IND17 Scatterometry

Final Publishable JRP Summary Report for IND17 Scatterometry

Metrology of small structures for the manufacturing of electronic and optical devices

Overview

This project developed sophisticated dimensional metrology of structures in the sub-micrometre range to support current and future manufacturing processes and further development of technologies for optics and semiconductor industries. Optical scatterometric methods and approaches have been developed and improved, supported by i) novel and sophisticated modelling and data analysis methods for scatterometry, and ii) improved and novel methods for atomic force microscopy (AFM). For the first time, traceable scatterometric measurements with a well-defined uncertainty budget and much improved agreement of measurement results between different scatterometric tools and other microscopic methods have been achieved. These achievements were supported by the development of the first scatterometry reference standard samples and a reliable calibration service for standard and customer samples.

Need for the project

Scatterometry is an optical method to determine geometrical and optical parameters of structures on a surface. The structured surface is illuminated by a light wave, the light diffracted or scattered at the surface is measured and the results, the measured distribution of the scattered light, are evaluated to provide geometrical and optical parameters. For future developments in the semiconductor industry, accurate and reliable measurements of the size of nanoelectronic device structures, the so called critical dimensions (CD), have been identified as essential but also as an unsolved problem[1]. Currently, scatterometers and critical dimensions scanning electron microscope systems (CD-SEMs) are the main metrological tools used for production measurements. Scatterometry usually shows an excellent sensitivity to small changes in the dimensions of the structures. However, before this project, traceable and absolute scatterometric measurements were not available and product-related standards for the characterisation and calibration of scatterometers did not exist. As a consequence, scatterometric measurements often showed systematic deviations when compared with CD-SEM measurements.

With the continuous shrinking of structure dimensions and a clear trend towards much more complex 3D structures for future nanoelectronic devices, the need exists for improved measurement tools and methods appropriate to those dimensions.

In the optics industry, diffractive optics and in particular the characterisation of curved structured surfaces are becoming increasingly important because refractive-diffractive optics can replace multi-component products with a single component and thus produce miniaturised products that can be used for a wide range of applications. Currently, only microscopic measurement methods such as AFM or SEM, are used to test the size of diffractive structures. However, these microscopic methods are generally slow and not suited for manufacturing control of new optical devices.

[1] www.itrs.net

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Scatterometry is a promising candidate to measure structure dimensions and diffractive structures but optical scatterometric methods and approaches have to be improved.

Scientific and technical objectives

To overcome the limitations in optical scatterometry and to meet current and future metrology requirements this project addressed the following scientific and technical objectives:

Improvement of the accuracy, traceability and 3D capability of scatterometric methods

1. Improvement of the accuracy and traceability of scatterometric methods to the 1 nm range (for linewidth), corresponding to an improvement of one order of magnitude as compared with currently available linewidth metrology;
2. Improvement of the 3D capability, the efficiency and the measurement uncertainty, of scatterometric methods to achieve the suitability of scatterometry for applications in process development and quality control for 3D structures;
3. Evaluation of the sensitivity and robustness of scatterometric measurements to structure details;
4. Development of faster data analysis tools, which are 3D-capable and offer a reliable uncertainty estimation option and the flexibility to include complex structure geometries and detailed structure parameters

Extension of scatterometric methods

5. Methodical extension of scatterometry to shorter wavelengths (extreme ultraviolet - EUV, X-Ray), polarimetry and Fourier scatterometry;
6. Methodical extension of scatterometric methods for the characterisation of diffractive optical elements, especially on curved surfaces (diffractive-refractive optics);

Development of ultra-high resolution microscopy (AFM, SEM) to support scatterometry and to enable measurements comparisons with scatterometry

7. Development of ultra-high resolution microscopy (AFM, SEM) and short wavelength (EUV, GSAXS) scatterometry to deliver further structure details;
8. Combination of an AFM with x-ray and optical interferometry to provide high resolution measurements of local variations at the sub-nm level of grating periods;
9. Extension of the scatterometric and microscopic metrology systems used by the JRP-Partners to enable comparison measurements;

