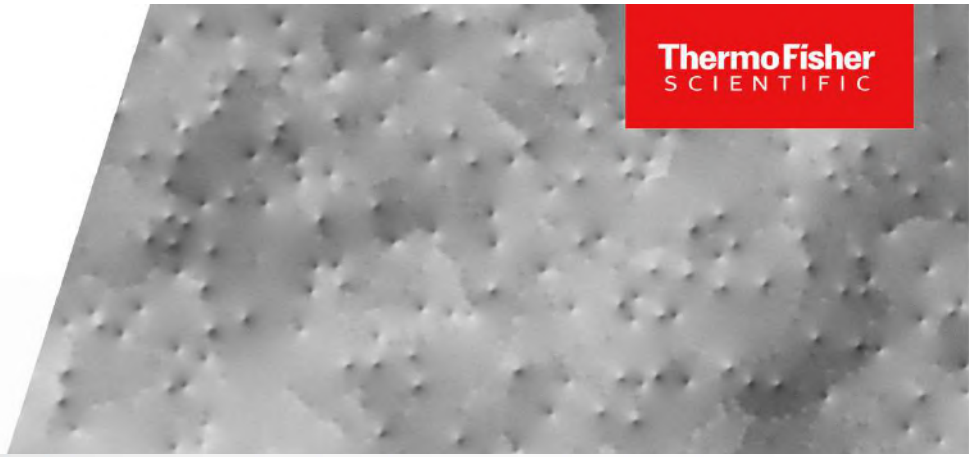
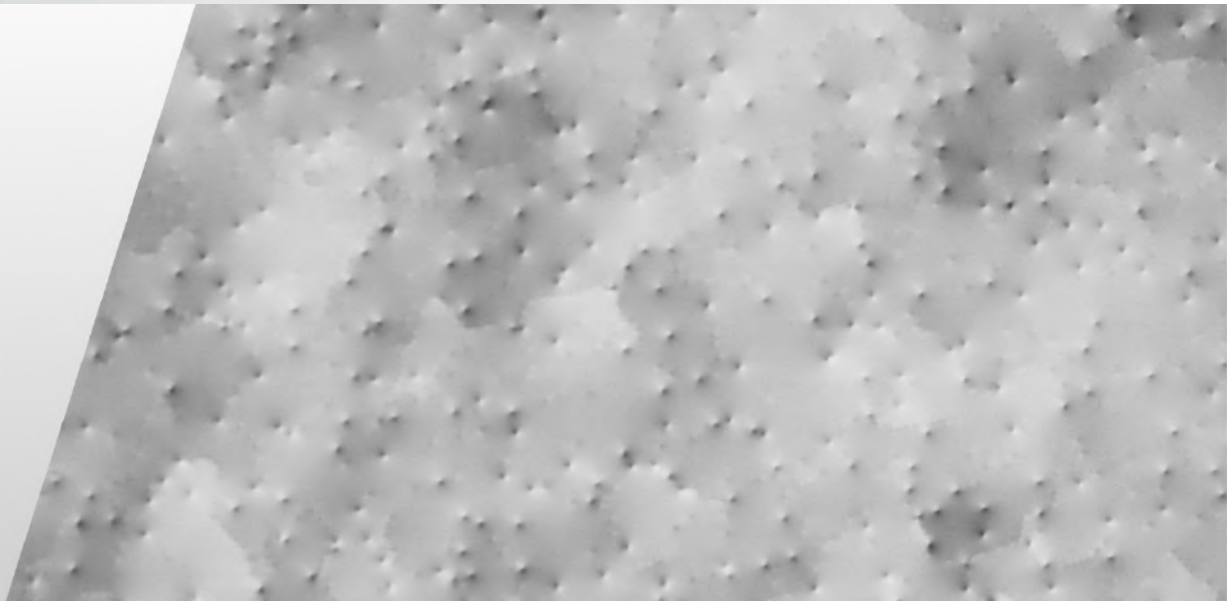


Non-destructive Characterization of Crystalline Defects using Diffraction Techniques in Scanning Electron Microscopes



Martin Čalkovský, Applications Scientist
martin.calkovsky@thermofisher.com

Introduction

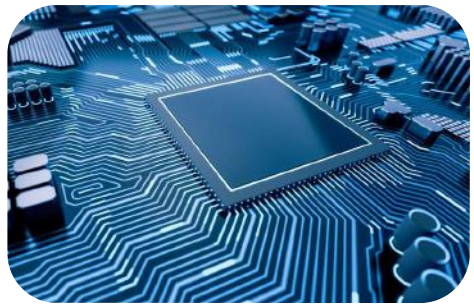
Significance of defects in III-V materials

Semiconductor Technology Trends

More Moore:
"Miniaturization"
(Processing)

More than Moore: "Diversification"
(covers interactions with environment and people)

Power / RF / Analog / Photonics



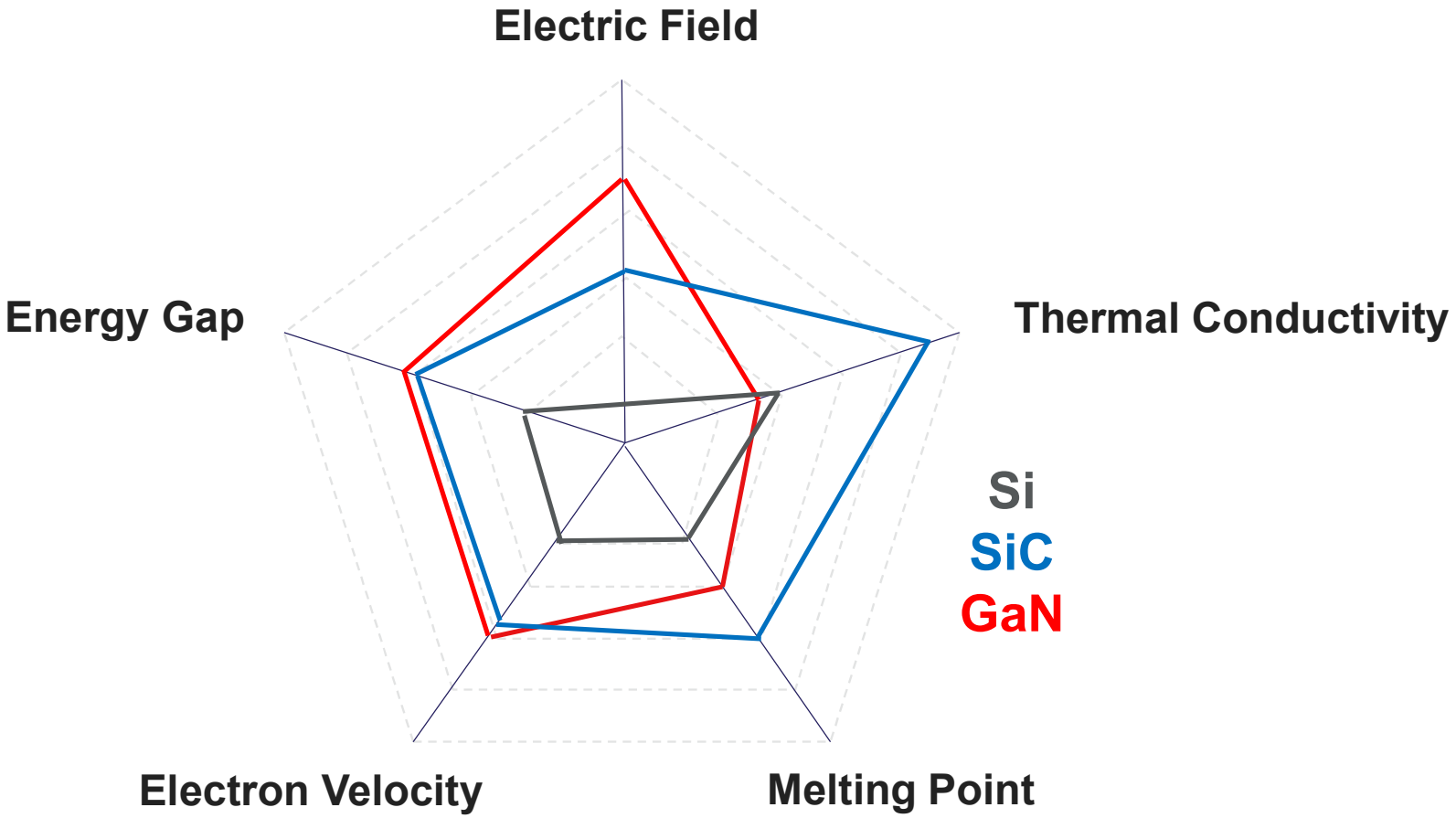
Depends on the implementing non-digital functionalities onto microelectronic systems

"**More than Moore**" technology requirements:

- **Power efficiency**
- **Operating frequency**
- **Rigorous environment**

All present challenges for traditional Si-based technology

Superior Properties of Compound Semiconductors



Larger Temperature Range

Higher Power Efficiency

Faster

Lower Latency

Higher Voltage

Superior physical properties open the door to more application scenarios

Bieniek *et. al.*, Nanotech 2019

Initiative ALL2GaN for GaN development

What is it?

- Industrial and academic collaboration across 12 EU countries
- Aim to achieve viable GaN-based devices for more sustainable applications

How are we helping?

- Thermo Fisher provides microscopy expertise for GaN defect analysis and metrology

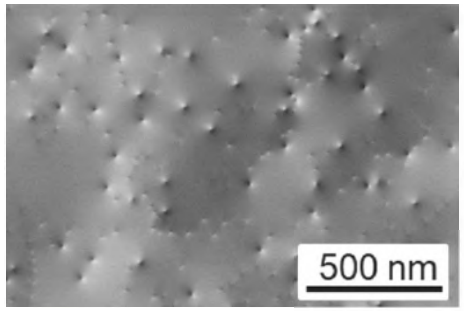
What is the problem to be solved?

- Crystalline defects inherent in GaN substrates impact device yield and reliability

Funded by the EU

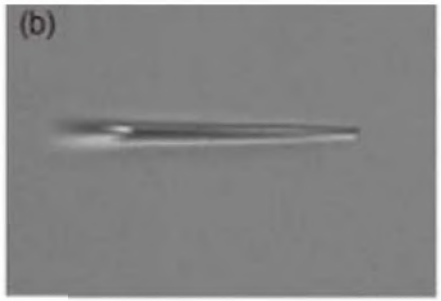
The ALL2GaN Project (Grant Agreement No. 101111890) is supported by the Chips Joint Undertaking and its members including the top-up funding by Austria, Belgium, Czech Republic, Denmark, Germany, Greece, Netherlands, Norway, Slovakia, Spain, Sweden and Switzerland. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, Chips JU or the national granting authorities. Neither the European Union nor the granting authorities can be held responsible for them.

