

X線トポグラフィーによるSiCの転位評価

産業技術総合研究所 山口 博 隆

X線トポグラフィーによるSiCの転位評価

山口博隆
産業技術総合研究所

パワーエレクトロニクス



4H-SiC

パワーエレクトロニクス材料として実用化研究が進められているワイドギャップ半導体

シリコンの物性限界を超えた
高効率・省エネルギー化へ

- パワーエレクトロニクス
電力の変換と制御を高速に効率よくおこなうためのエレクトロニクス

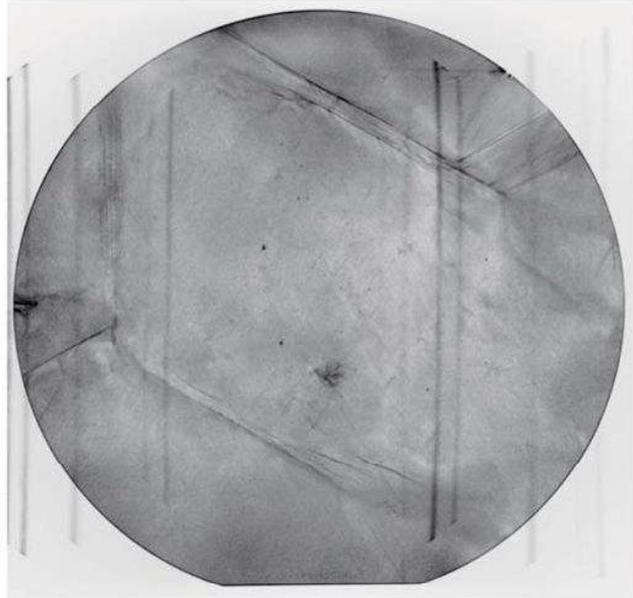
半導体の物性値（室温）

物質	Si	GaAs	SiC			GaN	Diamond	
			3C	6H	4H			
バンドギャップ (eV)	1.1135	1.428	2.2	2.86	3.02	3.39	5.47	
遷移型	ID	D	ID	ID	ID	D	ID	
結晶構造	Diamond	ZB	ZB	Hex.	Hex.	WZ	Diamond	
熱伝導度 (Wc/mK)	1.51	0.54	4.9	4.9	4.9	1.3	20.9	
移動度 (cm ² /Vs)	電子	1500	8500	800	460	1000	900	1800
	正孔	450	420	70	10	120	400	1600
誘電率	ε(0)	11.9	12.91	9.72	9.66/10.03	9.66/10.03	9.5/10.4	5.93
	ε(∞)	11.6	11.1	6.52	6.52/6.70	6.52/6.70	5.35/5.35	5.76
飽和ドリフト速度 (cm/s)	1×10 ⁷	2×10 ⁷	2.7×10 ⁷	2.0×10 ⁷	2.7×10 ⁷	2×10 ⁷	2×10 ⁷	
絶縁破壊電界 (MV/cm)	0.3	0.65	3	3	3.5	2.6	5.6	
真性半導体温度 (K)	600	850	1000	1300	1400	2000	3000	
性能指数	M _J	1	19	730	400	990	550	2500
	M _K	1	0.52	5.8	5	5.8	1.5	32
高速・高集積素子	M _{RON}	1	53	490	260	890	340	3900
高耐圧素子	M _{HF}	1	14	8	4.9	13	9.1	50
高周波素子								

