Light Scattering from Contamination and Defects – Measurement, Analysis, and Modelling

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Abstract. Light scattering induced by contamination and defects on optical components can quickly limit the component's performance. Therefore, imperfection analysis and budgeting are mandatory - but also challenging tasks. On the other hand, imperfections can be elegantly characterized using efficient, robust and non-contact light scattering techniques. This will be demonstrated in this contribution for area covering measurement approaches using laboratory instruments with highest sensitivity as well as elaborated sensor systems that are best suited for extended freeform surfaces. Moreover, the measurement results are used to derive practical imperfection scattering data and models that serve as input to model and predict the imperfection induced scattering on optical system level.

1 MOTIVATION

The performance of optical instruments might quickly be limited by particular or molecular organic contamination (PAC, MOC) and surface defects. Beside surface roughness, these imperfections are primary origins of light scattering [1-6] that causes a reduced imaging contrast or a loss of throughput. In particular for super-smooth surfaces or thin film coatings, as those applied in space or lithography industry, even lowest imperfections levels might be performance limiting.

However, imperfections on optical components are unavoidable and, therefore, budgeting and characterization becomes mandatory. On the other hand, the induced light scattering is an ideal, highly sensitive, fast, and flexible characterization tool for imperfection analysis [2-6] even on extended freeform surfaces [5].

Consequently, both aspects light scattering based instruments as well as modelling approaches for the analysis and budgeting of surface imperfections and their scattering are investigated at Fraunhofer IOF. Results ranging from pure angle resolved scattering measurements over full surface characterization regarding roughness, contamination, and defects, to modelling approaches that utilize the measured data for prediction of imaging quality in optical system design are presented.

2 Application examples

2.1 Angle resolved scattering of PAC and MOC

The angle resolved scattering (ARS, [2, 4, 7]) at 532 nm of a contaminated super-smooth silicon wafer with a percentual areal coverage (PAC) of 300 ppm is summarized in the Fig. 1. The upper part shows a full-area mapping into a fixed scattering direction to reveal the local particle distribution. The bottom part shows the ARS curves of selected particles and of the clean Si wafer.

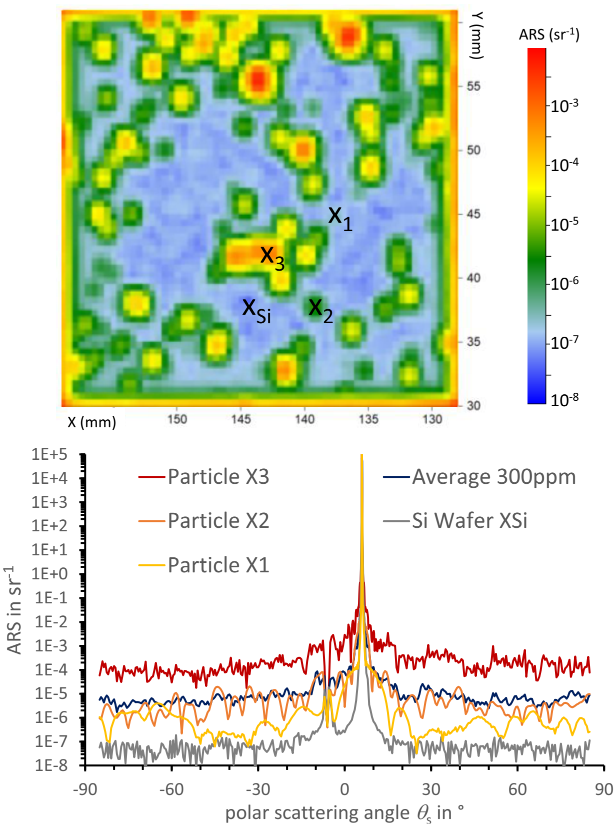

Fig. 1. Light scattering from contamination. Top: scattering mapping obtained by laterally scanning a supersmooth Si-wafer at fixed scattering angle direction; bottom: ARS of this silicon wafer at the indicated particle sites.

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The roughness induced scattering level of the silicon wafer is lower than ARS = 10^{-7} sr^{-1} enabling the characterization of PAC levels below 10 ppm. The particle induced scattering significantly increases the ARS level by up to 3 orders of magnitude for singular defects. Moreover, the curves show strong oscillations that correspond to feature size and form [3, 6].

