Publishable Summary for 20IND12 Elena
Electrical nanoscale metrology in industry

Overview

Consumer electronics, innovative quantum technologies, and Internet of Things applications all rely on semiconductors where reliable characterisation of electrical properties at the nanoscale is essential for European innovation and competitiveness. The measurement of these properties allows the evaluation of critical parameters used to define the performance of electronic materials and components. Currently, Conductive Atomic Force Microscopes and Scanning Microwave Microscopes enable nanoscale electrical characterisation but they are costly, complicated and, in many cases where they are used, unreliable as measurements are not traceable. This project aims to make such measurements traceable for the first time, with stated uncertainties, and affordable by developing and testing cost effective instrumentation and the first "out of lab" reference standards from DC to GHz. Robust calibration methods and good practice guides using simplified uncertainty budgets will underpin this effort.

Need

Micro- and nano-electronics are considered by the European Commission (EC) a Key Enabling Technology (KET) with high potential for innovation throughout the economy, currently accounting for 10 % of EU Gross domestic product (GDP), and fostering highly skilled employment. A competitive advantage in the semiconductor industry is gained through the exploitation of new materials and processes, translating into improved component performance. This requires a metrological infrastructure allowing reliable nanoscale characterisation of new materials and devices, particularly in terms of their electrical parameters and properties. The development of electrical nanoscale metrology has also been clearly identified in the Nano-electronics Standardisation Roadmap by the International Electrotechnical Committee (IEC-TC113).

The main metrological problem is the traceability and reliability of measurements of electrical properties at the nanoscale using conductive atomic force microscopes (C-AFM) and scanning microwave microscopes (SMM). As scanning probe microscopy (SPM) methods, C-AFM and SMM are particularly attractive for use in the characterisation of electrical properties at the nanoscale because they allow non-destructive analysis of electrical components. However, currently most measurements are taken with different instruments or using different reference standards and cannot be compared to each other nor used for modelling. This problem is compounded by a lack of established measurement protocols and a lack of easy to use reference standards. Furthermore, end users need best practice guides, worked examples, and access to easy to use 3D models to assess the influence of environmental conditions, the influence of the particular instruments used in the measurement, and the type of standards used. With these influencing factors, a simplified uncertainty budget can be established for the setup used for the measurement, which is a requirement in many quality standards. Additionally, to make measurements economically viable end users also require cost effective instrumentation, particularly for high frequency measurements.

Objectives

The overall objective of the project is to establish a European metrological infrastructure and cost-effective technologies for C-AFM and SMM to allow industry to conduct traceable measurements of electrical properties on materials and devices at the nanoscale.

The specific objectives are:

1. To develop and validate devices (DC to GHz reference standards with target uncertainties in the order of 10 % or less, probes, measurement microwave electronics), and procedures (broadband impedance matching) for GHz near field SMM. These developments should be suitable for DC-current

measurements, high frequency (from 100 MHz to 50 GHz), material characterisation and impedance measurements involving C-AFM and SMM techniques.

2. To use the devices and procedures from objective 1 to develop calibration methods for C-AFM and SMM techniques. This should include the quantification of uncertainty contributions due to influencing factors such as those that arise from the standards, from tip-sample interactions and those resulting from the measurement instrument itself in the laboratory environment.
3. To develop reliable 3D multi-physics modelling based on analytical or numerical approaches, in order to evaluate the effect of the water meniscus, at the tip-sample interface, on the electrical measurement. This should also include an investigation of the effects of the tip's real shape and composition, and of the tip-sample electromagnetic interactions, on the electrical measurement. The modelling data will be compared to the experimental data from objective 2.
4. To establish simplified uncertainty budgets for the C-AFM and SMM techniques using the results from objectives 2 and 3. In addition, to develop calibration methods for the key electrical measurands, including DC current from fA to µA, DC resistance from 100 Ω to 100 TΩ and HF admittance from 100 nS to 100 mS, for use in industrial applications. To develop 'out of the lab' electrical standards, such as calibration kits based on micro-size capacitors, for the industrial calibration of C-AFM or SMM.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain in the micro- and nano-electronics sector (European industry, electrical SPM producers), standardisation organisations (IEC) and end users (NMIs and DIs, and academic and industrial R&D labs).