4H-SiC ウェーハ口径の拡大



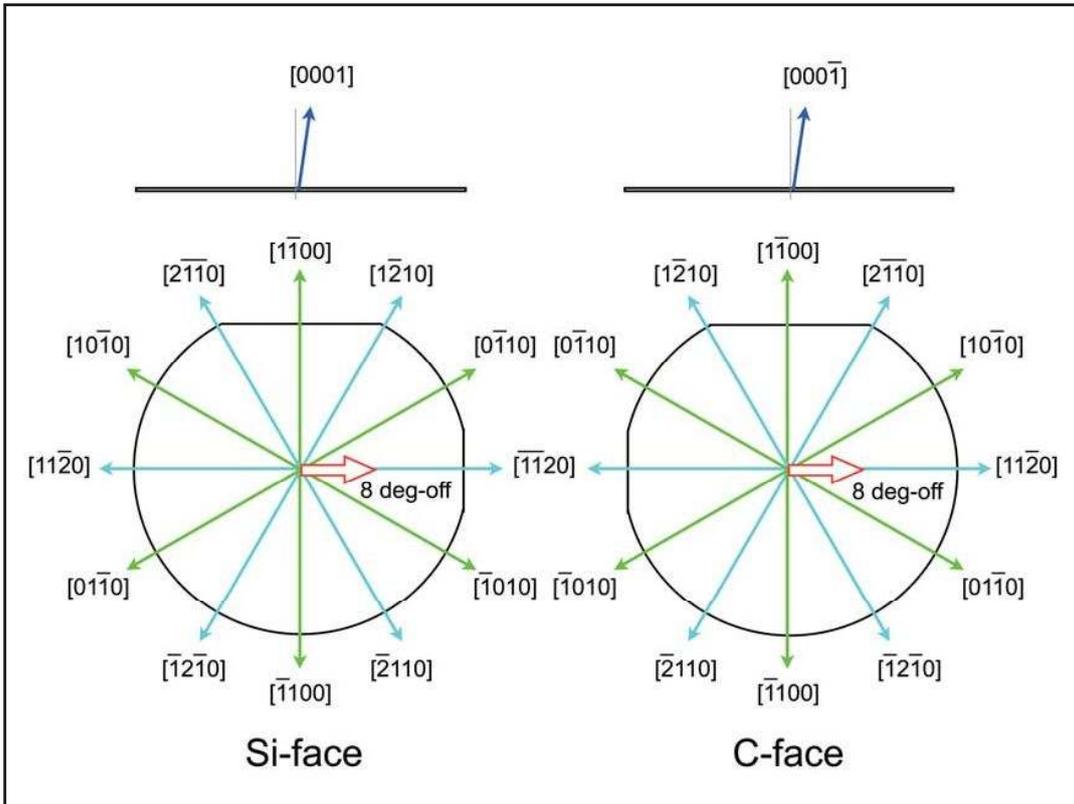
35mm ϕ



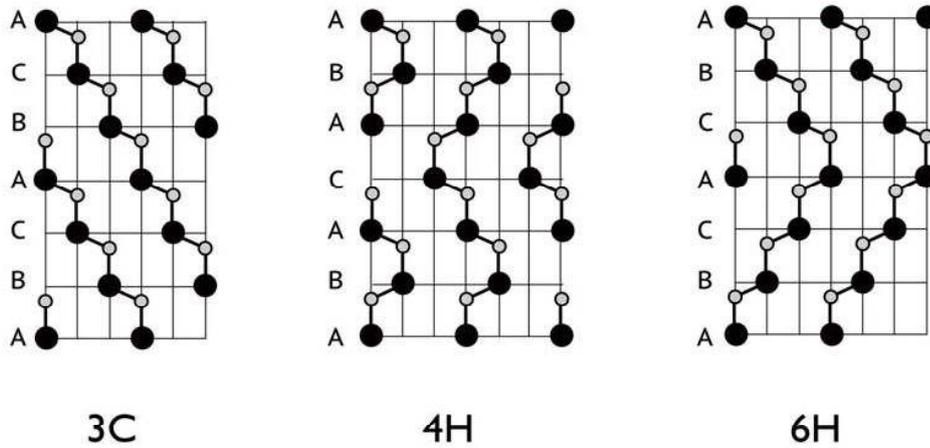
6" ϕ

内容

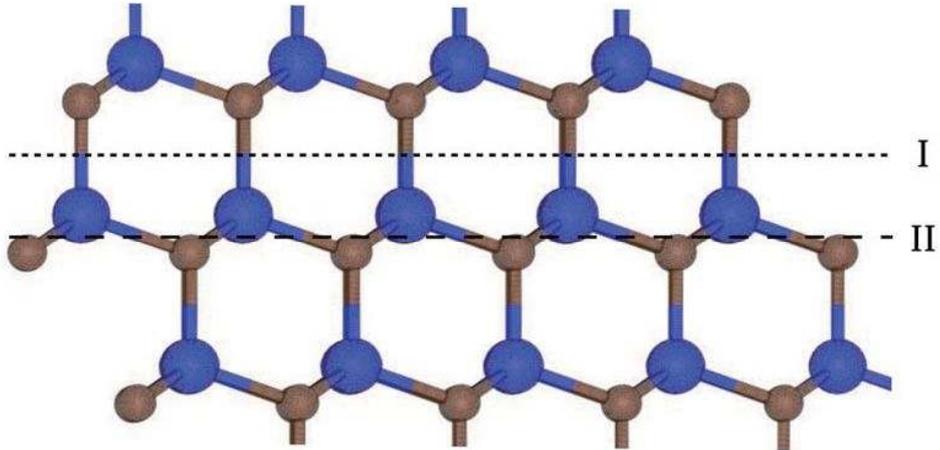
1. 六方晶系の座標系とすべり系
2. ステップフロー成長と積層欠陥
3. 表面形態異常
4. 貫通らせん転位の形態：キラ欠陥の探索