Crystalline Defects at Epitaxial Surface

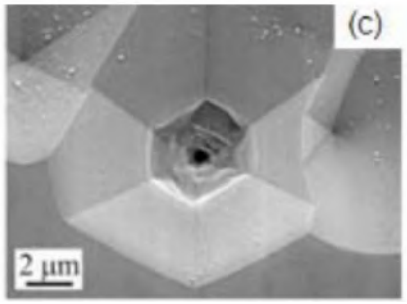


Threading dislocation

Screw dislocation, Edge dislocation

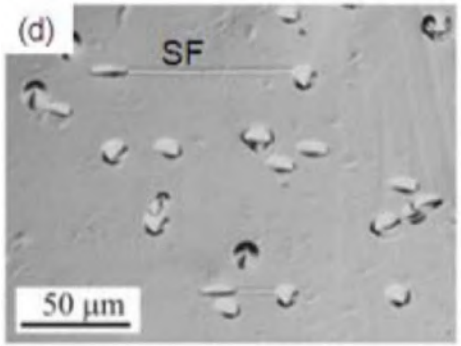


"Carrot" defect

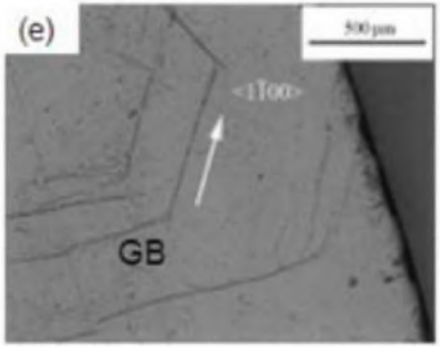


Micropipe

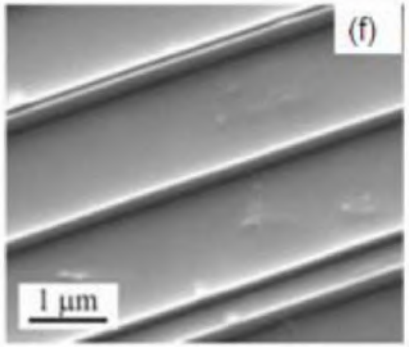
Device Leakage and Breakdown



Stacking fault



Grain boundary



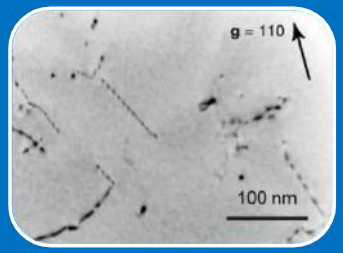
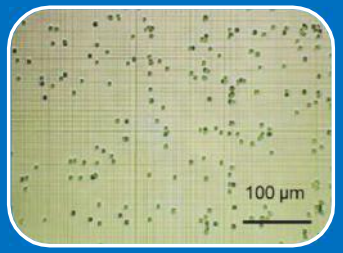
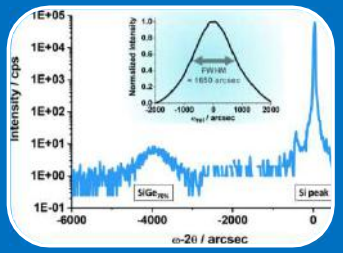
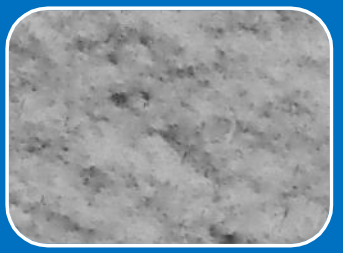
Stacking fault

Device Yield and Reliability

Reducing defects during epitaxial growth is key to improving device yield and reliability

https://www.researchgate.net/publication/253690045

Methodologies for Crystalline Defect Inspection

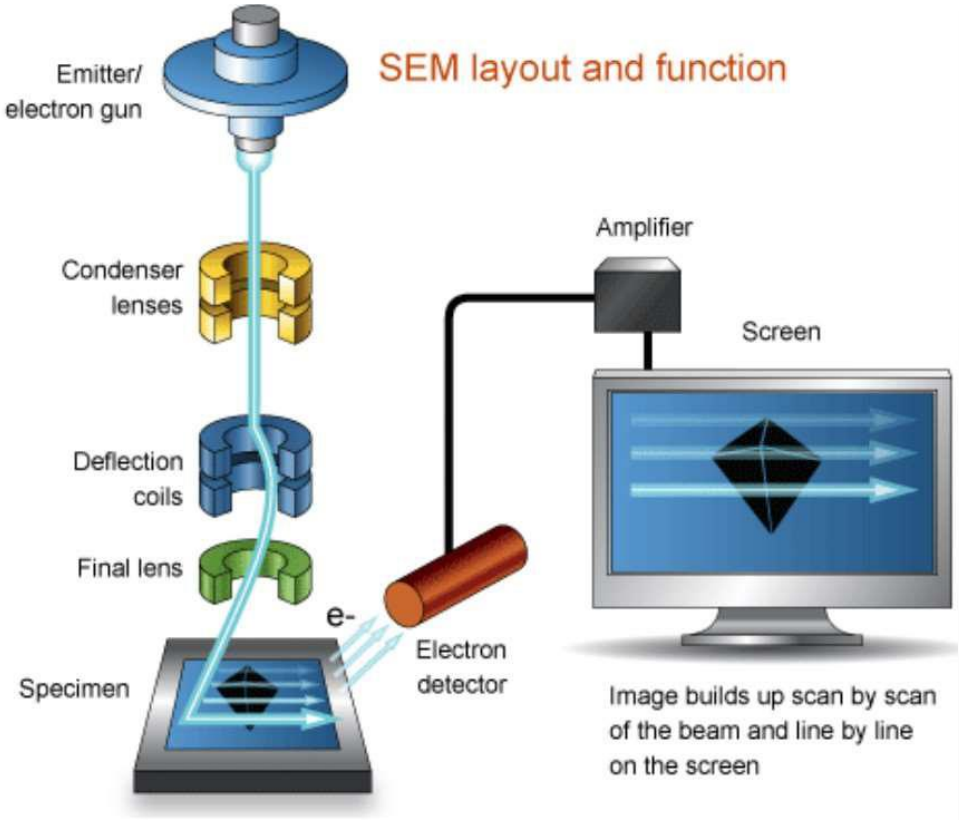
Techniques	TEM	Chemical Etching	XRD	ECCI
				
Sample Preparation	Destructive	Destructive	Non-Destructive	Non-Destructive
Detection Limit [cm^{-2}]	$>10^{7\sim8}$	$10^{4\sim7}$	$>10^{7}$	$>10^{6}$
Accuracy	Very High	Low	Low	High
Throughput	Low	High	High	Reasonable
Defect Visualization	Yes	Yes	No	Yes

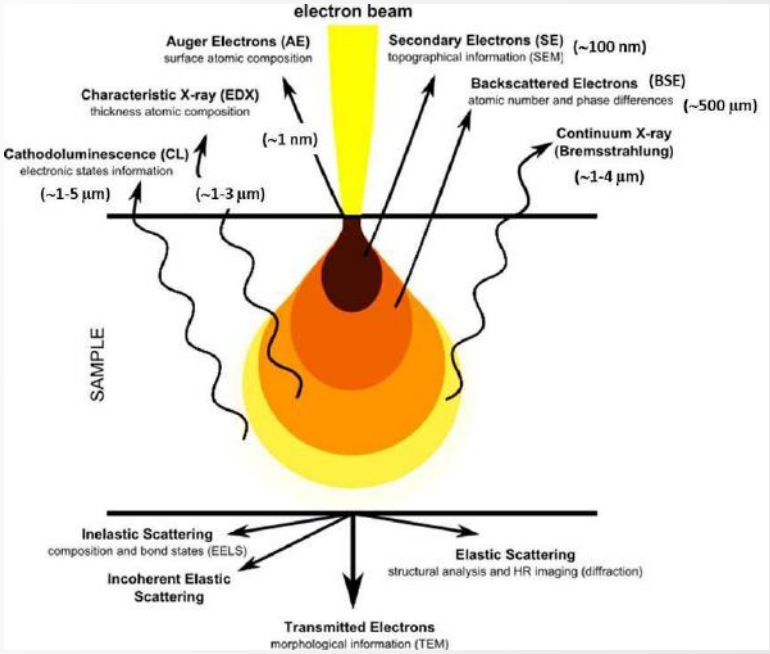
ECCI is the optimal method for crystalline defect inspection with a great balance of benefits

The Method

Electron channeling contrast imaging (ECCI)

Scanning Electron Microscope (SEM)



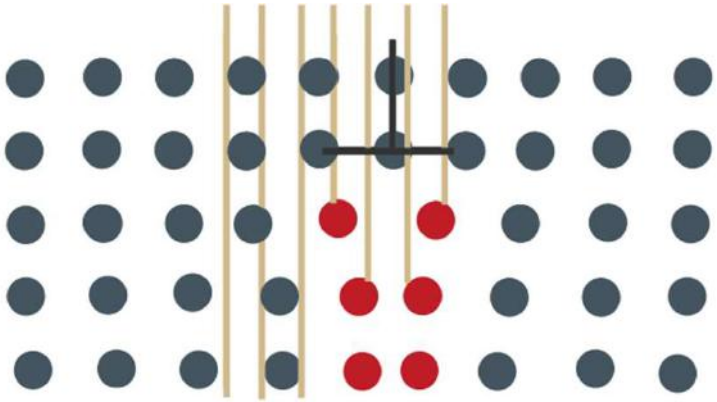


Source: https://myscope.training/

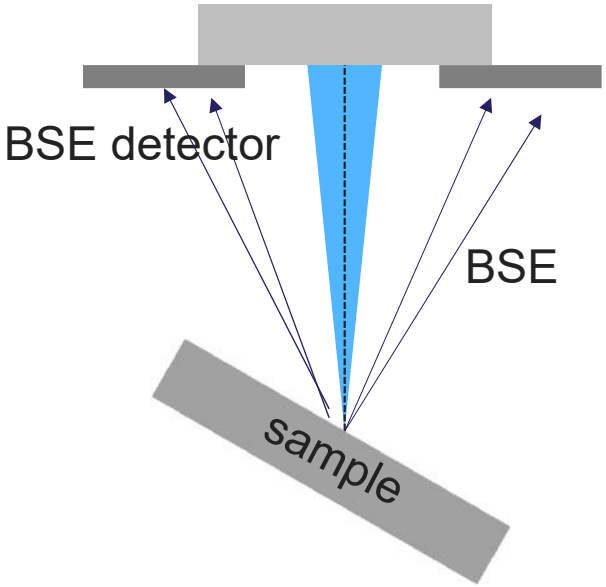
Channeling contrast in SEM

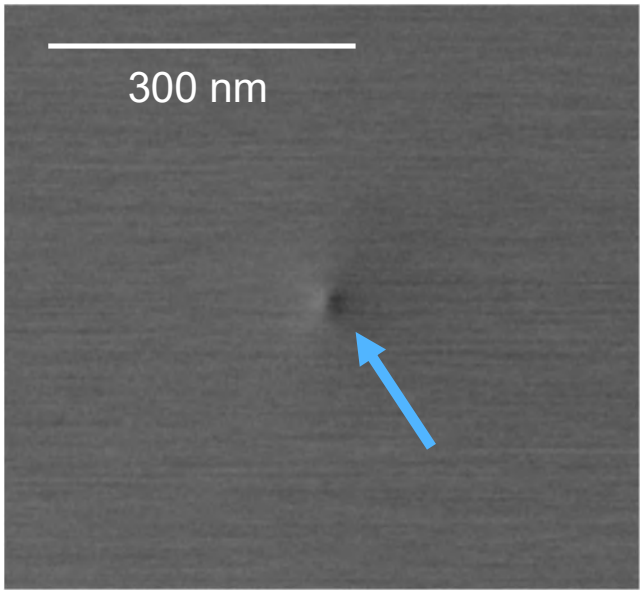
- **Backscattered electron (BSE) signal acquired**
- **Allows crystal lattice defect visualization**

