As grown and artificial mosaic GaAs crystals for hard x-ray astronomy

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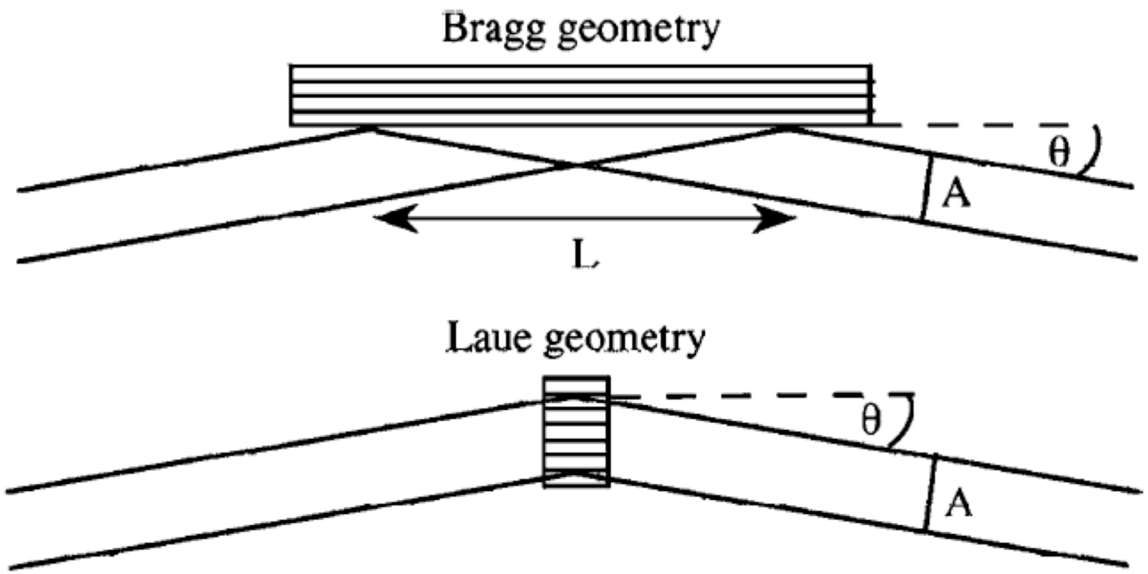
Outline

1. Laue lenses for hard x-ray astronomy
2. Mosaic crystals
3. GaAs crystals
4. X-ray diffraction characterization
5. “Artificial mosaic” crystals
6. Conclusions

Laue lens: why?

Hard x-rays: E > 60 keV

Bragg law: $2d\sin\theta_B = n\dfrac{hc}{E}$ ⇨ very small incident angle



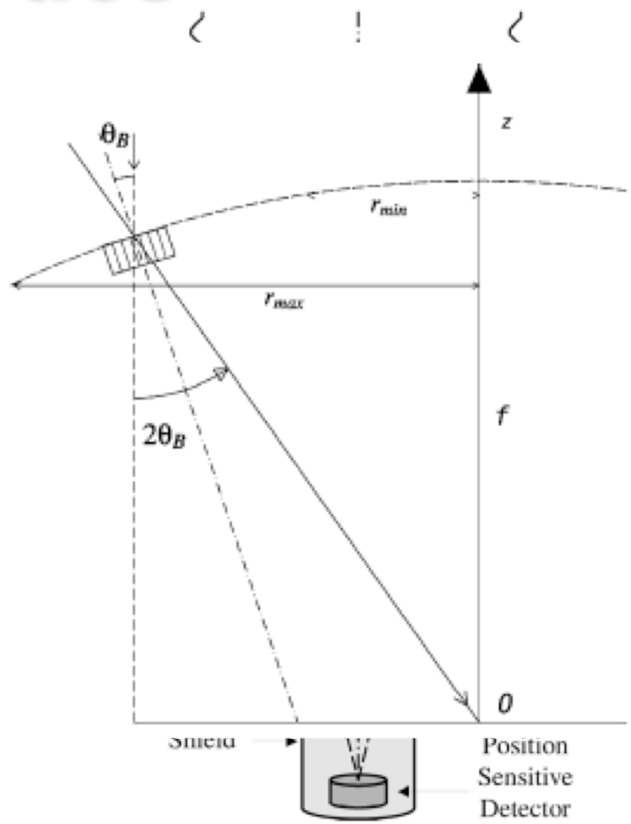
NO

OK

H. Halloin and P. Bastie, *Exp. Astron.* **20** (2005) 151

Laue lens: main properties

- Spherical shape with radius R
- Focal length f=R/2
- Crystal tiles, as small as possible, with lattice planes perpendicular to the front surface



D. Pellicciotta et al., *IEEE Trans. Nucl. Sci.* **53** (2006) 253

Resolution

a few tens of arcsec

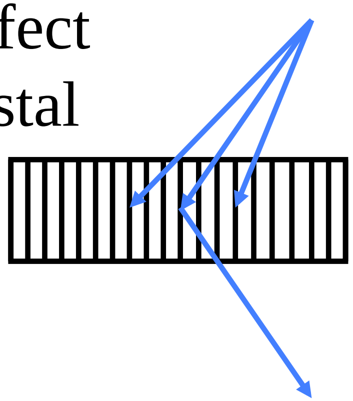
⇩

Fundamental requirement

a few tens of arcsec of angular acceptance

Crystal tiles

Perfect
crystal



$$FWHM \approx r_e \frac{F_H \lambda}{\pi V} d$$

- r_e = electronic radius
- λ = wavelength
- F_H = structure factor
- d = lattice spacing
- V = crystal cell volume

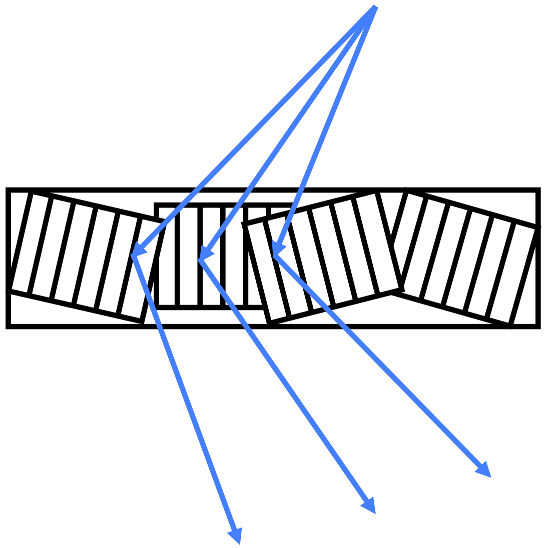
FWHM ~ 0.06 arcsec

Ge 400 diffraction at 500 keV

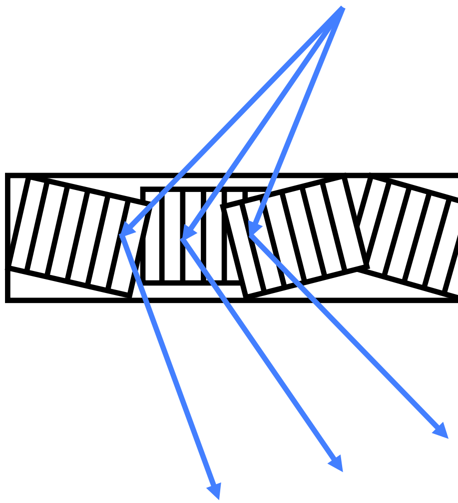
To improve the
collection efficiency

**MOSAIC
CRYSTALS**

can be used



Mosaic crystals



Crystal made of microscopic perfect crystal domains (crystallites) slightly misoriented with respect to each other

$$W(\vartheta)=\frac{1}{\sqrt{2\pi\eta}}\exp\left(-\frac{\vartheta^2}{2\eta^2}\right)$$

