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Joint ICTP-IAEA Advanced Workshop on Multi-Scale Modelling for Characterization and Basic Understanding of Radiation Damage Mechanisms in Materials

12 - 23 April 2010

Investigations of behavior of SiC materials under neutron and charged particle irradiation

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Fabrication of SiC

SiC ***was first synthesized in 1891 by Acheson:***

(E.G.Acheson, Chem.News 68 (1893) 179).

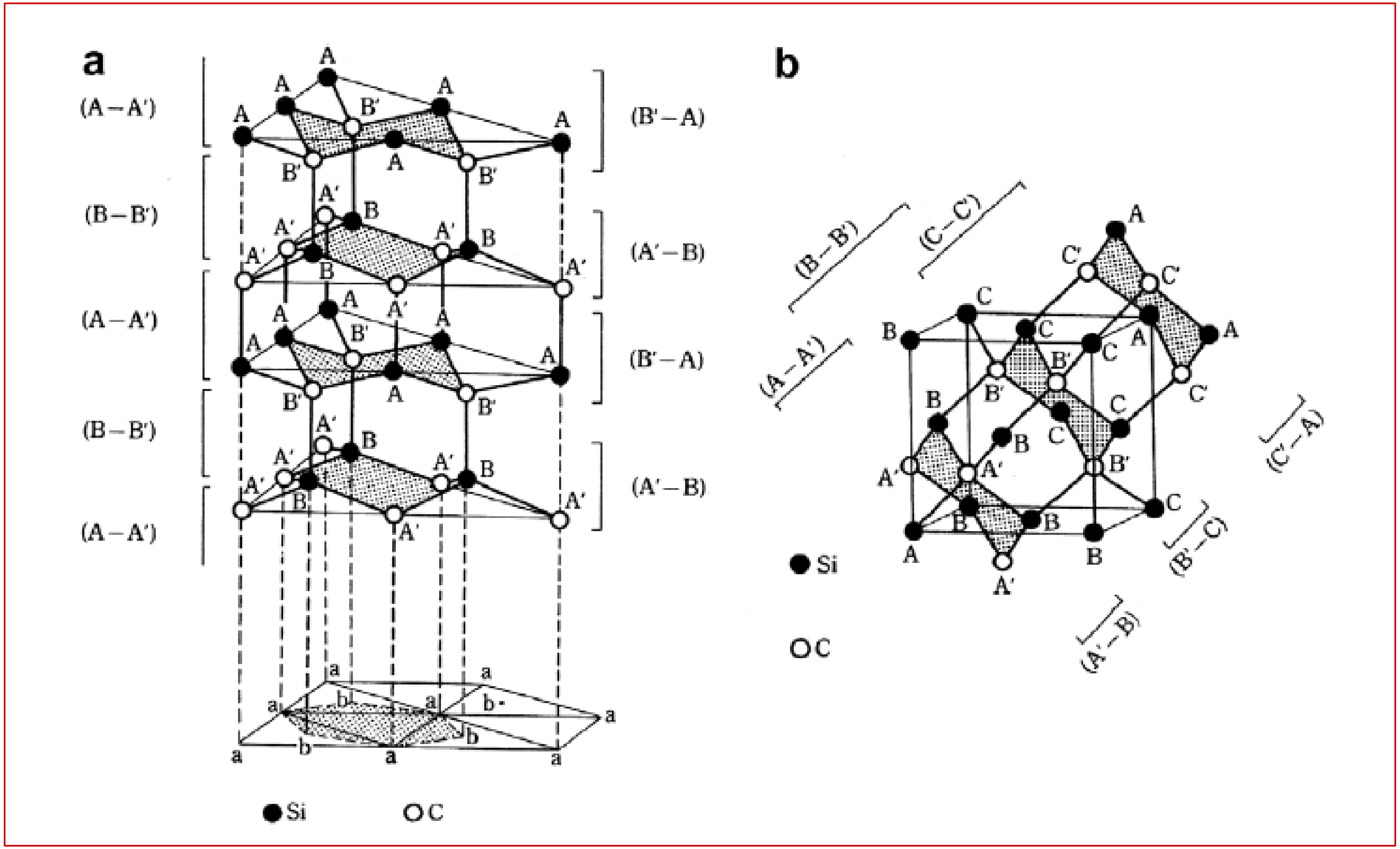
By electrochemical reaction in an electric furnace:

$$SiO_2 + 3C \rightarrow SiC + 2CO$$

α-SiC formed at T = 2373 K and

β-SiC formed at T = 1273 – 1873 K

Crystal structures of (a) α-SiC and (b) β-SiC

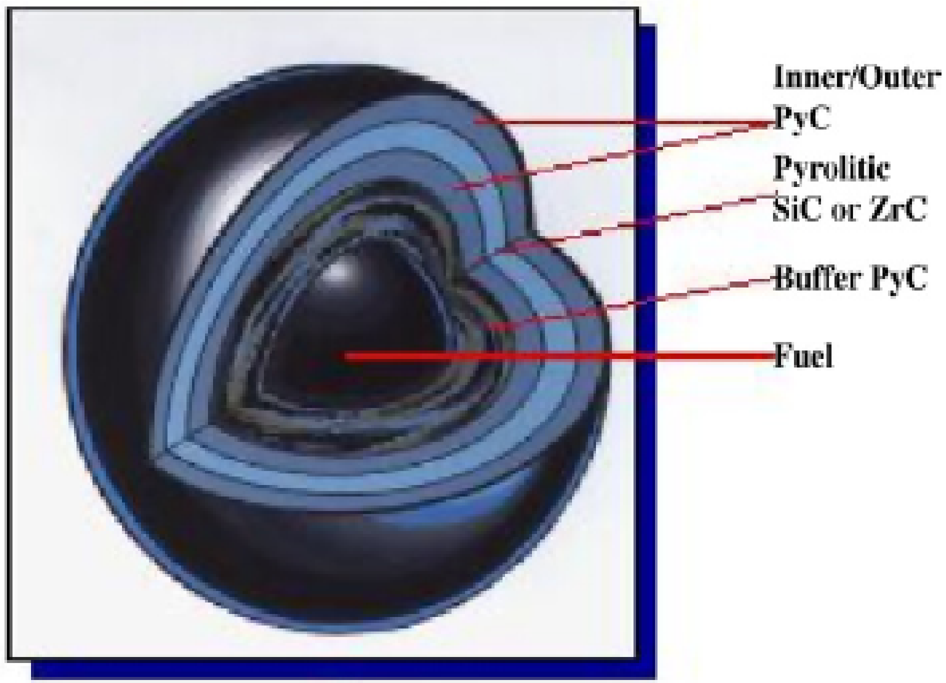


Possibility for using of SiC materials in nuclear energy systems:

- fuel element in high temperature gas-cooled reactor (HTGR)
- fuel blocks for the gas fast reactors (GFR)
- guide tubes materials in very high temperature reactors (VHTR)
- test blanket module designs for the ITER

Schematic illustration of fuel elements: nonirradiated (a) and irradiated (b)

