticity coordinates can be used as output plot.

Other outputs illustrate special design methods as vector or admittance diagrams, or the electric field distribution within the coating. Special performance parameters as group delay or group delay dispersion are also available in most of the programs. Naturally, parameter units can be changed easily, for example, length

units in nanometers or micrometers, spectral units in nanometers or electron volts, and reflectance or transmittance in percent or decibel.

15.1.4.8 Features of different software offers

Essential thin-film software products are listed in the Links section stated below. Each of the suppliers offers yearly updates and telephone support for its product. All the programs include packages for analysis, refinement, synthesis, and manufacture assistance, but there are special features:

- *FilmStar* has a BASIC module as an environment for customizing the program use and a MEASURE tool that can be used to drive different types of spectrometers directly by the thin-film software.
- *OptiLayer* is characterized by the needle optimization technique. This powerful synthesis method is also part of other software programs, but the *OptiLayer* supplier is the developer of the method. *OptiLayer* software also uses multi-threaded computations. This allows the user to interact with the software without interrupting computations.
- *TFCalc* is very easy to use and is a cost-effective solution if a lot of workstation has to be provided with thin-film software.
- *The Essential Macleod* includes a vStack as a special tool for the calculation and optimization of a set of nonparallel coatings, for example, an all-face coated prism. There are also tools for designing DWDM filters and induced-transmission filters. *Essential Macleod* designs can be directly exported to the ZEMAX optical design software.
- *Film-Wizard*TM combines optimization and synthesis design capabilities with powerful tools for analyzing spectroscopic and ellipsometric data, modeling thin film layers, and performing regressions to determine actual thicknesses and indices of multilayered thin-film structures.

15.1.5 Further reading

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15.1.6 Links

Further information on thin-film software:

- *FilmStar*: <http://www.ftgsoftware.com>
- *OptiLayer*: <http://www.optilayer.com>

- *TFCalc*: <http://www.sspectra.com>
- *The Essential Macleod*: <http://www.thinfilmcenter.com>
- *FilmWizard*: <http://www.sci-soft.com>

15.2 Electron-Beam Evaporation

M. Falz

15.2.1 Basic assessment of the technology

The technology essentially comprises the generation of atoms (or molecules) in a source that is heated resistively or by an electron beam. These atoms are transported to the substrate through a process chamber evacuated to high vacuum. The atoms are then condensed on the substrate and film growth is enabled.

15.2.2 Intended purpose of the technology

The optical properties of components (transmission, reflection, absorption) are affected precisely by means of resistance or e-beam evaporated films.

15.2.3 The technology's typical features

The technology includes evaporation of metals or compounds (oxides, fluorides, and so on) under high-vacuum conditions. By means of resistance-heated evaporators (coils, boots) or e-beams, the evaporating materials vaporize and are deposited on the substrates.

15.2.4 Description of process

15.2.4.1 Operating resources

- Vacuum chamber (diameter from 250 mm up to more than 2000 mm);
- Vacuum pumps (prevacuum pump or system in combination with high vacuum pumps such as diffusion-, turbo-, or cryopump);
- Glowing unit (plasma cleaning of substrates);
- Heating (front- or back-side heating for raising the substrate temperature);
- Evaporator (films of high purity with e-beam evaporator, less sophisticated layers with resistance evaporators);
- Substrate holders (palettes, calottes, or planetary systems);
- Shutters (start/stop of the deposition process and film thickness correction);
- Plant control (type: SPS or PC control);
- Measuring devices (quartz or optical monitoring for film thickness control).

15.2.4.2 Mode of operation

The parts to be coated are arranged in the upper section of a vacuum chamber on flat or slightly curved substrate holders. The vessel is evacuated to a high vacuum of lower than 10^{-4} mbar by use of combinations of powerful mechanical and high-vacuum pumps.

The evaporating sources are arranged on the bottom of the vessel. Depending on the technology, resistance or e-beam sources are used. E-beam evaporators are preferred to be used for films of high purity and, furthermore, for nonevaporable materials and high-temperature materials.

The performance of the evaporation sources is computer-controlled.

Shutters start and complete the deposition process. Normally, the deposition rate and the film thickness are measured by the quartz crystal method. In order to improve adhesion and the mechanical properties of the deposited films, the parts are plasma-treated by a glowing process prior to the actual coating step as well as preheated.

The common optical evaporation materials like Ti_3O_5 and SiO_2 are normally evaporated under a gas inlet (oxygen). A parallel operation of two evaporation sources is possible without problems.

15.2.5 Versions (state of the art)

Improvement of film quality by raising energy of vapor particles:

- PVD-IAD (ion-assisted physical vapor deposition),
- PVD-IP (ion plating),
- PVD-APS (advanced plasma source),
- PVD-magnetron sputtering,
- PVD-ion beam sputtering.

