Towards a crystal undulator

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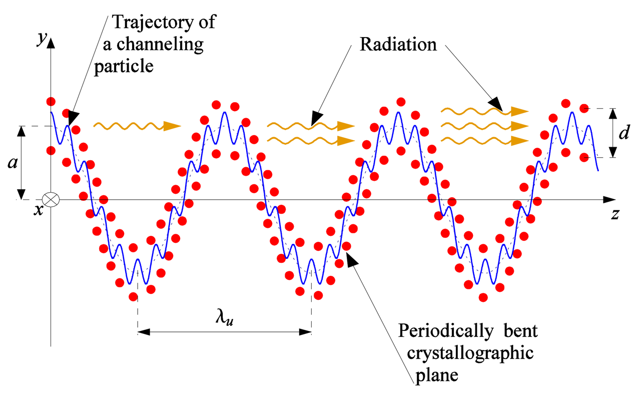
Introduction

A crystal undulator is similar to a normal undulator as typically found at a synchrotron for the production of extremely brilliant X-ray beams. The difference is the magnetic lattice is realized by the periodic electrostatic potential of a crystal lattice seen from the reference frame of the GeV range electron or positron beam. The extremely relativistic incident particle beam is captured in a high index crystallographic channel of a crystal superlattice. The particle beam will then "see" a many Tesla range periodically varying magnetic field with a few micron pitch.

This method could theoretically lead to an MeV range gamma ray laser by the FEL principal.

IRSES-CUTE and RISE PEARL collaborations

Partner name	Partner short name	Country
Frankfurt Institute for Advanced Studies, Goethe University	FIAS-GU	Germany
Aarhus University	UAAR	Denmark
Institute for Nuclear Physics, Mainz University	Uni-Mainz	Germany
Sensors and Semiconductors Laboratory, University of Ferrara	SSL-FU	Italy
St. Petersburg Polytechnical University	PTU	Russia
University of Johannesburg	UJ	South Africa
Zagazig University	ZU	Egypt

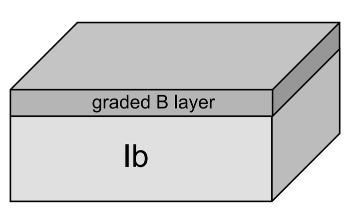


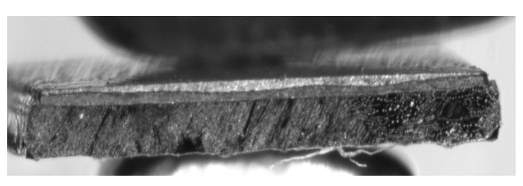
We have investigated a prototype diamond superlattice using x-ray diffraction topography. The undulator fabrication principle involved CVD growth of diamond on a diamond substrate while varying the concentration of boron in the gas phase during growth. This should lead to the periodic variation of the lattice dilatation by the varying concentration of the single substitutional boron impurity atom.

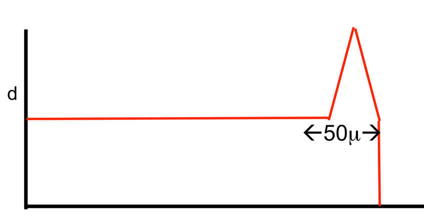
Doping with nitrogen, boron → expands the lattice. Boron is favoured. We expect one could obtain up to C_B < 1.5 at% maintaining excellent lattice quality. Using the "Lang" Dilatation Formula :

$$\frac{\Delta a}{a_0} = 0.144 \times C_B \quad \leftarrow C_B \text{ in at. fraction}$$

The first step to produce a diamond superlattice with a 100μm period has been taken by Element 6. A single graded doped B layer was produced by varying the boron concentration. This was varied up to ~7x10[20] at cm^{-3} (0.3% or 3000 ppm) as indicated, grown on a Ib substrate. The second sample is capped with an "intrinsic" layer, with very little (5-53 ppb) boron.







