X-ray diffraction studies of GaN p-i-n structures for high power electronics

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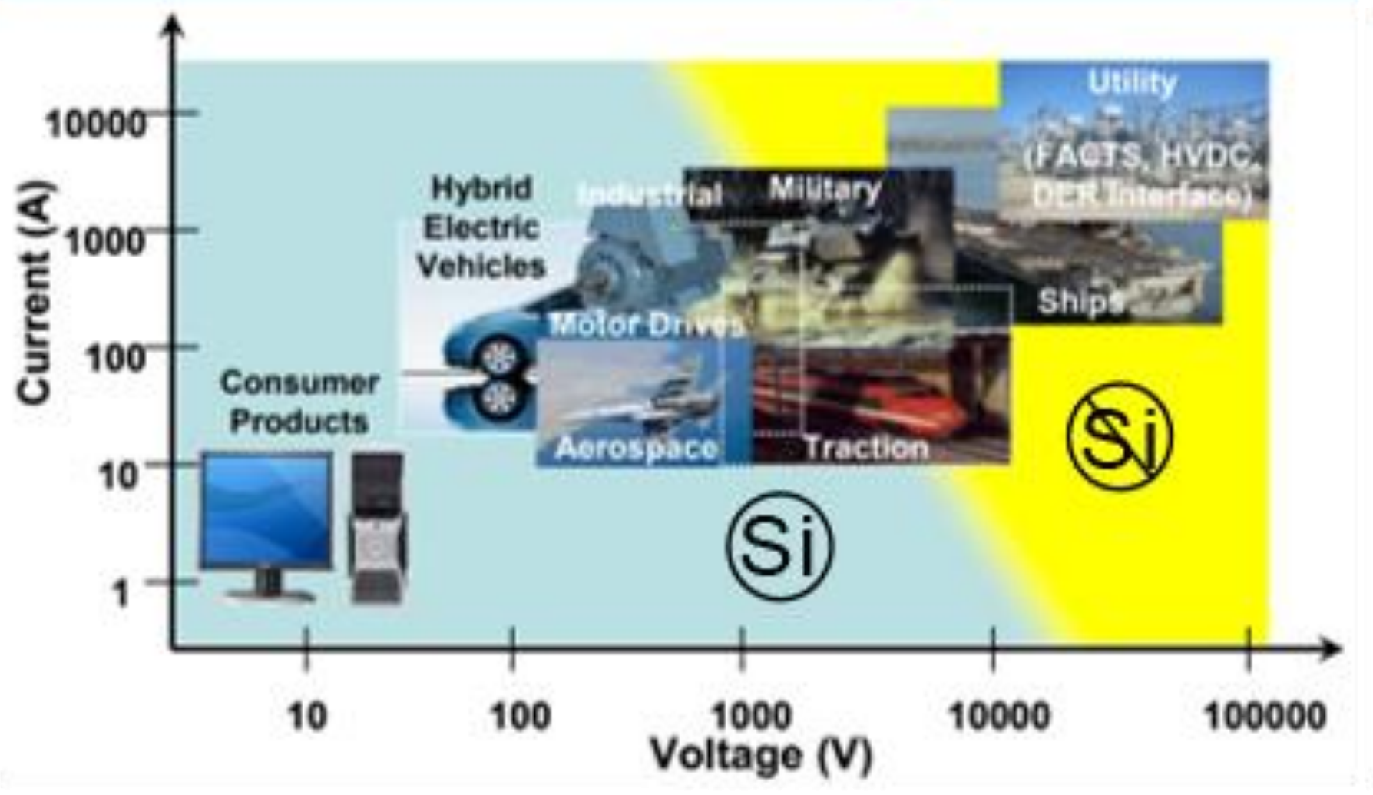
Introduction

Although Si-based electronics are used to power light-emitting diodes and electric vehicles, their utility in high power applications is limited by a low breakdown voltage. The most promising alternative power devices consist of vertical GaN devices, which often require regrown active regions. Here, we report on x-ray diffraction studies of the crystallinity of the GaN p-i-n structures prepared with and without ex-situ ambient exposure and/or chemical etching.

GaN for High Power Electronics



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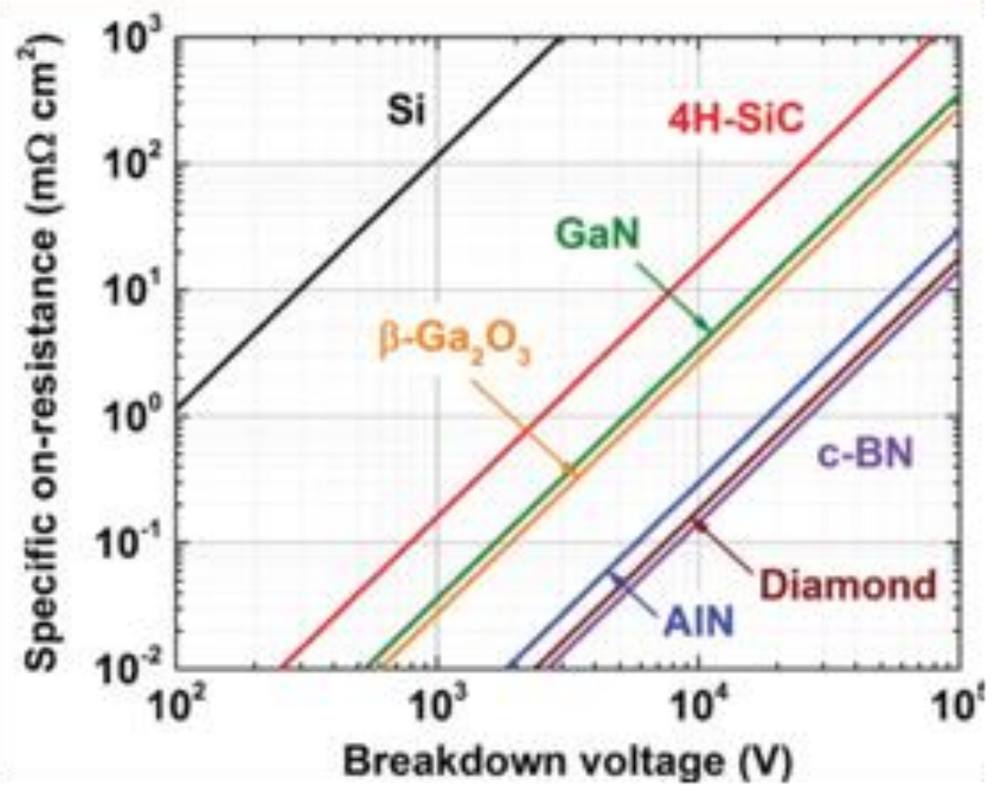
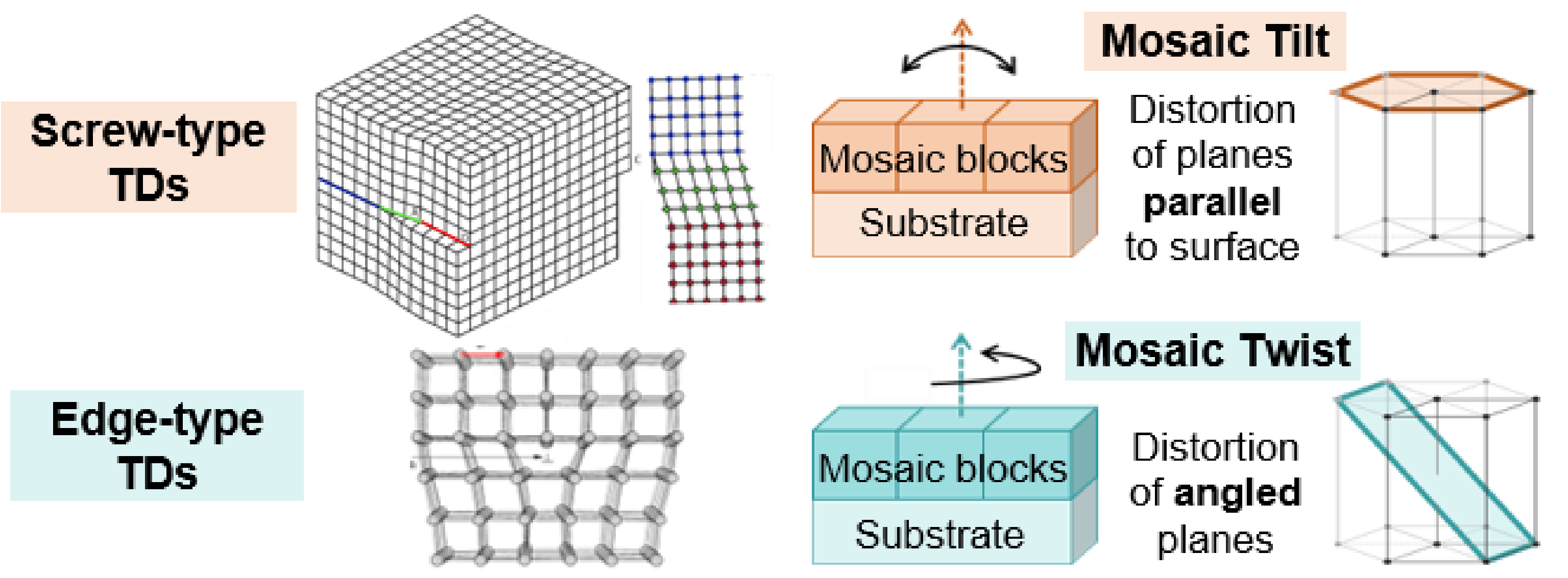


GaN outperforms Si, SiC with low on-resistance and high breakdown voltage [2].

Threading Dislocations (TDs)



Screw-type TDs

Mosaic Tilt

Mosaic blocks

Substrate

Distortion of planes **parallel** to surface

Edge-type TDs

Mosaic Twist

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Distortion of **angled** planes

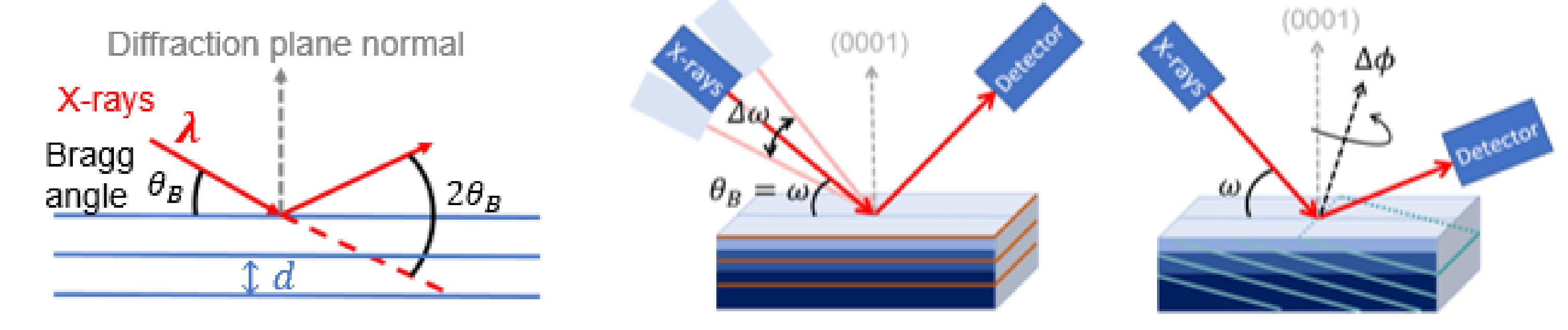
How can we quantify screw- and edge-type dislocation densities?

