Non-Destructive X-ray Diffraction Techniques for Analysis of Die Warpage and Stress Inside Fully Encapsulated Packaged Chips

CIICT
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(f) GlobalFoundries, Sunnyvale, CA, USA.

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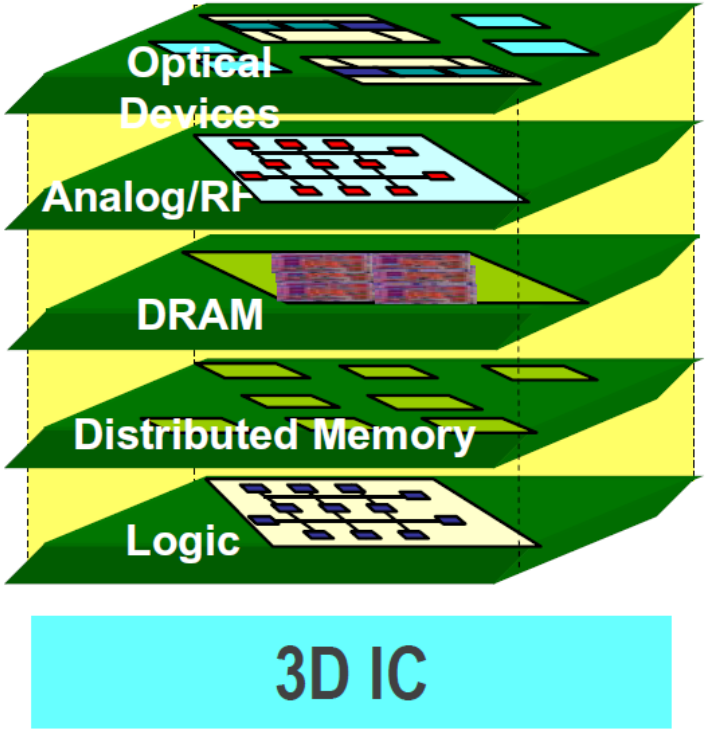
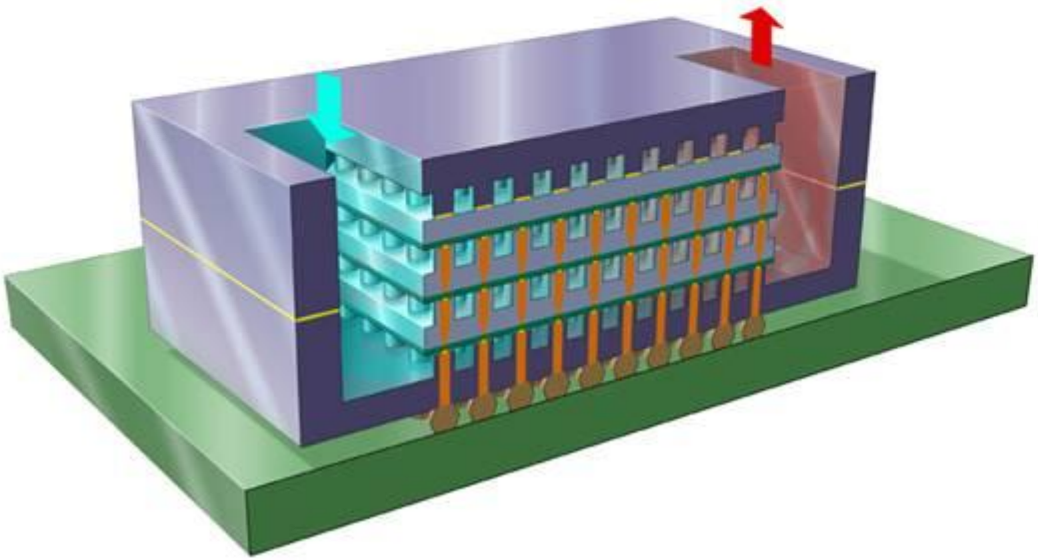
Industry Trends

http://esl.epfl.ch/files/content/sites/esl/files/shared/StdProjects/image002.jpg
http://fand.kaist.ac.kr/Images/3D%20IC.bmp





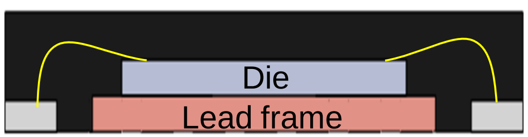
- Future advances will depend on "More than Moore" (MtM) approaches.
- SoC/SiP/3D IC advanced packages are the key enabling technologies.

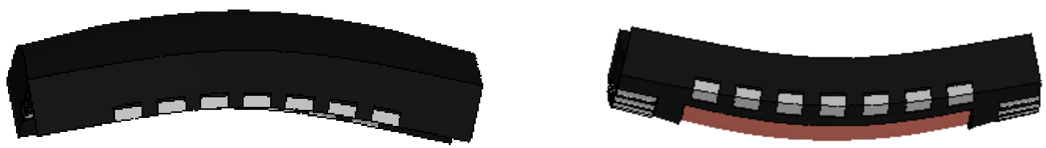
[1] ITRS More than Moore White Paper 2010. http://www.itrs.net/Links/2010ITRS/IRC-ITRS-MtM-v2%203.pdf

Advanced packaged chips

Plagued by reliability issues.

Manufacturing induced thermal stress





Warpage

No compelling metrologies that can non-destructively measure the stress/warpage inside packaged chips.

[2] ITRS More than Moore White Paper 2010. http://www.itrs.net/Links/2010ITRS/IRC-ITRS-MtM-v2%203.pdf

3DSM

- Metrology gap – need to **non-destructively** measure or image stress/strain, warpage or defects inside SoC/SiP/advanced packages.

3-Dimensional Surface Modelling (3DSM)

- 3DSM: the 3-dimensional reconstruction of strain field and lattice misorientation data from x-ray diffraction images.
- Novel tool for non-destructive *in situ* mapping of stresses, strains and deformations <u>inside</u> packaged systems.

[3] (Invited talk) J. Stopford *et al.* , International Conference on Materials for Advanced Technologies, Singapore, Jul 2011.
[4] J. Stopford *et al.,* European Microelectronics Packaging Conf. (EMPC 2011), Brighton, England, 12-15 Sept. 2011.

Synchrotron X-Ray Topography/ X-Ray Diffraction Imaging

- White beam, i.e. a continuous spectrum of wavelengths (λ) available.
- Bragg's Law:

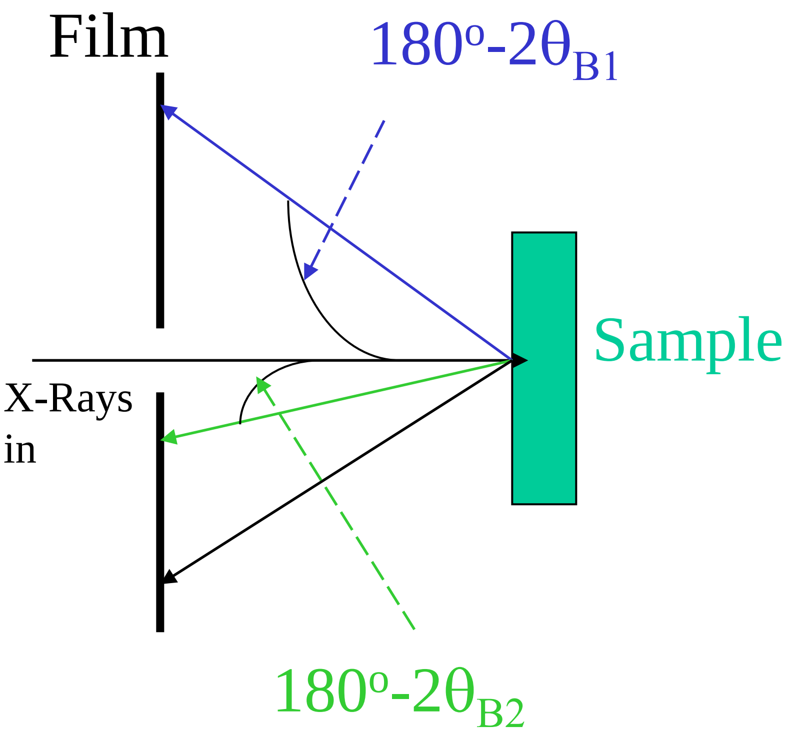
Many diffraction directions!!!

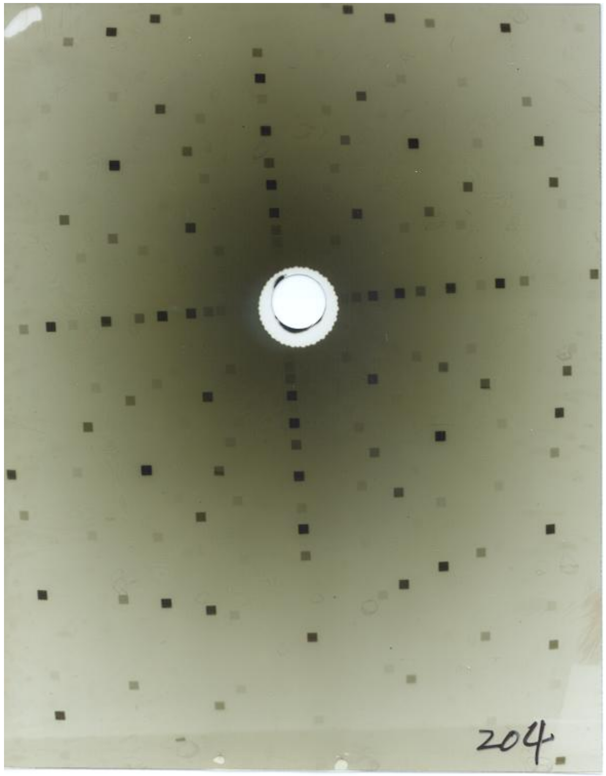
$$2d_{hkl} \sin\theta_B = \lambda$$

∞ no. of lattice planes

White beam: continuous distribution

SXRT/XRDI



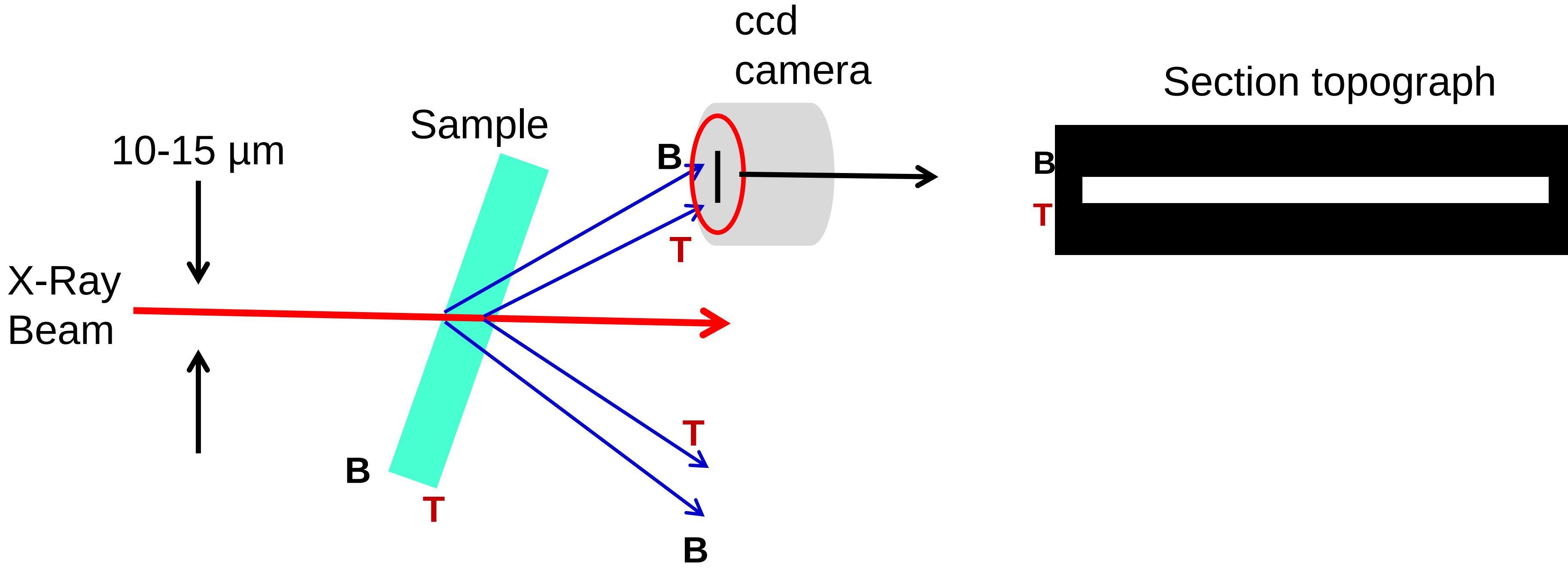


Back Reflection (Bragg) Geometry

Topographs form a Laue pattern → Each Laue spot is an x-ray topograph, arising from a different set of diffracting planes.

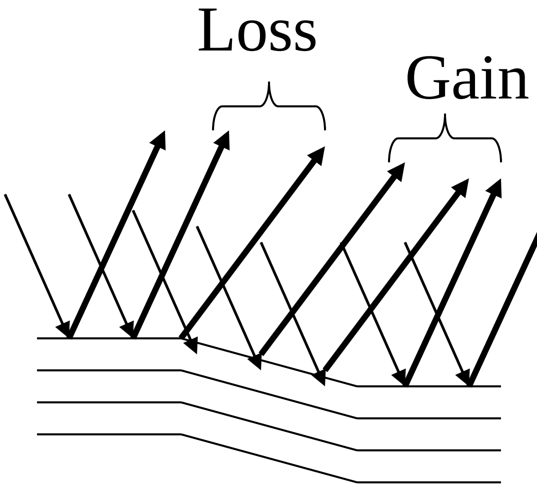
Synchrotron XRDI/3DSM

- 3DSM was first developed by our team using XRDI at synchrotron radiation source at ANKA, Institute for Synchrotron Radiation, Karlsruhe, Germany.
- White Beam- Continuous spectrum of radiation, high intensity, low divergence.

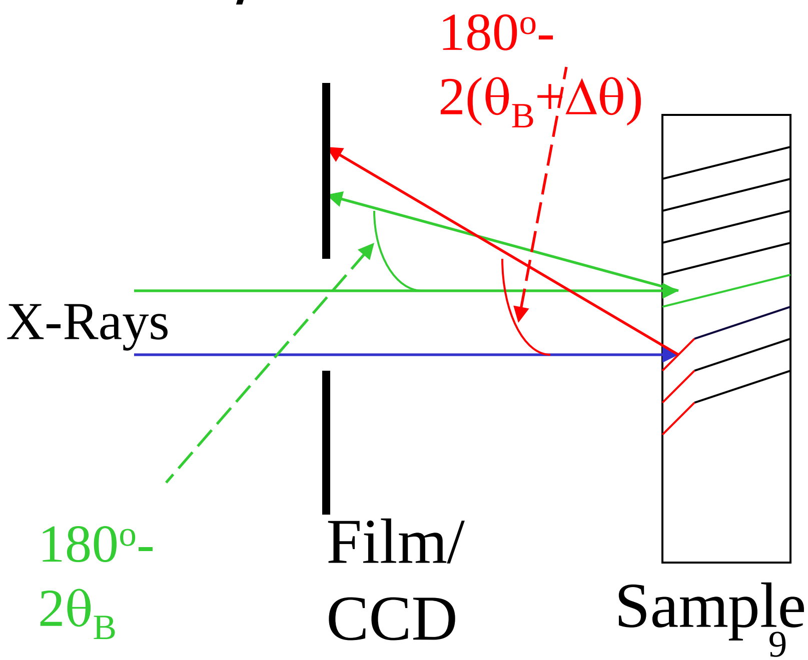


Orientational Contrast

- Diffracted beams can overlap or diverge due to lattice misorientation.

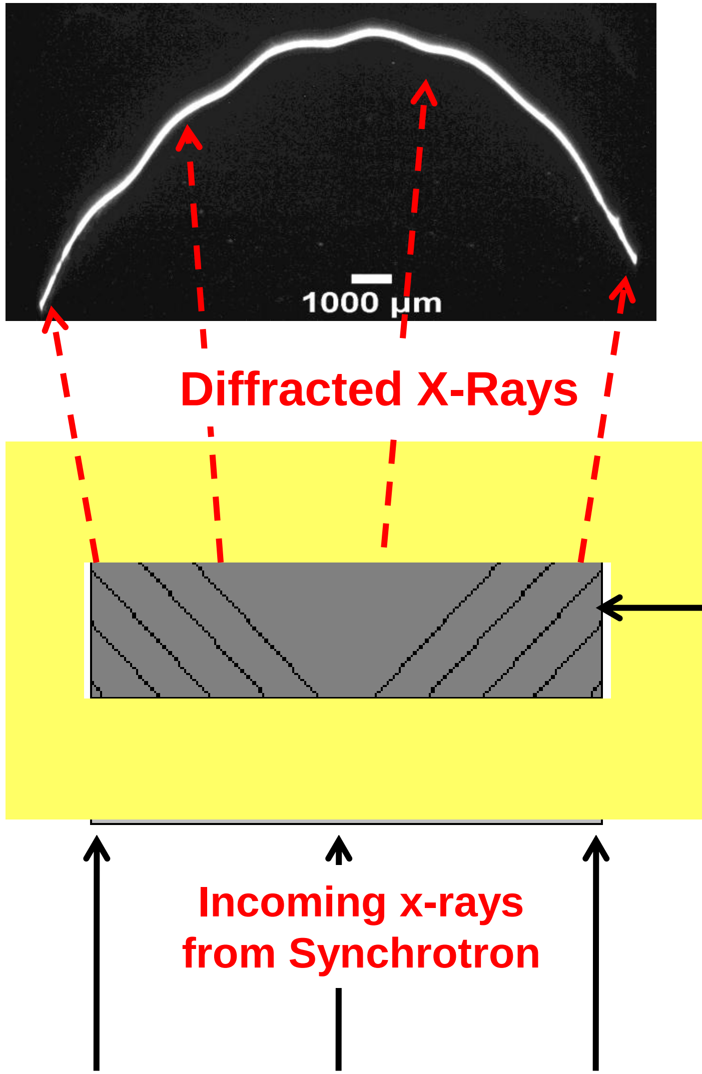


- Extremely misorientated regions can appear on a different place on the CCD/film!



NB:
•Gain = white on ccd (more intensity)
•Loss – ***black*** on ccd (less intensity)

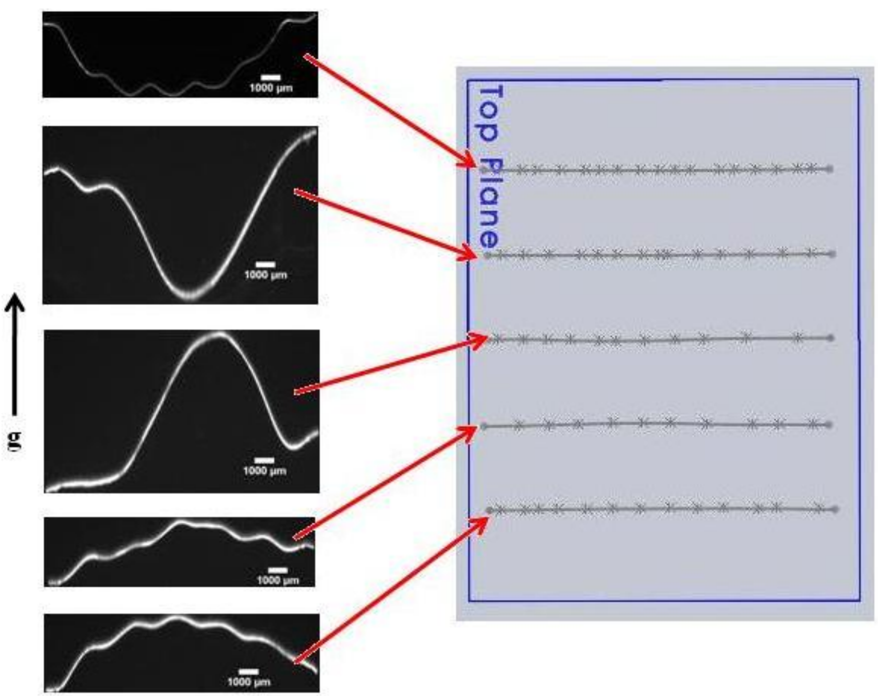
3DSM- Image formation



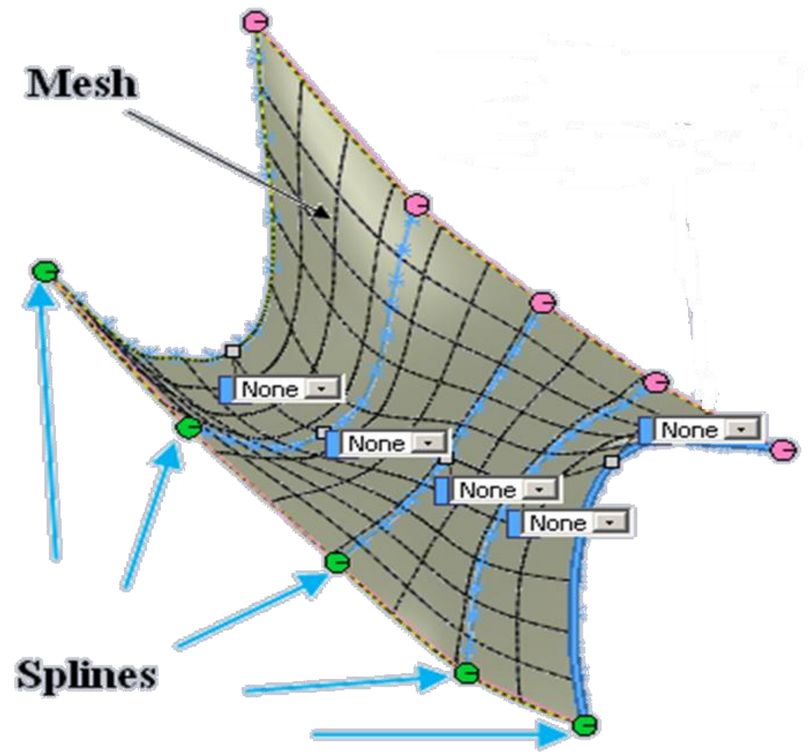
Section topograph (ST) of QFN package, showing lattice misorientation in Si chip

Silicon die in QFN package

3DSM



Horizontal ST topographs and corresponding horizontal B-Spline curves created in *SolidWorks™*.

