# 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) as 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 a 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 the electrical properties measurements 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, the majority of measurements are currently carried out with different instruments, using different reference standards. Thus, they can neither be compared to each other nor used for modelling. This problem is compounded by the lack of established measurement protocols and the 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. Considering these influencing factors, a simplified uncertainty budget can be established for the measurement’s setup, which is required in many quality standards. Additionally, to make measurements economically viable, end-users require a cost-effective instrumentation, particularly for high-frequency measurements.

To address these problems, the project will develop and characterise such an instrumentation and easy-to-use reference standards, establish protocols and good practice guides, and develop easily accessible 3D models and simplified uncertainty budgets. The objective 1 develops and validates devices and procedures to meet the need for traceable measurements with low uncertainties. The objective 2 aims at achieving a high reliability and reproducibility of the measurements by developing techniques to calibrate the C-AFM and SMM instruments, and evaluating uncertainty contributions due to influencing factors. The assessment of the influencing factors is further developed in objective 3 through multi-physics modelling. The objective 4 formalises robust and accurate measurement techniques, based on the C-AFM and SMM to meet the needs of industrial end-users.

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### Objectives

The overall objective of the project is to establish a European metrological infrastructure and cost-effective technologies for C-AFM and SMM, enabling the industrial actors 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 ≤10 %, probes, and 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, the tip-sample interactions, and the measurement instrument in the laboratory environment.
3. To develop reliable 3D multi-physics modelling based on analytical or numerical approaches, to evaluate the effect of the water meniscus (*i.e.*, 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 experimental results 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 the 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 uptake of the technology and the 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

Despite the key importance of traceable nanoelectrical measurements of materials and devices in nowadays technologies, no appropriate metrology infrastructure has been established so far neither in the academic literature nor in the industrial R&D sector.

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. The project has designed and manufactured first DC-current and resistance standards. They are undergoing their first characterization tests and will become available shortly as first reference samples with traceable values. These outcomes constitute a key milestone in establishing a pioneering metrology for the current and resistance measurements at the nanoscale.

In the GHz-range, only one capacitance calibration sample has been commercially available and very commonly used for the calibration of SMM measurements. Nonetheless, early works in the project succeeded in identifying the sources of errors limiting the level of uncertainty using this sample. In a close collaboration with the sample's manufacturer, the project proposed a novel design for an improved capacitance calibration sample with new features enabling the *in-situ* determination of the dielectric constant and the reduction of the uncertainties down to a few percent. The new design was adopted by the manufacturer leading to the fabrication of a new capacitance reference sample that is being tested by the consortium members for validation.

To facilitate the use of C-AFM and SMM techniques within the industry, the project will address the development of industry-compatible measurement instrumentation, and “out-of-the-lab” standards that are not only operational in a research laboratory. In the case of SMM, currently challenged with costly setups, the project is developing two instruments based on six-port and software defined radio (SDR) techniques. These developments will help alleviate the barriers for applying SMM measurements in industrial scenarios on existing AFM systems, enabling an accessible metrology of the microwave impedance measurements at the nanoscale. In parallel, the project developed a new class of AFM probes featuring incorporated coplanar waveguides along the cantilever leading to the tip. This novel approach aims at mitigating the stray fields in SMM measurements, which offer new means to reducing the uncertainties of the traceable measurements of high-frequency impedances. The project is currently working on the fitting of these probes to existing AFM probe holders, ensuring a proper impedance matching to maximize performances.

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Along the aforementioned development of reference samples and novel instrumentation, the project started investigating the sources of uncertainty in C-AFM and SMM measurements. Namely, the uncertainties originating from the geometrical deviations of the fabricated samples from the targeted dimensions, the frequency dependence of the dielectric properties, and the environmental effect such as the formation of water meniscus between the tip and the sample surface. Further investigation will be addressed covering the effects of the operational modes and the experimental setups. In a second step, these uncertainties will be propagated through different calibration methods, and uncertainty budgets will be established. Uncertainty budgets will be verified by comparing different calibration methods, *e.g.*, resistance and current for C-AFM and retraction curve versus the existing calibration techniques for SMM.

So far, the literature is still lacking available three-dimensional multi-physics models for simulating the nanoelectrical measurements in C-AFM and SMM at the nanoscale. In this direction, the project successfully built a first body of numerical simulation works enabling the modelling of the water meniscus at the interface between the AFM tip apex and the sample surface. These simulations are being extended to cover the effects of the tip’s shape and the applied forces on the quality of the nanoelectrical contact.. This will enable the data interpretation by varying the contact force in the simulations, which will be suitable for reducing the uncertainty related to the contact formation. Moreover, simpler analytical tools that will be developed for the treatment of some particular phenomena (*e.g.*, water meniscus) will be implemented into an open-source software (Gwyddion), which will introduce novel data processing capabilities that will become available for the scientific community.

