

シンクロトロン光を用いた トポグラフィとイメージング

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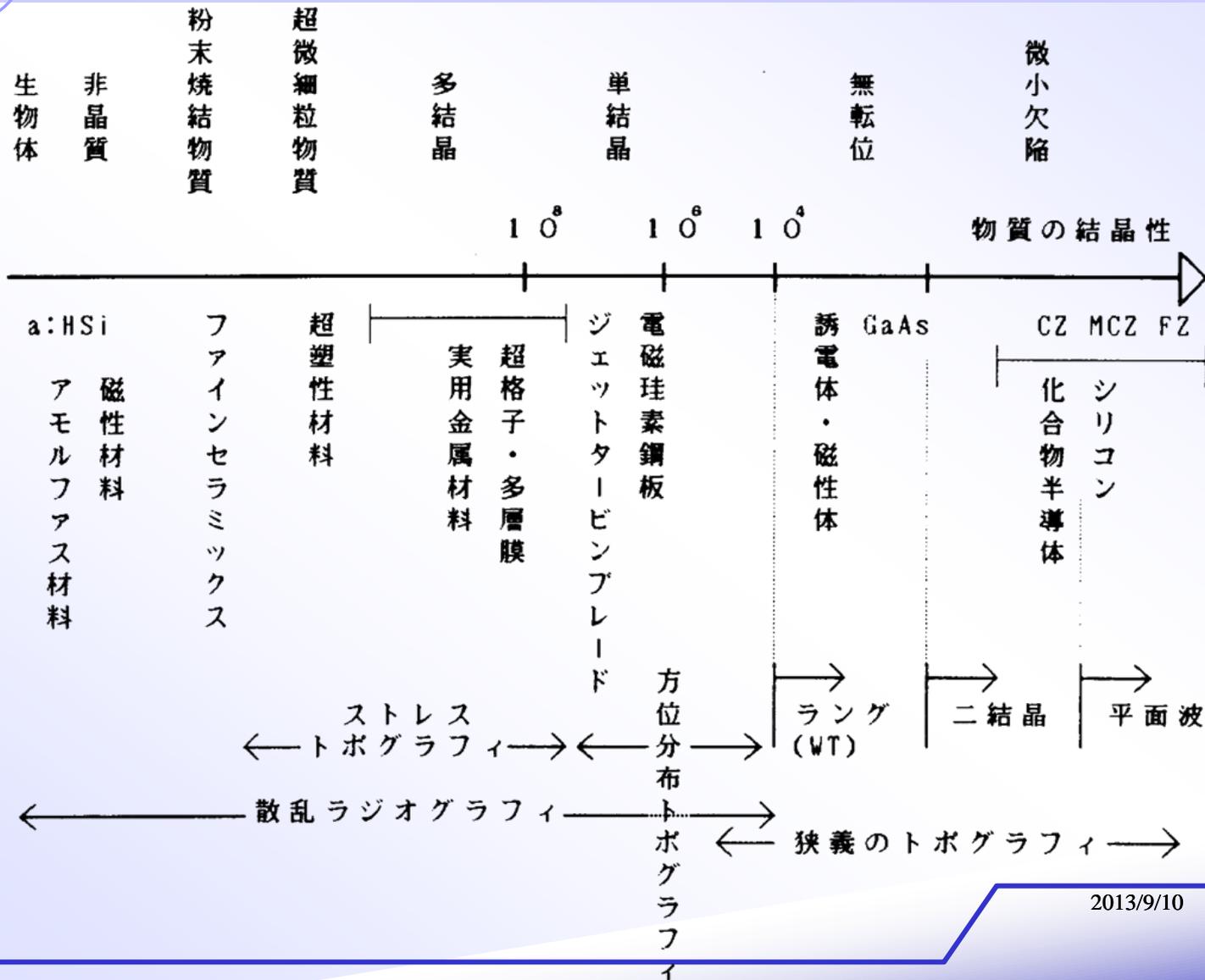
2013/9/10



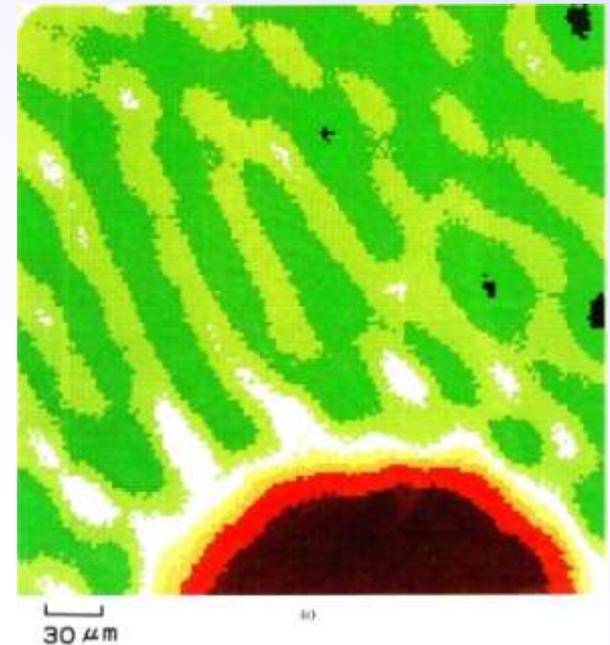
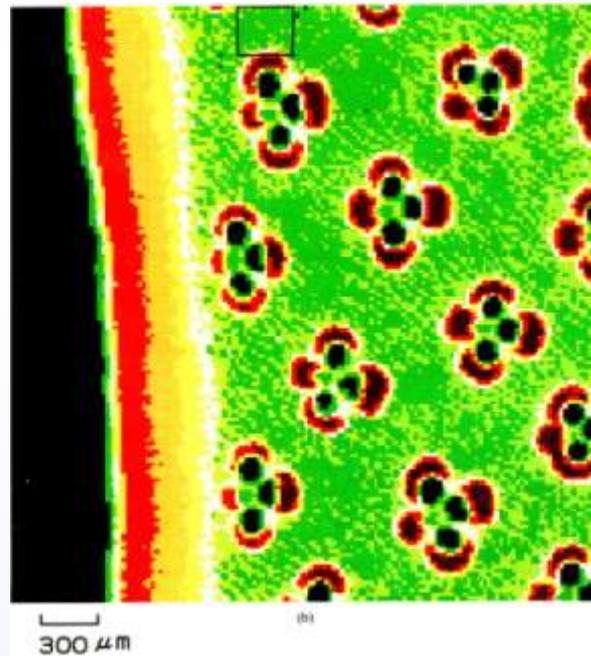
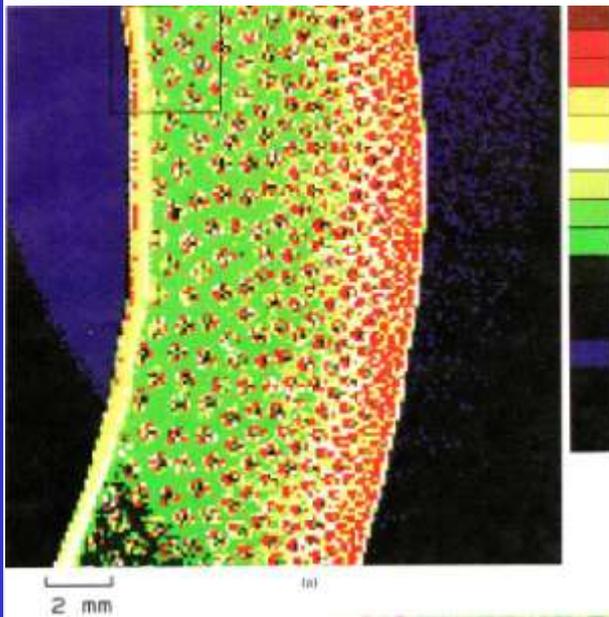
本日のおはなし

- ㊦ **X線散乱トポグラフィ**
 - X線散乱トポグラフィ(SR)の概念ならびに用途
 - 方位分布トポグラフィ(OR)、再構成方位分布トポグラフィ(ROR)
 - 例
- ㊦ **動力学回折理論シミュレーション(高木方程式)**
- ㊦ **CCDを用いた方位分布トポグラフィへの適応**
- ㊦ **極微小角入射X線回折(In-Plane 回折)**

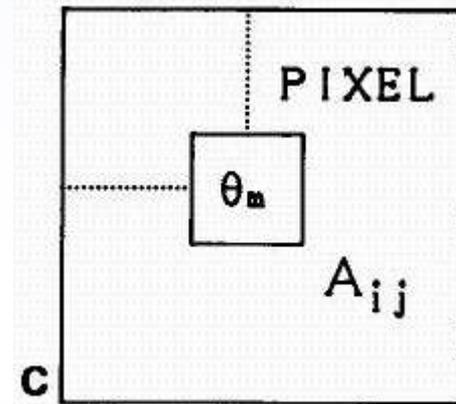
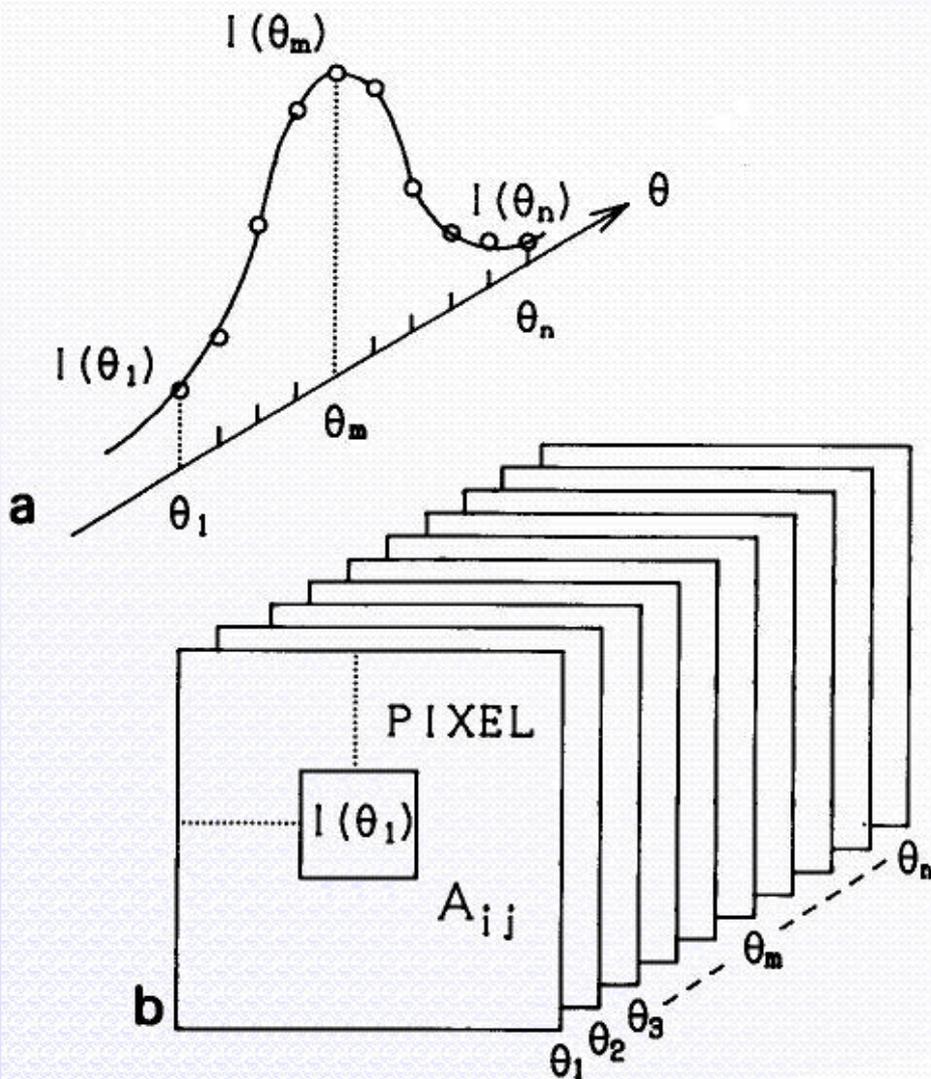
物質の結晶性と各種トポグラフィの関係