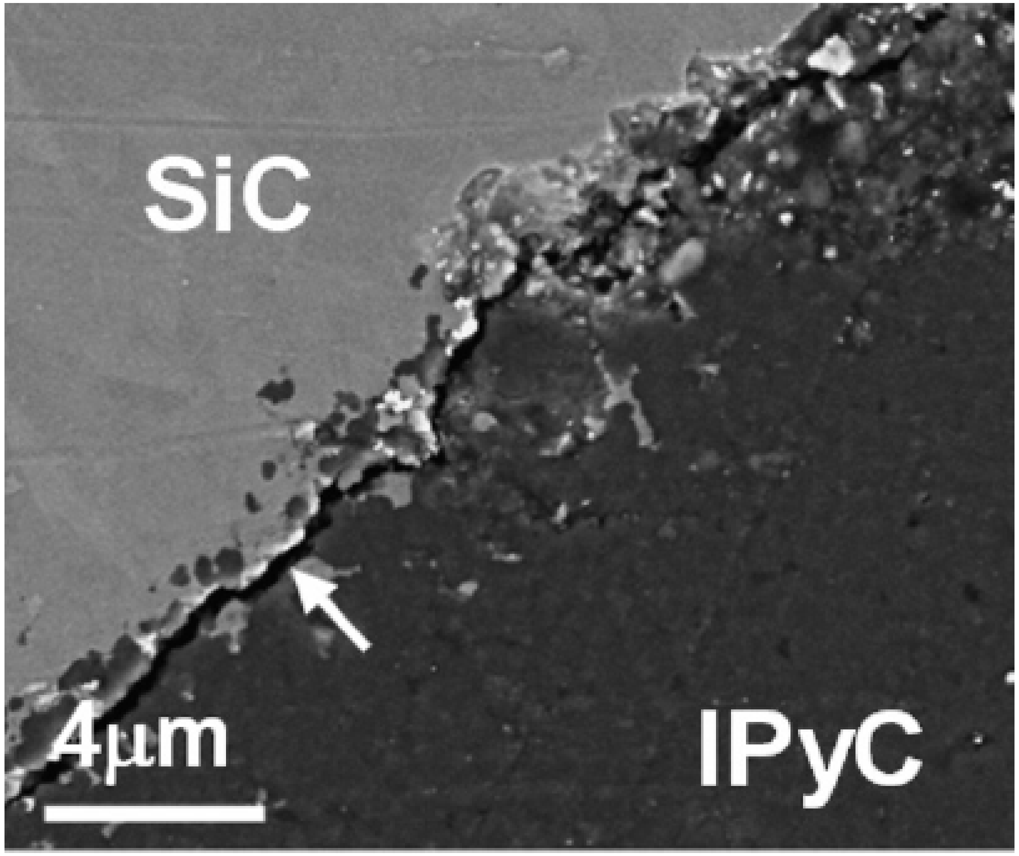
a



b

L. Snead, ORNL

Crack propagation at the inner Py/SiC interface



L. Snead, ORNL

Background and Objective

Silicon Carbide - Superior Performance for advanced Energy systems

Under the irradiation environment

- Potential irradiation resistance
- Low induced activity, Low after-heat

At the elevated Temperature

- High strength, Chemical stability