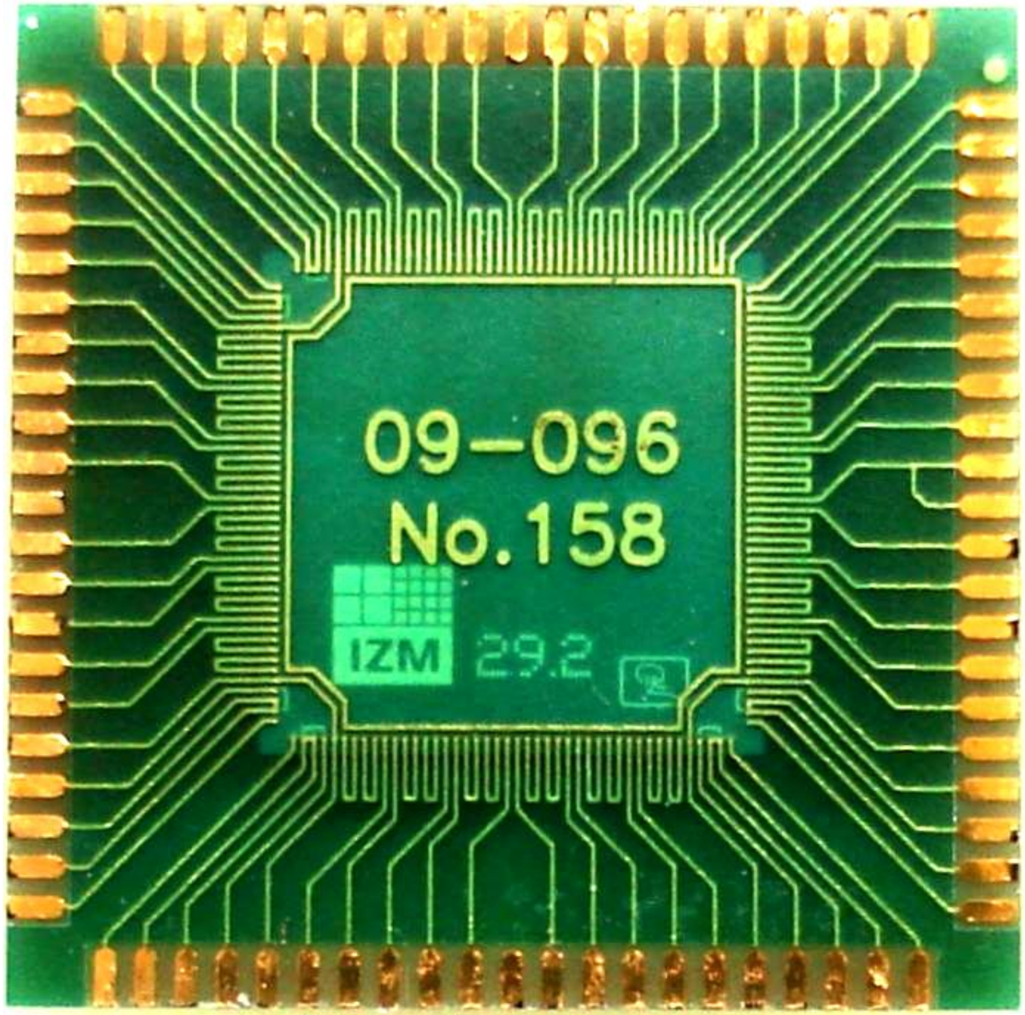


Boundary surface formation showing splines and mesh detail.

[3] (Invited talk) J. Stopford *et al.* , International Conference on Materials for Advanced Technologies, Singapore, Jul 2011.
[4] J. Stopford *et al.,* European Microelectronics Packaging Conf. (EMPC 2011), Brighton, England, 12-15 Sept. 2011.

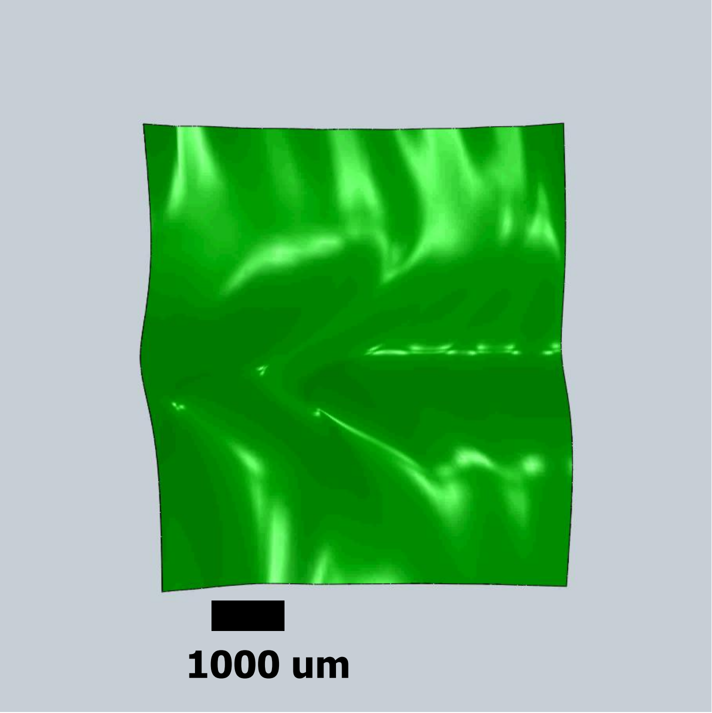
Synchrotron 3DSM

- Completely encapsulated QFN package.



Synchrotron 3DSM

- Example of 3DSM, showing the warpage/lattice deformation of the (220) planes in the Si chip of a completely encapsulated QFN package.



From Synchrotron Radiation Source □Lab-Based X-ray System

Synchrotron radiation source

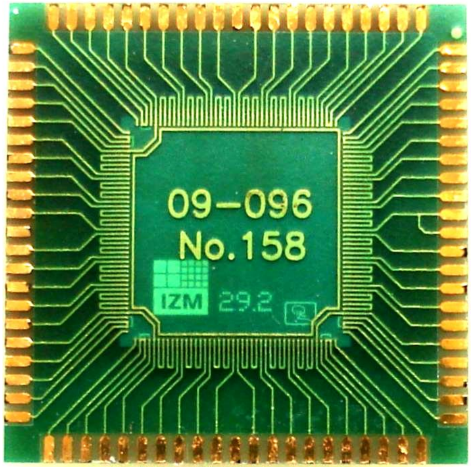
Lab. based XRD

JV Bede D1 High-resolution X-Ray Diffractometer

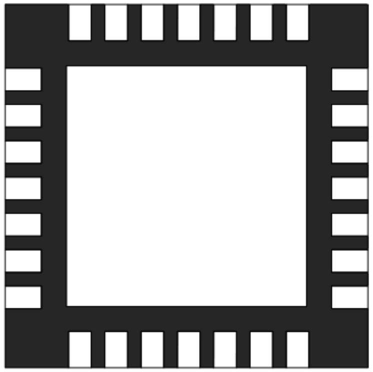
Laboratory based X-ray diffraction 3DSM
(Lab. XRD/3DSM)

Proof of Concept: Lab XRD/3DSM

- Embedded QFN packages provided by Fraunhofer IZM Berlin

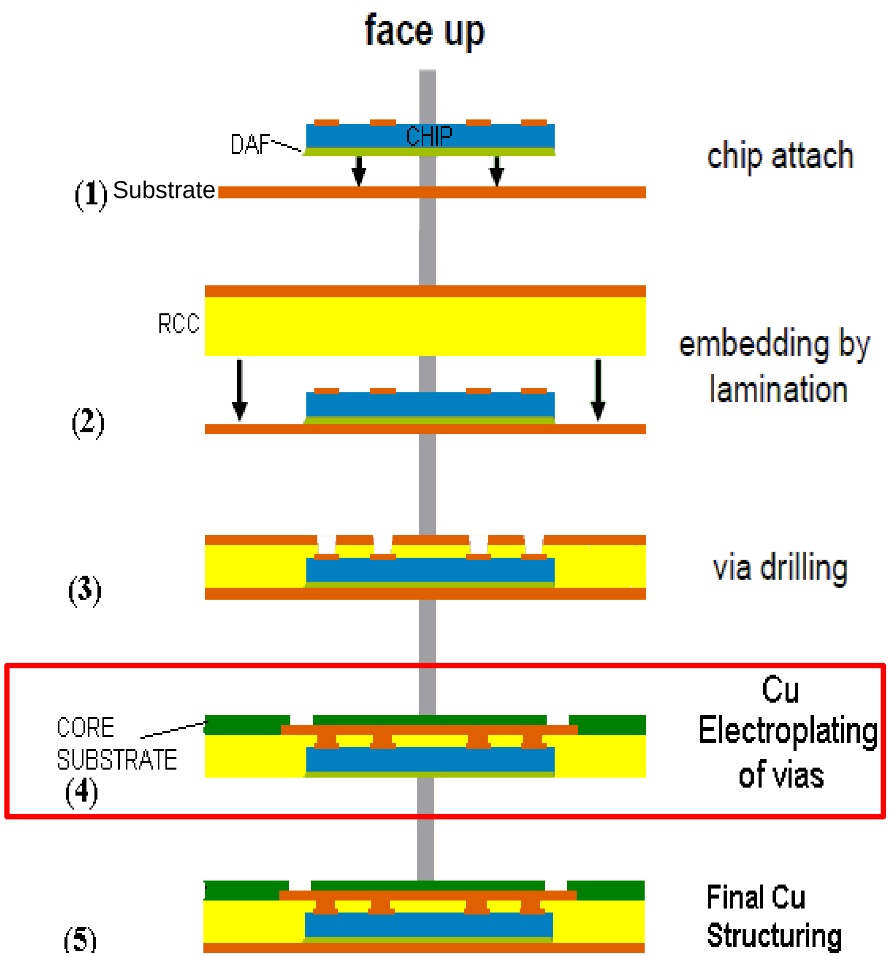


- Commercially available 28-pin Ultra-thin QFN (UQFN) flash microcontroller from Microchip



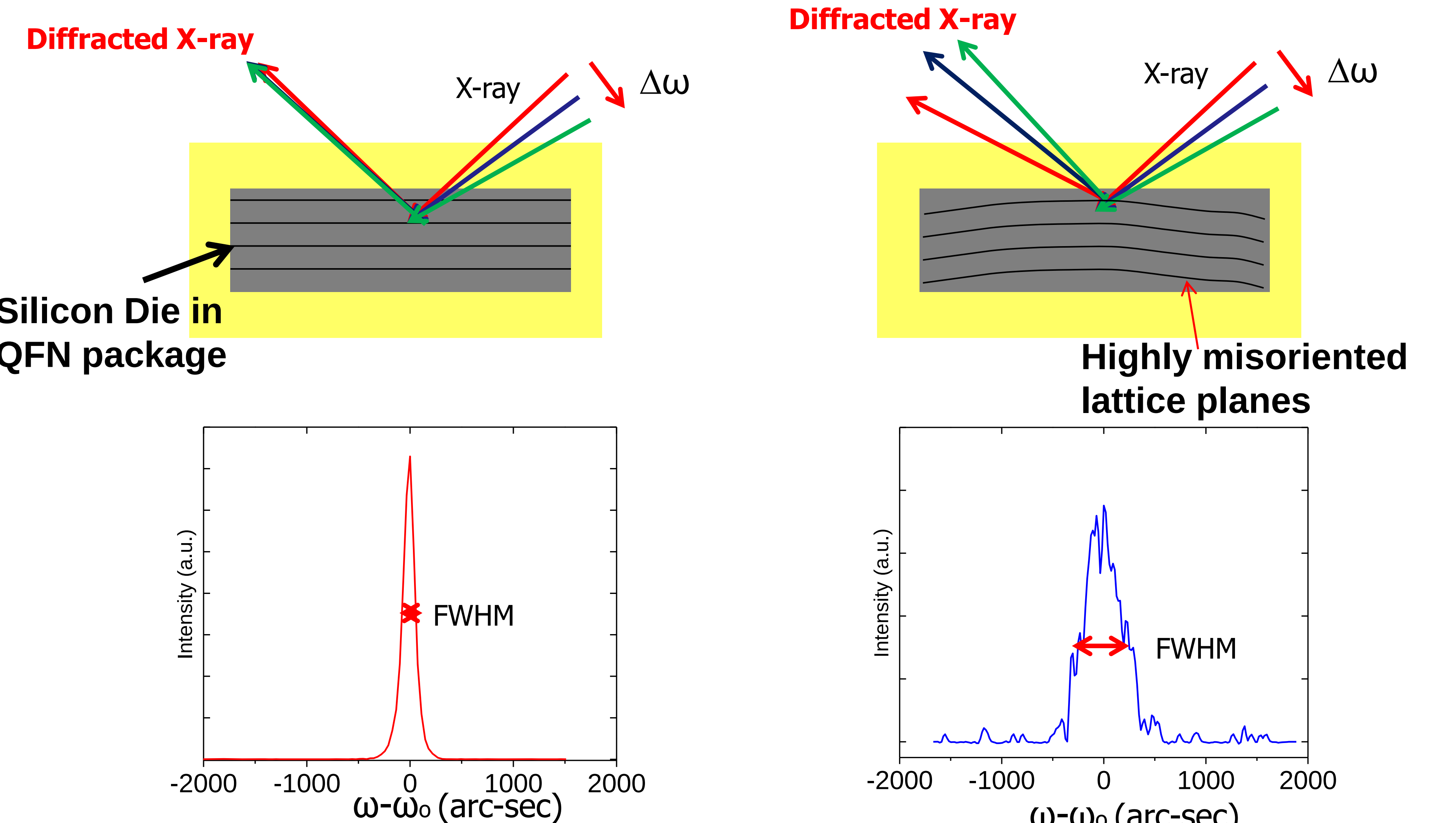
Embedded QFN Packages

QFN Embedding / Packaging Steps



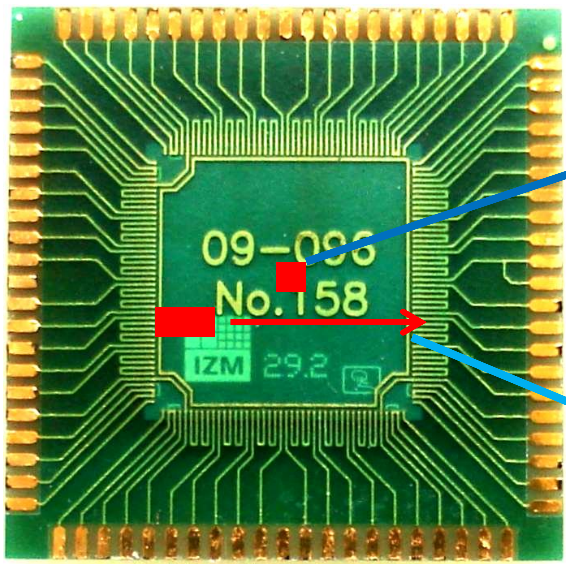
The package consists of a 5 mm x 5 mm Si die (with 50 μm thick), embedded face up in a substrate.

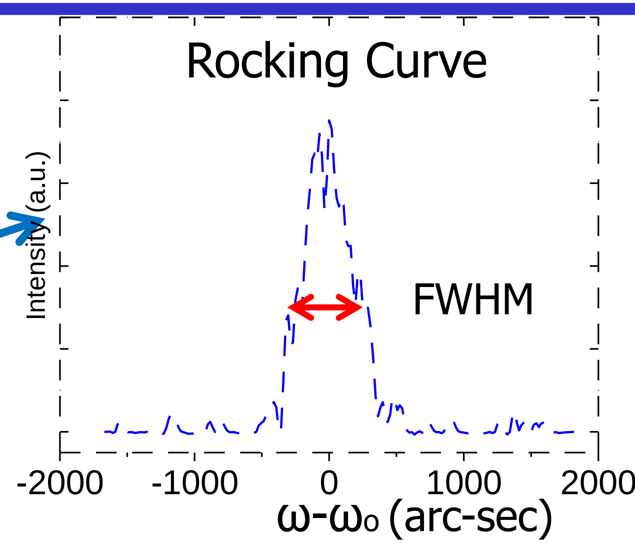
X-ray Diffraction Rocking Curve (XRD RC)

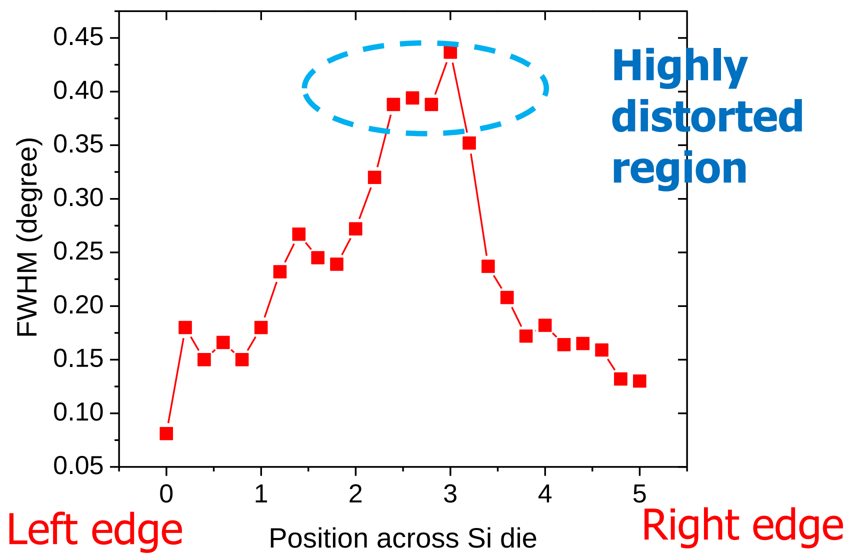


=> Peak is narrow **=> Peak is broadened due to warpage**

XRD RC FWHM line scan





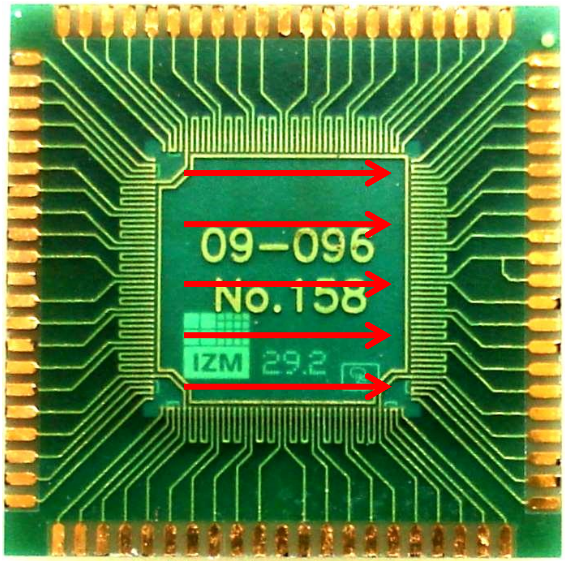


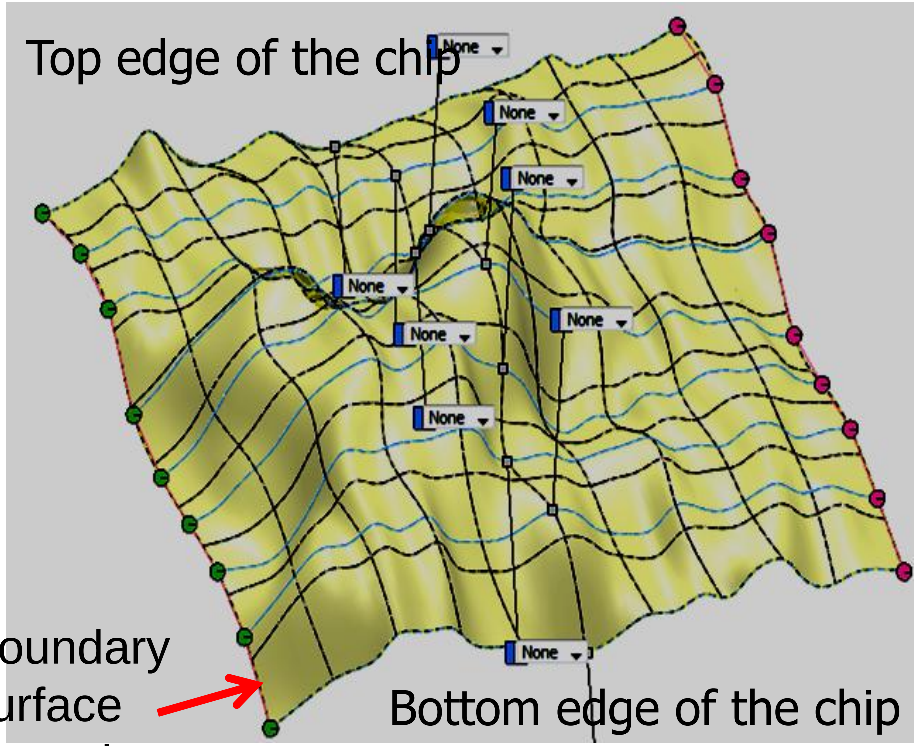
- X-ray spot size = 250 µm x 250 µm
- Step size = 200 µm

