Publishable Summary for 16ENG06 ADVENT
Metrology for advanced energy-saving technology in next-generation electronics applications

Overview

The roll-out of 5th Generation (5G) telecommunications across Europe by the year 2020, and the emergence of the Internet of Things (IoT) with 50 billion connected devices, will strongly increase the demand for energy due to the continuous power consumption of the electronic devices needed to deliver these technologies, leading to an associated demand for more energy-efficient systems. This project establishes the metrology required for this transformational objective for Europe by providing traceable measurements of power, losses and emerging electronic materials properties. Thus this project will enable European industries to optimise device and systems design for 5G and IoT applications requiring ultra-low power and more energy efficient operation.

Need

The ongoing IoT and the future 5G radio access network will have a fundamental impact on the daily life of all European citizens. Sensors (the cornerstone of IoT) will be found everywhere (car, house, industrial health monitoring, etc.) and 5G communication systems will provide greater connectivity (Machine-to-Machine, high data rates with low latency). The high data-rate aspect of 5G at mmWave frequencies makes the power consumption and thermal issues very challenging in wireless devices. By 2020, the Information and Communications Technology (ICT) sector is expected to contribute about 2 % of global CO2 emissions instead of 1.3 % in 2007 (Ericsson report, 2010). Within this, 20 % of the footprint may be attributed to personal mobile networks and mobile devices. Phones and tablets will produce the strongest percentage increase in the ICT's footprint.

Improvement of the energy efficiency of devices and processes is therefore a key component for sustainable development of European products. Due to restrictions in current scaling strategies and dramatic thermal issues (particularly in wireless systems), semiconductor and electronics manufacturing roadmaps are aimed at the introduction of novel materials, more complete component characterisation and more efficient power management at the system level that will lead to the development of novel ultra-low power devices. To support industry in facing these challenging issues, traceable measurement techniques are required that will establish a robust metrology framework for in-situ, in-operando and multiphysics characterisation of advanced materials and components, and for reliable and accurate data for an efficient power management system.

Objectives

The overall objective is to achieve traceable and accurate measurements of the power consumed by ultra-low power and high frequency energy efficient electronic materials, devices and systems in order to support their development in both industrial and research sectors.

The specific objectives of the project are:

1. To develop nanometrology adapted to the in-situ and in-operando characterisation of advanced new materials proposed for the next generation of ultra-low power energy-efficient devices. These measurements will include impedance measurements (capacitance, resistance and inductance), piezo-electric/piezoresistive stress (200 MPa) and strain (0.02 %) responses to the application of electric (up to 4 MV/cm) and magnetic (up to 2 T) fields, as well as temperature and pressure in the range encountered in electronic devices.
2. To develop frequency and time-domain techniques for the simultaneous measurement of dynamic thermal profiles, electro-magnetic field sensing, DC electrical power consumption and RF operating waveforms for a wide range of RF electronic components (operating in-situ, under realistic conditions).

These techniques to be combined with a multi-physics approach, which will establish rigorous energy budgets, and diagnostic capabilities, for a wide range of electronic components (operating in-situ, under realistic conditions), required for next-generation communications. The uncertainty in the measurement of the power efficiency to be reduced to less than 1 %.

3. To develop embedded sensors and the associated calibration and measurement techniques to accurately measure power consumption of wireless systems (mobile phones, tablets and connected devices) and to improve the effectiveness of analogue and RF tests of components and systems. The power measurement techniques will be able to characterise and calibrate on-chip power sensors with an uncertainty of less than 10 µW.
4. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories), standards developing organisations (ISO) and end users (the semiconductor industry, and the telecommunications sector).

Progress beyond the state of the art

This project will involve three complementary elements (materials, components and systems) to support European industries in the development of optimised energy devices and systems required for 5G and IoT applications.