This project will quantify and establish a complete uncertainty budget for the measurements of key electrical measurands, including the DC-current from fA to µA, the DC-resistance from 100 Ω to 100 TΩ, and the 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 the 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 the national metrology laboratories).

## Results

### *Instrumentation and reference standards (Objectives 1 and 4)*

A new batch of the current reference samples based on Fowler-Nordheim tunnelling junctions was fabricated. The new version of the samples differ from the previous one by the removal of the connection lines to large square contact pads on half of the junction features. This new design was intended to investigate the measurement errors induced by the extended contacts. Nonetheless, due to a misalignment problem of the lithography mask, shortcuts were induced to some of the junction features. Another batch was launched to correct for this artefact. The newly fabricated samples consisted of junctions with 4 nm and 8 nm oxide layer’s thicknesses.

Numerous test campaigns were conducted to investigate the stability and reproducibility of the current versus voltage (I-V) characteristics of the Fowler-Nordheim-based reference samples. The experiments highlighted the fragility of these structures against electrostatic discharging due to the small and confined dimensions of the junction. For this, we started designing a new architecture for the standard samples combining the current and resistance reference on the same device. The principle of this design relies on incorporating available diodes with the resistance structures to facilitate their practical use and reinforce their stability during test measurements.

The fabrication of the resistance-array standard samples and the alumina tablets for the high-resistance structures were completed and delivered by the manufacturer. For instance, the samples consist of the designed connection structure fabricated by lithography on a thick fused silica substrate. Fixing SMD resistors (from 100 $\Omega$ up to 100 G$\Omega$) and high-resistance structures (1 T$\Omega$ up to 100 T$\Omega$) at the designed locations on the sample is ongoing.

New standards for SMM measurements have been designed. Three designs are currently produced. One contains gold structures on a $SiO_2$ membrane; which suitable for coaxial tips with 20 µm or larger outer diameter. The second design involves ITO layers of different conductivity and thickness, which is suitable for arbitrarily thin coaxial tips. The third design includes gold discs on a silicon oxide staircase structure and CPW lines deposited on the same wafer for the characterization of the dielectric constant of $SiO_2$.

Different tip designs for SMM have been intensively discussed. The fixing mechanism of the probe onto the instruments' probe holders has been identified as a crucial point to ensure stable and reproducible impedance matching. The discussions around the best solution with the available clean room techniques are ongoing.

Three types of matching circuits have been characterised with respect to their gain and added noise. The matching networks are as follows. The first network is made with a Beatty line, the second is made with a Mach Zehnder interferometer based on couplers, and the third network involves a 90° as a directive element in the interferometer. The proposed measurement protocol has been executed by all participating partners, and the results have been reported.

Two types of microwave electronics for SMM have been produced. The SDR based instrument and the six-port based instrument have been tested for electrical performance when measuring known impedances. The SDR instrument has been tested in a real SMM application and will now to be adapted for application with the SMM instrument at LNE.

### _Calibration methods for C-AFM and SMM and quantification of uncertainty contributions (Objective 2)_

Current versus voltage (I-V) investigations of the DC-current standards were conducted on a two-probe station setup, which was adapted for reduced-noise current measurements under ambient conditions. Two classes of samples were measured, having a 4 nm and an 8 nm thick $SiO_2$ layer for the tunnelling junction. The samples belonged to two different batches fabricated with fully symmetric features (*i.e.*, all the micro-circular contact pads have extended connection lines to remote macro-square contacts) and non-symmetric features (*i.e.*, half of the micro-circular contact pads have no extended connection lines). The I-V curves exhibited hystereses depending on the voltage sweep rate. The results highlighted the importance of reducing the voltage step during the sweep and increasing the waiting time between steps, which seems to allow the system to stabilize after each voltage variation.

Additional measurements were conducted on samples with 4 nm thick $SiO_2$ (non-symmetric features batch) using the Resiscope system coupled to a Multimode AFM. The results showed the significant reduction of the hysteresis effect for the I-V curves measured on the isolated micro-circular pads compared to those with an extended connection line to a remote large square pad. These observations highlight the role of the connection lines in inducing measurement errors. A similar conclusion was obtained by measuring I-V curves on the micro-circular pads connected to a remote square contact pad. The hysteresis behaviour is more pronounced on the curves obtained on the large square contact pads compared those on the micro-circular contact of the same junction feature. Further investigations are still ongoing to define the best set of measurement's parameters for reproducible I-V measurements in accordance with the calculable Fowler-Nordheim model.