High Resolution X-ray Diffraction (HRXRD)

Bragg's Law: $n\lambda = 2d\sin\theta_B$

Symmetric Δω RC

Asymmetric Δϕ RC



Pseudo-Voigt Analysis of HRXRD

$$P(x) = I_0[\eta C(x) + (1-\eta)G(x)]$$

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Screw TD density

$$N_S = \frac{\alpha_\omega^2}{2\pi \boldsymbol{b}_S^2 \ln 2}$$

Edge TD Density

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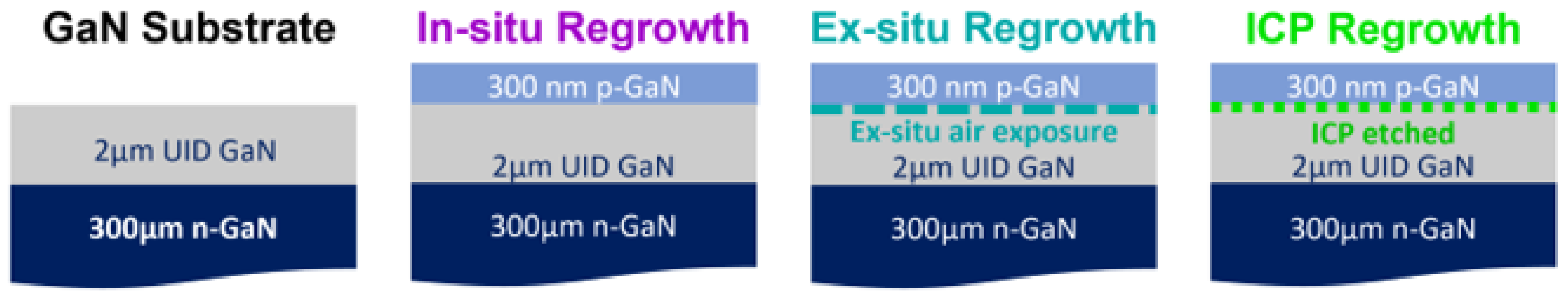
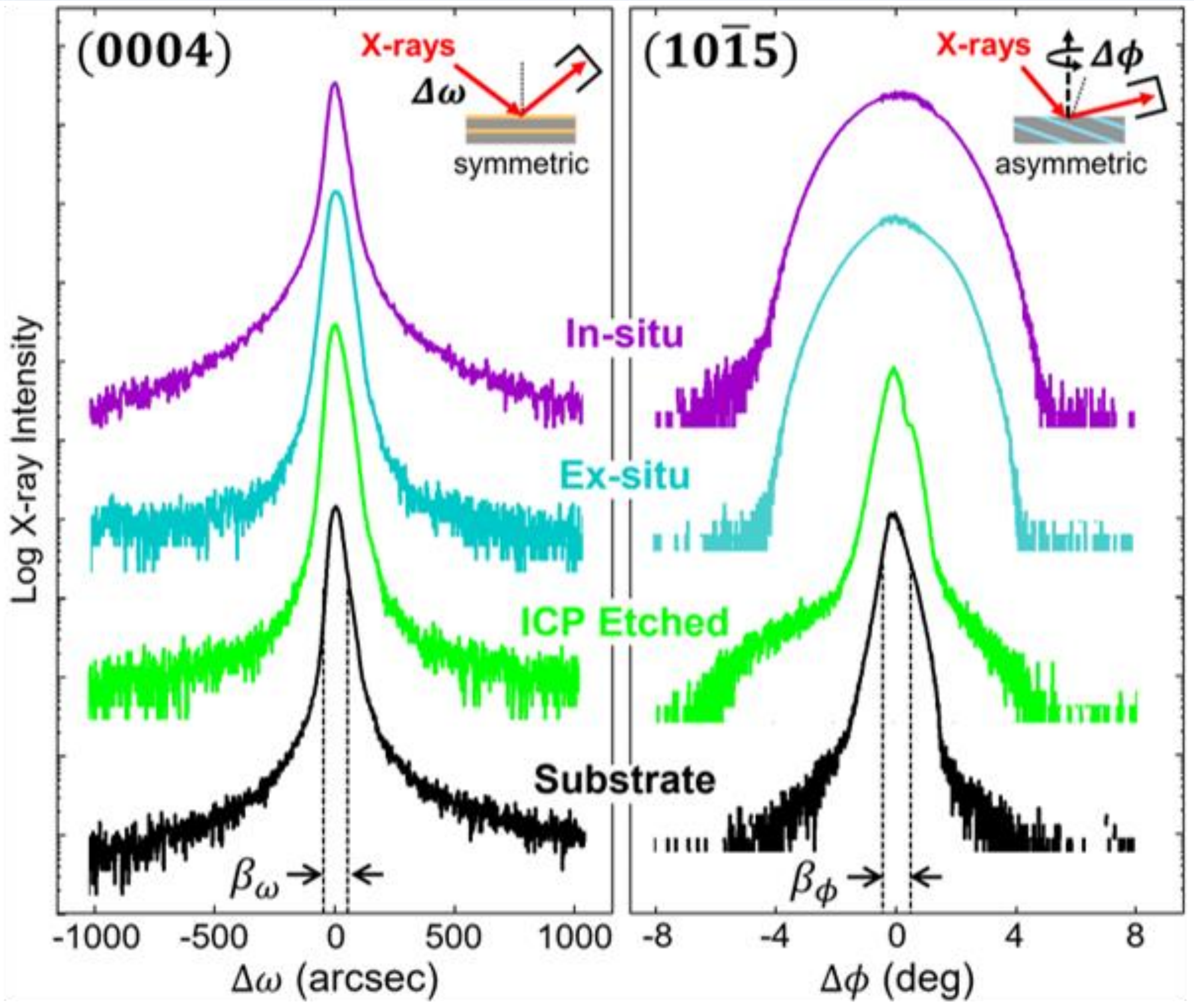
Regrowth Interface at p-n Junction



Symmetric and Asymmetric Scans



Structure & Electronic Properties Correlation

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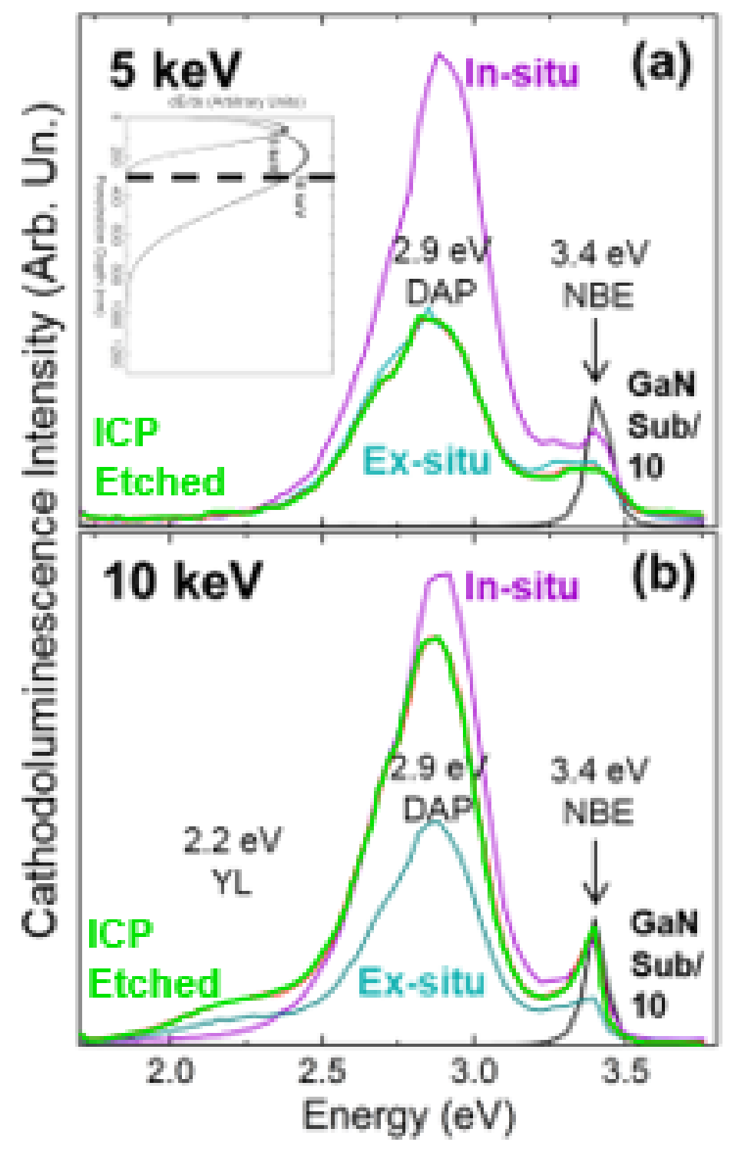

Probing the structure using XRD:

- Ex-situ and ICP Etched had the **largest** screw-type TD densities
- In-situ had the **lowest** screw-type TD density and the **highest** edge-type TD density

