Partner 1 – PTB (Coordinator, Internal Funded Partner)

The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany and the highest technical authority for the field of metrology and certain sectors of safety engineering. PTB comes under the auspices of the Federal Ministry of Economics and Technology. It meets the requirements for calibration and testing laboratories as defined in the EN ISO/IEC 17025. It has a staff of about 1900 employees of whom more than 500 are graduates. It is fundamental task of PTB to realize and maintain the legal units in compliance with the International System of Units (SI) and to disseminate them, which includes to maintain and develop the national measurement standards, above all within the framework of legal and industrial metrology. PTB uses its knowledge and unique facilities to ensure the reliability of measurements in industry, society and science, contributing to better products, quality of life and scientific knowledge.

The department 'Imaging and Wave Optics' belongs to PTB's optics division and develops methods for dimensional measurement of surfaces, covering the range of surface form metrology (flatness, spherical, aspherical to free-form), micro- and nano-structuring of surfaces laterally (feature widths and distances) as well as vertically (layers and layer systems) to X-ray optics (interferometry and topography applying the Si lattice parameter).

The working group Optical Nanometrology of PTB's optics division develops methods for the measurement of the size of surface structures in the µm to few nm range using optical methods. Important applications are the development of dimensional optical measuring techniques for current and future manufacturing technologies for semiconductor industry, for nanotechnologies and (diffractive) optical components. The group is developing and investigating state-of-the-art and novel optical nanometrology methods based mainly on optical microscopy, scatterometry and (Mueller) ellipsometry, strongly supported by work on modelling and data analysis methods including rigorous field modelling, sophisticated inverse solvers, modelling of optical imaging and hybrid metrology.

In this project, this group will work on the development and characterisation of label-free superresolution microscopy for more universal technical applications beyond fluorescence microscopy, on hybrid/holistic approaches on the enhancement of optical methods (scatterometry, microscopy) for nanometrology and the application of multispectral metamaterials to enable and develop novel nanometrology approaches all together with a specific focus on metrology aspects such as traceability and measurement uncertainty estimations and reduction.

Within this project PTB is providing the coordination of the project. PTB develops optical metrology (including advanced data analysis and mathematical modelling) for the characterisation of nanostructures and has an internationally renowned expertise in scatterometry, ellipsometry, nanometrology, inverse problems and hybrid metrology. PTB will contribute to the project's advanced hybrid/holistic metrology investigating e.g. the inclusion of polarisation and spatial diversities by Mueller ellipsometry and Acousto-Optic Modulator light states, respectively and by metamaterial and resonance enhanced scattering. Moreover, novel concepts for super-resolution SIM methods will be developed. PTB will also be responsible for the development and investigation of novel label-free pump-probe SRM techniques with a focus on a universal and broad range of applications and supports the work on bi- and multispectral enhanced nanometrology including multispectral plasmonic lenses.

Partner 2 – CMI (Internal Funded Partner)

The Czech Metrology Institute (CMI) is the National Metrology Institute of the Czech Republic. Since 1998, the Department of Nanometrology has focused on the development of scanning probe microscopy metrology and related methods. This includes providing traceability for scanning probe microscopy methods (metrology SPM), developing methods for quantitative analysis of different physical quantities with nanometre resolution and numerical analysis. The main effort of the Department is equally distributed between scientific projects, instrumentation development and publication activities.

Within this project CMI is providing expertise in local electromagnetic propagation calculations via Finite Difference Time Domain (FDTD) methods. An open-source code developed at CMI will be used for simulations of scattering of focused fields on diffraction gratings and for simulations of scattering of Near-field spectroscopic methods. CMI is also equipped by a set of tools for Near-field optical microscopy and spectroscopy that will be used for high resolution measurement of deep subwavelength structures. CMI will also provide expertise in uncertainty modelling related to near-field data interpretation and to computational aspect of the methods developed.

Partner 3 – DFM (Internal Funded Partner)

DFM is the Danish national metrological institute and possesses the highest level of measurement competences in Denmark within a range of key measurement capabilities. DFM provides critical infrastructure to the European industry by providing traceability at the highest possible international level within metrology. DFM's scientific research results in new knowledge, measurement techniques and standards, which support the need for accurate measurements required by European industry and authorities. The services offered are high level calibrations and reference materials traceable to national primary or reference standards, courses related to metrology and consultancy services.

DFM has a special role in developing measurement capabilities needed by small and medium sized high-tech companies in order for them to evolve and prosper. DFM works to ensure global confidence in European metrological services, which is critical for competing in the global marketplace.

