Measuring of High Quality Optics for Lithography

Fast and high-resolution measurement of stress birefringence in large-format optical materials

Highly homogeneous glasses and crystalline materials such as CaF_2 (calcium fluoride) are used in microlithographic applications. Inherent stresses in the material induced in manufacture lead to stress birefringence and thus to imaging errors, which is undesirable for semiconductor manufacture in view of the ever smaller structure sizes. Materials from which optical components for wafer steppers are manufactured must therefore also satisfy high requirements with regard to inherent stresses.

Optical materials for microlithography

In wafer steppers, different materials are used for guiding and forming the radiation depending upon the illumination wavelength. Here it means essentially that the material used has very high transmission at the wavelength in question. Since many lenses are located in the beam path in the illumination and projection system of modern wafer steppers (the optical path in the material is in the order of magnitude of one meter), even slight transmission losses in every individual lens lead to relatively high attenuation of the total radiant power. The throughput and thus the cost effectiveness of the semiconductor production process are impaired directly by this. Furthermore, absorption in the material at high radiation strengths in the kilowatt range leads to heating of the optical system. On one hand this leads to a further increase of absorption and on the other to imaging errors due to deformation.

In 365 nm lithography (structure sizes down to approx. 200 nm) so-called i-line glasses are essentially used. Quartz glass with correspondingly high UV transmission is mostly utilized at 248 nm. Structure sizes of approx. 40 nm and smaller can be achieved with the aid of immersion lithography at an illumination wavelength of 193 nm. Quartz glass is used normally in the projection system, whereas CaF_2 is used in the illumination system if the requirements are high.

Stress birefringence

Even slight inherent stresses lead to deformations of the microstructure in the material and thus to direction-dependent changes of the refractive index. Glass is optically isotropic in the fully relaxed condition, i.e. the refractive index is not dependent upon orientation. However, glass becomes birefringent under stress. This effect is designated as stress birefringence (SBR).

Of necessity, local changes of the refractive index have an effect on the imaging properties of optical systems manufactured from this material. Since immersion lithography especially operates at the boundary of what is technically possible, even the smallest imaging errors quickly have a negative effect on the performance of the overall system. Therefore exact determination of stress birefringence and its spatial distribution already in the lens blank is of great importance.

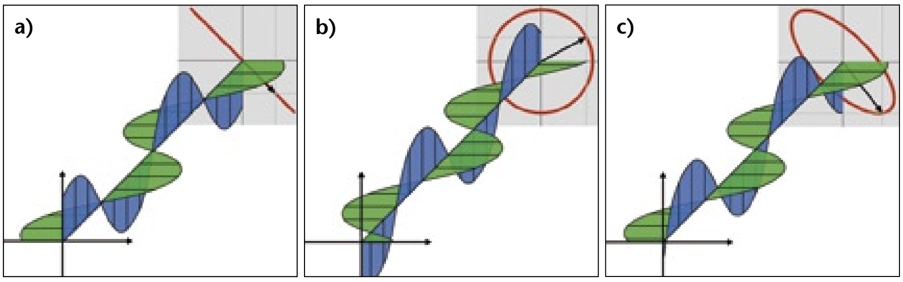

FIGURE 1: **Basic forms of polarisation:**
a) There is no phase shift without birefringence and the resulting light wave is again linearly polarised.
b) If the optical retardation is exactly one quarter of the wavelength, the field vector describes a circle and one speaks of circular polarisation.
c) If the optical retardation is larger or smaller than one quarter of the wavelength, then the resulting light wave is elliptically polarised.

Measuring principle

One uses the effect of photoelasticity for the quantitative determination of stress birefringence: If linearly polarised light strikes a birefringent material, then the emergent light wave is no longer linear, but elliptically polarised in the general case, i.e. its field vector describes an ellipse. One can imagine an elliptically polarised light wave as superimposition of two linearly polarised waves standing at right angles to one another and with a certain phase difference. The phase difference results from the optical retardations of the light waves, which are propagated with different velocities in