Development of efficient and reliable methods for a combined data analysis of the different metrology methods

10. Evaluation of the sensitivity of scatterometry to different structure details and implementation of *a priori* information delivered by additional (e. g. AFM-, SEM- or grazing incidence small angle X-ray scattering - GISAXS-) measurements in the data evaluation of scatterometry;
11. Development of efficient and reliable methods for a combined data analysis of different methods, both scatterometric and microscopic, with the aim to achieve measurement uncertainties well (i.e. more than 10%) below the individual measurement uncertainties;

Design, development, test and calibration of a scatterometry standard

12. Design, development, test and calibration of a scatterometry standard, which basically is also suitable for AFM and SEM testing.

Results

The scientific and technological methodologies developed within this project improved three relevant methods for dimensional and CD metrology in the semiconductor industry: CD-SEM, CD-AFM and scatterometry. The project's results improved the comparability of these methods and the developed data analysis schemes enabled an additional reduction of measurement uncertainty.

In addition, fast and reliable optical metrology methods have been developed and tested with scatterometry and Mueller polarimetry and are now available for the characterisation of diffractive and hybrid optical devices in optics industry.

Scatterometry reference standards have been designed, developed, characterised and calibrated to face the tough and ever-changing specifications of the semiconductor industry, in agreement with the *International Technology Roadmap for Semiconductors*[2]. For the first time, standards are available which are suitable for the test and calibration of scatterometers, AFMs and SEMs. This will facilitate the comparability of measurement results obtained using these different types of tools.

Improvement of the accuracy, traceability and 3D capability of scatterometric methods (this addresses objectives 1 to 4)

Novel sophisticated scatterometric systems have been built and adapted for systematic investigations, measurements comparisons and calibrations of scatterometry reference standards. The systems investigated included novel types of scatterometers, such as a coherent scanning focussed spot scatterometer (CSFS), short wavelength EUV and X-Ray scatterometers, Mueller polarimeters and Fourier scatterometers. The specific advantages and features have been successfully demonstrated and systematically characterised.

The influence of local effects has been analysed, and the impact of local structure roughness and finite spot size on accuracy has been quantified experimentally and numerically. Finite spot size effects were shown to be negligible for current scatterometer systems and spot sizes >> 10 µm, but will become significant for future in-die scatterometry applications. Neglecting line roughness introduces strong measurement deviations. Therefore, a model description has been developed and evaluated to compensate for the impact of line edge and widths roughness especially for short wavelength scatterometry. A significant influence of the size of the structures on optical material parameters has not been observed. The sensitivity and robustness of the different scatterometry methods on these structure details have been evaluated and proven. In particular the X-ray scatterometry method GISAXS has been tested and showed an excellent measurement capability for structure details such as stitching errors or line edge roughness.

To enhance and validate the 3D performance of scatterometry, a Fourier scatterometry method has been investigated and further developed. It was shown that this method is suitable to improve 3D measurements on structures. A model for the treatment of realistic roughness has been developed based on an efficient 2D Fourier transform approach. The software package GSvit has been extended to large size structured domains and further improved for realistic spectral properties and complex 3D geometries. A graphical user interface for better use of GSvit by a wide audience has been developed and is now published as open source software.

Different high quality small-pitch test samples with periods down to 50 nm have been acquired or specially manufactured for systematic investigations and measurement comparisons. Therewith possible error sources for different scatterometry methods have been systematically investigated, quantified and eliminated. A measurement comparison on 1D and 2D gratings using seven different scatterometry systems and methods and high resolution AFM and SEM measurements showed an excellent agreement at a level of a few nm, demonstrating the high level of comparability, accuracy and traceability reached. The strengths and weaknesses of the different methods have been analysed and are now much better characterised.

