Publishable Summary for 15SIB09 3Dnano
Traceable three-dimensional nanometrology

Overview

The overall goal of this project is to meet current and future requirements for traceable 3 dimensional (3D) metrology at the nanometre level with measurement uncertainties below 1 nm. To achieve this goal the project will set up to establish new routes for traceability, further develop existing instruments and validate 3D measurement procedures. Additionally, this project will develop new calibration artefacts and made them available to industry as traceable reference standards to enable valid comparison of fabrication and measurement results, and establish a robust basis for design of objects with traceable nanoscale dimensions and tolerances.

Scanning Probe Microscopes (SPMs) available in national metrology institutes (NMIs) have low uncertainties, are traceable to the SI-metre and significantly outperform commercial SPMs in accuracy. However, there is a large gap between SPMs and the rest of 3D metrology. This project aims is to further develop SPM instrumentation, measurement procedures, data interpretation and reference materials to bridge this gap, as proper understanding of probe-sample interactions is crucial for the reduction of measurement uncertainty.

Need

Nanotechnology is increasingly used in different sectors e.g. health, medicine, nanoelectronics, nanophotonics and nanostructured materials, and the market for final products incorporating nanotechnology is estimated to have increased ten-fold during the current decade. The progressive miniaturisation of advanced nanomanufacturing techniques that currently deliver nanodevices with feature size below 22 nm and the extensive use of complex nano-objects e.g. wiring, surface coatings, nanoparticles in consumer products in different application e.g. semiconductors, health and medical products, has therefore driven the need for improved accuracy in 3D nanometrology.

High accuracy measurements are needed in R&D and quality control, as many health and environmental effects of nano-objects and nanoparticles are dependent on the size and shape of structures. From a regulatory perspective, traceability is a must for measurement techniques, as if measurements are not traceable, they have little value from a judicial point of view. Currently there is insufficient traceability to the SI metre for true 3D nanomeasurements, because the existing level of uncertainty in measurements (5 nm) does not meet the requirements of industry and scientific research. 3D metrology differs from one directional (1D) height and pitch metrology, where the impact of tip geometry and the tip sample interaction at the top/bottom planes are self-compensating. Instead, measurements of 3D structures are bi-directional, where the effect of tip geometry and tip sample interactions at the left and right sidewalls are different. Measurement of line width is an example of bi-directional measurements. In addition, more and more complex particles are put on the market and used in processes, and these particles have different shapes e.g. rod, star, donut shape, which require real 3D characterisation. Furthermore, although high resolution instruments exist in industry, universities and research institutes, this does not necessarily result in high accuracy, as without proper calibration and understanding of probe-sample effects traceability is rarely established and errors in simple measurements can be up to 30 %. To achieve better uncertainty for 3D measurements the existing metrological Atomic Force Microscopy (AFMs) also need to be improved and lower noise, higher speed and large range are needed.

Hybrid metrology i.e. merging the measurement results from either different tools (instrument fusion) or different channels of a single tool (data fusion) is a promising way to measure complex nanostructures, however new algorithms and software are needed for data fusion.
Reference materials are also needed for the traceable calibration and characterisation of measurement instruments to enable the valid comparison of measurement results and to establish a solid basis for the design of objects with traceable nanoscale dimensions and tolerances. Furthermore, new types of reference materials are needed for 3D measurement and probe characterisation.

Objectives
The scientific and technical objectives of this project are to:

1. Reduce the 3D nanomeasurement uncertainty, by means of a bottom up approach, to less than 1 nm for nanodimensional measurands (including line width, height, pitch, and edge/width roughness) on engineered nanostructures and nanoparticles. In addition, to reduce the noise level of metrological AFMs (MAFMs) to 0.1 nm (rms) using a top-down approach, to raise the scanning speed up to 1 mm/s, and to extend the scanning range up to 25 mm/s by further developing the state-of-the-art optical and x-ray interferometry (XRI).
2. Develop reference materials for 3D nanometrology tools including AFM and Scanning Electron Microscopy (SEM). In particular, to realise test structures for characterising the tip geometry in AFMs and the beam size in SEMs and reference standards for width and sidewall roughness measurements.
3. Widen the understanding of probe-sample interactions in AFM and SEM measurements for reducing the measurement uncertainty. In particular, to study the tip-sample interaction force of AFM line width and nanoparticle measurements; to model the image formation of SEM; and to investigate the influence of humidity on AFM measurements.
4. Develop a hybrid metrology for merging measurement results from either different tools (e.g. AFM, SEM, Transmission Electron Microscopy (TEM), Mueller polarimetry and optical scatterometry) or different channels of a single tool.
5. Facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (accredited laboratories, instrument manufacturers) and end users (semiconductor industry, precision engineering, optical industry and nanoparticle researchers).

Progress beyond the state of the art
This project will use the lattice parameter of silicon as a traceable reference standard for nano and sub-nano length metrology, which builds on work done in previous iMERA-Plus and EMRP projects: T3 J1.1 Nanoparticles, T3 J1.4 NANOTRACE, T1 J1.2 (NAh), NEW01 TREND, IND17 Scatterometry, SIB08 Subnano and SIB61 CRYSTAL. However, this project aims to reduce 3D measurement uncertainty from 5 nm to below 1 nm.

Currently over 10 MAFMs have been set up in Europe, which are the main pillars at NMIs for versatile micro- and nanoscale metrology calibration. However, the measurement capabilities of these MAFMs need to be improved. This project will address current noise, range and speed limitations of MAFMs.