DFM is a non-profit university-owned subsidiary, with a high degree of solidity. DFM is part of the national technology infrastructure with task of maintaining core competences in the field of metrology. The main income (approx. 14 mio. DKK per annum) is a government contract for the operation of the national metrology institute, i.e., the maintenance, operation and dissemination of measurements from national standards, participation in the global metrology community, representing Denmark, and for research and development of standards, measurement methods and calibration services for the benefit of Danish industry and as contributions to the international development of a global coherent metrology system. The latter is cofounded by national and regional (e.g., EU) projects participation.

A certain amount of funds allocated in the government contract is for cofounding of participation in research and development projects. Furthermore, as a non-profit organisation, income from commercial services is used for co-funding. The nanometrology team has a profound experience in design and development of instruments for characterization of surface structures and materials. These services are offered both as consultancy for Danish and European companies and as part of international funded research projects. The team always aims to be at the frontier of the research in surface and material characterization in order to provide the best and newest solutions for our partners. The team is very active in communication of the new characterization methods and publish several papers every year in international peer-reviewed journals. The team also has recently developed the novel 'imaging scatterometry' method, which can be used for simultaneous defect detection and topography analysis of nanostructures.

Within this project DFM is developing a novel virtual instrument capable of characterising sub-wavelength nanostructures and will make experimental investigation of how the spatial resolution of microscopy can be enhanced using ball lenses as Photonic Nanojet (PNJ) sources. DFM's will use its expertise to work on metrological Stimulated Raman Scattering (SRS) with spatial super-resolution. The developed system will be integrated with the existing SRS microscope at DFM. DFM will also increase the SNR of the generated Raman signal using novel noise-cancellation strategies and non-classical light. Finally, DFM will work on optical microscopy and phase reconstruction algorithms to develop a highly phase sensitive interferometer using quantum engineered light states capable of producing holograms, with nm resolution and sub-nm uncertainty.

Partner 4 – INRIM (Internal Funded Partner)

INRIM is a national research institute devoted to research in metrology and innovative technologies (quantum technologies, nanotechnologies, ferromagnetic materials, artificial vision etc.). The quantum optics research program **http://quantumoptics.inrim.it/** of INRIM, led by M. Genovese, has developed large experience in the fields of quantum sensing and metrology and, in general, well established international experience in quantum optics. In INRIM quantum optics sector there are eight laboratories, equipped with various laser sources and optical and electronic equipment, which will represent the basis for developing the present work. A clean room is also under construction. Another fundamental resource is represented by the young and motivated people working in these labs (8 permanent researchers under 50 and 6 non-permanent researchers between 25 and 35). INRIM has several collaborations with European and foreign institutions: some group members have been the organizers of various international workshops and are editors of international journals. In the last years, the group has been involved in many international and national joint projects.

Within this project INRIM brings expertise in single photon emitters and in quantum metrology and has an internationally recognised expertise in methods for beating classical limits of measurement (e.g. the first experimental realisation of sub shot noise imaging, quantum illumination, protective measurements etc.). INRIM will provide the project with theoretical/numerical modelling and experimental work. INRIM has several laboratories equipped with laser systems, single photon detectors etc, and a clean room with temperature and unity control.

Partner 5 – SMD (Internal Funded Partner)

SMD is the Belgian national metrology institute, part of the Federal Public Service Economy. Its main task is to maintain national standards, to ensure the traceability towards these references through calibrations and to transfer metrological knowledge to industry and research sectors. The institute has a nanometrology section, which is mainly active in nanoparticle characterization by scanning probe microscopy (AFM) and light scattering techniques in line with chromatography technique (FFF-MALS-DLS). SMD has developed expertise in the mathematical treatment of the data using physical and mathematical modelling.

Within this project SMD brings its expertise from two fields: nanoparticle sizing with light scattering methods (with and without upstream separation), in addition to physical and statistical modelling. The nanometrology division at SMD has grown from AFM measurement to other complementary techniques: such as light scattering and chromatographic separation. SMD will support the project by improving light scattering models, Field-Flow-Fractionation modelling, and quantitatively assess sensitivity for arbitrary nanoparticle size distribution by Bayesian inversion.

Partner 6 - VSL (Internal Funded Partner)

VSL is the national metrology institute of the Netherlands and makes measurements results of companies, laboratories, and organizations directly traceable to international standards. The Dutch government has appointed VSL to maintain and develop the national measurement standards. VSL uses its knowledge and unique facilities to ensure the reliability of measurements in industry, society and science, contributing to better products, quality of life and scientific knowledge.