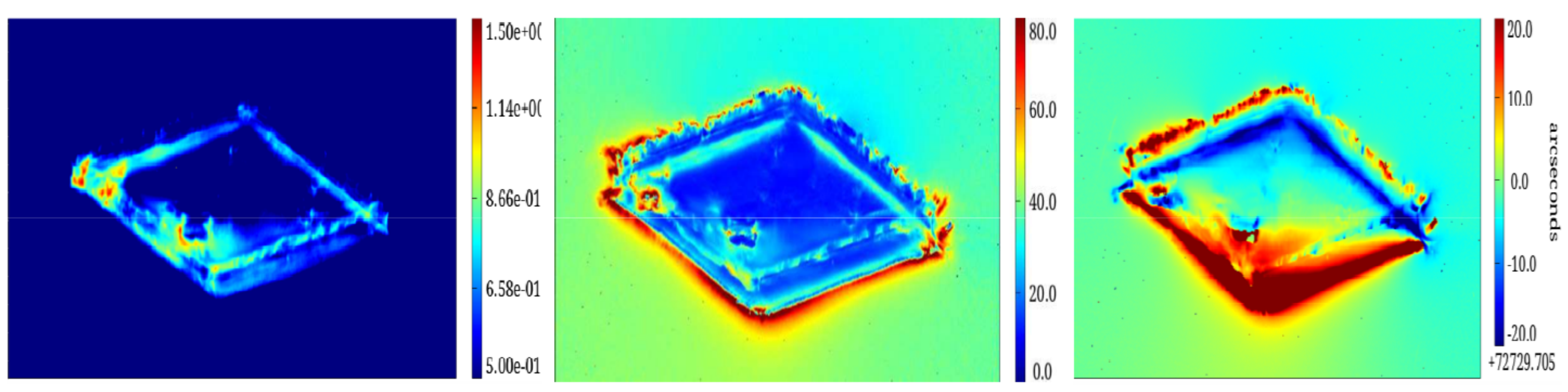
The expected dilatation for 3000 ppm :
$\delta d/d \sim 10^{-4}$
$\Delta\theta \sim 21''$ >> Darwin width

→ Expect a multi-layer mirror behaviour

Rocking Curve Imaging – Horizontal Configuration

$E_{X\text{-}ray}$~ 20 KeV, diffraction (400), θ_B ~ 20.240°, camera view ~ 10 x 10 mm^2 resolution (pixel size) ~10 µm

Diffraction is from the top surface, graded B-layer on the bottom.