RC FWHM line scan, 5mm

→ Line scan = 26 points

XRD RC FWHM line scan





Boundary surface formation

RC FWHM line scan, 5mm

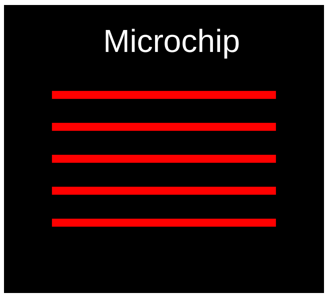
Line scan = 26 points

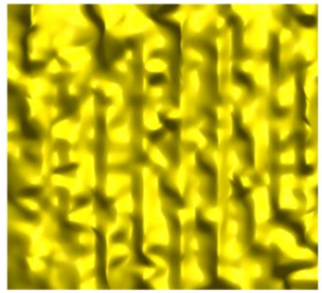
Mapping of RC FWHM line scan, 5 mm x 5 mm

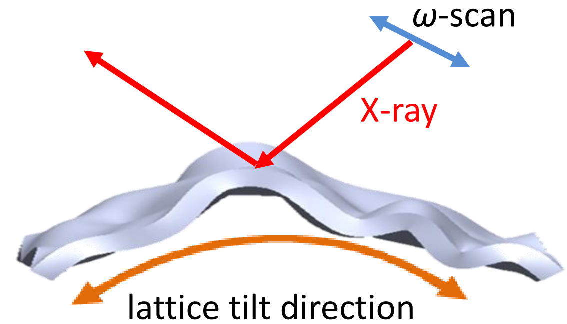
No. of points = 676

XRD/3DSMs recorded at phi = 0^{o} and 90^{o}

Phi=0 deg

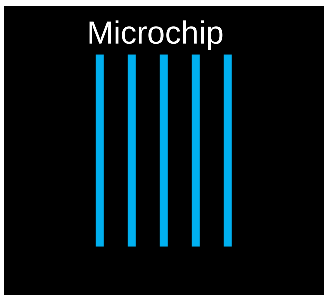


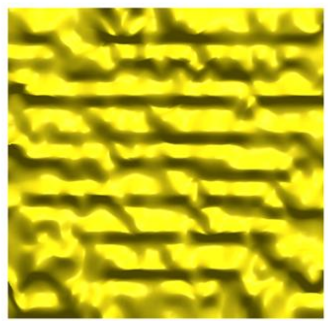




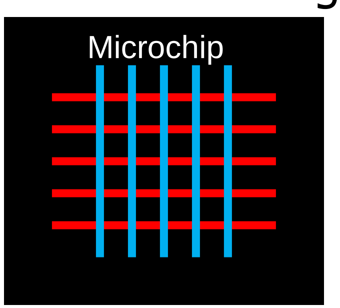
At phi = 0^{o}, ω-scan/RC is most sensitive to lattice tilt parallel to the ω-scan direction

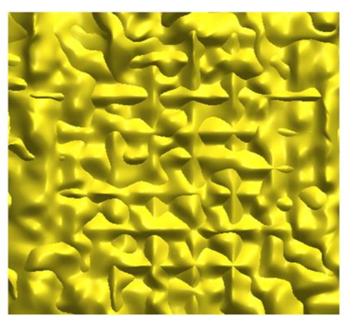
Phi=90 deg





Phi=0 + 90 deg

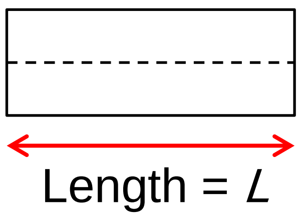




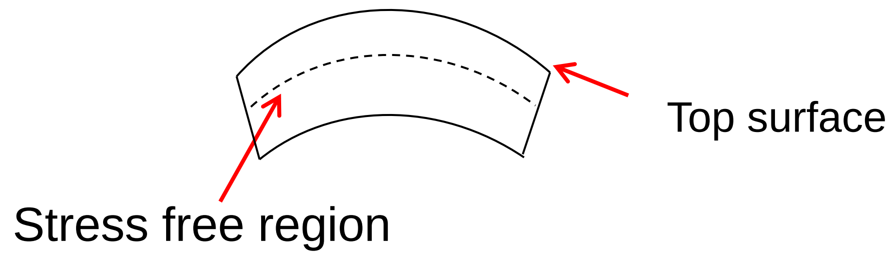
To investigate the lattice misorientations of the two orthogonal (110) planes

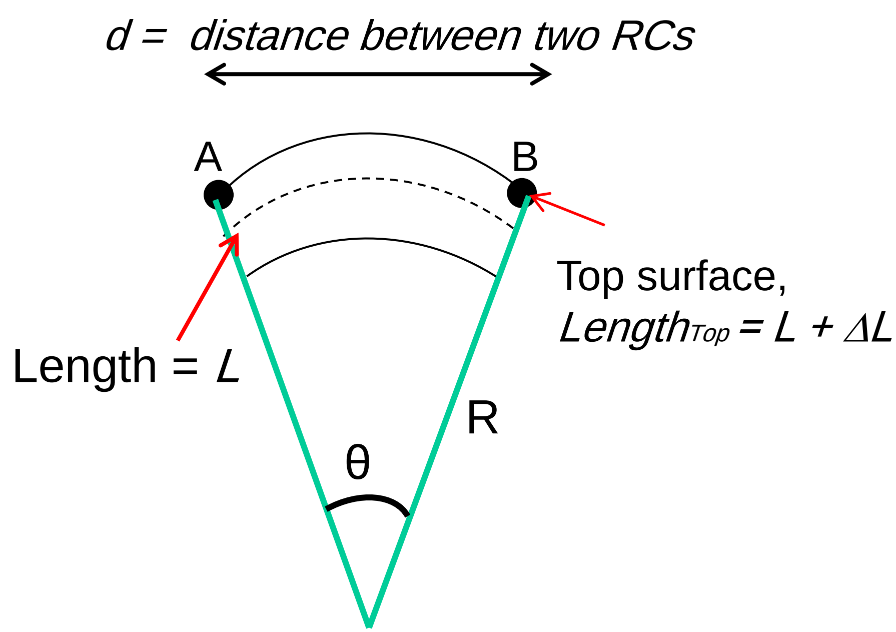
Stress Estimation

Without warpage



With warpage



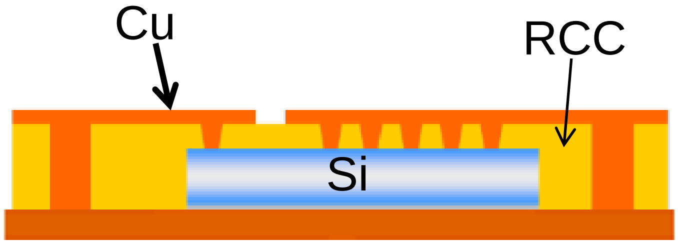


$$Stress = \frac{\Delta L}{L} \bullet E$$

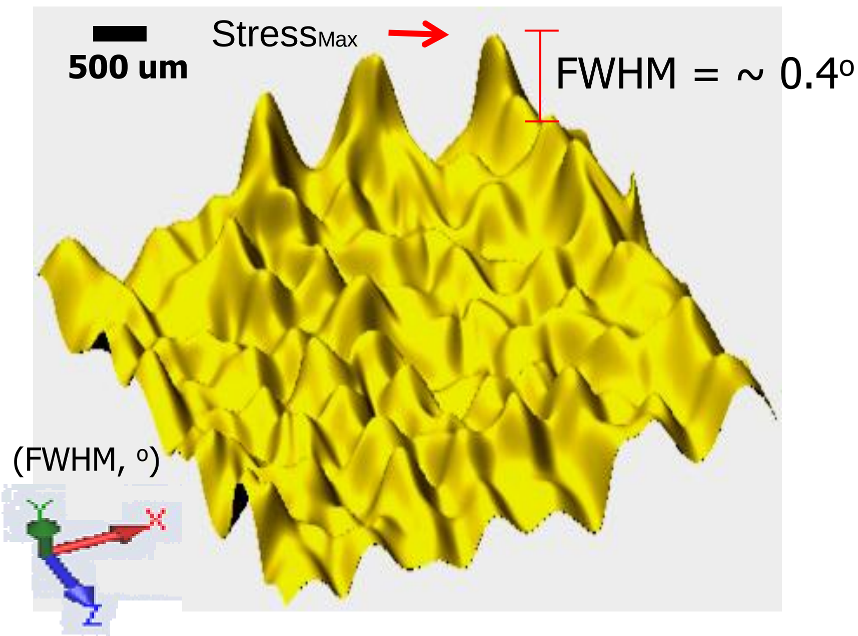
$$\left(\sigma_{xx} + \sigma_{yy}\right) = E\left(\frac{t\Delta\omega_{Bragg}}{2d}\right)$$

[5] Akio Toda and Nobuyuki Ikarashi, J. J. Appl. Phys. 49 (2010) 04DB03

Stage 4: Via Electroplating



Schematic diagram of Stage 4 chip.



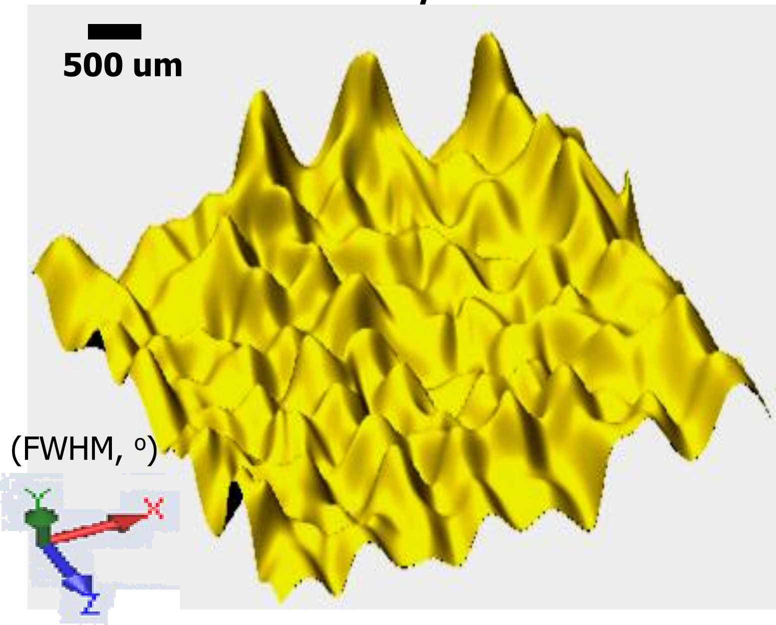
Lab. XRD/3DSM showing lattice deformation of the (110) planes in the Si chip after stage 4 of processing.

- Chip is covered from the top side with a resin-coated-copper (RCC), using vacuum lamination process.
- A pulsed 355 nm UV laser used to drill the microvias, and metallisation of vias.

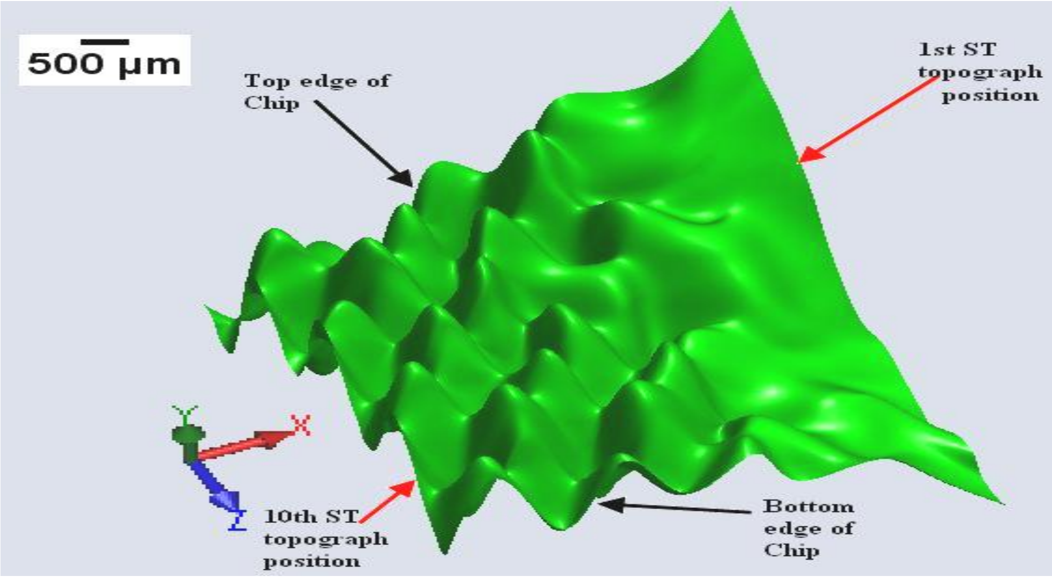
- Lab. XRD/3DSM reveals a distinctive 'rippled' profile, with a peak to peak pitch of 550 – 600 um.
- $FWHM_{Max}$ = ~ 0.40 deg
- $Stress_{Max}$ = ~ 140 MPa

Stage 4: Via Electroplating

Lab. XRD/3DSM

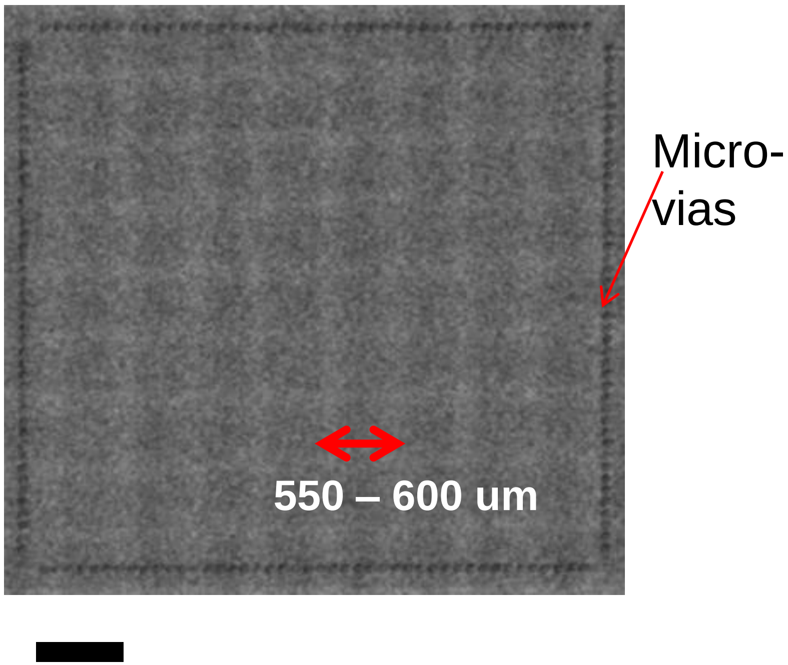


Synchrotron 3DSM



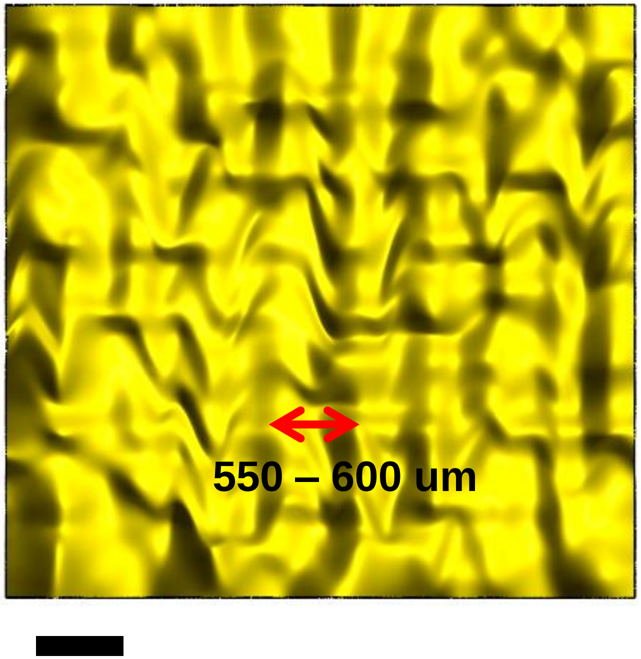
Stage 4: Via Electroplating

X-ray radiographic image



1000 um

Lab. XRD/3DSM

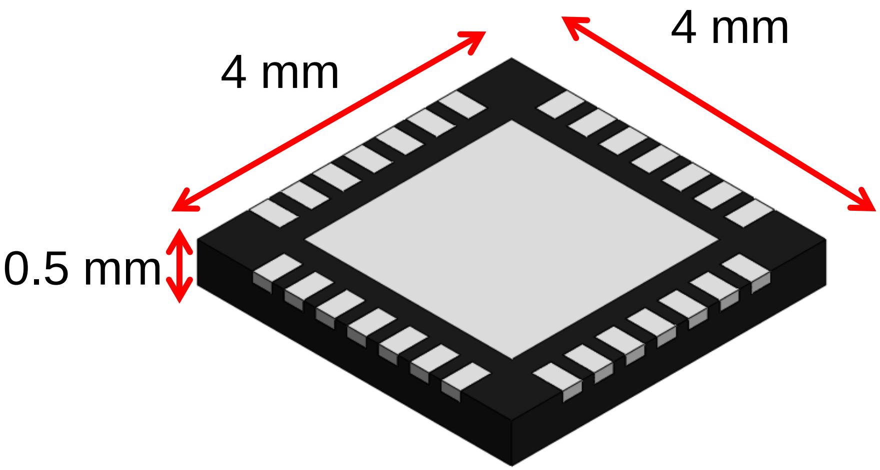


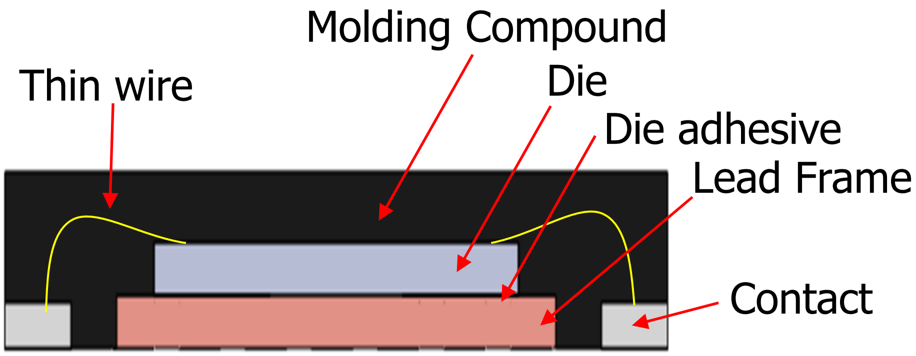
1000 um

The development of distinctive "rippled" profile
=> Stress most likely induced by vacuum lamination process

UQFN packages

- Commercially available 28-pin UQFN flash microcontroller from Microchip

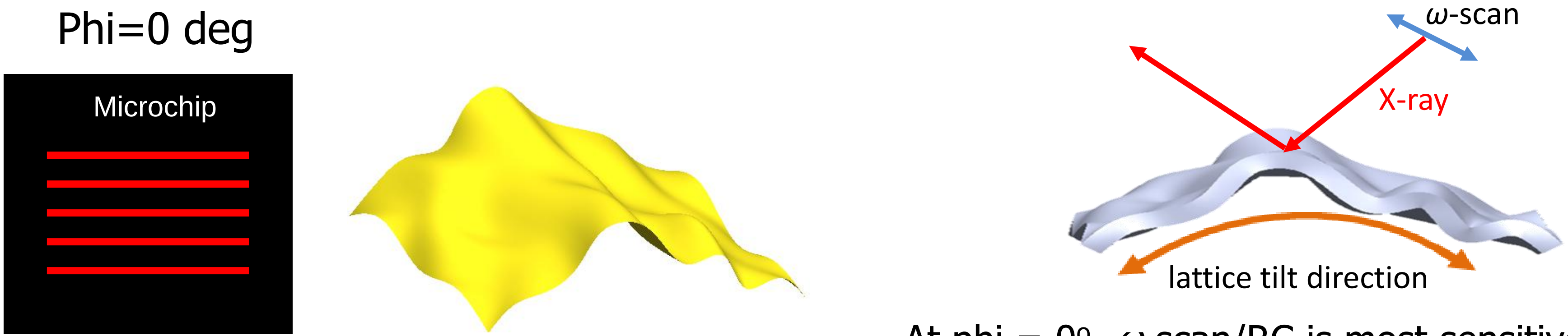




- The Si die is measured to be 2.2 mm x 2.4 mm in size.
- The thickness of Si die is ~ 150 um.

