New Metrological Tools for Quality Control of Wide Bandgap Semiconductors

PowerElec: European Metrology Research Project 2021-24

Metrology Institutes: BAM, Bundesamt für Eich- und Vermessungswesen, Czech Metrology Institute, PTB, NPL National Physical Laboratory, TÜBİTAK

Industry: AIXTRON, Compound Semiconductor Centre, Infineon

Academia & Research Institutes: ikz, leti CEA tech, TU Delft, TU Wien

Sebastian Wood

sebastian.wood@npl.co.uk

PE International, Brussels - April 2024

National Physical Laboratory

Providing Confidence in Measurements since 1900:

- UK's National Measurement Institute
- 800+ Graduate/PhD scientists – multidisciplinary
- Network of >2000 companies and >80 universities
- 388 laboratories and engineering centres
- World leading measurement science
- Provide traceability to 70,000+ UK businesses
- Influence International Standards on UK's behalf

Highest point of reference in measurement

Traceability / Accuracy/ Reproducibility

Unique UKAS accredited capabilities

Leading measurement standards development and dissemination

Metrology to underpin National Challenges

Accelerating innovation

Partnerships

Translating science into impact

International Engagement

International representation
Thought leadership
Foresighting
Future metrology challenges

EE Times EUROPE

News Focus Opinion Education Magazine Company Dire

News

Wolfspeed to Build 200-mm SiC Wafer Fab in Germany

February 8, 2023 Anne-Françoise Pelé

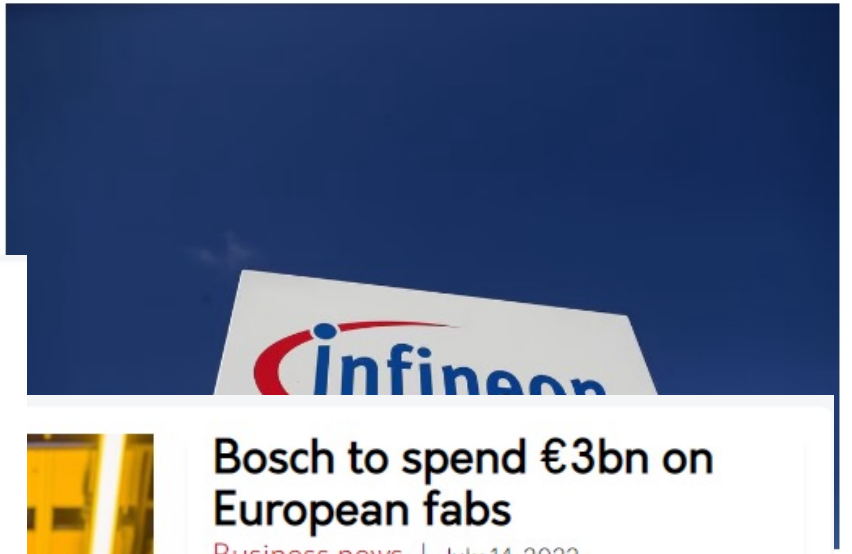
"Silicon carbide is the answer to some of the biggest issues of our time: energy savings and climate change," said G
Lowe, president and CEO of Wolfspeed.

Technology

2 minute read · February 16, 2023 9:41 AM GMT · Last Updated a day ago

Infineon to begin work on 5 bln euro chip plant in Germany

Reuters



Technology

2 minute read · October 5, 2022 2:23 PM GMT+1 · Last Updated 4 months ago

Boosting EU chip supplies, STMicroelectronics plans new plant in Italy

By Giulio Piovaccari

A logo is pictured on the factory of STMicroelectronics in Plan-les-Oautes near Geneva, Switzerland, December 6, 2016. REUTERS/Denis Balibouse

onsemi $450m boost to European silicon carbide wafer plant

Business news | September 21, 2022

By Nick Flaherty

AUTOMOTIVE MATERIALS & PROCESSES POWER MANAGEMENT

Bosch to spend €3bn on European fabs

Business news | July 14, 2022

By Nick Flaherty

SENSING / CONDITIONING MATERIALS & PROCESSES

.icon carbide (SiC) wafer plant in the Czech Republic with an
the next two years.

in the transition

Bosch plans to invest another €3bn in its semiconductor division by 2026 as part of the proposed European IPCEI programme on microelectronics and communications technology.

This will include 300mm wafer capacity for its MEMS devices and 1200V gallium nitride (GaN) devices for automotive.

"Transphorm TPH3208PS 650V GaN HEMT Reverse Costing", SystemPlus Consulting (2017)