Backscattering from defective area (close to Bragg angle)



Channeling in lattice

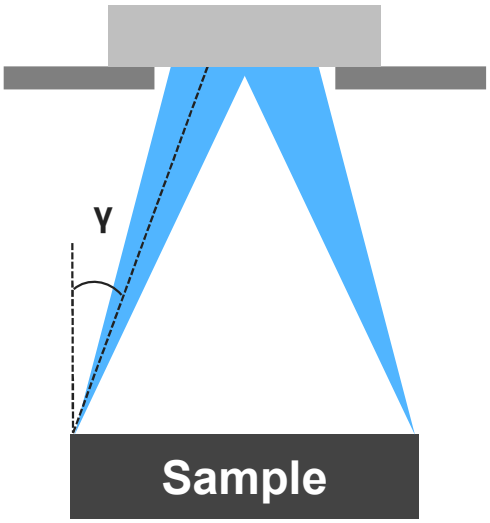




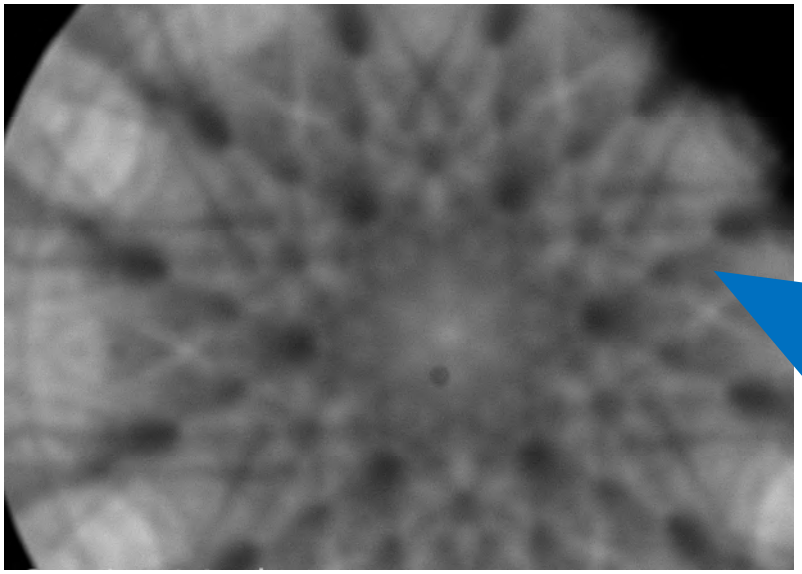
Electron Channeling Pattern (ECP) in SEM

ThermoFisher SCIENTIFIC

Low mag scanning single crystals



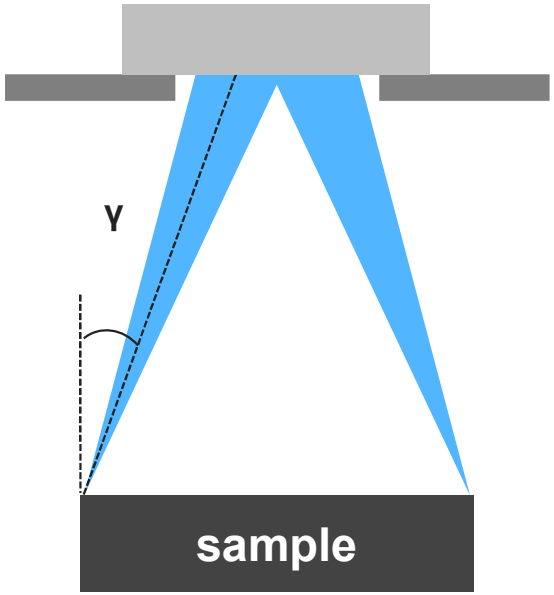
GaN [0001] Large area scan



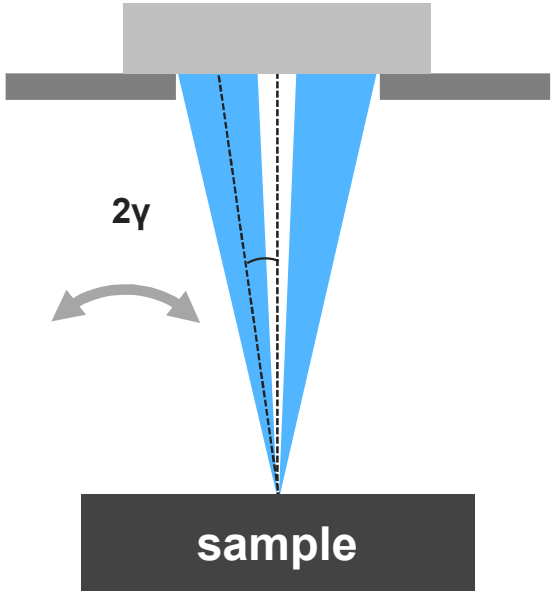
- ✓ Max field width
- ✓ Immersion mode
- ✓ 15 keV energy
- ✓ 5 mm distance
- ✓ 0 mm focus

More options for ECP in SEM

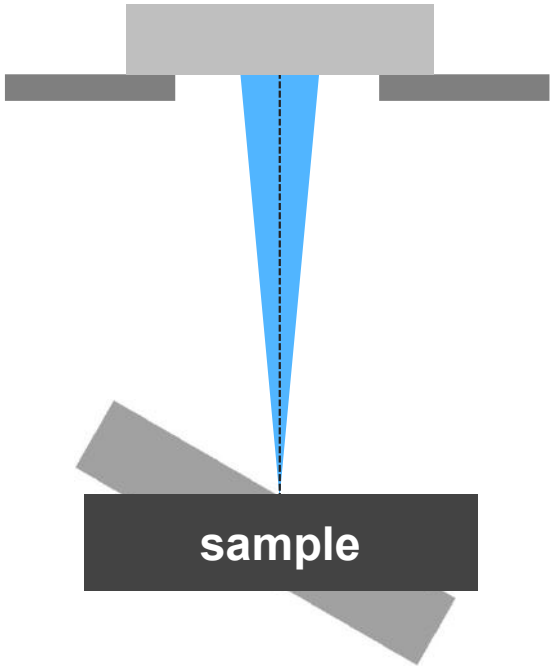
Low mag scanning:
single crystals



Beam rocking:
polycrystalline

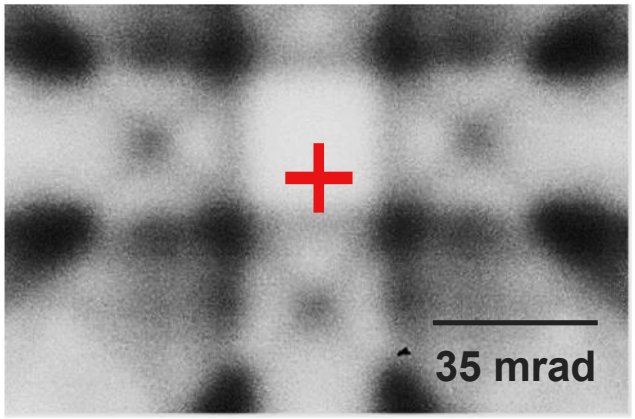


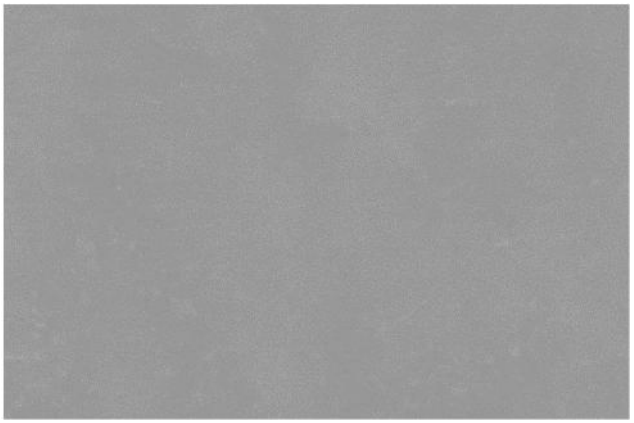
Stage (double) **tilt**



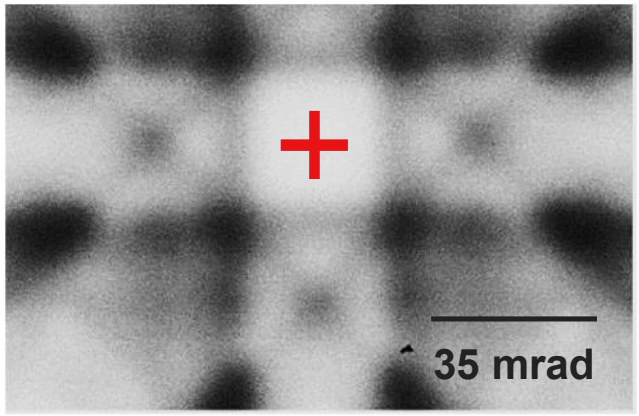
Channeling contrast in SEM

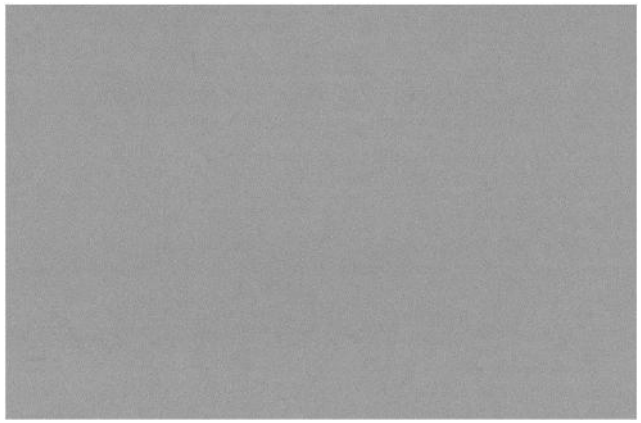
Out of Bragg



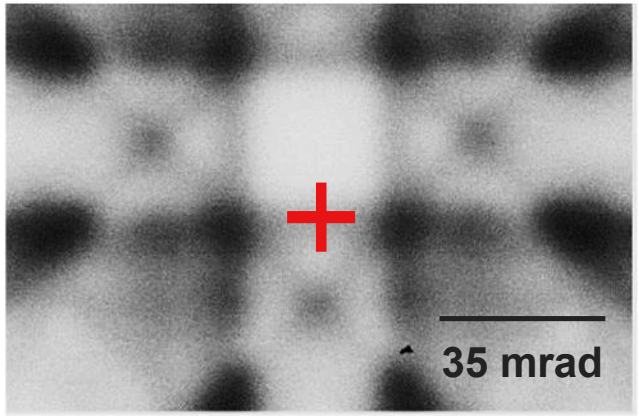


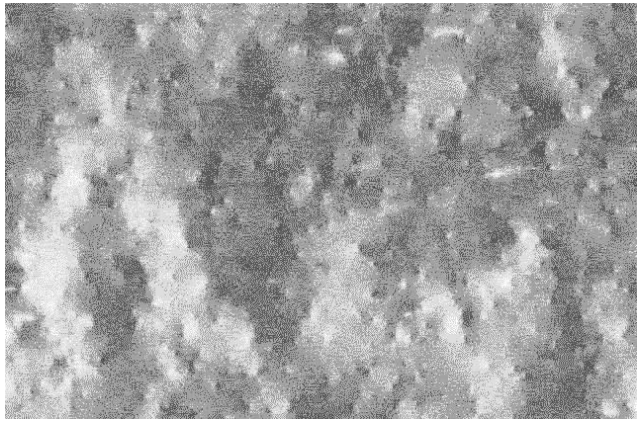
Out of Bragg (Zone axis)