15.2.6 Data for electron-beam evaporation (Tables 15.1–15.7)

Table 15.1 Coating materials.

Material	Application
Metals (Al, Ag, Cu, etc.)	Mirrors
Oxides (TiO_2 , HfO_2 , Ta_2O_5 , SiO_2 , etc.)	Interference filter, antireflection films
Fluorides (YbF_3 , MgF_2 , etc.)	Interference filter, antireflection films
Suboxides (CrO_x , SiO_x , etc.)	Adhesion/absorbing layers

Table 15.2 Antireflection system.

Reflection	Wavelength range	Remarks
$\leq 0.5\%$	420–680 nm	Per side

Table 15.3 Interference filter.

Maximum transmission	Blocking	Full-width-at-half-maximum
80%	0.01%	10–20 nm

Table 15.4 Typical operation parameters.

Parameter	Minimum	Maximum
Evaporation rate	0.05 nm/s	10 nm/s (metals)
Residual gas pressure	5×10^{-6} mbar	10^{-8} mbar
Reactive gas pressure	5×10^{-5} mbar	3×10^{-4} mbar

Table 15.5 Machinable dimension (in dependence on system diameter).

Geometrical dimension	Minimum	Maximum
Calotte	$\varnothing \sim 100$ mm	$\varnothing \sim 2000$ mm
Palette (plan)	$\varnothing \sim 100$ mm	$\varnothing \sim 2000$ mm
Planetary system	$\varnothing \sim 100$ mm (calotte)	$\varnothing \sim 700$ mm (calotte)

Table 15.6 Process measurement technique.

Measured variable	Method of measurement
<i>In-line</i>	
Deposition rate, film thickness	Quartz crystal frequency measurement
Transmission, reflection	Spectral photometry
Temperature	Thermocouple, pyrometer
<i>Off-line</i>	
Transmission, reflection	Spectral photometry
Polarization	Polarizer
Color	Spectral photometry
Mechanical/chemical properties	Various
Conductivity	Four-point probe

Table 15.7 Limits of the technology.

Parameter	Limiting value	Reason for limitation
Thickness uniformity	$\pm 0.5\%$	Distribution of vapor type of substrate holder
Minimum thickness	1 nm	Metrology
Maximum thickness	100 μm	Film stress

15.3 Ion-Assisted Deposition (IAD)

U. Brauneck

15.3.1 Basic assessment of the technology

The technology essentially comprises the generation of atoms (or molecules) in a source that is heated resistively or by an electron beam. These atoms are transported to the substrate through a high vacuum. The atoms then condense on the substrate and film growth occurs during concurrent bombardment with energetic ions accelerated from an ion gun.

15.3.2 Intended purpose of the technology

The technology has been developed for the production of temperature-stable and dense coatings with excellent climatic resistance.

15.3.3 The technology's typical features

IAD includes a densification of a coating during the growth process by ion bombardment.

15.3.4 Description of process

15.3.4.1 Operating resources

- The material is evaporated by an electron beam or evaporation boat (usually metal-oxide or metal).

- An ion source or plasma source is used to produce reaction gas ions and/or noble gas ions. In some versions of the process, the evaporated material is partly ionized (plasma-assisted deposition and ion-plating) in the vapor phase and can therefore direct kinetic energy towards the substrates via a bias voltage. In all versions, the film is bombarded by reactive gas ions and noble gas ions directly. These ions transfer momentum to the surface atoms and improve the mobility of these atoms. Free positions in the growing atom layers can so be filled, and loosely bound particles may be sputtered away. Voids and subsequent shadowing effects (typical of conventional evaporation) are avoided.

15.3.4.2 Mode of operation

The mode of operation is described in Fig. 15.4.

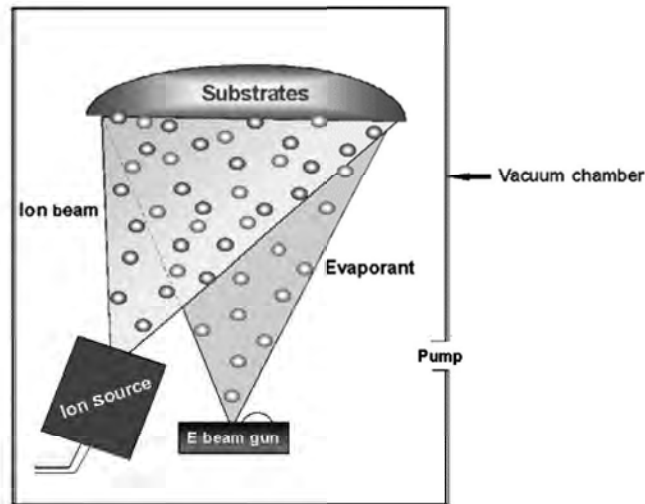


Figure 15.4 Sketch of principle of ion-assisted evaporation.

