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Motion of dislocations in freestanding (0001) GaN single crystals

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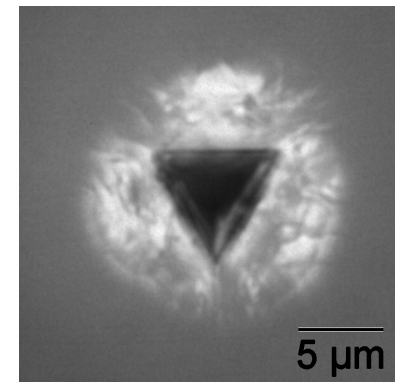
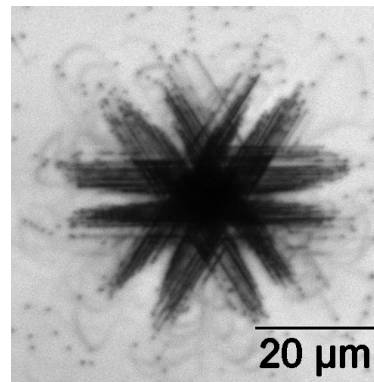
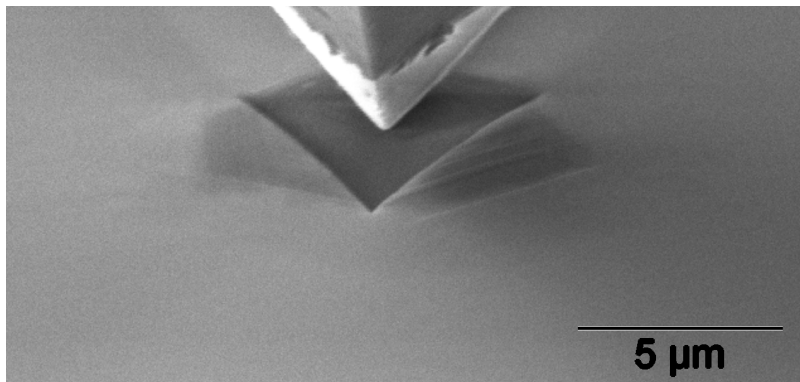
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Introduction

- Aim: description of dislocations and cracks in GaN
- GaN: direct band gap of 3.4 eV, basic material for opto-electronic devices
blue LD, blue and white LED, high-power devices

Properties of GaN improved: Freestanding crystals instead of thin GaN



Deformation of GaN by indentation

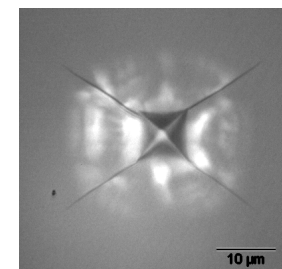
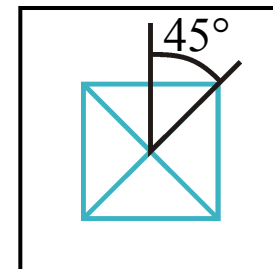
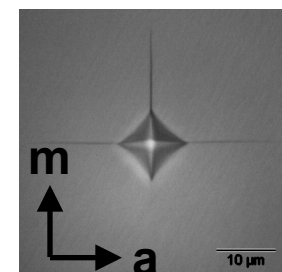
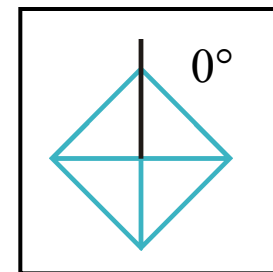
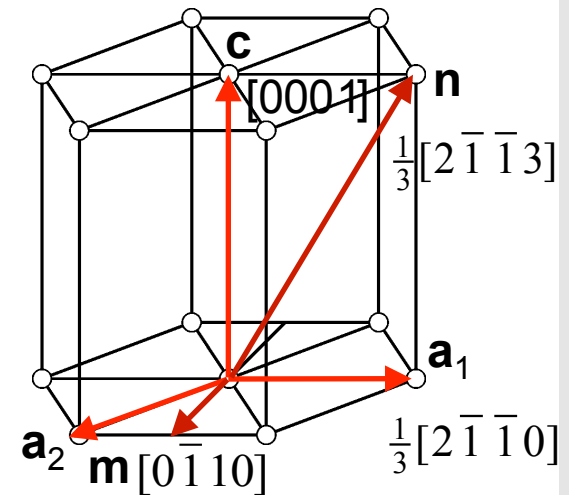
Investigation of dislocations and cracks

Application:

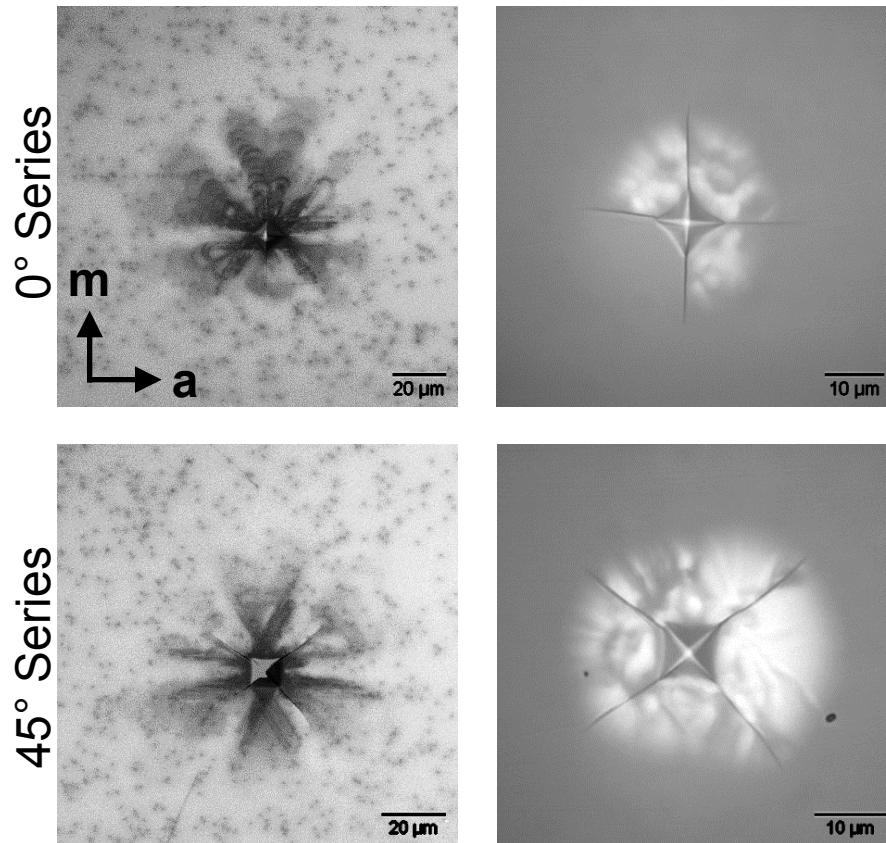
- increasing of crystal size, decreasing of defect density at growth
- optimizing of mechanical processing of GaN single crystals

Introduction

- GaN: Hydride vapor phase epitaxy on sapphire
- Thickness: 2 mm, Diameter: 50 mm
- Dislocation density: $\rho_D = 9 \cdot 10^6 \text{ cm}^{-2}$
- GaN: Wurtzite structure
- a-axes ($a = 0,3189 \text{ nm}$), c-axes ($c = 0,5185 \text{ nm}$)
- Cleavage planes: m-planes
- Indentation of Ga-polar c-face
- Vickers indenter at room temperature
- Load: 0.05 to 1.0 N
- Indenter orientations: 0° and 45°
- 6 indentations per load and orientation



Dislocations and cracks at indentations



CL images

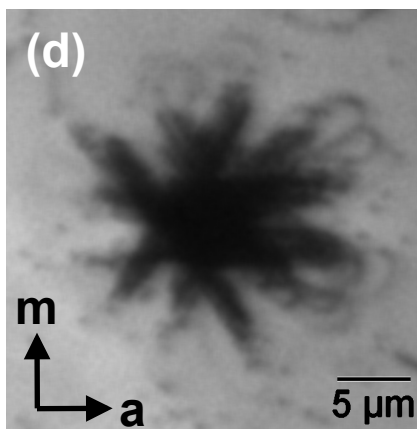
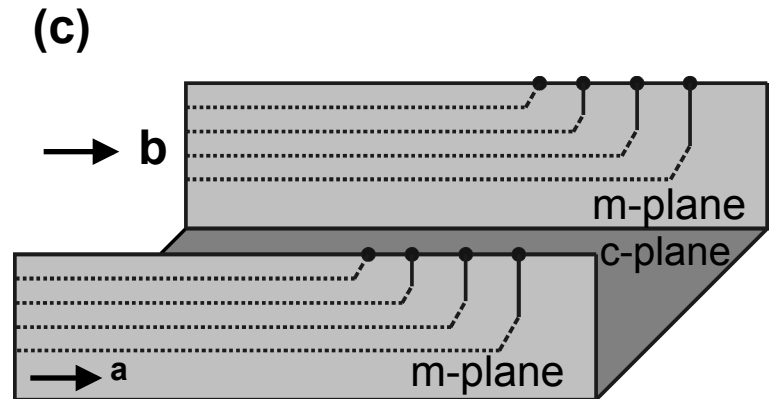
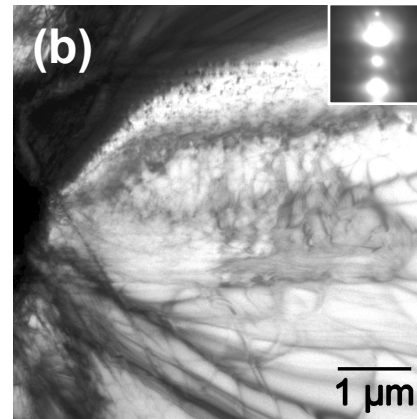
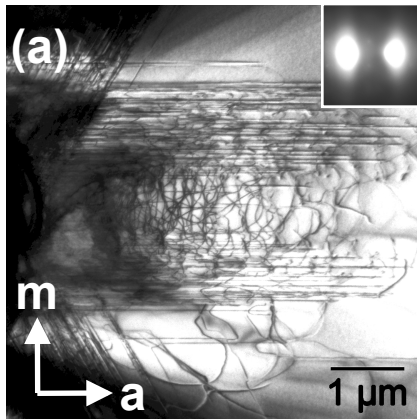
SE images