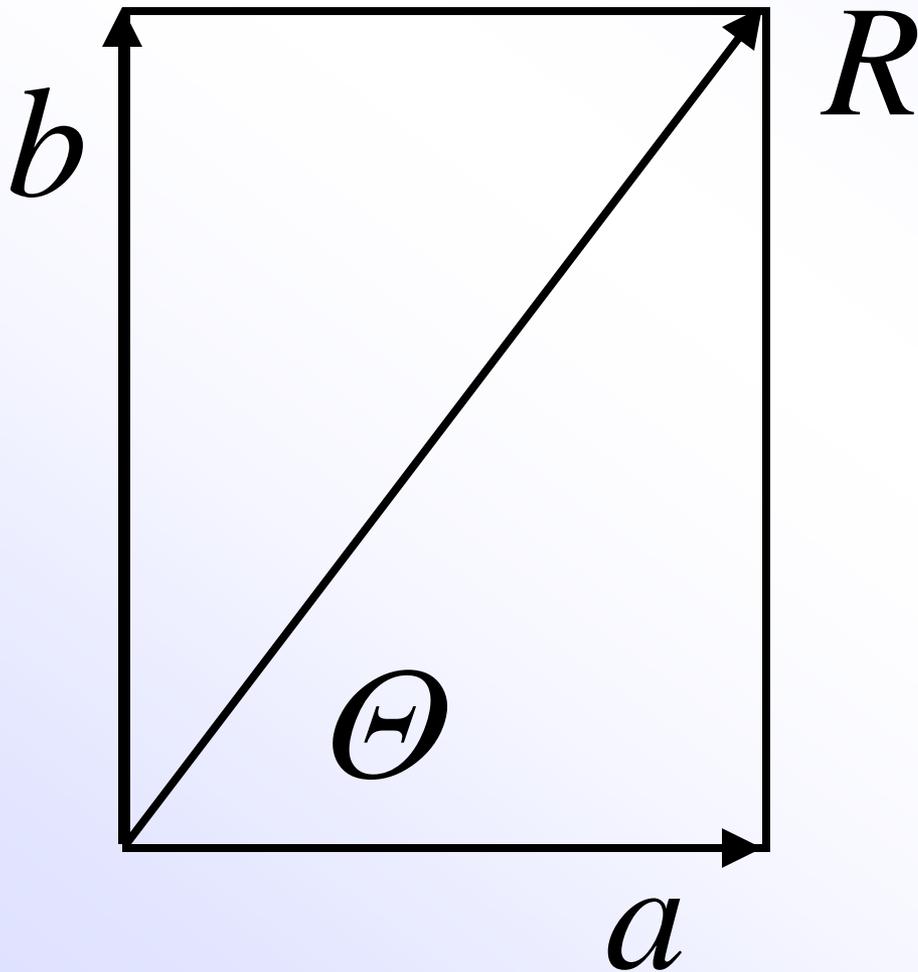
High-Resolution X-ray Scattering Topography Using Synchrotron Radiation Microbeam



方位分布トポグラフィ (one axis OR)



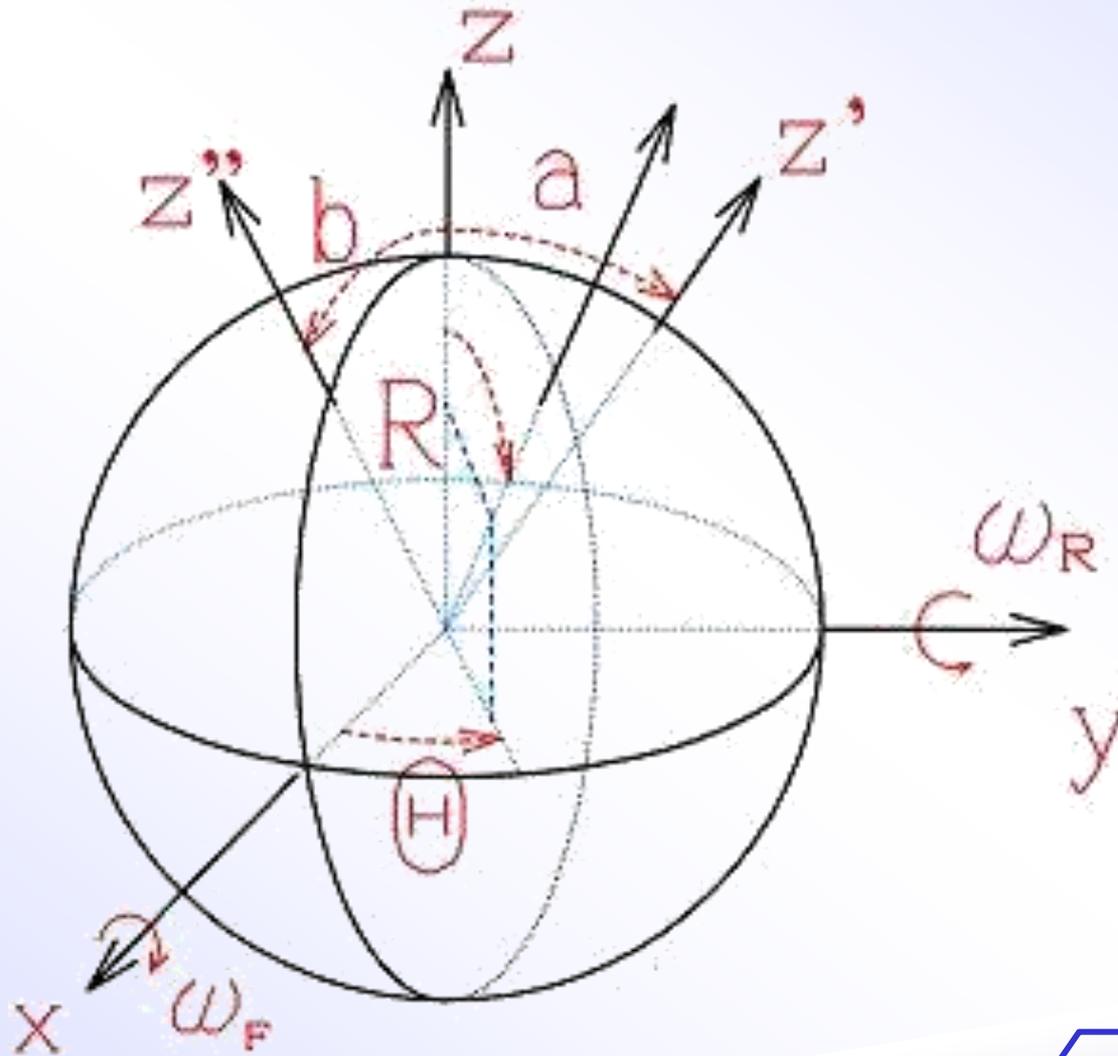
再構成方位分布トポグラフィ(ROR)