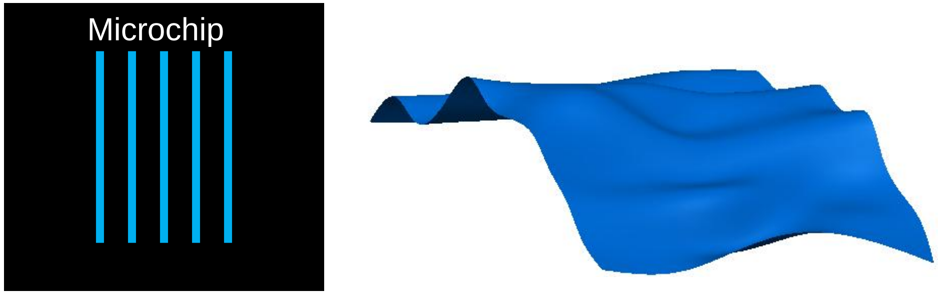
XRD/3DSMs recorded at phi = 0° and 90°

Phi=0 deg



At phi = 0°, *ω*-scan/RC is most sensitive to lattice tilt parallel to the *ω*-scan direction

Phi=90 deg

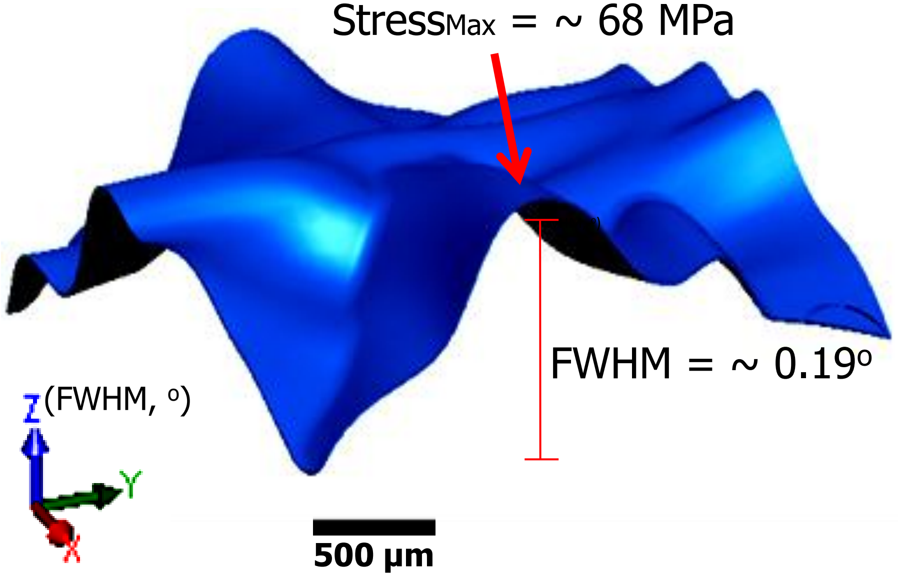


Phi=0 + 90 deg

To investigate the lattice misorientations of the two orthogonal (110) planes

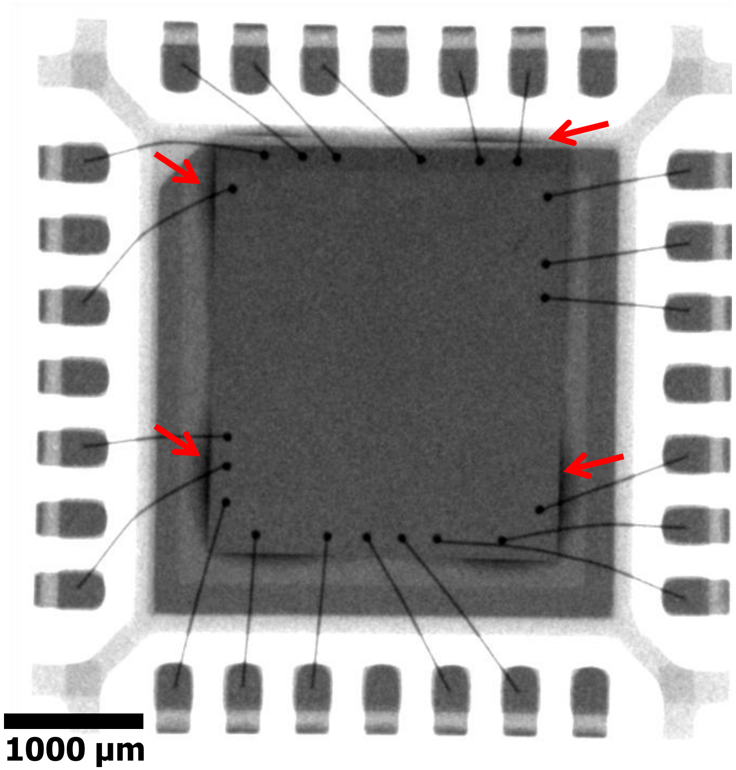
UQFN packages

Lab. XRD/3DSM



- Lab. XRD/3DSM showing lattice deformation of the (110) planes in the Si chip
- Warpage is relatively low at the corners of the chip and increases gradually approaching the centre of the Si die.

X-ray radiographic image

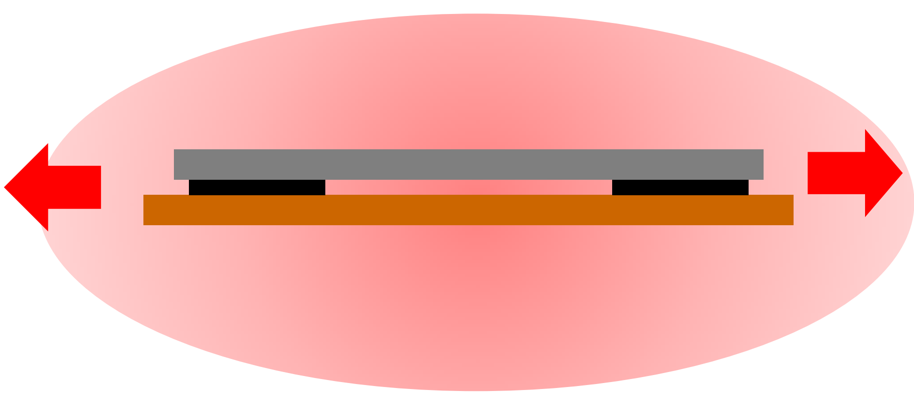


- Die adhesive applied mainly around the corners of the Si die.

UQFN packages

- Die attach process taking place at an elevated temperature, >100ºC

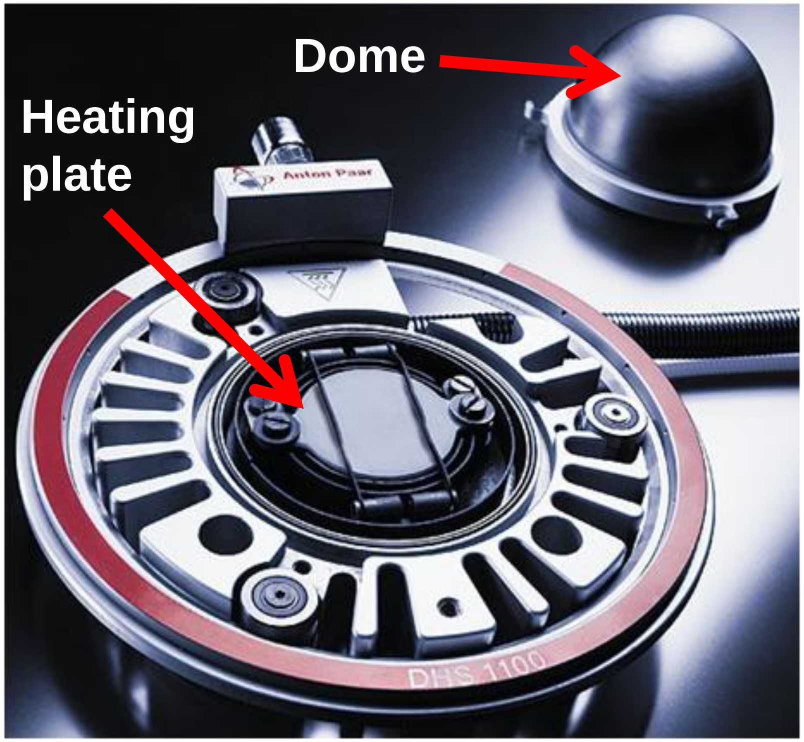
- Thermal stress is formed upon cooling down to room temperature => warpage

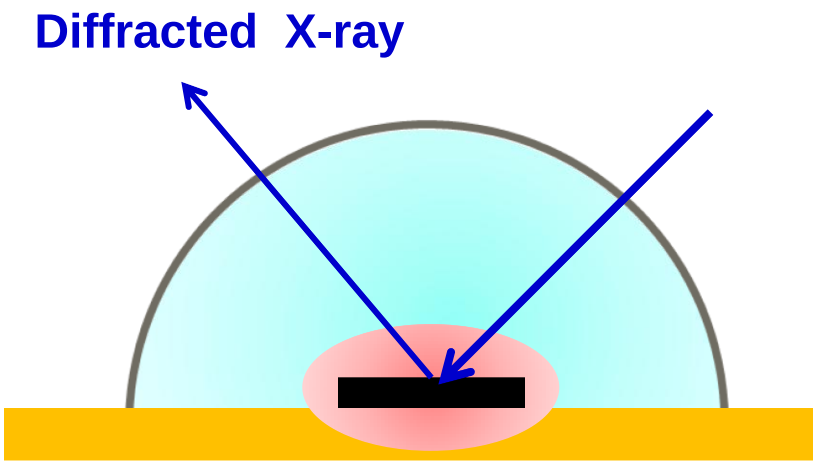


- The warpage is expected to relax back if a thermal load is applied.

In situ XRD Annealing

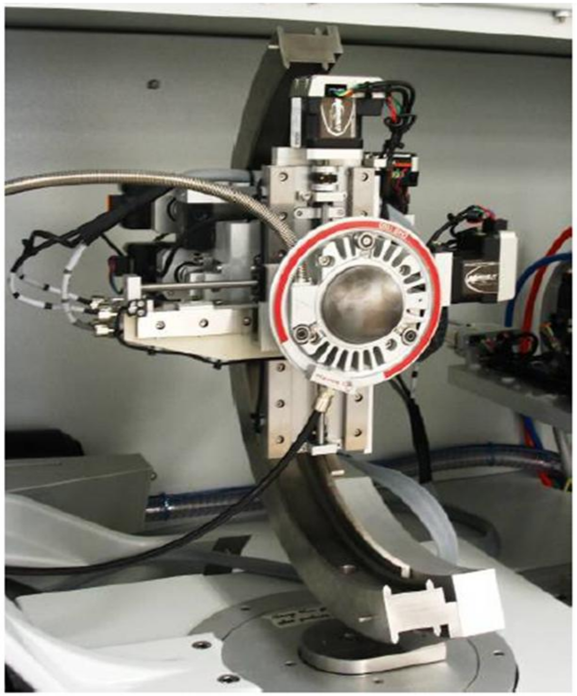
- JV Bede D1 High-resolution X-Ray Diffractometer
  -equipped with an Anton Paar DHS 1100 heating stage





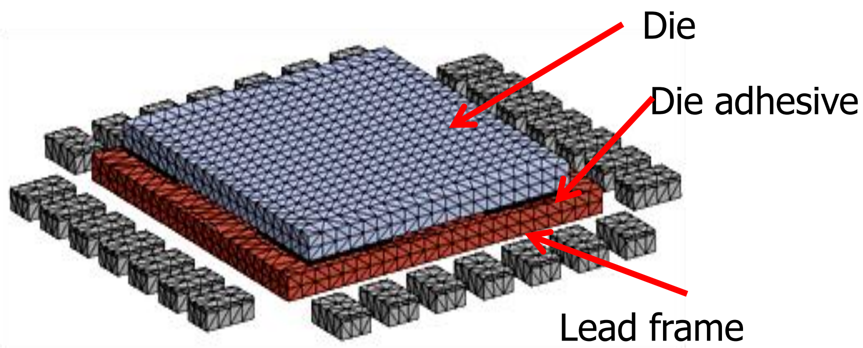
In situ XRD Annealing

In situ XRD Annealing Experiments
- Anton Paar DHS 1100 heating stage



- at 25 °C, 55 °C, 85 °C and 115 °C

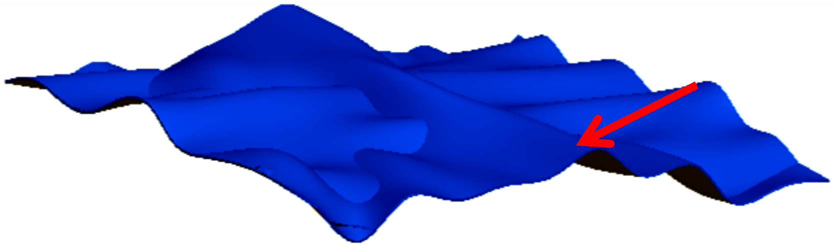
Finite Element Analysis (FEA)
- by SolidWorks™



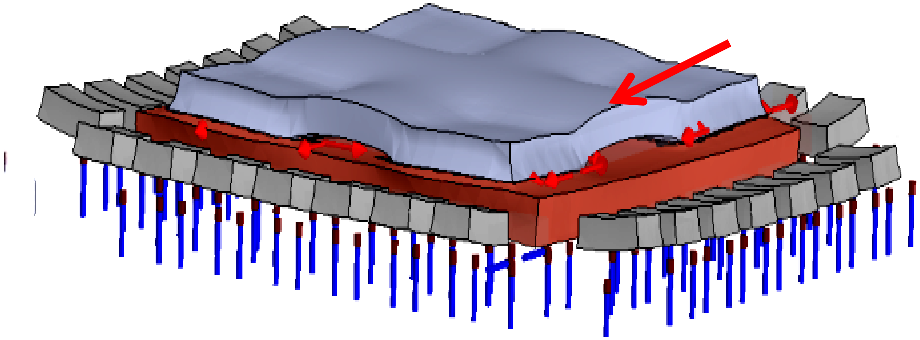
- Finite element model of the full QFN package (**a simple approximation*)

In situ XRD Annealing

Experimental results :
XRD/3DSM

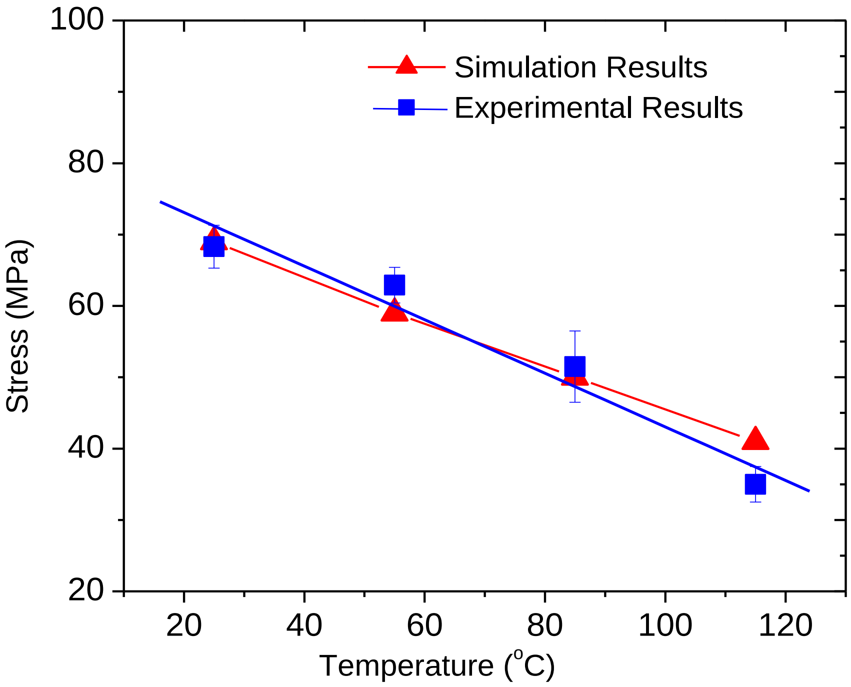


FEA Simulation



At 115 °C

In situ XRD Annealing



- Excellent agreement between the experimental and simulation results.
- The lead frame expands more rapidly at elevated temperature, and compensates and relaxes the warpage.

Most of the stress is developed during the die attach process

Outlook

Chip Size (mm)		Scan Step Size (mm)		Beam size (mm)	Total Scan Time (hrs)	Notes
x	y	x	y			
2.5	2.5	0.2	0.2	0.25 x 0.25	**~ 4 ***	High resolution
2.5	2.5	0.4	0.4	0.25 x 0.25	**~ 1.5 ***	Med resolution
2.5	2.5	0.4	0.6	0.25 x 0.25	**< 1 ***	Low resolution

*Exploring new methods to reduce the scan time

Lab. XRD/3DSM is a promising technique for future metrology challenges.

Conclusions

- Laboratory-based X-ray diffraction analysis technique:
  - XRD/3DSM
  - Maps major warpage features non-destructively in fully encapsulated packaged chips.

- Future:
  - Diagnosing sources of stresses and their minimisation/elimination.
  - Lab XRD/3DSM:
    - Straightforward, non-destructive and *in situ* characterisation methodology for providing detailed information on the lattice warpage developed in packaged chips.

Acknowledgements

This work was supported by the EU FP7 MNT ERA-Net 'ENGAGE' project with local support from Enterprise Ireland & Science Foundation Ireland "Precision" Cluster.

PRECISION Strategic Research Cluster

ENTERPRISE IRELAND

welcome to inspire

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SEVENTH FRAMEWORK PROGRAMME

Thank you!

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Synchrotron X-Ray Topography (SXRT)

White Beam: Continuous spectrum of radiation, high intensity, low divergence.

Bragg's Law:

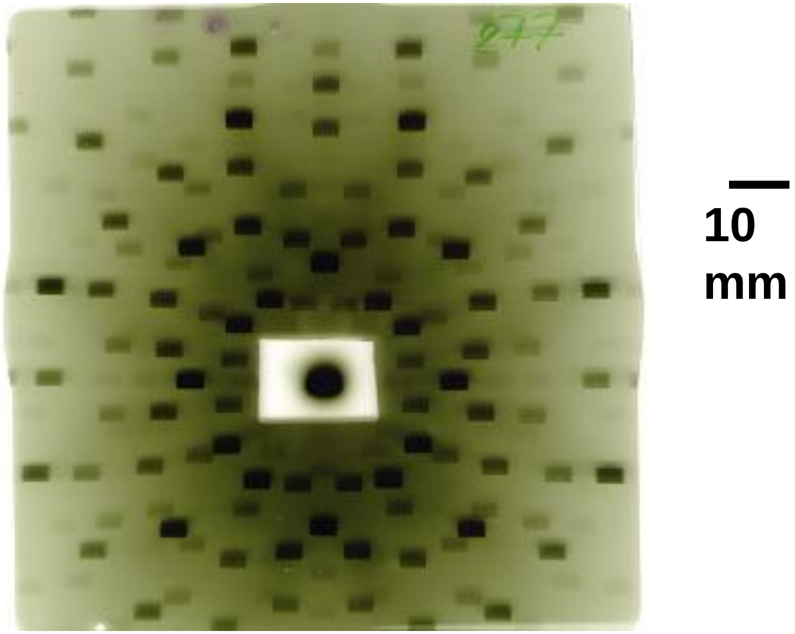
$$2d_{hkl}\sin\theta_B = \lambda$$

where:

•***d*** *is the interplanar spacing → infinite no. of lattice planes.*

•***λ*** *is the wavelength of the incident beam → white beam provides a continuous spectrum of wavelengths.*

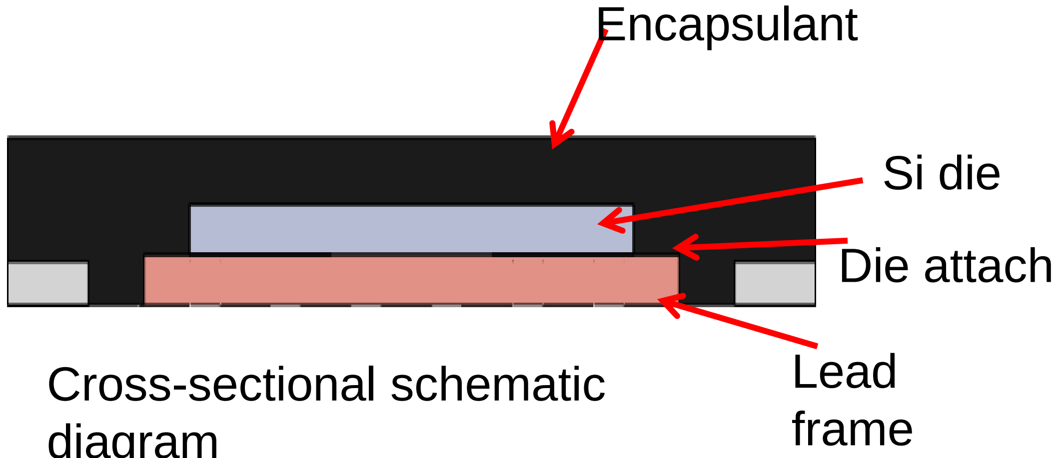
•θ_B *is the Bragg angle → satisfied for many diffraction directions.*



Topographs form a Laue pattern → Each Laue spot is an x-ray topograph, arising from a different set of diffracting planes.

uQFN – Solidworks Simulation

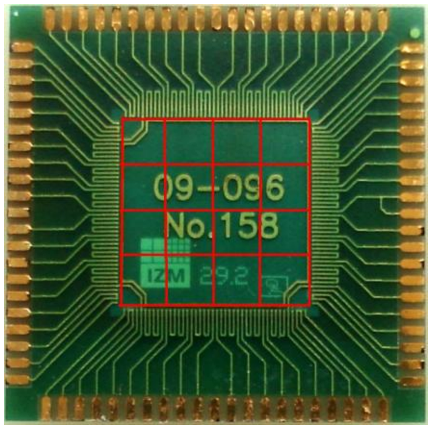
Simulation



Cross-sectional schematic diagram

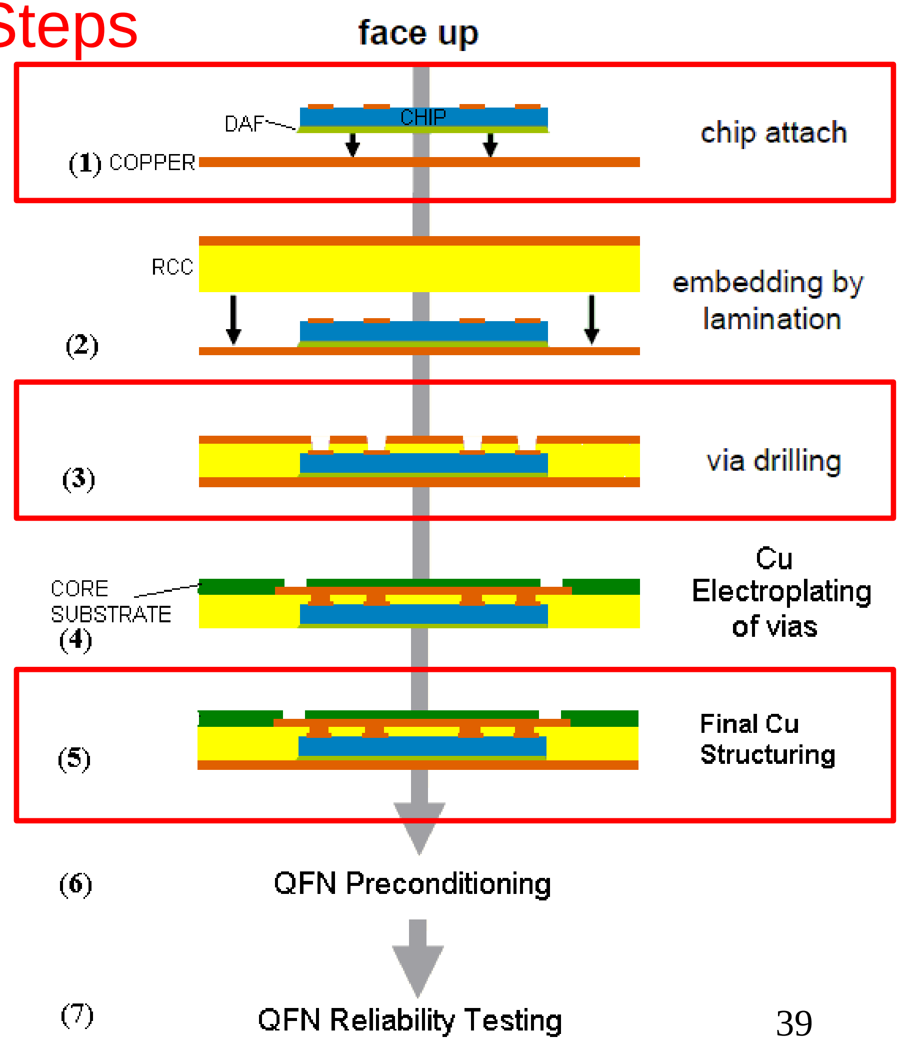
	Lead Frame	**Die attach**	**Die**	**Encapsulant**
Material	Copper	Epoxy (Silver)	Silicon	Epoxy Resin
Modulus (Gpa)	110	11	162	2.4
CTE (ppm/k)	24	65	2.7	55

Quad Flat Non-lead (QFN) Packaged Chips

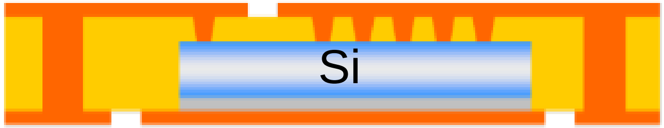


The package consists of an active die bonded Si chip, 5 mm x 5 mm in size and 50 µm thick, embedded face up in a substrate, with a peripheral bond pad pitch of 100 µm.