Probing electronic properties using cathodoluminescence

- Donor acceptor pair emission (DAP) near the surface is lowest for Ex-situ and ICP Etched
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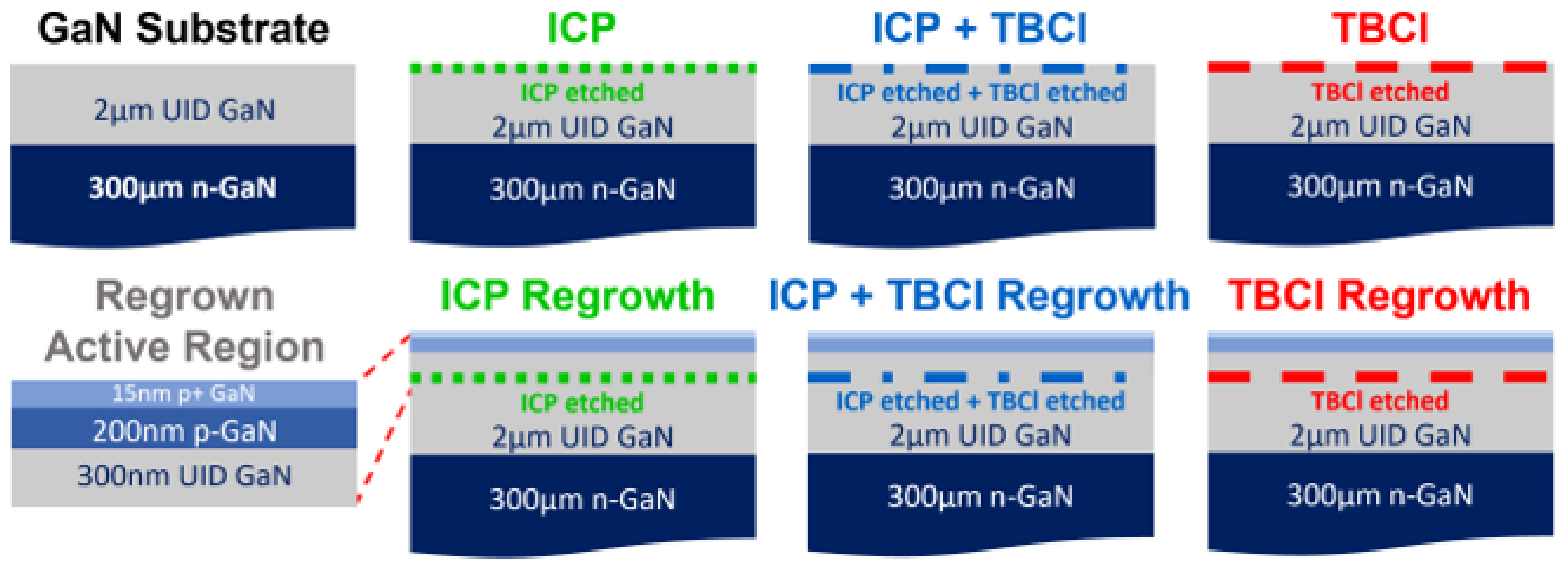
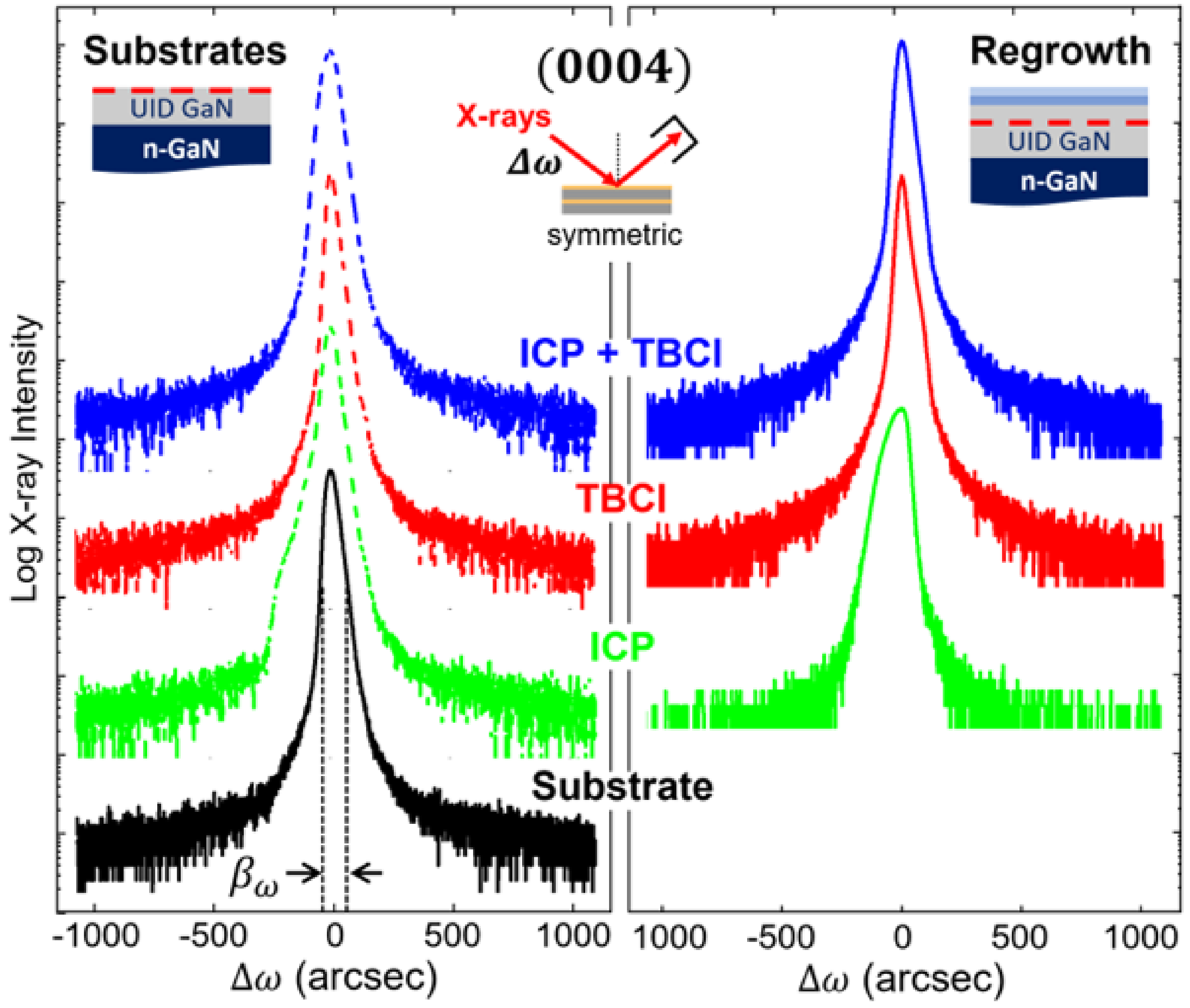
Ambient air exposure worsens crystallinity and electronic properties, but ICP etching can **partially restore the electronic properties.**

Regrowth Interface in UID Layer



Symmetric Scans Only



Probing the structure with XRD & RBS

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ICP + TBCI	70	0.059	3.2	**8.5**	6.6	***Future XRD work:*** • *Conduct (10-15) phi scans* • *Calculate twist angle* • *Calculate edge-type TD density*	
ICP + TBCI Regrowth	47	0.287	1.6	**2.3**	2.5		
TBCI	37	0.372	1.2	**1.1**	2.6		
TBCI Regrowth	36	0.547	0.9	**0.7**	1.9		
ICP	53	0.322	1.8	**2.7**	2.0		
ICP Regrowth	89	0.117	3.8	**12.2**	2.9		
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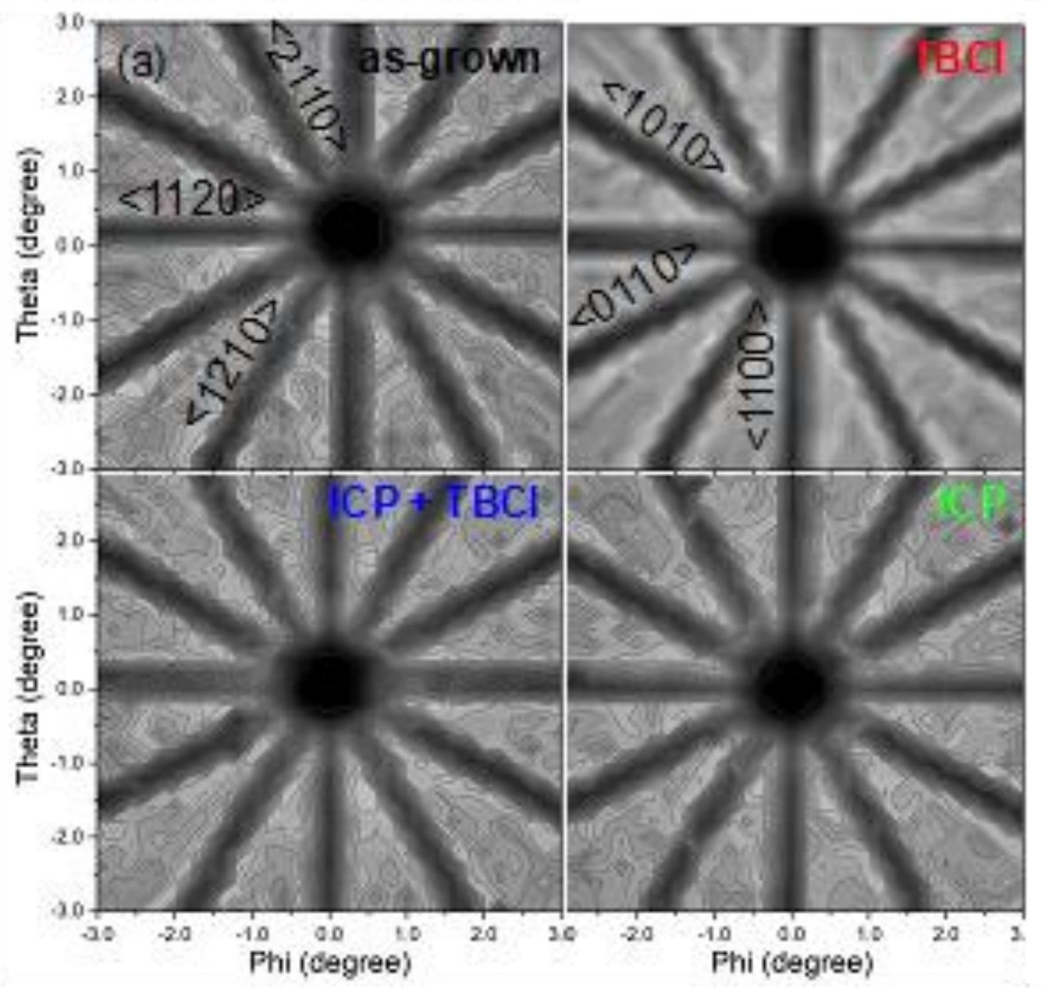
XRD and RBS reveal ICP Etching lowers crystal quality overall.



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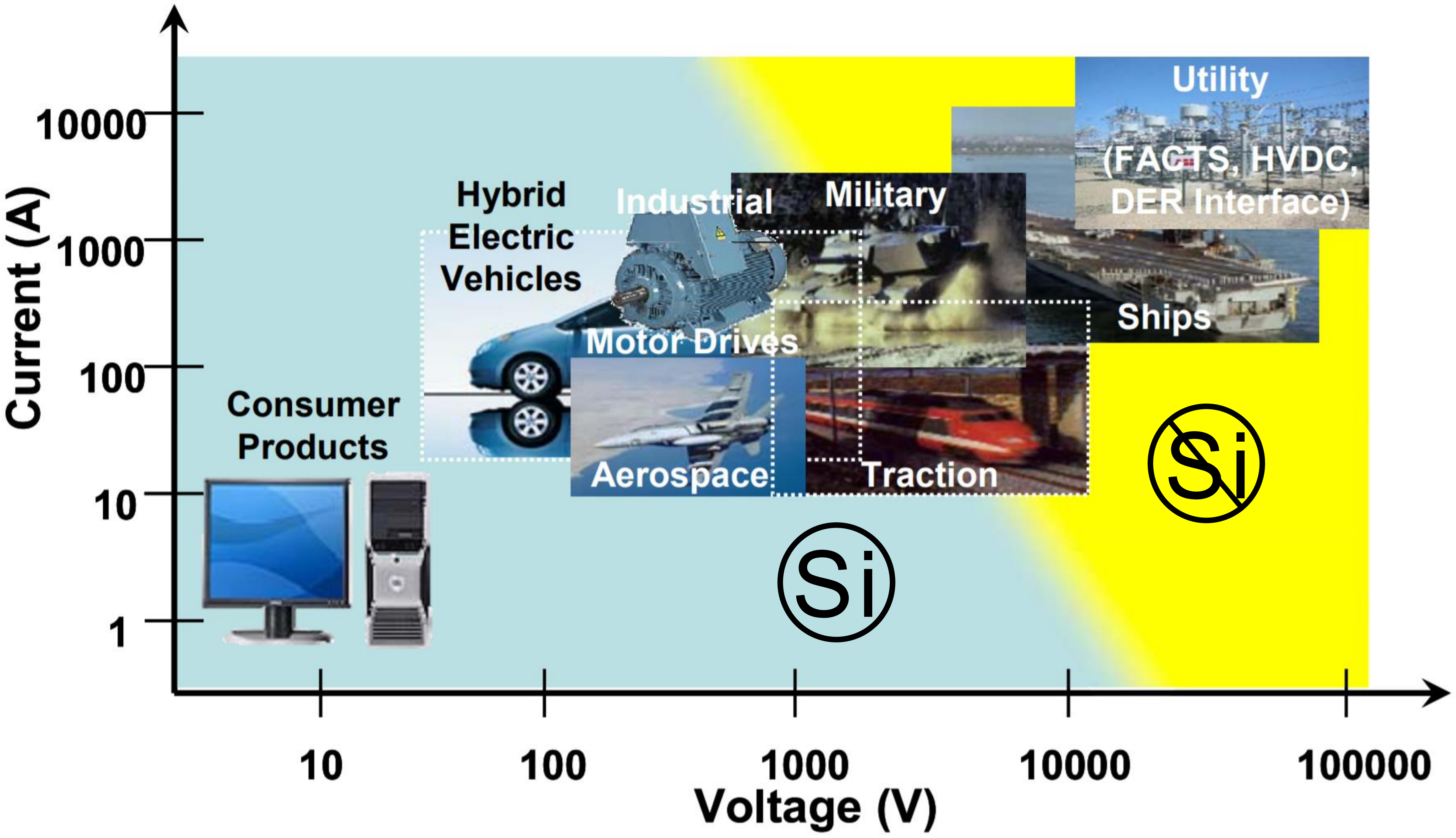