Vickers indentations, load: 1.0 N

- Cathodoluminescence (CL):
dislocations: non-radiative
- 6 dislocation arms in **a**-direction
- Long dislocation segments:
parallel and near to surface
- Point contrast in arms:
intersection points at surface
- Point contrasts outside rosette:
in-grown dislocation, statistical
distribution

Arrangement of dislocations in GaN

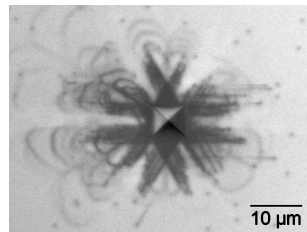
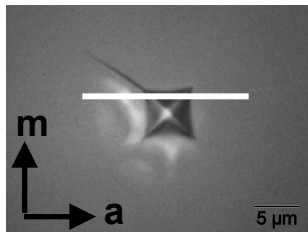
TEM, diffraction contrast in bright-field, dislocations at Vickers indentations



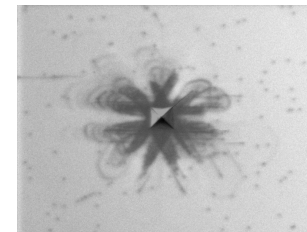
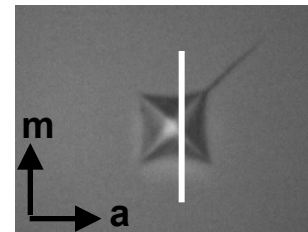
- CL image: 6 dislocation arms (Fig. d)
- \mathbf{g} -vector in \mathbf{a} -direction: maximum contrast (Fig. a)
- \mathbf{g} -vector in \mathbf{m} -direction: minimal contrast (Fig. b)
- $\mathbf{g} \cdot \mathbf{b} = 0 \rightarrow \mathbf{a}$ -type Burgers-Vector
- Glide prism model: dislocation segments
 \mathbf{a} -type screw dis. $\rightarrow 58^\circ$ / edge dislocations (Fig. c)

Arrangement of dislocations in GaN

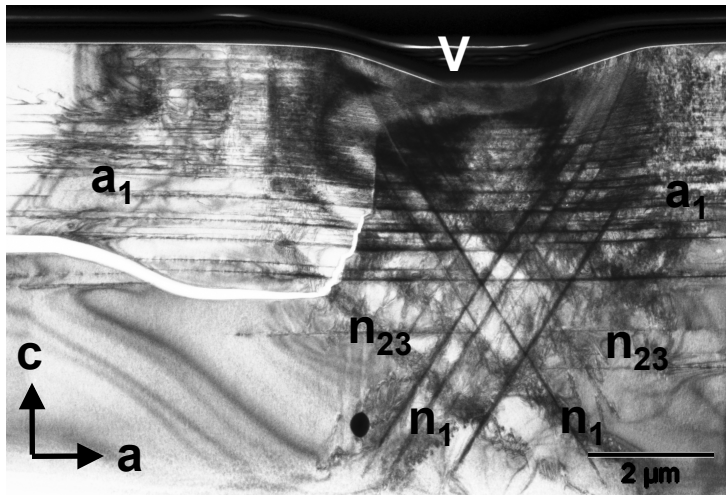
Preparation of cross section by FIB (Focused Ion Beam)