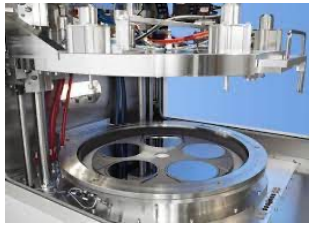
Metrology for WBG Semi

NPL

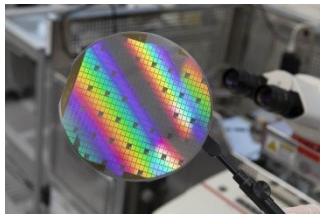
Boule

Wafer

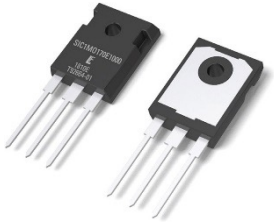
Epitaxy



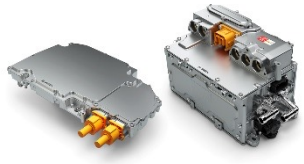
Fabrication



Packaging



Module



System

Process Development

Defect Inspection

Material Quality

Process Monitoring

Device Testing & Reliability

Regulatory Compliance

Metrology & Inspection Instruments

Calibration & Standards

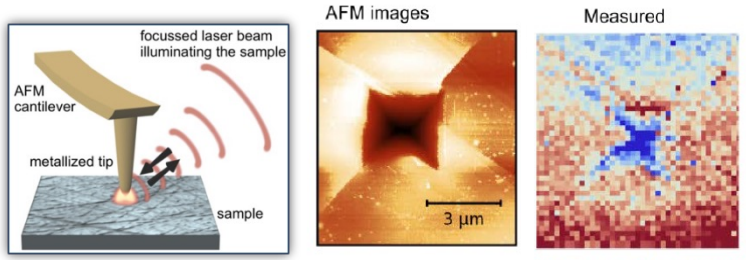
PowerElec Project Goals

Increasing sensitivity

Novel application of near-field spectroscopy to WBG defects

Combined KPFM-cathodoluminescence technique for defect discrimination

Advanced sampling techniques to optimise speed and accuracy



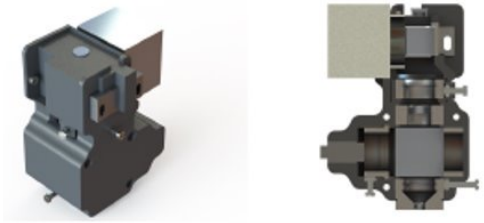
Increasing throughput

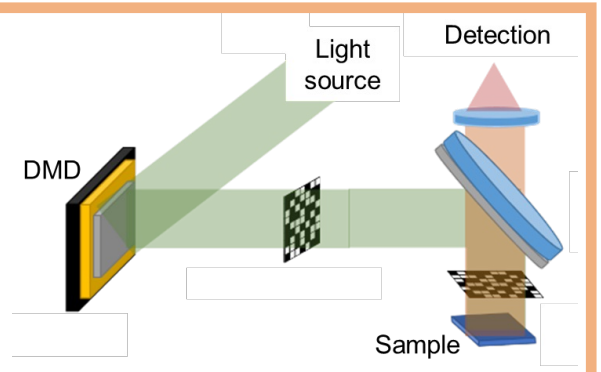
Parallelised scatterometry, fast-ellipsometry, PL imaging

Mueller ellipsometry as complementary technique

Structured light for compressed sensing

(faster measurement, higher signal-to-noise)





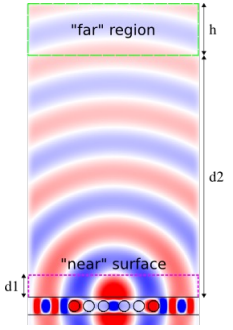
Increasing confidence

Hybrid metrology: combining local and ensemble measurements to enhance sensitivity & speed

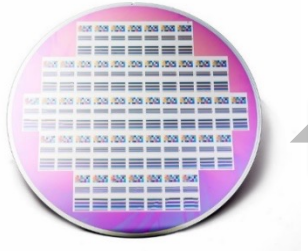
Uncertainty evaluation in compressed sensing reconstruction

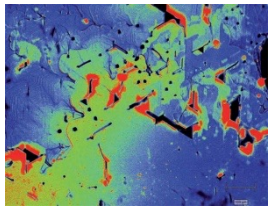
Traceable measurement of device performance & reliability

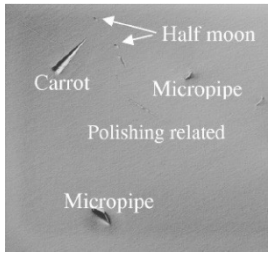
Identification of critical defects and key measurands

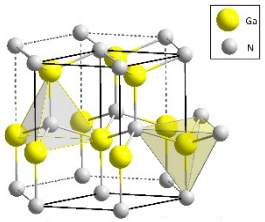


PowerElec Project









mm

µm

nm

WP1. In-line wafer inspection
Optical techniques combining: scatterometry, ellipsometry, optical imaging

WP3. Quantifying material quality using: Data fusion, hybrid metrology, compressed sensing, machine learning

WP2. Off-line nanocharacterisation
Combining nanoscale microscopy: IR s-SNOM, TERS/TEPL, KPFM, cathodoluminescence

WP5. Creating Impact:
Knowledge transfer, training, uptake, exploitation

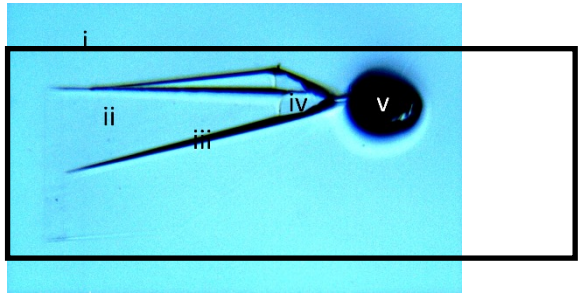
WP4. Identifying key measurands:
Correlating material quality with device performance: mobility, dynamic R_{on}, reverse bias stability

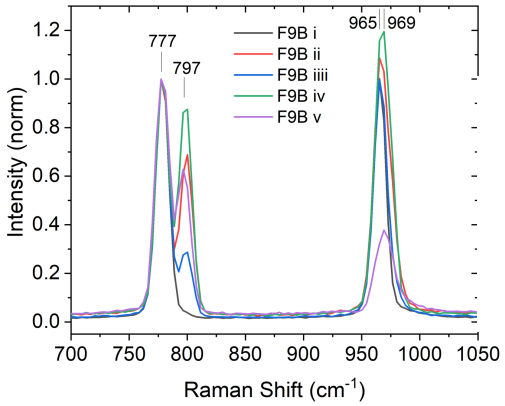
WP6. Management and Coordination:
Project management, meetings, reporting

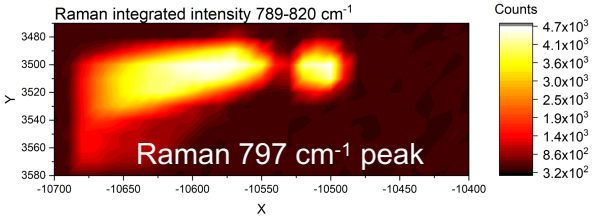
Near-field optical spectroscopy (SiC)

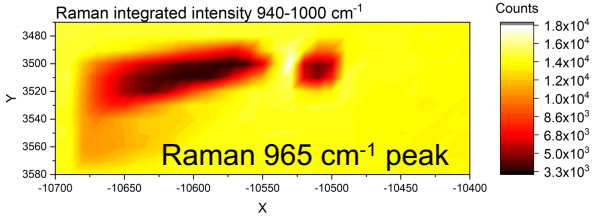
- Optical spectroscopy offers sensitivity to chemical and structural properties, but spatial resolution is limited by diffraction.