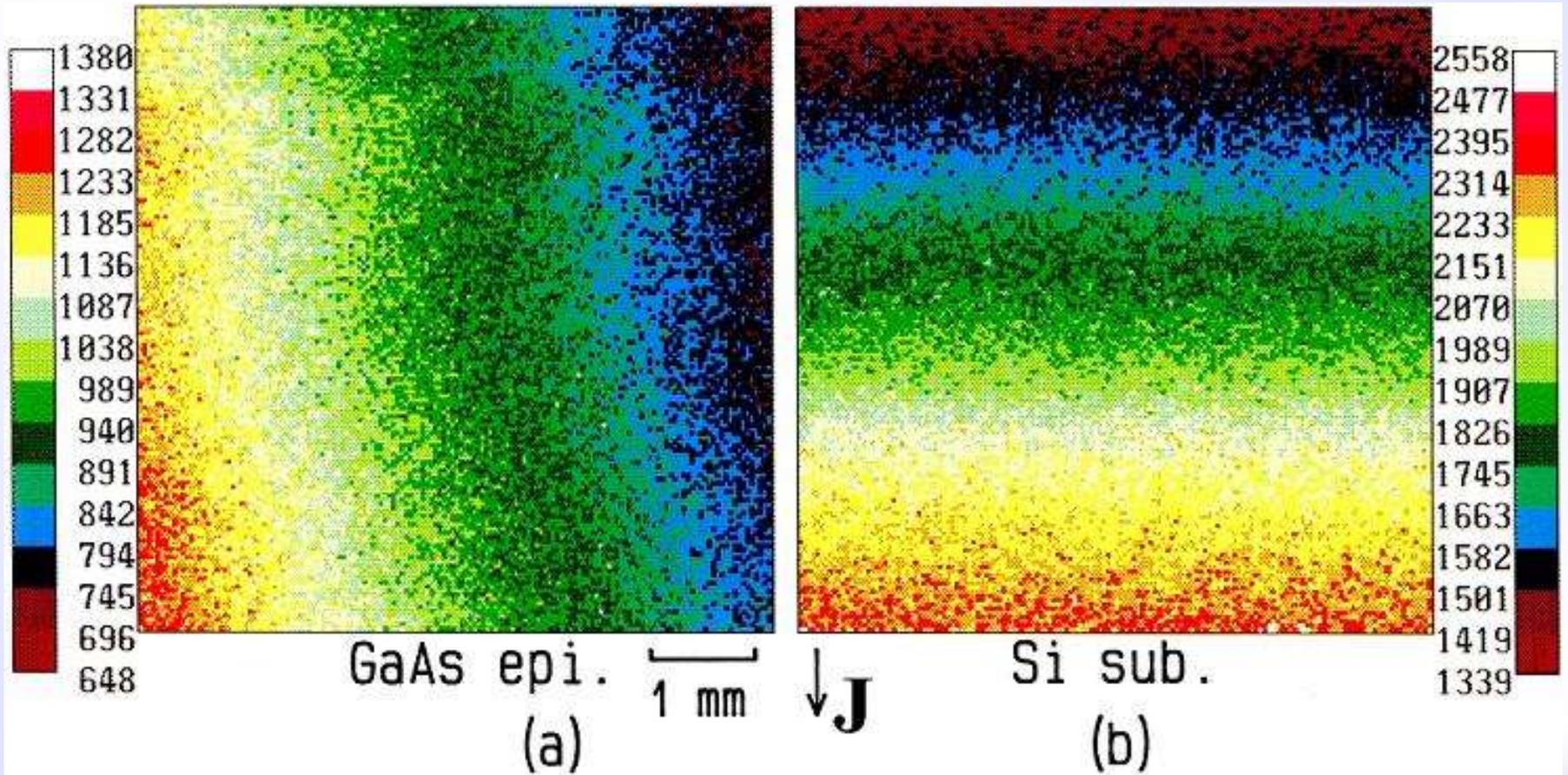
$$\Theta = \tan^{-1} \frac{a}{b}$$

$$R = \sqrt{a^2 + b^2}$$

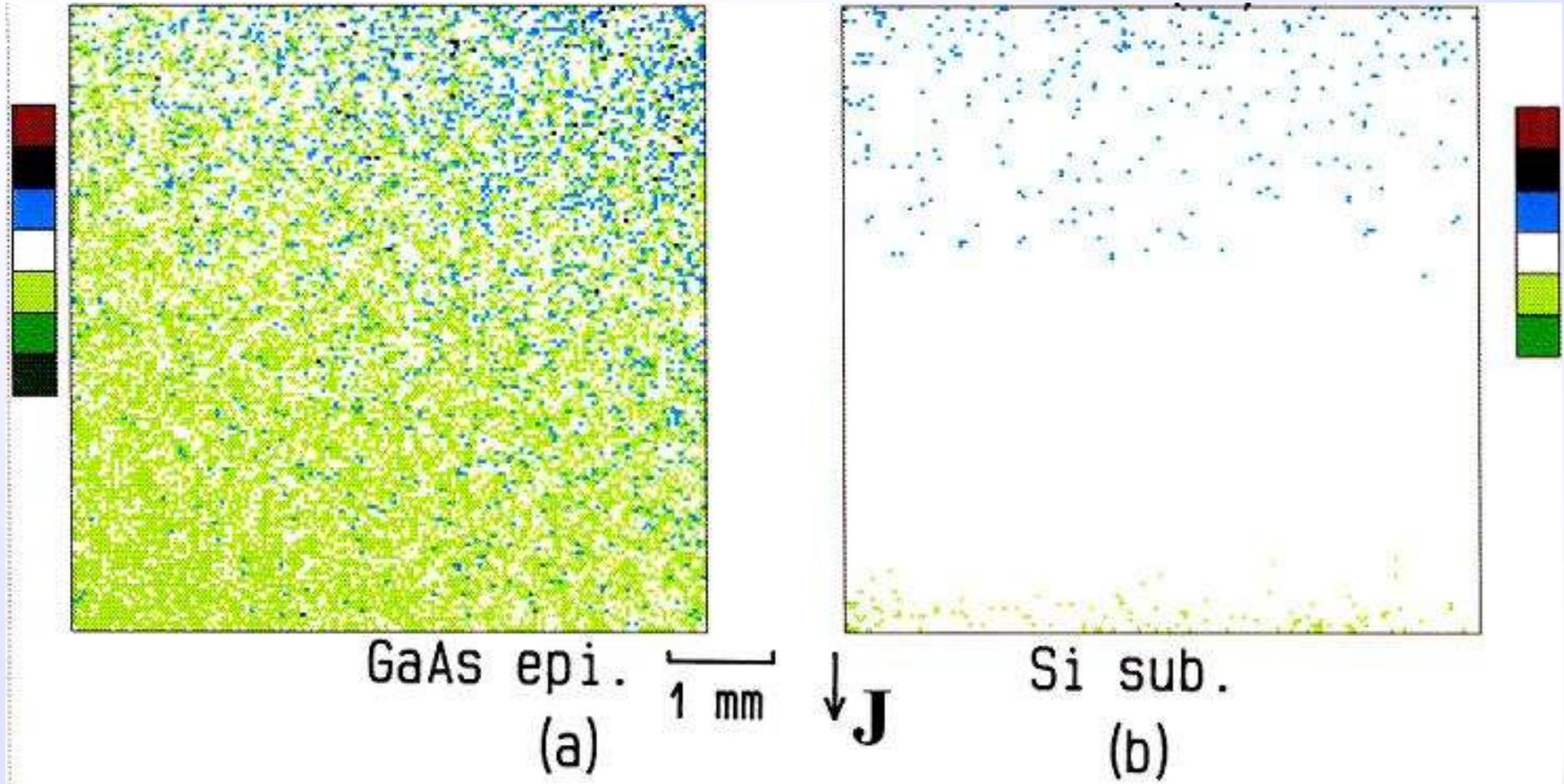
再構成方位分布トポグラフィ (ROR)



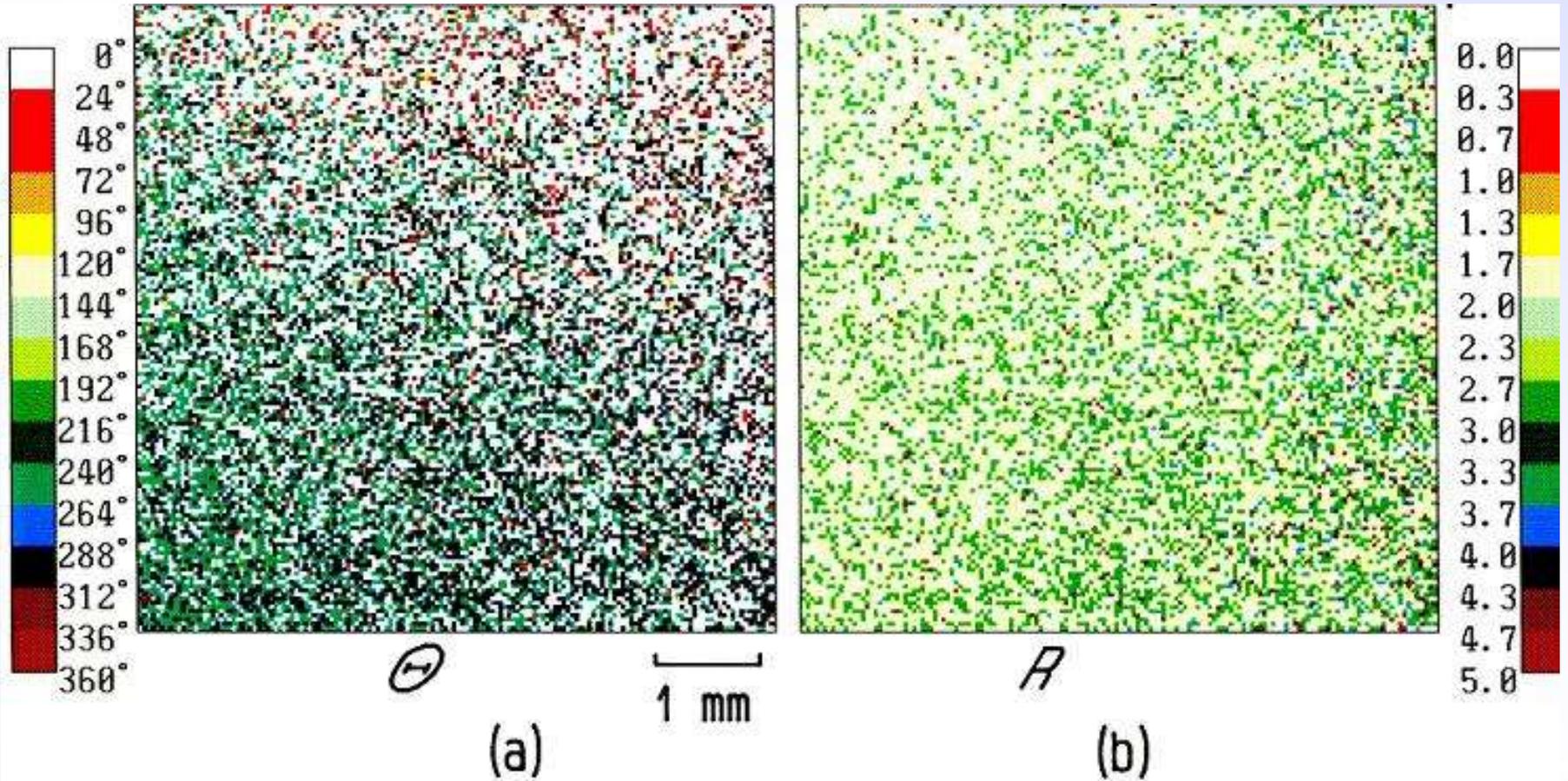
X-ray Scattering Topography (SR) for GaAs on Si



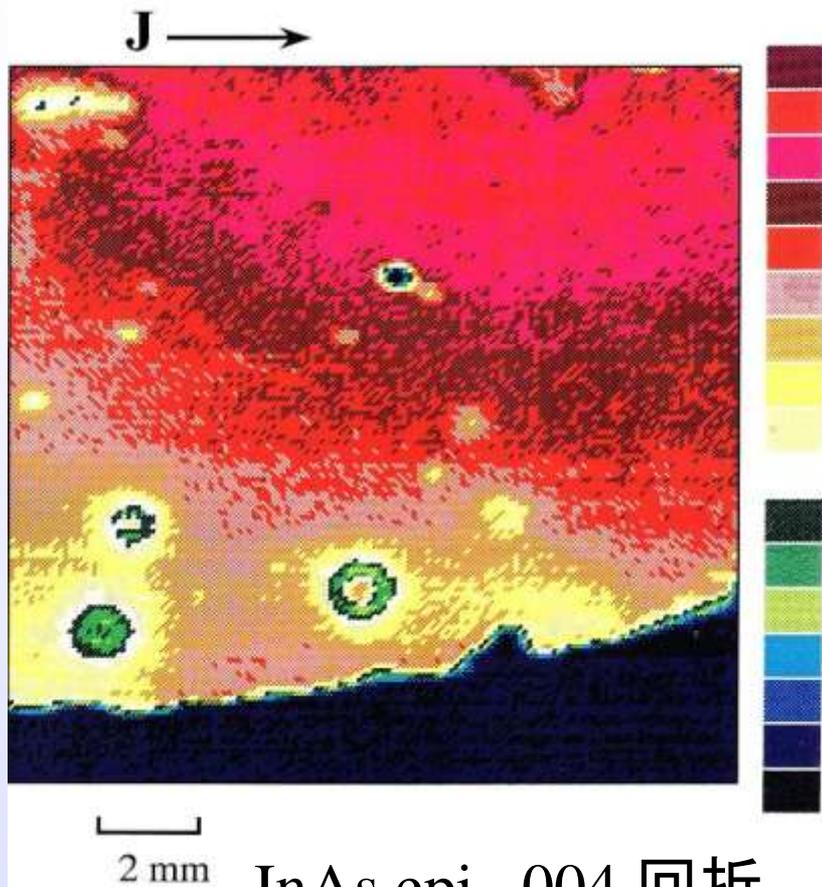
Orientation Topography (OR) for GaAs on Si