QFN Embedding / Packaging Steps

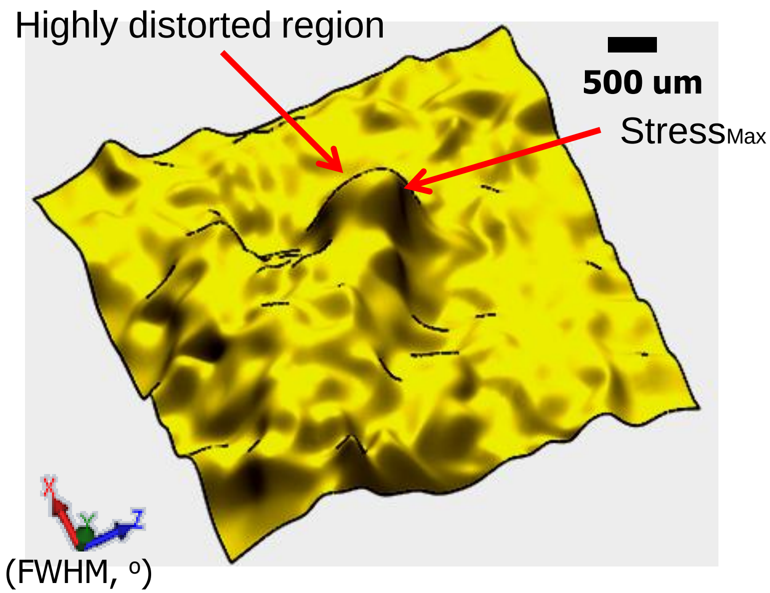


Stage 5: Post Production



Schematic diagram of Stage 5 chip.

- Cu structuring on the bottom side of the package.

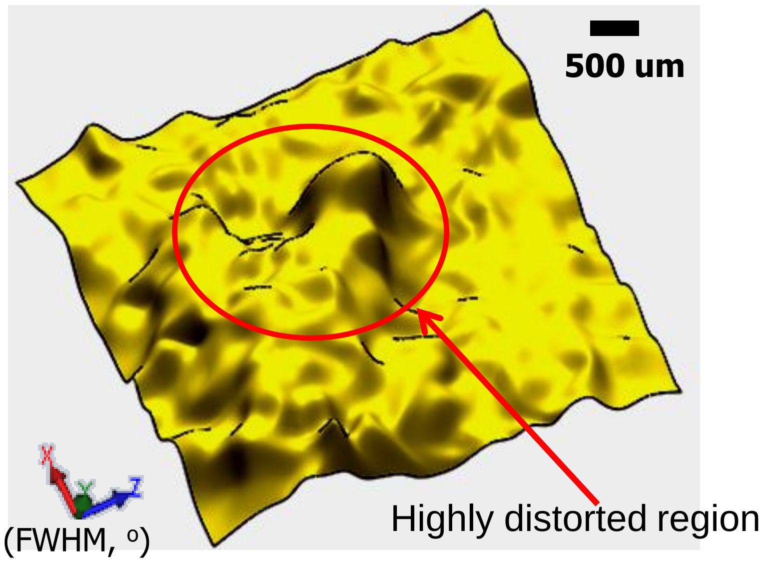


- From Lab. XRD/3DSM, the highly distorted region corresponding to the region circled in red.
- $FWHM_{Max}$ = ~ 0.44 deg
- $Stress_{Max}$ = ~ 170 MPa

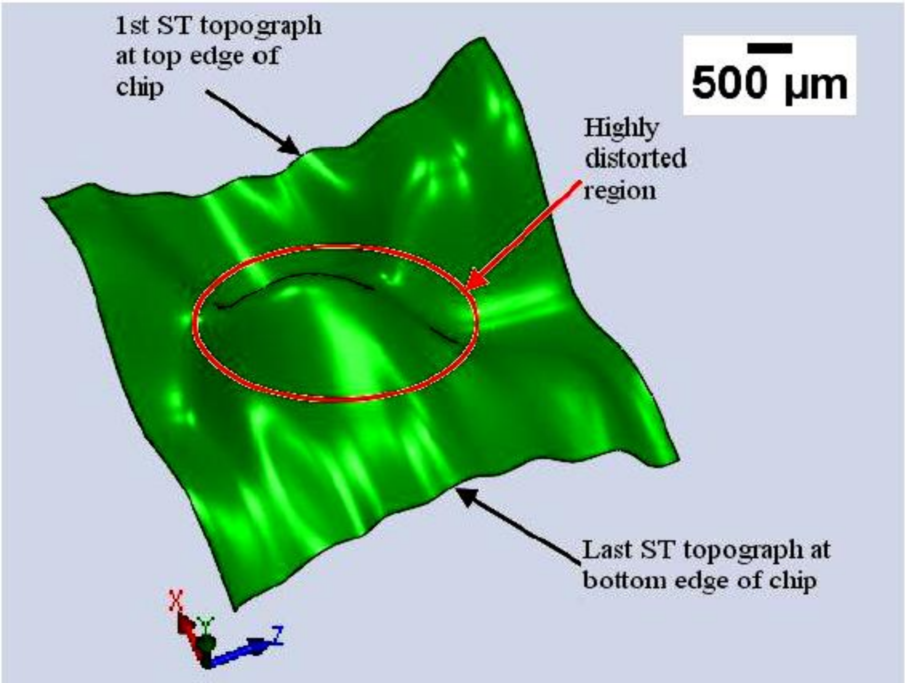
Lab. XRD/3DSM showing warpage/lattice deformation of the (110) planes inside the packaged chip after Stage 5 of processing.

Stage 5: Post Production

Lab. XRD/3DSM

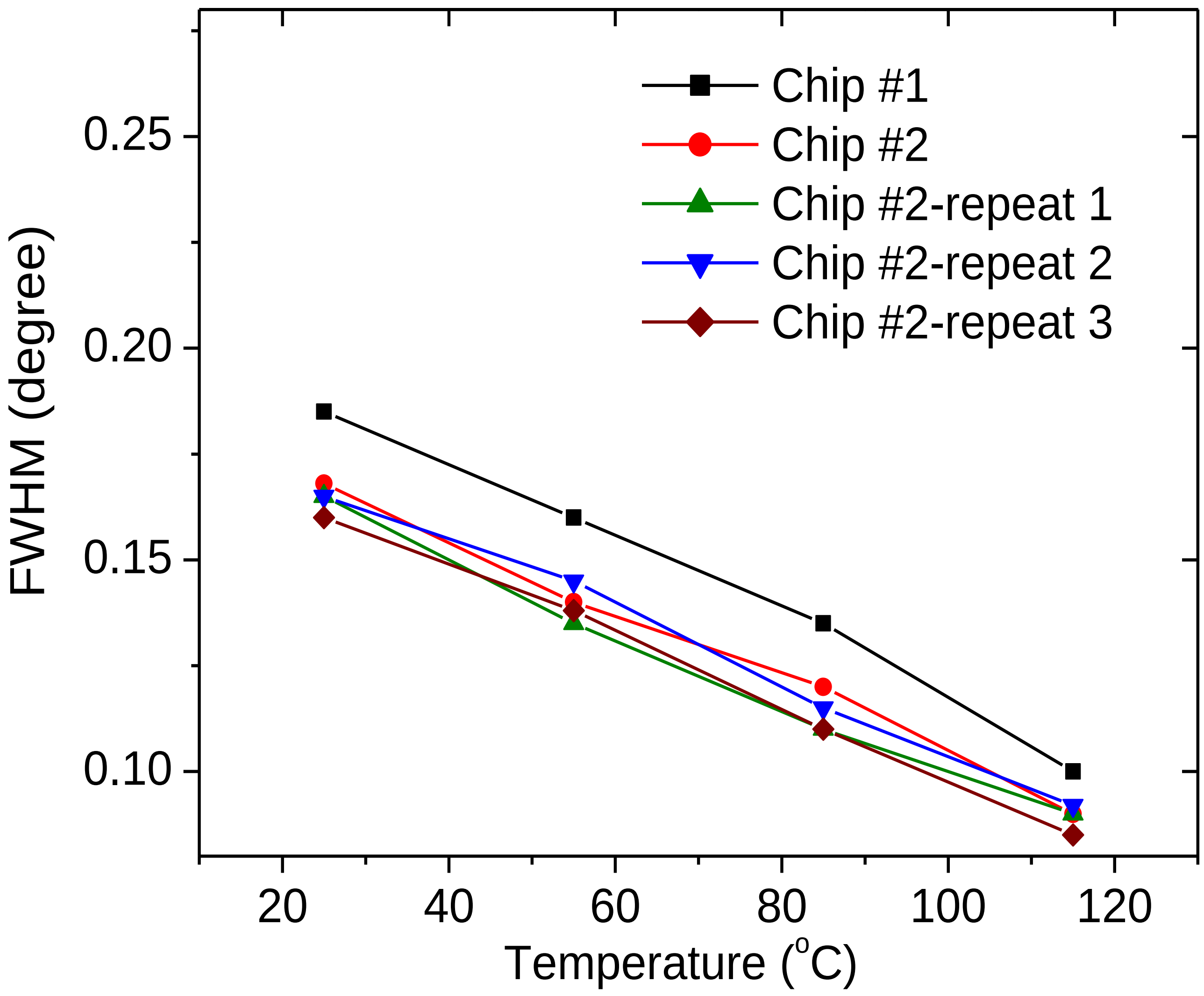


Synchrotron-3DSM



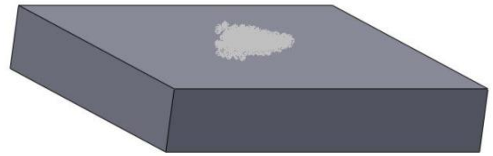
This suggests that the lattice distortions are linked to the manufacturing process

Extracted RC FWHM vs Temperature

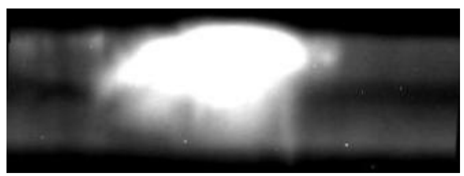


3D-X-Ray Diffraction Imaging (3D-XRDI)

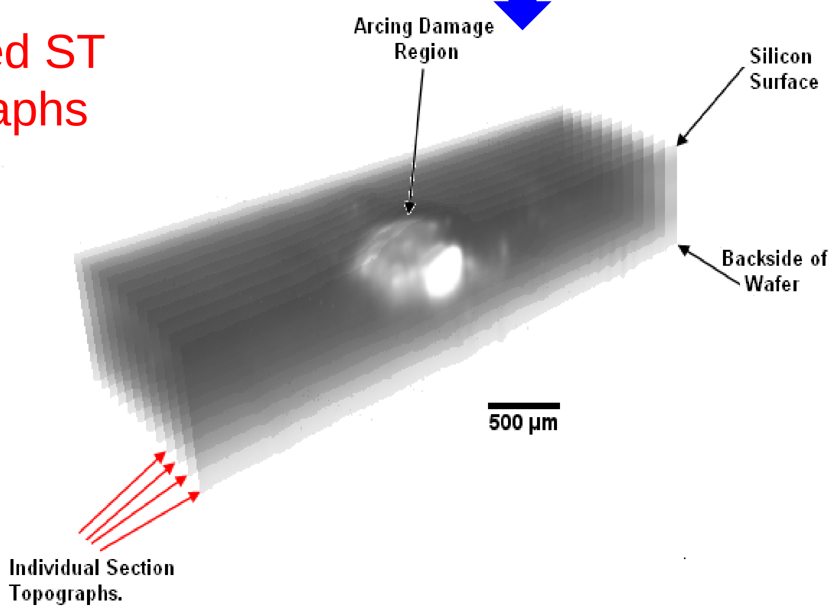
Damaged Sample



Single Section Transmission Topograph

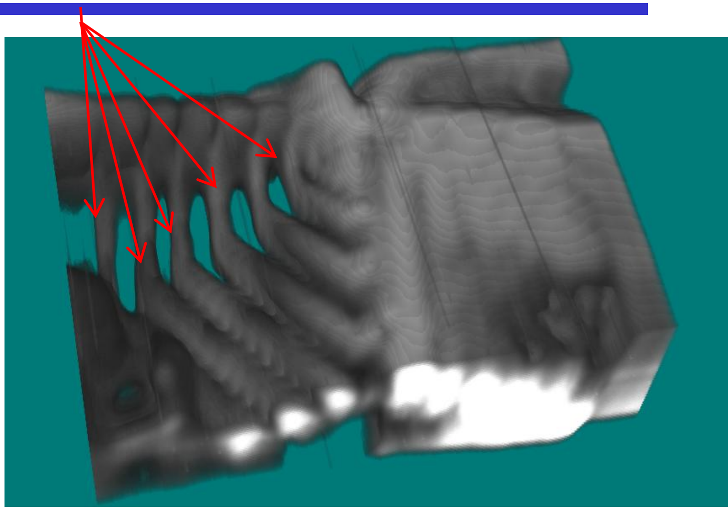


Rendered ST Topographs



- Series of Section Transmission (ST) Topographs are rendered together to form 3D-XRDI of damaged wafer.
- Use ImageJ and plugins: http://rsbweb.nih.gov/ij/

3D-XRDI



Dislocation loops begin to propagate at ~ 950 °C.

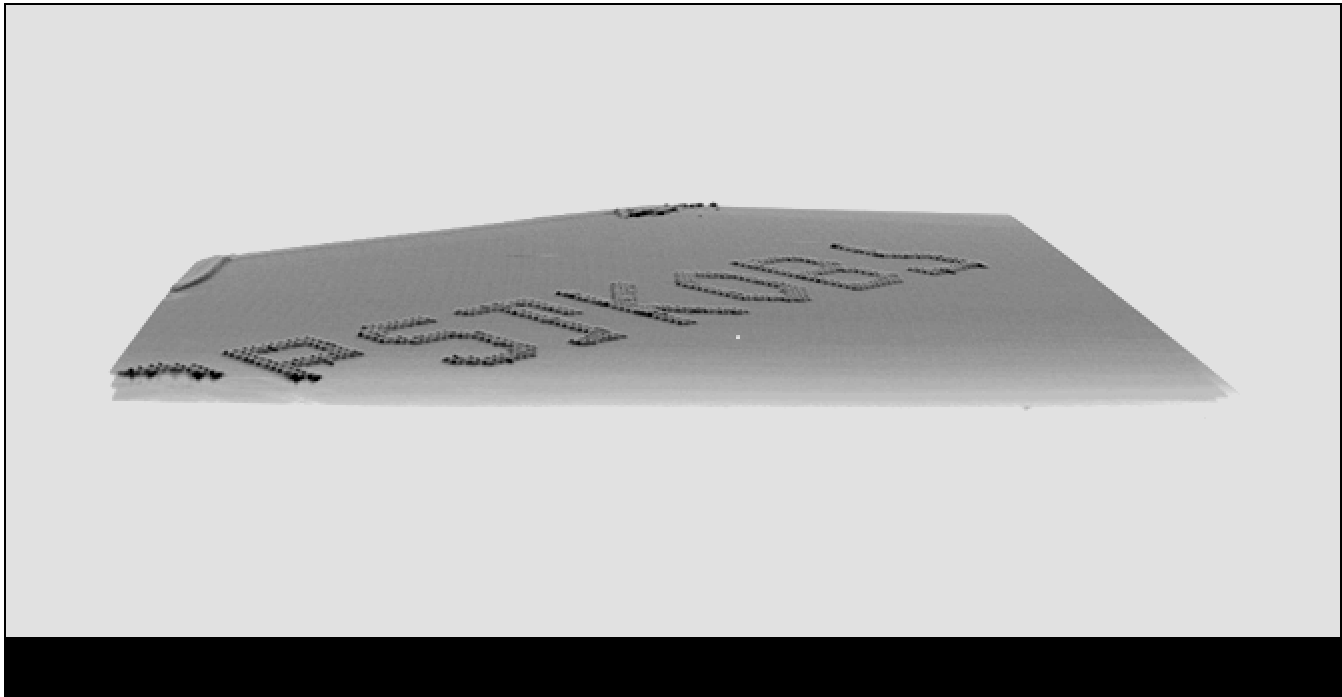
• Rendering is from 45 images that took ~ 3 hours to capture.

• Can now capture ~1200 images in 10 hours.

3D-XRDI of the Laser marks on a silicon wafer.

• Rendering is from 400 images that took ~ 2hours to capture.

• Perfectly renders writing on wafer (N.B rendered form 400 slice images!!)



SiP / SoC

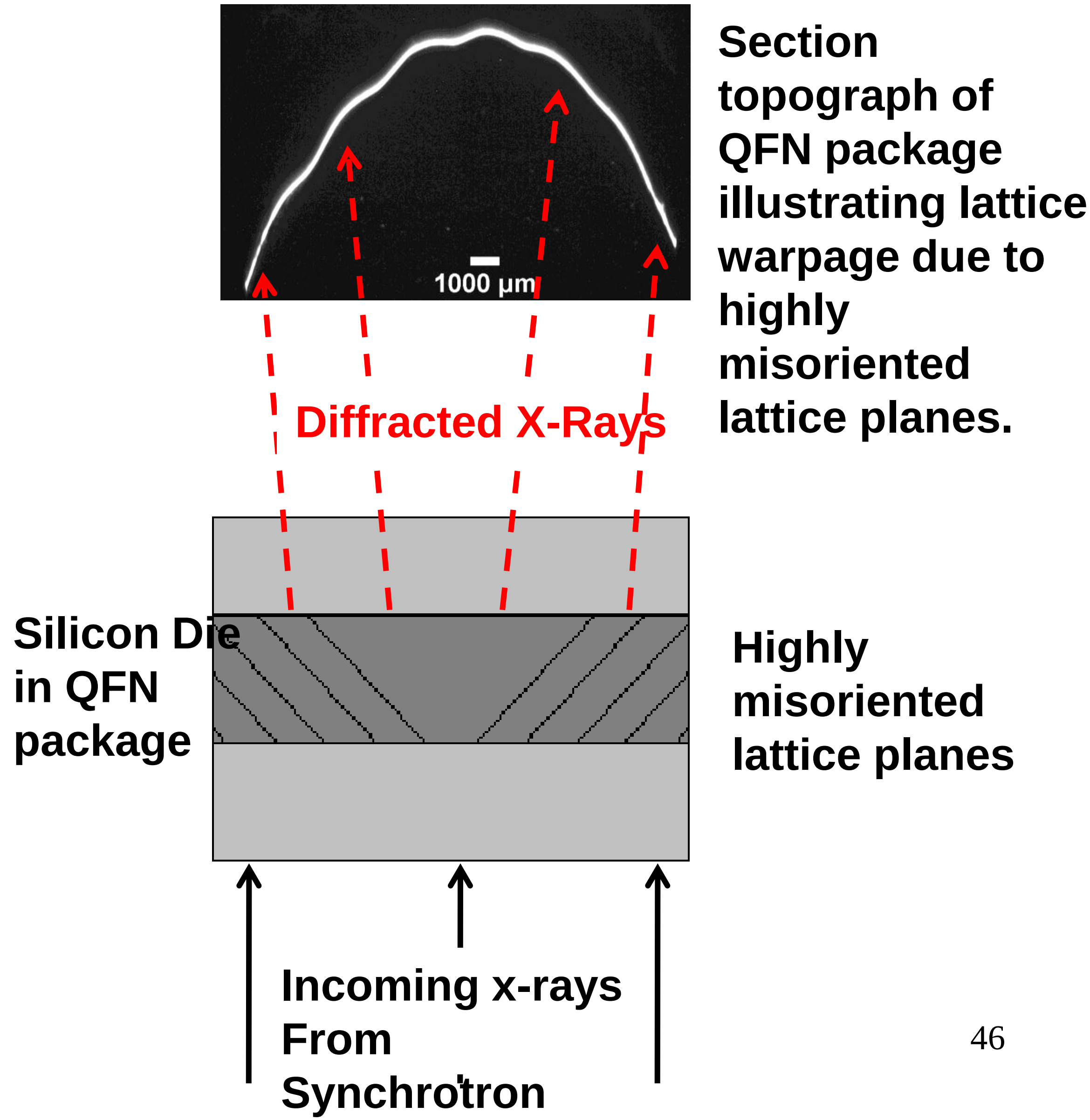
- Plagued by reliability problems.
- Metrology gap – need to **non-destructively** measure or image stress/strain, warpage or defects inside SoC/SiP/advanced packages.