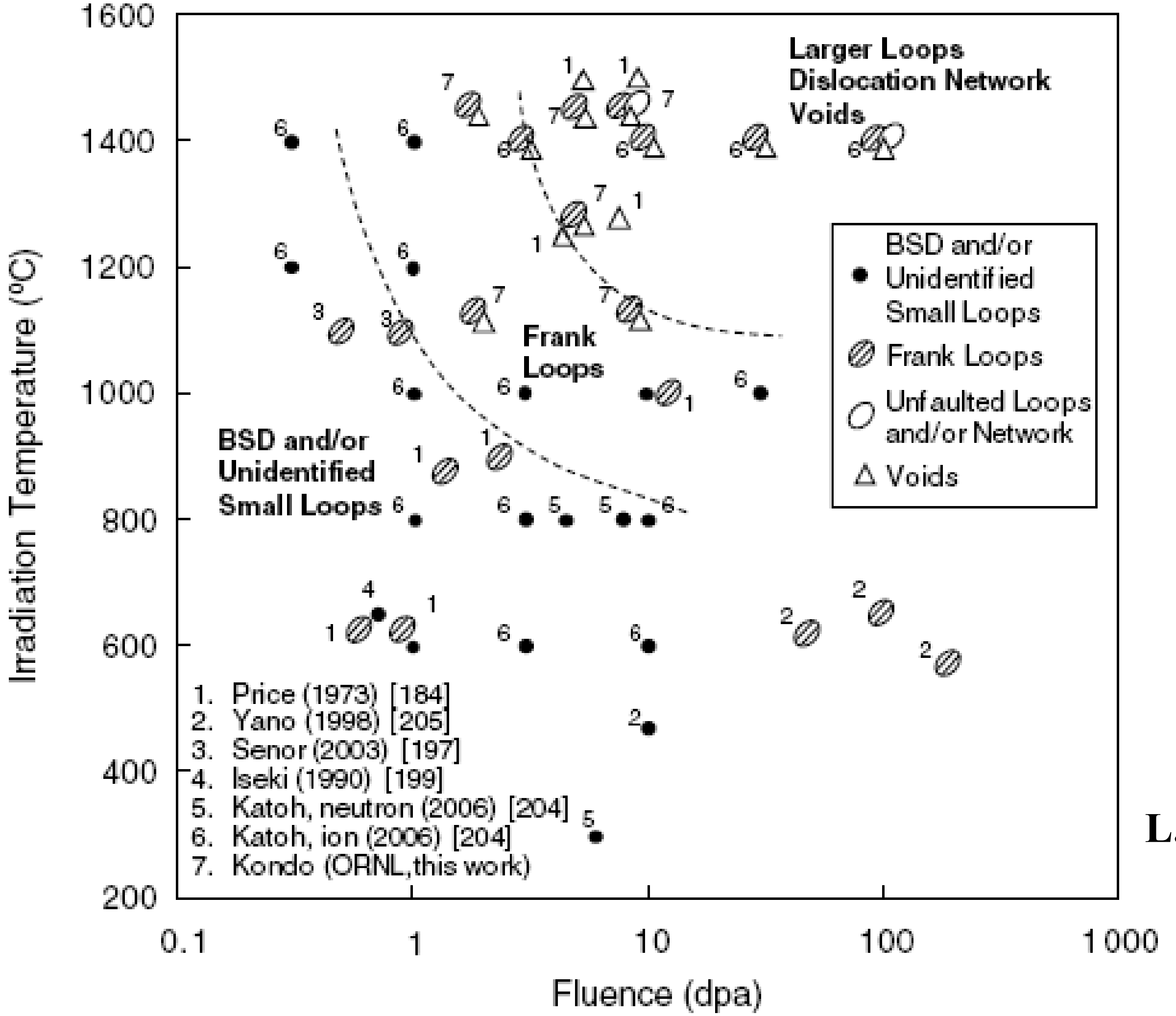
Issues under irradiation environment

- Irradiation induced volume expansion (swelling)
- Effects of helium production through (n, α) nuclear reaction (in fusion)

Objective

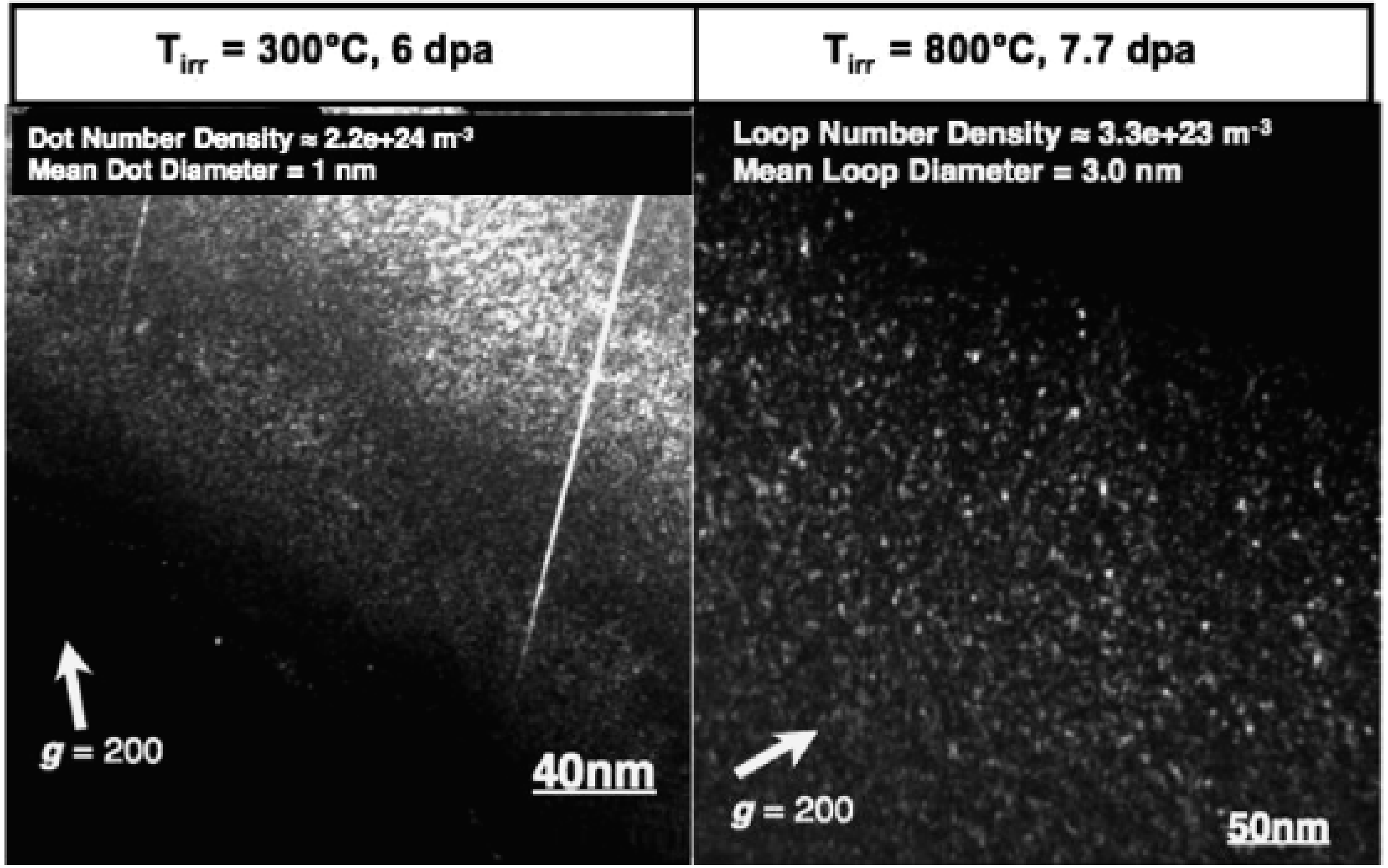
- Determine the effects of irradiation conditions on swelling in SiC
- Investigation of the synergistic effects of displacement damage and helium production