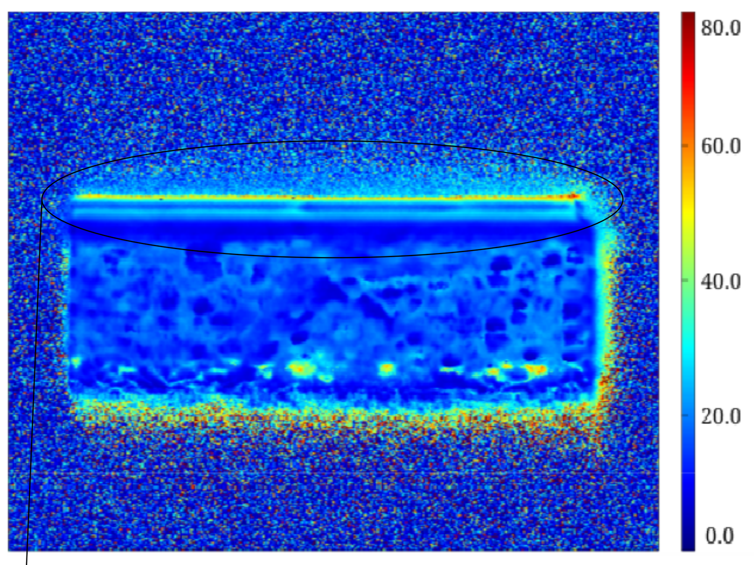


Integrated map FWHM map Peak position map

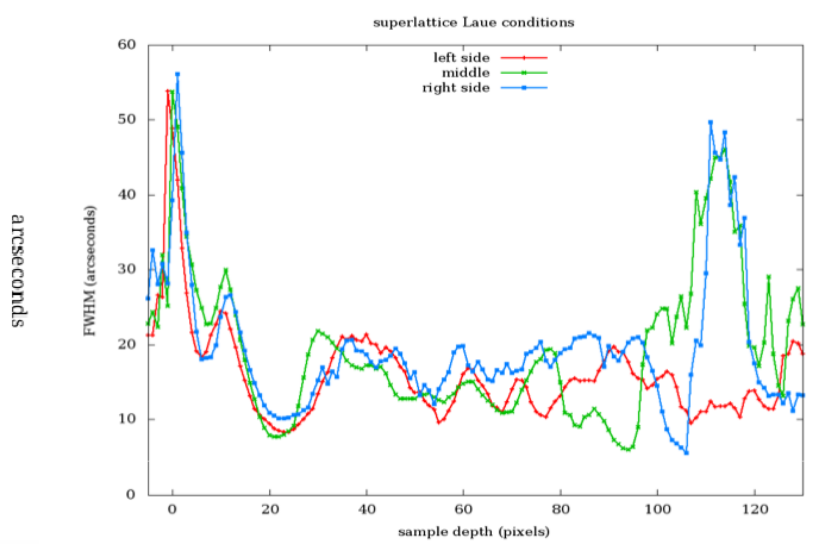
- The FWHM ~10" corresponds to the intrinsic width of diffraction convoluted with instrumental broadening, which indicates in most areas a very high crystalline quality.
- The FWHM measured on the "non perfect" area is higher, and shows regions, associated with dislocations, where this variation goes up to 60''.
- Two polished edges show clearly less deformation to the as-grown edges.
- The graded B-layer can be seen where the "3D" effect of the projection image reveals the bottom surface.
- When the graded B-layer is on top it acts like a very high reflectivity (multilayer) mirror with a broad acceptance of about 40" for this particular layer.
- The evolution of the Peak position in this region is consistent with the successful production of the graded B-layer.

Mixed Laue and Laue-Bragg case

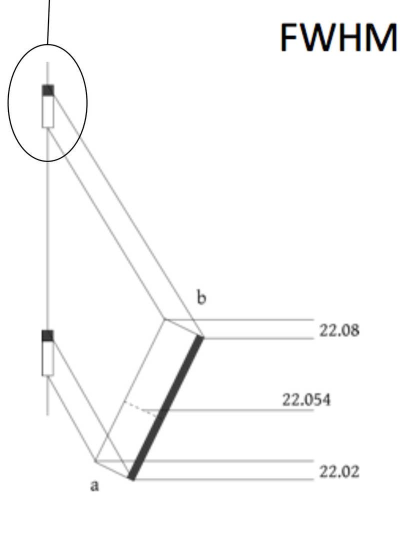
$E_{X\text{-}ray}$~ 20 KeV, diffraction (400), θ_B ~ 20.240°, resolution (pixel size) ~10 µm



FWHM map



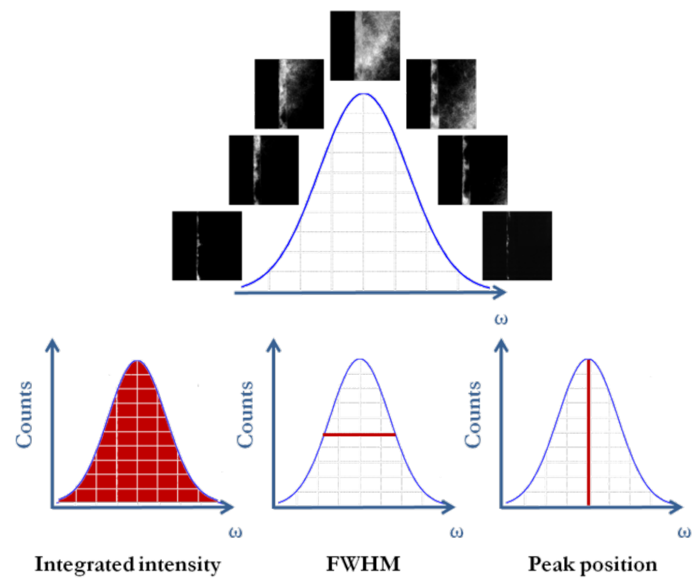
Cross section from the top to bottom part at three position of the crystal



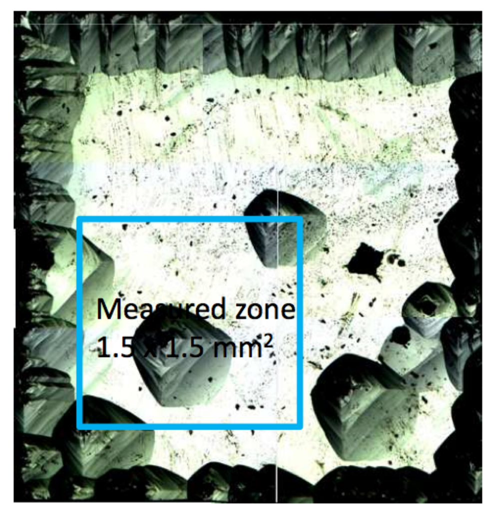
- Laue case for the most part but Brag case for the top edge.
- Top edge polished, bottom edge as grown, the former is improved.
- Top edge shows FWHM ~ 55" for the B-layer
- The substrate bulk has low quality, improve substrates in future.
- The unpolished bottom edge also exhibits substantial strain.
- The cross section on the FWHM map (3 lines) shows peak on the top (left of image b) with FWHM values up to 55", associated with the Boron doped layer.
- The thickness is ~ 5 pixels (50µm).

