Publishable Summary for 20FUN02 POLight
Pushing boundaries of nano-dimensional metrology by light

Overview

Innovative devices, such as nanochips, high-capacity memories, novel materials and future point-of-care tools all rely on our ability to shape matter at the nanoscale. Thus, the European Commission has identified four Key Enabling Technology (KETs) (i.e. nanotechnology, micro-nanoelectronics, photonics and advanced materials) as strategically important for the European Union (EU). However, the fast-paced technological progress of these four KETs is currently creating a “metrology gap” when compared to the progress in developing metrology methods, critical for validating the development of KETs. This project addresses this issue by developing novel methods to help bridge the metrology gap and in turn foster KET innovation. More specifically, this project will push the boundaries of optical measurement methods by realising a new generation of optical metrology systems, with unprecedented performances in terms of spatial resolution, traceability, reliability, and robustness.

Need

KETs are technological domains identified and prioritised by the EU because they drive innovation throughout the economy and cut across industries. These KETs are transforming our economies and generating new markets and their total economic impact is huge. In 2015, the global KETS market was evaluated to be 1 trillion Euros and at this time the EU produced 23 % of the world’s exports in KETs-based products . However, the competition in these KETs is fierce, and Europe is currently struggling to keep up with East-Asia and the US. Therefore, the EU is calling for urgent action to regain a worldwide leading position on these technologies.

This project aligns with the EU’s request for action by developing the next generation of optical metrology methods which can cope with the challenges represented by the evolution foreseen in the KETs. Indeed, the development of the four KETs; Nanotechnology, Micro-nanoelectronics, Photonics and Advanced materials is strongly underpinned by optics-based measurement methods.

These four KETs build on the manipulation of matter at the nanoscale, in a predictable, reliable and reproducible way, and hence require appropriate optical metrology solutions in place to support them. Despite the many advantages of optical systems (e.g. speed, non-invasiveness, high-precision, affordable investments involved, integrability) their spatial resolution is continuously challenged by the increasingly smaller sizes of the new generation of devices fabricated. The result of this is an endless race between technical demands and metrological responses. But only by developing, new metrology solutions can we confidently push technologies to the next level and pave the route for even better advances in KETs.

Objectives

The overall goal of this project is to push the boundaries of optical measurement methods by realising a new generation of optical metrology systems, with unprecedented performances in terms of spatial resolution, traceability, reliability, and robustness. The objectives of the project are:

1. To develop accurate methods for measuring lateral features size below 10 nm at uncertainty levels of 0.1 nm using two types of far-field illumination far-field detection optical methods.

   - diffraction-based optical methods within the classical Rayleigh regime (e.g. optical scatterometry with structured illumination, 3D through focus microscopy, hybrid/holistic metrology (e.g. combined spectral Mueller Matrix Ellipsometry and goniometric scatterometry), coherent scatterometry (CFS) and Multi Angle Light Scattering (MALS) for particle metrology) or
   - super-resolution through multiple scattering beyond the Born regime (e.g. ptychography).

This includes developing advanced inversion algorithms. Both the diffraction-based and super-resolution optical methods (i) should allow nanoscale-level metrology of objects located at different penetration depths in media and in the presence of intermediate layers, and (ii) encompass spectral diversity, angular diversity, spatial diversity, and polarisation diversity. Furthermore, to create new artefacts to validate and test the performance of the optical methods developed and investigated.

2. To develop innovative inelastic, non-linear or resonant optical metrology methods with a target uncertainty level of 1 nm, such as linear and non-linear SIM, and pump-probe Super Resolution Microscopy (SRM) techniques (e.g. Surface plasmon resonances (SPR) assisted Raman, coherent multiphoton-Raman and Stimulated Emission Depletion (STED). This should include the integration of non-linear effects with super-resolution metamaterials-enhanced scattering with methods such as enhanced scatterometry, enhanced internal reflection ellipsometry, multispectral plasmonic lenses and Photonic Nanojet (PNJ) illumination in SRM). The targeted spatial resolution of the different imaging methods will be below a tenth of the wavelength.
3. To develop innovative imaging methods (e.g. a wide field SIM microscope exploiting single photon emission from colour centres in diamond or quantum correlated beams) based on engineering the spatial shape of light in the classical and quantum domains in order to achieve either super-sensitivity or super-resolution (or both) in nano-dimensional measurements. Such methods should fully exploit the spatial degrees of freedom of the classical or quantum field, respectively and achieve sub-Poisson sensitivity in the quantum regime. These innovative methods should enable traceable classical and quantum-based absolute phase-sensitive optical measurements.
4. To facilitate the take up of the knowledge, technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (ISO, CEN) and end users in nanotechnology, micro-nanoelectronics, photonics and advanced materials.