Progress beyond the state of the art and results

Instrumentation and reference standards (Objectives 1 and 4)

DC current and resistance standards with target uncertainties in the order of 10 % and dedicated calibration set-up will be developed for C-AFM. This will involve the testing of instruments able to provide results over wide ranges, from µA down to fA, and from 100 Ω up to 100 TΩ. So far, no reference standards exist for resistance and current calibration.

For SMM a novel capacitive calibration kit will be developed as a capacitance standard enabling in situ determination of the dielectric constant and reducing the uncertainties down to a few percent. The lowest uncertainties published so far are in the order of 10 % and with the only existing (and commercially available) capacitance standard.

To facilitate the use of C-AFM and SMM techniques within the industry, the project will address the development of industrial compatible measurement instrumentation, and "out of the lab" standards that are not only operational in a research laboratory. The developed instrumentation includes new SMM probes incorporating a small-geometry coplanar waveguide leading to the tip which will result in negligible (or non-measurable) stray fields in SMM and new microwave electronics as alternative solutions to the usually used vector network analyser which is a big cost factor for an upgrade from AFM to SMM.

Calibration methods for C-AFM and SMM and quantification of uncertainty contributions (Objective 2)

The sources of C-AFM and SMM measurement uncertainty will be investigated by dedicated experiments. The main contributors addressed by such experiments are the reference standards used (geometrical deviations from targeted nanofabrication dimensions, frequency dependent dielectric constant), environmental conditions (*e.g.* presence of water meniscus at the tip sample interface due to the environmental humidity), operational parameters (*e.g.* applied electrical fields) and the instrument itself. In a second step these uncertainties will be propagated through different calibration methods, and uncertainty budgets will be established. Uncertainty budgets are verified by comparing different calibration methods, e.g. resistance and current for C-AFM and retraction curve versus standard based techniques for SMM.

Reliable 3D multi-physics modelling (Objective 3)

Different numerical concepts will be combined to simulate the probe-sample interaction including different phenomena. For C-AFM these are formation of water meniscus, mechanical contact formation, tip shape and presence of local contamination. For the SMM these are the formation of water meniscus and electromagnetic tip sample interaction. This will enable data interpretation from the modulation of the contact force and will be suitable for reduction of the uncertainty related to the contact formation. Moreover, simpler analytical tools that will be developed for treatment of some particular phenomena, like water meniscus, will be implemented into open source software Gwyddion, which will make novel data processing capabilities available to the scientific community.

Simplified uncertainty budgets for the C-AFM and SMM techniques (Objective 4)

This project will quantify and establish a complete uncertainty budget for the measurements of key electrical measurands, including DC current from fA to µA, DC resistance from 100 Ω to 100 TΩ and HF admittance from 100 nS to 100 mS using C-AFM and SMM with the help of new devices, procedures and numerical or analytical models. Electrical measurements performed in various controlled environmental conditions will identify the impact of tip-sample interaction on the electrical measurement. Tip-sample interaction data will be collected and provided for 3D multiphysics modelling. These activities will contribute significantly to the development of simplified uncertainty budgets and inform new calibration methods and reference standards for industrial users (*i.e.* outside of the national metrology laboratories).

Impact

Impact on industrial and other user communities

Several manufacturers of SPM and semiconductor electronics will provide relevant samples for test beds and case studies planned during the project.

Equipment manufacturers of C-AFM and SMM will increase sales as users become confident about the ability of these instruments to quantify electrical properties at the nanoscale with stated uncertainties. This will be enabled by establishing reliable calibration procedures and developing “out of lab” reference standards.

These new reference standards (DC current and DC resistance standards, resistive HF impedance standard and admittance calibration kit), and measurement probes will be fabricated by means of industrially proven and standardised methods, such that widespread uptake and commercialisation will be facilitated. High dimensional and parametric reproducibility of the DC to GHz reference standards fabricated will allow their wide dissemination without the need for extensive and costly calibration of individual elements. The IP generated here will be exploited through licensing agreements with foreseen EU instrument manufacturers.

Innovation in developing methods for C-AFM and SMM will be accelerated through use of the new fast and reliable 3D modelling software developed in this project. This new software will be open source to enable wider uptake.

Promoting the industrial immediate uptake will involve presentations at three trade shows, publications in trade journals, training via two stakeholder workshops and three on-site sessions.

Impact on the metrology and scientific communities

The project will achieve a landmark progress in the broader use of nanoscale electrical measurements by providing the missing calibration and traceability infrastructure, moving away from poorly reproducible and relatively inaccurate measurements and achieving traceable and quantifiable measurements with well-defined calibration procedures.

