Conclusion

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The characterization of features such as geometrical dimensions or functional parameters like roughness or degree of cross-linking plays an important role during production in industries such as semiconductors, organic-electronics and the photovoltaics industry. The ability to gather measurements in a process-integrated fashion is of high interest.

The scope of this work, in this context, was the development of an optical metrology tool which is capable to provide information on surface features and material properties in a fast and versatile way. In contrast to existing technologies, a novel approach was developed which delivered information on surface line profiles without the need for mechanical scanning and with higher resolution. Furthermore, in some aspects the approach was also able to gather information which was not accessible in a spatially-resolved fashion before. The developed setup was based on a modified, dispersion-enhanced low-coherence interferometer (DE-LCI). The properties of interest were characterized in the three major applications surface profilometry, polymer and thin-film characterization.

In the main part of this work, the DE-LCI approach was designed and implemented for surface profilometry. Here, it was shown how controlled dispersion can be used to encode path length differences in an interferometer and therefore surface height information in the spectral domain. The dispersion was controlled by a dispersive element, i.e. a glass window, which was used as one possibility to adjust the axial measurement range of the setup. Additionally, it was demonstrated how an appropriately designed imaging spectrometer can be utilized to gather the surface height information along a line profile in a single data acquisition without the need for mechanical scanning. The introduction of an additional, movable lens after the interferometric recombination extended the setups capabilities and allowed the acquisition of three-dimensional surface height information. The development of a custom data analysis and fitting routine led to an estimation of the axial measure-

Ch. Taudt, *Development and Characterization of a Dispersion-Encoded Method for Low-Coherence Interferometry*,
https://doi.org/10.1007/978-3-658-35926-3_6

ment range of $\Delta z = 79.91\,\mu\text{m}$ while a theoretical axial resolution of 0.088 nm was calculated for a selected experimental configuration. With these values, a dynamic range in the axial dimension of $\text{DR} = 9.0 \times 10^5$ was estimated.

The characterization of a setup with the calculated properties was performed by analyzing the surface profiles of different measured step height standards. Most notably, the determination of the profile and the height of (101.8 ± 0.1) nm on a silicon height standard demonstrated the capabilities of the setup. It could be shown that the setup has a repeatability of $\overline{\sigma_z} = 0.13$ nm while the axial resolution was found to be $\Delta z_{min} = 0.1$ nm. In relation to the available measurement range of $\Delta z = 79.91\,\mu\text{m}$, the experimentally determined dynamic range was $\text{DR} = 7.99 \times 10^5$. This value is about 6 times higher than comparable current approaches known from literature, [119].

Furthermore, it could be demonstrated that functional parameters such as surface roughness are measurable with the same axial resolution like surface profiles although this data was gathered over a lateral measurement range of up to 1.5 mm. This separates the novel approach distinctively from established technologies such as tactile profilometry or confocal laser scanning microscopy which rely on time consuming and error-prone methods of scanning or stitching to enable lateral measurement ranges of the same order.

The capabilities of the setup regarding the acquisition of three-dimensional surface height information were evaluated with a measurement of a μm-sized, PTB-calibrated height standard. By imaging an area of $1.5 \times 0.25\,\text{mm}^2$ with sub-nm resolution, the measurement of steps with heights of (971.26 ± 0.31), (4951.40 ± 0.28) and (19924.00 ± 0.36) nm was performed while additional features such as the roughness of each step could be acquired simultaneously.

An extension of the setup with an imaging spectrometer for the NIR spectral range $(\Delta\lambda = (1133 - 1251)\,\text{nm})$ enabled tomographic measurements of a silicon sample. Specifically, the front and back surface of a thinned wafer could be investigated.

In summary, the developed dispersion-encoded approach to interferometry for surface profilometry proved to be of high resolution in the axial dimension while capturing large measurement ranges in the lateral dimension. Due to the high-dynamic range and fast data processing, an application can be envisioned in process-integrated metrology for industrial production.

The determination of the degree of cross-linking is an important criterion in quality assurance of polymer processing. The degree of cross-linking determines important mechanical properties of the fabricated products as well as their long-term durability. Additionally, the cross-linking process bears potential for optimization during production in regard to speed and properties. Therefore, production accompanying monitoring is desirable.