Rocking Curve Imaging : Vertical configuration

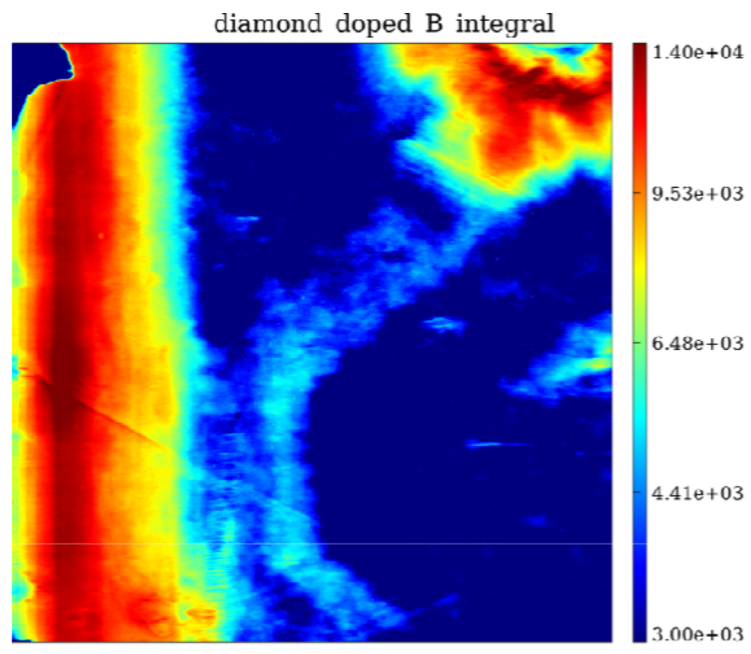
$E_{X\text{-}ray}$~ 20 KeV, diffraction (400),θ_B ~ 20.240°camera view ~ 1.5 x 1.5 mm^2, resolution (pixel size) ~0.75 µm



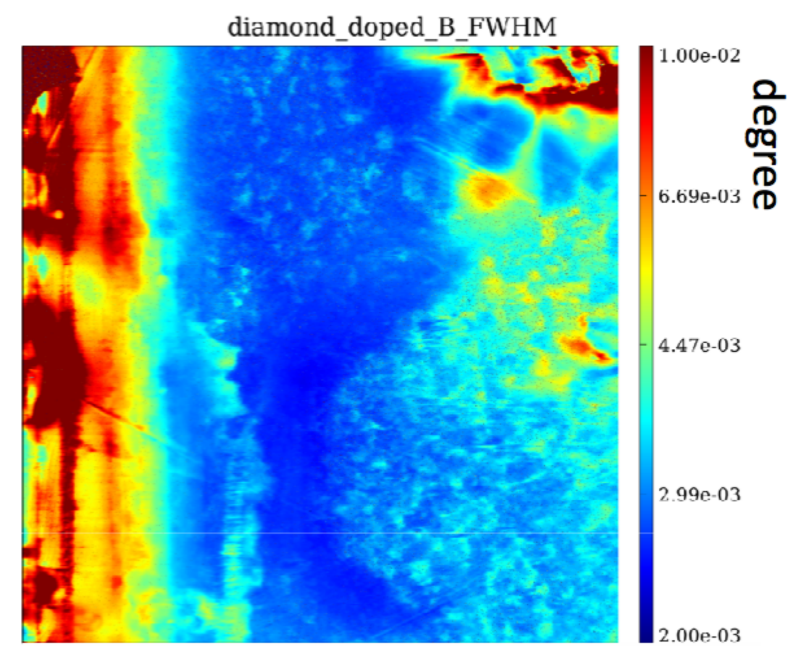
Dispersive mode acquisition followed by digital dispersion correction



Growth surface by digital microscopy shows hillocks on the surface caused by boron rejection during the growth.