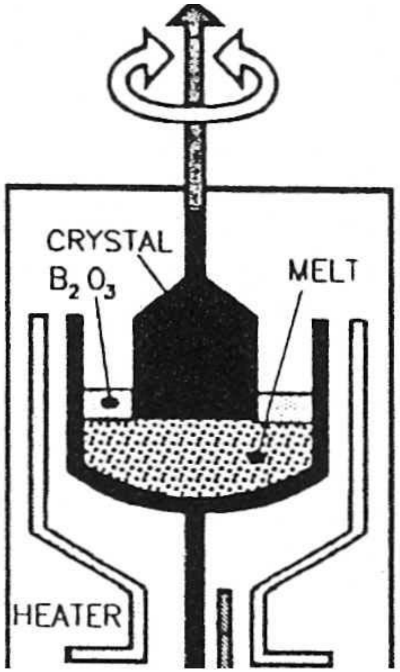
Mosaic spread

$$\sigma = FWHM = 2\eta\sqrt{\ln 4}$$

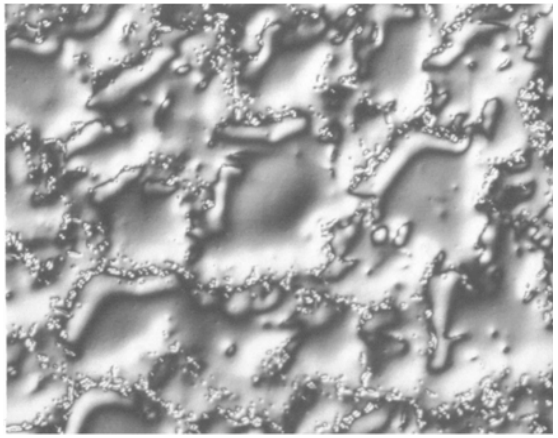
Bandwidth diffracted by the crystal

$$\Delta E = \frac{E\sigma}{\tan\theta_B}$$

GaAs crystals

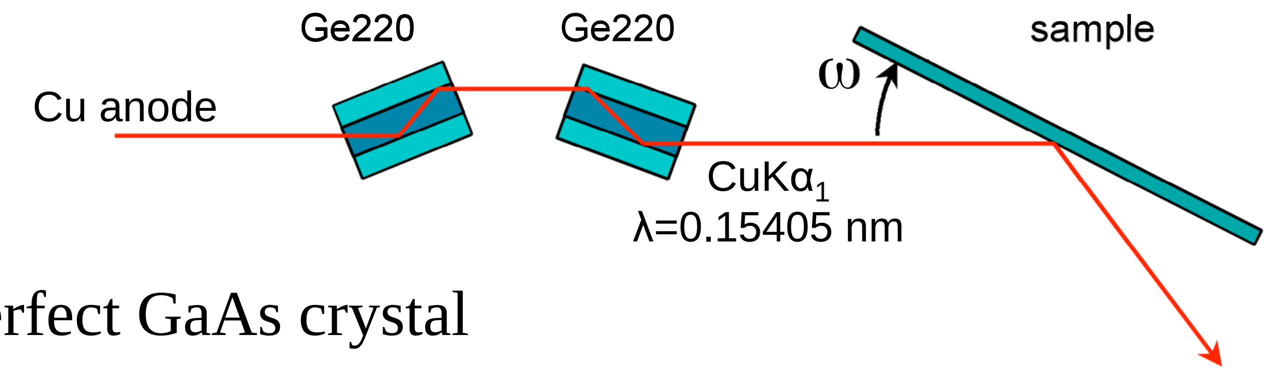


- Grown by using the Liquid Encapsulated Czochralsky (LEC) technique
- The same crystal structure (fcc), lattice spacing, and electron density of Ge crystals
- Spontaneous mosaicity, that can be controlled by changing growth parameters



X-ray diffraction characterization

by means of a high resolution X-Pert Pro Philips diffractometer



Perfect GaAs crystal

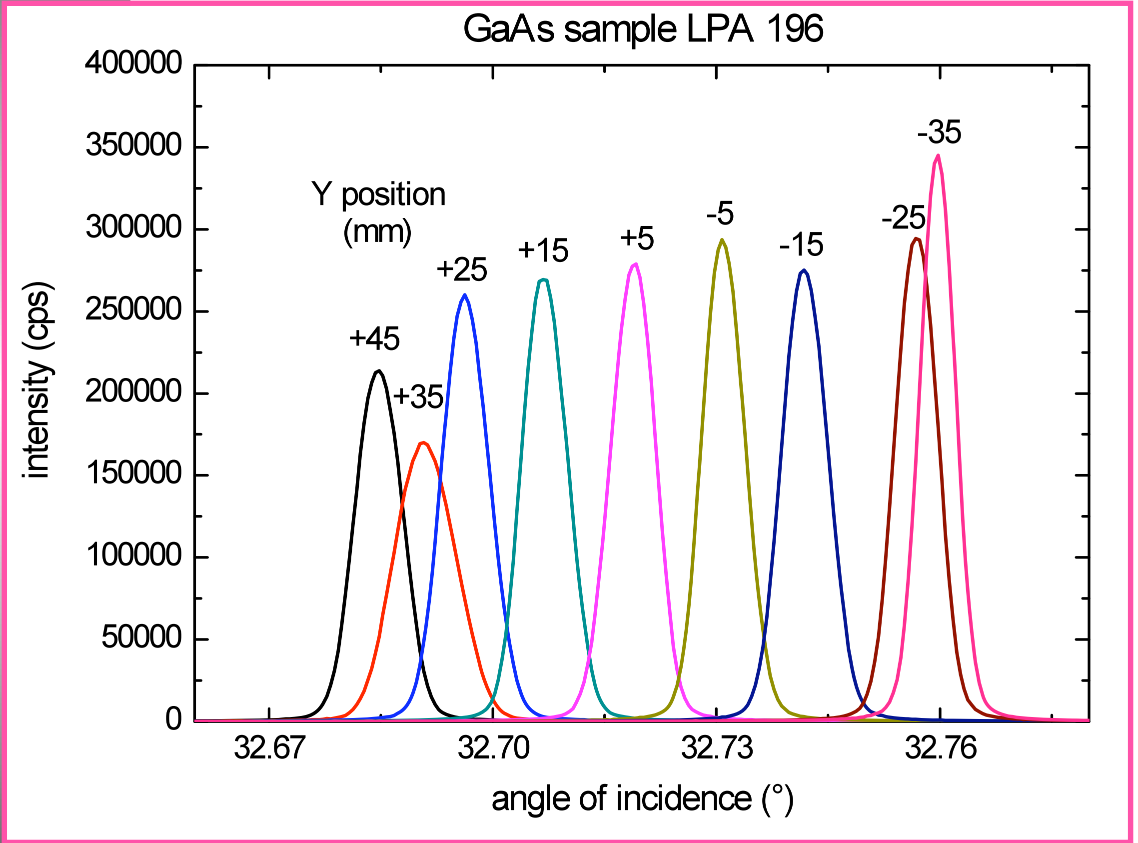
$FWHM(004) = 15.8$ arcsec

$$\sigma = \sqrt{FWHM^2_{exper} - FWHM^2_{instrum}}$$

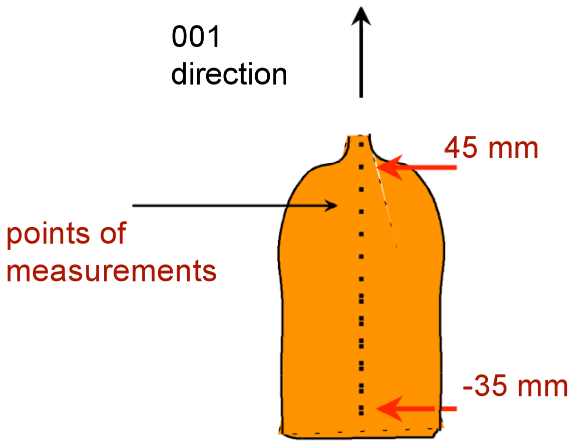
$$FWHM^2_{instrum} \parallel FWHM(004)$$