4H-SiC epi defect

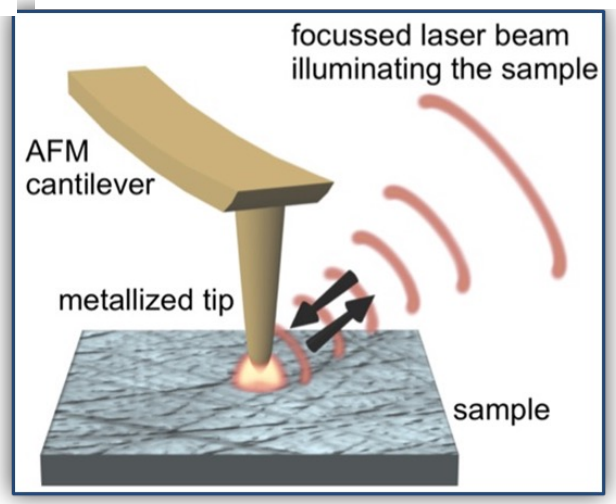






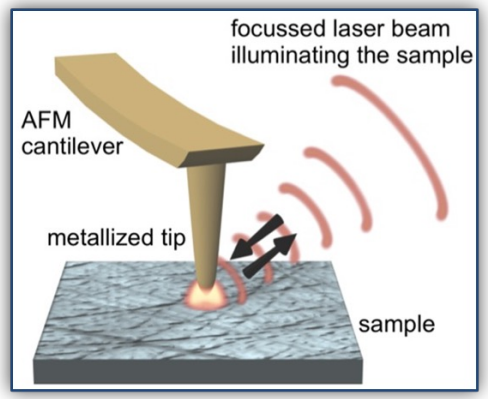


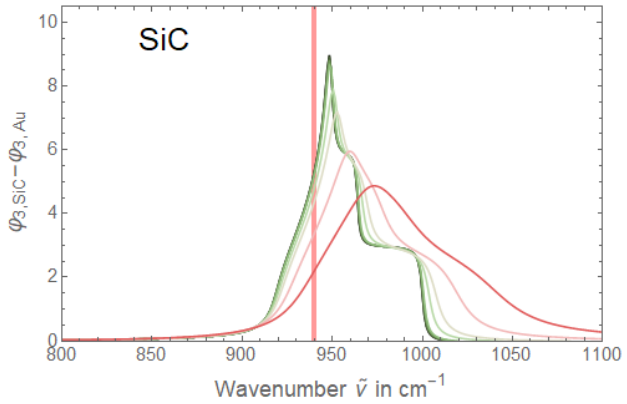
- Scanning probe microscopy (AFM) offers nanometre spatial resolution for surface topography.
- Near-field spectroscopy combines AFM with spectroscopy to achieve nano-scale optical measurements.

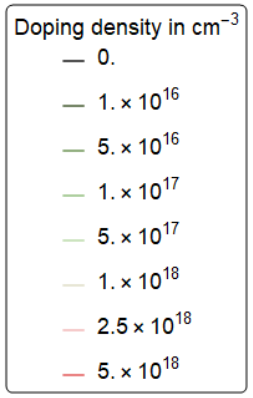


IR scattering-SNOM (SiC)

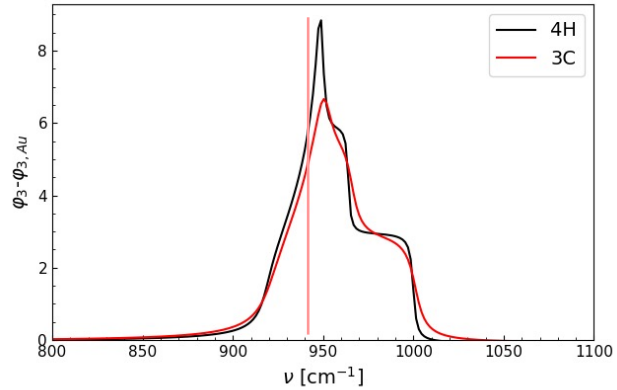
- IR scattering from sharp tip probes local phonon modes with sensitivity to doping density and polytypes.