Close to Bragg

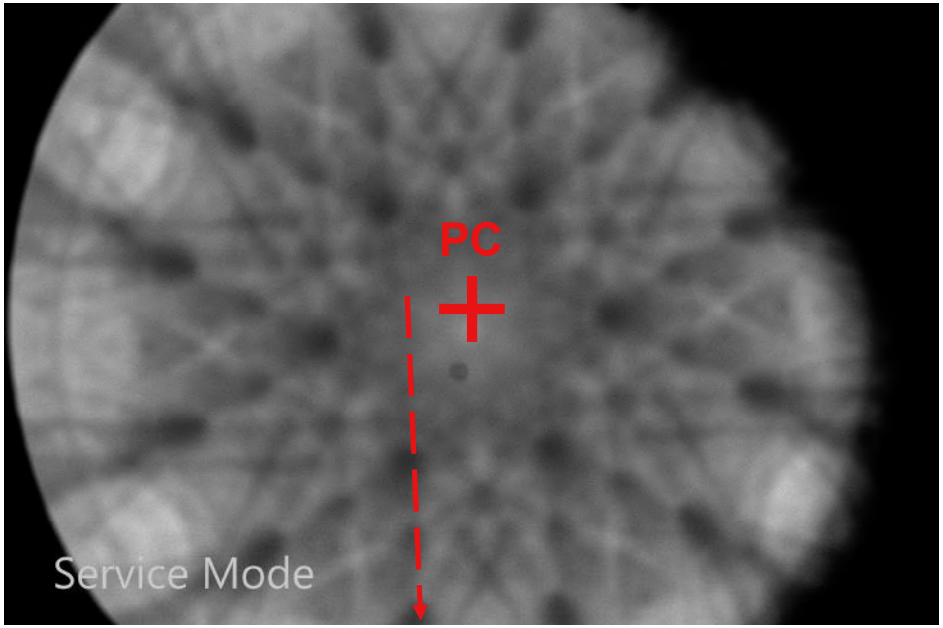




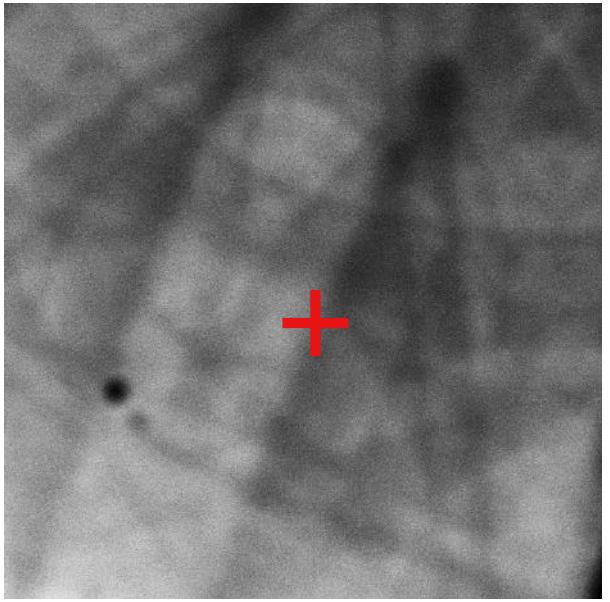
SiGe blanket layer with high dislocation density, HFW 3.45 um

Sample orientation – 2-beam diffraction condition

- ECP on BSE detector at low magnification
- Set diffraction condition with sample rotation & tilt

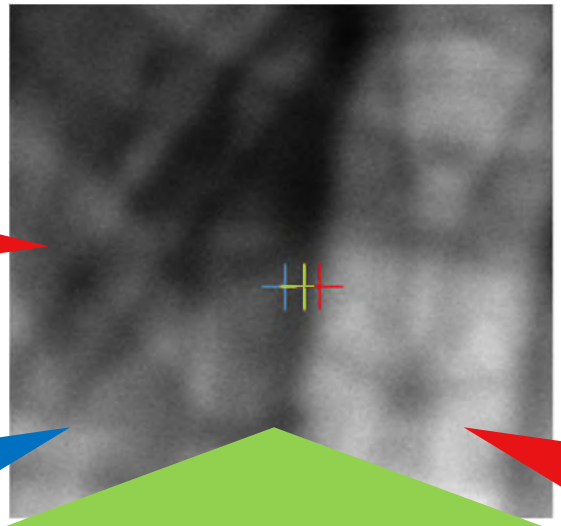


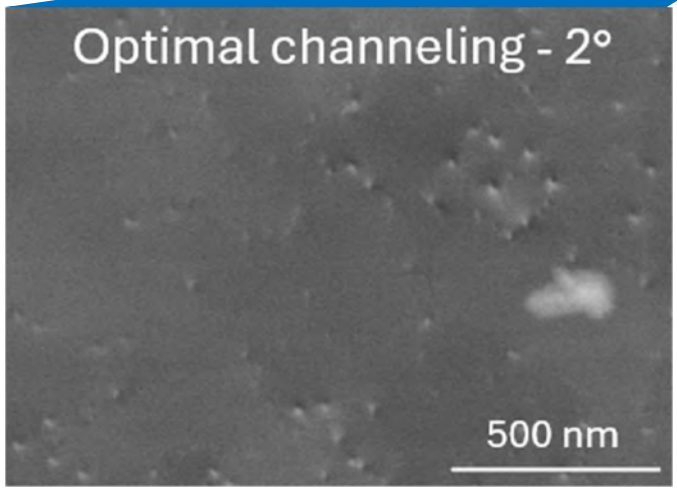
Sample Rotation & Tilt

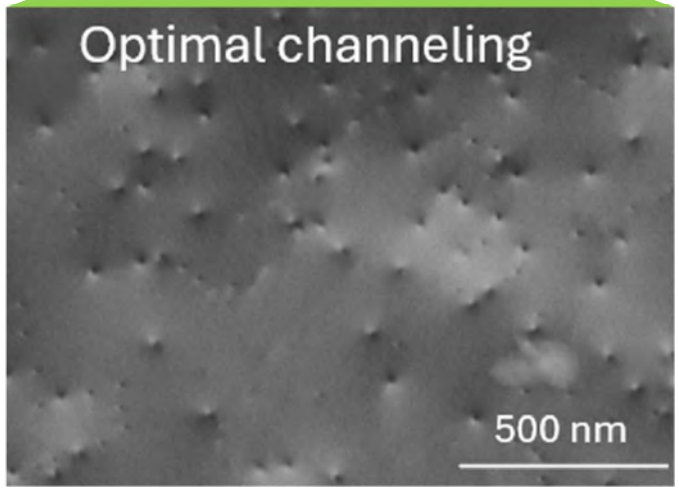


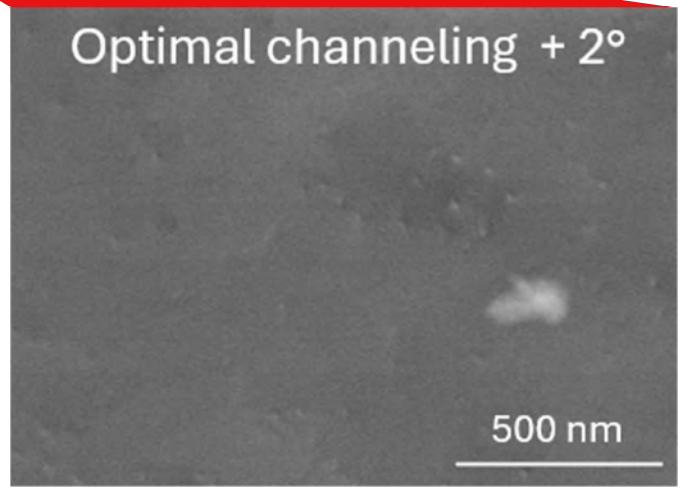
Importance of sample orientation for ECCI

Sample orientation is key to good ECCI!