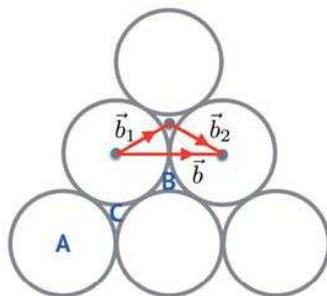
3C-、4H-、6H-SiCの結晶構造



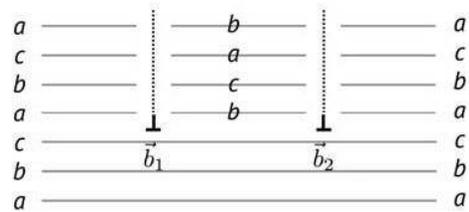
“Shuffle” and “Glide” set dislocations



Dissociation of unit dislocation



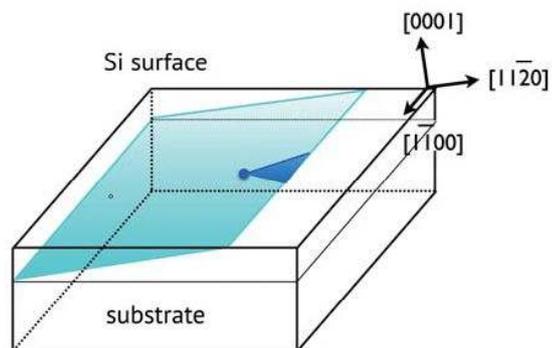
Shockley partial dislocation



内容

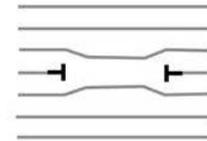
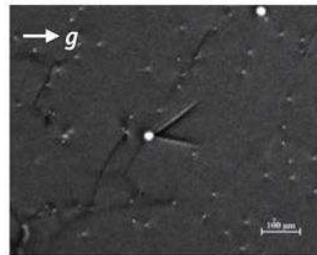
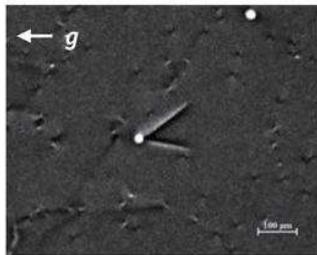
1. 六方晶系の座標系とすべり系
2. ステップフロー成長と積層欠陥
3. 表面形態異常
4. 貫通らせん転位の形態：キラ欠陥の探索

エピ欠陥

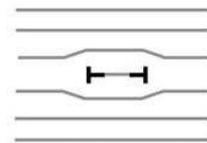
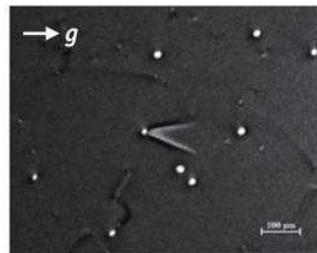
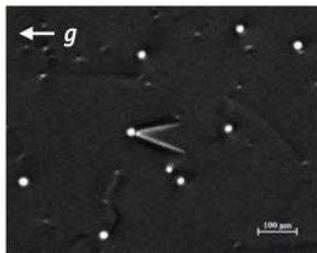