Microstructural development in cubic SiC during neutron and ion irradiations



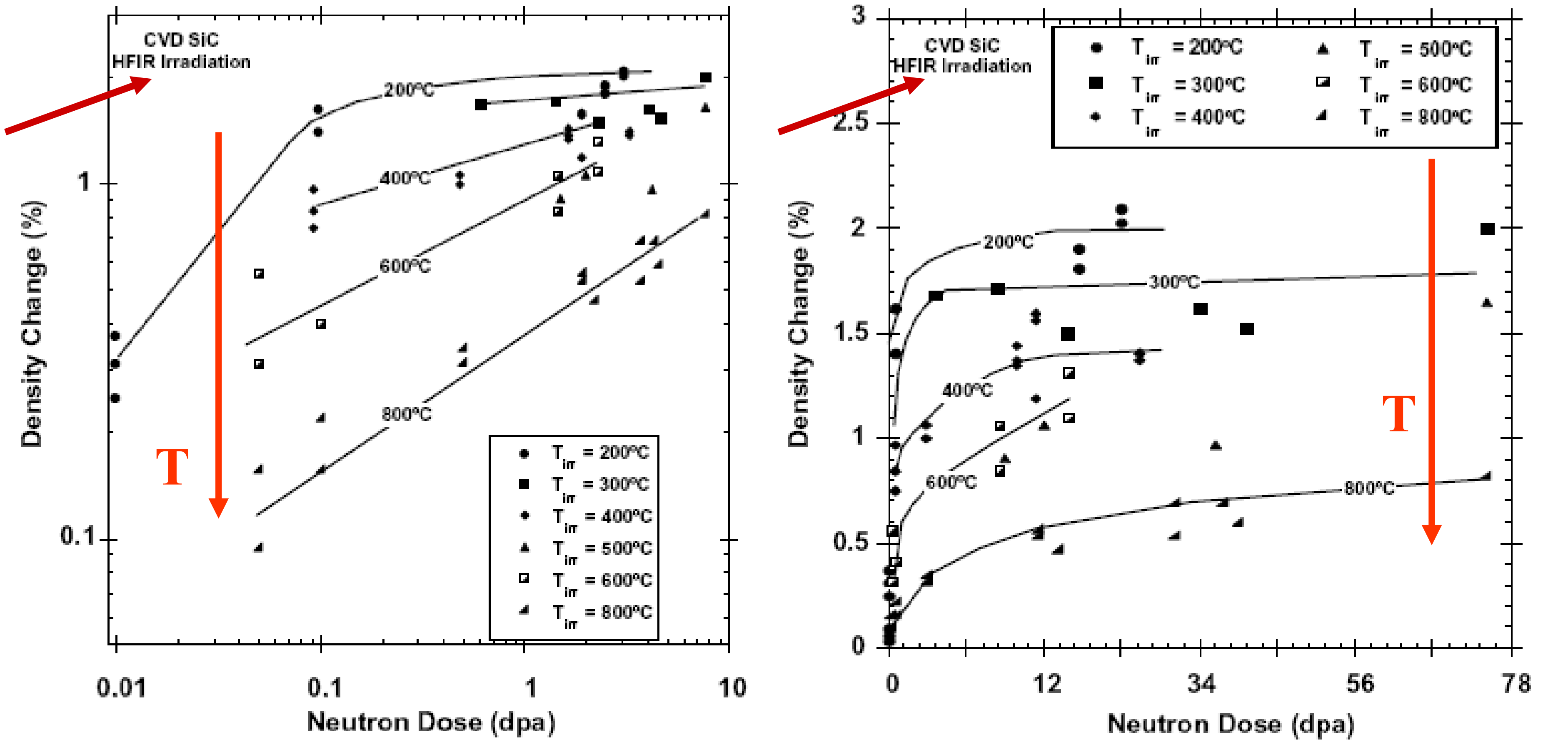
L. Snead, Y. Katoh, ORNL (2007)