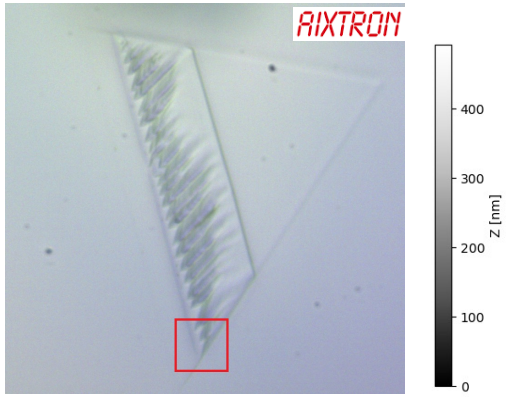


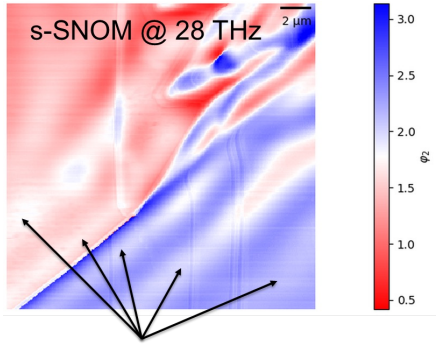
Carrier density dependence



Polytype dependence

4H-SiC epi defect

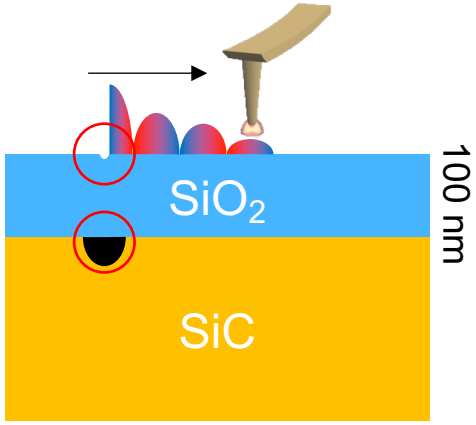




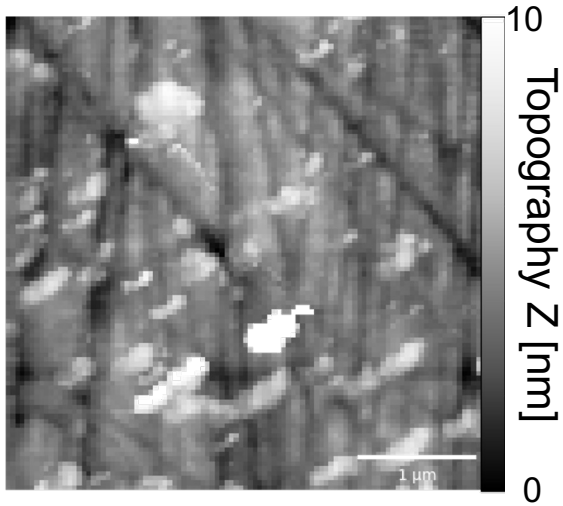
Propagating surface phonon polaritons

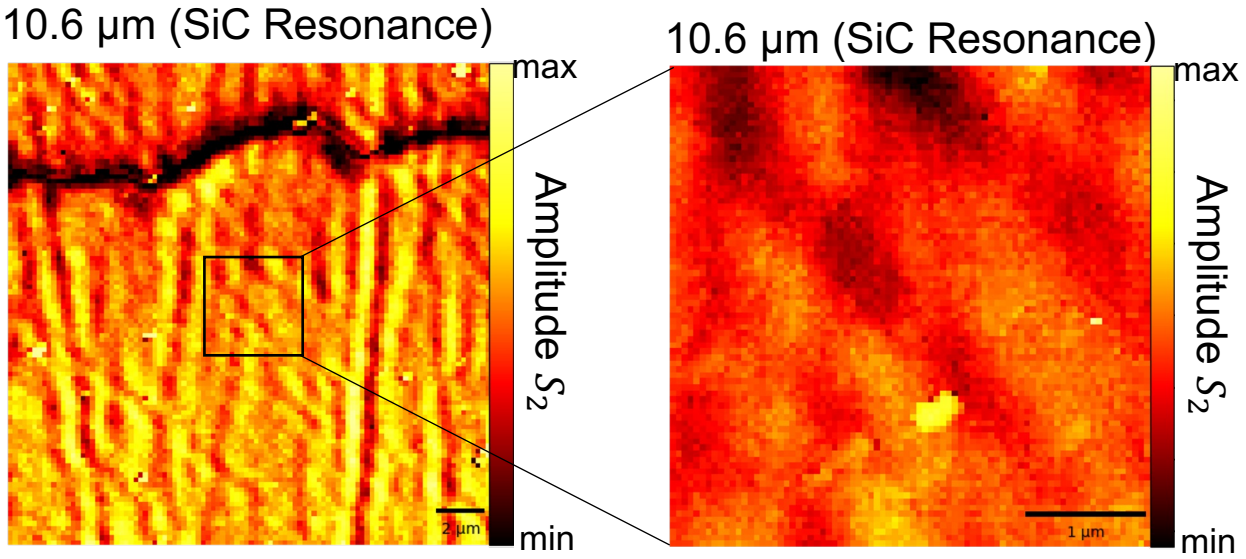
IR scattering-SNOM (SiC)

- Defects at the SiC/SiO_2 interface are known to impact device performance
- sSNOM signal relates to sub-surface nanoscale features at the oxide interface – in this case probably polishing defects



Surface phonon polaritons due to buried defects

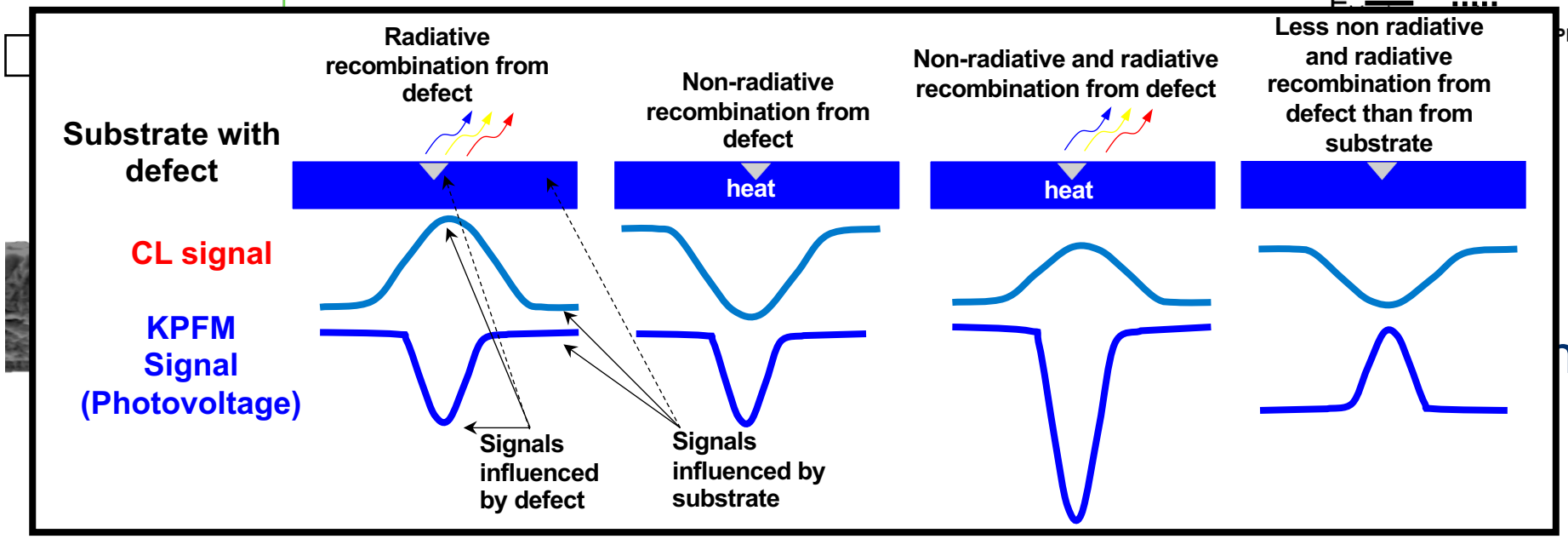




Multi-modal microscopy (GaN)

- CL measures radiative recombination
- KPFM measures surface potential

Radiative recombination



hotovoltage

- Combined measurements make it possible to separate recombination mechanisms associated with nanoscale defects.

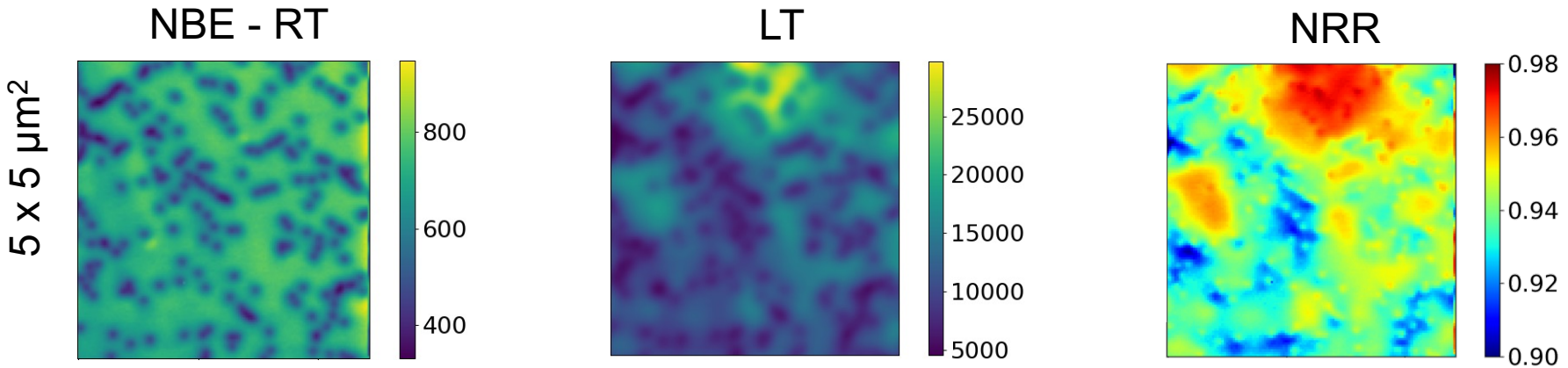
Multi-modal microscopy (GaN)