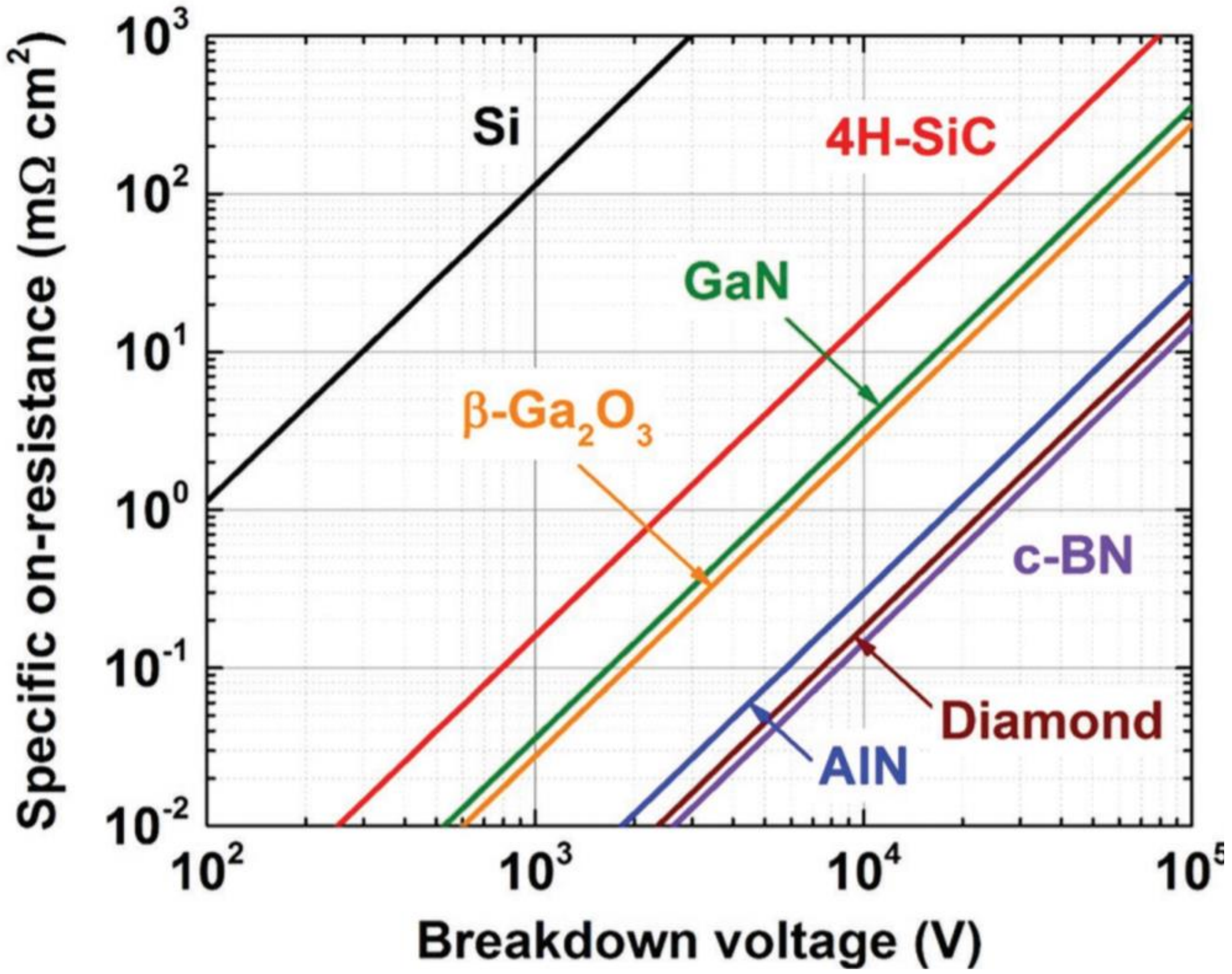

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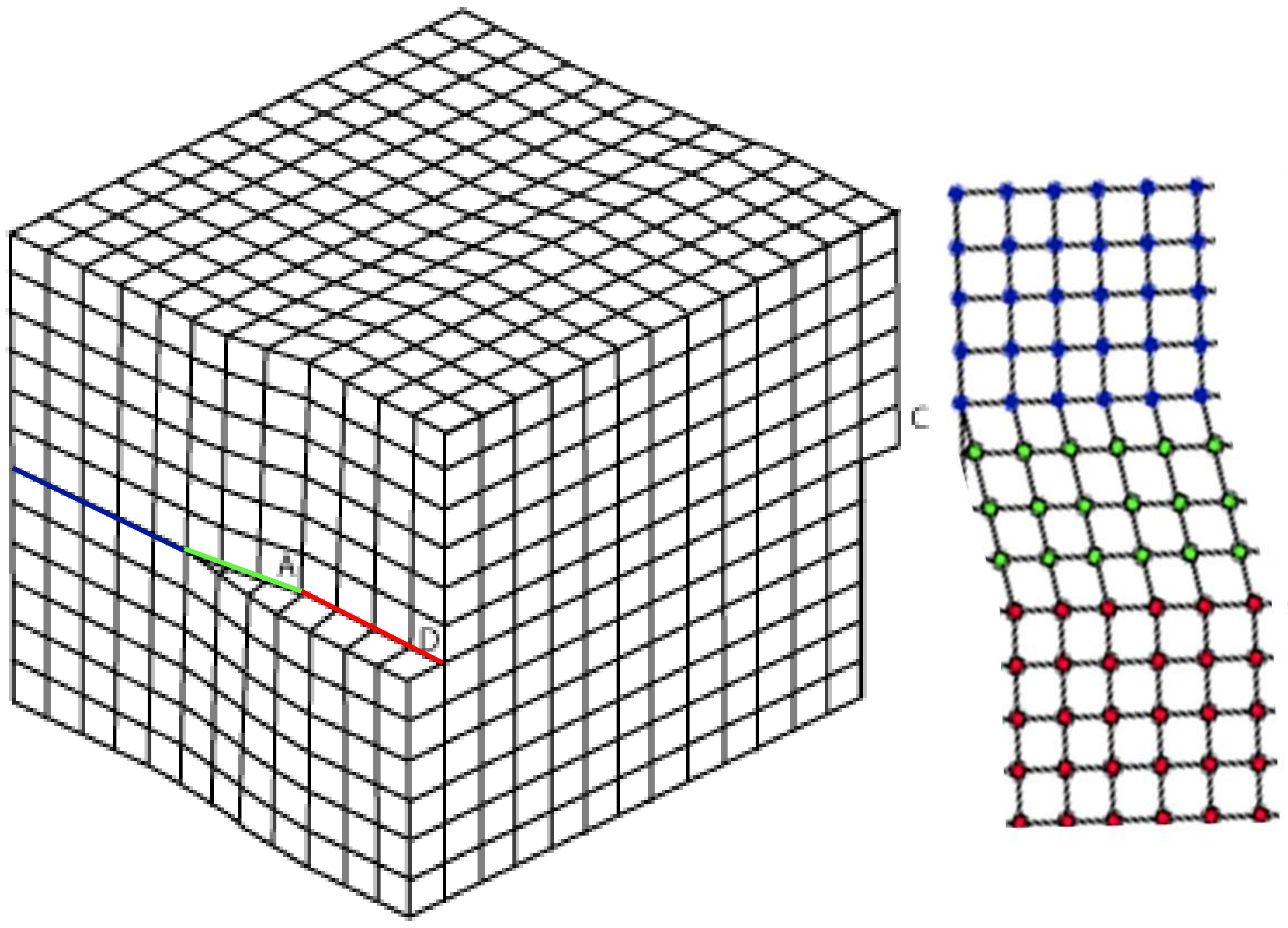
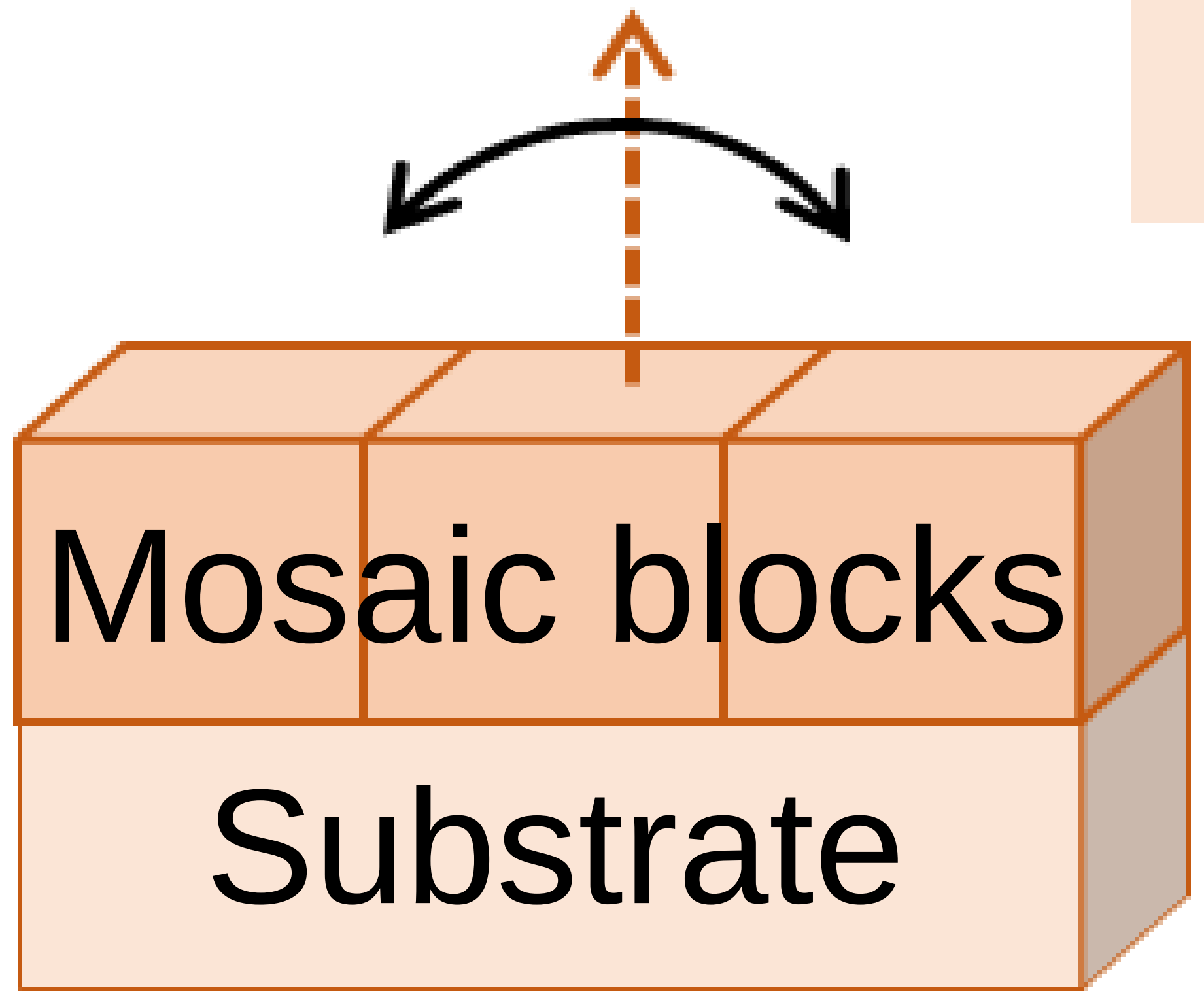