Saturated microstructure for (chemically vapor deposited) CVD SiC neutron irradiated at 573 K and 1073K



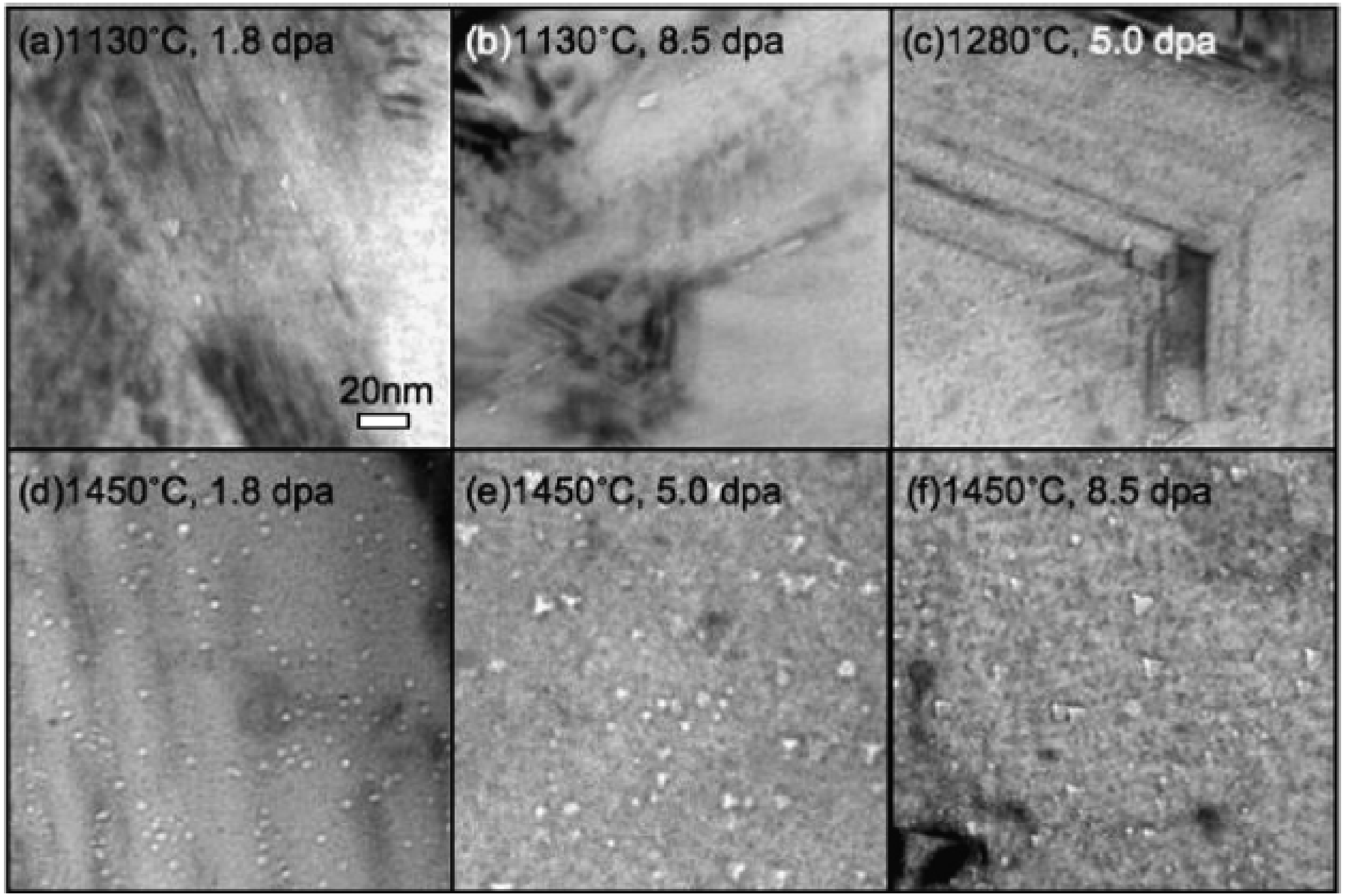
L. Snead, ORNL (2007)