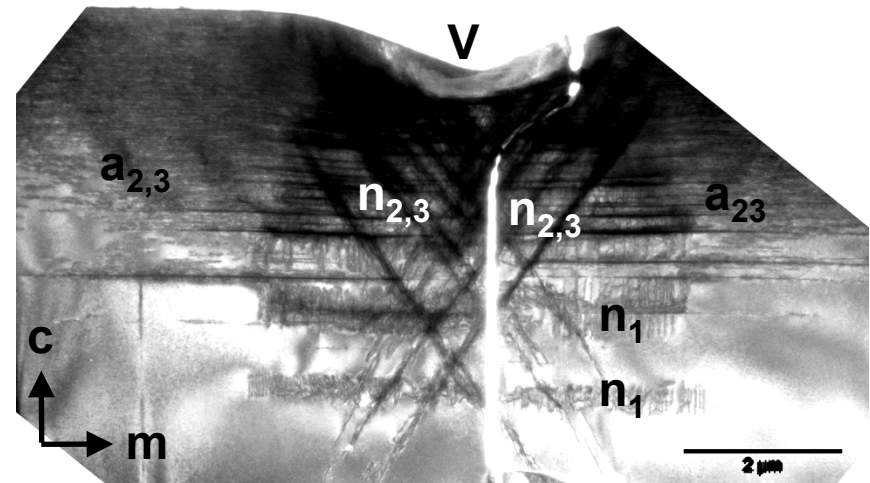
OM
and
CL+SE



OM
and
CL+SE



Three Bands: a_1 : 0° , n_1 : 58° , $n_{2,3}$: 38°

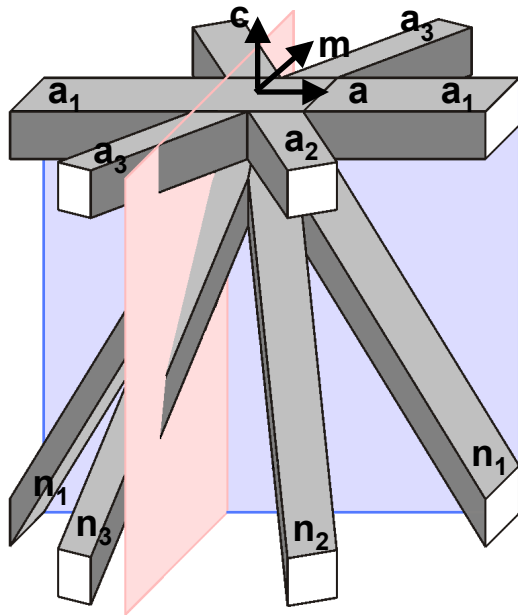


Three Bands: a_1 , n_1 : surface parallel, $n_{2,3}$: 53°

Arrangement of dislocations in **a**-direction and **n**-direction

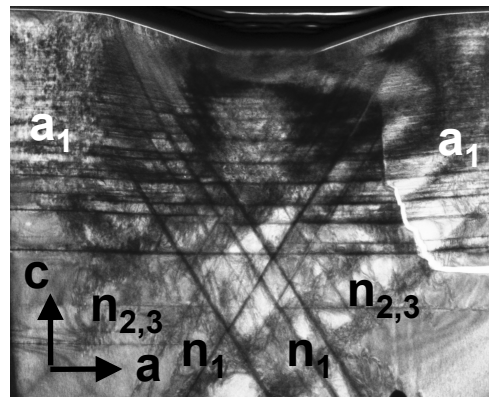
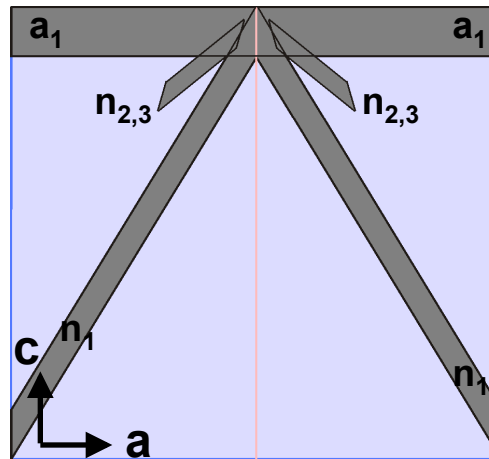
Arrangement of dislocations in GaN