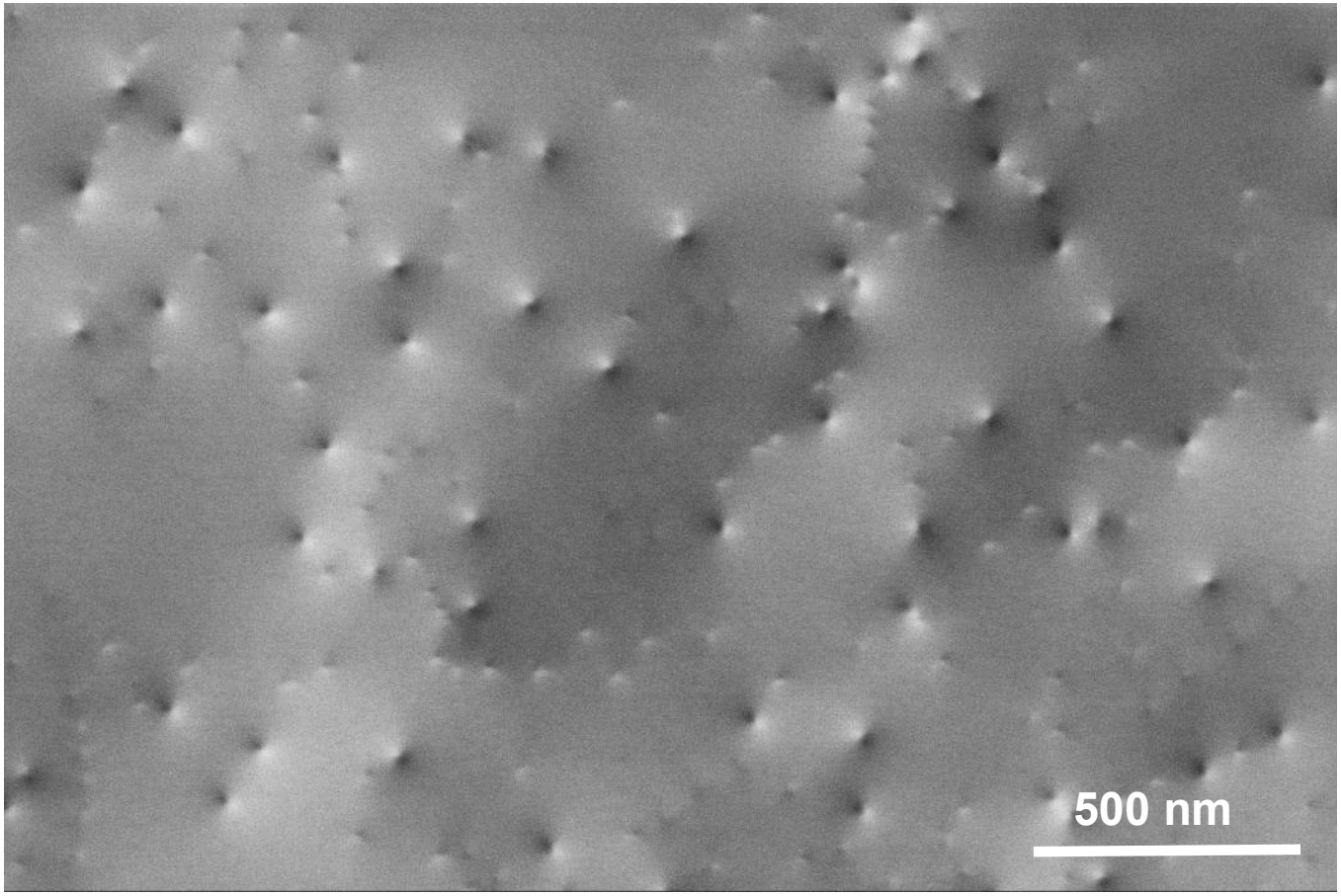




ECCI conditions in SEM

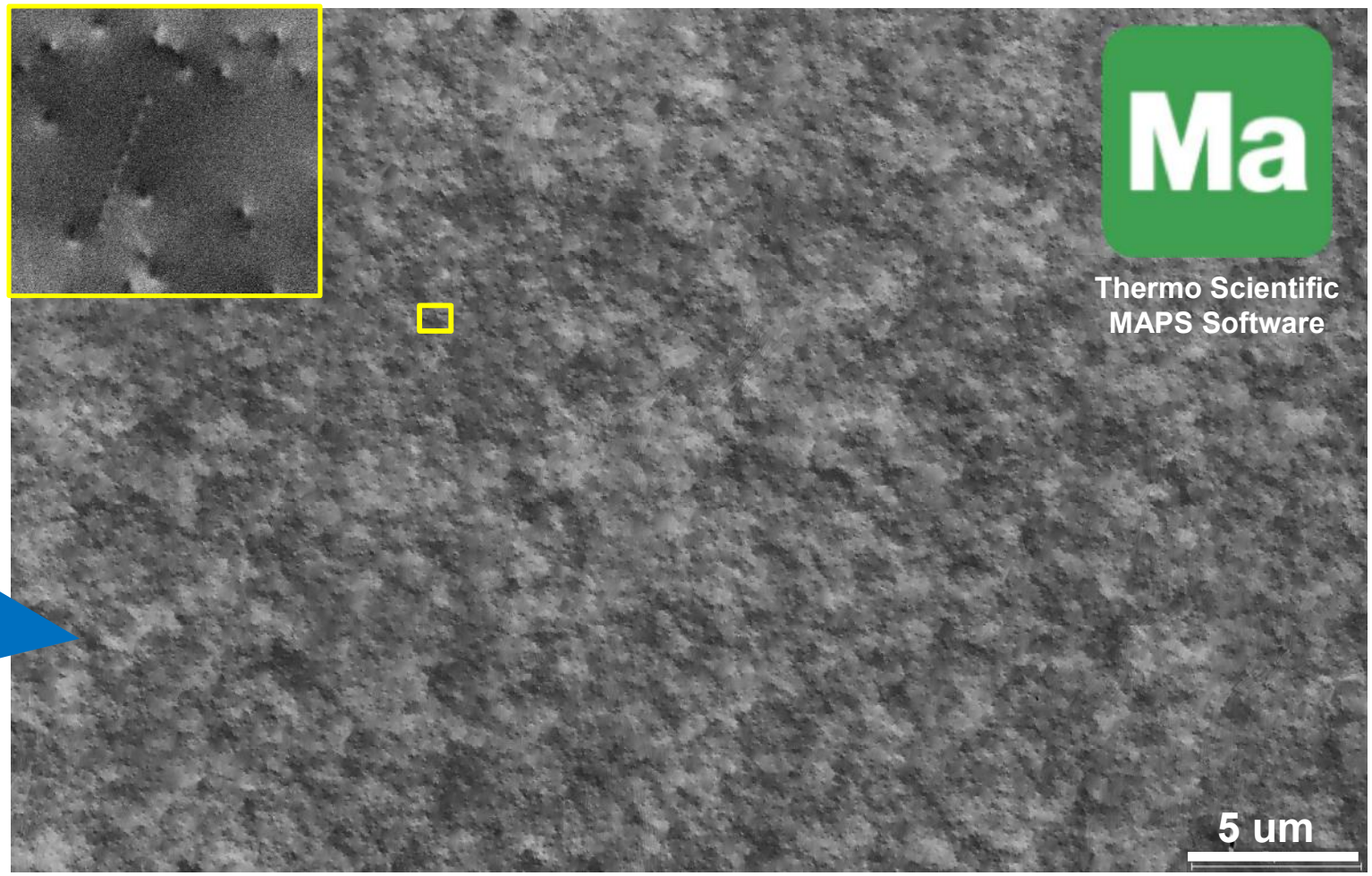
Requirements:

- ✓ Field Width: 3 – 10 um
- ✓ Energy: 5 – 25 keV
- ✓ Current: 0.5 – 15 nA
- ✓ Convergence: < 5 mrad
- ✓ Detection: BSE
- ✓ Frame time: 30 – 120 s

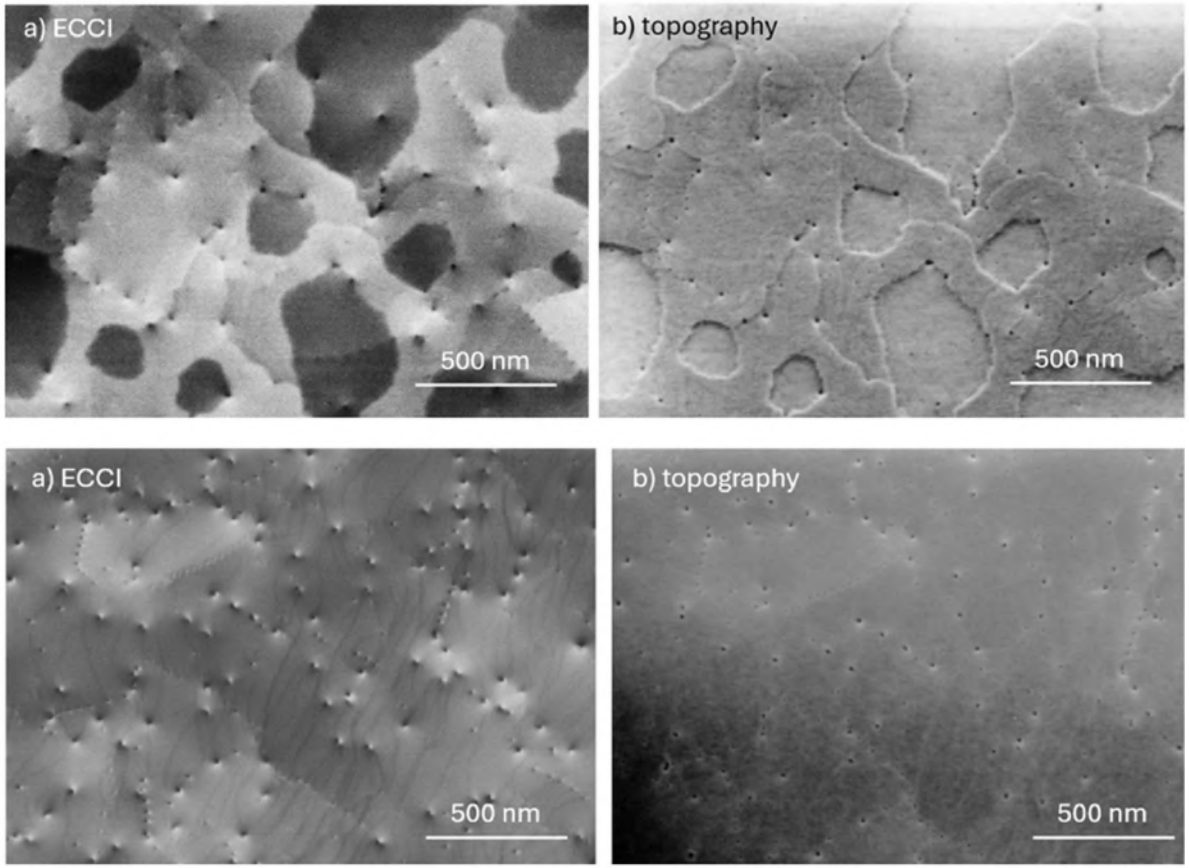


Defects on a larger scale

- ✓ Field Width: 40 um
- ✓ Immersion mode
- ✓ Energy: 15 keV
- ✓ Current: 1.6 nA
- ✓ Detection: T1, BSE
- ✓ 1 us dwell time
- ✓ Line integration: 8
- ✓ Pixel resolution: 40k x 30k



Sample surface dependence



- ECCI is influenced by surface quality
- Leads to contrast variations
- “Smooth” surface shows atomic steps

Challenge: Robust automatic detection of threading dislocations

The Workflow

Metrology and automation

Crystalline defect metrology workflow

Optional

Sample prep
- Sample cleaning
- ROI selection

Sample orientation
- Identify bands
- Define and setup diffraction condition 1

ECCI (1)
- Large ROI for defect quant

Sample orientation
Identify bands
Define and setup diffraction condition 2

ECCI (2)
- Acquire data from same region

Register image sets

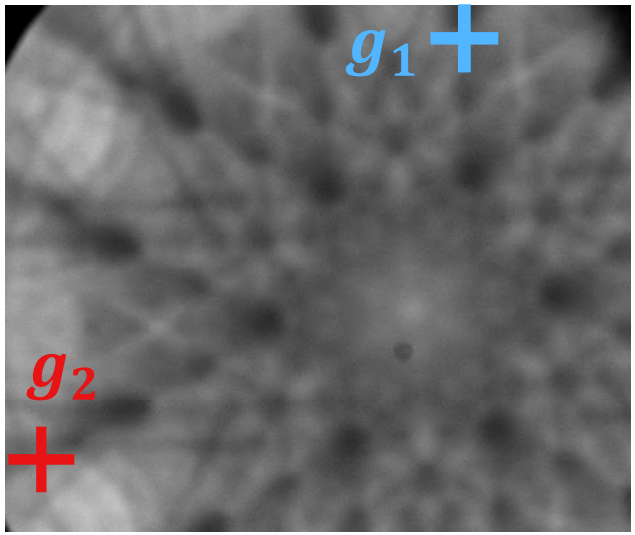
Quantification
- Image processing
- Count # of defects

