

Title: Metrology in manufacturing compound semiconductors for power electronics

Abstract

The global power electronics industry is manufacturing new wide bandgap compound semiconductors, which offer huge benefits for device performance. However, poor yields, compromised performance and reliability issues are hindering commercialisation. In addition, these defects are difficult to characterise with existing techniques. Therefore, novel metrology and instrumentation need to be developed for the high speed, quantitative characterisation of the defects in these materials in order to accelerate the development of wide bandgap power electronics.

Keywords

Compound semiconductor, compressed sensing, defect characterisation, in-line metrology, nanometrology, power electronics, quality control, scanning probe microscopy, scatterometry, spectroscopy, wide bandgap

Background to the Metrological Challenges

The power electronics market is currently dominated by silicon technology, but European companies are leading the transition towards wide bandgap compound semiconductors (e.g. GaN and SiC) for the electrification of transport, 5G communications, and renewable energy distribution networks. Although these new materials have higher voltage/current ratings, lower losses, faster switching and higher temperature operation, they are highly sensitive to defects in the nanoscale crystal lattice and in interfaces with dielectric layers. These defects either occur in the semiconductor wafer or they are formed during subsequent processing. At present, various techniques are used to detect and characterise these defects, including optical imaging, spectroscopy, scatterometry, electron microscopy, X-ray techniques and scanning probe microscopy. However, poor yields, compromised performance and reliability issues continue to hinder commercialisation. Yield enhancement is a Grand Challenge for the semiconductor industry, requiring new methods to detect and quantify defect density and species at high speed as well as new methods to eliminate the defects that arise during wafer and die production. Defect characterisation is metrologically challenging due to their small dimensions and due to the trade-off between the sensitivity and throughput of each of the characterisation techniques. It is also essential to understand how the material quality parameters affect device performance.

Manufacturers of wide bandgap compound semiconductor wafers and dies require rapid, high throughput, in-line defect detection techniques. Optical techniques, including spectroscopic imaging, are currently used as they are non-destructive, non-invasive and highly scalable. However, acquisition times are long and defects smaller than ~100 nm cannot be resolved. Methods based on structured light illumination, compressed sensing algorithms, and machine learning are needed to address these limitations. Other optical techniques, such as ellipsometry and scatterometry, can detect some defects that are smaller than 10 nm, but these methods have not been applied to wide bandgap compound semiconductors and their capabilities are unknown. Therefore, new instruments need to be developed for the rapid (< 1 minute), accurate and non-destructive detection of nanoscale (< 100 nm) defects in wide bandgap compound semiconductor wafers and dies.

The industry also needs off-line characterisation techniques, which are slower, but more accurate, for establishing how specific defects, in the 5 nm to 10 µm range, impact on device performance, thus enabling them to assess whether the material should be scrapped or retained. Traditional scanning probe microscopy (SPM) techniques are currently used, but new advanced SPM techniques, such as near-field optical spectroscopy, scanning microwave microscopy and scanning Kelvin probe microscopy, have the required chemical sensitivity, spatial resolution and the ability to probe the electronic properties of semiconducting materials. However, the accuracy and traceability of the defect characterisations performed with these, and other new methods, needs to be verified for both individual and combined methods.

The relationships between off-line SPM measurements and in-line optical measurements are unknown. Therefore, the results obtained using these techniques need to be correlated with consideration of both material and processing defects. One approach would be to use the set of data fusion tools, which was developed for combining complementary measurements in hybrid metrology, in order to meet the need for accurate and traceable methods for quantifying the quality of compound semiconductor wafers with uncertainties < 10 %. There is also a clear need to identify key measurands that will ensure the quality of industrially relevant wide-bandgap materials, e.g. GaN and SiC, and other emerging materials e.g. Ga₂O₃. It is also necessary to determine the effects of different types of defect on the materials' optoelectronic properties and on the performance of a range of power electronics devices, which use these materials.

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 compound semiconductors for use in power electronics.

The specific objectives are

1. To develop instruments for the rapid (< 1 minute), accurate and non-destructive detection of nanoscale (< 100 nm) defects in industrially relevant compound semiconductor wafers (≥ 15 cm diameter) and dies. The instruments should be based on optical scatterometric, spectroscopic, compressed sensing or other in-line techniques.
2. To develop highly accurate and traceable methods for the detailed characterisation of defects in industrially relevant compound semiconductors in the 5 nm to 10 μm range. The methods should be based on advanced optical and electrical scanning probe microscopy or other off-line techniques. Multiple methods could be used, but each method should have a spatial resolution better than 50 nm.
3. To develop accurate and traceable methods for quantifying the quality, i.e. defect type and density, of compound semiconductor wafers with uncertainties < 10 %. The results from fast optical spectroscopic analyses should be correlated with those obtained using advanced scanning probe microscopy and both material and processing defects should be considered.
4. To identify key measurands that will ensure the quality of industrially relevant wide-bandgap materials, e.g. GaN and SiC, and other emerging materials e.g. Ga₂O₃. This should include an assessment of the effects of different types of defect on the materials' optoelectronic properties and on the performance of a range of power electronics devices, which use these materials.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (CEN, ISO) and end users (compound semiconductor industry, power electronics industry).

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.

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 compound semiconductor and power electronics sectors.

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.