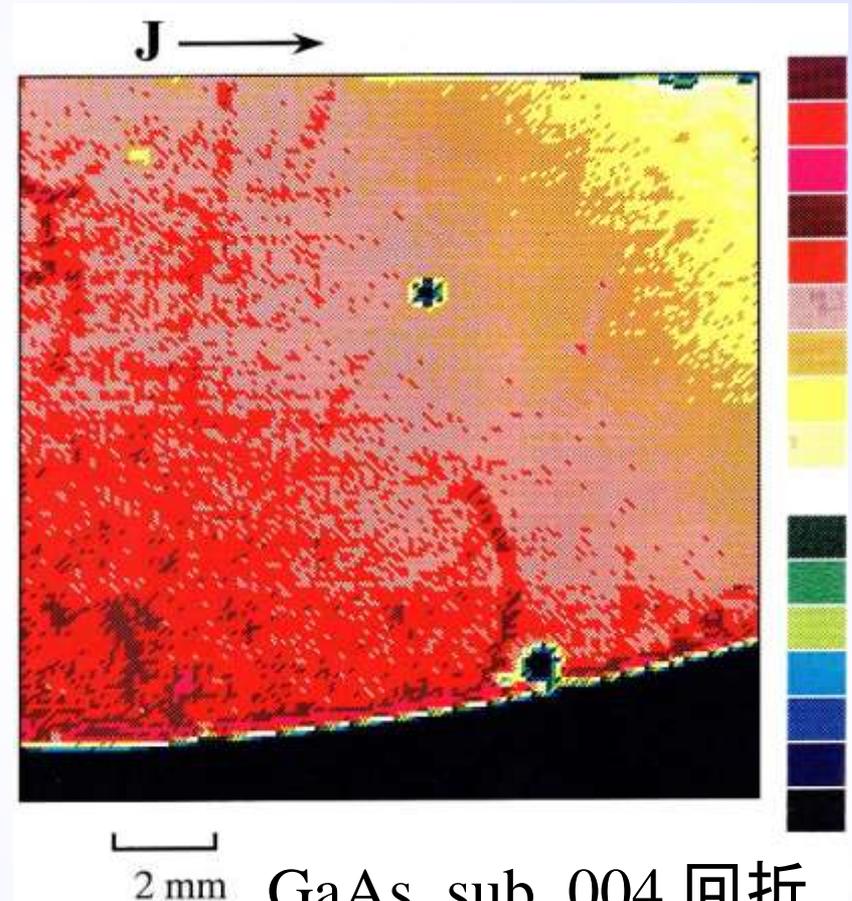
Reconstruction Orientation Topography (ROR) GaAs epitaxial layer (GaAs on Si)



X-ray Scattering Topography (SR) for InAs on GaAs



InAs epi. 004 回折

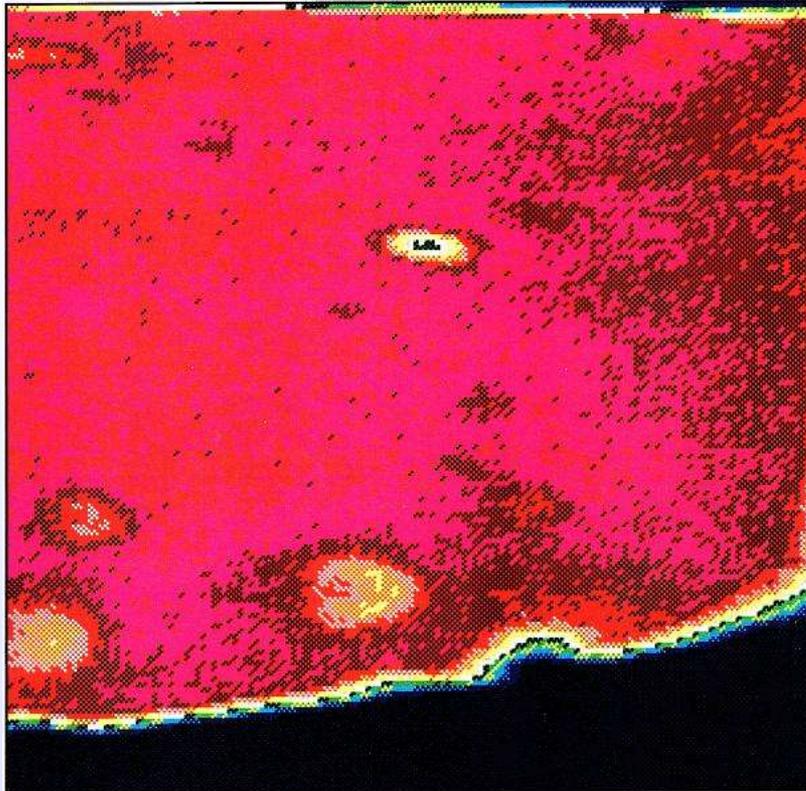


GaAs sub. 004 回折

X-ray Scattering Topography (SR)