Measurements along ingot Y axis

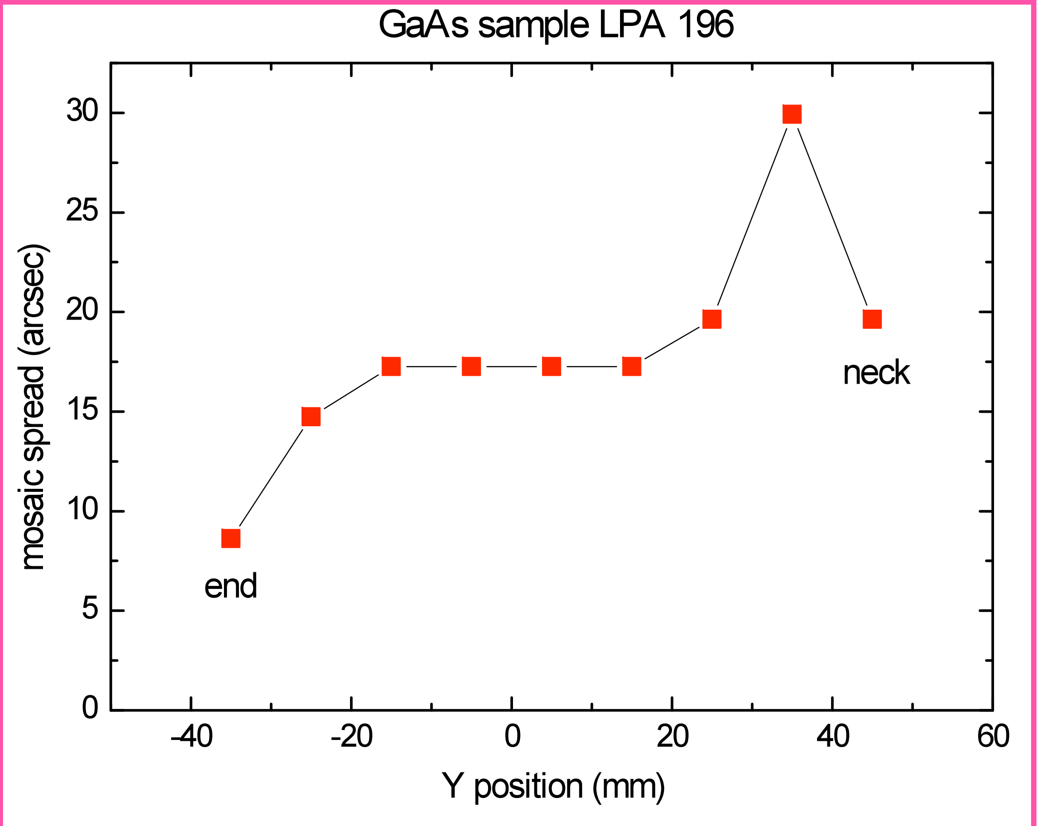
Sample: slice cut **along** the growth axis of a GaAs ingot



004 diffraction profiles

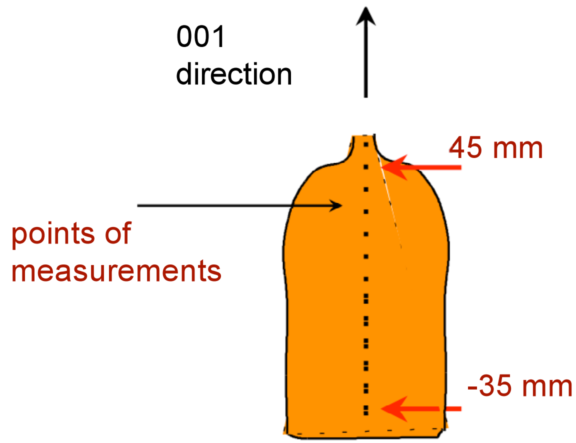


Measurements along ingot Y axis



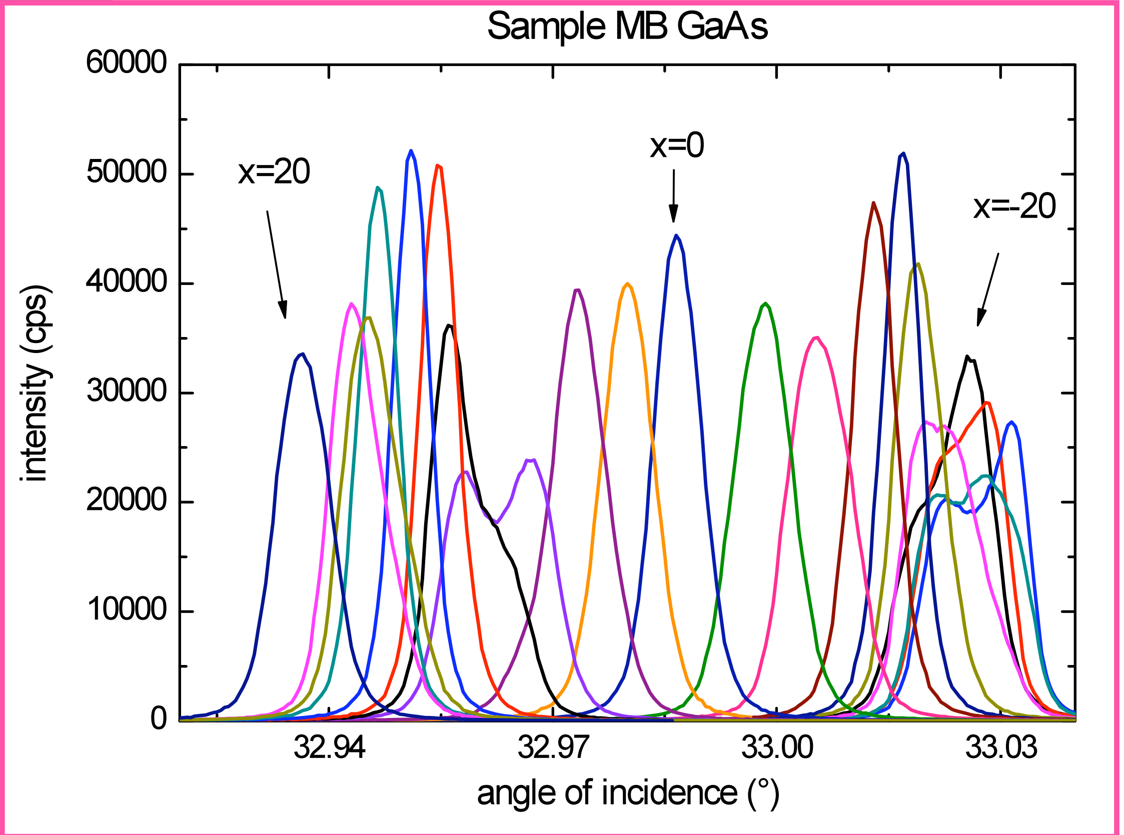
Sample: slice cut **along** the growth axis of a GaAs ingot

Mosaic spread



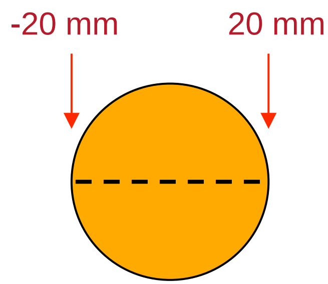
Central zone (from -20 to 20 mm) with nearly constant σ value: σ ~ 18 arcsec