Mosaic Tilt



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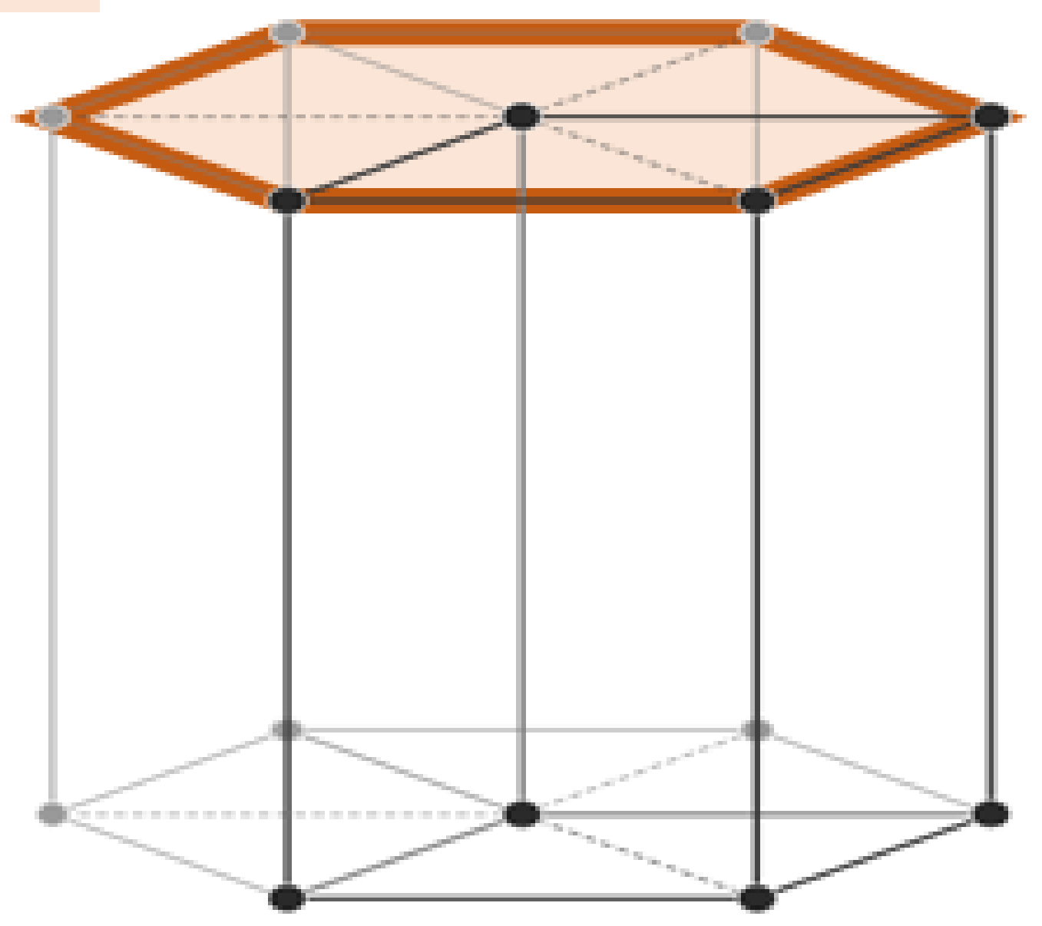

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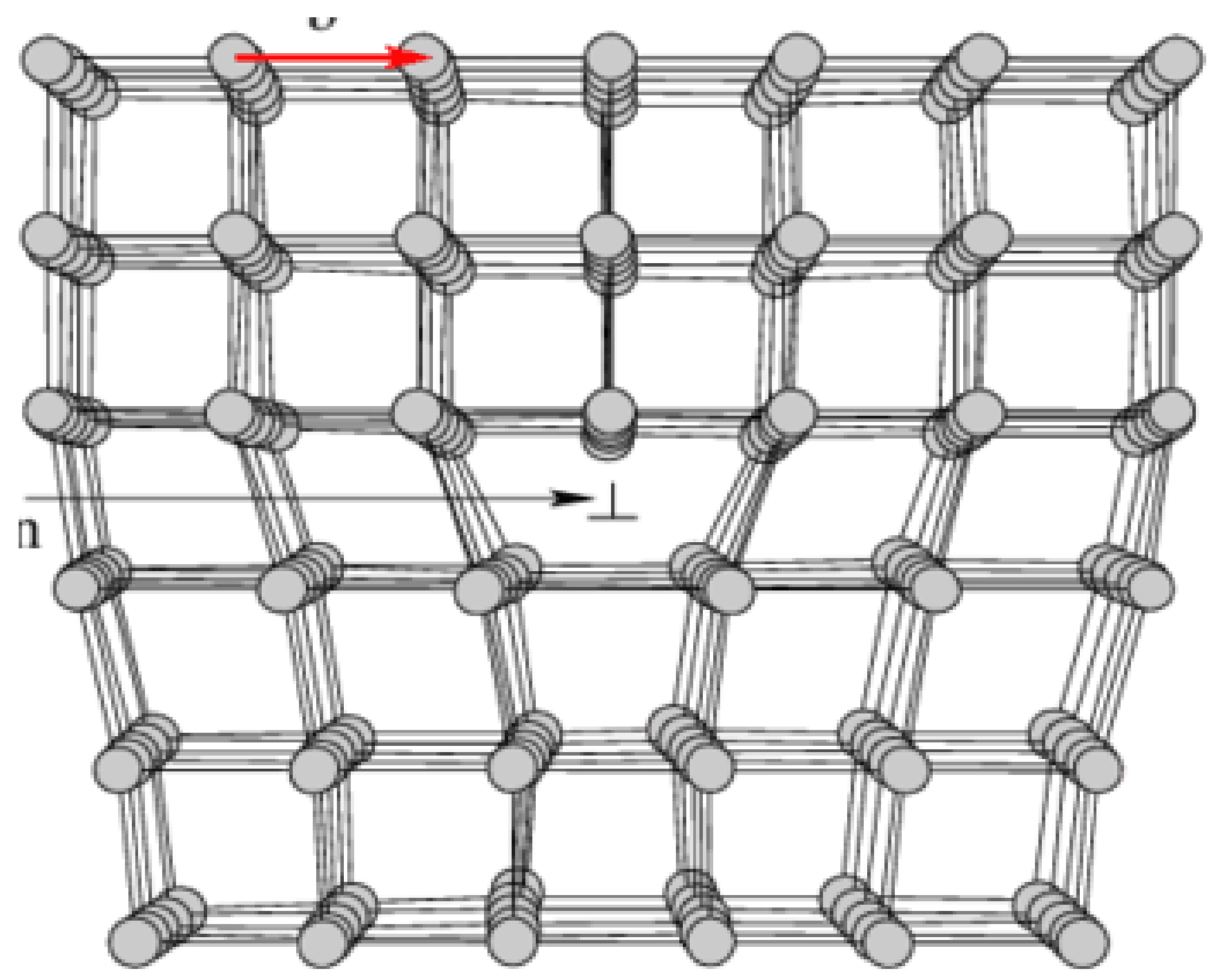

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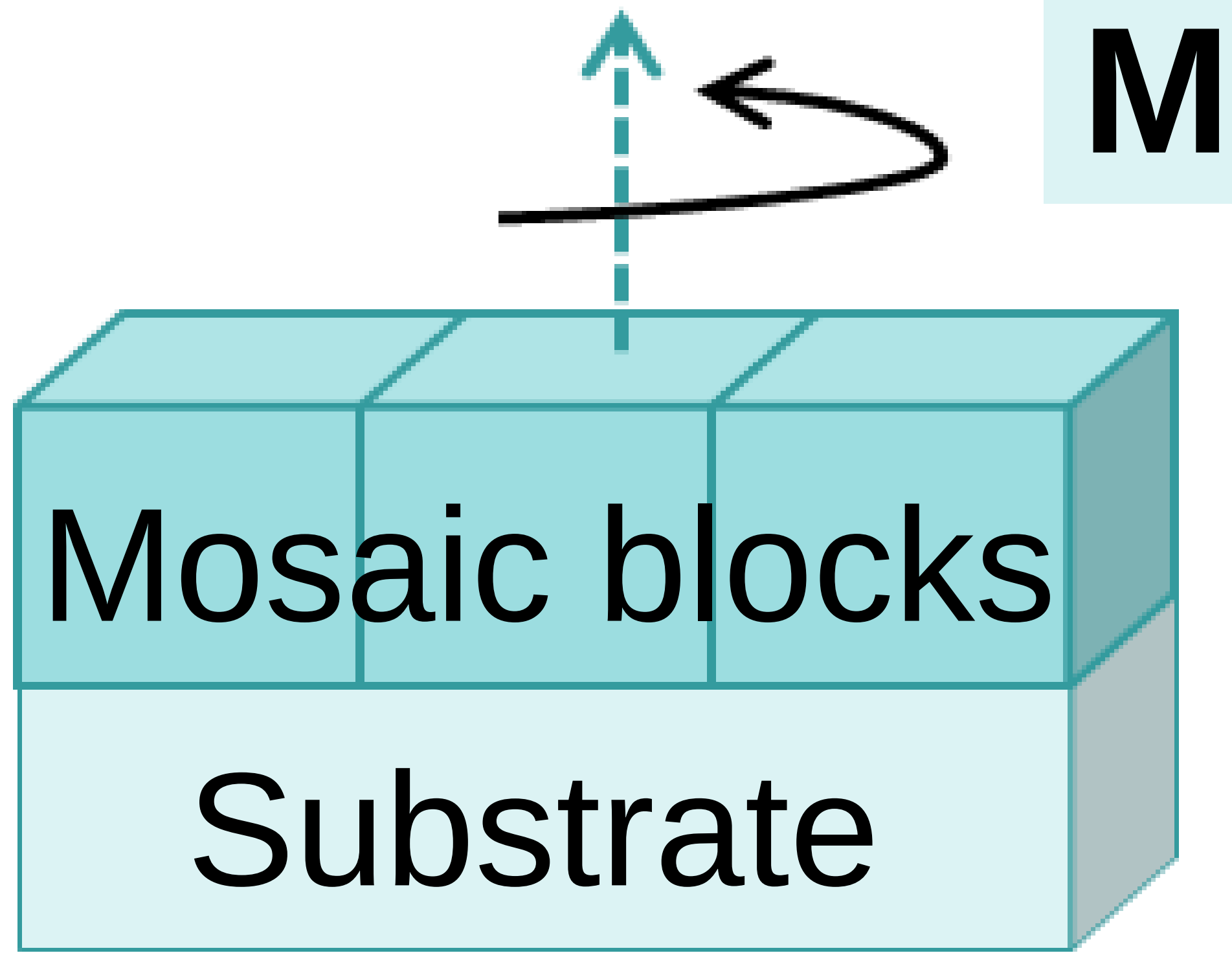