Materials

The characterisation of novel materials, such as ferroelectric, multiferroic, and piezoelectric-resistive materials, requires a joint effort in improved impedance, material structure and compositional metrology. Currently, the impedance measurement and structural analysis at nanoscale of such materials suffers from a lack of traceability, insufficient resolution and reliability. This project will develop a broad platform of metrologies to extend the spatial resolution of material structure and compositional measurement down to the nanometre scale, to quantify impedance of novel materials with an uncertainty of 10 %, and to extend measurement of stress and strain responses to electric field up to 4 MV/cm and magnetic fields up to 2 T.

RF components

RF electronic components are never single transistors and it is critical to understand design limitations by measuring the electromagnetic fields, temperatures and losses distribution as the device operates. In Europe, no metrology basis exists to measure simultaneously and in-operando the electromagnetic and thermal responses of RF and microwave components under realistic operating conditions and to measure switching losses accurately. This project will combine a range of contacting and non-contacting techniques to reduce the current uncertainty in evaluating the power efficiency of such electronic components from 2 % to 1 %.

Systems and devices

To optimise the power consumption and system performance of battery-supplied devices, it is necessary to monitor and adjust the transmitted RF power accurately and continuously. On-chip power levels measured in these devices can be as low as the micro watt level. Even if power and thermal measurements are becoming increasingly integrated by many semiconductor suppliers at chip level, the traceability of on-chip power measurements does not exist at NMI levels. This project will develop traceable high frequency power metrology for on-chip power measurements with an uncertainty of less than 10 µW.

Results

Nanometrology for characterisation of new materials

The 1st objective aims to develop the metrology required in Europe for the measurement of impedance at nanoscale and characterisation of advanced materials such as piezo and ferroelectric materials. Scanning Microwave Microscopy (SMM) has been applied towards capacitance, resistance and inductance measurements and different aspects affecting the experimental outcome are being verified. Standards are being developed. Final designs of impedance standards are now established, capacitance devices are currently under fabrication and a first set of resistance and inductance devices are being tested by NMIs involved in the project. COMSOL simulations were performed in view of establishing a traceability chain. In addition, SMM measurements have been performed using commercial samples in order to start evaluating experimental errors and uncertainties. Regarding the Mesoscale and Analytical in-situ X-ray characterisation studies, the required samples have been delivered to the partners and first dynamic EXAFS and XRD experiments have taken place. The aim is to record the response of the thin piezoelectric films to different electric fields being applied. Therefore the access to synchrotron radiation has been beneficial. From the perspective of studying stress and strain responses of piezoelectric materials a stress-strain rig was designed and is in the final procurement phase. Finally, advances in FIB (Focused Ion Beam) proved to be instrumental for the preparation of nano-structured devices for TEM (Transmission Electron Microscopy) and IR-SNOM (Infrared Scanning Near-Field Optical Microscopy) based in-situ strain studies.

Multiphysics characterisation of RF components

This 2nd objective aims to develop and combine time- and frequency-domain, electromagnetic field and thermal mapping measurement techniques to establish rigorous energy budgets, and diagnostic capabilities, for a wide range of electronic components (operating in-situ, under realistic conditions), required for next-generation communications. Characterizations of real devices used in electronic and telecommunication sectors were performed by all partners which has enabled significant progress to be made on the multiphysics approach. Large area temperature measurements (up to 25 mm x 25 mm) were performed on real devices. On one side thermal and electromagnetic field measurements, and on other side frequency and time domain load pull characterizations were performed separately on different devices. These first experiments have made it possible to study devices under different load conditions and on other side to identify impedance operating points of the device providing maximum efficiency and output power. Programming codes based on Finite Difference Time Domain method (FDTD) are currently being developed to simulate large setups similar of those used in Scanning Microwave Measurements (SMM). Finally, the time domain approach is now in place: the method to correct distortion from oscilloscope probes is effective as well as the programming code to make measurements and to analyse data. The method has started to be applied on real devices such as GaN power transistors.