Measurements along wafer diameter

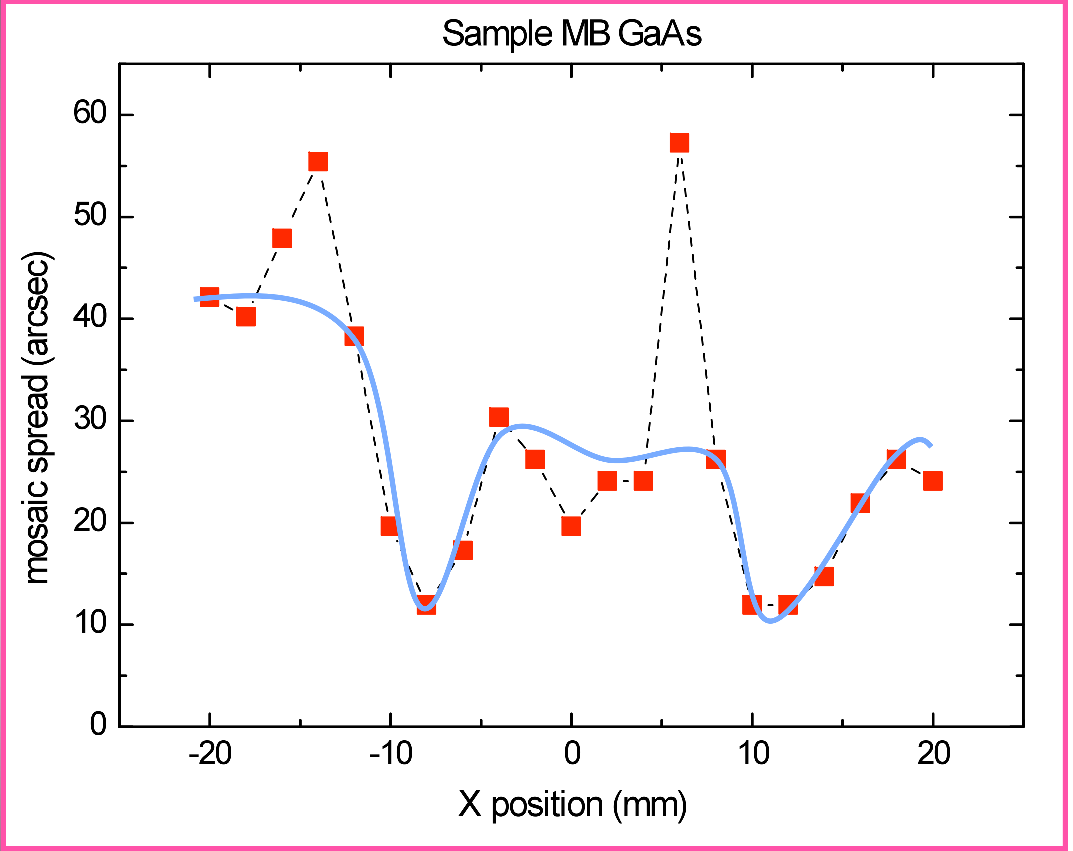


Sample: wafer cut **perpendicularly** to the growth axis of a GaAs ingot

004 diffraction profiles

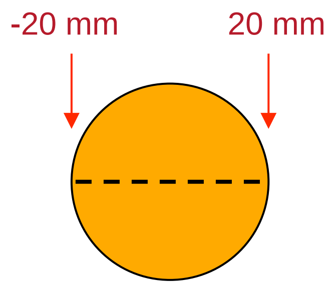


Measurements along wafer diameter



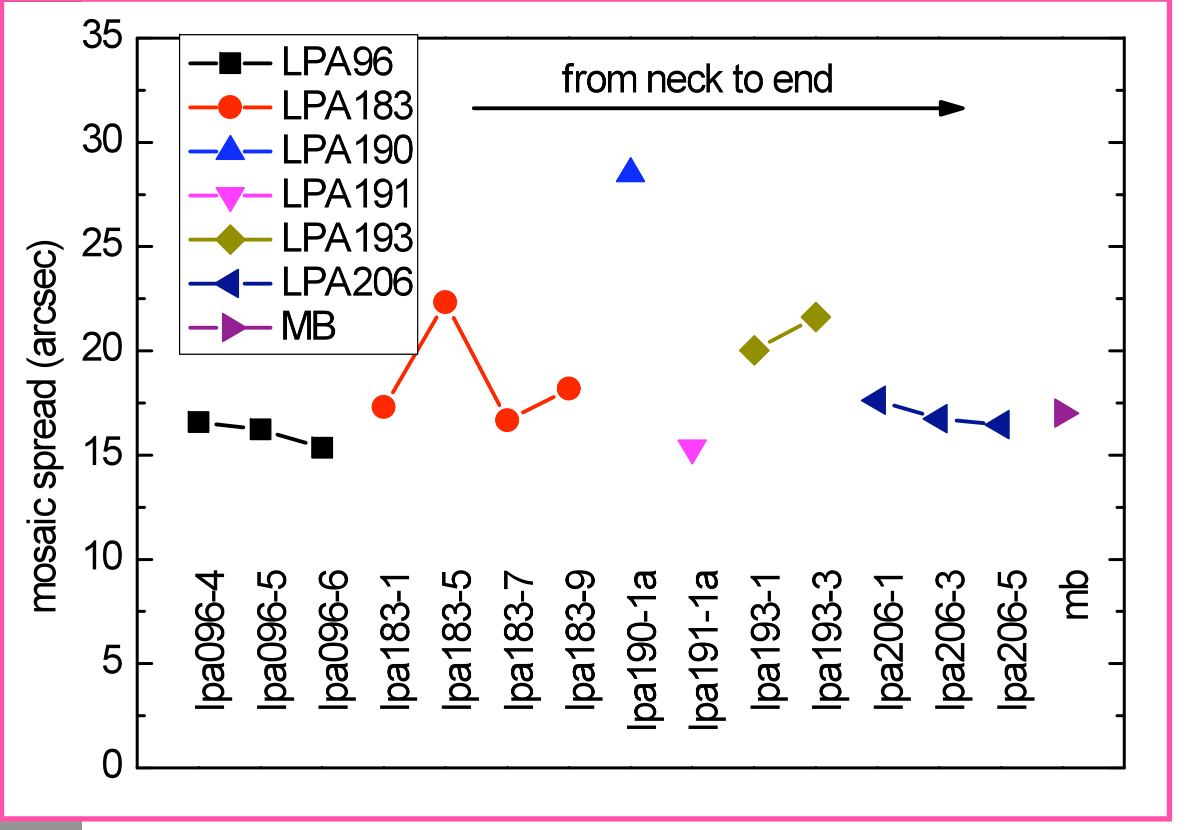
Sample: wafer cut **perpendicularly** to the growth axis of a GaAs ingot

Mosaic spread



σ follows the typical W shape of the dislocation density

Mosaic spread



Mosaic spread obtained from rocking curves collected near the centre of wafers cut at different heights of ingots grown in different conditions

Growth conditions and **doping** may affect the mosaic spread

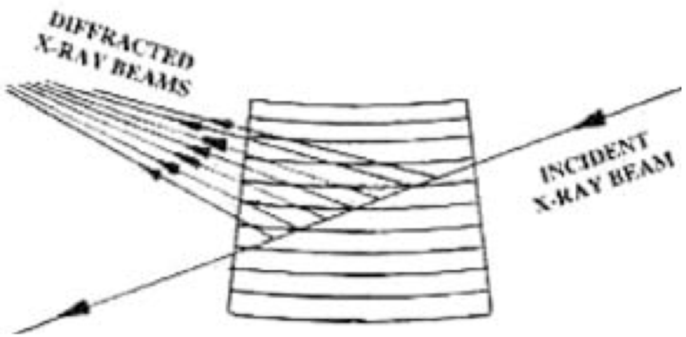
sample N° 096: Cr-doped
samples N° 183, 193, 206, MB: undoped stoichiometric
samples N° 190, 191: As-rich

“Artificial mosaic” crystals

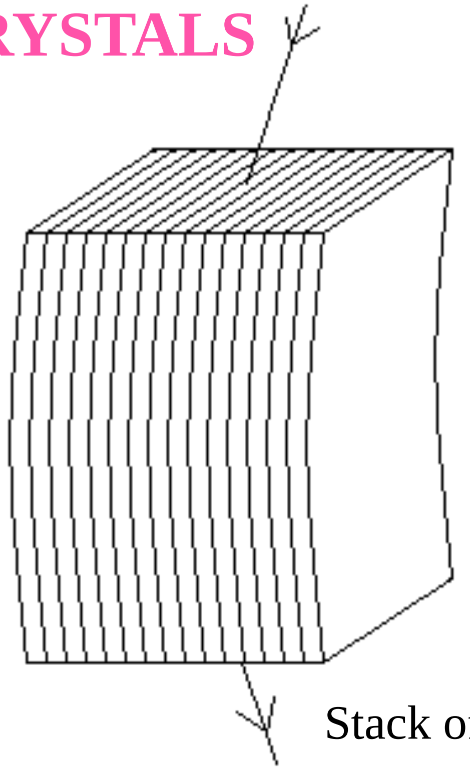
A complementary strategy to increase the Darwin width of the diffraction curve can be the use of “artificial mosaic” crystals:

STACKS OF CURVED CRYSTALS

- High diffraction efficiency
- Broad energy bandwidth



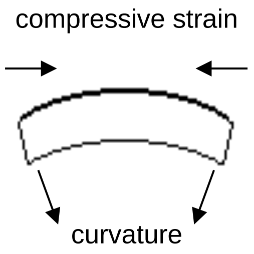
R. K. Smither et al., *Exp. Astron.* **20** (2005) 201



Stack of curved crystals

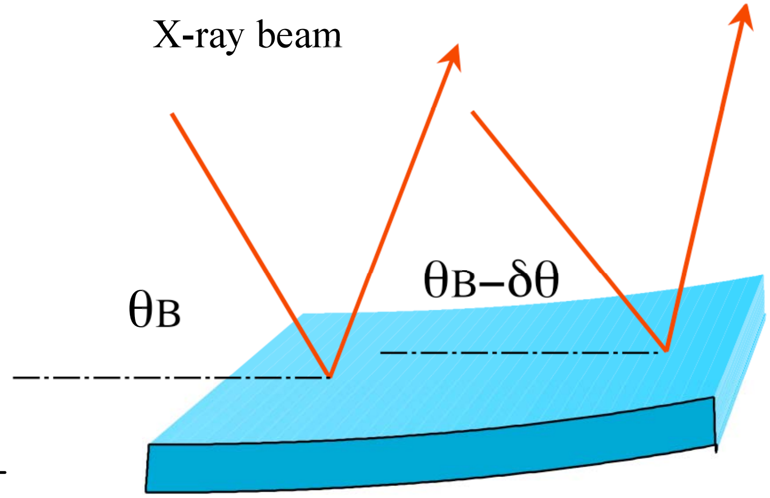
Incurvation technique

The curvature is obtained by introducing a compressive stress on the crystal surface by damaging it with fine sand paper