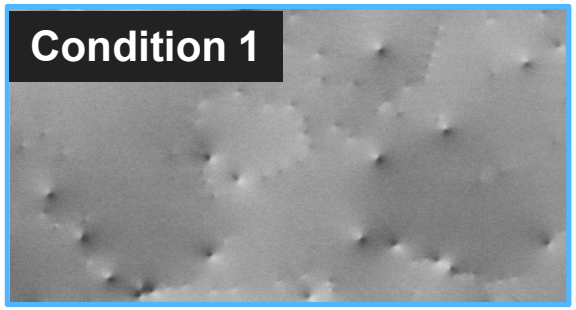
Classification
- Image processing
- Classify defects

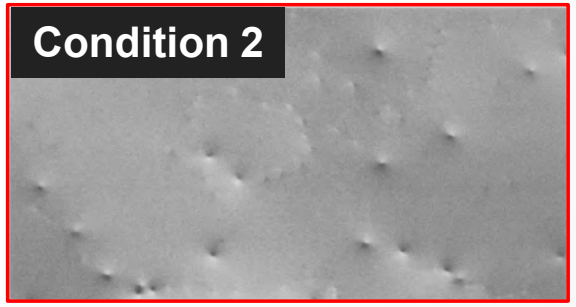
Results
- Defect density
- % killer defects

Defect classification

Images of the same region under two different diffraction conditions enables classification (edge, screw, mixed)





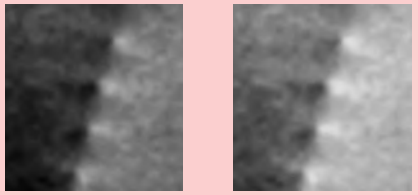


g_1 =(11-20) g_1 =(2-1-10)

c type TD
$\overrightarrow{b_c} = \langle 0001 \rangle$

B-W contrast is orthogonal to **g**

a type TD
$\overrightarrow{b_a} = \frac{1}{3}\langle 11\bar{2}0 \rangle$



B-W contrast is relative to **g**

a+c type TD
$\overrightarrow{b_{a+c}} = \overrightarrow{b_a} + \overrightarrow{b_c}$

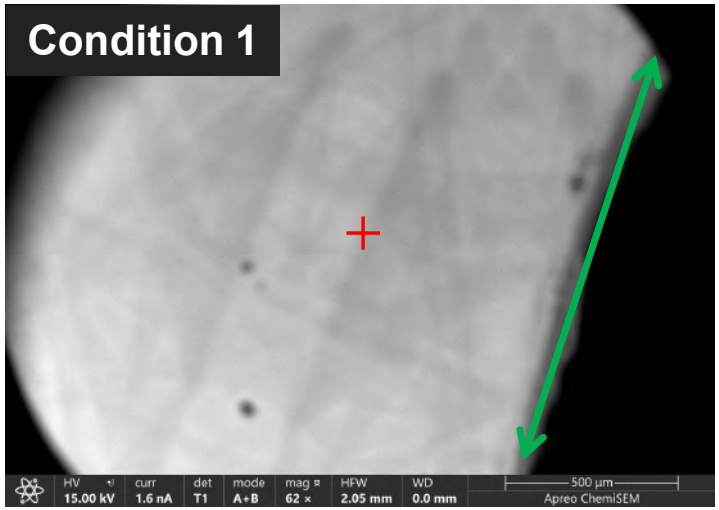
B-W contrast does not follow **g** or **b**

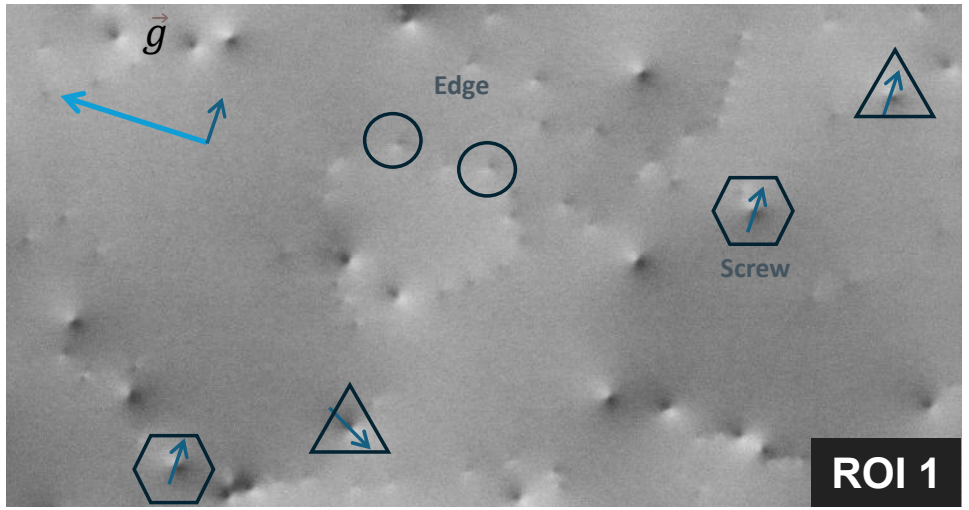
PRL 108, 135503 (2012) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2012

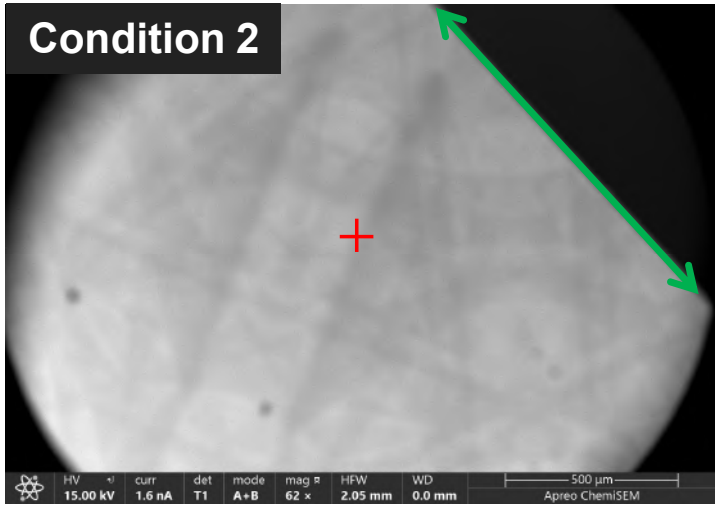
Rapid Nondestructive Analysis of Threading Dislocations in Wurtzite Materials Using the Scanning Electron Microscope

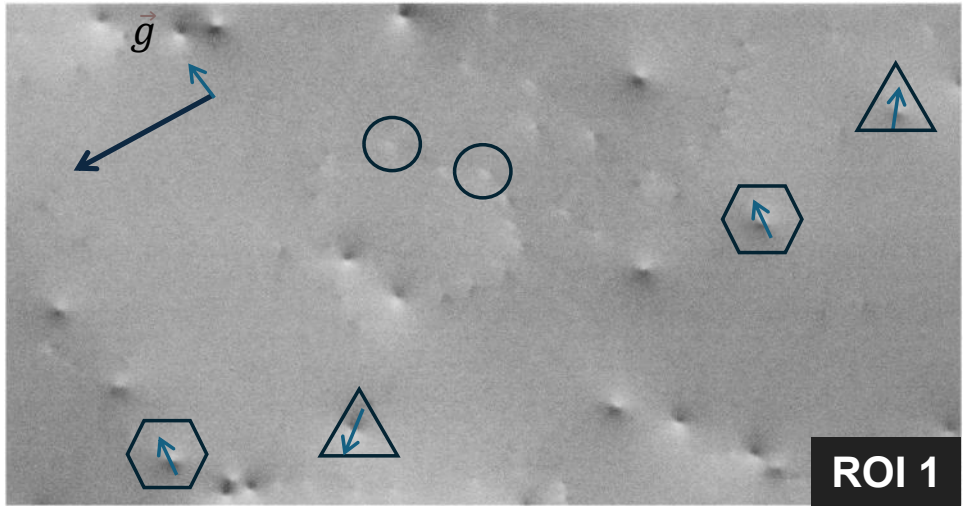
G. Naresh-Kumar,[1] B. Hourahine,[1] P. R. Edwards,[1] A. P. Day,[2] A. Winkelmann,[3] A. J. Wilkinson,[4] P. J. Parbrook,[5,*] G. England,[6] and C. Trager-Cowan[1,†]