➡ 3DSM: 3-dimensional surface mapping

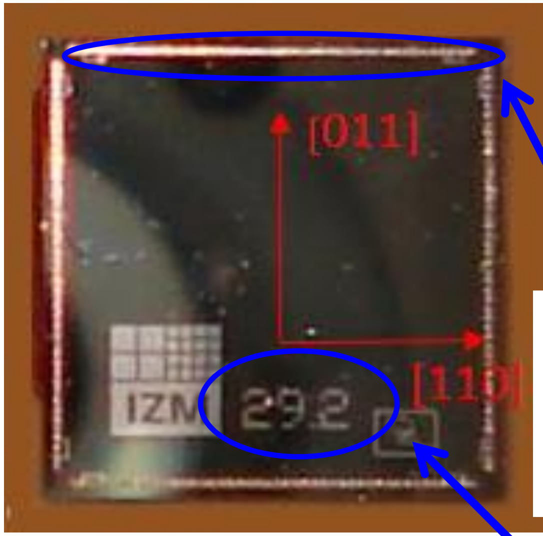
- 3DSM: the 3-dimensional reconstruction of strain field and lattice misorientation data from x-ray diffraction Images.
- Novel tool for non-destructive *in situ* mapping of stresses, strains and deformations and inside packaged systems.

3DSM – Image Formation

Misorientated lattice planes diffract incoming x-rays as shown, resulting in formation of highly distorted section transmission topograph image on ccd.



Stage 1 – Chip Attach

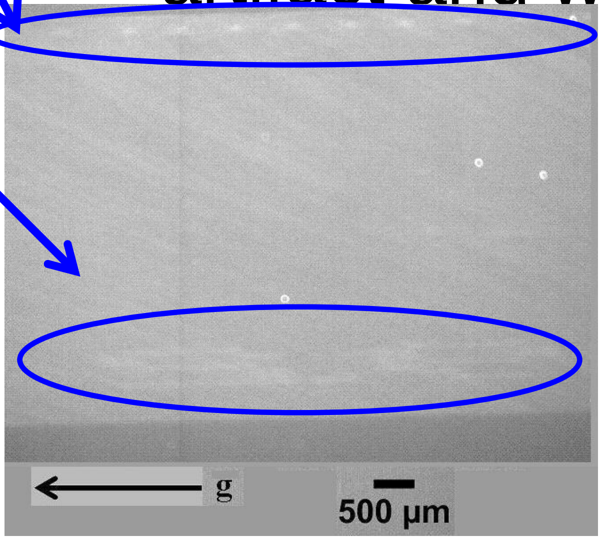


Corresponding features on topograph and chip.

- LAT topograph of sample shows some patterning.
- Elongation of LAT image occurs parallel to **g**. (Generally treat as an artifact and we remove

Optical image of Stage 1 chip.

5 mm × 5mm square of 50 µm thick Silicon embedded face up on a Cu substrate.



LAT topograph of Stage 1 chip (partial image).

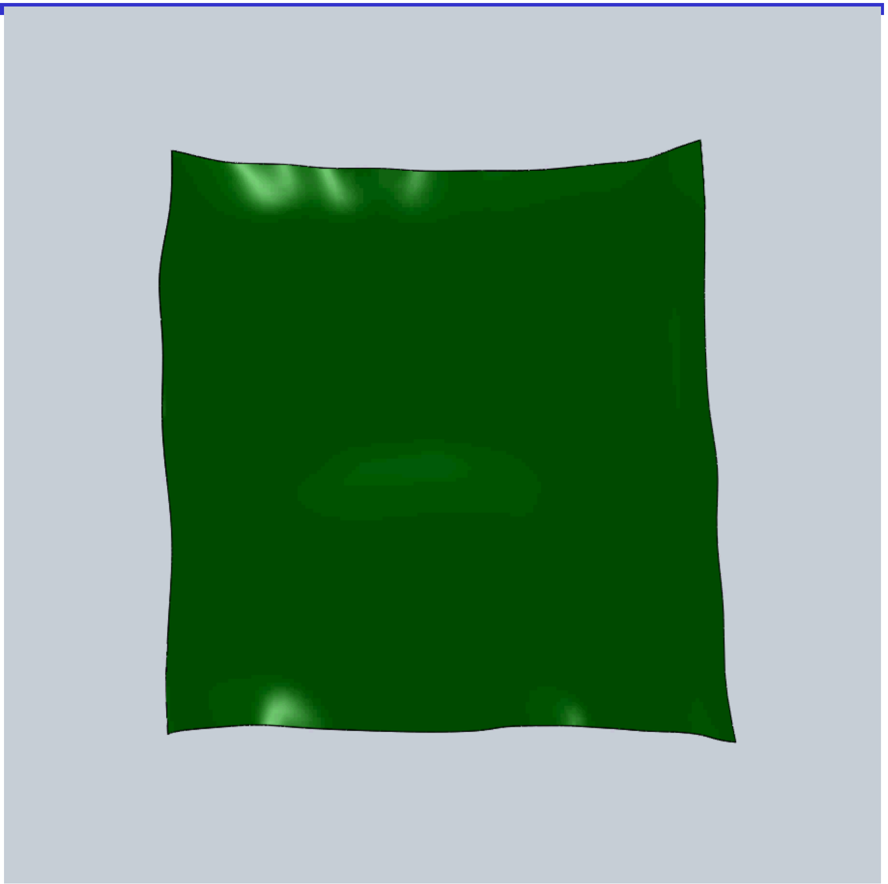
Stage 1 – Chip Attach

•3DSM has been normalised to reflect the square shape of the chip.

•Greatest lattice distortion is observed at the edges of the 3DSM.

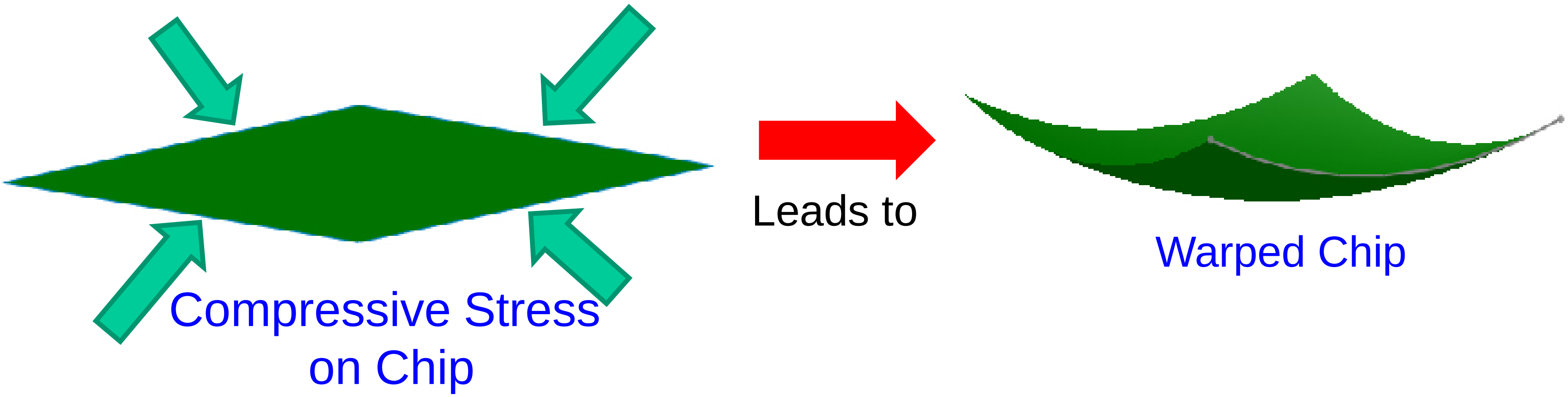
•$\Delta\alpha_{MAX} \approx 3.00$ arcsec.

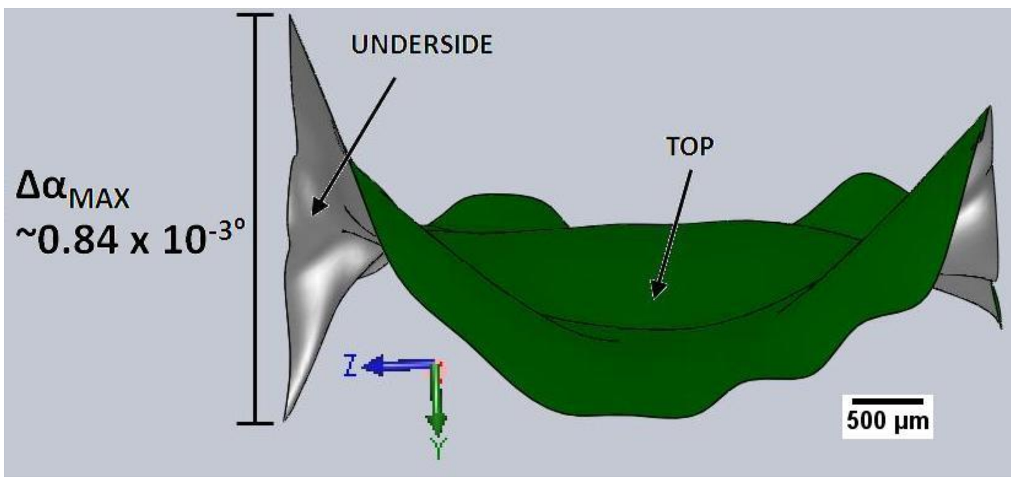
•Raman measurements show chip to be in compressive stress, ~0-460 MPa.



3DSM (animation) showing the misorientation of the 2 2 0 planes in the Si chip.

Stage 1 – Chip Attach





3DSM of Stage 1 chip viewed end on, showing Δα, the misorientation of the 2 2 0 Si planes.

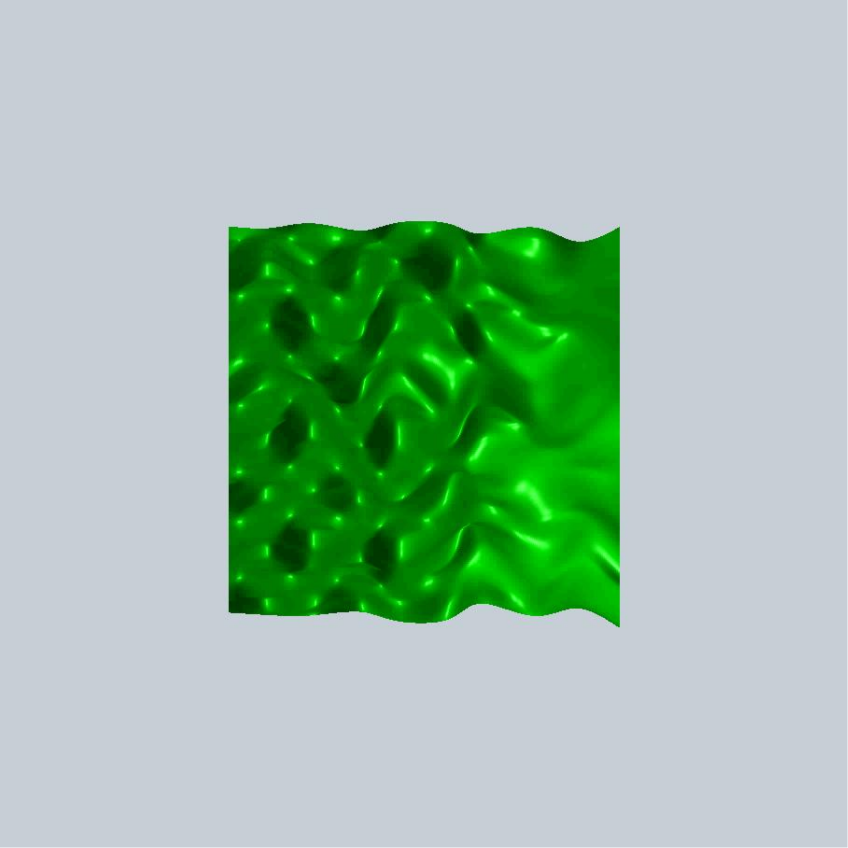
- Average Δα ≈ 2.56 arcsec.
- Standard Deviation Δα ≈ 1.66 arcsec.

Stage 3 – Via Electroplating

- Distinctive bumps correspond to peaks on LAT topograph.

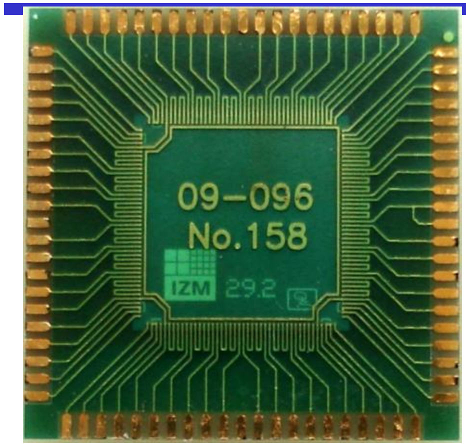
- $\Delta\alpha_{MAX} \approx 3.24$ arcsec.
- Average $\Delta\alpha \approx 1.73$ arcsec.
- Standard Deviation $\Delta\alpha \approx 0.40$ arcsec.
- Maximum lattice displacement is at edges of 3DSM.

- Distortion most likely linked to vacuum lamination process → presence of voids or variations in epoxy coverage.



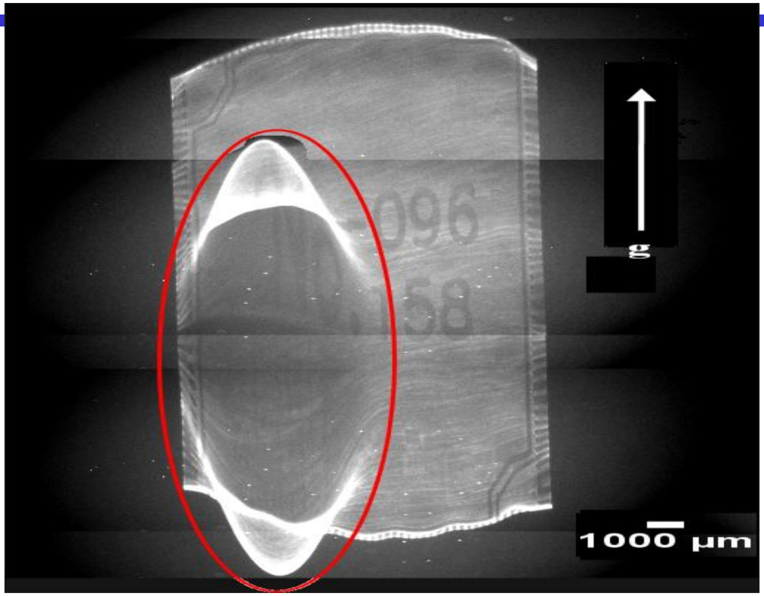
3DSM (animation) showing the misorientation of the 2 2 0 planes in the Si chip after stage 3 processing.

Stage 5 – Post Production



Optical image of chip 09-096 no. 158 after Cu structuring on the bottom side of the package.

Packages were processed in large panel format and separated by sawing.



LAT topographs of stage 5 chip. Image is comprised of 6 camera images patched together.

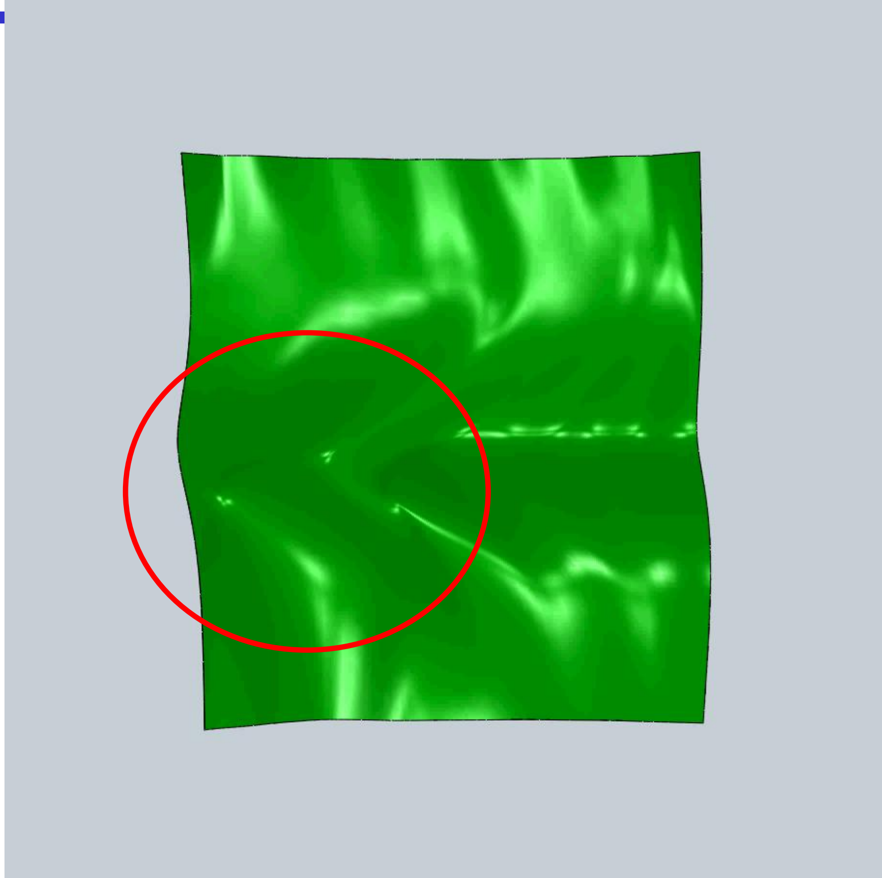
Region circled in red corresponds to region of high lattice distortion. Image has been normalised to compensate for geometric distortion

Stage 5 – Post Production

•3DSM clearly pinpoints the highly distorted region, corresponding to the same region highlighted in the LAT topograph.

•$\Delta\alpha_{MAX} \approx$ 5 arcsec.
•Average $\Delta\alpha \approx$ 2.54 arcsec.
•Standard Deviation $\Delta\alpha \approx$ 1.67 arcsec.

•Region circled in red corresponds to region of maximum lattice displacement.



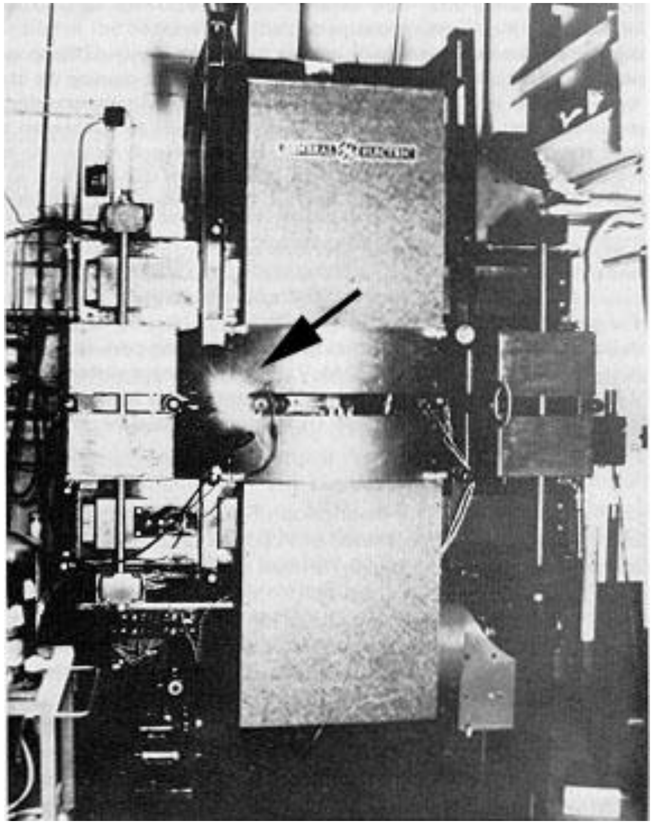
3DSM (animation) showing the misorientation of the 2 2 0 planes in the Si chip after stage 5 processing.