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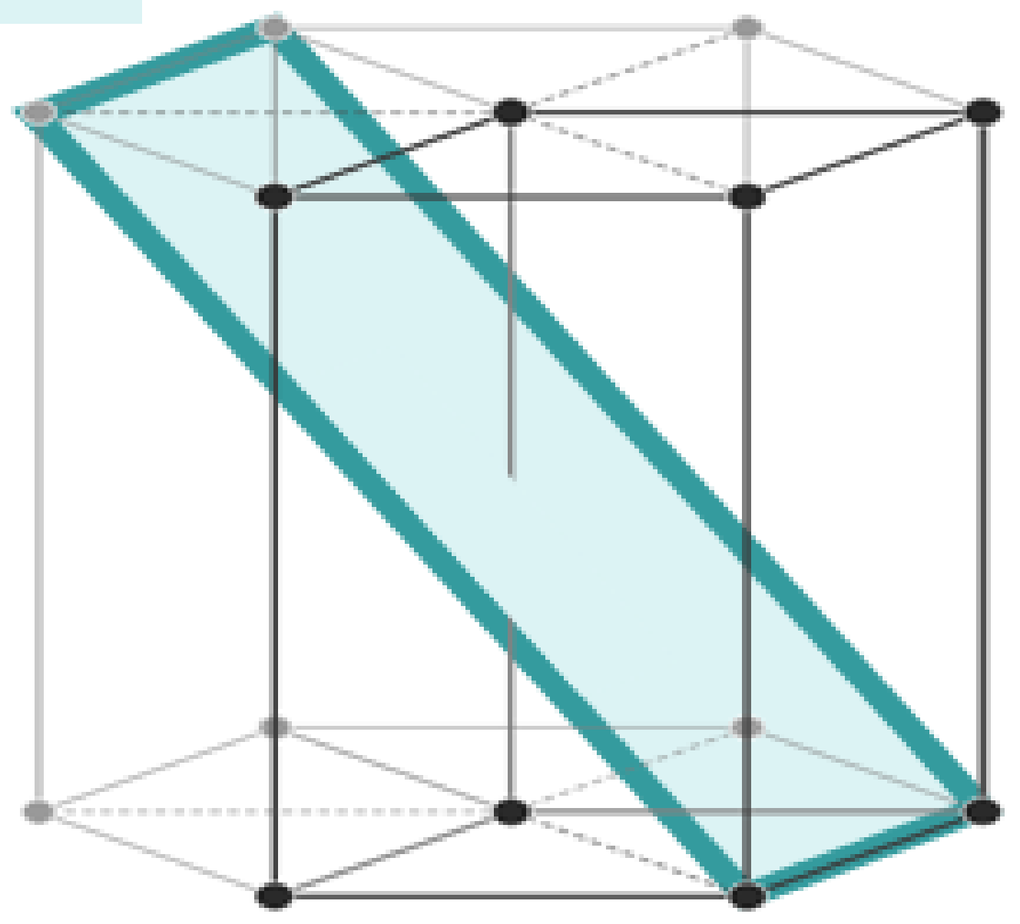

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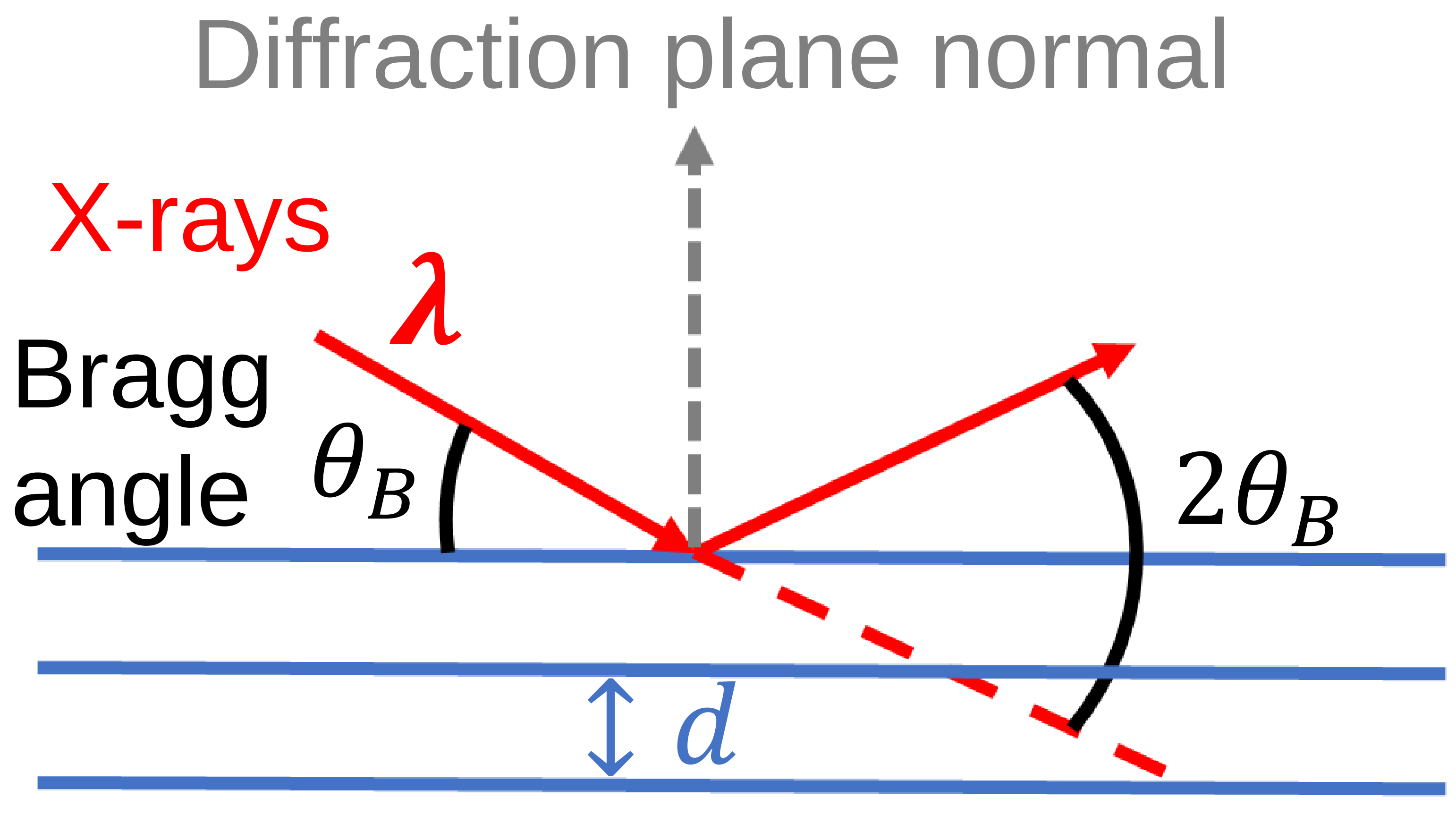

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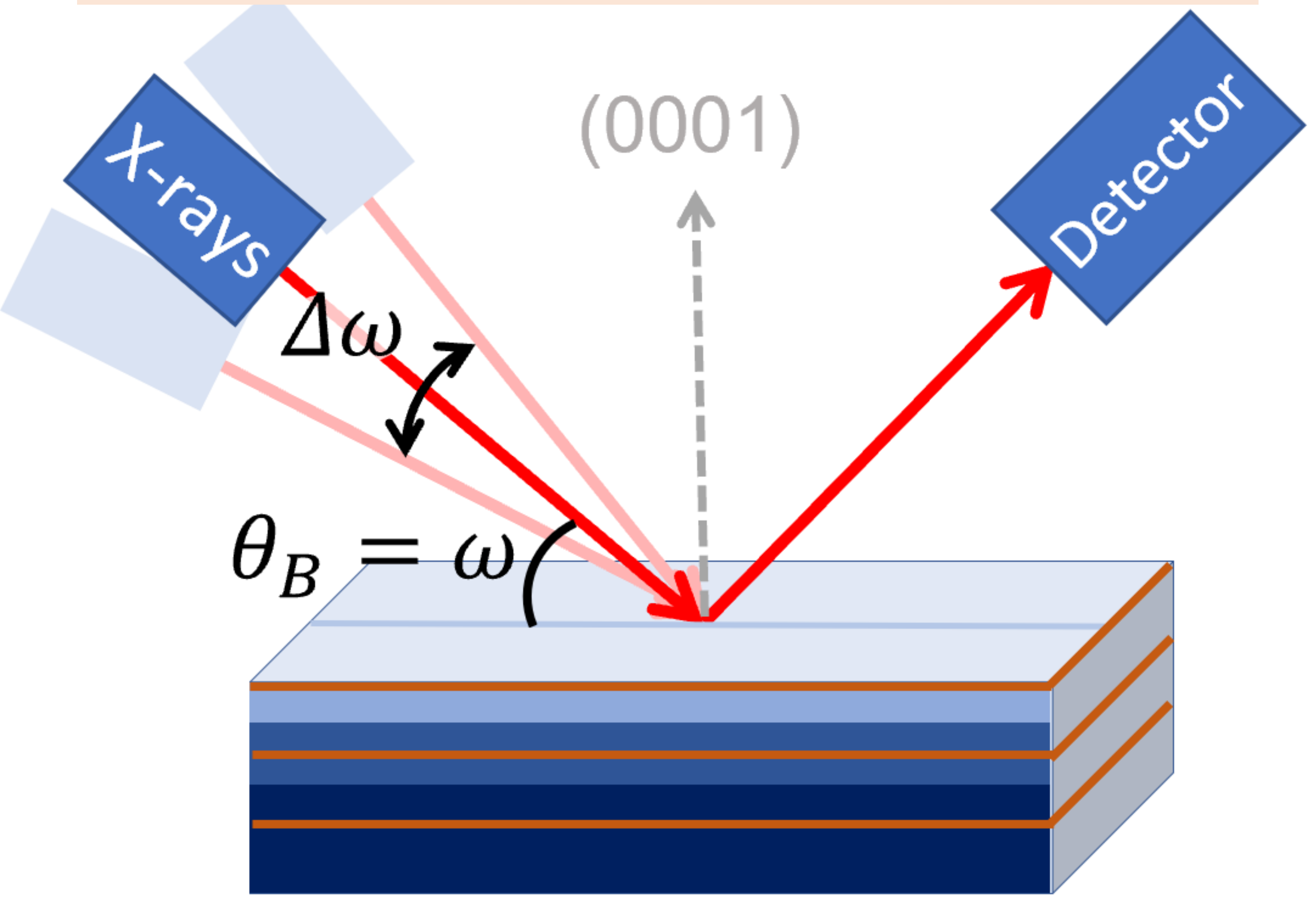

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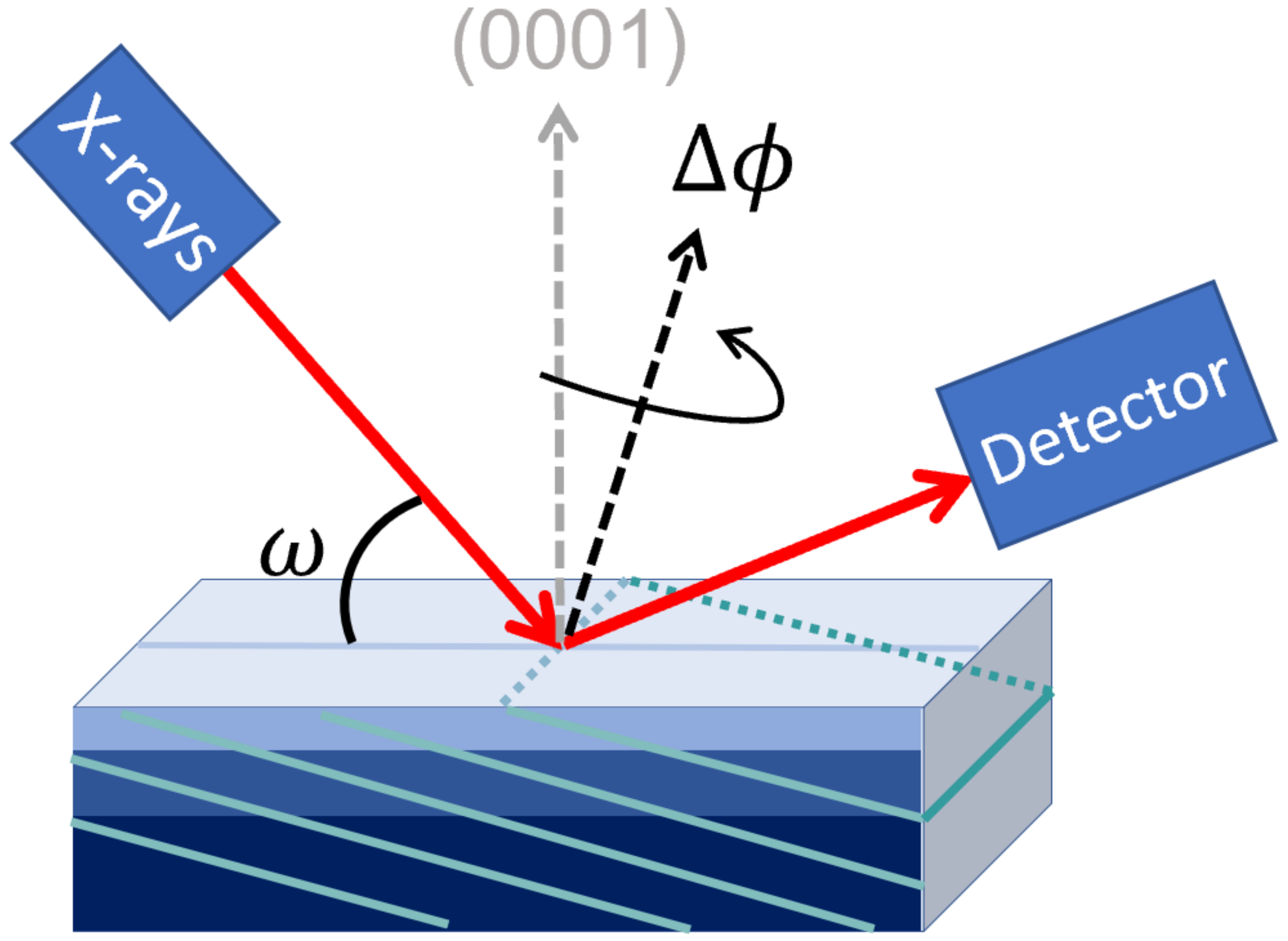