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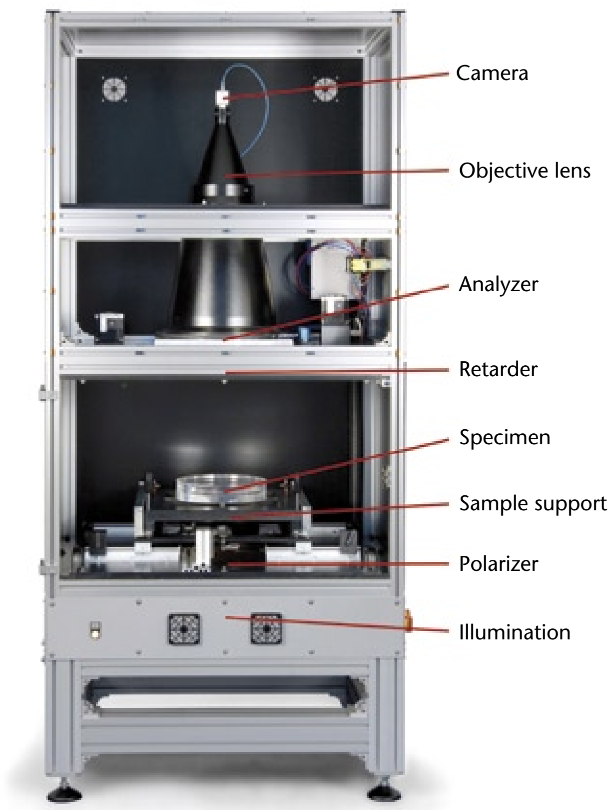

FIGURE 2: **StrainMatic M4/320 polarimeter system in vertical design for fast measurement of stress birefringence in lens blanks up to approx. 320 mm diameter and 300 mm thickness.**

FIGURE 3: **Internal construction of the StrainMatic® M4/320 polarimeter system.**

the material corresponding to the differences in refractive index. The resulting optical retardation determines the minor to major axis ratio of the imagined ellipse, and depends upon the ratio of the refractive indices as well as the optical path lengths. Therefore the ellipticity is a direct measure of the birefringence and thus of the underlying inherent stresses. Figure 1 illustrates the different polarisation states.

The elliptically polarised light is converted by means of a quarter wave plate (also named retarder) back into linearly polarised light, the oscillation plane of which is changed by a certain angle in relation to the original polarisation direction. This angle is directly proportional to the optical retardation and can be determined relatively simple by a second, rotatable linear polarizer (named analyser) [1].

Compared with a simple intensity evaluation with crossed polarisation filters, this method has the advantage that it is independent of the transmission of the measured object and the brightness of the illumination – calibration depending on the measured object or on the light source is not necessary.

In optical materials stress birefringence is frequently specified in the unit of nm/cm. Therefore as a rule the determined optical retardation is normalised to 1 cm layer thickness by division by the specimen thickness. The underlying mechanical force in MPa can be calculated from the normalised optical retardation by multiplication with the photoelastic coefficient, a temperature and wavelength-dependent material constant, which for example lies in the range of 3.4–3.6 TPa^{-1} in quartz glass. Here it must be noted that such normalisations are valid only for so-called membrane stresses, therefore stresses that are homogeneous along the measuring ray.

Measurement technology

Automatic systems with a single detector are predominantly used for measuring stress birefringence in optical materials. These permit precise determination of even low SBR values for individual measuring points. The mechanically rotating analyser is frequently replaced here by an optoelectronic element, which modulates the polarisation without moving parts. The test specimen must be scanned successively by the measuring ray and moved mechanically in order to be able to measure the spatial distribution of the stress birefringence.

The lateral resolution achievable in practice is limited on one hand by the ray geometry. For example, with a typical ray diameter of one millimetre, no statements about structures smaller than this size can be made. On the other hand – and this is often the practical limitation – the available measuring time limits the number of measuring points and thus the achievable spatial resolution. To achieve the required throughput, frequently only a small part of the specimen area therefore is measured. The data density may normally be large enough to generate reliable statements about mean

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The ilis gmbh develops, produces and distributes software solutions, measuring technology as well as automatic test equipment for quality assurance in the glass and optical industry. With the measuring and test equipment of the StrainMatic series, the company has specialised in the development of imaging polarimeter systems for the automatic and objective measurement of stress birefringence in glass, plastics and crystalline materials.