Based on the scattering mapping, single ARS curves of selected postions, and stochastic data analysis, an averaged ARS is derived (blue curve). This curve represents the ARS of the homogeneously illuminated sample and can be utilized as scattering input in optic design software.

2.2 Sensor for freeform surfaces assessment

For a rapid full surface analysis of particles and defects on extended surfaces, a compact hybrid sensor with a CMOS detector matrix for ARS measurement [3] and a microscope for geometrical feature analysis was developed. This sensor is traced over sample surfaces using a robotic handling system [5] that enables the characterization of freeform components. Hence, the resulting mapping data can be analyzed for local rms-roughness, homogeneity, local and averaged 3D-ARS data, or PAC by evaluating the scattering or feature geometry data. Exemplary results and a scheme of the sensor are shown in Fig. 2.

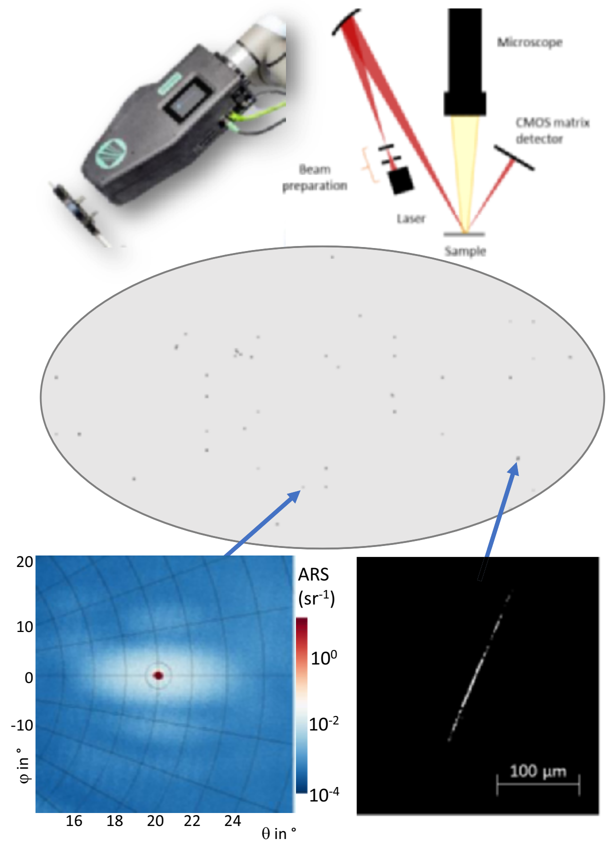

Fig. 2. Hybrid scattering sensor for imperfection assessment. Top: image and scheme of the sensor. Middle: binarized imperfection mapping of an ellipsoidal mirror substrate (120 x 70 mm²). Bottom: typical 3D-ARS image of a defect (left) and microscopy image of a scratch (right).

2.3 Application in optical system design

Once angle resolved scattering data is obtained that is representative for an entire surface or component, it can be directly transferred into raytracing software (e.g. FRED, ASAP, …) for a realistic prediction of the contamination induced scattering on system level.

For example Fig. 3 shows the possible image degradation for a simple Gaussian double lens induced by a PAC of 0.1 % using transfer function theory [7].

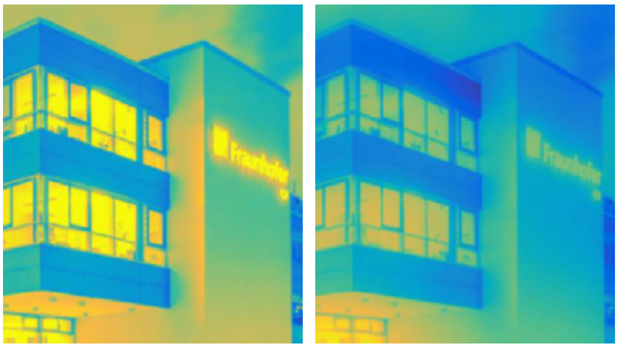

Fig. 3. Image degradation induced by contamination with a PAC of 0.1% for a Gaussian double lens (without aberrations). Left: ideal image, right: degraded image.

Vice versa meaningful and easy to handle scattering models (ARS or BSDF) can be derived that enable the predication of acceptable contamination budgets for the specific optical system application.

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