15.3.5 Versions (state of the art)

- IAD (ion-assisted deposition),
- Plasma-IAP,
- Ion plating.

15.3.6 Data for ion-assisted deposition (Tables 15.8–15.14)

Table 15.8 Coating materials.

Material	Application
SiO ₂	Vis/NIR coatings
TiO ₂	Vis/NIR coatings
Ta ₂ O ₅	Vis (+partly UV) coatings
Nb ₂ O ₅	Vis (+partly UV) coatings
HfO ₂ , ZrO ₂	UV + Vis coatings

Table 15.9 Antireflection system.

Reflection	Wavelength range
Per side 0.5%	420–680 nm

Table 15.10 Interference filter.

Maximum transmission	Blocking	Full-width-at-half-maximum
80%	0.01%	10–20 nm

Table 15.11 Typical operation parameters.

Parameter	Minimum	Maximum
Evaporation rate	0.1 nm/s	>2 nm/s
Residual gas pressure	5×10^{-6} mbar	10^{-8} mbar
Reactive gas pressure	8×10^{-5} mbar	2×10^{-4} mbar

Table 15.12 Machinable dimensions (in dependence on system diameter).

Kind of substrate holder	Maximum geometrical dimension of filter	Maximum geometrical dimension of antireflection system
Calotte	~ 120 mm	~ 400 mm
Plate	~ 400 mm	> 1000 mm

Table 15.13 Process measurement technique.

Measured variable	Method of measurement
<i>In-line</i>	
Transmission, reflection	Monochromator, spectral photometer
Ellipsometric angles	Ellipsometer
<i>Off-line</i>	
Transmission, reflection, absorption, and derived values	Photometry
Color (+derived values, temperature, R_s , and so on)	Photometry
State of polarization	Polarizer, analyzer
Laser damage threshold	Laser damage setup

Table 15.14 Limits of the technology.

Parameter	Limiting value	Reason for limitation
Thickness homogeneity	$\pm 0.5\%$	Form of evaporation “cloud”
IAD of fluorides	e.g., $R_{vis} < 0.2\%$	Decomposition of fluoride-component

15.3.7 Links

Further reading:

- http://www.uni-stuttgart.de/izfm/lehre/DunS_Auf.pdf

Plant engineering and construction:

- <http://www.leyboldoptics.com>
- <http://www.unaxis.com>
- <http://www.dentonvacuum.com>
- <http://www.satis-vacuum.com>

Toolmakers and suppliers of auxiliary materials:

- <http://www.merck.de>
- <http://www.gfe-online.de>
- <http://www.unicore.com>

Research and development:

- <http://www.iof.fhg.de>

15.4 Ion Plating (IP) Deposition

H.K. Pulker, A. Wälti

15.4.1 Basic assessment of the technology

The technology involves generation and ionization of atoms (or molecules) in a source that is heated by an electron beam and bombarded by a plasma beam accelerated from a low-voltage, high-current electron source. The ionized atoms are transported to the substrate through a low-pressure plasma environment. Condensation of the atoms on the substrate and film growth occurs in a reactive gaseous environment, with concurrent bombardment with energetic ions accelerated from the ionized vapor source.

15.4.2 Intended purpose of the technology

The technology has been developed for the technology production of dense, amorphous, abrasion-resistant, and environmentally stable films with excellent optical and functional properties.

15.4.3 The technology's typical features

A low-voltage, high-current electron source operating in a low-pressure argon atmosphere produces a dense plasma by electron impact into the coating material vapor cloud above an anodic crucible and into an introduced reactive gas. Depositing accelerated positive ions of the coating material, the working and reactive gas, generated by the repulsive force of the anode and a self bias potential of the insulated substrates, form well adherent, dense, stoichiometric, and generally constrained amorphous and smooth films on large-area substrates. Film properties are controlled by gas composition, pressure, and electrical data in a batch-coating system.

15.4.4 Description of process

15.4.4.1 Operation resources

- Vacuum box coater system of various chamber and substrate holder sizes (BAP-800 substrate holder, 800 mm);
- Different rotating substrate holder systems (palette, calotte, planetary);
- E-beam evaporation sources:

- Substrate heating device;
- *In situ* quartz crystal (rate) and optical (thickness) monitoring;
- Integrated fully automated control system; and
- Low-voltage, high-current electron source operated in argon with an e-beam crucible as the anode.