SI traceability and simplified but still accurate uncertainty budgets composed of a reduced number of uncertainty components will stimulate international comparisons of electrical quantities at the nanoscale, accelerating progress and uptake of instrumentation (reference standards, probes) and methods within the metrology and scientific communities. Development and validation of uncertainty budgets will provide a roadmap for future development of C-AFM and SMM.

Uptake of SMM and C-AFM for use in characterising electrical properties in materials and components will increase and application areas will be extended through the publication of good practice guides, provision of calibration samples and of open source software for robust modelling. The improved reproducibility of these methods will speed up scientific progress in the development and understanding of nano-electronics materials, such as 2D materials, and materials for power electronics. The development of novel and improved nanoscale characterisation methods will be accelerated due to a better understanding of tip-sample interaction volume and other measurement influencing factors enabled by the validated new 3D-modelling and the uncertainty analysis developed in this project.

The multi-level knowledge dissemination plan together with scientific publication from the project research will ensure fast accessibility of the techniques generated within the project. With world-class research excellence in C-AFM and SMM, several external funded partners and collaborators will be contributing research efforts and measurement instrumentation, though they are not delivering work necessary for the project to achieve its objectives. This will enhance the quality of research outputs and maximise the impact from the project. This impact will be further enhanced by dissemination through the liaison with national (Club nanoMétrologie, Systematic Paris-region, GDR “Name”) and European research networks (NanoFabNet, EuroNanoLab) and social professional networks (LinkedIN, ResearchGate).

Impact on relevant standards

The development of good practice guides, calibration procedures and protocols for measuring electrical properties at nanoscale will impact international standards directly. This will be facilitated by direct engagement of project partners with the relevant standards committees (IEC, CEN, ISO). Project partners are already active members of these committees, including IEC TC113 *Nanotechnologies* which is the natural entry point for standardisation in nano-electronics and will establish a subgroup responsible for the standardisation promoted by this project. This Elena Standardisation Group (ESG) will act as the interface to the international Standards Developing Organisations (SDO) to optimise mutual understanding and to deliver guidelines, protocols and standard operating procedures. These will then be submitted as two draft Technical Specifications, on C-AFM and SMM calibration, in line with the strategic priorities of the standards committees.

Longer-term economic, social and environmental impacts

Europe hosts the world-leading manufacturers of instrumentation for SPM and the development of its new modes. Reliable eSPM metrology will accelerate progress in nano-electronics, ensuring that Europe maintains its leading position. These techniques are currently used by industrial and academic R&D labs in three Key Enabling Technologies considered by the EC as a major driver of economic growth in Europe: nanotechnology, micro and nano-electronics and advanced materials.

Currently, Europe has the third largest share (10.2 %) of the multibillion global semiconductor market, which is expected to increase from 342 billion USD in 2015 to 655.6 billion USD by 2025. In parallel, functional and emerging Advanced Materials represented a 286 billion USD global market in 2016 with Europe expected to expand at the highest Compound Annual Growth Rate (CAGR) of 5.9 % in the proceeding 5 years. This project develops the underpinning metrology to quantify nanoscale electrical properties which are critical to increase innovation and competitiveness and resilience of these industries.

As an environmental consideration, reduction of waste in semiconductor manufacturing is critical. Defects identified early in the complex production process due to well-calibrated inspection techniques save many energy-expensive processes as the product goes to waste. Reliable metrology at the nanoscale will also enable a faster route to market of critical low carbon industrial technologies, including renewable energy sources, more efficient energy electronics, and digital data processors. Both waste reduction and faster market access will have significant impact on the key EC target of Green Manufacturing.

Finally, it is of key importance that Europe retains and strengthens its position in digital data processing to maintain digital autonomy. The future development of information technology in hardware and software will ensure a key component of the security of all European citizens.

List of publications

None

Project start date and duration:	1st Sept 2021 for 3 years	
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Internal Funded Partners: 1. LNE, France 2. BAM, Germany 3. CMI, Czech Republic 4. DFM, Denmark 5. METAS, Switzerland 6. PTB, Germany 7. TUBITAK, Turkey	External Funded Partners: 8. CEA, France 9. CNRS, France 10. ISC, Germany 11. JKU, Austria 12. ULille, France 13. UofG, UK	Unfunded Partners:
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