Methodical extension of scatterometric methods for the characterisation of diffractive optics (this addresses objectives 5 and 6)

Diffractive optical test samples, including planar and curved substrates for validation of scatterometry as metrology for such devices, have been designed, manufactured and measured. Good agreement between

[2] www.itrs.net/reports.html: update 2012, metrology tables

dimensional parameters obtained from AFM and scatterometry measurements has been achieved for simple binary grating structures. Mueller Polarimetry shows higher sensitive to grating structure details than conventional scatterometry. Combined inverse modelling of Mueller polarimeter and scatterometry data have been successfully tested and a combined set-up for Mueller Polarimetry and scatterometry has been tested. Mueller Polarimetry has shown to be more sensitive for gratings with pitch to wavelength ratio below 10, whereas scatterometry shows higher sensitivity for larger pitch to wavelength ratios. DOE-structures with subwavelength gratings important for future applications have been successfully measured.

Development of ultra-high resolution microscopy (AFM, SEM) to support scatterometry and to enable measurements comparisons with scatterometry (this addresses the objectives 7 to 9)

Two different AFM techniques, CD-AFM and tilting-AFM, have been developed and applied to measure structure details such as height, sidewall angle, corner rounding and footing. In addition, a low voltage SEM has been used for the characterisation of structure details. A special edge detection algorithm has been tested to analyse linewidth and edge details such as top or bottom edge position corresponding to the local edge angle. These tools were shown to be useful in the analysis of structure details and provide a valuable input to scatterometry.

The design and uncertainty budget for an X-ray-interferometer-coupled AFM have been completed and a new AFM head has been developed and successfully tested. This system will be ready in the near future and will be a valuable top level reference tool for local pitch variations. Due to technical issues with the x-ray interferometer the measurements of local period variations have been performed with another top level optical-interferometer-controlled AFM reference system with sub-nm uncertainty.

Another special long range 3D AFM has been developed to provide reliable microscopic comparison measurements. This system is based on a novel sampling technique for real 3D measurements, which has been developed and successfully tested within this project.

In total four different AFMs and one SEM have been set-up or modified to enable systematic comparison measurements. These tools and methods are available at the different NMIs and project partners enabling measurement comparisons and facilitating the detection of possible sources of systematic measurement errors useful e. g. for novel technology steps in semiconductor industries.

Development of efficient and reliable methods for a combined data analysis of the different metrology methods (this addresses the objectives 10 and 11)

The maximum likelihood approach was successfully tested and implemented to solve the inverse diffraction problem, which is required to analyse scatterometry measurements. Results have shown that the refinement of the geometry model, including more realistic structure parameters, leads to a significant reduction of variances in the measurement uncertainty for CD. The Bayesian approach for combined measurement data analysis was developed and applied to combine scatterometry and AFM measurements. For this purpose the software package GSvit-scattering was developed for direct calculation of far field diffraction patterns from AFM data, applicable both for periodic and randomly rough surfaces. It was demonstrated that the combination of both measurement techniques reduced the overall uncertainties by typically more than 10% with respect to the individual measurement uncertainties. .

Design, development, test and calibration of a scatterometry standard (addressing objective 12)

Design and specifications of the scatterometry reference standards have been developed and discussed with the stakeholder community, in particular with colleagues from NIST, SEMATECH and important European companies from semiconductor industry, adding valuable feedback to the final designs and specifications. The manufacturing process has been optimised using an iterative approach with experimental characterisations both for Si and the dielectric Si_3N_4 version of the standards. High quality samples of both type with excellent structure qualities and with grating periods between 50 nm and 250 nm and CD values between 25 nm and 100 nm have been manufactured, tested and evaluated. The partners have calibrated all standards samples using a combination of GISAXS, EUV and DUV scatterometry and Mueller polarimetry, supported by the structure information obtained with the AFM measurements. The final reference standards are finished and available. A calibration service will soon be offered by DFM and PTB, and an additional service at VSL is planned too.