Defect classification



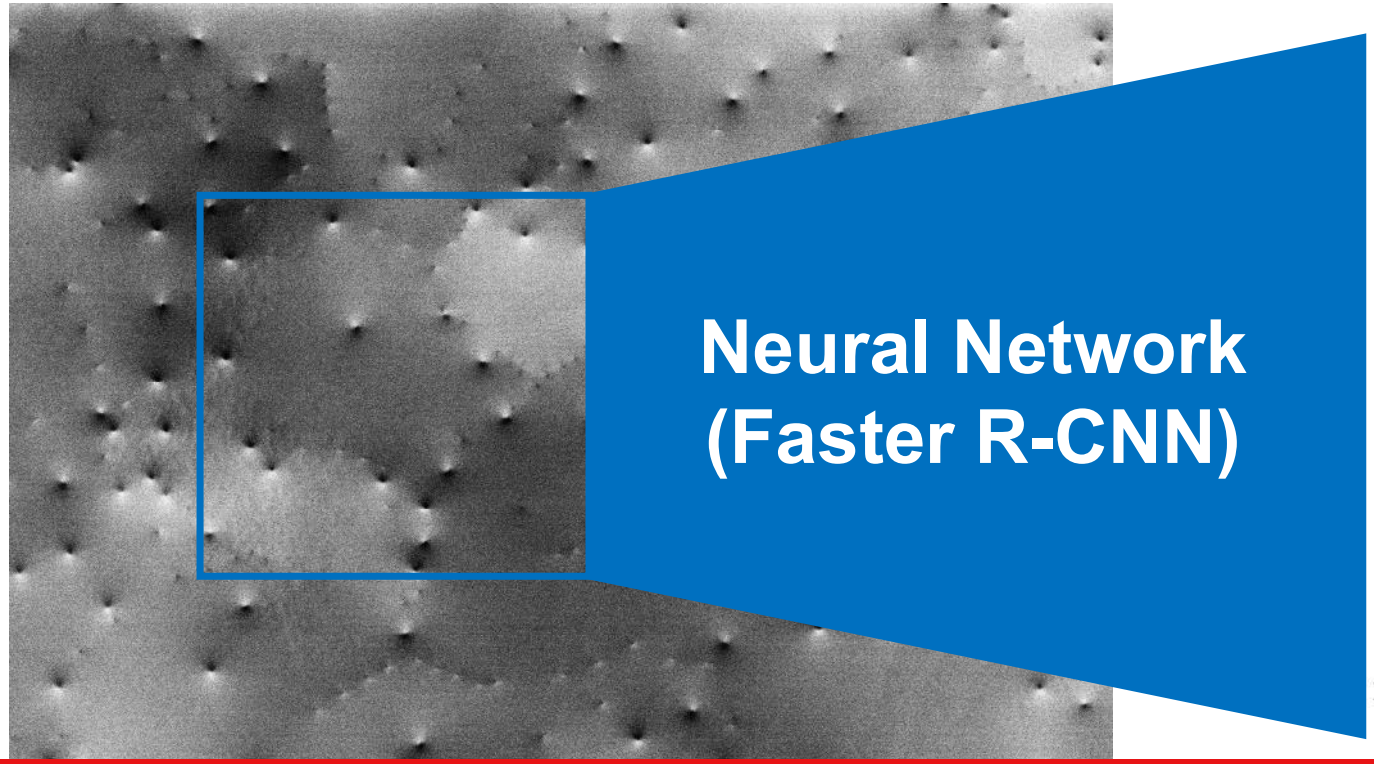


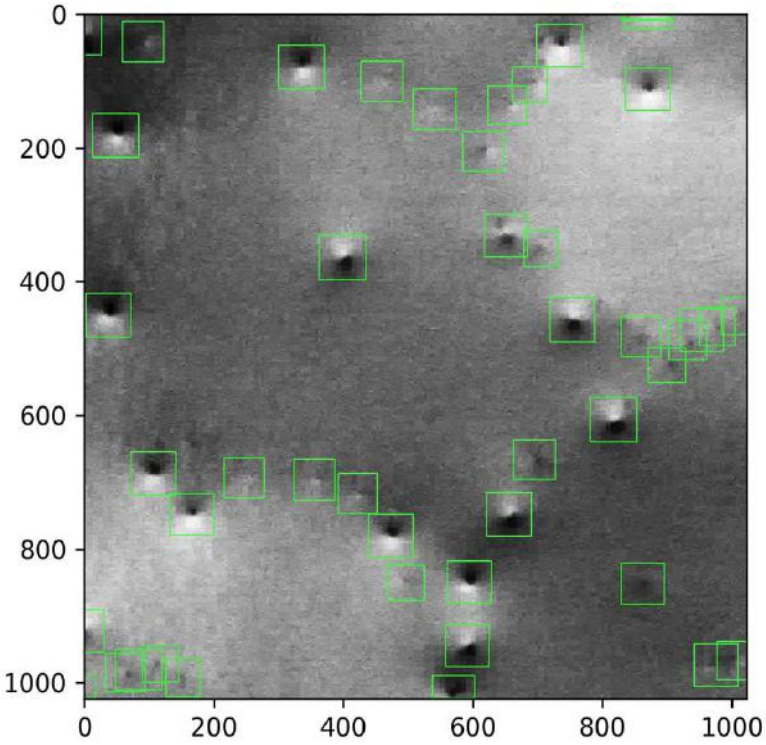




Defect detection using AI

1. Split image into smaller tiles **2.** Preprocess tiles (denoise) **3.** Find defects



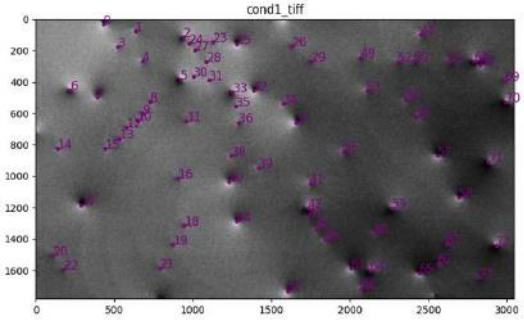


Defect density = # of defects / sample area

Automatic defect detection and classification

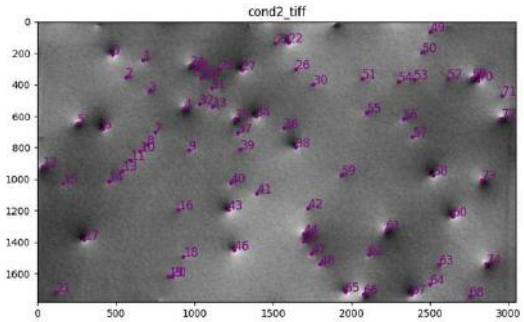
Input:

Images of condition 1&2



Background filtering,

Defect detection



Output:

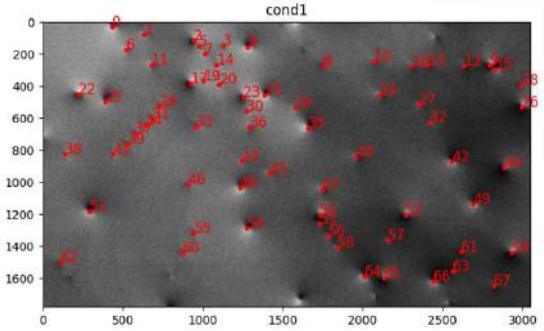
Coordinates of defects

In condition 1&2

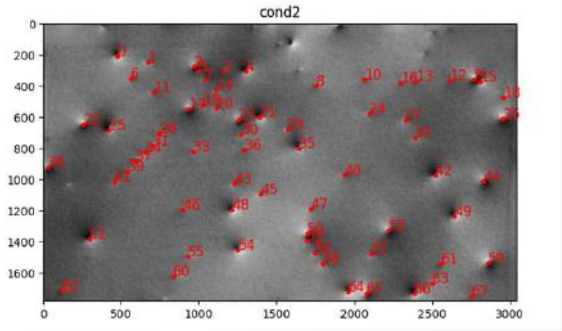
Input:

Images of condition 1&2

with defect coordinates



Cross correlation of defect position images and sorting



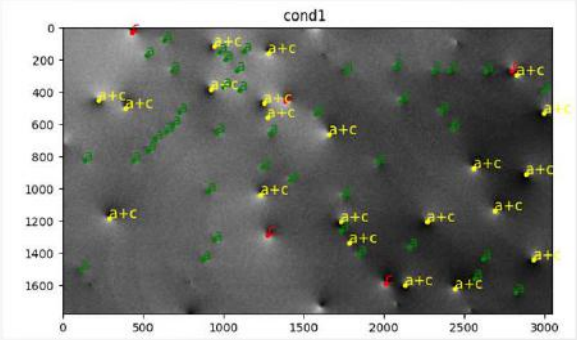
Output:

Coordinates of defects

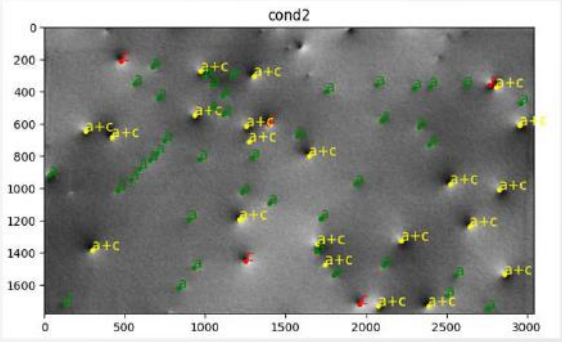
In condition 1&2 with matched ID

Input:

Images of condition 1&2, matched defect coordinates



Applying classification criteria



Output:

Classified defects

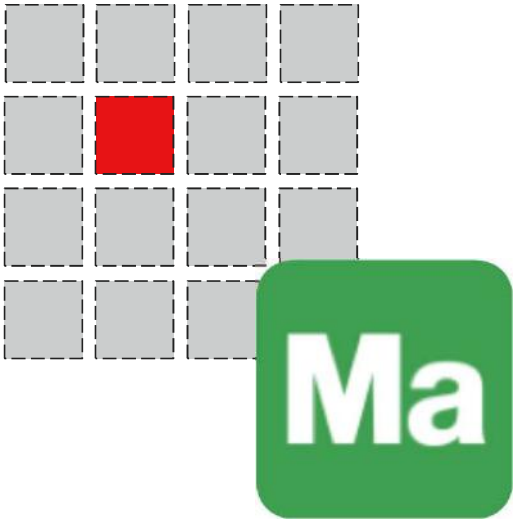
High throughput analysis – process automation

Set proper imaging conditions

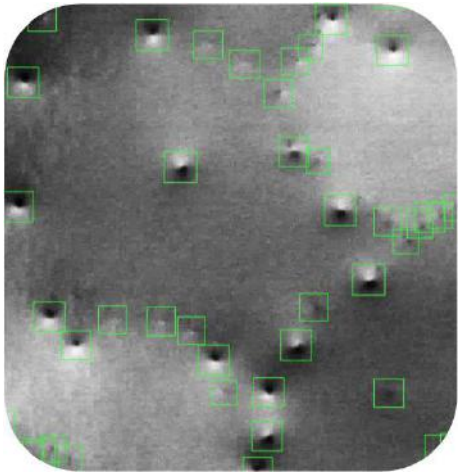
Acquire and stitch large area (automated)

Analyze images (automated)

Thermo Scientific Apreo SEM



Thermo Scientific MAPS Software



Number of defects, defect density

Apreo 2 – SEM Workhorse for (M)any Applications

- Chemical composition analysis
- Large area crystalline defect visualization
- Nanoprobing, EBIC, EBAC
- Air/moisture sensitive samples
- SPM, Mechanical testing

Apreo 2 Configurations

Apreo 2 C		Apreo 2 S
Wide range of applications	**Target application(s)**	Failure Analysis
High resolution with non-magnetic immersion	**Strengths**	Sub 1 nm resolution at low kV
“Swiss-knife” tool for any purpose adaptation	**Customer Fit**	FA with demand on quality imaging, automation
1nm@1kV	**Resolution**	0.8nm@500V
✓✓✓	**Imaging**	✓✓✓✓
✓✓	**STEM**	✓✓
✓✓	**EDS integrated**	✓✓
✓✓	**Automation/Metrology**	✓✓✓
$$	**Investment**	$$$