Frank Sessile Dislocation

(1) Intrinsic



(2) Extrinsic

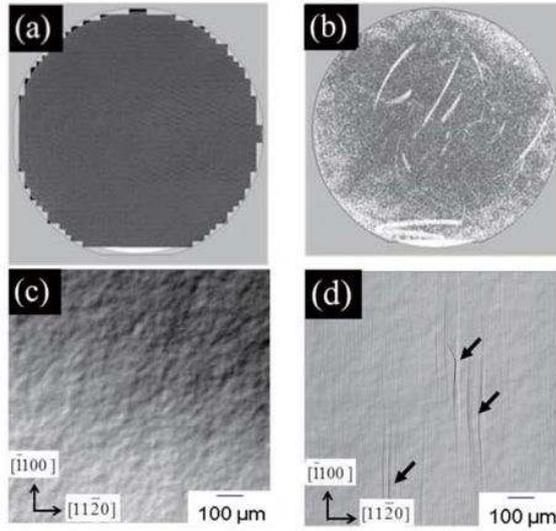


内容

1. 六方晶系の座標系とすべり系
2. ステップフロー成長と積層欠陥
3. 表面形態異常
4. 貫通らせん転位の形態：キラー欠陥の探索

Surface morphology of wafer surface before and after epitaxial growth

CDIC

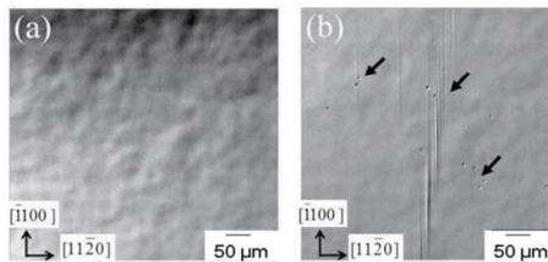


CMP processed surface
Before epitaxial growth

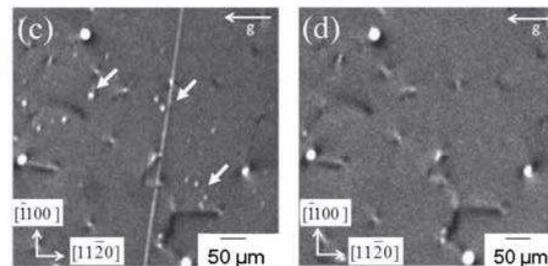
After epitaxial growth

Surface morphology of wafer surface before and after hydrogen etching

CDIC



X-ray topograph

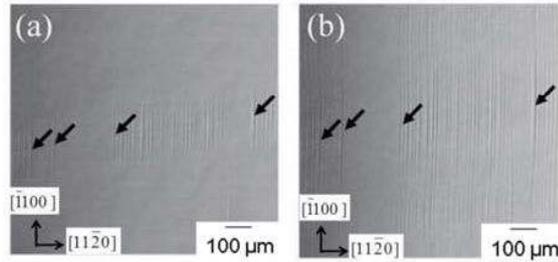


CMP processed surface
Before hydrogen etching

After hydrogen etching

Surface morphology of wafer surface after hydrogen etching and after epitaxial growth

CDIC

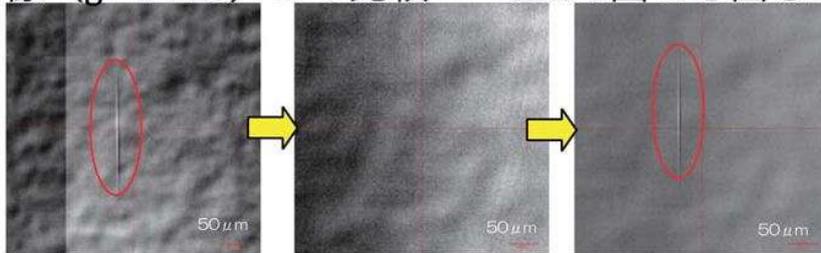


After hydrogen etching

After epitaxial growth

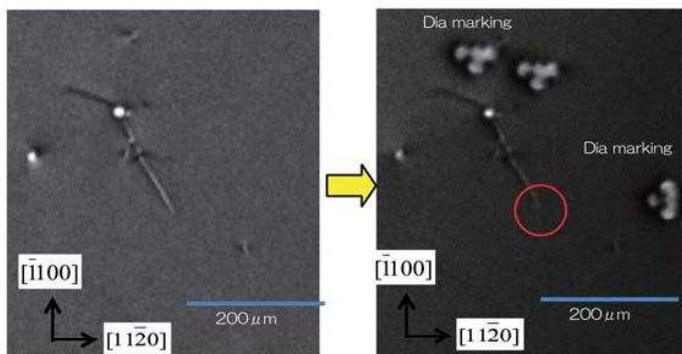
トポ像 (g=-1-128) との比較

SBが2回とも出るBPD



①1回目水素エッチングSICA像

②2回目水素エッチングSICA像



トポ像 CMP後(1回目水素エッチング前)