	GaN	2000 nm
25% Al	AlGaN	900 nm
50% Al	AlGaN	600 nm
	AlN	600 nm
	Si (111)	

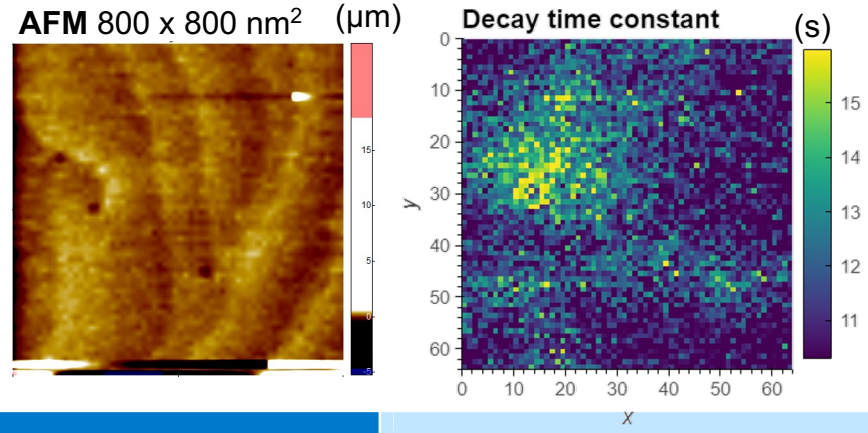
NPL

- Temperature controlled CL → isolate non-radiative recombination

$$NNR\% = (I_{CL}(LT) - I_{CL}(RT))/I_{CL}(LT)$$



- Light-dependent KPFM → quantitative rates for combined recombination



Ongoing challenge to achieve repeatability for quantitative measurements.

leti cea tech

Pre-Standardisation Research

NPL

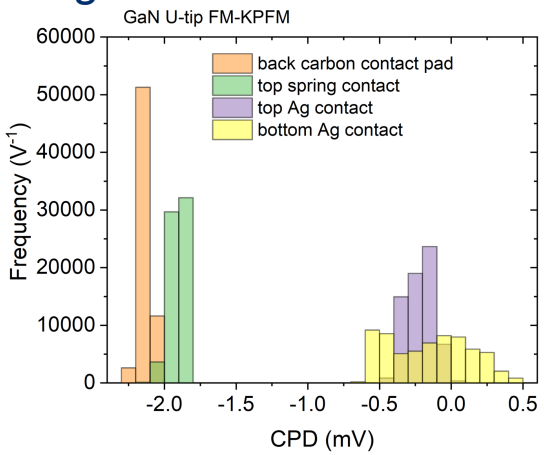
"For silicon everything is standardised but for compound semiconductors nothing is."

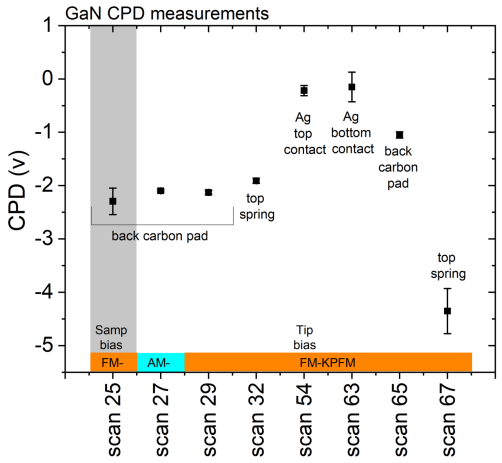
- National Metrology Institutes have a role to play in supporting industry through standards development.

VAMAS DIN bsi. ISO IEC semi JEDEC

- Emerging metrological methods must be demonstrated as reliable and quantitative – this is achieved through pre-normative interlaboratory comparisons.

e.g. KPFM on GaN



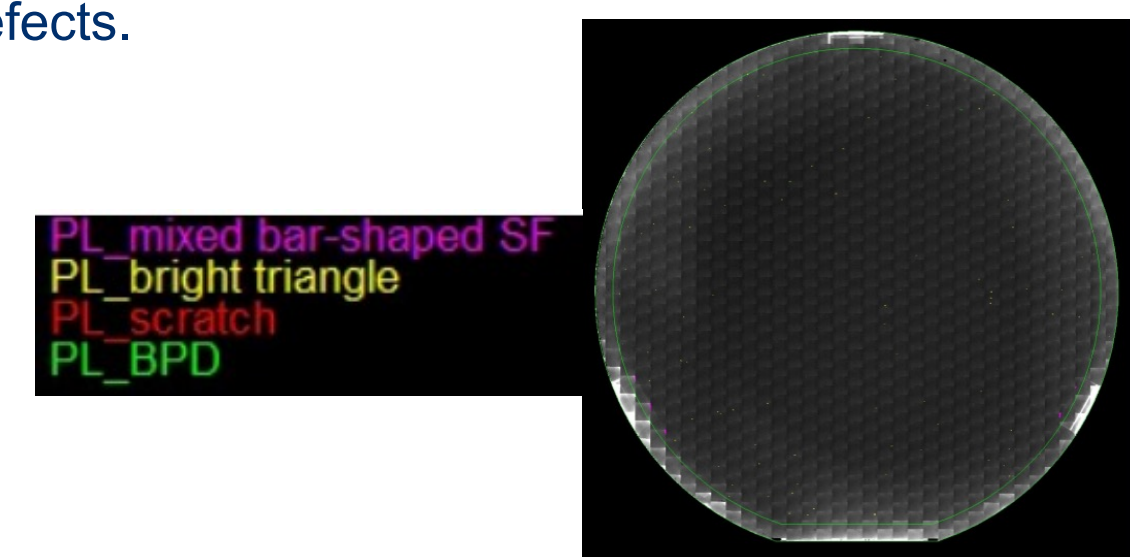


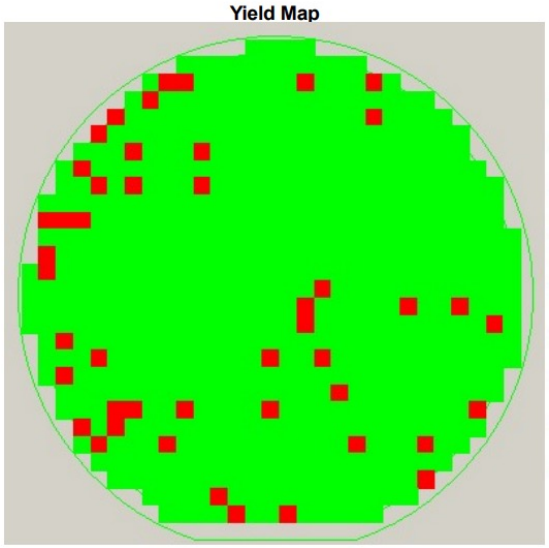
CZECH METROLOGY INSTITUTE leti ceatech

Nano-scale | Wafer-scale | Advanced sampling

Wafer-scale Defect Inspection

- Optical methods are best suited to high-throughput, in-line wafer metrology.
- State of the art tools for WBG epi-wafers use light/dark field scattering, PL, DIC to detect and classify defects.