History of Synchrotron Radiation

- 1895: Roentgen discovers x-rays!! (Nobel Prize in Physics in 1901)
- 1909: Barkla and Sadler discover characteristic x-ray radiation. (1917 Nobel Prize to Barkla)
- 1912: von Laue, Friedrich, and Knipping observe x-ray diffraction. (1914 Nobel Prize to von Laue)
- 1913: Bragg, father and son, build an x-ray spectrometer. (1915 Nobel Prize)

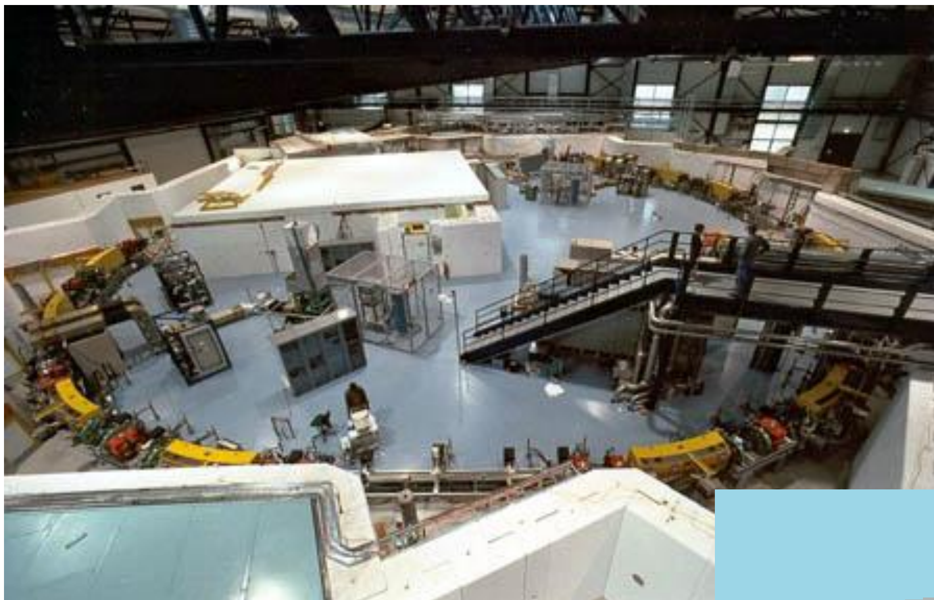
History of Synchrotron Radiation

- 1930s: First accelerators (cyclotrons) were built by particle physicists.
- The nucleus of the atom was split using the collision of high energy particles.
- Synchrotron radiation was seen for the first time by researchers at General Electric (Langmuir, Pollack, Blewett *et al*.) in 1947 in a different type of accelerator – the synchrotron.
- Was considered a nuisance because it caused the particles to lose energy…

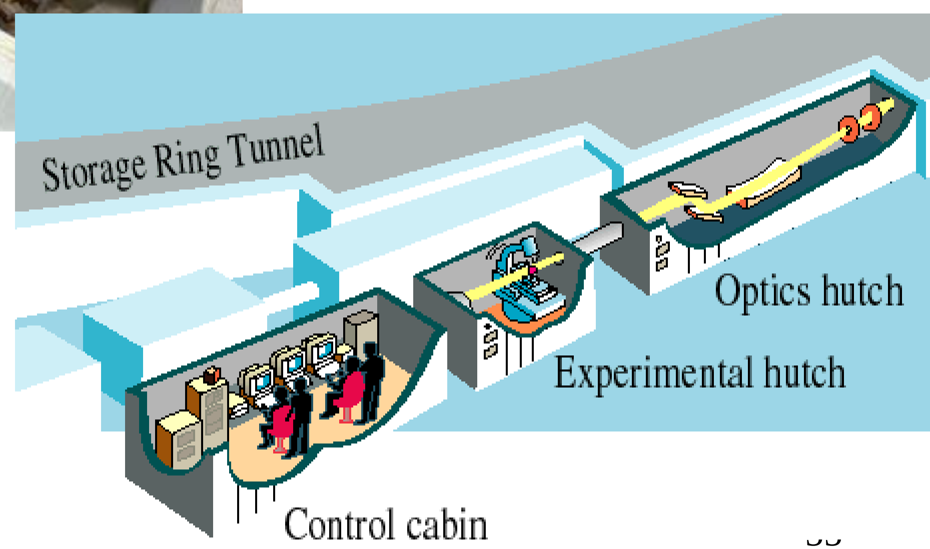


Synchrotron light from the 70MeV electron synchrotron at GE.

ANKA, Institute for Synchrotron Radiation, Karlsruhe, Germany.

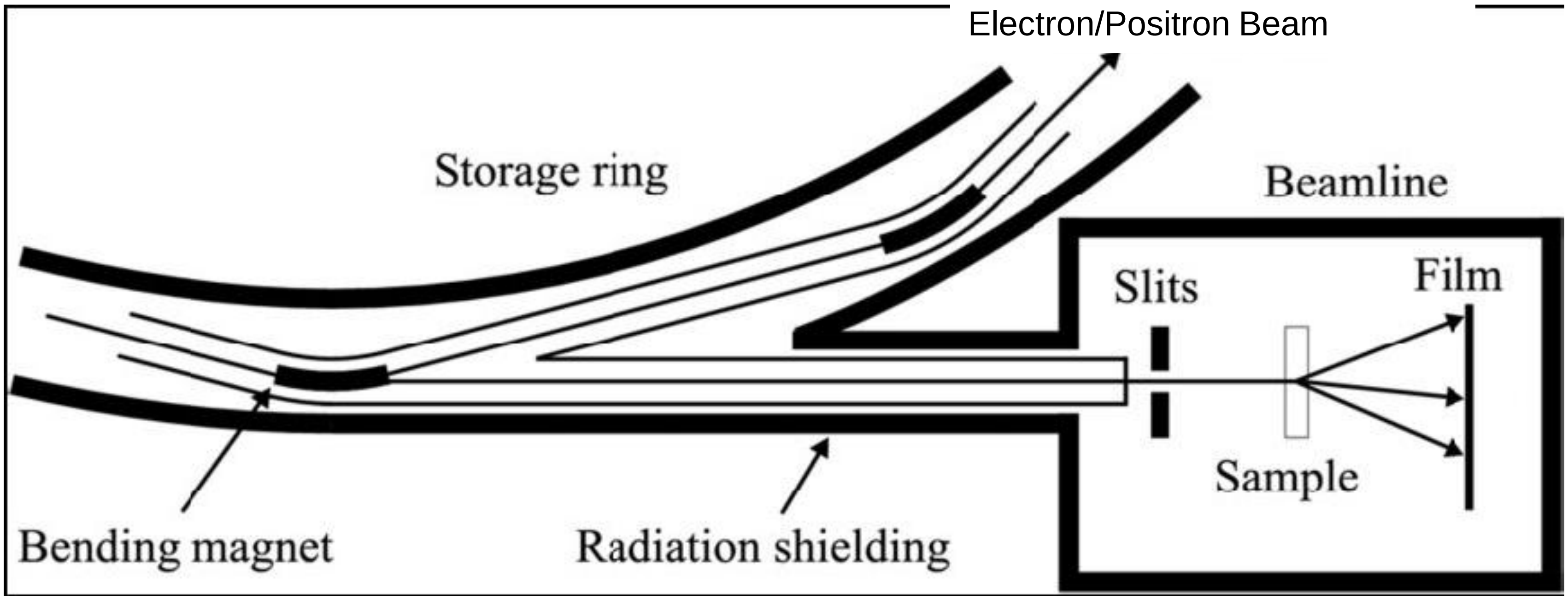


E=2.5GeV



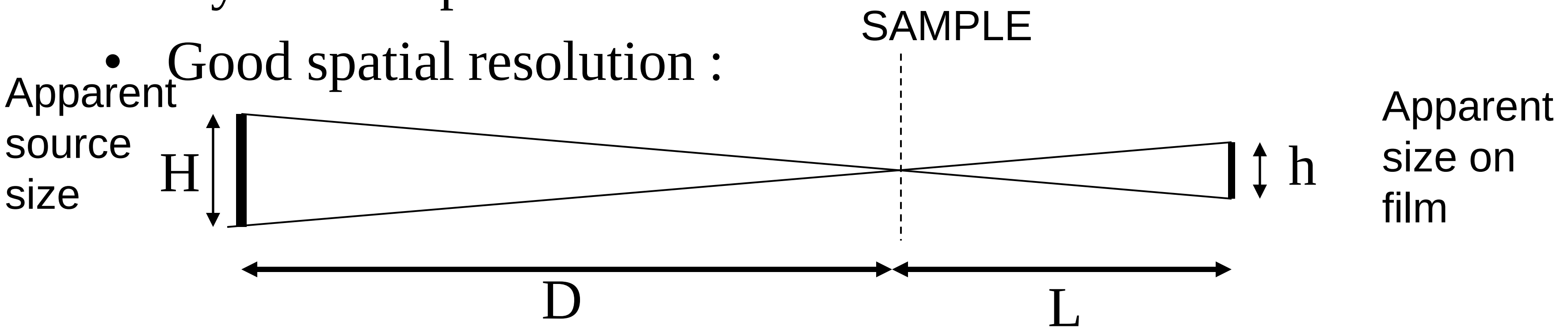
Diamond Light Source, Oxfordshire, UK

Typical SXRT Arrangement



High Intensity X-Rays

- Easy to penetrate relatively highly absorbing samples e.g. 1 mm of Si or SiC, 500 µm of GaN, GaAs….
- X-ray beam emerging from source has low divergence, i.e. rays almost parallel.
- Good spatial resolution :



$$h = \frac{L}{D} H \approx \frac{50mm}{32m} 1.1mm \approx 1.7\,\mu m$$

(DORIS III @ HASYLAB)

Synchrotron X-Ray Topography

- White beam, i.e. a continuous spectrum of wavelengths (λ) available.
- Bragg's Law:

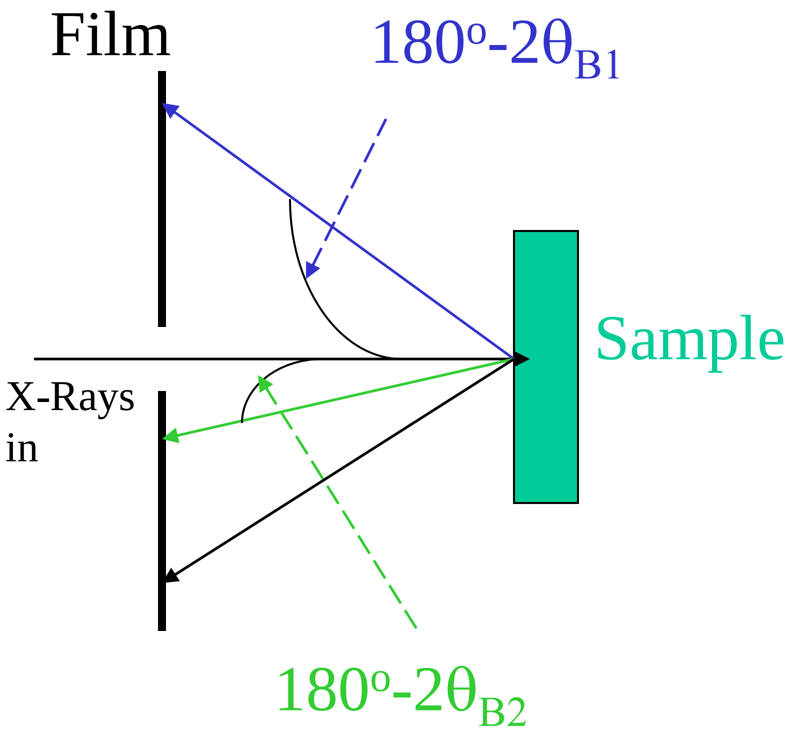
Many diffraction directions!!!

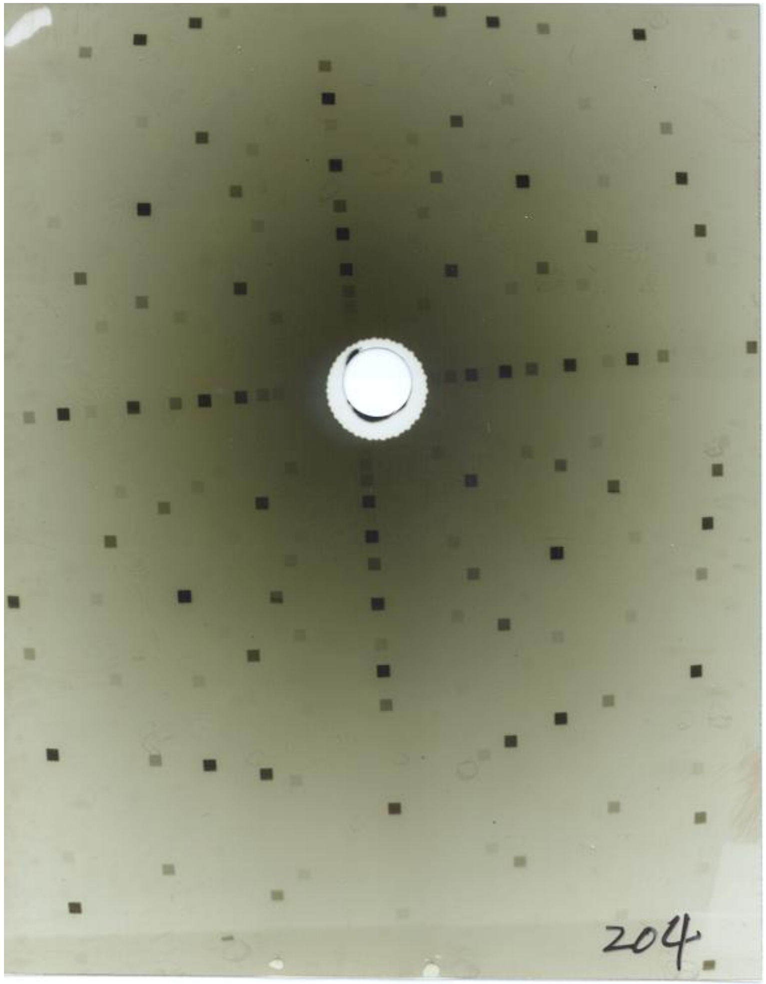
$$2d_{hkl}\sin\theta_B = \lambda$$

∞ no. of lattice planes

White beam: continuous distribution

SXRT





Back Reflection (Bragg) Geometry

Synchrotron X-Ray Topography (SXRT)/ X-Ray Diffraction Imaging (XRDI)

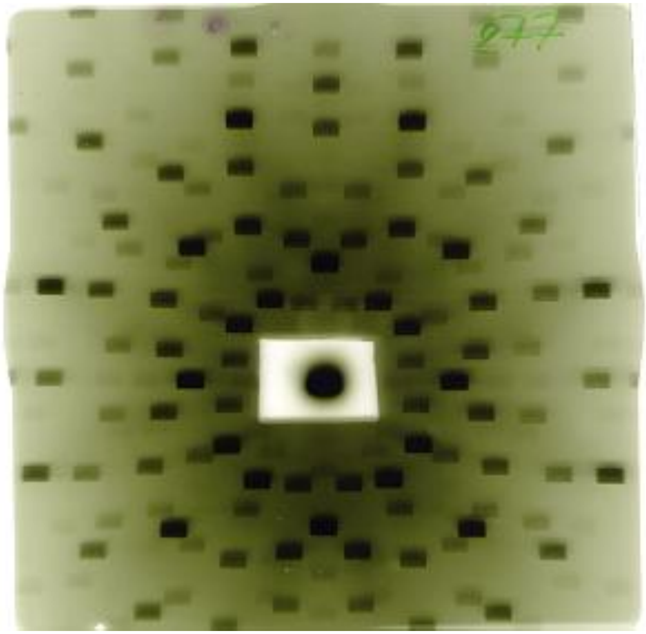
White Beam: Continuous spectrum of radiation, high intensity, low divergence.

Bragg's Law:

$$2d_{hkl}\, sin\theta_B = \lambda$$

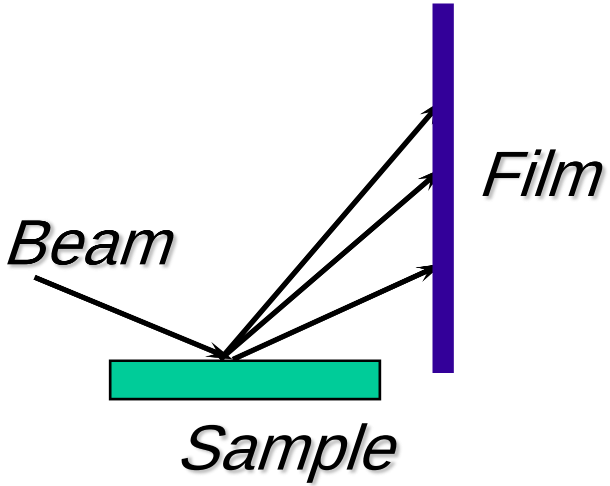
where:

- ***d*** *is the interplanar spacing → infinite no. of lattice planes.*
- ***λ*** *is the wavelength of the incident beam → white beam provides a continuous spectrum of wavelengths.*
- **θ_B** *is the Bragg angle → satisfied for many diffraction directions.*

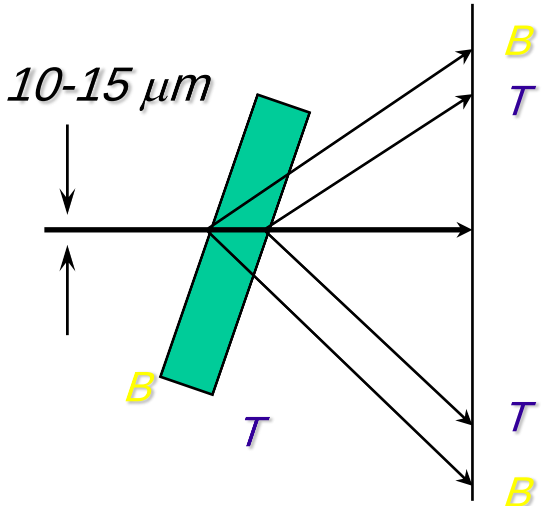


Topographs form a Laue pattern → Each Laue spot is an x-ray topograph, arising from a different set of diffracting planes.

Many geometries are possible

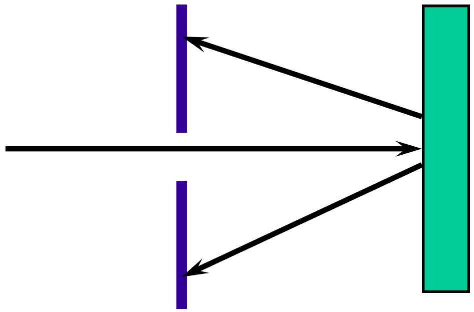


Grazing Incidence Diffraction and/or Total Reflection Topography

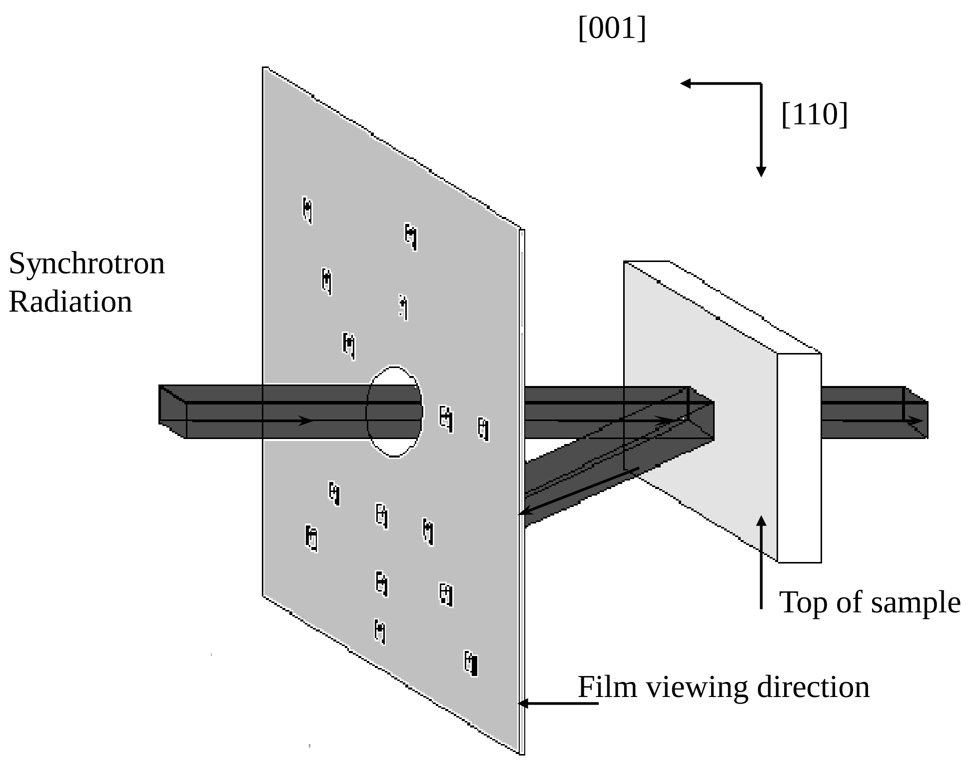


Section Topography (Transmission or Back Reflection)

Back Reflection Topography



Large Area Back Reflection Topography Set-up (LA-BRT)

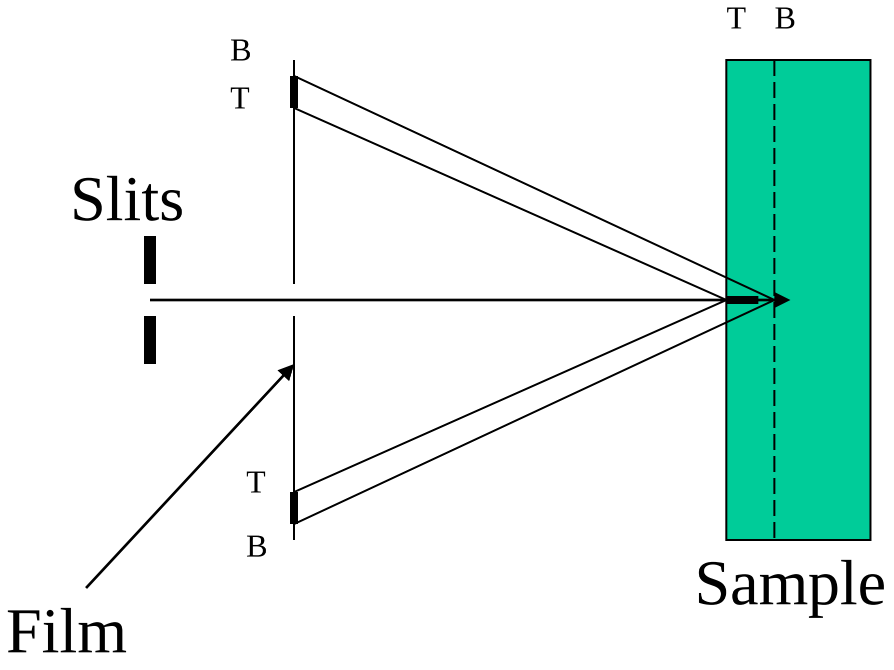


(a)