15.4.4.2 Mode of operation

The reactive IP process is performed in a specially designed automatic box-type plating system, the BALZERS BAP-800, shown schematically in Fig. 15.5. It can be used for deposition of single-layer and multilayer oxide coatings onto unheated glass and other unheated substrates. The evaporations are made by two special 270 deg deflection-type electron-beam evaporators. The starting materials, metals or suboxides, form electrically conducting melts. Very effective ionization and activation of the evaporating coating material atoms and the admitted reactive gas molecules results mainly from a low-voltage (typically 60 V), high-current (typically 40–50 A) electron beam of a non-self-sustaining thermionic arc discharge plasma directed to the anodic crucible of the e-beam evaporators. The cathode of the non-self-sustaining arc discharge is a resistance heated Ta filament in a separate chamber kept under a relatively high argon pressure. The substrate holder is electrically insulated. In contact with the formed plasma cloud, the substrates receive a relatively high negative self-biasing potential of -15 to -25 V with respect to the plasma, which together with the repulsive forces of the positive ions from the anodic crucible (potential typically between 70 and 40 eV) mainly determines the impact energy of the film-forming ions.

The total pressure in the plant is in the low 10^{-3} mbar range. Film deposition is started and stopped by opening or closing moveable shutters in front of the electron

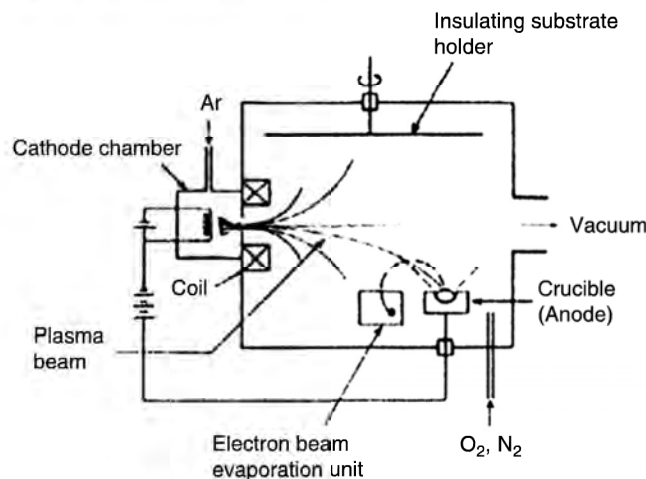


Figure 15.5 Operating principle of IP.

beam evaporators. Film thickness and deposition rate are controlled by optical thickness monitoring and oscillating quartz crystal monitoring.

Quarter-wave films in the visible are deposited within 2–5 min. A uniformity in thickness distribution of <1% over the whole substrate holder of 800 mm can be achieved with a simple static correction shield.

15.4.5 Data for ion plating deposition (Tables 15.15–15.22)

Table 15.15 Coating materials.

Material	Application
SiO ₂ , Ta ₂ O ₅	AR coatings
SiO ₂ , Ta ₂ O ₅ , HfO ₂ , Al ₂ O ₃	Interference filters 0.193–5.0 μm
SiO _x N _y , Si ₃ N ₄ , TiN	Decorative coatings
Ag, Al, Au, Ta, Nb, Ni, Si	Mirrors, absorbing layers
TiN, Ni	Antistress layers

Table 15.16 Versions (state of the art).

Coating machine	Substrate holder diameter
Balzers BAP	800 mm
Balzers BAP	1050 mm
Balzers BAV-1250	1250 mm
Evatec BAP-800	800 mm

Table 15.17 Antireflection system.

Reflection	Wavelength range
<0.2%	0.2–3 μm

Table 15.18 Interference filter.

Maximum transmission	Blocking	Full-width-at-half-maximum
>90%	<0.1%	1 nm

Table 15.19 Typical operation parameters.

Parameter	Minimum	Maximum
Process temperature	40 °C	280 °C
Residual gas pressure	2×10^{-4} mbar	1×10^{-3} mbar
Reactive gas pressure	8×10^{-4} mbar	1×10^{-3} mbar

Table 15.20 Machinable dimensions (in dependence on system diameter).

	Minimum	Maximum
Geometrical dimension	800 mm	1200 mm

Table 15.21 Process measurement technique.

Measured variable	Method of measurement
<i>In-line</i>	
Deposited mass	Quartz crystal frequency measurement
Transmittance, reflectance	Spectrophotometry
Temperature	Thermocouple
<i>Off-line</i>	
Conductivity	Four-point probe
Mechanical and chemical properties	Various
Transmittance, reflectance	Spectrophotometry

Table 15.22 Limits of the technology.

Parameter	Limiting value	Reason for limitation
Minimum thickness	1 nm	Metrology
Maximum thickness	100 μm	Coating stress
Homogeneity (m^2)	0.5%	Evaporation plume
Homogeneity (cm^2)	0.01%	Evaporation plume

15.4.6 Links

For further information see

- <http://www.evatecnet.com>

For further reading, plant engineering and construction, toolmakers and suppliers of auxiliary materials, and research and development.