Within this project VSL is contributing to the development of optical nanometrology by multiwavelength coherent Fourier scatterometry. Further to this VSL will use its expertise to work on metrological phase retrieval methods and to investigate the potential of topology-based modal methods.

Partner 7 – DTU (External Funded Partner)

Technical University of Denmark (DTU) is an international elite technical university that delivers excellent innovation and education founded in world-class research. A leading Nordic technical university, with Leiden ranking at no. 1 in the Nordic region w.r.t. the proportion of publications in Top 10%, DTU is a Scandinavian and a European academic leader in multidisciplinary technical and natural sciences. In addition to having several ERC Advanced Grant holders, the University participates in numerous European innovation networks and clusters, sector development projects, and collaborations including the European Space Agency and the European Food Safety Authority. Globally, DTU serves NASA, WHO, the World Bank, the UN Environmental Programme and other research programs. DTU is widely recognized for its ability to transfer research into technology in close collaboration with academic, commercial, and public partners.

Department of Applied Mathematics and Computer Science (DTU Compute) is DTU's competence hub for modern mathematical modelling and computation in engineering and the natural sciences. It is the largest environment for mathematics and computer science in Denmark. The Department, with its 11 research sections and 9 research centers, covers a wide spectrum of mathematical, statistical, and computational subjects, from in-depth theory to concrete applications. In addition to research and teaching, DTU Compute undertakes large-scale commissioned research assignments and provides research-based consultancy of both the public and the private sectors. The Department's 3D Imaging Center is the new Danish national research flagship, integrated into a research alliance with the coming European Spallation Source (ESS) and the MAX IV synchrotron in Lund, Sweden.

Within this project DTU is adding expertise in Uncertainty Quantification and High-Performance Computing. DTU will support the project by delivering significant improvements in deterministic and stochastic partial differential equation (PDE) modelling and large-scale computation for scatterometry problems, including the quantification of uncertainty propagation in the models. DTU will also use PDE based and machine learning-based methods to achieve numerical control of PNJ for super-resolution imaging. DTU will also support the pre-processing/de-noising of measurement data, speckle pattern analysis, sparsity-promoting regularisation of inverse scattering problems, and optimal selection of observations in a Bayesian framework for inverse problems.

Partner 8 – EK MFA (External Funded Partner)

The Institute of Technical Physics and Materials Science (MFA) in the Centre for Energy Research (EK) is dealing with interdisciplinary research on complex functional materials and nanometer-scale structures, exploration of physical, chemical, and biological principles, their exploitation in integrated micro- and nanosystems, and in the development of characterization techniques. The Photonics Department of MFA has decades of experience in characterization techniques, microfabrication and optical simulation, analysis and design for optical characterizations. MFA has the necessary equipment and tools for the participation in the project, including ellipsometers, spectrometers, software and know-how for the evaluation of optical data.

MFA and its project leader have extensive experiences with EU projects being WP leaders in many of them. MFA participated in numerous large-scale EU and National projects since the 5th framework programme. The target of numerous projects and activities have been the development of optical metrology.

Within this project EK MFA is adding excellent knowledge and equipment of ellipsometry and optical material characterisation and is active in the development of both instrumentation and evaluation methods. In this project EK will contribute with phase-sensitive interface nanometrology at the far-field, using resonant conditions by design of nanostructures and nanomaterials. New multilayers and combinatorial structures will also be developed for optical nanometrology.

Partner 9 – FSU Jena (External Funded Partner)

The Institute of Applied Physics (IAP) of the Friedrich-Schiller-University Jena (FSU Jena) has more than 25 years experience in the field of micro- and nano-structured optics. Starting with the realization of integrated optical devices in the 1980, the research focus has evolved via diffractive optical elements, sub-wavelength and effective refractive index structures, photonic crystals, plasmonic elements towards meta-materials. Expertise consists in the optical modelling and designs of such structures as well as in their fabrication by lithographic technologies. For that, an extensive clean-room facility is available, containing infrastructure for electron-beam lithography, focused ion-beam etching, Helium-Ion microscopy, various reactive ion-etching tools, and the related characterization equipment (SEM, AFM, dual-beam SEM/FIB, various interferometers). Examples of elements realized in the past comprises diffractive beam-splitters and shapers, high performance diffraction gratings for ultra-short-pulse laser compression and space spectrometers, micro-structured polarizers and retarder structures, nano-antennas, and a lot more.

Within this project FSU Jena is providing state of the art fabrication technology. Furthermore, nano optical elements providing diattenuation and artificial birefringence will be incorporated onto individual pixels of a complementary metal–oxide–semiconductor (CMOS) image sensor to achieve parallelised multichannel polarimeters. This will enable miniaturisation of polarimetric setups, e.g., for Mueller-matrix ellipsometry.