Progress beyond the state of the art and results

The race towards developing even smaller nanodevices has created a metrology gap that cannot be solved by simply reducing the wavelength of the light source used in current optical measurement methods. In fact, while shorter wavelengths (e.g. Extreme Ultraviolet (EUV) light at 13.5 nm) can be used to resolve smaller dimensions, the penetration depth in matter reduces drastically at those wavelengths. For instance, current Solid-State Devices memories contain many layers and have a total thickness of a few microns; that is inaccessible by EUV light which barely reaches 200 nm penetration depth in matter. Additionally, as physical parameters do not scale with wavelength, some material properties are not best unveiled with shorter wavelengths. Therefore, there is a mismatch between what is needed to progress technology and what is currently achievable by optical metrology systems results. This metrology gap also creates its own metrology dilemma: i.e. whether to measure at high spatial resolution (i.e. at shorter wavelengths), but only at surface level, or to measure in depth (i.e. at longer wavelengths) but at lower spatial resolution?

The current project intends to address this problem by defining novel paradigms that enable optical metrology to access spatial resolutions at 10 nm level while keeping the penetration depth in the several micrometres range.

This project will build upon the results of the preceding project 17FUN01 BeCOMe and will push the boundaries of current state-of-the-art by:

- Realising novel methods that concurrently exploit the full diversity of information available in electromagnetic fields in the optical domain. This encompasses spectral diversity (broad and continuous range of wavelengths), angular diversity (from low Numerical Aperture (NA) to high-NA), spatial diversity (engineered amplitude and phase profiles, exploitation of topological information carried by a field), polarisation diversity (non-trivial local polarisation states) and metamaterials-enhanced scattering
- Exploring the potential of diffraction-based optical methods (like optical scatterometry, Mueller matrix ellipsometry, bright field and phase sensitive imaging) that integrate the classical Rayleigh regime with inelastic, non-linear, and resonant regimes. The goal is to establish novel techniques, such as coherent or incoherent Raman scatterometry, to exploit non-linear effects for super-resolution and integrate them with methods based on multiple scattering beyond the Born regime

- Setting the metrological foundations of iterative phase-sensitive methods, structured-illumination (linear or non-linear) and pump-probe microscopy. This will require mapping of the transfer of the phase information from the near-field to the far-field in light-matter interaction processes as well as creating new artefacts (areal and profile standards) and advanced inversion algorithms (e.g. Bayesian inversion, machine learning-based), defining the calibration uncertainty and establishing the appropriate metrology chain to validate these innovative methods
- Realising quantum-optics measurement schemes that use engineered quantum states of light to achieve super-sensitivity in dimensional measurements. This encompasses the combination of spatial entanglement with phase sensitive methods (ptychography, through-focus, self-referencing interferometry, ellipsometry etc.) by using modern tools, such as Spatial Light Modulators (SLM) or Digital Micromirror Devices (DMD). The goal is to obtain a full exploitation of the spatial (amplitude and phase) degrees of freedom of a quantum field through deep sub-Poisson sensitivity.

Impact

Impact on industrial and other user communities

The European high-tech industry must continue to innovate if it is to be competitive in the global market. In recent years the EU has experienced a problem with its innovation capacity, currently lagging behind East-Asia and the lack of proper innovation" […] *is generally attributed to the EU having its economic structure concentrated in medium-technology sectors, and failing to move into new, higher technology sectors with more scope for innovation-based growth*."

This project targets the semiconductor, photonics and nanoelectronics sectors due to their strong dependence on the availability of advanced optical measurement techniques. These advanced optical measurement methods are normally used for process control, accurate alignment of parts, and detection of defects. This project intends to perform fundamental research on nano-dimensional metrology using light, to tackle the current metrology limits of advanced optical systems and to go beyond the current state of the art. The project will help European high-tech industries to remain competitive and regain a dominant position on the KETs.

The project aims to achieve impact by engaging, at early stage, with key stakeholders operating in the targeted, KETs and hence applications relevant to such end-users can be assessed and tested in a relatively short time. This will be supported by the implementation of a stakeholder committee, who will provide useful end user feedback to the project as well as helping to promote the outputs of the project. Additionally, the project will organise end user focussed events to disseminate it's results such as a topical meeting on optics-based dimensional metrology within the Annual Meeting of the European Optical Society (EOSAM), and 2 scientific workshops on (i) Phase-sensitive optical metrology and (ii) current and future trends in Quantum Optics-based measurements methods.

Impact on the metrology and scientific communities

This project encourages collaboration between the scientific communities working in materials science, instruments design, classical and quantum optics, and will stimulate these communities to unite their efforts to advanced innovation in optical nanometrology.