InAs on GaAs with 002, 006 diffraction

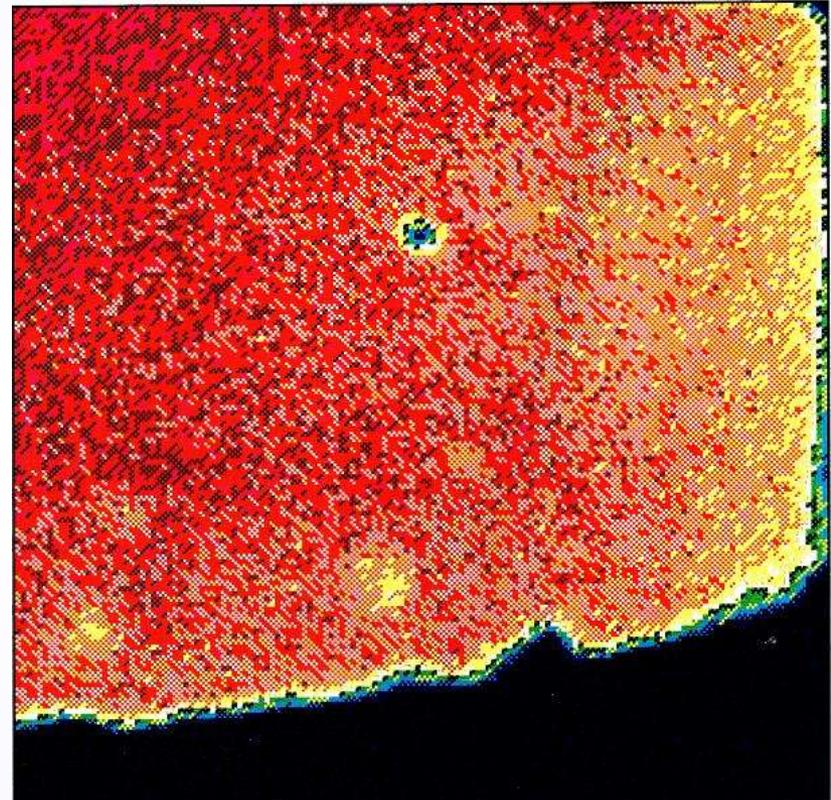
J →



2 mm

002 diffraction

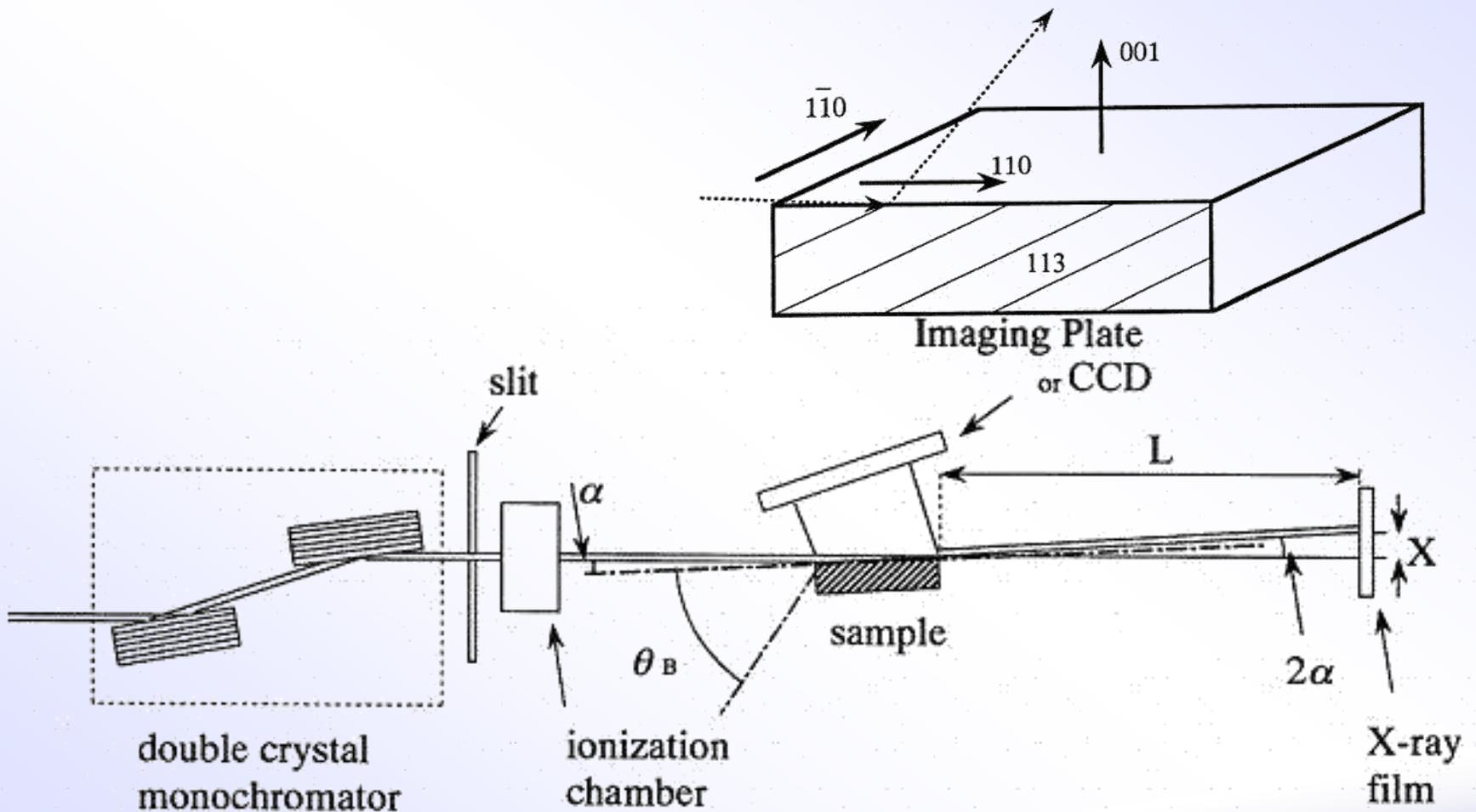
J →



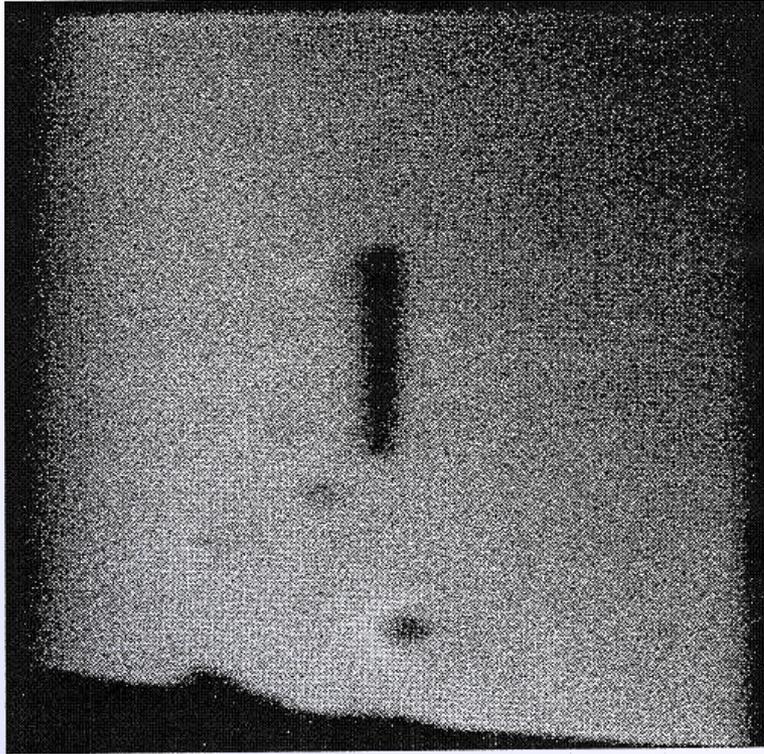
2 mm

006 diffraction

Diffraction geometry with the crystal orientation and X-ray Optics at HASYLABO



Topographs of InAs epitaxial layer



113 GID

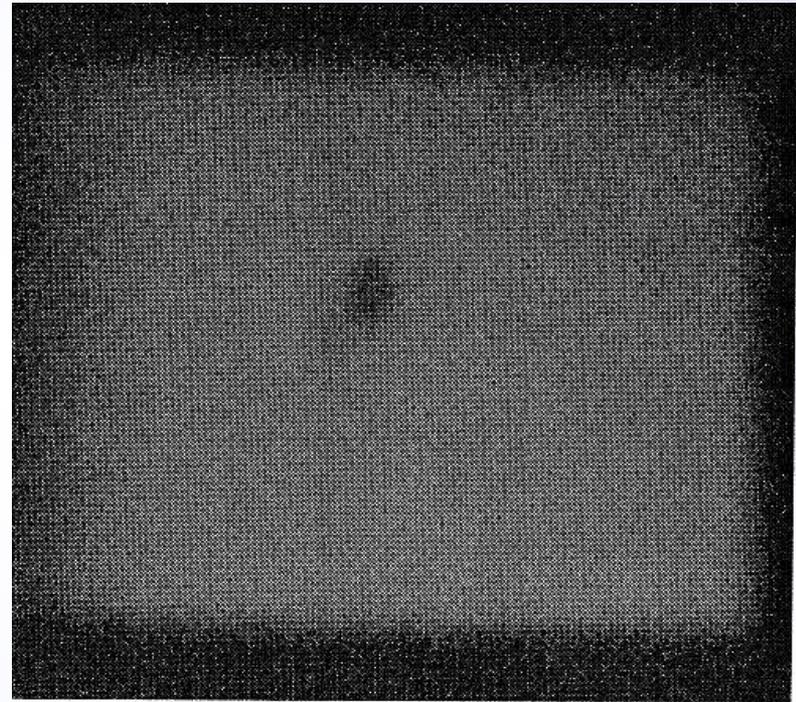
$E = 7.6 \text{ keV}$

$\alpha_i = 0.95^\circ$

g



1 mm



J



1 mm

006 sym.

$E = 11.48 \text{ keV}$

$\alpha_i = 31.98^\circ$

2013/9/10



$$l_{ex} = \frac{\lambda (\gamma_0 |\gamma_h|)^{1/2}}{2 \pi C |\chi_g|}$$

l_{ex} : extinction distance

$$\gamma_0 = \sin (\theta_B - \alpha), \quad \gamma_h = \sin (\theta_B + \alpha)$$

C : Polarization factor

λ : Wavelength of X-ray

χ : Electric Susceptibility

$$\chi = R_e \frac{\lambda^2 F}{\pi V_a}$$

R_e : classical electron radius

V_a : unit cell volume

F : structure factor

	InAs	GaAs
200	1.025 μm	4.986 μm
400	0.589 μm	0.674 μm
600	5.753 μm	14.47 μm

■ 高木方程式

X線の結晶内の振る舞いを説明する式であり、歪みを含む不完全結晶にも適用できる動力的回折理論の基本方程式

$$\frac{\partial}{\partial S_0} D_0 = -i\pi K \chi_{\bar{h}} D_h(\mathbf{r})$$

$$\frac{\partial}{\partial S_h} D_h = -i\pi K \chi_h D_0(\mathbf{r}) + 2i\pi \left[K \beta_h - \frac{\partial}{\partial S_h} \{\mathbf{h} \cdot \mathbf{u}(\mathbf{r})\} \right] D_h(\mathbf{r})$$

D_0 : 透過波の振幅 D_h : 回折波の振幅 χ : 電気感受率 $\mathbf{u}(\mathbf{r})$: 原子の格子点からの変位
 \mathbf{r} : 結晶の変位ベクトル \mathbf{h} : 回折波のベクトル
 S_h : 回折方向 S_0 : 透過方向 K : 波数 β_h : ブラッグ角からのずれを示すパラメータ

コンピュータシミュレーション

プログラムしやすい形にするため、高木方程式を
 アッペルボーインの近似式” half-step deviation”を用いて式
 の変形させる。

$$\begin{bmatrix} D_0(s_0, s_h) \\ D_h(s_0, s_h) \end{bmatrix} = 1/d \begin{bmatrix} C_2 & AC_2 & AB & AC_1 \\ B & AB & B & C_1 \end{bmatrix} \begin{bmatrix} D_0(s_0 - p, s_h) \\ D_h(s_0 - p, s_h) \\ D_0(s_0, s_h - q) \\ D_h(s_0, s_h - q) \end{bmatrix}$$

$$A = -\frac{1}{2} ip\pi K \chi_{\bar{h}}$$

$$B = -\frac{1}{2} iq\pi K \chi_h$$

$$W = iq\pi \left\{ K \beta_h - \frac{\partial}{\partial s_h} [h \cdot u(\mathbf{r})] \right\}$$

A: 回折の関数
 B: 透過の関数
 W: ずれの関数

$$d = 1 - W - AB$$

$$C_1 = 1 + W$$

$$C_2 = 1 - W$$

計算 1.0 μm InAs

$$\frac{\partial}{\partial S_0} D_0 = -i\pi K \chi_{\bar{h}} D_h(\mathbf{r})$$

$$\frac{\partial}{\partial S_h} D_h = -i\pi K \chi_h D_0(\mathbf{r}) + 2i\pi \left[K \beta_h - \frac{\partial}{\partial S_h} \{ \mathbf{h} \cdot \mathbf{u}(\mathbf{r}) \} \right] D_h(\mathbf{r})$$

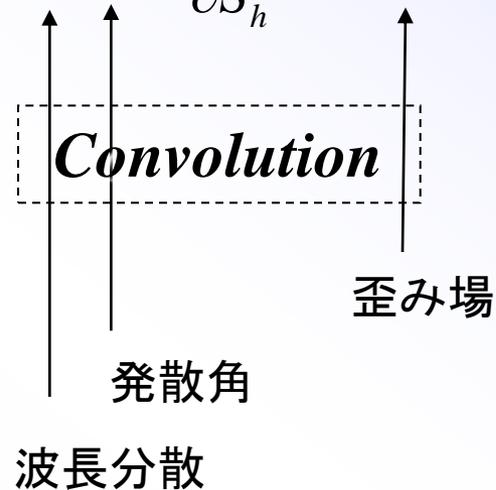
a ブラッグ-ケース

a 境界条件

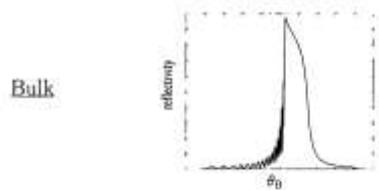
: 界面で、

$$D_h = 0, D_0 = 1$$

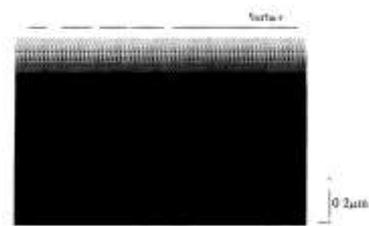
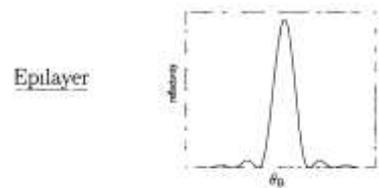
a 相反原理



2. X-ray Penetration Depth for Large Lattice-Mismatched Heteroepitaxial Layer by Dynamical Diffraction Theory using Computer Simulation



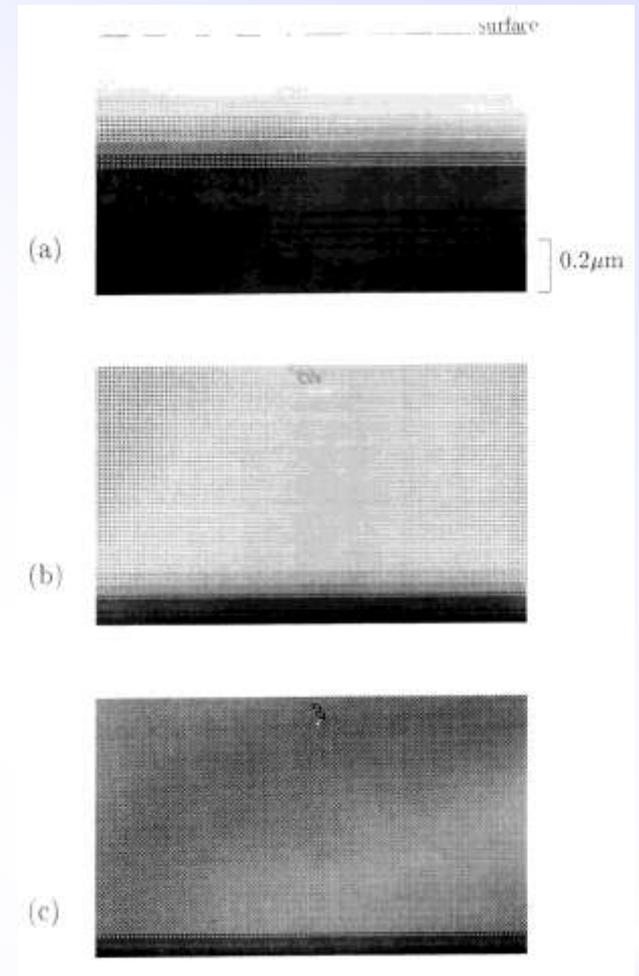
(a)



(b)