Integrated map



FWHM map

Blue regions indicate a very high crystalline quality, over most of the diamond, except for the red regions where the quality is poor and associated with dislocations.

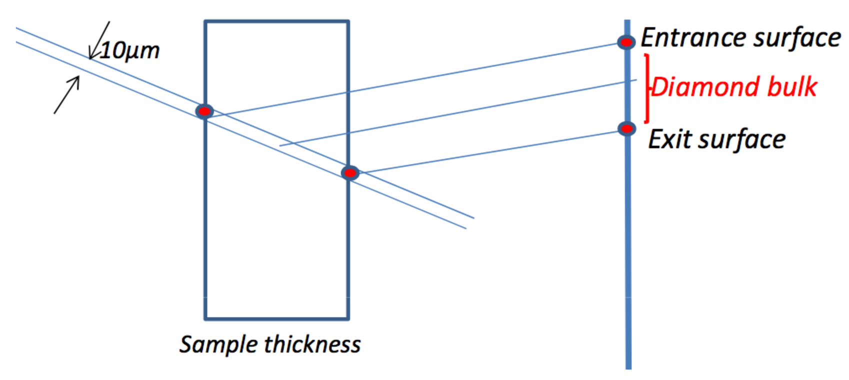
Section Topography

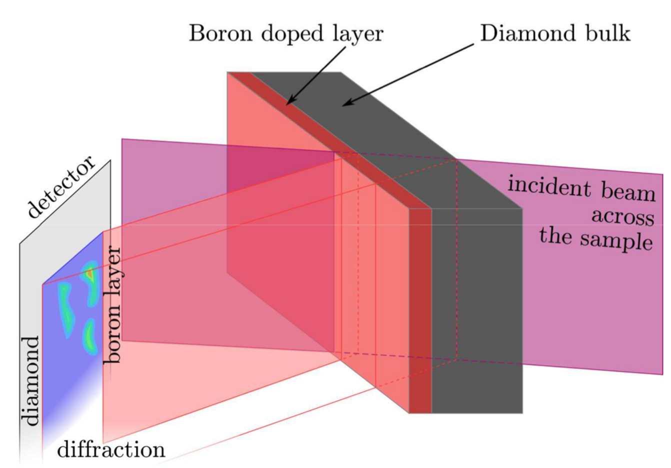
$E_{X\text{-}ray}$~ 20 KeV, diffraction (400),θ_B ~ 20.240°

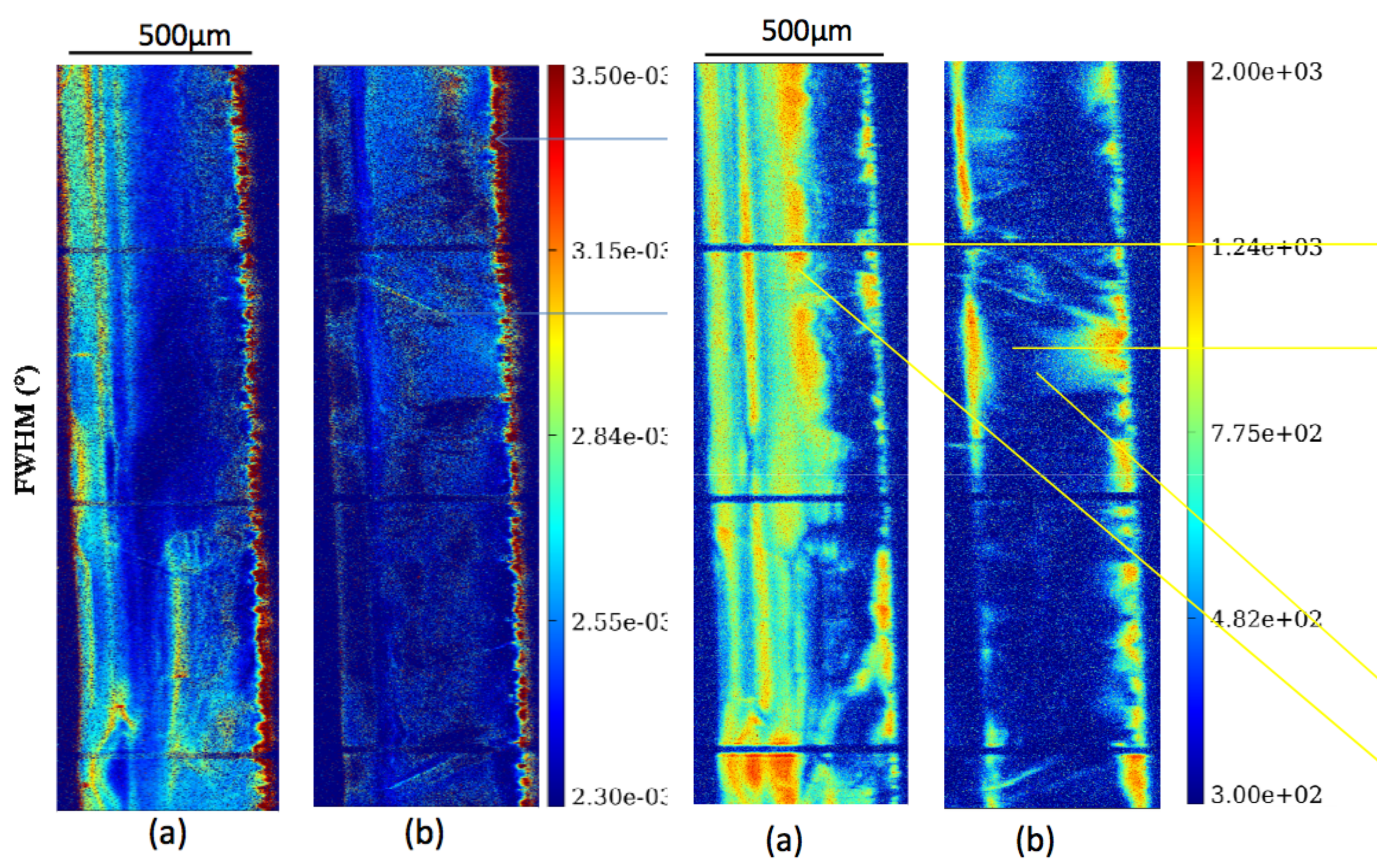
Section topography allows the depth resolution to be recovered and defect imaging within a "nearly -2D" virtual volume defined by the intersection of the 10 µm wide beam with the crystal.