3D model

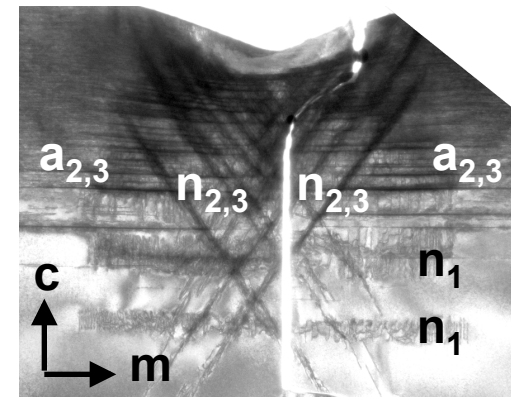
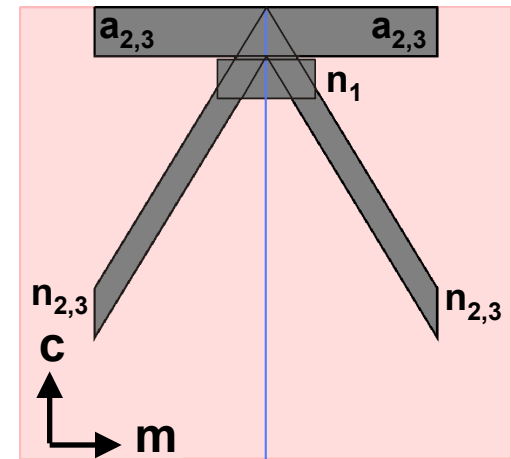


Glide prism model for indentation of the c-plane

m-plane



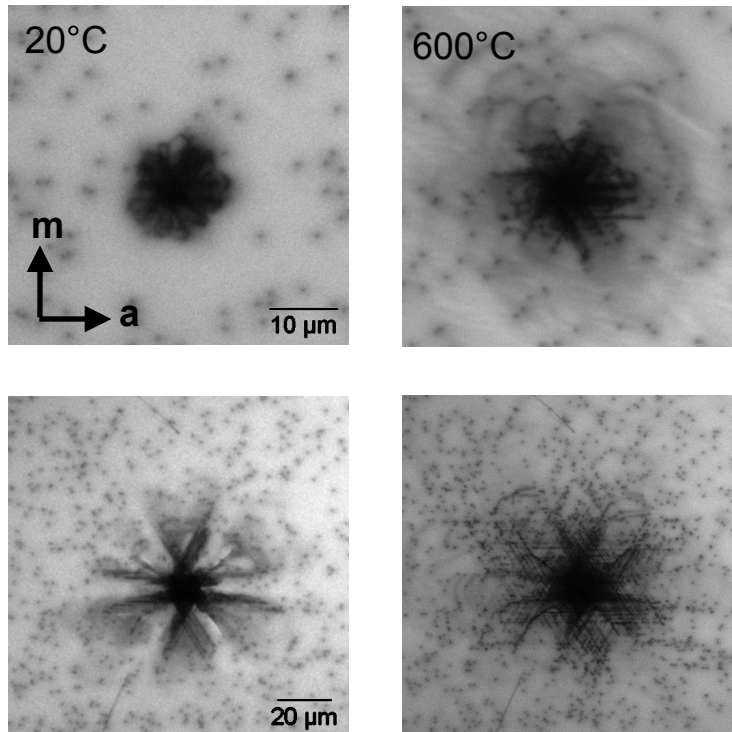
a-plane



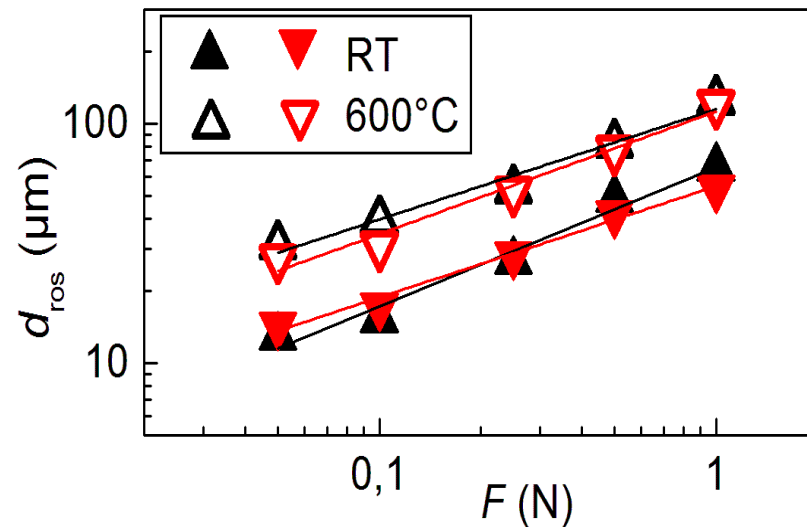
Accordance of model and TEM images

Motion of dislocations in GaN

- Temperature steps (60 minutes) and CL investigation
- 200 – 600 °C (100 °C steps)