Bragg-case
におけるバルク及び薄膜の回折強度曲線

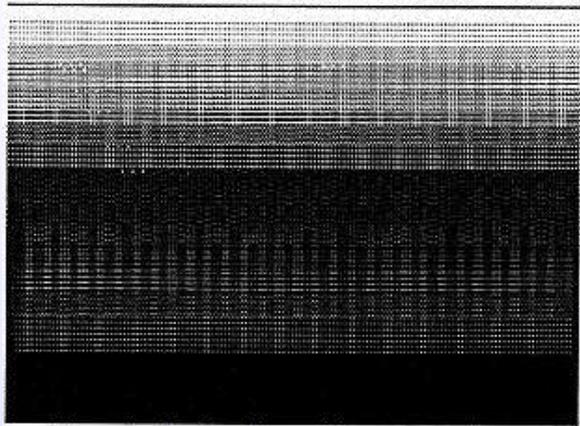
エピ膜（歪場を含む）断面の回折強度分布



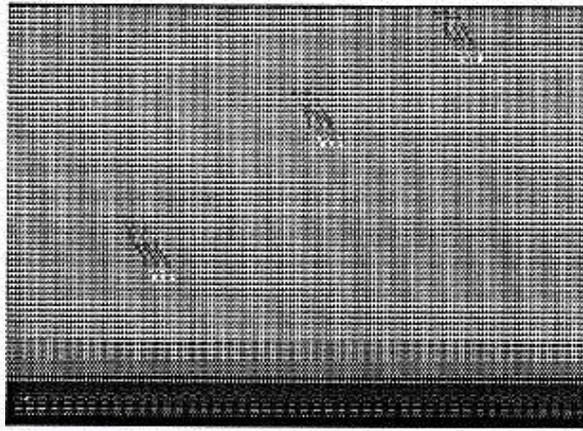
エピ層断面の波動場（歪み場を含む）

002

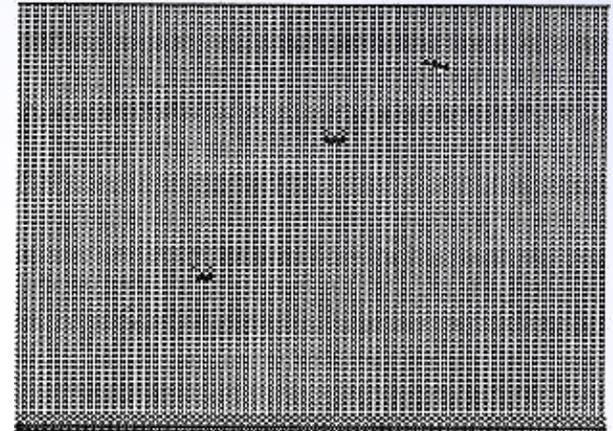
surface



004

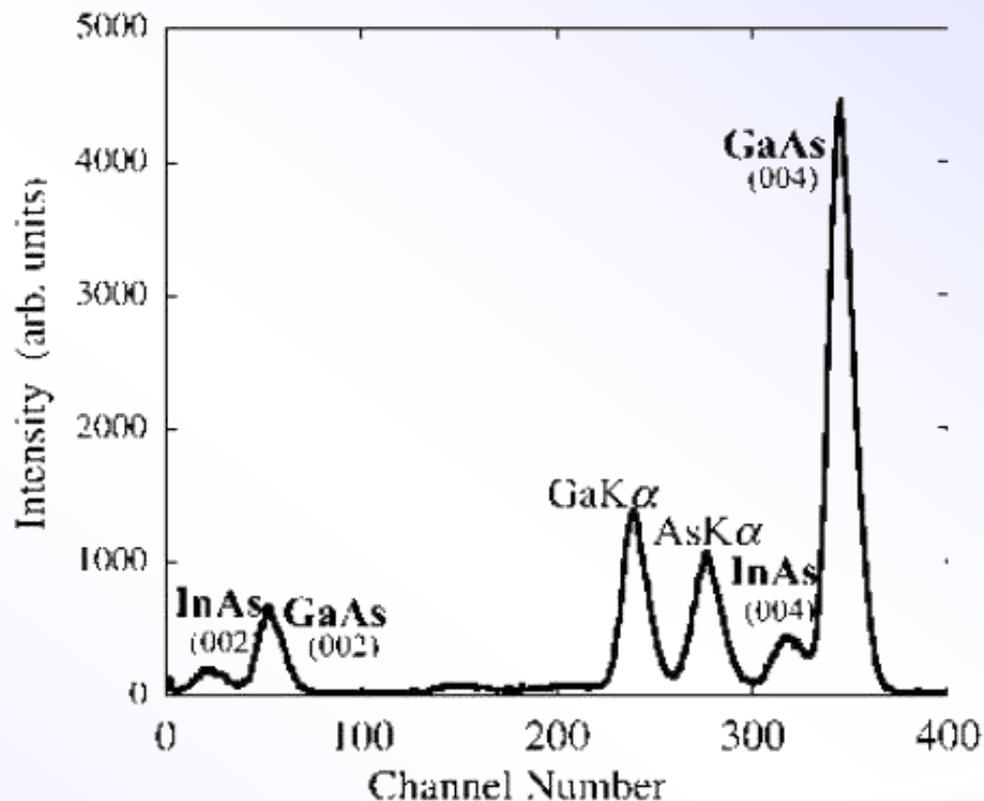
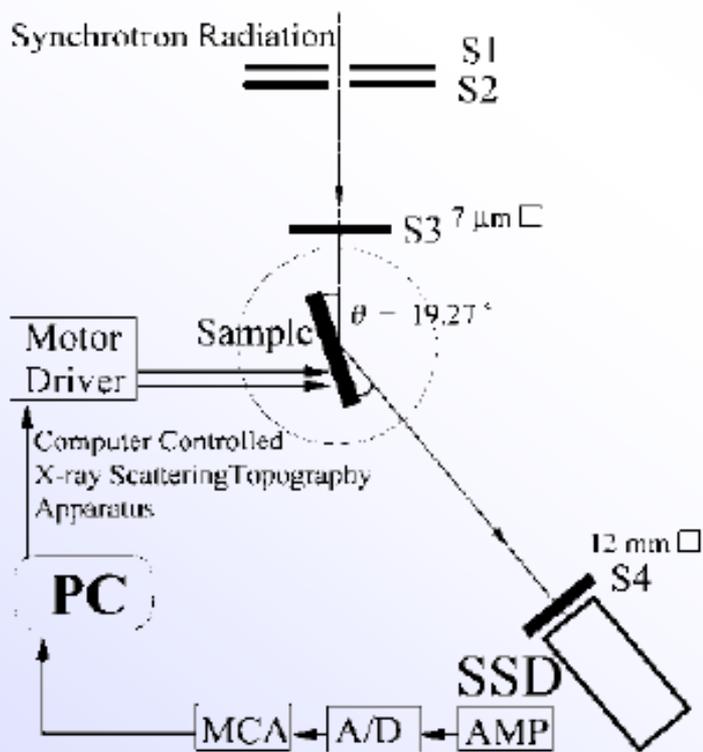


006

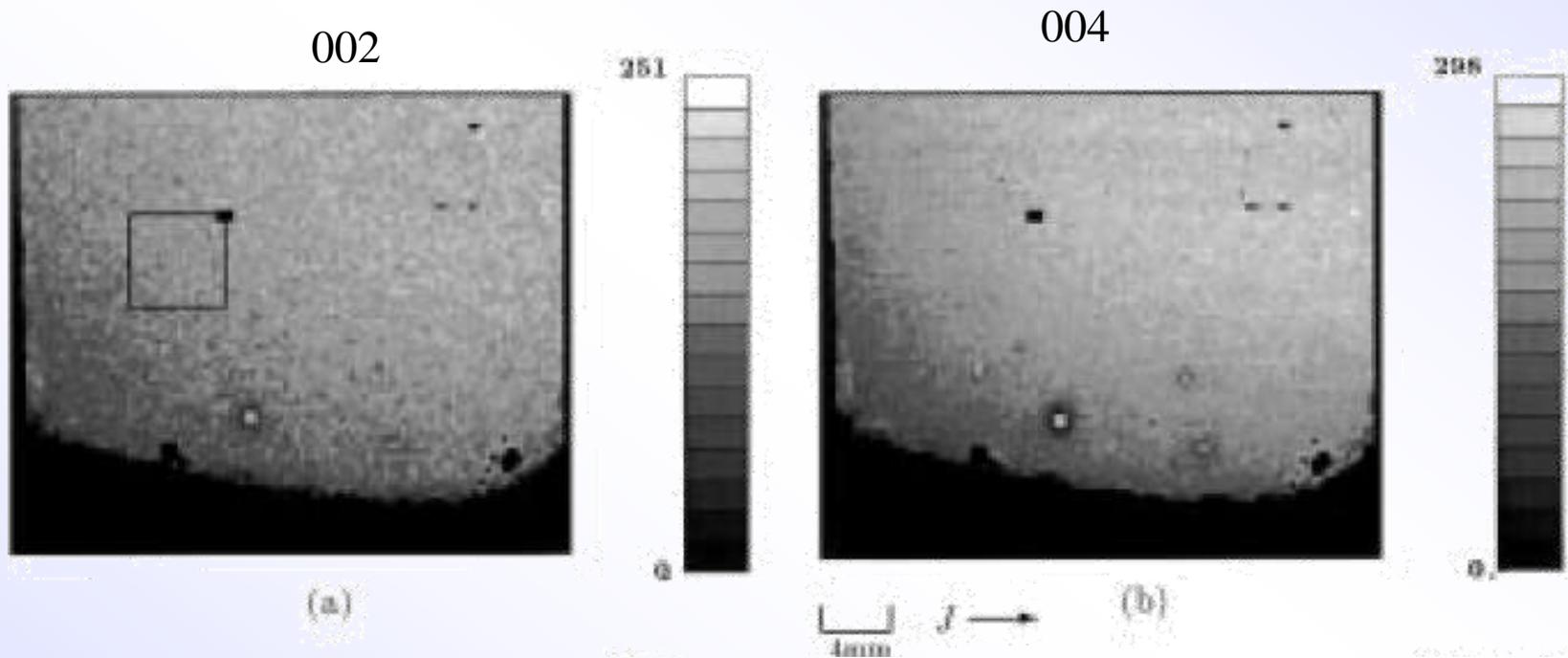


0.2 μ m

Energy-Dispersive Synchrotron Radiation Topographic Observation of InAs/GaAs Lattice-Mismatched Layer

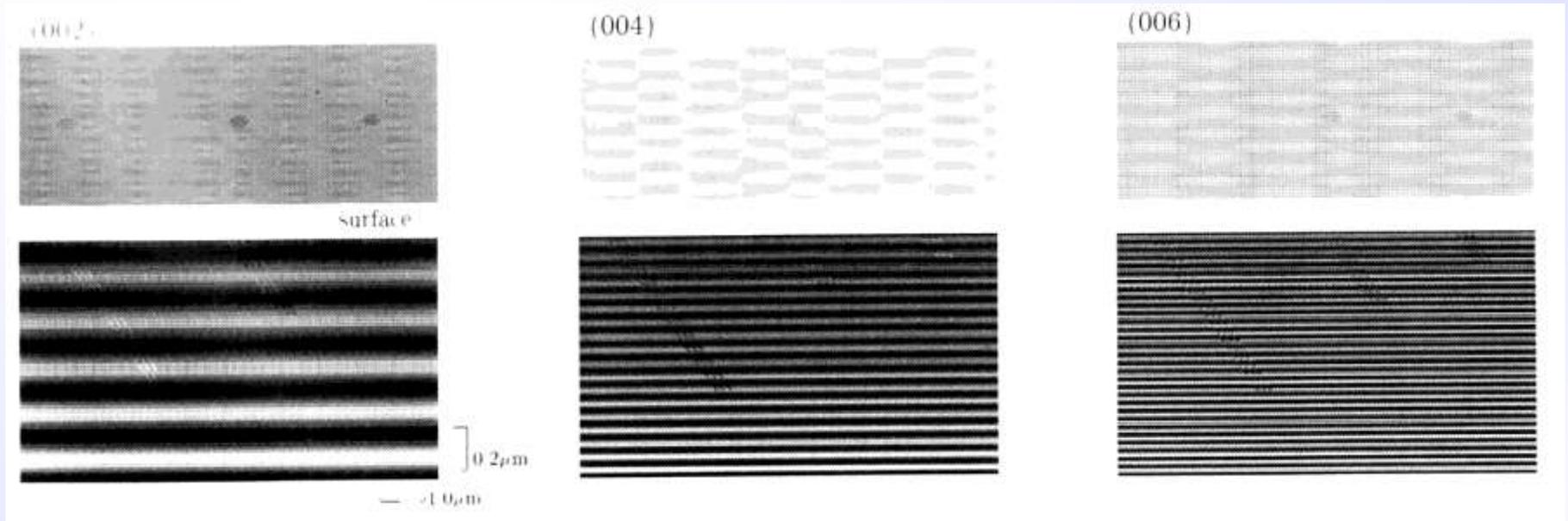


Energy-Dispersive Synchrotron Radiation Topographic Observation of InAs Layer



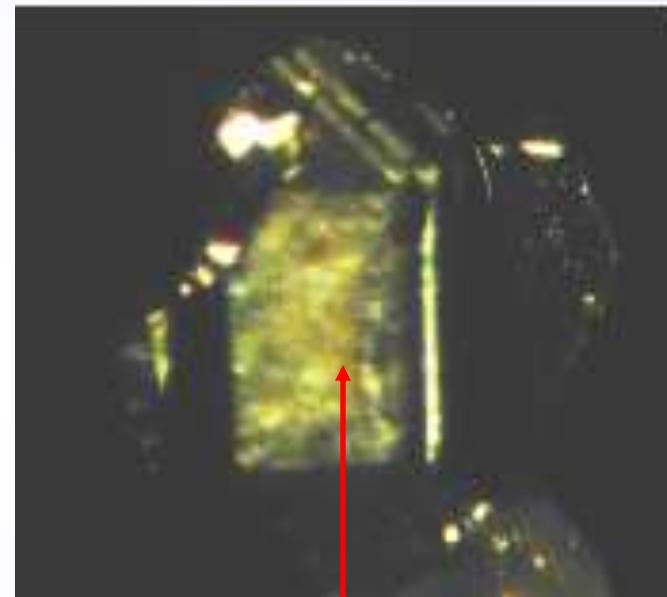


Energy-Dispersive Synchrotron Radiation Topographic Observation of InAs/GaAs Lattice-Mismatched Layer