Partner 10 – ICFO (External Funded Partner)

ICFO - The Institute of Photonic Sciences (www.icfo.eu) is a research institute located in a specially designed, 14.000 m2-building situated in the Mediterranean Technology Park in the metropolitan area of Barcelona. It currently hosts more than 350 researchers, including research group leaders, post-doctoral researchers, PhD students, research engineers, and staff, organized in 26 research groups working in 60 state-of-the-art research laboratories, equipped with the latest experimental facilities and supported by a range of cutting-edge facilities for nanofabrication, characterization, imaging and engineering.

ICFO-Institute of Photonic Sciences has a strong in-house Knowledge & Technology Transfer (KTT) Team, through which it conducts many relevant research collaborations with industrial partners. ICFO holds a portfolio of more than 90 patent families and has relevant experience in more than 50 industrial projects with different corporations, as for example IBM, Graphenea, Procter & Gamble, Puig, Zeiss, IRIS, Monocrom, B. Braun, Accelerate Diagnostics, Sorigué, Alter Technologies, Thales, M Squared, Time Bandwidth, and Nokia. ICFO is also very proactive in fostering entrepreneurial activities and spin-off creation. The center offers its researchers the Launchpad, a space and support structure, which allows innovative ideas to develop into new technology spinoffs. To date, ICFO has helped create 7 start-up companies (Radiantis, Signadyne, Cosingo, ProCareLight, HemoPhotonics, QuSide and Droplite).

Within this project ICFO is adding significant knowledge of the engineering of the spatial properties of light beams at the classical and quantum levels. ICFO also has expertise in the design and implementation of techniques to generate, manipulate, control and detect spatial modes. ICFO's

laboratories have several SLM that can work at different frequency bands, a DMD, and the software for these devices. Using these devices ICFO can detect light even at the single photon level with single photon counting modules and measure correlations between light beams in classical and quantum scenarios.

Partner 11 – JCM (External Funded Partner)

JCMwave GmbH (JCM) is an SME located in Berlin, Germany (www.jcmwave.com). It is a spin-off company from Zuse Institute Berlin, a research institute for numerical mathematics. JCM has a long-standing background in the development and application of simulation tools for rigorous simulations of Maxwell's equations with an emphasis on nanooptics applications. JCM's technology relies on advanced finite-element methods for applications where high accuracy and fast performance are required. JCM's main customer basis is in the fields of semiconductor industries (computational lithography), metrology applications (scatterometry), and photovoltaics (thin-film solar cells), as well as in fields of academic, fundamental research.

Within this project JCM is yielding its background in development and application of simulation tools for Maxwell's equations with an emphasis on nanooptics and metrology applications. Numerical developments which will be adapted and applied in this project include machine-learning based, efficient methods for optimisation of scattering targets and for parameter retrieval. JCM will also contribute to Gaussian Process Regression and resonance assisted scattering.

Partner 12 – SwanU (External Funded Partner)

SwanU University (SU) is the second largest university in Wales and invested in major nanotechnology infrastructures through the Centre for Printing and Coating, advanced electron microscopy and fabrication facilities. The facilities relevant for the project include a tip-enhanced Raman spectrometer (TERS) with equipped with multiple lasers including 532nm, 633nm and 785 nm lasers, JEOL 7800F high resolution FEG SEM and a Zeiss Cross Beam 540 focused ion beam (FIB) system attached with a high resolution SEM. SU is a research led university and runs a number of courses including core subjects such as physics, chemistry, biology and engineering as well as interdisciplinary courses including biomedical engineering and nanomedicine where this research topic will be very relevant.

Within this project SwanU is providing expertise on Raman spectroscopy and inelastic scattering regimes. SwanU will lead delivery of super-resolution Raman imaging using far-field and near-field methods and will perform far-field measurements using metamaterials. SwanU will also develop super-resolution imaging using non-linear scattering which can be extended to multiphoton Raman scattering such as CARS.

