**EMPIR Call 2020 – Fundamental, Industry and Normative**

Selected Research Topic number: **SRT-i06**
Version: 1.0

# Title: Electrical nanoscale metrology in industry

## Abstract

Consumer electronics, IoT applications, and innovative quantum technologies all rely on semiconductors where the reliable characterisation of nanoscale material electrical properties underpins functionality. Non-destructive Electrical Scanning Probe Microscope (eSPM) techniques have been identified as key enabling technologies by the EC for characterising the materials used and for determining their electrical properties. However, to maintain Europe's place in the global semiconductor market it must support the development of robust calibrations and standardised methods for these techniques. Broadly based collaborative research is requested to develop the measurement infrastructure required to increase eSPM technique uptake through the development of affordable electronics, probes and standards with improved accuracy to enable rigorous nanoscale characterisation of innovative 2D and 3D materials in the frequency range from DC to GHz.

## Keywords

Nanoscale, conductive atomic force microscope, scanning microwave microscope, eSPM techniques, probes, microwave electronics, DC to GHz, calibrations, standards, uncertainty budget, 3D multi-physics modelling.

## Background to the Metrological Challenges

Next generation materials will be at the heart of the future global semiconductor industry that has a predicted value of 655.6 billion USD by 2025. For Europe to remain a leader in this market, it must develop the metrology capabilities required to generate an advanced understanding of nanoscale material properties. As 3D circuit integration expands and higher densities, switching speeds, and increased functionality drives breakthroughs in fabrication and device control, measurement science must develop to keep pace with innovations.

The eSPM techniques conductive atomic force microscopy, C-AFM, and scanning microwave microscopy (SMM), have been identified by the EC as Key Enabling Technologies that require further development and greater standardisation to increase their uptake outside of academia and big industrial R&D labs. These versatile techniques have already undergone initial measurement developments that have introduced SI traceability. However, a greater knowledge of the effects of the measurement environment, measurement tip characteristics, and parasitic effects are still required. For SMM, investigations of resonances within a sample's body, stray fields and capacitances are areas of specific importance.

Non-invasive microwave SMM measurements can be performed by upgrading atomic force microscope/scanning tunnelling microscope (AFM/STM) instruments to enable highly sensitive determinations of the magnitude and phase of microwave scattering S-parameters important for quantifying the electrical properties of materials. Existing calibrations provide traceability for doping density, permittivity and capacitance studies performed on Si and III-V semiconductor heterostructures, 2D materials and complex oxides without the need for special sample treatments.

Contact mode AFM, C-AFM can provide sample resistance and current mapping across the DC dynamic range 50 fA to 1 mA but probe friction on fragile materials can cause mechanical deformations that effect measurement reproducibility. Newly developed "Peak force", or "soft Resiscope" could be used to avoid these contact effects once calibrations based on well characterised standardised samples have been developed. Research is needed to enable this innovative technique to reach its full potential and increase its use in the high frequency measurement range.

To deliver the nanoscale accuracy required by the semiconductor industry, eSCM instrument calibration procedures need revision and kits based on micro-size capacitor development, to take calibrations capabilities into industrial processes. In addition, complex measurement uncertainty budgets require simplification to make C-AFM and microwave SMM measurements more suitable for industrial users.

## Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of eSPM techniques for use in underpinning the metrology infrastructure required to support industrial adoption of innovative semiconductor materials.

The specific objectives are:

1. To develop and validate probes, measurement microwave electronics, and broadband impedance matching procedures for GHz near field scanning microwave microscopes (SMM) and DC to GHz reference standards. These developments should be suitable for DC-current measurements, high frequency (from 100 MHz to 50 GHz) material characterisation and impedance measurements involving conductive atomic force microscopes (C-AFM) and SMM techniques.
2. To use the results from objective 1 to develop calibration methods for two eSPM techniques: C-AFM and SMM. This should include the quantification of uncertainty contributions such as those that arise from the standards, from tip-sample interactions and those resulting from the measurement instrument itself.
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.
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 3 mS 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-/nanoelectronics sector (European industry, electrical scanning probe microscope producers), standards developing organisations (IEC) and end users (NMIs and DIs, and academic and industrial R&D labs).

Proposers shall give priority to work that meets documented industrial needs and include measures to support transfer into industry by cooperation and by standardisation. An active involvement of industrial stakeholders is expected in order to align the project with their needs – both through project steering boards and participation in the research activities.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP projects IND02 EMINDA, and ENG51 SolCell and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 30 % of the total EU Contribution across all selected projects in this TP.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

## Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the "end user" community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to the electronics and communications sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

## Time-scale

The project should be of up to 3 years duration.