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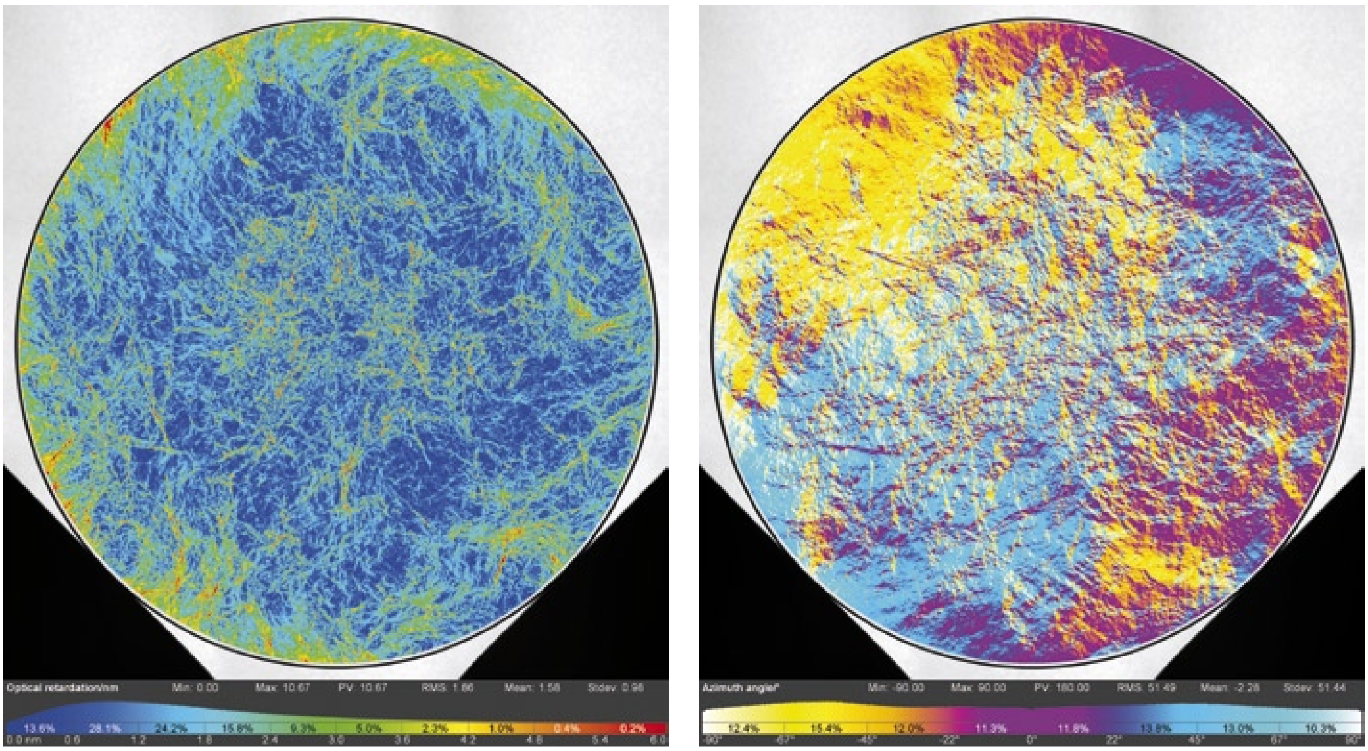
FIGURE 4: StrainMatic M4/160 polarimeter system in horizontal design with fully automatic stitching for specimen measurements up to 400 x 400 x 100 mm³ and 100 kg weight.

value and spread, but the lateral resolution is often not sufficient for reliable determination of maximum and minimum values.

Apart from limiting the measuring throughput, the scanning mode of operation makes high demands on ambient conditions due to the relatively long measuring time. In many optical materials, the SBR distribution shows strong dependence upon temperature gradients in the material. If the ambient temperature changes during the measurement, the three-dimensional distribution of the SBR may also change and the values determined at the beginning of the measuring sequence are no longer suitable for the following measuring points. The necessary stabilisation of the temperature over the entire measuring period therefore often requires complex air-conditioning of the entire test room resulting in high costs.

Last but not least, scanning methods make high demands on the plane parallelism as well as the surface quality of the test specimen. A measurement through lapped surfaces is possible as a rule by wetting with an immersion solution that is adapted in its refractive index to the specimen material, and in this way smoothens the surface optically (otherwise the measuring ray would be scattered and miss the detector). In any case, with scanning systems it is not possible to measure wedge-shaped or lenticular specimens without further aids.