$$\varsigma = \frac{E_s t_s^2 \kappa}{6 t_f (1 - \nu_s)}$$

Stoney formula



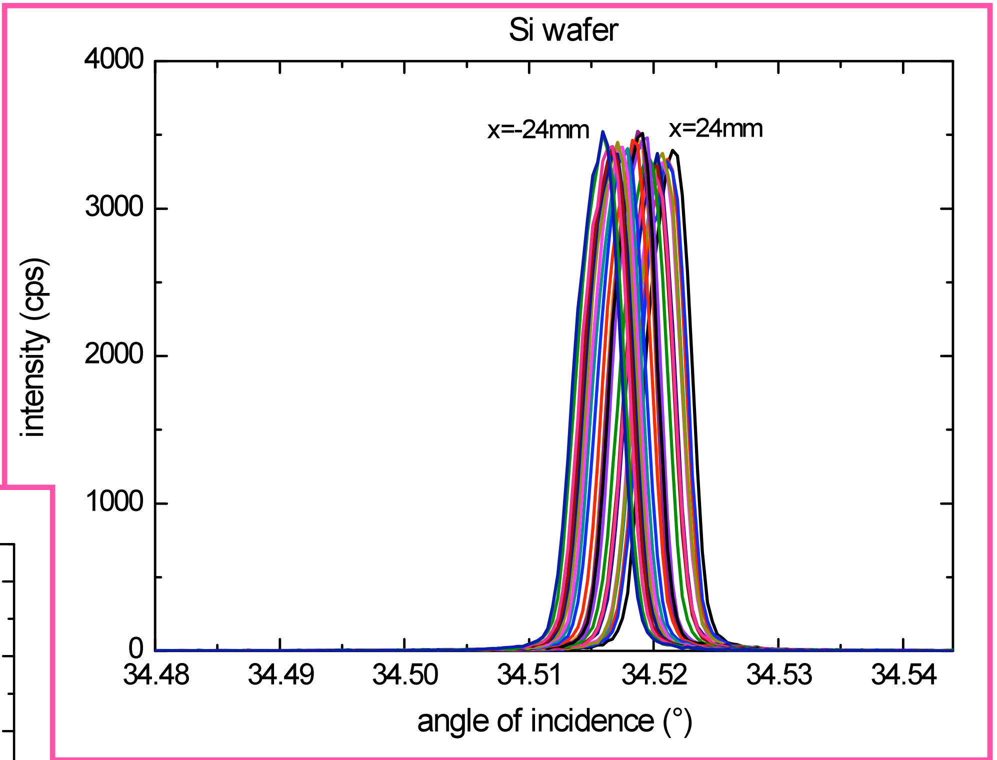
Thickness t
Angular acceptance α ⇨ $R = \dfrac{t}{\alpha}$

It is possible to check the crystal curvature monitoring the angular shift of the rocking curves

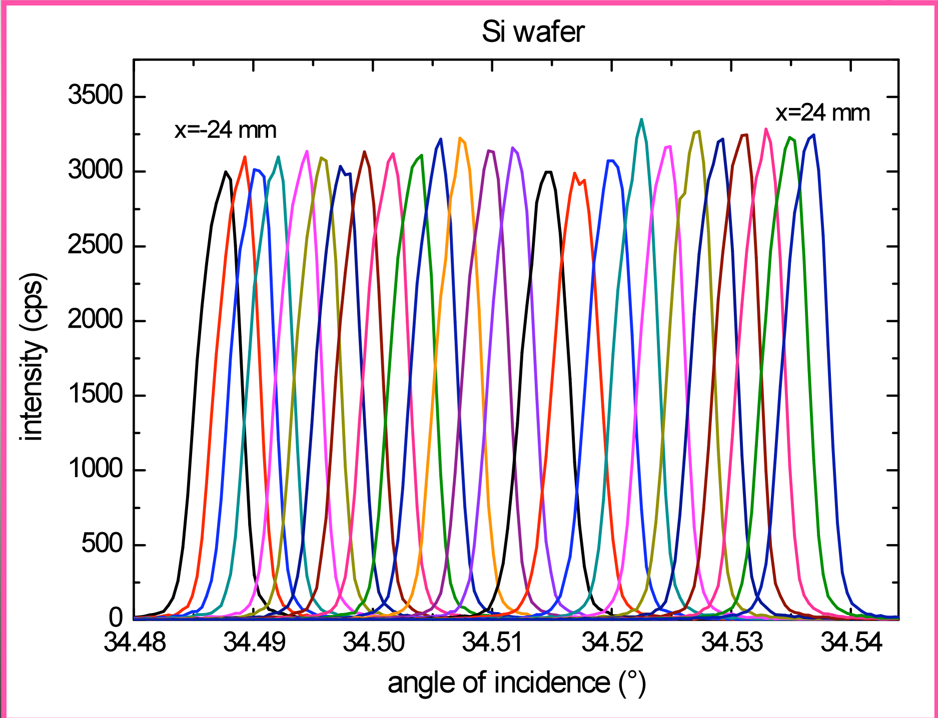
Analyzed materials:

- Si crystals
- GaAs crystals

Si wafer



After a treatment of three hours with sand paper

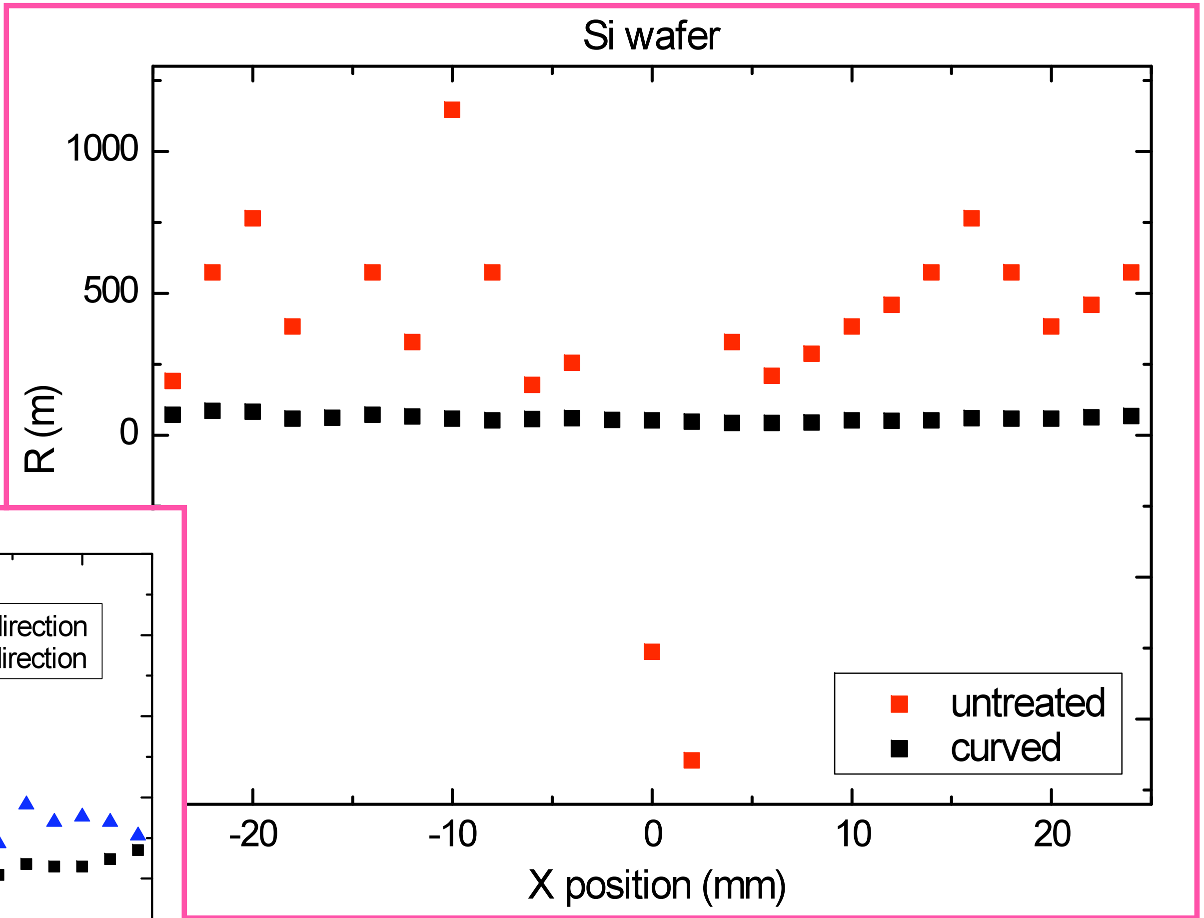


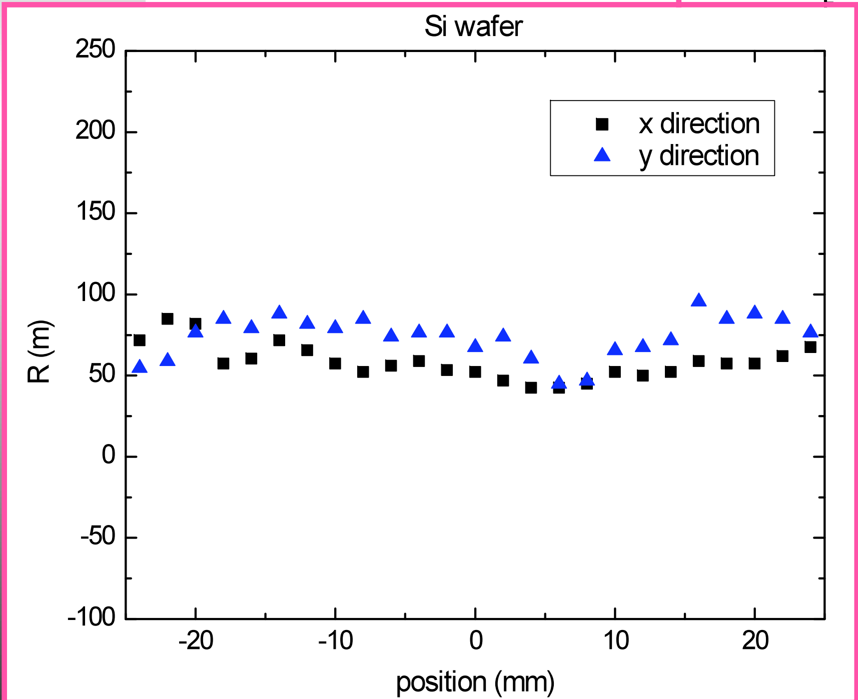
Shift ~ 0.006 °

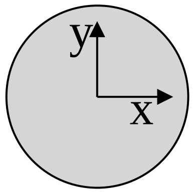
Shift ~ 0.05 °

Si wafer

<R> ~ 58 m







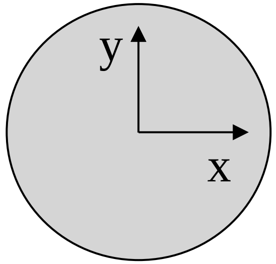
GaAs wafer

Si doped

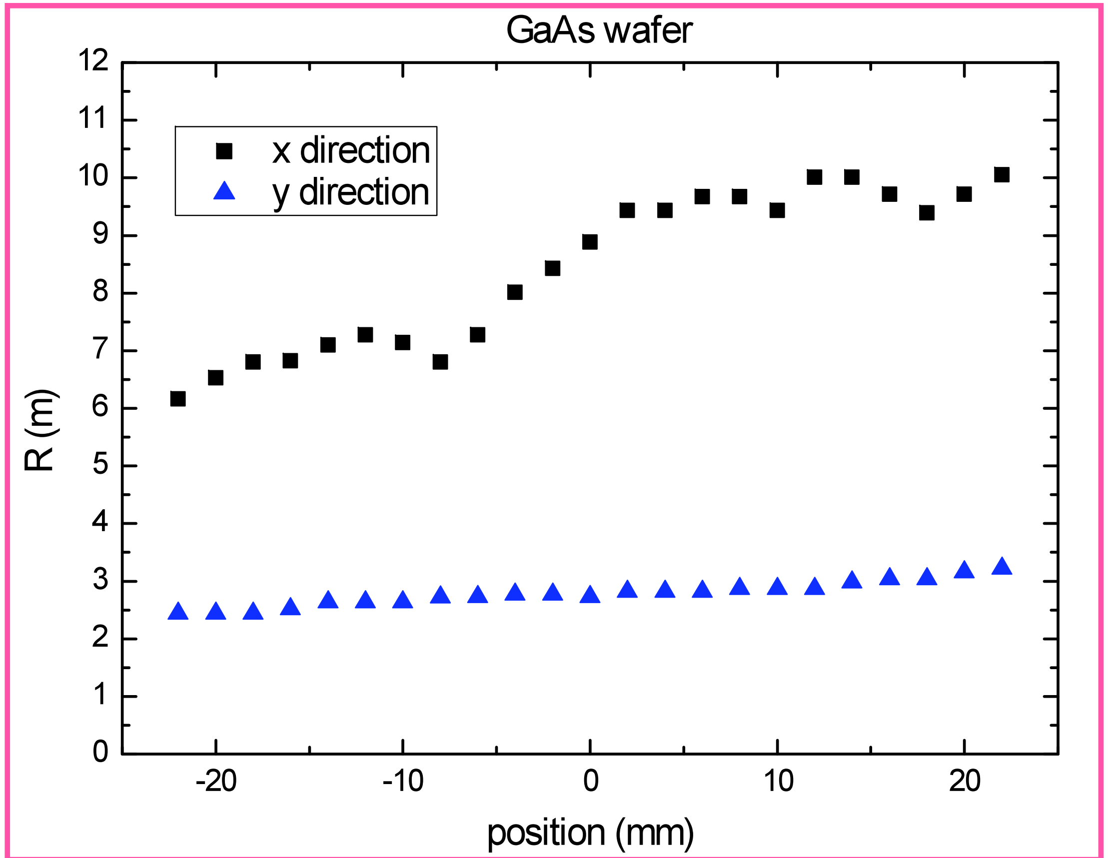
Dislocation free sample

$FWHM$ = 15 arcsec

Rocking curves collected along two perpendicular direction



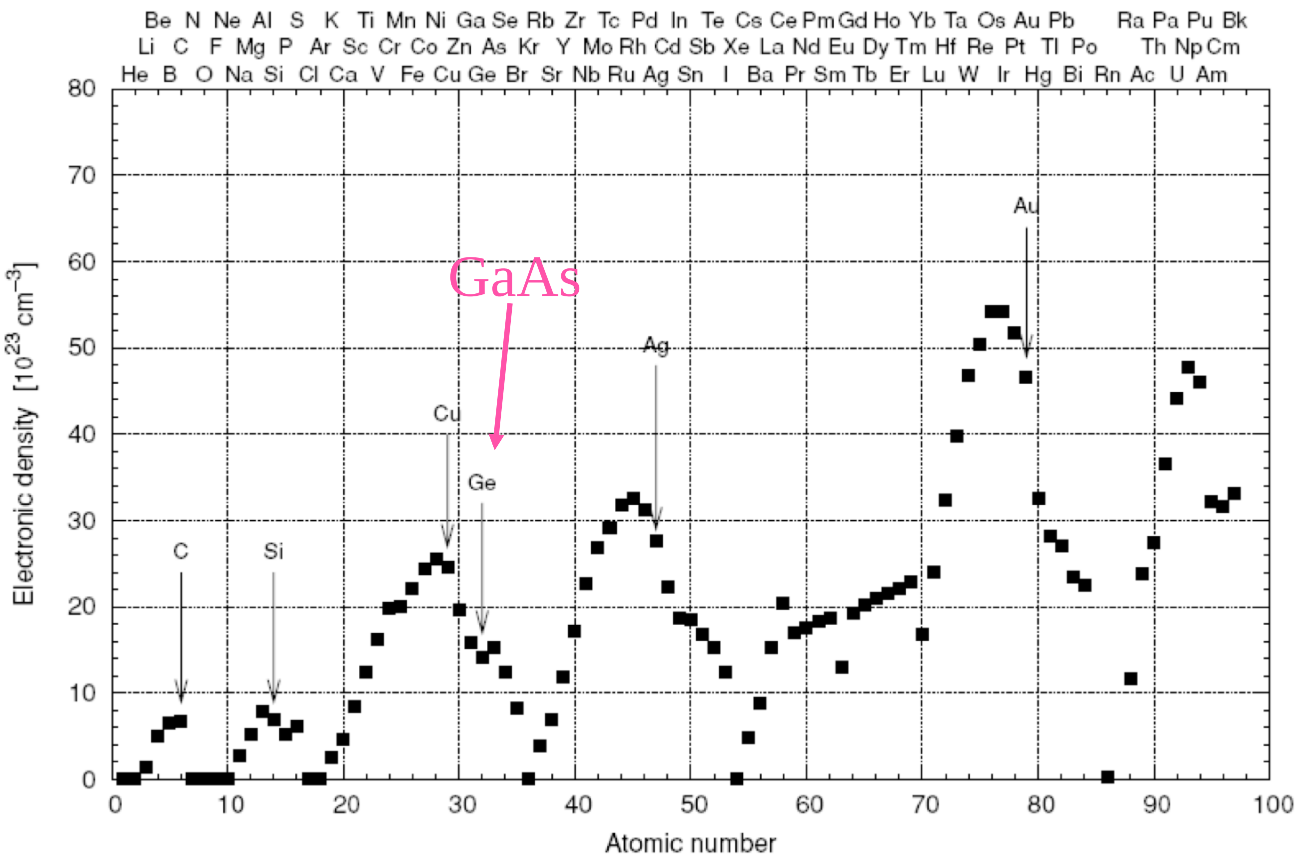
After a treatment of 10 minutes with sand paper