Based on these conditions, the DE-LCI approach was adapted accordingly and tested for its ability to characterize polymers. The characterization was based on the measurement of the wavelength-dependent refractive index $n(\lambda)$ as a measure for the degree of cross-linking. The DE-LCI approach was utilized in a temporal scanning as well as in a scan-free configuration. Using the temporal scanning configuration, $n(\lambda)$ could be analyzed over large spectral ranges of $\Delta\lambda = (400 - 1000)\,\mathrm{nm}$ while a resolution in terms of the group refractive index of $\overline{\sigma_5(n_g)} = 2.13 \times 10^{-4}$ was achieved. The measurement took several seconds and no spatial resolution could be accomplished. In contrast, the scan-free configuration was capable to measure the refractive index with a resolution of 3.36×10^{-5} on a profile of 250 µm length in 50 ms. The spectral range was about 20 nm. In context of the scan-free configuration, a novel mathematical method for the analysis of phase data based on wrapped-phase derivative evaluation (WPDE) was developed and qualified. Both configurations were tested using typical samples from the photovoltaics and semiconductor industry respectively.

In contrast to existing technologies to determine the degree of cross-linking, the novel approach is fast, non-destructive and capable to perform spatially-resolved measurements with a lateral resolution of about 5 µm. The combination of characteristics is unique to the novel approach.

The precise control of single-layer thickness in the production of thin-film systems is crucial for the performance of these systems e.g. in the organic electronics or photovoltaics industry.

The DE-LCI setup was adapted as a Mach-Zehnder type interferometer in order to characterize the thickness of single-layer thin-films. By measuring a layer of ITO on a bulk glass substrate, it was demonstrated that the layer thickness can be measured with a resolution of 1.6 nm. The modification of the setup by using a secondary spectrometric detection channel allowed to capture back-reflected light of the sample. This way, it was possible to in-situ evaluate the substrate thickness of a flexible substrate ($t_{sub} = 135\,\mu\mathrm{m}$) while measuring the film thickness of a layer of ITO ($t_{ITO} = 151.6\,\mathrm{nm}$) simultaneously. This improved the robustness of the underlying transfer-matrix model which was utilized to calculate the film thickness from recorded spectral data.

The ability to capture film thickness data with spatial resolution within a single frame acquisition separates the DE-LCI approach from existing technologies and determines its usability as a process-integratable tool in future applications.

As demonstrated, the scope of this work was to show a range of possible applications of the developed DE-LCI approach while examining each application in depth. While answering the major questions by experiments and analysis, some additional questions arose which could not be addressed within the scope of this work. Most notably, alternative approaches might be addressed in future works in order to analyze the captured data. Preliminary experiments have shown that methods of image processing and statistical analysis are promising with regard to resolution, speed and robustness. Furthermore, it can be noted that the analysis of the captured data by means of FD-OCT is possible, [98]. Here, the different dispersion in the interferometer arms has to be compensated by multiplying the spectral data with an appropriate phase function, [258]. After re-sampling and Fourier transformation the data contains three components: the desired peak in depth space, second the broadened mirror term and third the broadened DC term. Due to the signal construction in an DE-LCI approach, these terms overlap and need more sophisticated compensation in order to perform analysis known from full-range OCT approaches, [111]. Nevertheless, this approach bears potential for future work as it will increase the possible axial measurement range of the approach. Additionally, the development of fitting routines which can deal with data where the equalization wavelength lies not within the spectral range of the detector are interesting to enhance with respect to the axial measurement range. Beside these approaches to data analysis, advanced design and construction efforts with regard to mechanical stability and thermal management are interesting to further improvements of e.g. the repeatability of the setup. In terms of hardware aspects, the utilization of the triggerable high-power NIR supercontinuum light source makes possible the characterization of dynamic surface profilometry of oscillating samples in a stroboscopic acquisition mode. The experimental validation of theoretical designed methods to gather three-dimensional surface information in a scan-free fashion is of high interest as well.

Furthermore, the characterization of cross-linking mechanisms during actual processes with high temporal resolution as well as the monitoring of internal stresses during cross-linking by polarization enhanced DE-LCI is an interesting topic for future research.

The extension of the data analysis in thin-film characterizations towards multi-layered systems can be envisioned.

The combination of advantageous features such as the versatility of applications, the high dynamic range in the axial as well as the lateral domain, the capabilities to tune the measurement ranges easily and the high resolution characterize the developed approach. In conclusion, it can be said that the DE-LCI approach was developed and qualified in its main features and bears the potential for interesting applications in research as well as in industry.