Reference materials and standards are widely used to calibrate, test and verify industrial equipment. Nanoscale standards such as step height and lateral 1D/2D gratings have been developed in the last decade which can satisfy some industrial needs for scale calibration, and tip characterisers with sharp edges and a blind tip characterisation method are available for characterising probe geometries. However, the accuracy of the state-of-the-art tip characterisation is ~5 nm or worse. Therefore, this project will design, manufacture and characterise new Line Edge Roughness (LER) and Line Width Roughness (LWR) reference materials, new Critical Dimension (CD) standards and new tip characterisers.

The study of probe-sample interaction is key for improving measurement uncertainty. In the field of AFM, most studies are limited to measurements of nearly flat surfaces. Therefore, in order to use existing models in 3D measurements, these models need to be considerably improved. In the field of SEM, post-processing of the SEM measurement images is done using Monte-Carlo simulations. Therefore this project will simulate tip probe-sample interaction in true 3D AFM measurements and validated them experimentally.

It is well recognised that the combination of multiple metrology techniques i.e. “hybrid metrology” is very promising in terms of meeting current measurement challenges. However, neither practical application with hybrid metrology nor software for data fusion are currently available. Although some solutions to combining information measured with different instruments exist, these methods suffer from limitations in the exchangeability of the information due to metrological limitations. Therefore, this project will develop a feasible topology for executing a “bottom-up” metrology approach for hybrid metrology. Furthermore, a method and software will be developed for data fusion from different tools for the measurement of CD and roughness of complex nanoparticles or agglomerates of nanoparticles.

Results

Reduction of i) 3D measurement uncertainty to less than 1 nm and ii) noise level of MAFMs to 0.1 nm (rms)

A new bottom-up approach will be used for the cross-section of TEM structures with atomic resolution. In such a way, the CD can be directly linked to the atomic spacing in the crystal lattice, which will be traceably calibrated using a combined optical interferometry and XRI. Additionally, tools and measurement procedures will be optimised for true 3D measurands, and AFM tips will be characterised and developed for metrology at the nanometre range. Further to this, improved displacement measurement sensors will be applied in the MAFMs, to lower noise (0.1 nm root mean square (rms) and reduce nonlinearity errors and the range of the positioning stages will be increased to 25 mm. To address the current speed limitations for AFM metrology and progress beyond current state of the art, two approaches will be followed: i) the development of high speed AFM heads that are suitable for NMI based instrumentation and video rate AFMs (scanning speed over 1 mm/s), and ii) the application of metrology to video rate AFMs that surpass the speed of MAFMs.

Development of reference materials for 3D nanometrology tools

New types of reference materials will be designed, manufactured and characterised: LER/LWR reference materials, new CD standards and new tip characterisers.

Improvement of the understanding of probe-sample interactions in AFM and SEM measurements

Critical issues such as structure/tip deformation due to the measurement force and humidity will be theoretically and experimentally studied. A special reference material will also be developed to improve the metrological characterisation of the AFM probe.

Develop industrial solutions for hybrid metrology

A feasible topology will be developed for executing a “bottom-up” metrology approach on hybrid metrology. Furthermore, a method and software for data fusion from different tools (TEM, AFM, SEM and optical scatterometer) will be developed for the measurement of CD and roughness of complex nanoparticles or agglomerates of nanoparticles.

Impact

Impact on relevant standards

The knowledge gained from this project will be disseminated to regulatory bodies and international standards committees e.g. EURAMET Technical Committee in Length (TC-L). This project will also provide input to the revision of existing or creation of new documentary standards at ISO 201/TC201/SC9 “Scanning probe microscopy”, ISO 201/TC201/SC3 “Data management and treatment”, and ISO/TC229/JWG2 “Nanotechnologies: Measurement and characterisation” based on the metrology progress achieved within this project.

Impact on industrial and other user communities

The outputs from this project will create early impact on industrial and other user communities by:

- Establishing 3D nanometrology services which will be available to industry, research, academics and regulation bodies (taking advantage of the improved capabilities at NMIs/DIs);
- Exploiting new calibration and comparison methods developed in this project e.g. improved tip characterisation methods required for the AFM industry, lower uncertainties in comparison with CD, LER/LWR and SWA reference materials for the semiconductor industry, and a comparison with nanoparticle reference samples (to provide input to regulatory bodies). WP4 also includes a series of end-user demonstrations and dissemination activities to raise awareness of the project and its outputs amongst important end-user communities;
- Supporting innovations for industry and science
- Developing reference materials for the characterisation and calibration of nano measuring instruments
- Writing and disseminating to stakeholders a Good practice guide for dimensional metrology at the nanometre scale and for using the developed reference standards and methodologies, including guidance: i) on the use of the characterised reference materials for the semiconductor industry, ii) for nanoparticle measurements, iii) for using hybrid metrology in industry and software developed for data fusion and for iv) 3D nanometrology for nanophotonics.

Impact on the metrology and scientific communities

The key impact to the metrological and scientific communities, from this project, will be the traceability of 3D nanomeasurements to the SI metre, which will enable NMIs to offer metrological support to industry. Currently the traceability chain is broken because the uncertainty levels of traceable measurements at NMIs do not meet the requirements of the scientific community and industry.

In addition, the project's research will lead to new and improved draft Calibration and Measurement Capabilities (CMC) statements.

This project will lead to progresses in advanced dimensional nanometrology that is needed for the development and expansion of European high technology industries.

List of publications

There are no publications thus far.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 October 2016, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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<tr><td>Internal Funded Partners:
1 VTT, Finland
2 CMI, Czech Republic
3 DFM, Denmark
4 NPL, United Kingdom
5 PTB, Germany
6 SMD, Belgium
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