Conclusions

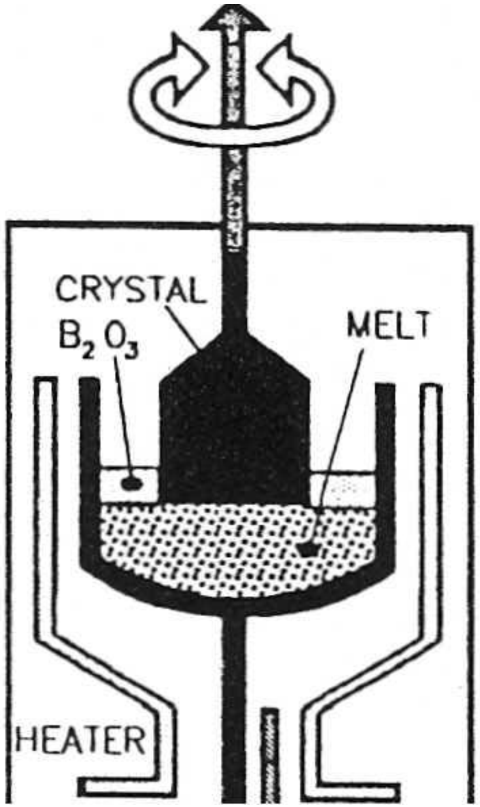
- GaAs is suitable for hard x-ray Laue lens due to its mosaic structure
- It is possible to tailor the mosaic structure by adjusting the growth conditions or introducing dopants
- The mosaic spread measured in different GaAs crystals varies between 10 and 40 arcsec
- An alternative optical element for the Laue lens made of a stack of curved crystals is proposed
- Nearly spherical curvature can be obtained in Si and GaAs samples by introducing a crystal surface damage

Thank you for your attention



As first approximation the diffraction efficiency is linked to the electronic density (in figure)

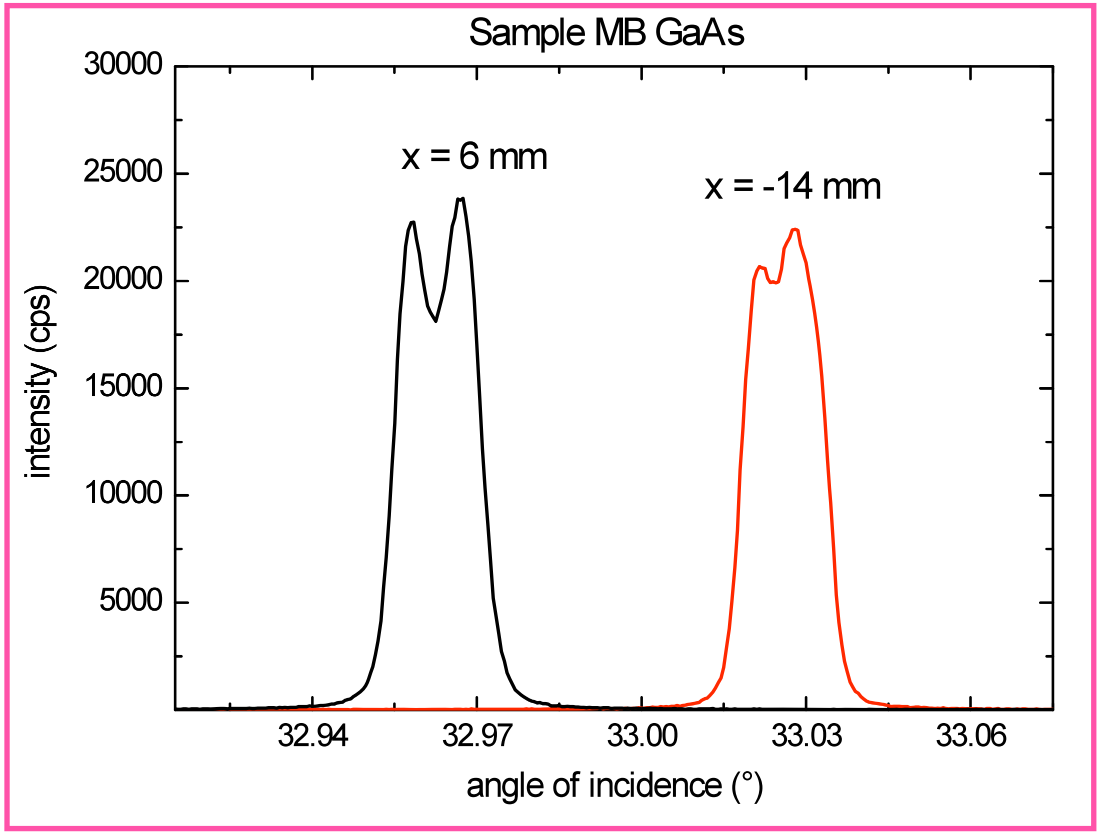
H. Halloin, *Exp. Astron.* **20** (2005) 171



Schematic of LEC growth

Growth parameters

- boron oxide thickness of 15 mm
- argon counter pressure of 20 atm
- thermal gradient at solid/liquid interface in the range of 30°-50°C
- pulling rate of 10 mm/h
- growth direction: <100>

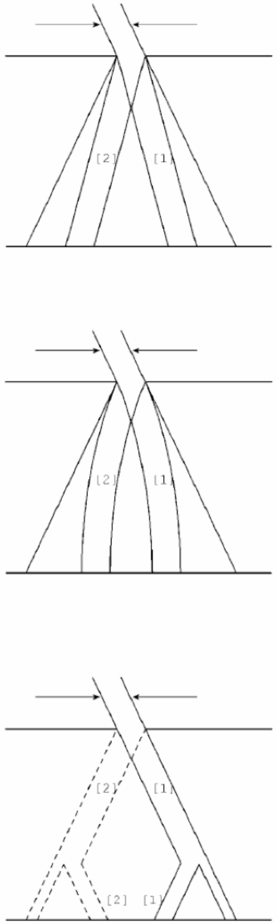


Low angle grain boundaries

Distorted crystals: from dynamical to kinematical theory

Λ = extinction length $\quad \Lambda = \dfrac{V}{r_e \lambda F_h}$

δ = Darwin width



$$\partial\theta = \frac{1}{k\,\sin 2\theta}\,\frac{\partial}{\partial s_h}\,(\mathbf{h.u})$$

Variation of the angle of incidence on reflecting planes due to the distortion

$$\frac{1}{k\,\sin 2\theta}\,\frac{\partial^2}{\partial s_0 \partial s_h}\,(\mathbf{h.u}) << \frac{\delta}{\Lambda}$$

Condition for application of geometrical optics

If we define $\beta = \dfrac{\Lambda}{\cos^2\theta}\,\dfrac{\partial^2}{\partial s_0 \partial s_h}\,(\mathbf{h.u}) \longrightarrow \beta\Lambda << 1$