2回目水素エッチング後

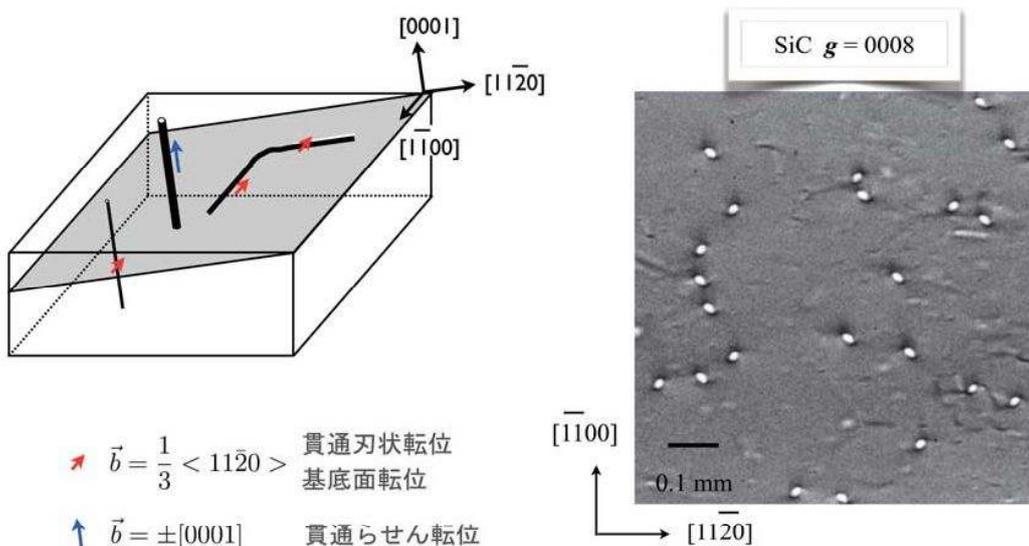
TypeA⇒BP
Dの先端に
対応。

20

内容

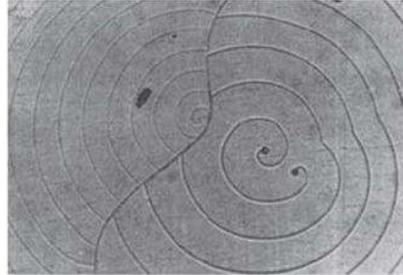
1. 六方晶系の座標系とすべり系
2. ステップフロー成長と積層欠陥
3. 表面形態異常
4. 貫通らせん転位の形態：キラ欠陥の探索

SiCの転位



Threading Screw Dislocation

$$\vec{b} = \pm[0001] \quad \vec{\ell} = \pm[0001]$$



Effect on device performance:

- low breakdown voltage
- reverse bias leakage
- short life time
- \vdots

but not all



Threading Screw Dislocation

TSDs – Which is killer?

- “Pure” screw dislocation

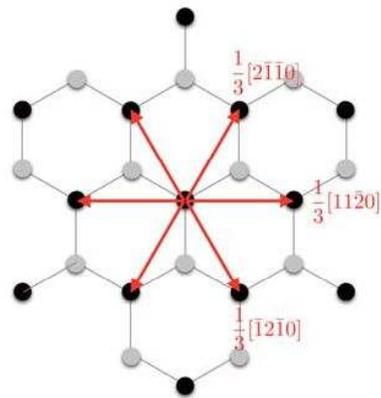
$$\vec{b} = \vec{b}_s$$

- Mixed dislocation

$$\vec{b} = \vec{b}_s + \vec{b}_e$$

$$\vec{b}_s = \pm[0001]$$

$$\vec{b}_e = \frac{1}{3}\langle 11\bar{2}0 \rangle$$



Burgers vector of edge component

Threading Screw Dislocation

Three types of TSDs – Which are killers?

- “Pure” screw dislocation

$$\vec{b} = \vec{b}_s$$

- Mixed dislocation (1)

$$\vec{b} = \vec{b}_s + \vec{b}_e$$

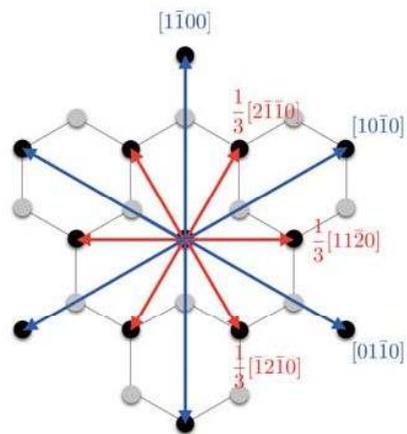
- Mixed dislocation (2)

$$\vec{b} = \vec{b}_s + \vec{b}'_e$$

$$\vec{b}_s = \pm[0001]$$

$$\vec{b}_e = \frac{1}{3}\langle 11\bar{2}0 \rangle$$

$$\vec{b}'_e = \langle 1\bar{1}00 \rangle$$



Burgers vector of edge component

X-ray Topography

- To identify character of TSDs

TEM or X-ray topography

- wide field of view
- nondestructive analysis
 - a number of samples
 - subsequent device check