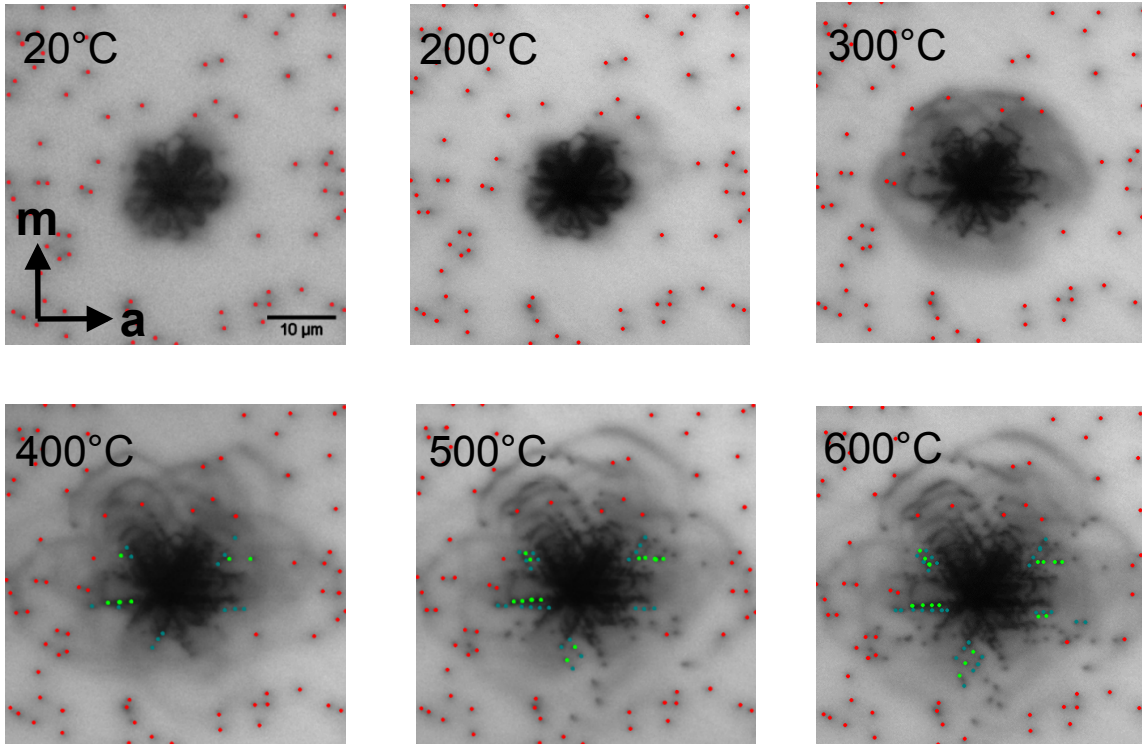
CL imaging after annealing



d_{ros} (μm)	0° Serie	45° Serie
RT	$65.46 \cdot (F/N)^{0.581}$	$54.70 \cdot (F/N)^{0.465}$
600°C	$114.6 \cdot (F/N)^{0.460}$	$112.2 \cdot (F/N)^{0.512}$

Size of dislocation rosettes

Motion of dislocations in GaN

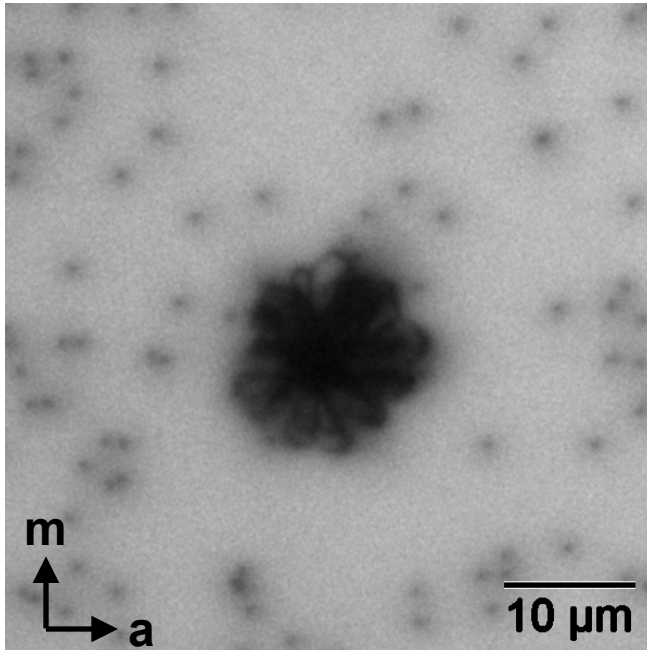


- 20°C, 200°C:
circular shape
no motion
- 300°C:
dislocation motion
circular shape
- 400°C:
dislocation arms
become visible
- 500°C, 600°C
extension and
broadening of
dislocation arms