Power consumption measurement of wireless systems and devices

This 3rd objective aims to provide to industry low cost and traceable sensors and fast scanning measurement data to improve on-chip power traceability. The modelling of the sensor allows demonstrating now the limitations (matching, noise) and adjusting a variety of important parameters such as: bias current parameters, size, etc. The traceability of this power sensor is based on chip direct comparison system and on chip power standard. This latter has been designed and is currently under fabrication. The detector is based on the thermoelectric principle and simple planar structure (single layer sensor) that will make it possible its calibration by using the Microcalorimeter technique which is the calibration method at NMIs level. A completely novel approach to extract losses on PCB circuits has been developed and tested. To do this, the magnetic field of the device under test is measured using a near field scanner. It has demonstrated that the current distribution can be extracted from these measurements if material properties are known. The near field technique will be used in association with reference circuits to detect local or abrupt current variations in the structure that will provide a qualitative or comparative approach to evaluate power losses on PCBs.

Impact

12 presentations and 2 posters have been made to conferences at various European locations, and 2 open-access publications have been accepted. 1 workshop has already been organized and an additional workshop will be presented at the European Microwave Week conference in September 2019. Information on the project's activities has also been disseminated through newsletters and flyers.

A workshop “X-ray and Neutron Scattering and Spectroscopies in Ferroelectric and Multiferroic Research Workshop V” was held at IOM3 (The Institute of Materials, Minerals and Mining) in London on 4-5 February 2019. The workshop brought together experts from the multiferroics, magneto-electrics and ferroelectrics communities with neutron, synchrotron and other spectroscopy facility end-users to present the project's latest developments. The approximate size of audience was 55 experts coming from European countries, Asia and United States of America. Five partners from the consortium participated and gave presentations. Participants of the workshop responded positively to the high level of technical knowledge shown by the ADVENT presentations and showed particular interest in the results obtained using diffraction and Transmission Electron Microscopy methods.

Impact on industrial and other user communities

A project advisory group (PAG) has been set up to provide feedback from collaborators on the strategy and preliminary results of the project.

The PAG comprises seven end-users from industry (semiconductor, electronic, instrumentation), research centres and university, covering all the required expertise to review results and guide their exploitation. Six collaborators also support the technical activities carried out in the project and have expressed their interest in the results via letters of agreement. A meeting dedicated to PAG members and collaborators was held on the 23rd April 2018 at PTB (Berlin, Germany).

A meeting was organised on 9th April 2018 at LNE Trappes (France) with two key representatives from Alliance Electronique. This organisation is the major French professional union for industry and manufacturers in the electronics sector. During this meeting a discussion was carried out to organise the dissemination of results to manufacturers and industrial members of Acsiel Alliance Electronique.

Stakeholders and collaborators are already benefiting from the dissemination of project outputs through their participation in the advisory group and teleconferences specifically organized during the project meetings. The project outputs have been broadly disseminated to the external industrial and academic community thanks to the participation of partners in a large number of conferences and workshops in Europe and internationally.

Stakeholders and collaborators of the project have already been able to take advantage of project outputs through early access to data measurement results explaining the limitations and potential functionalities of materials they are using and or which are under development.

Calibration kits to improve the reliability of impedance measurements at the nanoscale, as performed by end-users such as the academic community and the semiconductor industry will also be available shortly.

Impact on the metrology and scientific communities

The current development of capacitance and inductance standards enables traceability of impedance, permittivity and loss measurements to be established at the nanoscale. These advances will extend the measurement capabilities of the leading European NMI partners of the project. NMIs, universities and research centres within the consortium are currently improving their capabilities in terms of characterization of advanced materials such as ferro-electric, multi-ferroic, and piezoelectric-resistive materials under electric and magnetic field applications with more accuracy and reliability.

The multiphysics approach adopted in the project has already improved the measurements capabilities and skills of universities and NMIs involved in the microwave components characterization area by the combined use of new equipment and through the internal training of resources. Metrology of devices operating under non 50 Ω conditions has been investigated for the first time in Europe and is likely to lead to new measurement capabilities in this area.