Swelling regime of CVD SiC at different irradiation doses and temperatures.



L. Snead, ORNL

Evolution of voids in high temperature irradiated CVD SiC



L. Snead, ORNL

Experimental

Materials: *Morton CVD-SiC (Polycrystalline β-SiC)*

Specimen geometry: **$3.0mm^{f}$ x $0.25mm^{t}$**

Ion beam irradiation:

Specimens are covered with molybdenum meshes

Facility:	*HIT facility, University of Tokyo*
Ions:	*4MeV Ni*
	4MeV Ni + 1MeV He (degraded)
Temperature:	*T = 333K, 473K, 673K, 873 K*
Dose rate:	*f = $1x10^{-5}$ - $1x10^{-3}$ dpa/s (nominal)*
Dose:	*0.005-100dpa (nominal)*
He/dpa ratio:	*60 appm He/dpa (nominal)*

Swelling characterization :

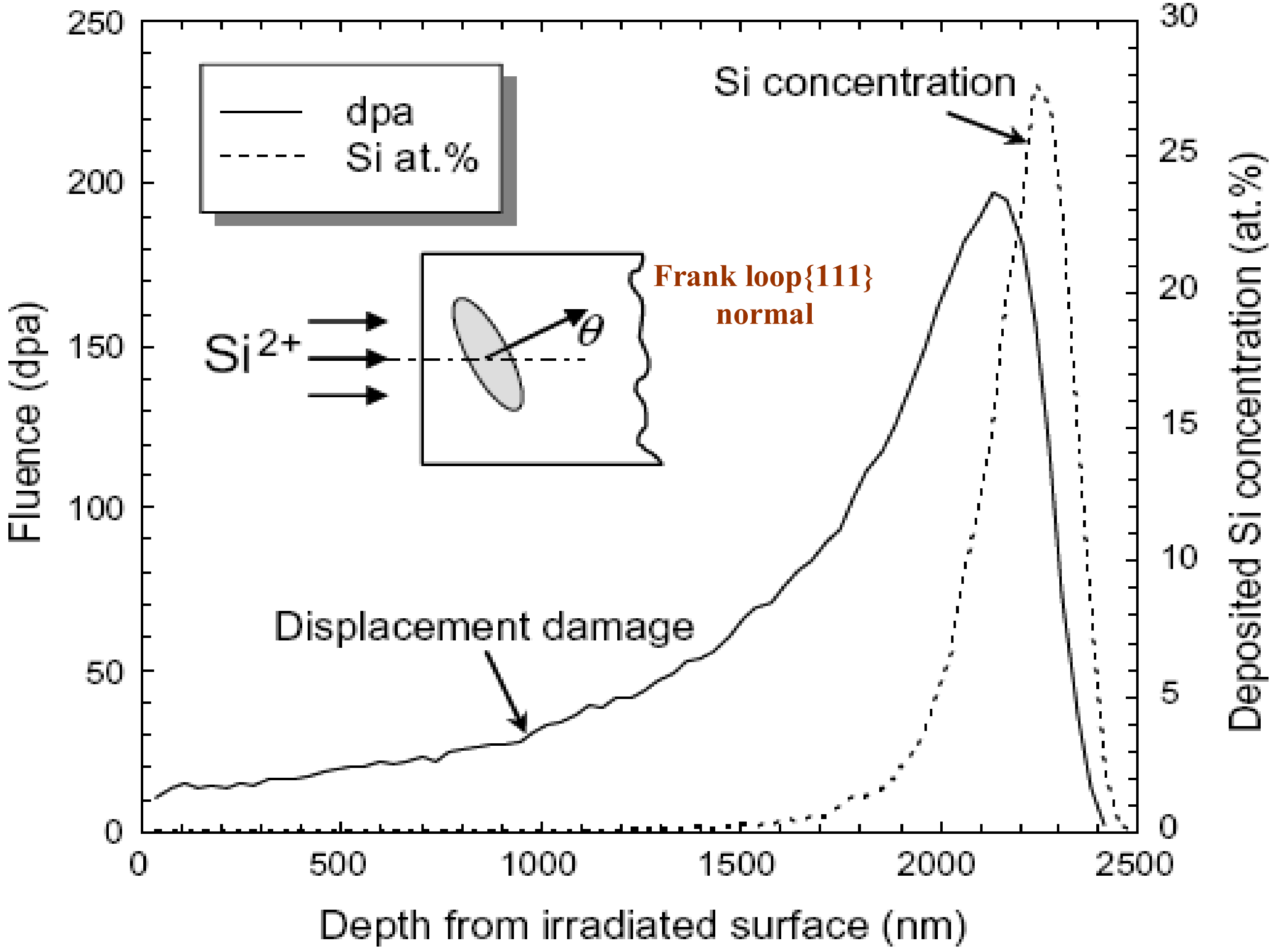
Surface profilometry by the optical interferometry