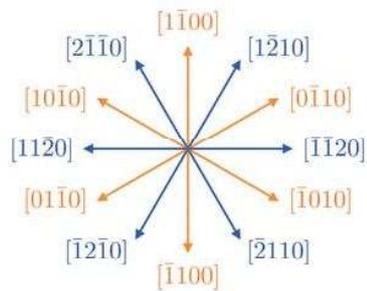
Burgers vector determination

$\vec{g} \cdot \vec{b}$ invisibility criterion

Contrast in X-ray topograph is

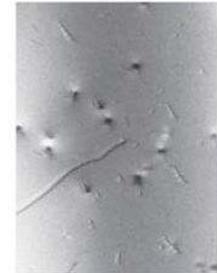
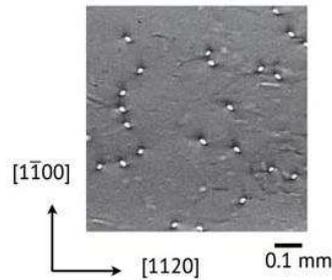
maximum if $\vec{g} \cdot \vec{b} = gb$ ($\vec{g} \parallel \vec{b}$)

zero if $\vec{g} \cdot \vec{b} = 0$ ($\vec{g} \perp \vec{b}$)



0008 reflection

1100 transmission



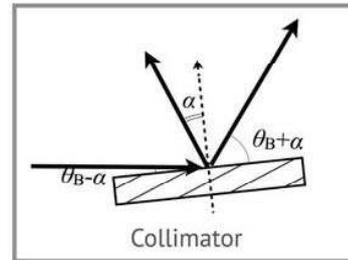
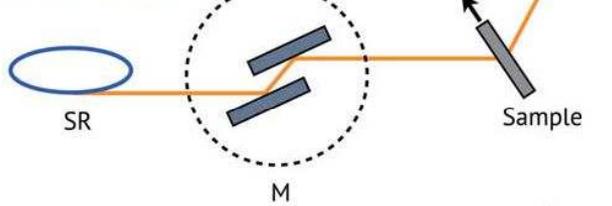
$$\vec{g} \cdot \vec{b}_s = \pm gb_s$$

$$\vec{g} \cdot \vec{b}_e = 0$$

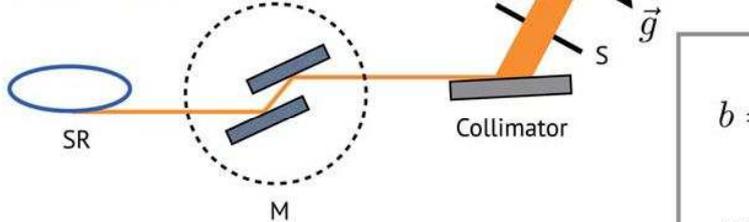
$$\vec{g} \cdot \vec{b}'_e = 0$$

$$\vec{g} \cdot \vec{b}_s = 0$$

Single-Crystal



Double-Crystal



$$b = \frac{\sin(\theta_B - \alpha)}{\sin(\theta_B + \alpha)}$$

$$\omega = \sqrt{b} \times \omega_{sym}$$

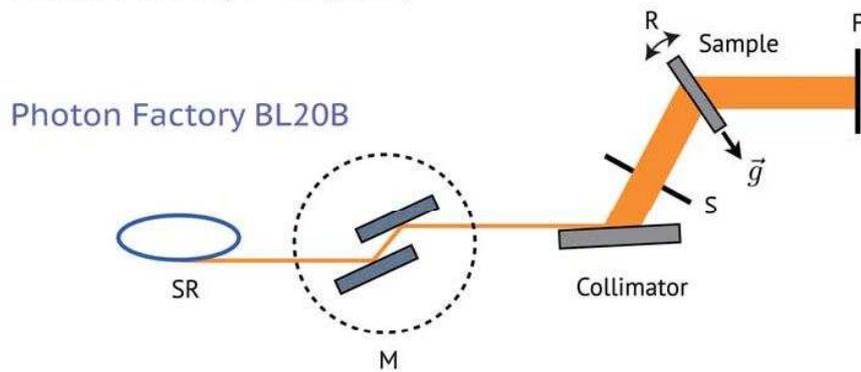
Experiment Double-Crystal X-ray topography