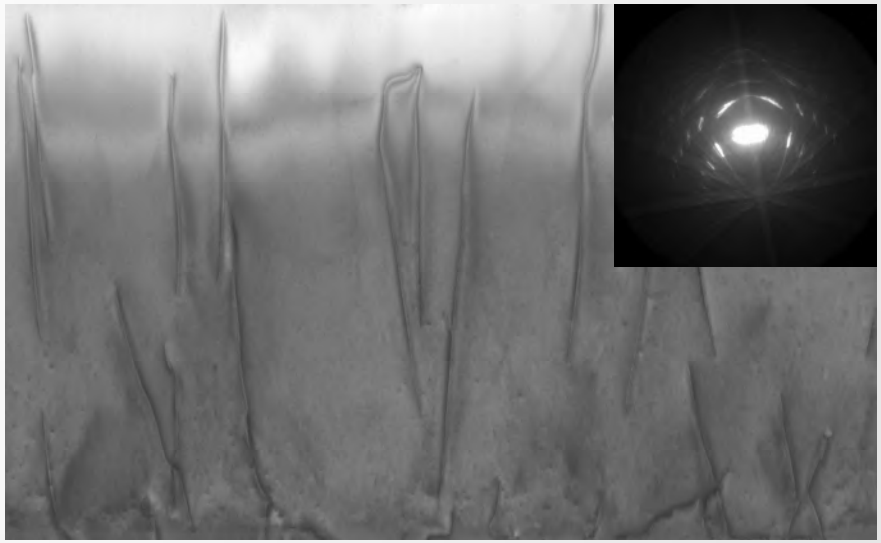
Traditional TEM defect characterization

- Cons: destructive & low throughput
- Pros: Comprehensive

- FIB SEM

- TEM lamella prep

- TEM lamella analysis

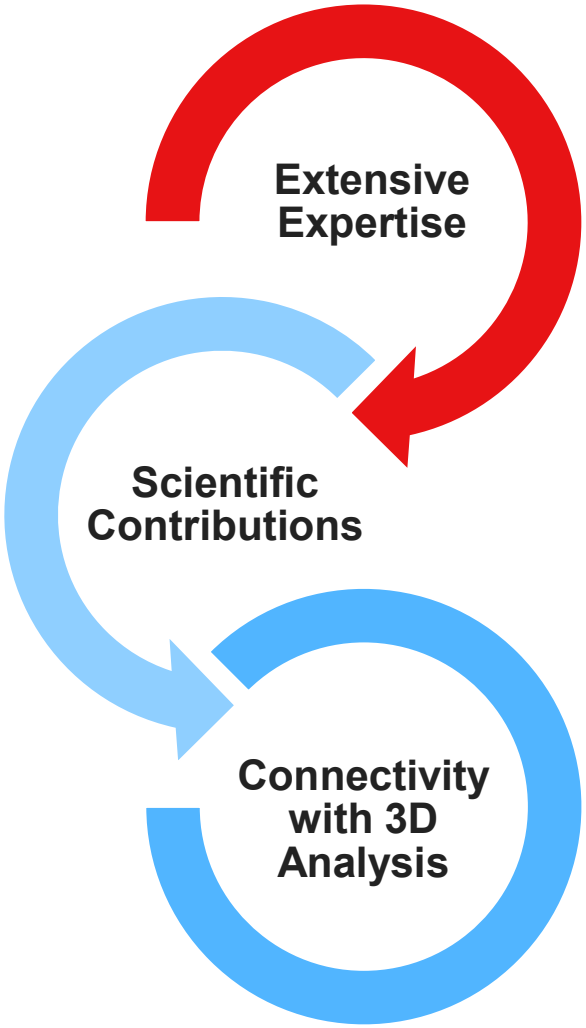


TEM analysis could be an addition to the proposed ECCI workflow

Conclusion

Key Takeaways for ECCI

Our Unique Strengths on ECCI



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Application of electron channeling contrast imaging to 3D semiconductor structures through proper detector configurations

Han Han[a,b,*], Thomas Hantschel[a], Libor Strakos[c], Tomas Vystavel[c], Marina Baryshnikova[a], Yves Mols[a], Bernardette Kunert[a], Robert Langer[a], Wilfried Vandervorst[a,b], Matty Caymax[a]

[a] imec, Kapeldreef 75, Leuven 3001, Belgium
[b] KU Leuven, Dept. of Physics and Astronomy, Celestijnenlaan 200D, Leuven 3001, Belgium
[c] Thermo Fisher Scientific, Vlastimila Pecha 12, Brno 62700, Czech Republic

Ultramicroscopy 210 (2020) 112922

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Enhancing the defect contrast in ECCI through angular filtering of BSEs

Han Han[a,b,*], Thomas Hantschel[a], Andreas Schulze[a,d], Libor Strakos[c], Tomas Vystavel[c], Roger Loo[a], Bernardette Kunert[a], Robert Langer[a], Wilfried Vandervorst[a,b], Matty Caymax[a]

[a] imec, Kapeldreef 75, Leuven 3001, Belgium
[b] Dept. of Physics and Astronomy, KU Leuven, Celestijnenlaan 200D, Leuven 3001, Belgium
[c] Thermo Fisher Scientific, Vlastimila Pecha 12, Brno 62700, Czech Republic
[d] Now with Applied Materials, 3340 Scott Blvd, Santa Clara, CA 95054, USA

Nanoscale

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Non-destructive characterization of extended crystalline defects in confined semiconductor device structures†

Andreas Schulze, [a] Libor Strakos, [b] Tomas Vystavel, [b] Roger Loo, [a] Antoine Pacco, [a] Nadine Collaert, [a] Wilfried Vandervorst[a,c] and Matty Caymax[a]

Micron 150 (2021) 103123

Contents lists available at ScienceDirect

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Crystalline defect analysis in epitaxial $Si_{0.7}Ge_{0.3}$ layer using site-specific ECCI-STEM

Han Han [a,*], Libor Strakos [b], Thomas Hantschel [a], Clement Porret [a], Tomas Vystavel [b], Roger Loo [a], Matty Caymax [a]

[a] imec, Kapeldreef 75, 3001, Leuven, Belgium
[b] Thermo Fisher Scientific, Vlastimila Pecha 12, 62700, Brno, Czech Republic

ECS Transactions

Ascertaining the Nature and Distribution of Extended Crystalline Defects in Emerging Semiconductor Materials Using Electron Channeling Contrast Imaging

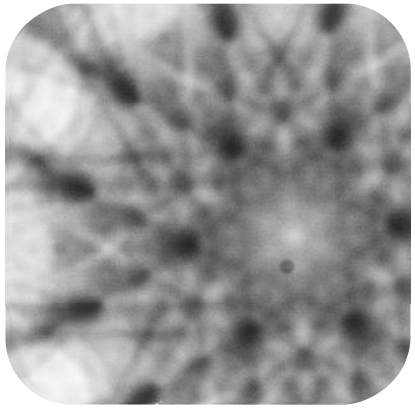
Andreas Schulze[1], Han Han[1,2], Libor Strakos[3], Tomas Vystavel[3], Clement Porret[1], Roger Loo[1] and Matty Caymax[1]

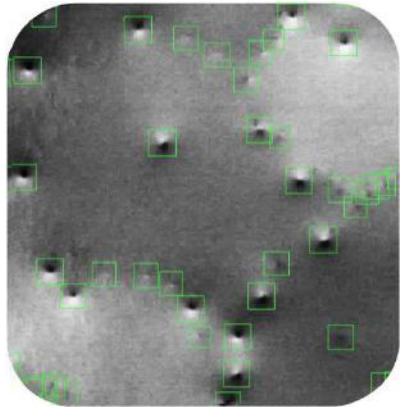
ECS Transactions, Volume 86, Number 7

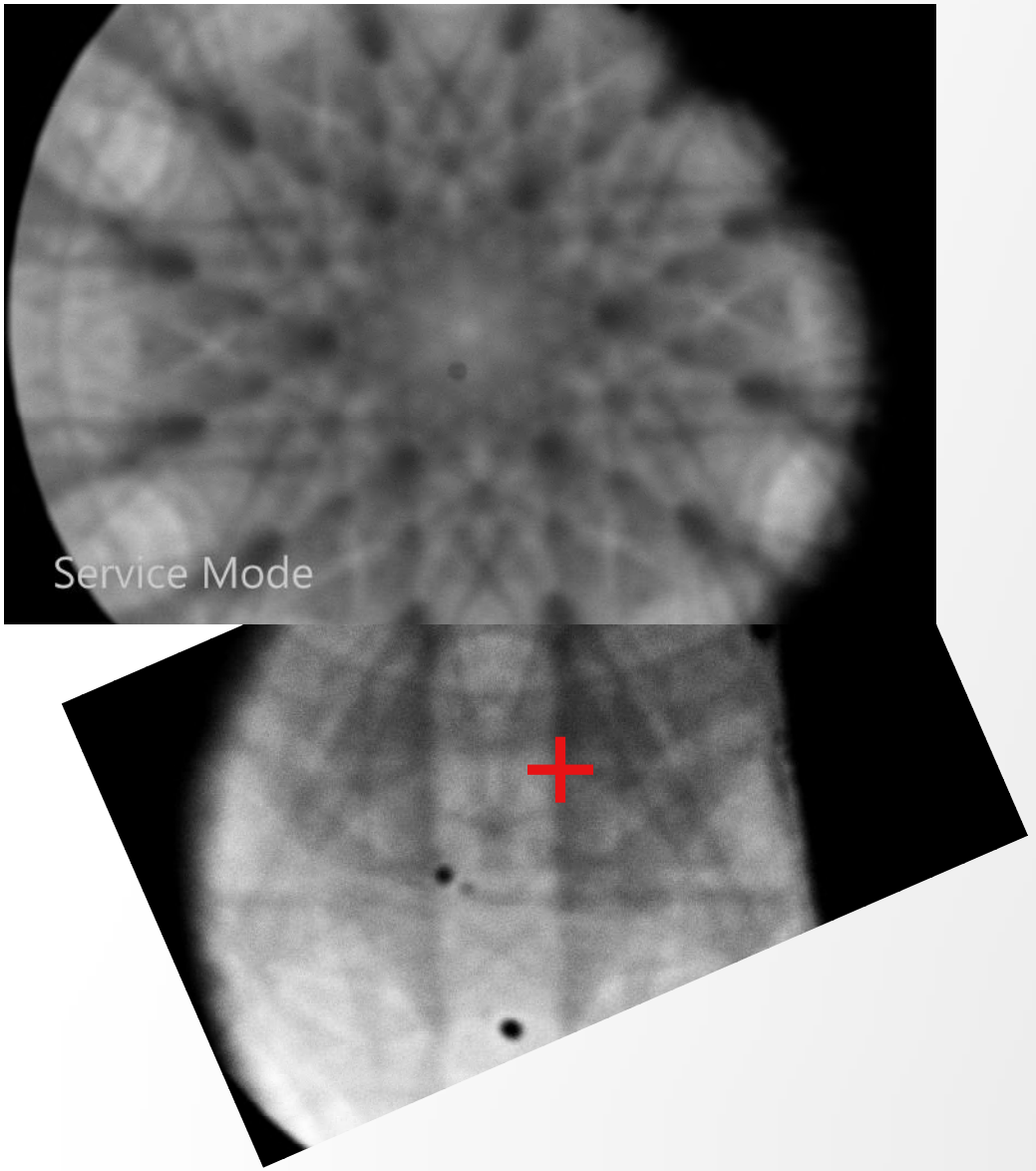
Citation Andreas Schulze *et al* 2018 *ECS Trans.* **86** 387

ECCI:

- ✓ Non-destructive, high-throughput, and quantitative
- ✓ Crystal defect visualization & classification in GaN
- ✓ Semi-automated by Apreo and Thermo Fisher software



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