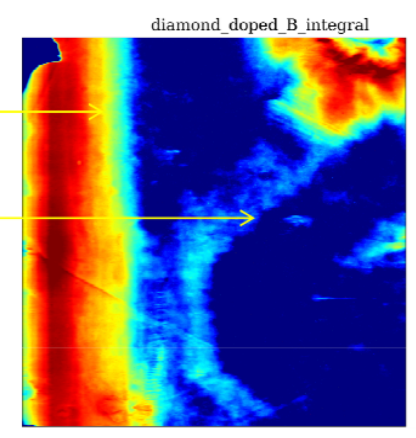
Below are the FWHM and the Integrated Intensity section maps.

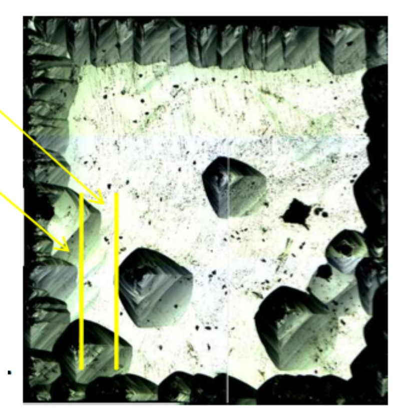
The section labeled (a) is in the region where there are dislocations in the bulk and that labelled (b) is in the higher quality diamond.











A distortion at the interface of the intrinsic diamond and the boronated diamond interface is revealed. It has a value of 2.45 x 10^{-3} = 9". It is about 30% higher when the section topograph intersects the region with dislocations.

Conclusions

1. X-ray diffraction topography has validated the production of a graded B-layer, 50μm thick.
2. The lattice parameter evolves over the depth of the graded layer.
3. The interface has introduced a distortion in the lattice.
4. The graded B layer can act as a very effective multi-layer mirror.
5. It would be preferable to develop the graded layer on the best possible (lattice) quality substrates.

References

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[2] A. V. Korol, A. V. Solov'yov, and W. Greiner, "**Coherent radiation of an ultrarelativistic charged particle channelled in a periodically bent crystal**", J. Phys. **G24**, L45 (1998);

[3] A. V. Korol, A. V. Solov'yov, and W. Greiner, "**Channeling of Charged Particles Through Periodically Bent Crystals: on the Possibility of a Gamma Ray Laser**", Int. J. Mod. Phys. E **8**, 49 (1999)