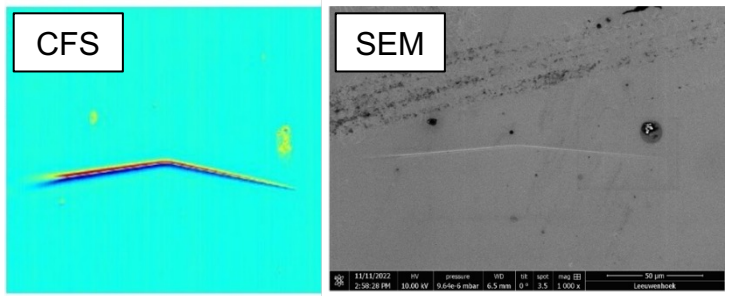


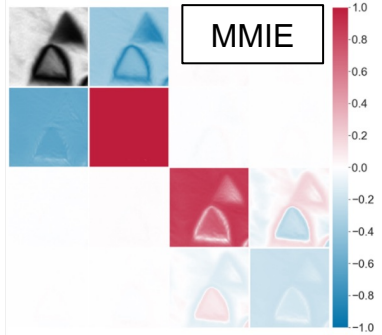
- Not all defects are device killers so accurate classification is required.
- Multi-channel Machine Learning enabled classification is used but there is no method to quantify confidence

Wafer-scale Defect Inspection

- Challenge for instrumentation is to achieve BOTH improved sensitivity and throughput.
- Coherent Fourier Scatterometry is a fast and sensitive beam-based technique, with sensitivity to the optical properties, size and shape of defects, but requires modelling to analyse quantitatively. Multiple beams enables parallelised measurement (× 9 demonstrated).

TU Delft



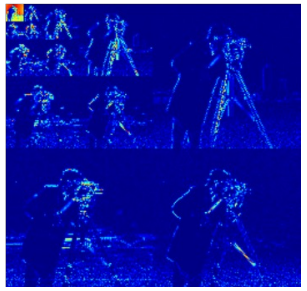


BAM

PTB

- Mueller Matrix Ellipsometry is also very sensitive to defects via optical properties and can be parallelised with an imaging detector.
- Parallelised measurements are still bandwidth limited so cannot escape the trade-off between throughput and sensitivity.

Compressed Sensing

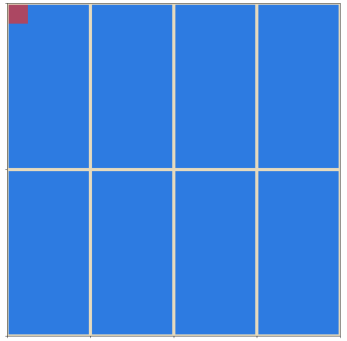


- “Data compression applied during acquisition”
- Measurement is under-sampled and reconstructed:

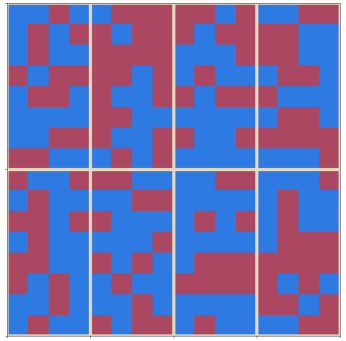
  i.e. Measuring N signal elements with M observations, where M<N.

- Benefits of compressed sensing:
  - Fewer measurements so faster than point-by-point sampling
  - Multiple simultaneous points results in improved signal-to-noise ratio and dynamic range benefit
  - Compression is optimal for sparse signals e.g. localised defects.

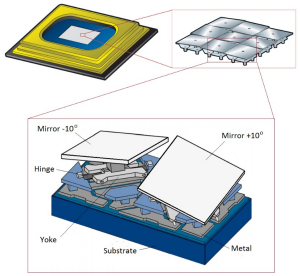
Raster

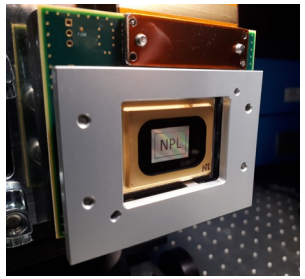


(Pseudo) Random Patterns



Digital Micromirror Device for structured illumination





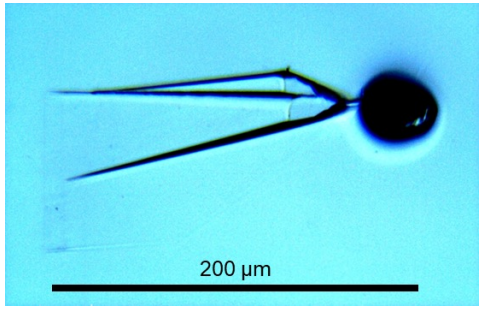
E.J. Candes and T. Tao, IEEE Trans. Inf. Theory, 52, 5406–5425 (2006)
D. Donoho, IEEE Trans. Inf. Theory, 52, 1289–1306 (2006)

Compressed Sensing for PL of SiC

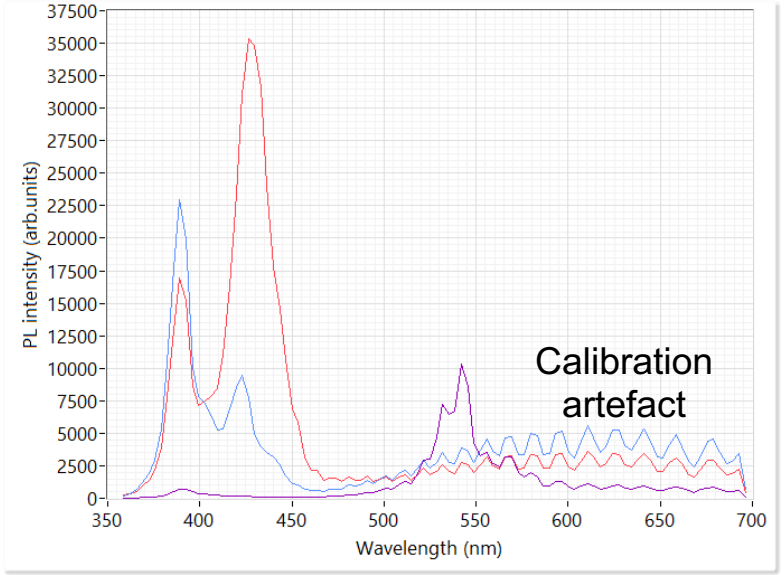
- Photoluminescence spectroscopy of SiC can identify polytypes:

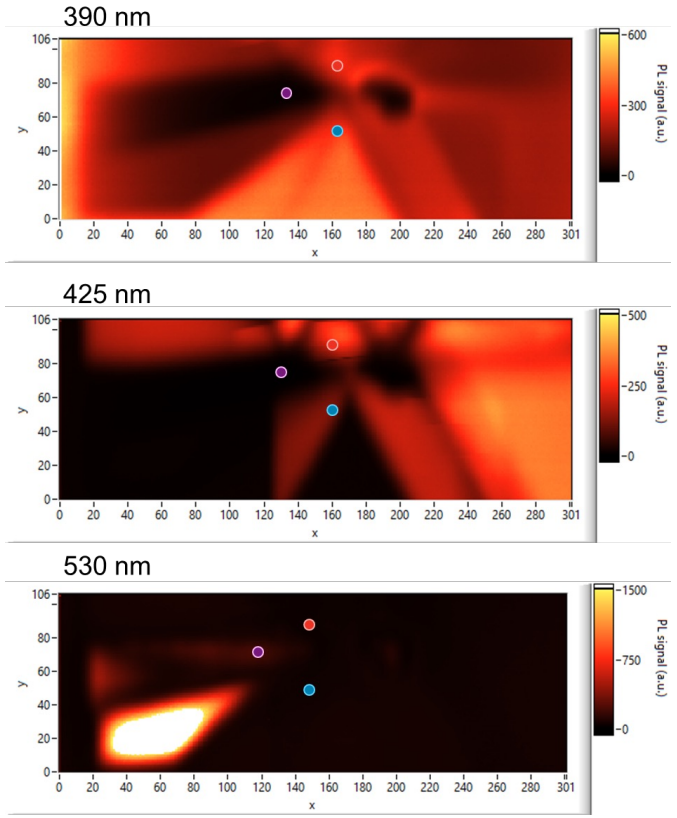
  4H-SiC (3.23 eV bandgap), 6H-SiC (3.05 eV bandgap), 3C-SiC (2.36 eV bandgap)

- Feasibility testing of compressed sensing PL through simulation



Confocal PL map of polytype inclusion

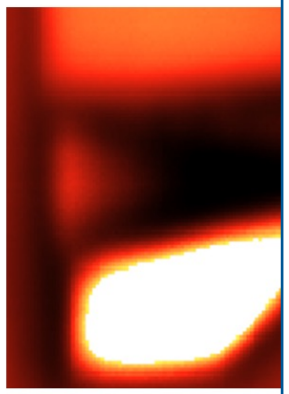


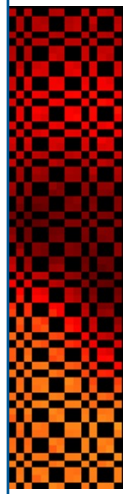


IEC 63068-4 Semiconductor devices - Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices - Part 4