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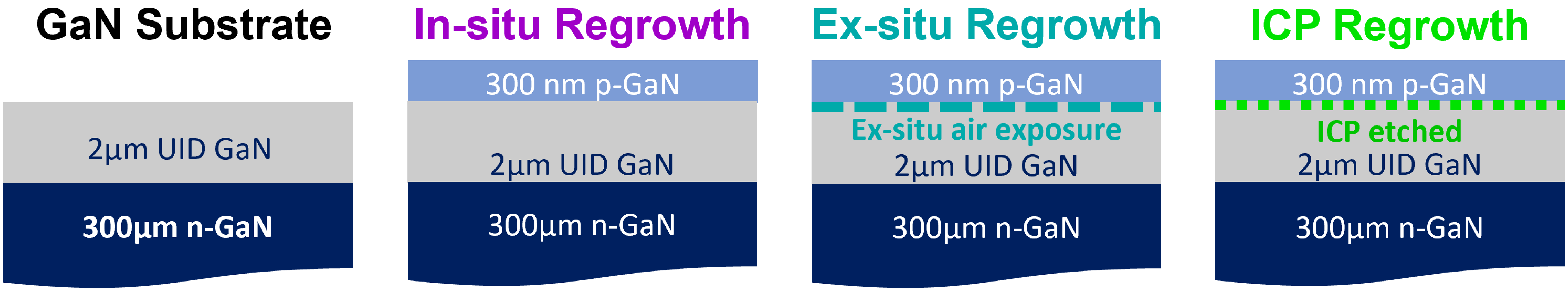

GaN Substrate

2µm UID GaN

300µm n-GaN

In-situ Regrowth

300 nm p-GaN

2µm UID GaN

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Ex-situ Regrowth

300 nm p-GaN

Ex-situ air exposure

2µm UID GaN

300µm n-GaN

ICP Regrowth

300 nm p-GaN

ICP etched

2µm UID GaN

300µm n-GaN

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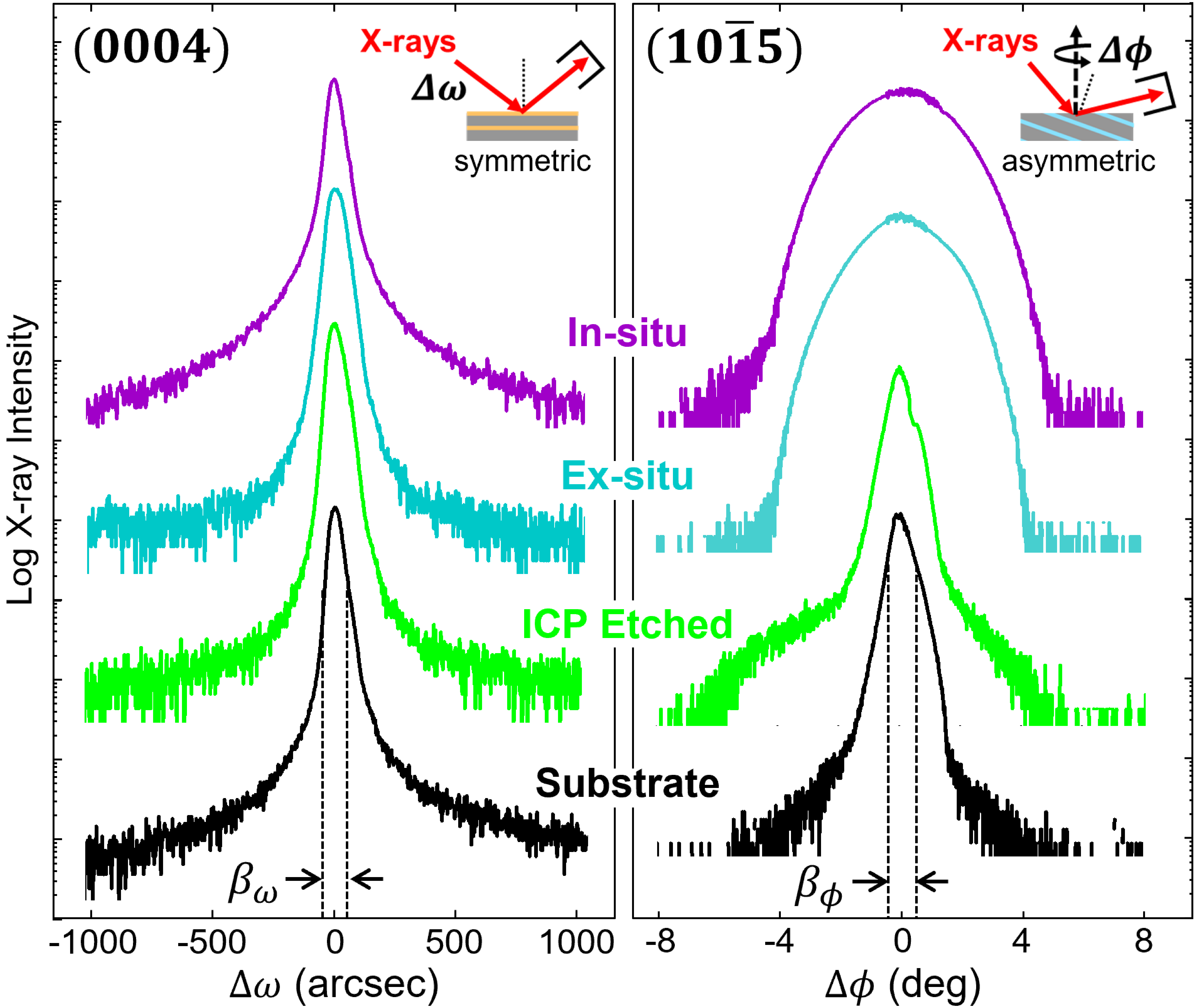

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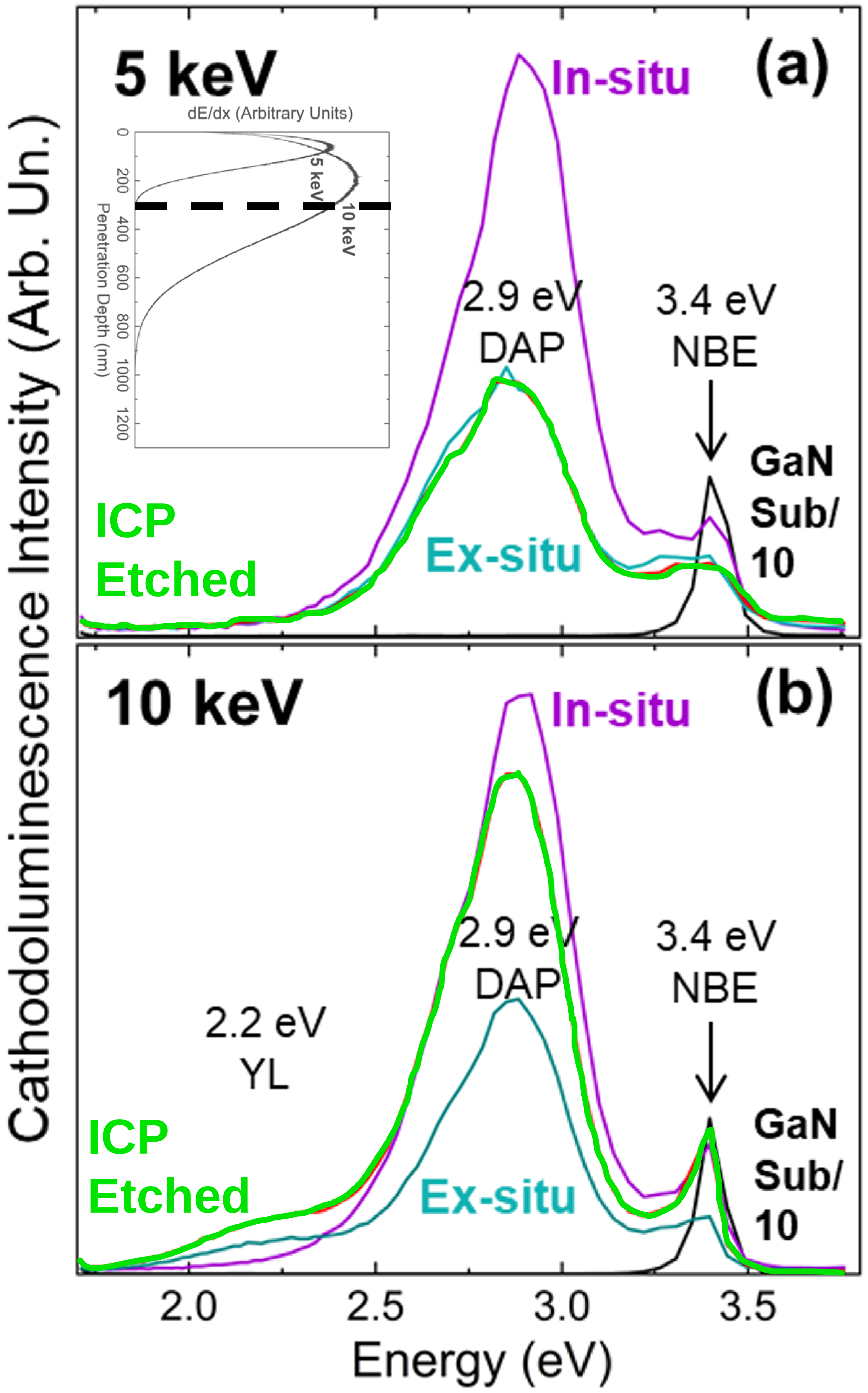