X-ray: $\lambda=0.069$ nm

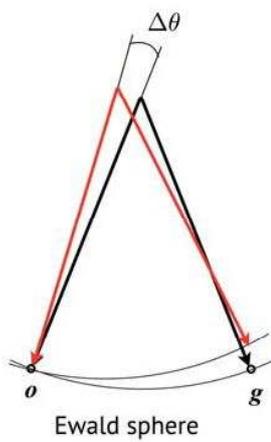
Collimator: Si 331

Asymmetry factor: $\sim 1/30$

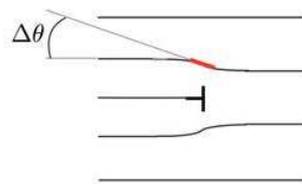
Specimens: 4H-SiC; 4° -off (0001)



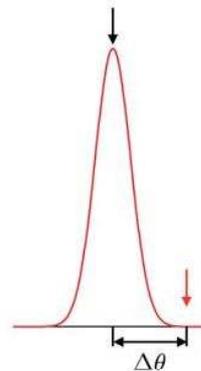
Weak-beam Method



Reciprocal space



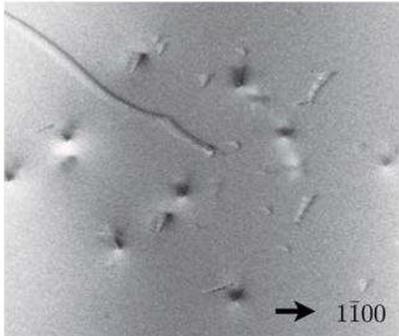
Real space



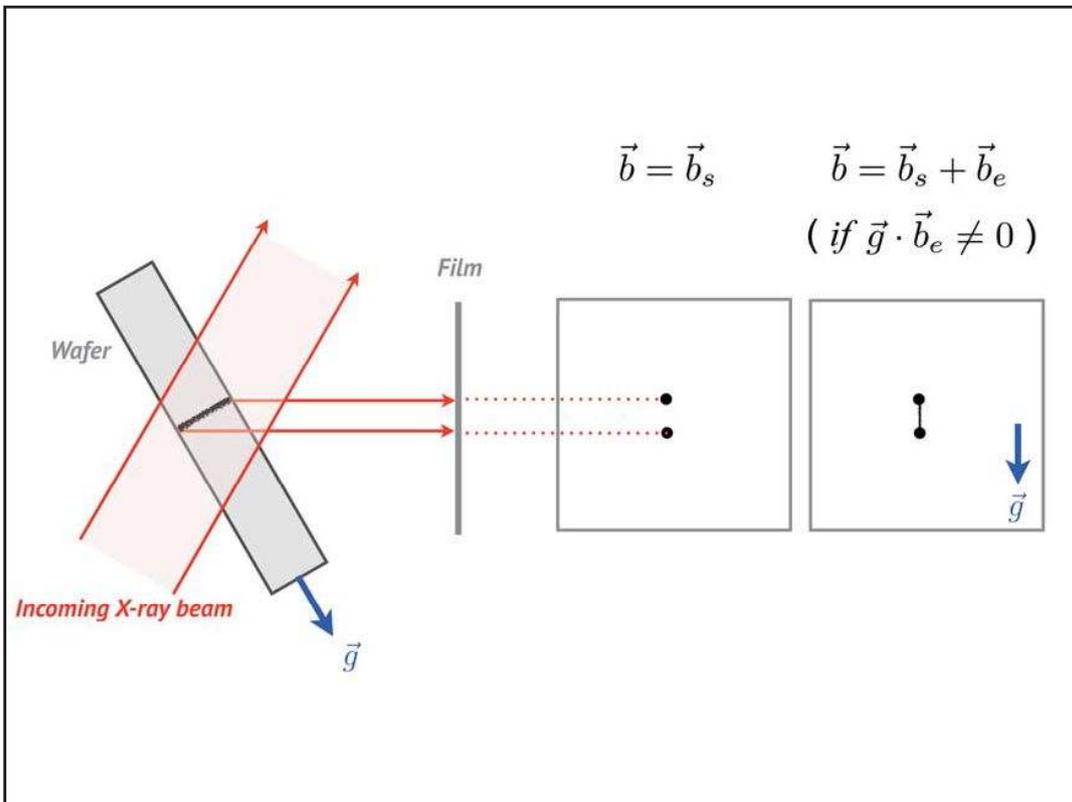
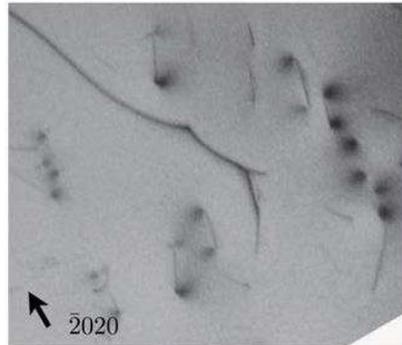
Rocking curve