Actual and potential impact

Dissemination

The project and the scientific and technical results described above have been extensively presented in 79 presentations at national and international conferences (e.g. SPIE conference Modelling Aspects in Optical Metrology 2013, chaired by the project coordinator, and the Nanoscale 2013) and workshops, with some of those presentations being invited keynotes. Moreover, these results have been published in 19 peer reviewed publications and 23 conference proceedings, and at least 4 more peer reviewed publications are scheduled for the near future. Additionally, training activities have been offered to the stakeholder community in August 2013 in Berlin and in the context of an international EOS summer school in advance of the EOSAM 2014.

To promote the dissemination of the project outcomes, the partners have organised a successful scatterometry workshop as part of the Annual Meeting of the European Optical Society (EOSAM 2014) in Berlin, Germany. The workshop attracted 60 participants and included a special session dedicated to this project. In total the project results have been presented in 10 talks given at this workshop and 3 more papers in another EOSAM subconference.

This project's results have been discussed regularly with stakeholders from the scientific and industrial communities and also via personal contacts with e.g. Carl Zeiss AG, ASML, NIST, SENTECH and the AMTC. NIST, ASML and SEMATECH have been actively involved in discussions regarding the scatterometry reference standards. The coordinator has supported NIST in organising the annual SPIE conference *Instrumentation, Metrology, and Standards for Nanomanufacturing* on 20th August 2013 in San Diego, USA as a member of the program committee of this conference. Furthermore PTB is member member of the German *Arbeitskreis Ellipsometrie (AKE) Paul Drude e. V.,* where many ellipsometry companies and users were involved and has discussed with some other members the specific requirements of spectroscopic ellipsometers on a scatterometry standard. Several project participants have visited the AKE international workshops on ellipsometry in March 2013 in Leipzig and 2014 in Dresden for dissemination of project results as well as for further detailed exchange with many stakeholders (e. g. SENTECH, Osiris GmbH, NamLab Dresden). The stakeholders have always been invited to join the project meetings and, for example, ASML has joined regularly.

Impact on standardisation

The progress of this project, in particular the developed scatterometry reference standards and the status of the SEMI *Guide to establishing uncertainties of scatterometry measurements* have been discussed with members of the SEMI Microlithography committee. Further development of this guide has been stopped by the chairman of the corresponding SEMI Scatterometry Task Force (NIST), but based on the results of this project a future discussion is planned aiming to revert that decision.

Impact on the metrological and scientific communities

Software developed within the project will be used and further developed after the end of this project, either as part of the company services of JCMwave GmbH or as an open source application (CMI). The developed methodology for numerical simulations is part of the software documentation and will be available to other users of the software. These existing software solutions with enhanced capabilities and specific features (e. g. enhanced 3D capabilities, fast algorithms and procedures for combined data analysis to support future developments in hybrid metrology) are already in use by the scientific and metrology community, as well as in industrial applications.

Impact on industrial and other user communities

Direct uptake of the project's outputs, in particular low cost diffractive optics, provides European manufacturers such as Nanocomp access to fast and efficient optical metrology for manufacturing. This will enable improved and faster quality control and process development supporting the success and growth of manufacturers of diffractive optics. In particular, Nanocomp has shown great interest on the VTT scatterometer and is planning to either use a measurement service from VTT or build its own scatterometer based on the knowledge obtained in this project. Both options significantly benefit from the work done in the project.

Different stakeholders such as manufacturers of scatterometry-based metrology tools and European manufacturers of integrated circuits have shown interest in the developed reference standard samples, and it is expected that several stakeholders will use these standard samples as soon as they are commercially available. The availability of reliable scatterometry reference standard samples and the knowledge and methods developed in this project will support manufacturers e. g. ASML, SENTECH in the development of their products and therefore contribute to support their already strong international European position.

Following on from the suggestion and interest of the Advanced Mask and Technology Center (AMTC), PTB has started testing novel EUV photomasks currently developed by the AMTC for their new mask manufacturing processes. This testing takes advantage of EUV scatterometry, AFM, optical scatterometry and GISAXS facilities further developed in this project.

The improved and partly novel metrology capabilities developed within this project are already contributing to the development of new and better products of European semiconductor companies and in the longer term will contribute to sustain and extend the success of the European and international semiconductor industry.

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