The two-probe station setup for current measurements on the current standard samples is being customized for dark environment measurements to eliminate potential effects of the illumination on carriers' generation within the junction.

Simulations have been performed using a finite element solver. The conditions for analysing a dielectric materials located underneath an Au-layer were identified using resonator modes of the Au-pad. One Au-etch is available to use with one of the calibration samples for investigating the $SiO_2$ layer using the SNOM and to investigate the issues related to the homogeneity of the structure. It is highly expected to reach a good sensitivity to sub-Au properties by analysing the spatial resonance pattern.

Preliminary tests on the conductivity of the connection lines in the resistance standard samples were completed. A set of practical tests were launched to position and solder the micro-resistance components to the standard sample's structure.

Discussions were initiated covering the issue of the reliable interfacing of the VNA / interferometer system to the probes in SMM. Dummy hardware was exchanges for mechanical examination.

Measurements on various types of cantilevers were conducted, using the new stress-free holder which was tested for a direct use with other cantilever studies, *e.g.* when using reference cantilever approach. The method is ready to be used for the comparison study. In parallel, an automated tip calibration, based on Sader and Hutter method, was successfully implemented on an SMM system. Comparisons to nano-indentation tests are foreseen soon.

The thicknesses of the resonator layer were measured by means of spectroscopic imaging ellipsometry. For this, a measurement scheme was developed including an imaging mask for measuring thicknesses around the gold contacts. The same quantities were measured by means of white light interferometry microscopy (WLIM), showing very good correlation with the results in the first method. This constitutes the first demonstration of this kind of measurements using ellipsometry with other polarimetric reflectometry methods.

ITO layers were designed and manufactured with a range of conductivities through a collaboration between partners. These layers were structured by lithography into a checkerboard pattern. Measurements with C-AFM and spectroscopic microfocus ellipsometry were performed. This is the first ever attempt to correlate nano-conductivity measurements with ellipsometry using ITO (or any TCO) in the aim of developing a reference sample.

SMM measurements were carried out on MC2 calibration kit considering tip apex sizes from 100 nm down to sub-20 nm. Retrosimulations using COMSOL® showed a good agreement between measurements and simulations. These measurements were conducted under ambient humidity atmosphere in the microwave range up to 20 GHz. Additional measurements were done under vacuum at the microwave frequency of 3 GHz and the millimeter-wave frequency of 30 GHz, with no impedance matching network, showing possible reduction of the water meniscus.

The six-port demodulator was fully developed and the measurement performance was quantified, which must be completed by additional coupler to design the reflectometer. The broadband matching using interferometry was demonstrated. A calibration technique specific to complex impedance has been developed for the six-port reflectometer. A broadband calibration workflow is under development that offers high signal-to-noise ratio and quasi-broadband capabilities. First tests with cable assemblies look promising, however, calibrated SMM are still to be done to prove precise calibration.

The procedure for identifying the noise generated by the vector network analyser (VNA) and the impedance matching network in an SMM setup has been established and first measurements were carried out.

### *Reliable 3D multi-physics modelling (Objective 3)*

The modelling of the meniscus was carried out after a selection among three different analytical expressions applicable in a finite element simulation (COMSOL® software). The chosen model showed a reduced number of parameters and enabled the variation in the width and height of the water meniscus, and the thickness of the water layer covering the surface of the sample. This model was used to perform a self-calibration of the tip-sample model. Comparisons between shielded and non-shielded probes is in progress. The simulations of the water layer's influence, with and without the meniscus, started. A particular focus is made on the water layer's influence when the calibration samples are used (*i.e.* with a known capacitance that allows evaluating the impedance of the meniscus).

The meniscus was modelled using Bezier curves and the simulations were conducted with the SFEPy package (in python). A realistic shape of the water meniscus can be obtained using software (such Surface Evolver) that take into account the surface energies, the real shape of the tip, and its hydrophylic nature. An external company has been contacted to organize experiments where the water meniscus will be imaged in a scanning electron microscope (SEM), which will help gaining a better knowledge on the amount of water that must be considered in the models. The benchmarking of the different methods used to compute the influence of the water meniscus will be done.