Compressed Sensing for PL of SiC

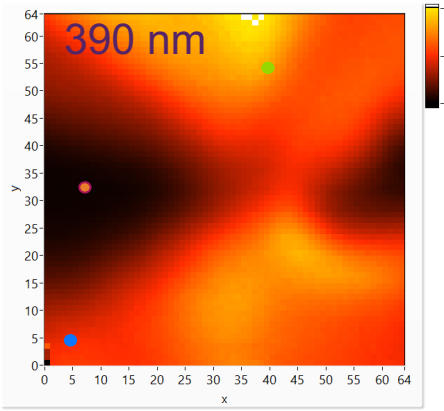
- Simulate com… …tern series) and ev…

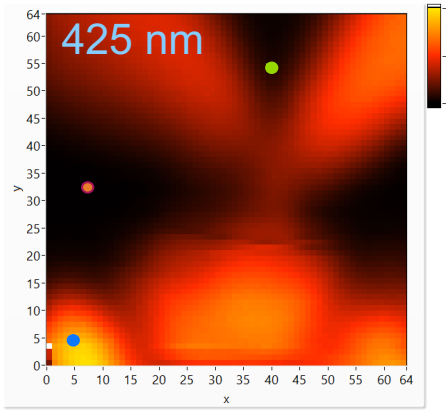


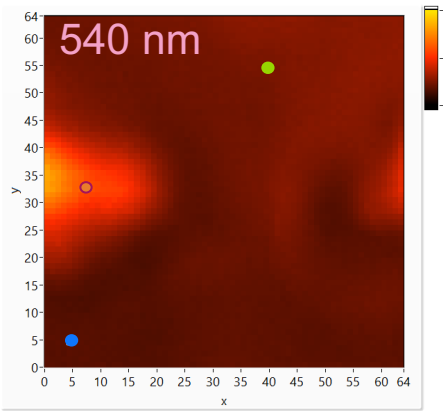


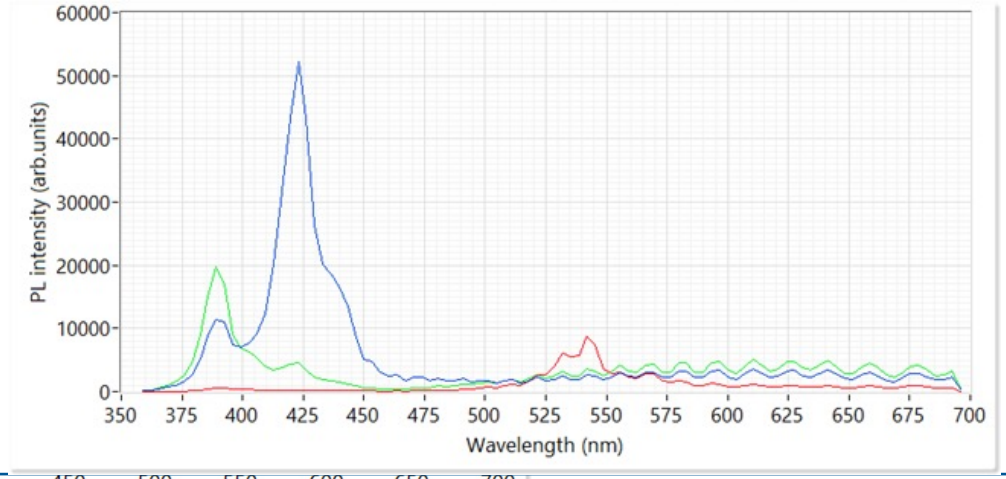
…nematical …map for each …ngth

Reconstructed spectral maps





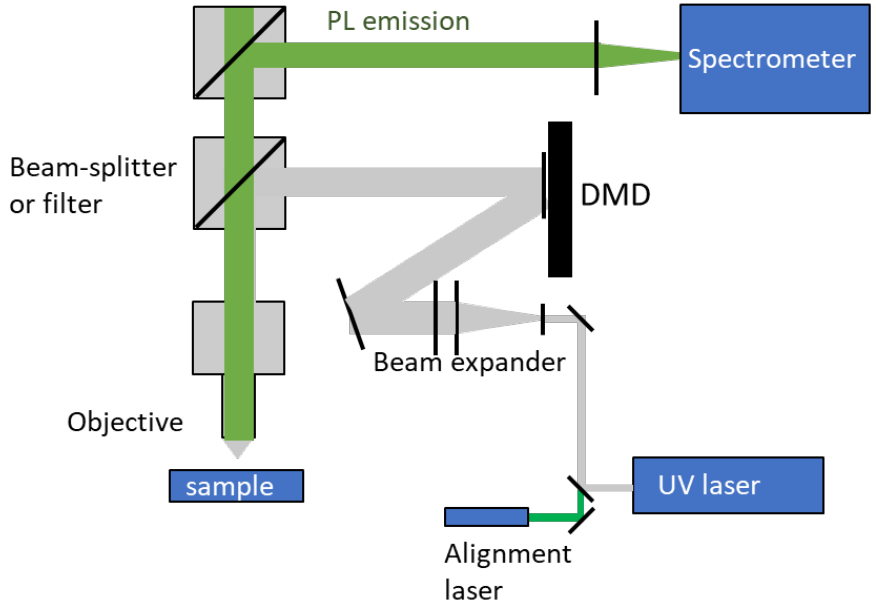


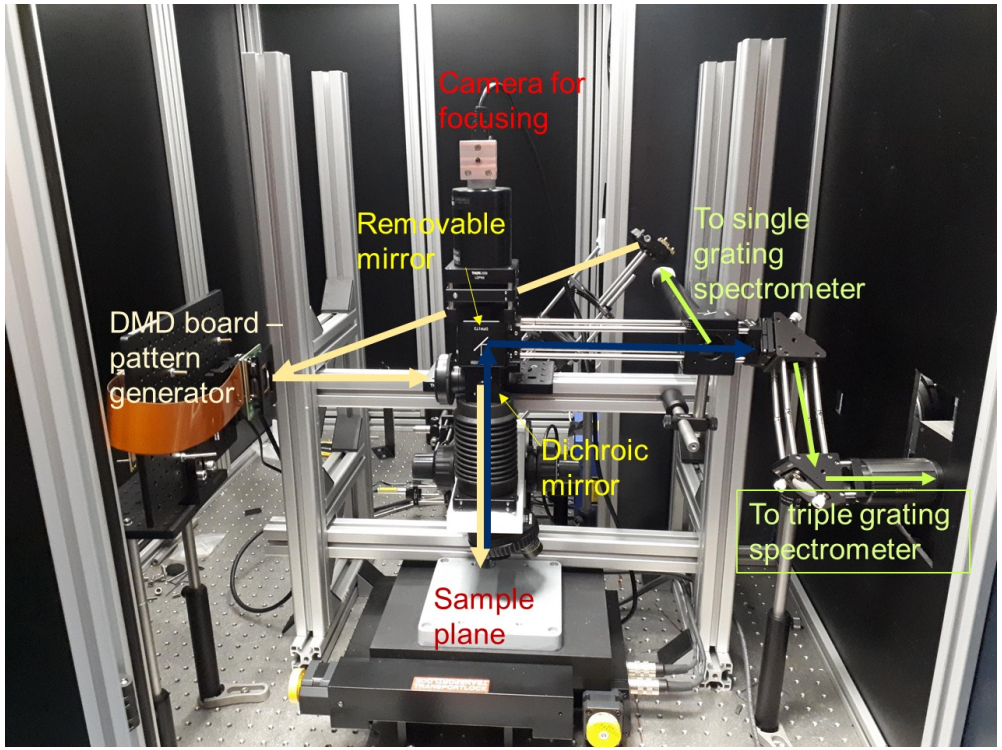


Compressed Sensing for PL of SiC

- Measu
  - Ac
  - Ca

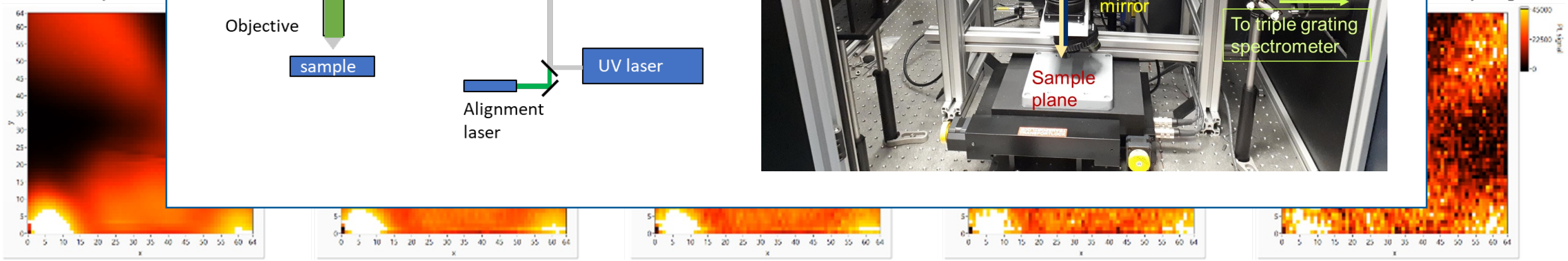
Prototype instrument under development for experimental test of spatial compressed sensing for PL spectral mapping





Sampled P

sampling



Nano-scale | Wafer-scale | Advanced sampling

Conclusions

The PowerElec Project is tackling metrological challenges for epiwafer material quality presented by SiC, GaN, and Ga_2O_3.

- **Increasing sensitivity**

Some defects currently lack suitable measurement solutions (e.g. nanoscale defects, buried features).

→ Near-field spectroscopy, CL, KPFM (including combined modes) can distinguish sub-surface defects and probe local charge carrier dynamics.

- **Increasing throughput**

Requirement for high-throughput, high-sensitivity metrology for defect identification and quality assurance.

→ Novel parallelised optical measurements, and compressed sensing offer potential solutions.

- **Increasing confidence**

Quantification of measurements using novel metrology methods and uncertainty analysis.

Contributions to standardisation for WBG measurements is underway but a lot still to be done.

Acknowledgements

National Metrology Institutes:

BAM

Bundesamt für Eich- und Vermessungswesen

CZECH METROLOGY INSTITUTE

NPL National Physical Laboratory

PTB

TÜBİTAK

Universities:

TU Delft

TU WIEN

Research Institutes:

ikz

leti ceatech

Department for Science, Innovation & Technology

Industry:

AIXTRON

Compound Semiconductor Centre

Infineon

EMPIR

EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States