エピ膜（歪場を含む）断面の回折強度分布

Lattice Orientation Imaging of C₆₀-Fullerene Single Crystal using CCD Detector

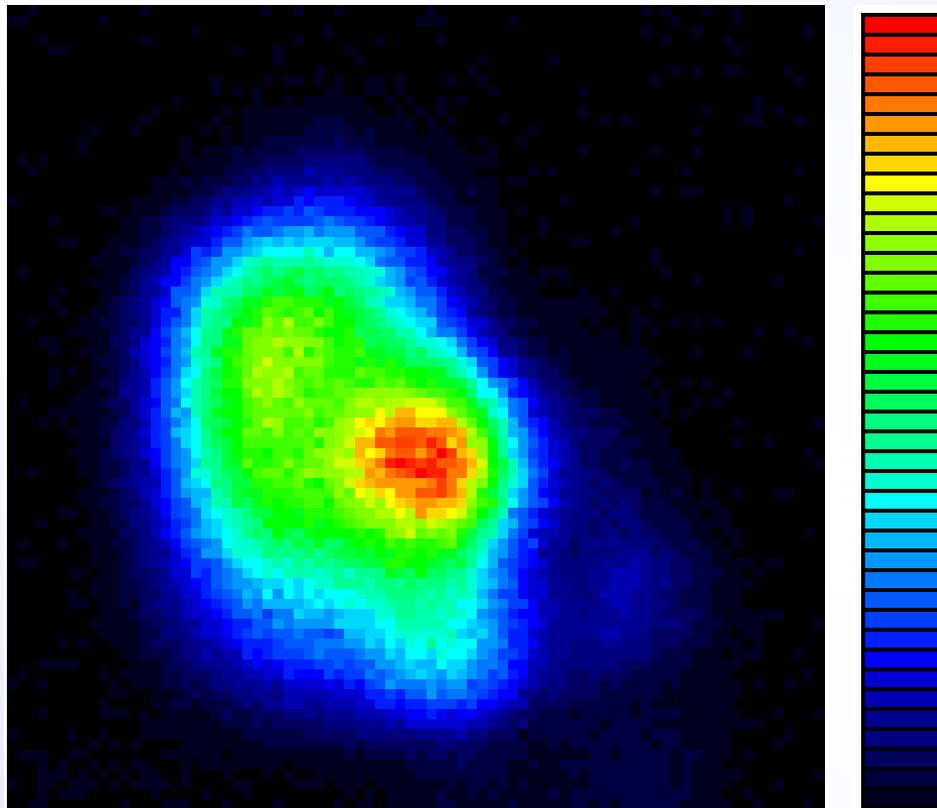


0.1 mm

(2 0 0)

C₆₀ 単結晶

C₆₀ X線散乱トポグラフィ像



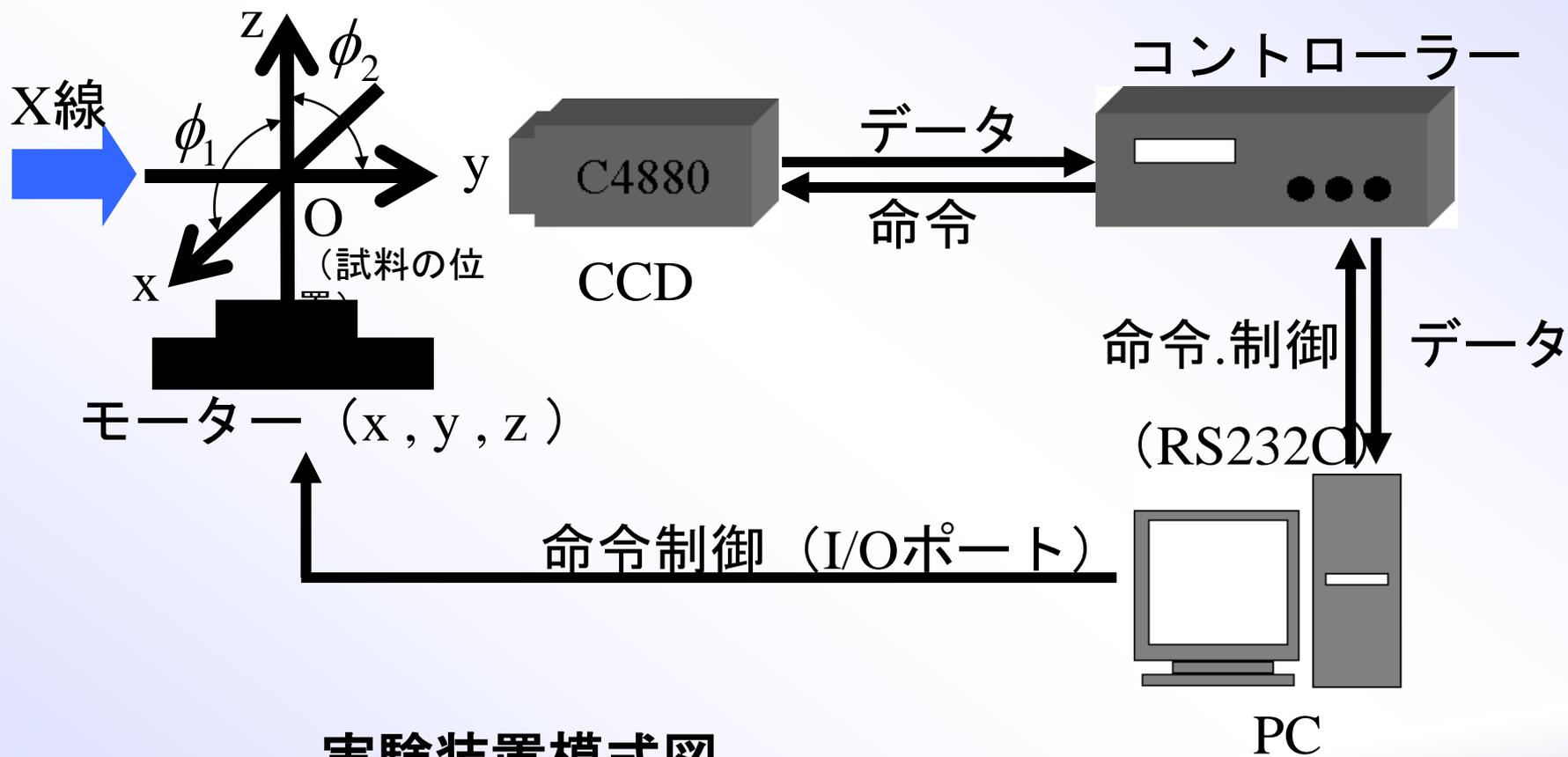
0.1 mm

試料 : C₆₀単結晶

80 × 80

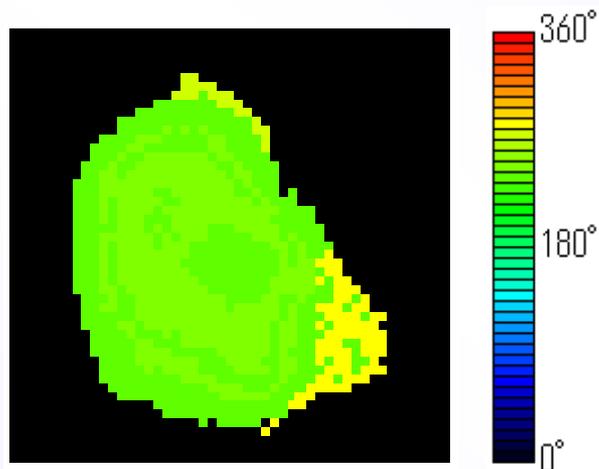
Step : 10 μm

実験装置 測定系

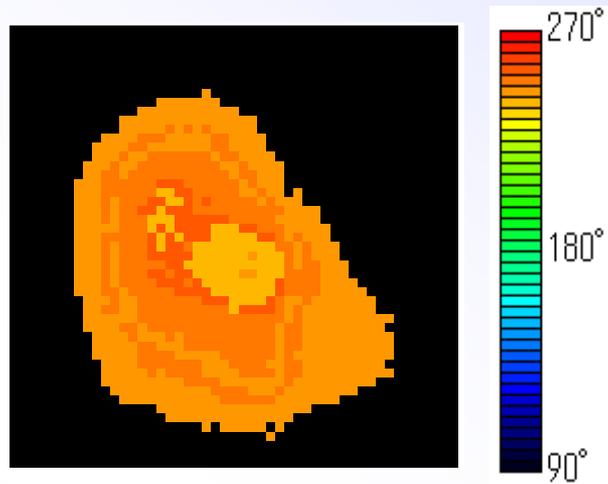


実験装置模式図

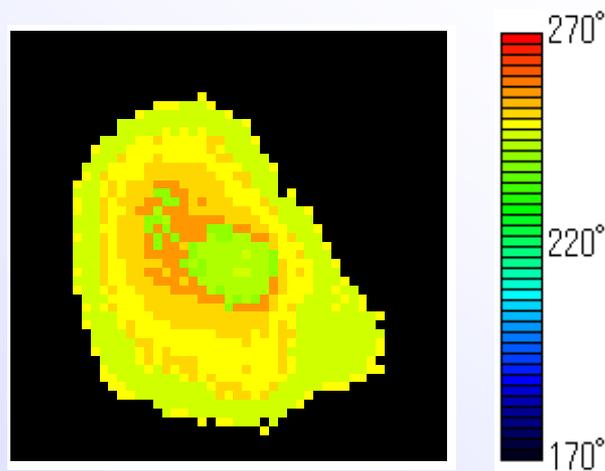
CCDを用いたX線散乱トポグラフ (角度差: ϕ_1 方向、 閾値: 低)