Partner 13 – TUBS (External Funded Partner)

The Technical University of Braunschweig (TUBS) belongs to the 9 most important technically oriented universities of Germany (TU9 German Institutes of Technology). TUBS has 20,000 students and offers more than 70 different courses. Metrology is one of the four main research foci of TUBS. Recently, TUBS has established the LENA Laboratory for Emerging Nanometrology as a joint research initiative together with PTB. The LENA Lab aims at the precise and quantitative measurement of nanoscale structures with special focus on three-dimensional structures. The goal is lay the foundation for a better understanding of smallest structures and pave the way for an improved standardization and finally industrial use.
The research group "Metrology for functional nanosystems" located at the LENA Laboratory for Emerging Nanometrology carries out research on nanooptical surfaces for high-precision metrology and sensing applications and investigates methods for optical characterization of bulk materials as well as of micro- and nanoscale optical and opto-mechanical systems. The group is currently formed by group leader Prof. S. Kroker, 5 PhD students and 3 Bachelor students. Beside tailoring light-matter interaction in ultra-low noise metasurfaces for high-precision optical metrology and characterization of relevant material properties (e.g. refractive indices, mechanical losses, photoelasticity, photothermal properties), the group's research focus is on the investigation on techniques for metamaterial enhanced nanometrology. The research group theoretically and experimentally investigates optical methods to characterize the nanostructures. To this end, the group has optical facilities for the optical characterization of nanostructures (laser sources, spectrometer, polarimeter) and additionally has access to sophisticated instruments for the characterization of nanooptical functional surfaces (e.g. high resolution TEM, FIB-SEM, THz microscope, 3D AFM and SAXS) at the LENA laboratory.

Within this project TUBS is introducing its experience in the development of photonic systems for application in sensing and metrology. TUBS has expertise in modelling techniques, access to clean room facilities for sample processing and various setups for characterisation. Within the project TUBS will work on metrology by multispectral plasmonic lenses and on the development of angular momentum metrology to increase the information diversity in the optical characterisation of nanostructures. TUBS will design metasurfaces enabling and/or enhancing information retrieval and will also support the pump-probe techniques studied in this project.

Partner 14 – TU Delft (External Funded Partner)

Delft University of Technology provides top-level technical and scientific education in a great number of technical areas. The research conducted by TU Delft is internationally renowned and recognized by the scientific community as well as the business community. It is research that has determined the image of technical and scientific developments in the Netherlands since 1842. The Master of Science International Programme of TU Delft offers several programs in the English language.

The Optics Research Group is part of the Department of Imaging Physics of the Faculty of Applied Sciences of TU Delft. The group focuses on teaching and research in various fields of applied optics. The group is formed by a group leader (Prof. H. P. Urbach), one part time industrial professor, one associate professor, one part time associate professor and two assistant professors plus technical staff. In average, the group has about 15 PhD students, 3 post-docs, master students and interns. The aim is to pursue high-level research in the field of optical instrumentation and optical technology. Key areas are of research are:

- metrology for the next-generation lithography
- surface inspection using optical techniques for solar cells and OLEDs
- sub-wavelength optics and plasmonics
- sensor solutions using integrated photonics
- advanced optical design

These projects are sponsored by national institutions, the European Union, industry (C. Zeiss, ASML, Philips), and the Dutch Science and Industry Institute (TNO). Furthermore, we are also involved in projects together with the metrology institutes VSL (Netherlands) and PTB (Germany).

The Optics Group participates actively in teaching for undergraduate and graduate courses in Applied Physics. It has participated in the Erasmus Mundus program Optics Science and Technology of the European Union at master level and has coordinated *SMETHODS*, an EU-Support Action for training in optical design for European SME's.

In the last few years, the Optics group of TU Delft has also organised summer schools inside the Marie Curie training programs and topical meetings of the European Optical Society.

Within this project TU Delft is adding its experience in electromagnetic simulations and experimental optics, with applications in sensing, imaging, and characterisation of nanostructures. TU Delft also has expertise in diffraction problems and expertise on experimental optics including innovative inspection methods metrology for the next-generation lithography and surface inspection using optical techniques. Furthermore, TU Delft has expertise on sub-wavelength optics and plasmonics and theories involving the control of light-matter interaction at the nanoscale.

Partner 15 – UNITO (External Funded Partner)

The UNITO team members are affiliated to the Physics Department of the University of Torino, which operates since many years within the "Nanostructured Interfaces and Surfaces" inter-departmental centre of the University of Torino (NIS) [http://www.nis.unito.it/]. The UNITO team [http://www.solid.unito.it/] has an experience dating back from early 90's on the science and technology of artificial diamond [https://goo.gl/xDVHqn].

Within this project UNITO is bringing in its expertise in artificial diamond science and technology. UNITO has well-established expertise and experimental facilities for the processing and characterisation of the optical, electrical, and structural properties of artificial diamond, including a class 10,000 cleanroom and a state-of-the-art single-photon-sensitive confocal luminescence microscope. UNITO also has a state-of-the-art multi-species ion implanter which will be used for the engineering of defect-based quantum emitters in solid state.