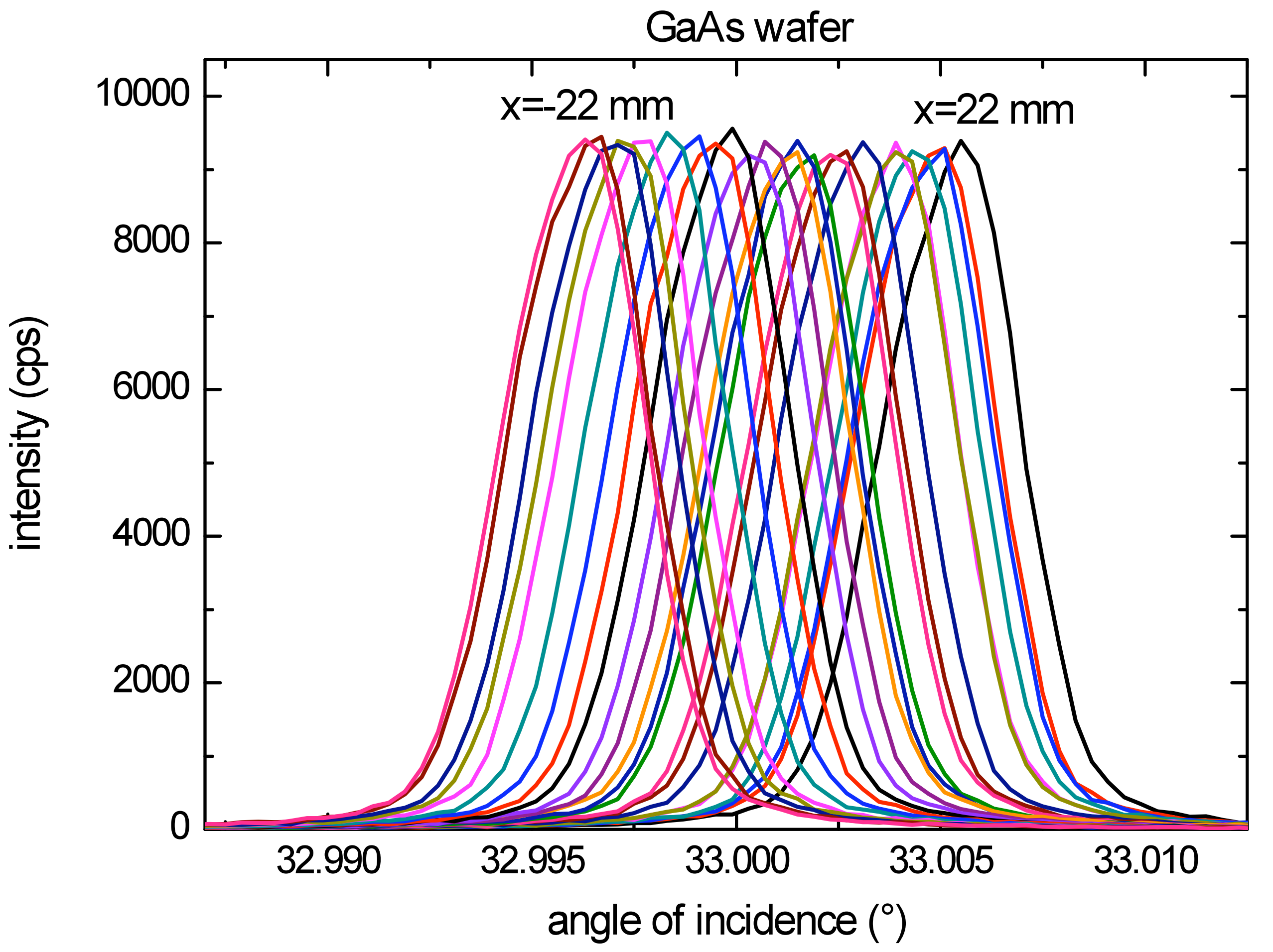
In a distorted crystal the transition from the dynamical to the kinematical diffraction theory can be driven also by the distortion

dynamical $\longrightarrow$ **kinematical**

decreasing wavelength
decreasing structure factor

C. Malgrange, *Cryst. Res. Technol.* **37** (2002) 7

GaAs wafer


GaAs wafer
x=-22 mm
x=22 mm
10000
8000
6000
4000
2000
0
intensity (cps)
32.990
32.995
33.000
33.005
33.010
angle of incidence (°)

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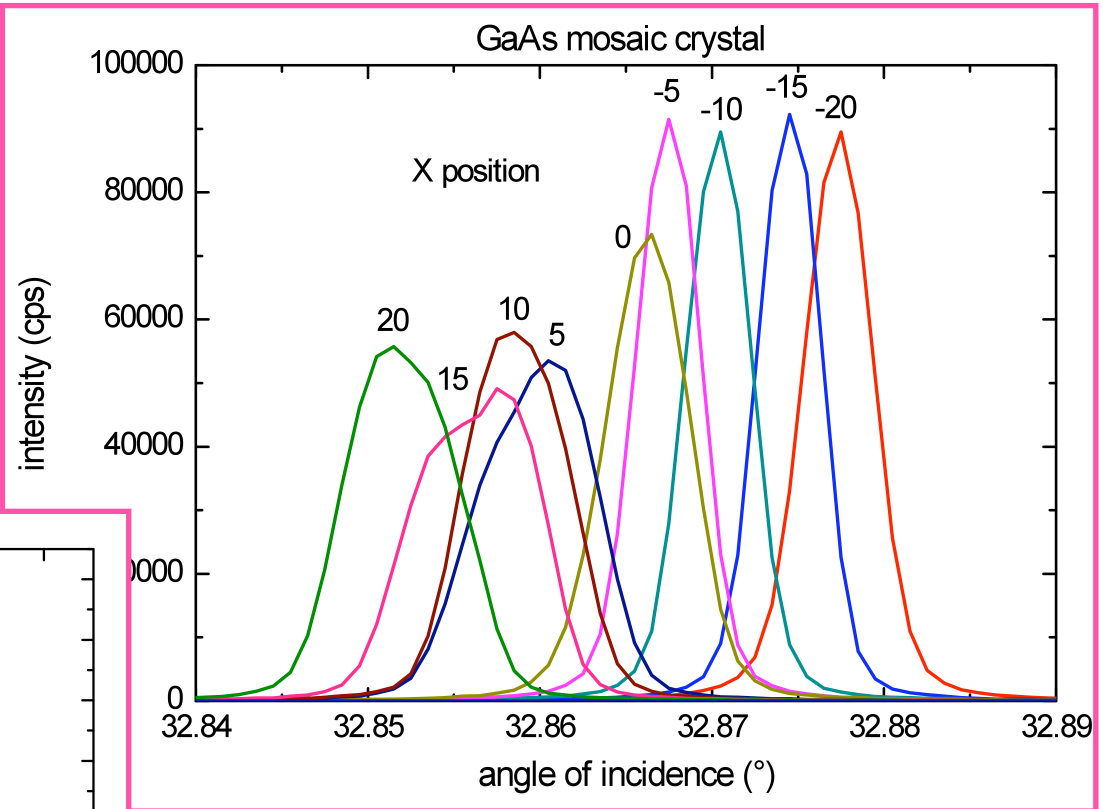
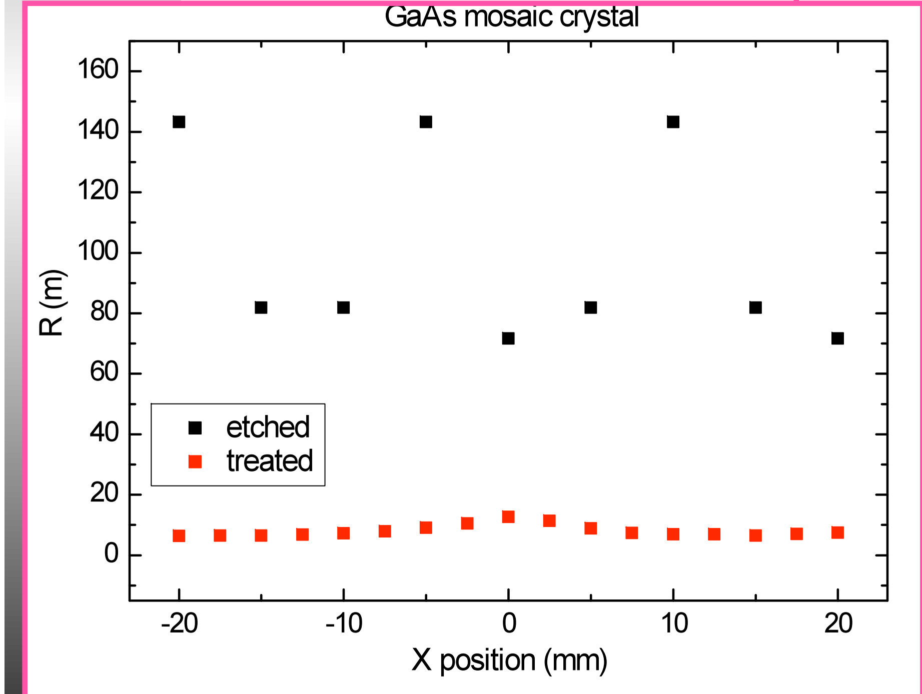
GaAs wafer

Mosaic crystal



After a treatment of 5 minutes with sand paper



σ from 0 up to 25 arcsec

<R> ~ 8 m $\xrightarrow{t = 1\text{ cm}}$ α ~ 4 minutes of arc