The results of the project will go far beyond the current-state-of-the-art; in particular the novel measurement paradigms proposed for nano-scale dimensional metrology by light. The project's work on extending the "measurement space" of optical methods (objectives 1 and 2) and the inception of classical and quantum phase-sensitive measurement methods (objective 3 and 4), along with the assessment of their metrological value, also have high scientific potential.

The project's impact on the metrology and scientific communities will be promoted via several training activities, including a school of physics, lectures within a course on *Advanced Photonics* offered at partner TU Delft, several screencasts and a dedicated session on project topics organised at the Nanoscale conference.

Further to this, the project results will be distributed within the ellipsometry community via communication within the German Association on Ellipsometry, the AK Ellipsometrie Paul-Drude e. V. and presentations on the regular AKE workshops: http://www.ake-pdv.org/index.php/about-us/ake-pauld-drude-e-v. Project partners are also members of the European Materials Characterisation Council (EMCC), working group 1 "Instrumentation and Metrology", and will disseminate the project's results through this working group.

In addition, the project will benefit the metrology community through the direct engagement of European NMIs and Technical Committees. The use of optics-based measurement methods is expected to grow in the future, therefore early engagement of the metrology community with the most recent advances in this area could lead to new Calibration and Measurement Capabilities (CMCs). Furthermore, the project is aligned with the EURAMET Strategic Research Agenda for Metrology in Europe "*Nanotechnologies and nanoscience are triggered by diverse fields and applications. Miniaturisation in industrial environments and the relentless requirements of the International Technology Semiconductor Roadmap (ITRS) are driving processes to sub-nm accuracy level for critical features and positioning tasks"*.

Impact on relevant standards

As a fundamental metrology project, achieving a wide impact on written standards is not expected. However, the project's results will be disseminated by partners to technical groups and/or standardisation bodies where project partners are involved. These include the EURAMET Technical Committee Length (TC-L), the BIPM Consultative Committee for Length Working Group on Dimensional Nanometrology (CCL-WG-N), the Technical Work Area (TWA) Versailles Project on Advanced Materials and Standards (VAMAS) 42-TWA on Raman and microscopy, ISO/TC 229 Nanotechnologies, CEN/TC 352 Nanotechnologies, DIN NA062- 01- 61 AA Materials Testing - Measuring and test methods for coatings and coating systems and IMEKO TC 21 Mathematical Tools for Measurements.

The project partners who are members of these technical committees, will regularly inform them about the results of this project and will endeavour to ensure they are incorporated in any updates to standards.

Longer-term economic, social and environmental impacts

The European Commission (EC) formally recognised the importance of Nanotechnology, Micro-Nanoelectronics, Photonics and Advanced materials by designating them as four KETs. The total economic impact of these four KETs is huge and in 2015, the EU contributed approx. 23 % of the world's exports in KETs-based products. However, the EU is facing fierce competition from East-Asia e.g. between 2002 to 2015 the share in total KETs exports for East-Asia increased from 45.86 % to 62.7 1%, whereas that of the EU only increased from 21.61 % to 22.14 % Furthermore the share of total KETs patents, in the same period, increased for East-Asia from 36.86 % to 43.56 % while that of the EU reduced from 25.71 % to 21.74 %. These figures clearly indicate the large-scale investments of East-Asian countries on KETs and has led to a strong pressure exerted on European high-tech companies to innovate and protect their novel technologies.

This project will support the metrological innovation needed for these strategic KET sectors and to help the scientific community and European industries sustain a worldwide competitive position. By pushing forward the boundaries of optical measurement methods and by realising a new generation of optical metrology systems, with unprecedented performances in terms of spatial resolution, traceability, reliability and robustness, this project will help to place the EU at the forefront of advanced and sustainable economies. This is vital as KETs are expected to "[…] *contribute to achieving reindustrialisation, energy, and climate change targets simultaneously, making them compatible and reinforcing their impact on growth and job creation*".

<table>
<tr><td colspan="2">Project start date and duration:</td><td>September 2021, 36 months</td></tr>
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<tr><td>Internal Funded Partners:
1. PTB, Germany
2. CMI, Czech Republic
3. DFM, Denmark
4. INRIM, Italy
5. SMD, Belgium
6. VSL, Netherlands</td><td>External Funded Partners:
7. DTU, Denmark
8. EK, Hungary
9. FSU Jena, Germany
10. ICFO, Spain
11. JCM, Germany
12. SwanU, United Kingdom
13. TU Delft, Netherlands
14. TUBS, Germany
15. UNITO, Italy</td><td>Unfunded partners</td></tr>
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