The capacitance produced by the tip apex and the tip cone was modelled analytically using simplified hypotheses. SEM images and GWYDDION software were used to estimate the parameters of the model, in particular the radius of curvature of the tip. The analytical model was compared to COMSOL® calculations, showing a fair agreement. The model will be adapted to a dielectric sample. SMM in a SEM will be used to evaluate the influence of the water meniscus on calibrated samples.

The tip wear during SMM measurements was evaluated, which will be introduced into the models (diameter of the tip evolving from 50 nm before the experiment up to 500 nm after the experiment).

A novel structure of microwave probe was proposed, which corresponds to a modification of the commercial solution proposed by Rocky Mountain Nanotechnology. The main idea is to support a guided microstrip propagating mode along the probe. For this, a microstrip line and a ground plane were designed according to the ceramic substrate thickness. The probe was simulated, leading to the calculation of the amplitude and phase-shift of the complex reflection coefficient. The electric field in the vicinity of the probe was modelled, leading to the conclusion that the probe is more sensitive to the electrical and dielectric properties of the materials, compared to their magnetic properties. The study of the lateral and in-depth resolution of SMM started, with an initial focus on the electromagnetic coupling between two close devices.

A comparison between the Finite Elements and Finite Difference Methods was conducted for the resolution of the Poisson’s equation, taking into account the tip shape and the frequency of operation. The boundary conditions were refined to enable more realistic results.

*Simplified uncertainty budgets and case studies (objective 4)*

A case study on the measurement of the electrical properties of graphene in demonstrator layers and real devices was initiated with an industrial collaborator. The collaborator delivered samples (graphene layers on Si and metal substrates, graphene-based devices). First samples are being currently characterised by one of the project’s partners. The results are expected to deliver electrical properties such as conductivity calculated from the dielectric function of graphene layers on the micro- and nanoscale.

## Impact

To promote the uptake of the project’s results and to share insights generated throughout the project, the results were shared broadly with scientific and industrial end-users. Three papers and one joint-paper reporting project results are being drafted for publication in open-access peer-reviewed international journals. Moreover, three 2-pages summary papers were approved and awaiting for their open-access publication. In addition, an article will be published on February 2023 in a large-audience industrial journal, while three articles were published in industrial newsletters or press release.

Twelve presentations were given at conferences among which nine are leading international conferences. The project was presented to over 100 participants at two leading international conferences and at one plenary session of a national conference dedicated to nanomaterials for energy applications.

The project was presented at national and international standardization committees and was posted regularly on social media through ResearchGate and LinkedIn. The project website containing all the posts appearing in social media was set up and is periodically updated. Two webinars for training in the field of standardization were broadcasted with remote project partner attendees. The number of people trained amounts to about 15.

*Impact on industrial and other user communities*

Several SPM manufacturers 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 their 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-the-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, to facilitate their widespread uptake and commercialisation. High dimensional and parametric reproducibility of the fabricated DC to GHz reference standards 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 the use of the new fast and reliable 3D modelling software developed in this project. This new software will be made open-source to enable a wider uptake.

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

In the first half of the project, industrial users were contacted and relative key persons were invited to join the Stakeholder committee which counts now 21 members.

A standard sample manufacturer collaborated with one member of the consortium to design and manufacture a new capacitance calibration kit. This collaboration led to an improved calibration reference, which is put at the service of the community through commercialization.

A first online open-session dedicated to the stakeholder committee members was successfully conducted, as an additional event to the already planned stakeholder workshops. This open session, gathering 16 committee members, raised the awareness of all industrial stakeholders to the importance of nanoscale electrical calibrations. Two stakeholders shared samples with members of the consortium as case studies. For example, graphene-based Field Effect Transistor structures were provided by a leading European graphene manufacturer to demonstrate the use of the methods developed by the consortium in industrial manufacturing. Other stakeholders have explicitly expressed their interest in proposing samples for the same goal.

*Impact on the metrology and scientific communities*

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

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

The 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 and the provision of calibration samples and open source software for robust modelling. The improved reproducibility of these methods will speed up the 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 the tip-sample interaction volume and other 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 a fast accessibility to the procedures developed within the project. With world-class research excellence in C-AFM and SMM, several external funded partners and collaborators will be contributing with 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 the research outputs and maximise the impact from the project. This impact will be further enhanced by the dissemination through the liaison with national (C'nano, Systematic Paris-region, GDR "Name") and European research networks (NanoFabNet, EuroNanoLab) and social professional networks (LinkedIN, ResearchGate).