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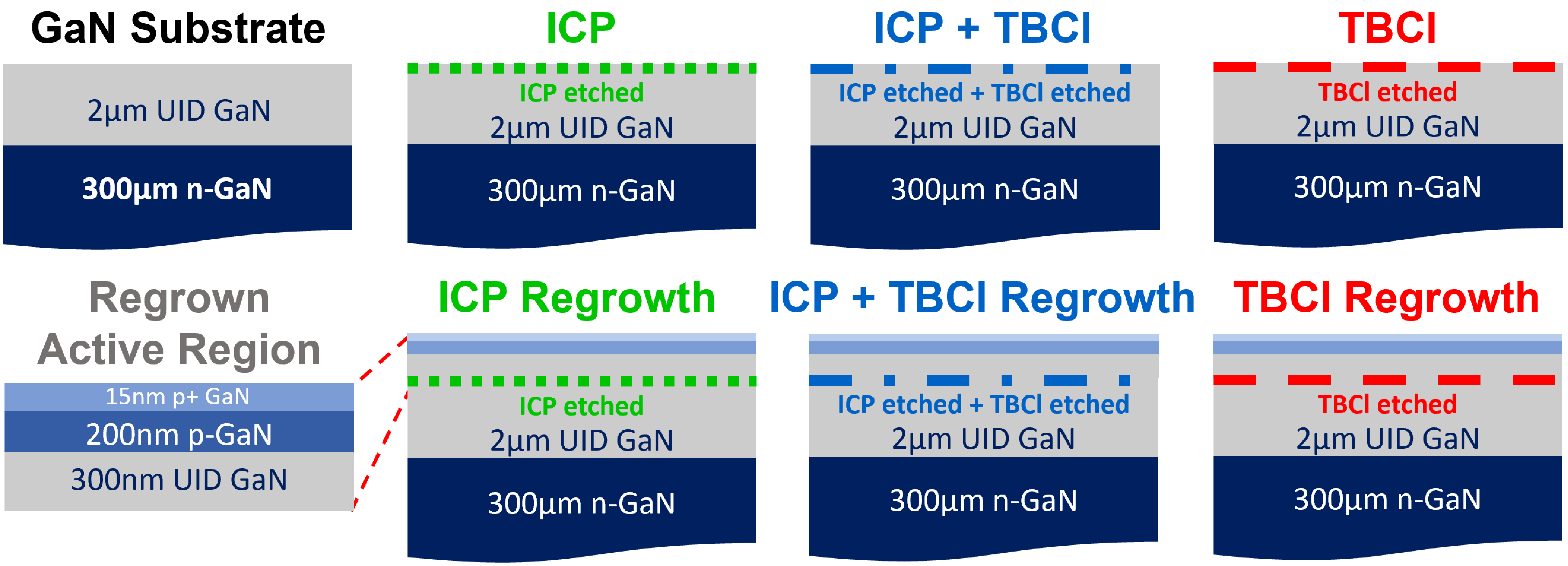

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ICP

ICP etched

2µm UID GaN

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ICP + TBCl

ICP etched + TBCl etched

2µm UID GaN

300µm n-GaN

TBCl

TBCl etched

2µm UID GaN

300µm n-GaN

Regrown Active Region

15nm p+ GaN

200nm p-GaN

300nm UID GaN

ICP Regrowth

ICP etched

2µm UID GaN

300µm n-GaN

ICP + TBCl Regrowth

ICP etched + TBCl etched

2µm UID GaN

300µm n-GaN

TBCl Regrowth

TBCl etched

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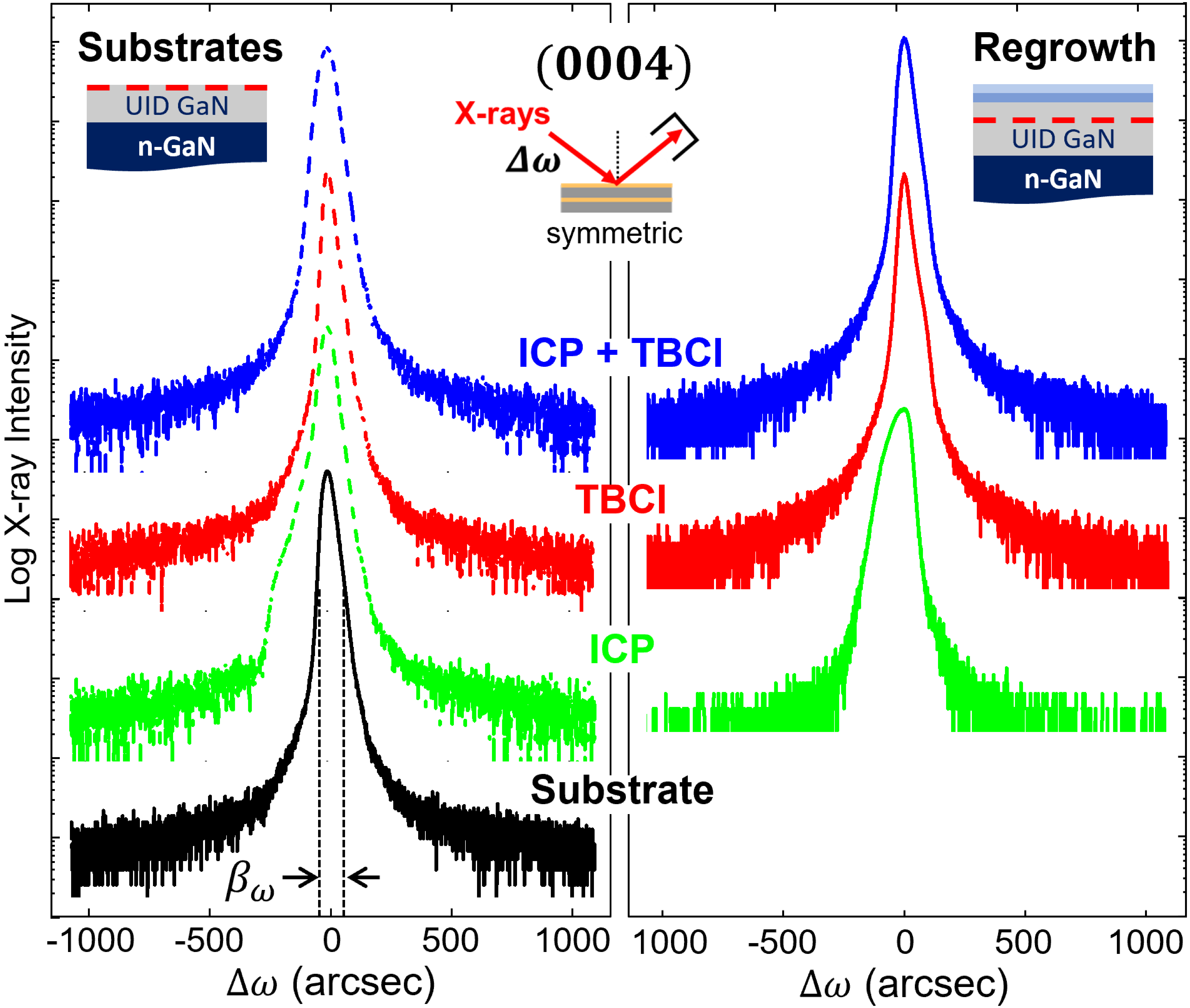
Symmetric Scans Only



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Future XRD work:

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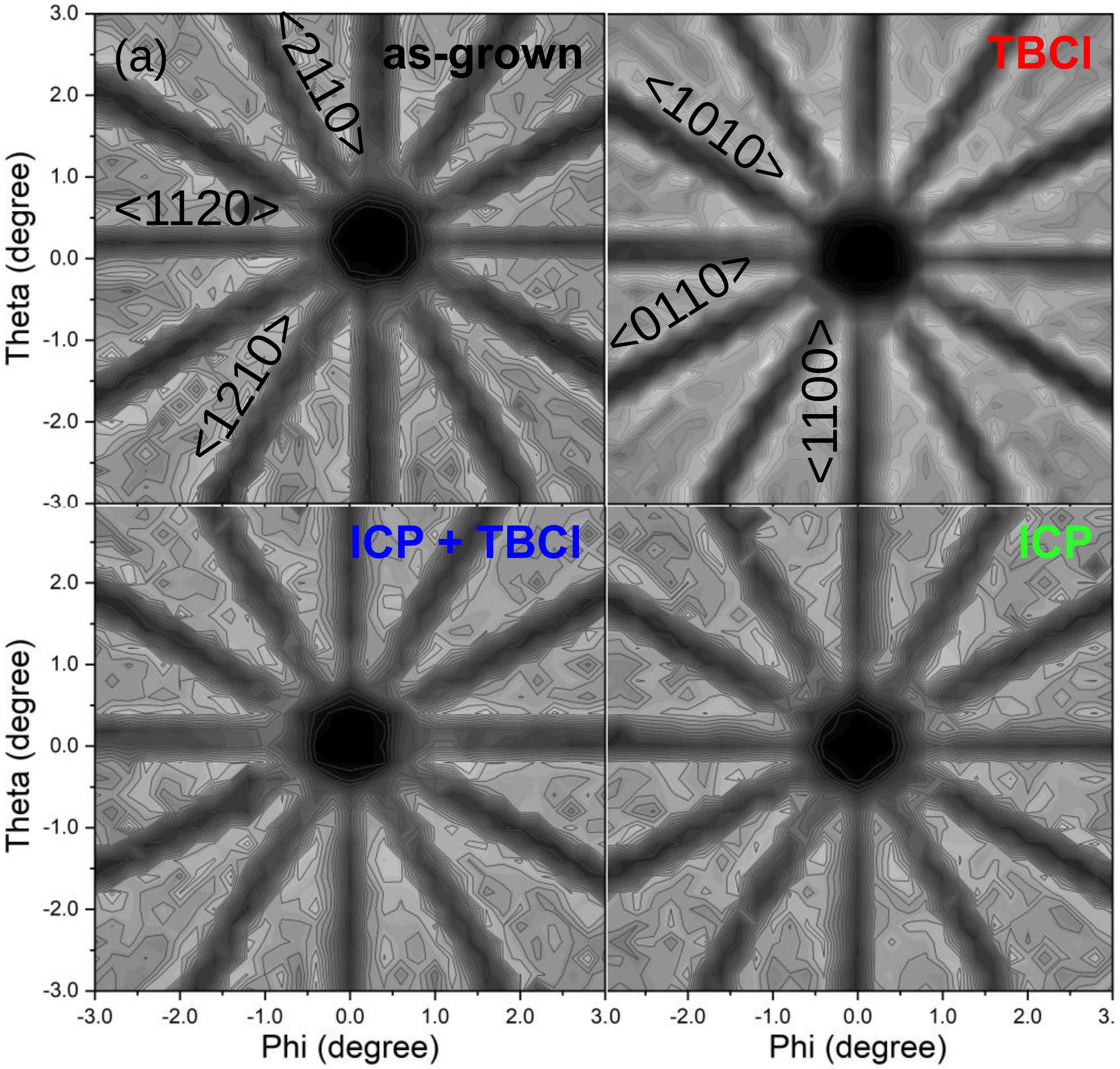

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2. J.Y. Tsao et al., "Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges". Adv. Electronic Mat.
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4. De Keijser, T. , Mittemeijer, E. J. and Rozendaal, H. C., “The determination of crystallite-size and lattice-strain parameters in conjunction with the profile-refinement method for the determination of crystal structures.” J. Appl. Cryst., 16: 309-316 (1983)
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The Pseudo-Voigt function, $P(x)$, approximates the convolution of Cauchy, $C(x)$,and Gaussian, $G(x)$, profiles and is given by equations (1):

$$P(x) = I_0[\eta C(x) + (1-\eta)G(x)]$$

and $0 \leq \eta \leq 1$, where η is a fitting parameter [6]. The lateral correlation length, $L_{\parallel}$, and tilt angle, α_ω, can then be calculated using equations (2) and (3), respectively:

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where λ is the x-ray wavelength, $\delta\omega$ is the FWHM of the $\Delta\omega$ rocking curve, and θ_B is the Bragg angle [6].

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