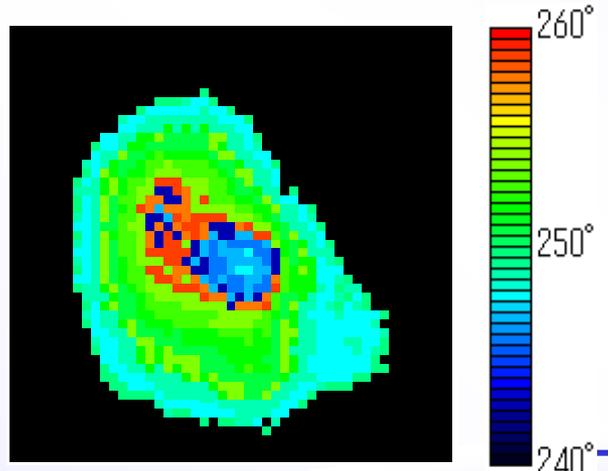
(1) $180^\circ \pm 180^\circ$



(2) $180^\circ \pm 90^\circ$

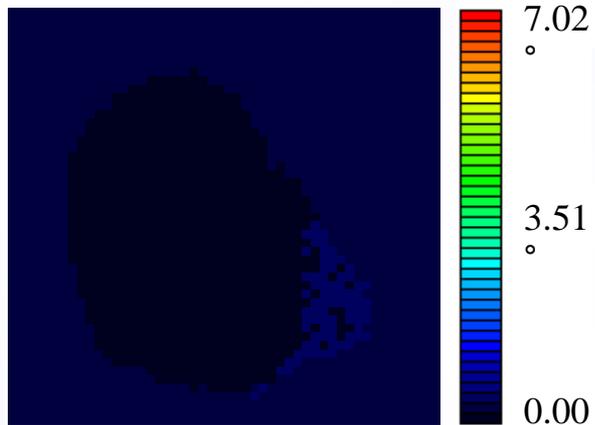


(3) $220^\circ \pm 50^\circ$

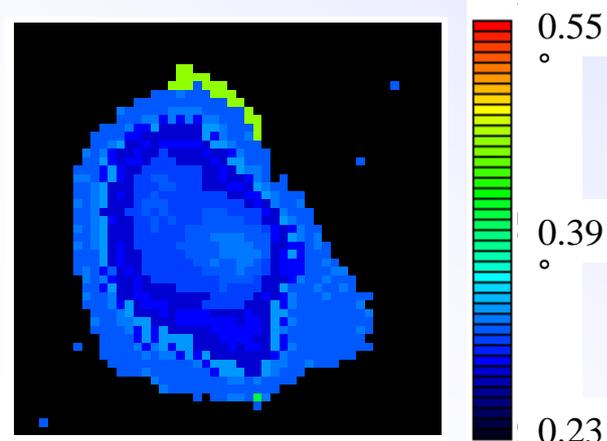


(4) $250^\circ \pm 10^\circ$

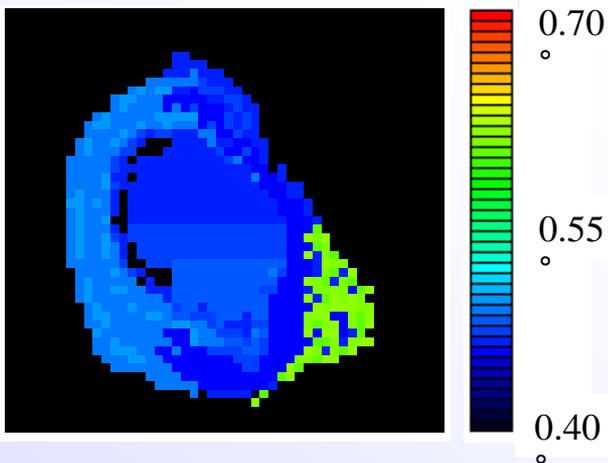
CCDを用いたX線散乱トポグラフ (角度差: ϕ_2 方向、 閾値: 低)



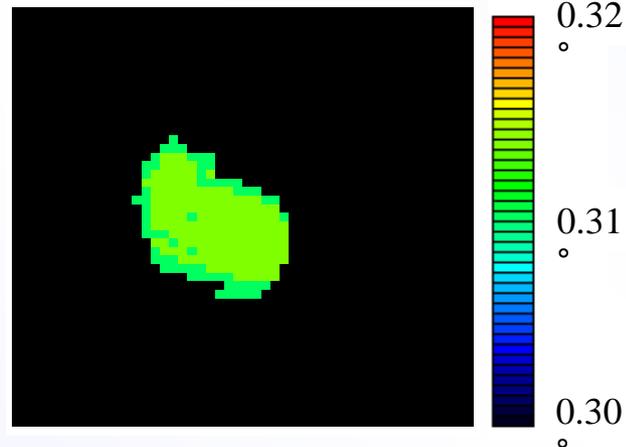
(1) $3.51^\circ \pm 3.51^\circ$



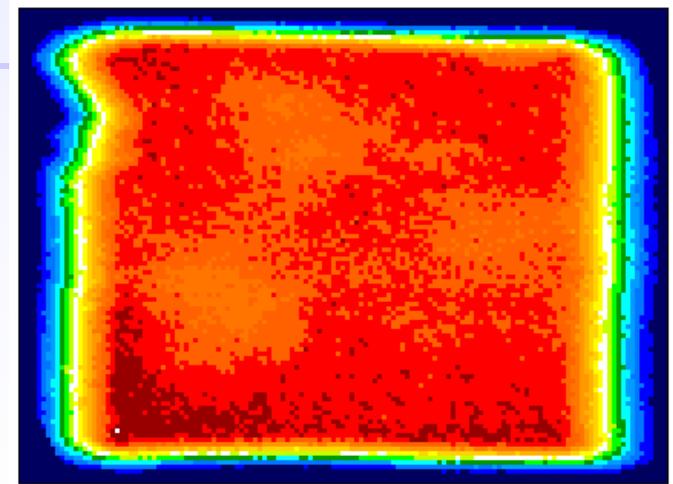
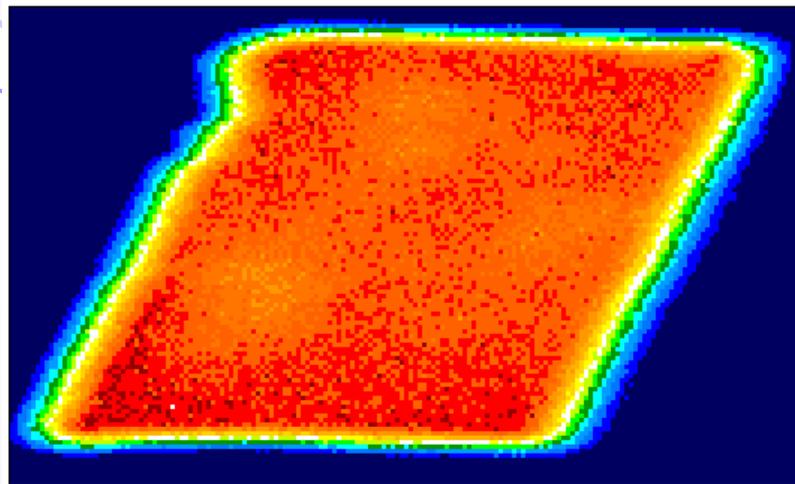
(2) $0.39^\circ \pm 0.16^\circ$



(3) $0.55^\circ \pm 15^\circ$



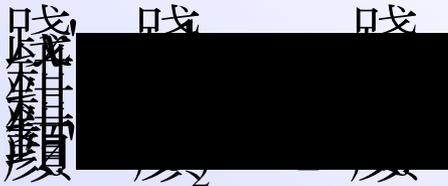
(4) $0.31^\circ \pm 0.01^\circ$



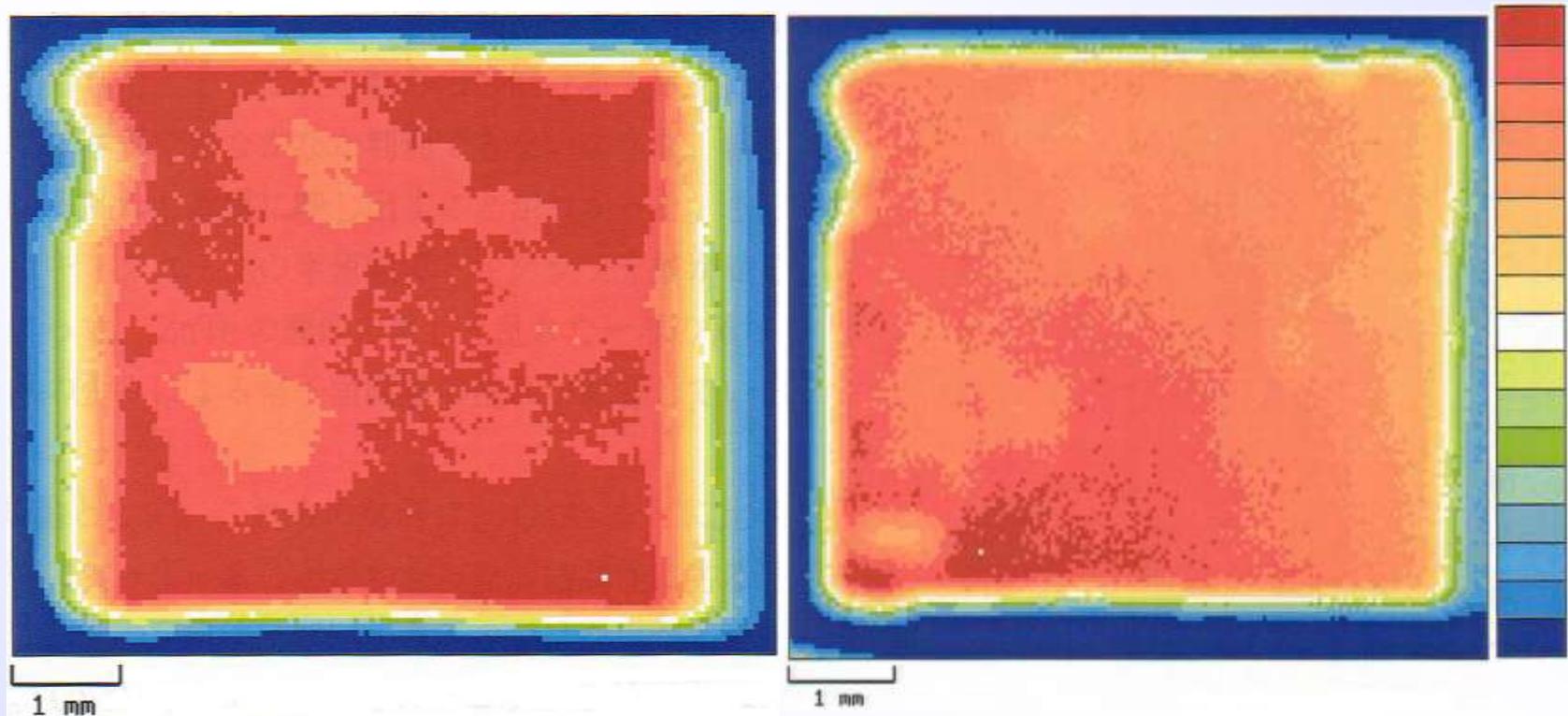
Affine transformation

linear interpolation

$$I(i, j) = I(x, h)(1-p)(1-q) + I(x+1, h)p(1-q) + I(x, h+1)(1-p)q + I(x+1, h+1)pq$$



X線散乱トポグラフィ



ウルツァイトGaN(1011)

ジंकブレンドGaN(004)

ジンクブレンドGaN 220