Dislocation Images

single crystal



double crystal
weak beam



Character Identification of TSDs

Sample

High quality 4°-off 4H-SiC wafer

Experiment

X-ray: $\lambda=0.069$ nm

Collimator: Si 331

Asymmetry factor: $\sim 1/30$

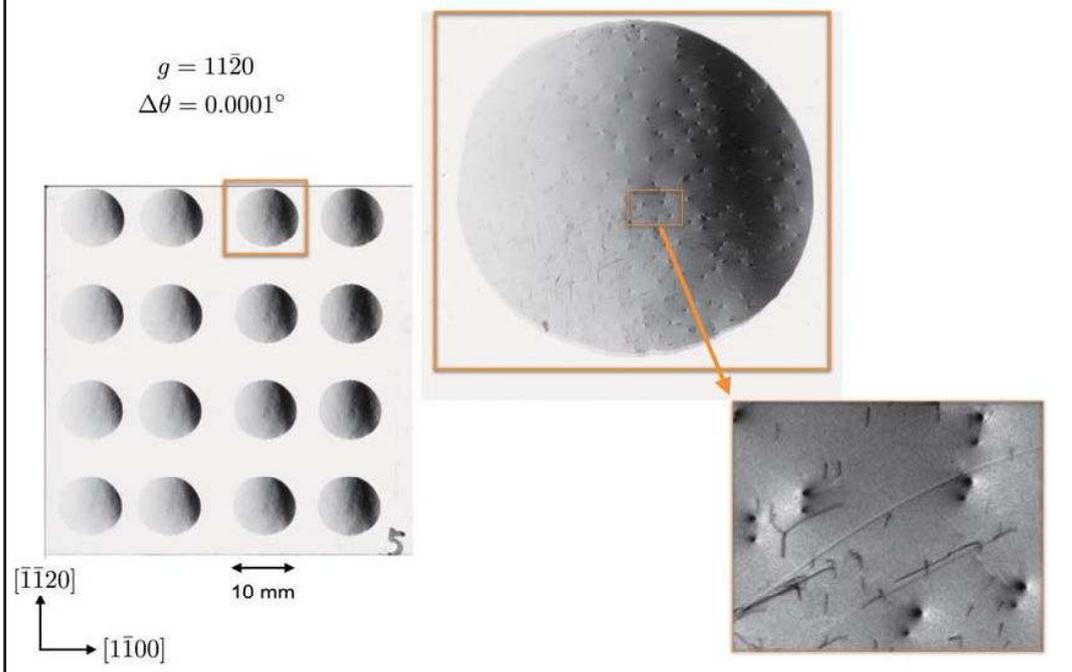
Specimens: 4H-SiC; 4°-off (0001)

Reflections:

$11\bar{2}0, \bar{2}110, 1\bar{2}10$

$2\bar{2}00, \bar{2}020, 02\bar{2}0$

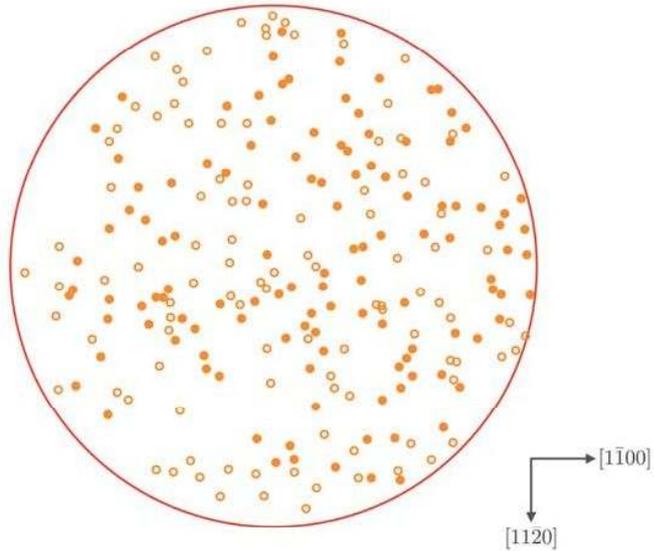
Character Identification of TSDs



Character Identification of TSDs

Pure screw or mixed dislocation

	<i>N</i>
total	245
pure screw	105
mixed	140



まとめ

SiCの結晶欠陥をX線トポグラフィーによって評価した

- 基底面転位の拡張
- エピタキシャル面の積層欠陥
- エピタキシャル面の表面形態異常
- 貫通らせん転位のウィークビームトポグラフ