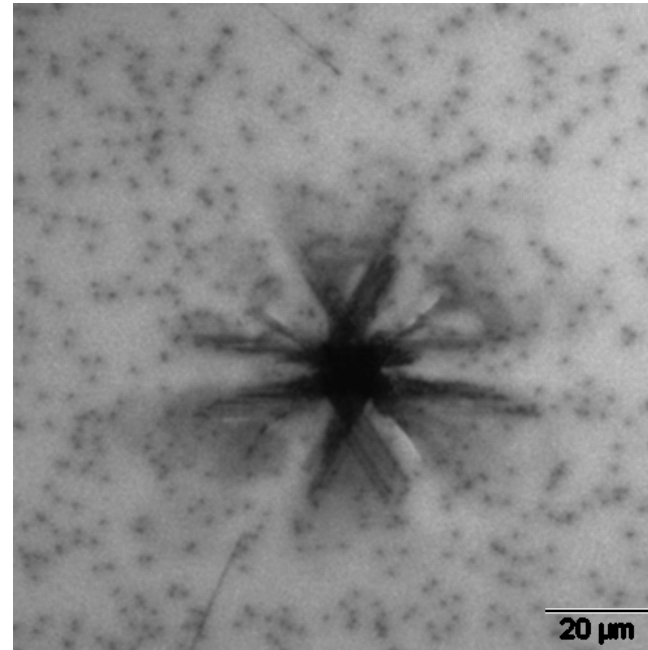
Motion of individual dislocations, Vickers indentation, 0° series, 0.1 N, classification of dislocation by color: in-grown (red), dislocations in arms (green, cyan)

Motion of dislocations in GaN

0° Series, 0.1 N



45° Series, 1.0 N

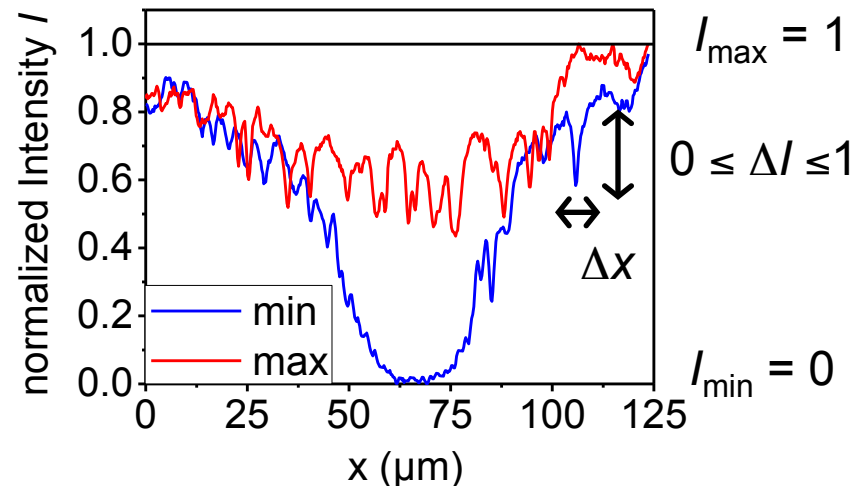
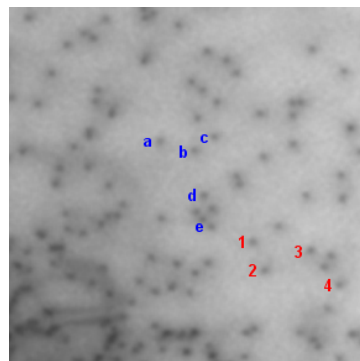
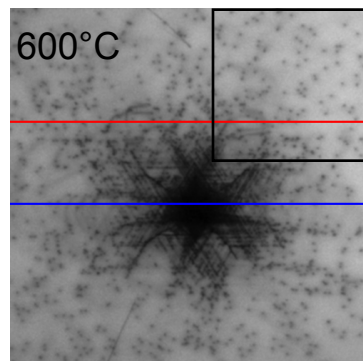
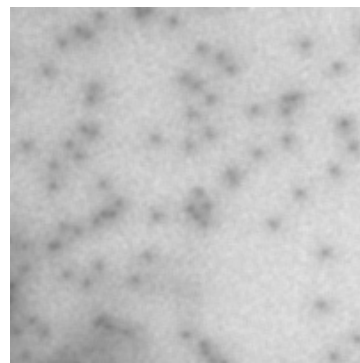
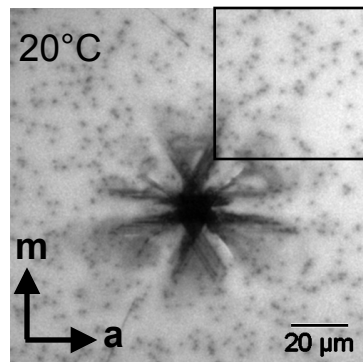


Motion of dislocations in the residual strain field of indentations

- Indentation-induced dislocations: mobile
- Grown-in dislocations: sessile
- → No strain relaxation via dislocation motion