Back Reflection Section Topography (BRST)

- Similar to LA-BRT.
- Now, x-rays collimated into a narrow ribbon only 10-15 μm high.
- Produces non-destructive section image of upper regions of sample.

$$t_p = \left[\mu(\lambda) \left(\frac{1}{\sin \phi_i} + \frac{1}{\sin \phi_f} \right) \right]^{-1}$$



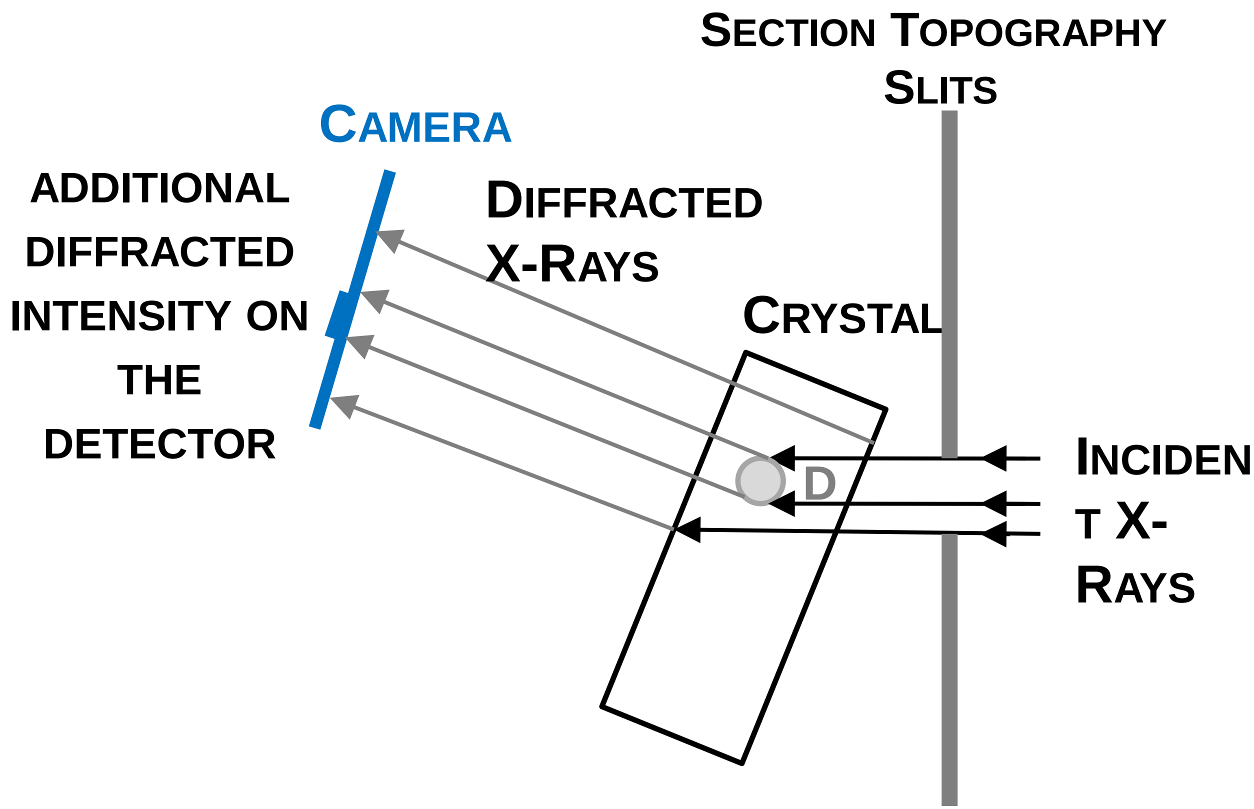
Imaging Defects & Strain

- Low divergence synchrotron beam.
- Magnify each Bragg/Laue spot $\Rightarrow$ X-RAY TOPOGRAPH - a real space image of the energy flow of x-rays through the sample.
- Strain fields in the crystal modify this flow of energy.
- Observed as changes in recorded intensity.

- *Sources of strain/defects:*
  - dislocations
  - strain due to metallic/dielectric overlayers
  - stacking faults
  - precipitates
  - magnetic domains
  - grain boundaries, etc.

- There are many different DEFECT CONTRAST MECHANISMS IN SXRT.

Direct Image Formation

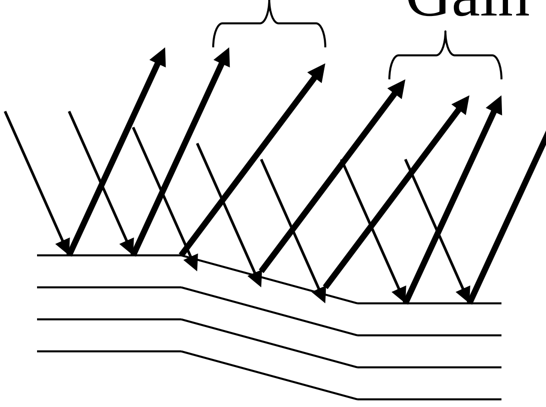


Diffracted intensity from defect, D, is greater than for perfect crystal.

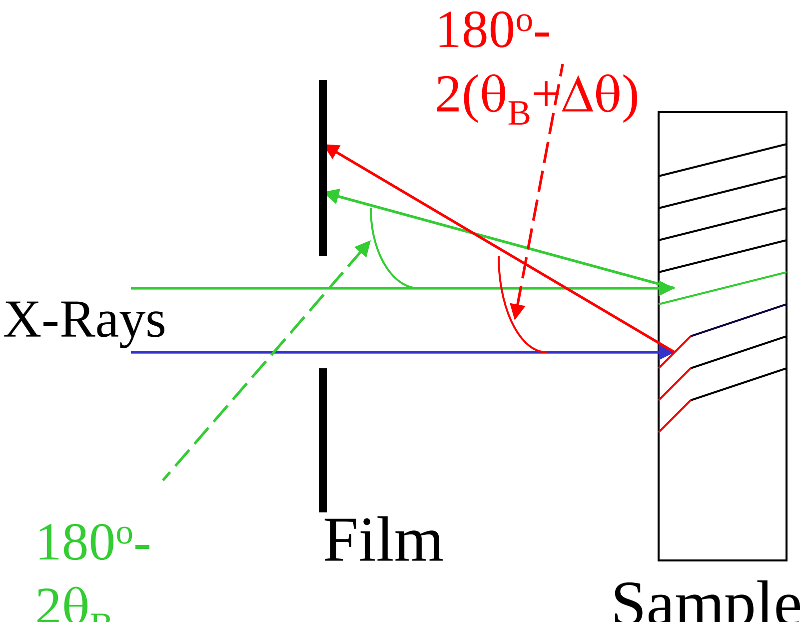
- Section topograph images used in XRDI are formed from direct image contrast.
- X-Rays from imperfect region in crystal have greater intensity than for perfect crystal.
  → Defects appear as regions of high intensity (white) on camera.

1. Orientational Contrast

- Diffracted beams can overlap or diverge due to lattice misorientation.



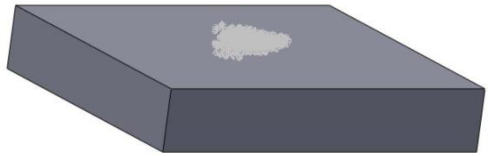
- Extremely misorientated regions can appear on a different place on the recording film!



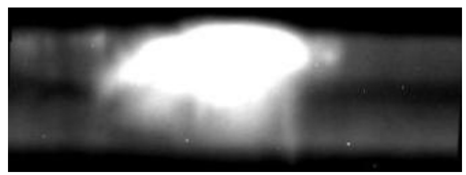
NB:
•Gain = **black** on film (more intensity)
•Loss – *white* on film (less intensity)

3D-X-Ray Diffraction Imaging (3D-XRDI)

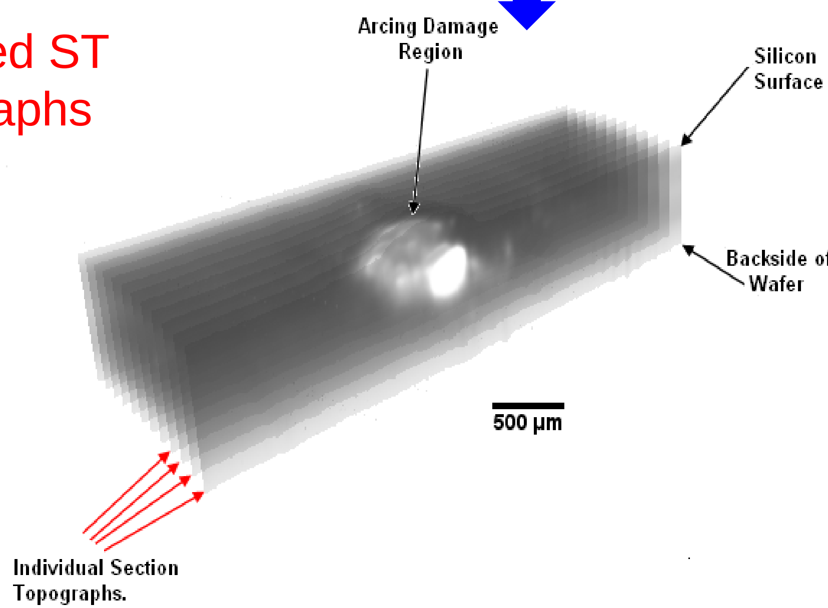
Damaged Sample



Single Section Transmission Topograph



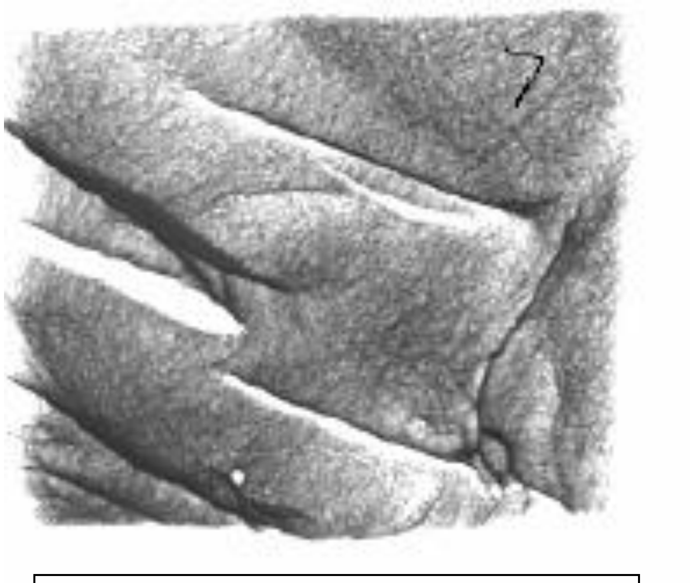
Rendered ST Topographs

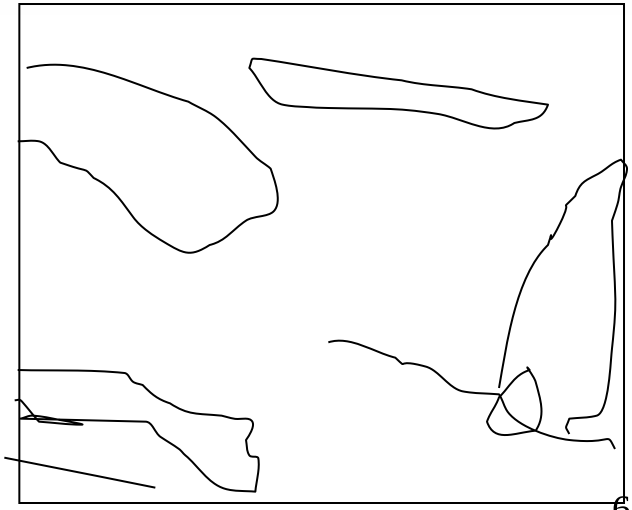


- Series of Section Transmission (ST) Topographs are rendered together to form 3D-XRDI of damaged wafer.
- Use ImageJ and plugins: http://rsbweb.nih.gov/ij/

LA-BRT of Grain Boundaries in SiC

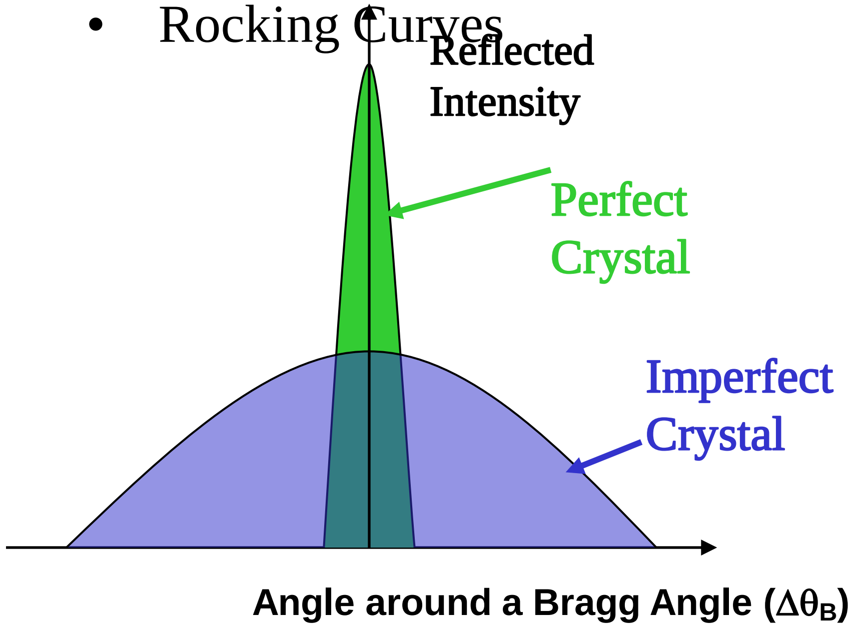
- Area of topograph ~ 2mm x 2mm.
- Different sub-grains slightly misoriented with respect to each other.
- Low angle grain boundaries.





2. Extinction or Kinematical Contrast

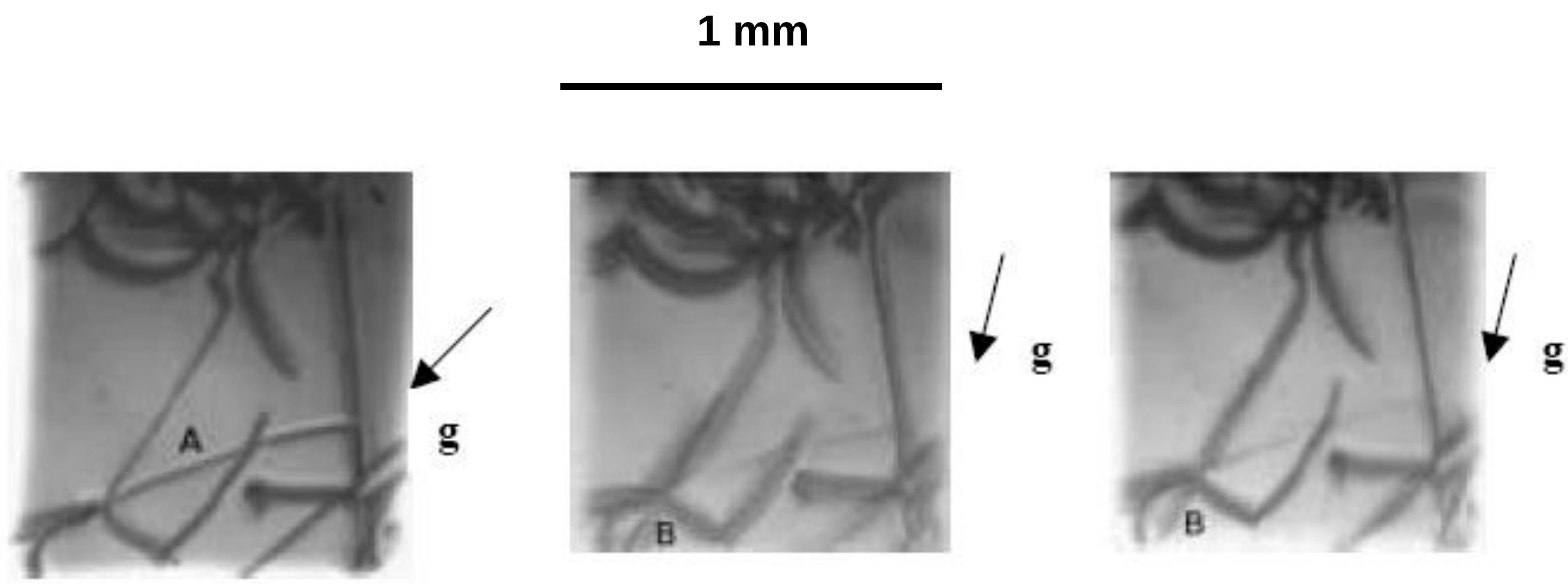
- Rocking Curves



Shading □ integrated reflected intensity which is = <u>scattering power</u>

- Perfect Crystal:
  - Rocking curve narrow.
  - Peak reflectivity ~ 100%.
  - Scattering Power ~ |S| (S = structure factor).
- Imperfect Crystal:
  - Broader rocking curve.
  - Peak R << 100%.
  - But Scattering Power ~ $|S|^2$.
- Thus, diffracted intensity from <u>imperfect regions</u> is <u>greater</u> than for perfect crystal
- DEFECTS/DISLOCATIONS APPEAR BLACK ON FILM!!

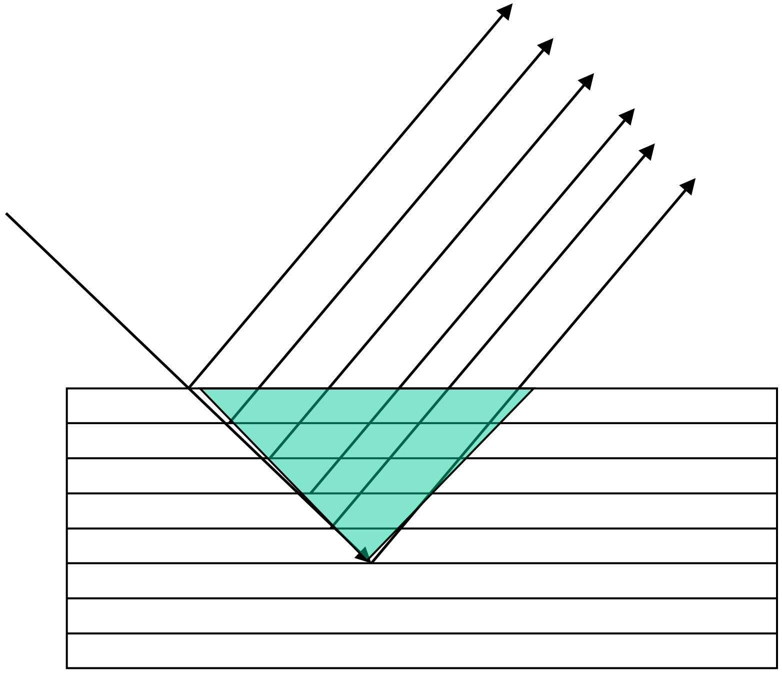
LA-BRT of Dislocations in Sapphire



(a) $2\bar{1}\bar{1}0$ Reflection (b) $20\bar{2}\bar{1}$ Reflection (c) $10\bar{1}0$ Reflection

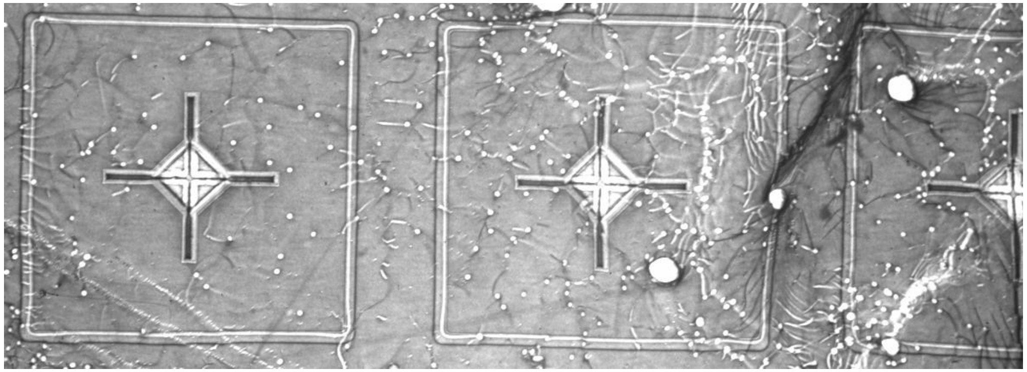
3. Dynamical Imaging/Contrast

- Most x-ray energy exists within a triangle called the BORRMANN FAN (BF).
- But, in fact, what happens inside the BF is a complicated interference between waves set up at every atomic site by incoming and outgoing x-ray wavefronts.



Dynamical Imaging/Contrast

- Any defects inside the BF will disrupt the propagation of waves within the BF, leading to a loss of intensity.
- Thus DEFECT IMAGES APPEAR WHITE on the film.



•Dynamical images of line defects in SiC diodes