The multiphysics approach opens up the opportunity for establishing detailed energy budgets of RF and microwave components that will benefit manufacturers of electronic components intended for 5G circuits and subsystems. The time-domain method developed to measure switching losses of transistors is based on the use of oscilloscopes and probes. An innovative procedure is now available to remove errors related to probes which will strengthen the leading position in Europe of the project’s industrial and academic collaborators involved in time-domain measurements. An oscilloscope manufacturer is a collaborator on the project which maximises the opportunity to implement this technique.

Research work on on-chip power measurements is currently creating new on-chip power measurements capabilities which don’t exist in Europe or elsewhere. Partners involved in the development of on-chip power sensors targeted for 5G frequencies and in near field electromagnetic techniques are using the latest BICMOS 55 nm technology and the most recent instrumentation provided by two collaborators in the project. Using the latest fabrication processes improves the experience of the project’s collaborators from the industrial and academic sectors in this new technology and maximises the uptake and exploitation of the power detectors that are being developed. These detectors should consequently be more easily exploited by electronic component manufacturers engaged in the development of 5G products.

Impact on relevant standards

Project progress and engagement is being reported to IEC (TC 47, 49 and 113), ISO (TC46 and TC206), IEEE (P1859/D6), VAMAS (TWA24) and EURAMET TC-EM SC-RF&MW/EMC, and SC-LF committee meetings. These reports describe the dissemination of good practice guides and the organisation of meetings dedicated to standardisation activities relating to semiconductor devices, piezoelectric and dielectric devices and characterisation of materials at the nanoscale. So far, the Consortium has carried out the following actions:

The publishable summary updated at M9 was sent to TC 113, TC 47 and 49 officers. Consortium activities and research results have been presented to the IEEE Working Group P1859 at the annual meeting (May 2018).

Consortium partners will make presentations to EURAMET TC-EM SC-RF&MW/EMC and TC-LF at the next annual meetings (in May or June 2019). This will be an excellent opportunity to disseminate research outputs to the metrological community in the area of electromagnetics.

Longer-term economic, social and environmental impacts

The new traceability path and measurements impedance capabilities developed will enable industry to produce higher technological products and consequently boost the industrial competitiveness of instrument manufacturers for nanoscale measurements.

Dissemination of high level scientific knowledge of piezo and ferroelectric material under realistic conditions will generate a skills base in Europe that can be accessed by European industry, providing a significant commercial advantage and reduced time-to-market.

Calibration services for evaluating power efficiency, based on the multi-physics approach developed in this project, will allow industry to reduce development costs: reduced energy dissipation of the integrated circuits thus minimising the need for cooling equipment and expensive packages.

Traceable and accurate data produced by the new power sensors developed in WP3 will enable European manufacturers of mobile devices to improve the efficiency of the power management system involved in smartphones and tablets. The battery remains a significant expense and reduced energy expenditure will improve battery lifetimes.

The multi-disciplinary metrology approaches developed will support industry impacting the ICT sector in the development of ultra-low power devices and therefore in the reduction of the European (and global) carbon footprint. The less power that is consumed by an electronic device means the longer it will continue functioning without recharging or changing the battery.

List of publications

1. Bernd Kästner, Franko Schmähling, Andrea Hornemann, Georg Ulrich, Arne Hoehl, Mattias Kruskopf, Klaus Pierz, Markus B. Raschke, Gerd Wübbeler, and Clemens Elster, “Compressed sensing FTIR nano-spectroscopy and nano-imaging”, Optic Express, April 2018, https://doi.org/10.1364/OE.26.018115.

2. Bernd Kästner, C. Magnus Johnson, Peter Hermann, Mattias Kruskopf, Klaus Pierz, Arne Hoehl, Andrea Hornemann, Georg Ulrich, Jakob Fehmel, Piotr Patoka, Eckart Rühl, and Gerhard Ulm, “Infrared Nanospectroscopy of Phospholipid and Surfactin Monolayer”, ACS Omega, April 2018, https://pubs.acs.org/doi/10.1021/acsomega.7b01931

Project start date and duration:		1 September 2017, 36 months
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