Motion of dislocations in GaN

Contrast analysis of dislocations in panchromatic CL at room temperature

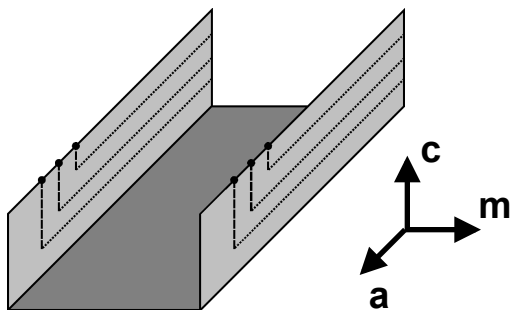


Dislocations	ΔI in %	Δx in μm
Sessile (a-e)	26 ± 1	1.45 ± 0.12
Mobile (1-4)	29 ± 1	1.31 ± 0.09

Comparison of sessile and mobile dislocations:

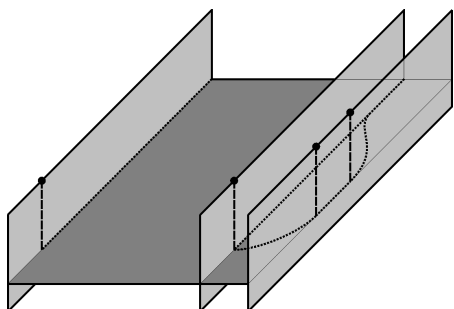
- Similar contrast in panchromatic CL images at room temperature

Motion of dislocations in GaN



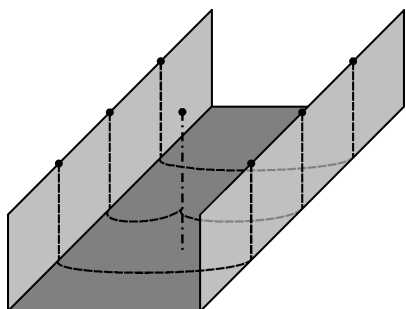
Arrangement of dislocations in one rosette arm:

- Segment: **a**-type screw and edge dislocations
- Motion of dislocations in **a**-direction on a **m**-plane
- Extension of dislocation arms



Double cross of slip dislocations

- 1. cross slip of screw dislocation on **c**-plane
- 2. cross slip on **m**-plane, motion to surface
- Dislocation multiplication, motion in **m**-direction
- Broadening of dislocation arms



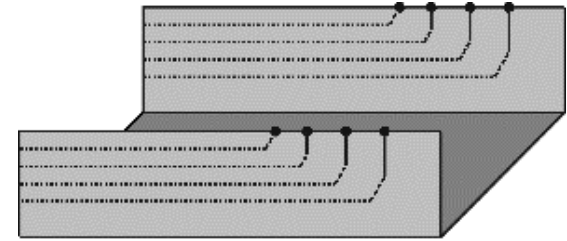
Motion of dislocation loops in **a**-direction

- Cutting process with in-grown dislocation
- Motion beyond in-grown dislocations

Summary

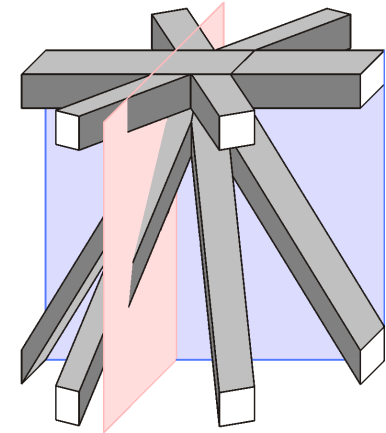
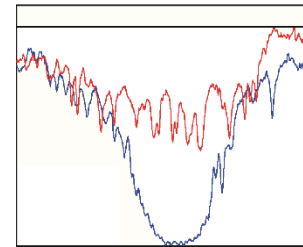
Dislocations at indentations in (0001) GaN

- Dislocations \leftrightarrow crystal symmetry
- TEM in 3 planes \rightarrow 3D Model for dislocations



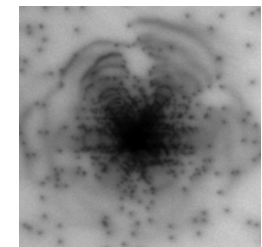
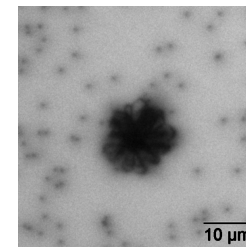
Motion of dislocations

- Indentation-induced dislocations: mobile
- Grown-in dislocations: sessile
- No contrast differences visible



Models for dislocation motion

- Extension of dislocation arms (glide)
- Broadening of dislocation arms (cross slip)
- Intersection processes





Thank you for your Attention

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