FIGURE 5: Measuring result stitched together from nine single measurements of a CaF_2 disk 240 mm in diameter:
a) Distribution of the SBR intensities, b) False colour display of the axis orientations



Alternative approach

An innovative type of imaging polarimeter newly developed by ilis allows fast characterisation of stress birefringence with high spatial resolution. The measuring principle corresponds to a very large extent to the configuration of narrow-band light source, linear polarizer, quarter wave plate and analyser already described, but with the difference that not only the analyser rotates, but also the retarder and polarizer. Apart from SBR values, the axial orientations (azimuth angles) can be determined precisely, and that with the same spatial resolution and high accuracy in the order of one angular degree.

Figure 2 shows such a measuring system with a useable aperture of up to 320 mm for the fast measurement of lens blanks and other components. The internal construction can be seen in Figure 3. The horizontal positioning of the specimen on an XY slide with telescopic rail extension facilitates fast loading and unloading. Thanks to the telecentric optical system with large depth of field, even very thick specimens can be measured without perspective errors. The lateral resolution (pixel spacing) extends according to the camera used from 0.18 mm (1.4 megapixel, 256 x 192 mm² measuring field size), through 0.16 mm (3.3 megapixels, 320 mm measuring field diameter) up to 0.11 mm (4.2 megapixels, 225 x 225 mm² measuring field size). The achievable data density is therefore up to 82 measurement values per mm², so that reliable determination of peak values is also possible. The short measuring time of less than one minute enables high specimen throughput and reliable measurement of materials with temperature-sensitive SBR distribution, such as i-line glass. Thanks to the use of high-quality optical components and robust evaluation algorithms, reproducibilities of better than 0.005 nm/cm optical retardation (related to 100 mm specimen thickness) can be achieved in practical operation.

A further increase in spatial resolution can be achieved by reducing the size of the measuring field. To be able to measure large-format specimens completely despite this, several measurements must be performed at different specimen positions and stitched together by the software. However, in comparison to the purely scanning measuring method, only a few single measurements are necessary even for large specimens, so that the total measuring time remains acceptable. Figure 4 shows such a measuring system with a measuring field size of 112 x 112 mm² and 4.2 megapixels image resolution. The ray path runs horizontally here, i.e. the specimen stands on its side so that no part of the measuring area is covered by the specimen fixture. The specimen, the weight of which including specimen support can be up to 100 kg, is positioned by two linear units with an absolute accuracy of better than 0.05 mm. The software stitches the individual measurements together fully automated. Illumination is coaxial as standard, but can also be made to diverge by changeable diffusers, so that wedge-shaped or curved specimens, for example, can be measured.

Due to the high lateral spatial resolution of 50 µm, even the finest structures and smallest defects in the glass or crystal matrix can be reliably quantified. Figure 5 shows as an example the measuring result of a lens blank made of CaF_2 with a spatial resolution of 15 million pixels and a data density of 334 pixels/mm².

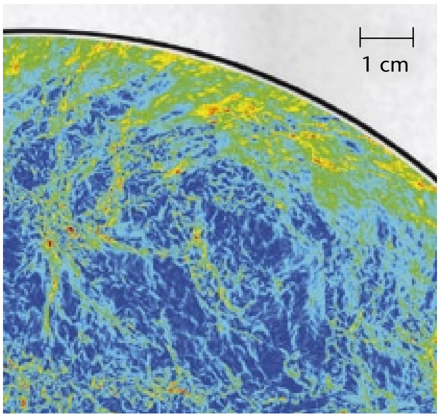


FIGURE 6: **Detail enlargement of the measuring result in Fig. 5a**

Summary

Imaging polarimeter systems facilitate fast and accurate measurement of stress birefringence with previously not achievable resolution. In combination with automatic specimen positioning, even very large specimens can be characterised with high accuracy and without loss of spatial resolution. In contrast to purely scanning methods, the high spatial resolution enables a statement to be made even about the finest structures in the material, and that comparatively low requirements on surface quality and ambient conditions.

References

[1] H. Katte, Imaging measurement of stress birefringence in optical materials and components, Photonik international 2009/1, p. 39