In the first half of the project, three instrumentation manufacturers showed strong interest to commercialize the reference standards for C-AFM and SMM produced in this project. In addition, one industrial stakeholder clearly expressed their interest in acquiring one DC reference standard for the current calibration in the pA range for a novel instrumental development they are conducting before launching their new product. The development of such electrical standards will impact the metrology and scientific community because these new standards enable the calibration of DC-current $I$, resistance $R$, resistance inductance product $R \cdot L$, and capacitance $C$ compared to only $C$ calibration. They can be seemingly used for other electrical SPM techniques such as scanning capacitance microscopy (SCM).

In collaboration with one of the stakeholders, a one-day workshop for users working on energy nanomaterials was organised, gathering 40 attendees.

In collaboration with several stakeholders, mostly SPM manufacturers, the consortium members are organising a one-week international summer school dedicated to nanometrology. This summer school will be held on June 2024 at Frejus (France) with an expected audience of 60 attendees.

*Impact on relevant standards*

The development of good practice guides, calibration procedures, and protocols for measuring electrical properties at the nanoscale will impact the international standards directly. This will be facilitated by the 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 the standardisation in nano-electronics. It will establish a subgroup responsible for the standardisation promoted by this project. This Elena Standardisation Group (ESG) will act as the interface with the international Standards Developing Organisations (SDO) to optimise mutual understanding and to deliver guidelines, protocols, and standard operating procedures. These will be further submitted as two draft Technical Specifications, on C-AFM and SMM calibrations, in line with the strategic priorities of the standards committees.

During the first half of the project, two Preliminary Work Items (PWI) were approved by the IEC TC 113:

- PWI 113-144 "Electrical nanoscale metrology in industry – Conductive atomic force microscopy (C-AFM)"
- PWI 113-145 "Electrical nanoscale metrology in industry – Scanning microwave microscopy (SMM)".

The preparation of the two draft Technical Specifications, on C-AFM and SMM calibrations, is in progress. With the establishment of two PWIs in IEC TC113, a significant step was made to ensure that two standards will be developed reaching the Committee Draft stage or higher within the project duration. The consortium members confirmed their support of these standards until publication beyond the project duration. Standardization if necessary. A minimum of two standards will be published within the regular time frame of 36 months after the IEC TC113 Spring meeting in 2023.

As IEC TC113 cooperates with other Standards Developing Organizations (SDO), the activities of the consortium are made available to those committees via formal liaisons. The full list of these SDOs can be found on the IEC TC113 website. Examples are: GFSC (Graphene Flagship Standardization Committee), IEEE, SEMI, IEC TC 47 (Semiconductor devices), IEC TC 119 (Printed electronics), ISO TC 229 (Nanotechnologies), ISO TC 201 SC 9 (Scanning probe microscopy), CEN TC 352 (Nanotechnology).

The consortium takes active part in the standardisation of ellipsometry as a metrological technique. Within DIN NA 062-01-61 – "Measurement and testing methods of layers and layer systems", the standard series DIN50989-x is developed which is intended as a sample independent definition and best practice guide for ellipsometry. This standard series is developed into an international standard series ISO23131-x, which are written in ISO/TC 107 – “Metallic and other inorganic coatings” and ISO/TC 107 JWG 4 – “Thickness determination of coatings, paints, and varnishes”.

*Longer-term economic, social and environmental impacts*

Europe hosts the world-leading manufacturers of SPM instrumentation and the development of its new modes. Reliable eSPM metrology will accelerate the 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 major drivers of the 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 the nanoscale electrical properties, which are critical to increase the innovation, the competitiveness, and the resilience of these industries.

As an environmental consideration, the 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

No publication yet

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| Project start date and duration: | 1st Sept 2021 for 36 months | |
| Coordinator: *François Piquemal, LNE* Tel: +33 1 30 69 21 73 E-mail: francois.piquemal@lne.fr<br>Project website https://projects.lne.eu/jrp-elena/ | | |
| Internal Funded Partners:<br>1. LNE, France<br>2. BAM, Germany<br>3. CMI, Czech Republic<br>4. DFM, Denmark<br>5. METAS, Switzerland<br>6. PTB, Germany<br>7. TUBITAK, Turkey | External Funded Partners:<br>8. CEA, France<br>9. CNRS, France<br>10. ISC, Germany<br>11. JKU, Austria<br>12. ULILLE, France<br>13. UofG, UK | Unfunded Partners: |
| Linked Third Parties: 14. INSA Lyon, France (linked to CNRS) | | |