Thin film Processing :

Performed by Focused ion beam (FIB) devise
/JEOL/Micrion JFIB-2100

TEM observation : */JEOL JEM-2010 (200kV)*

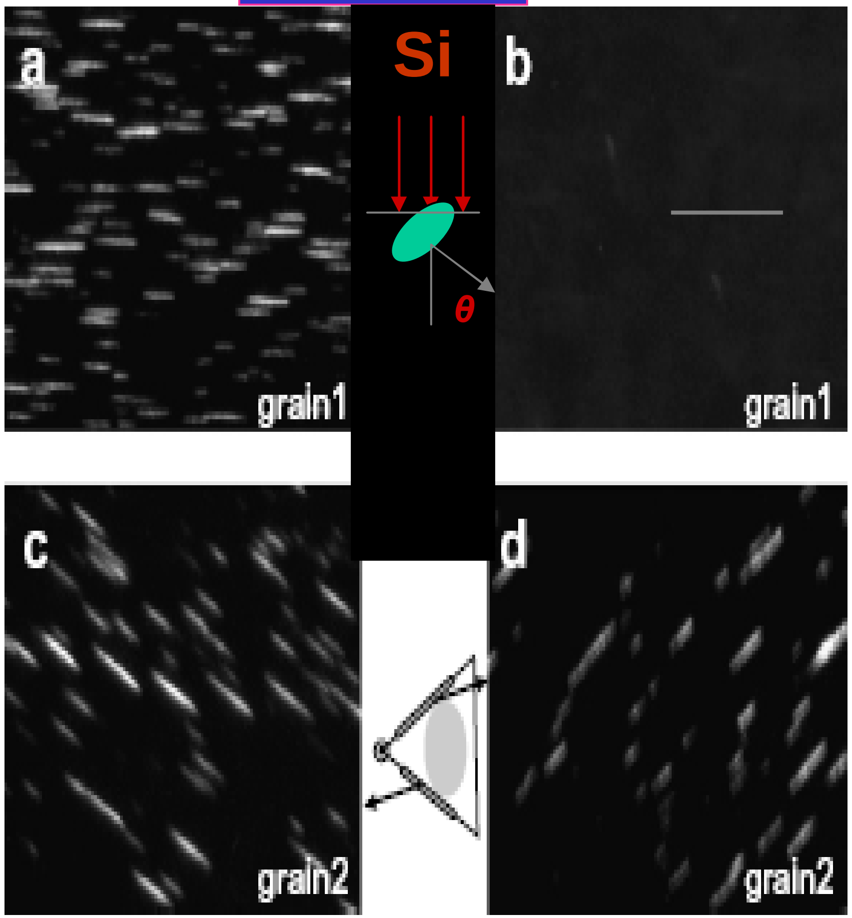
Displacement damage and ion deposited rate profiles in SiC irradiated by 5.1 MeV Si ions

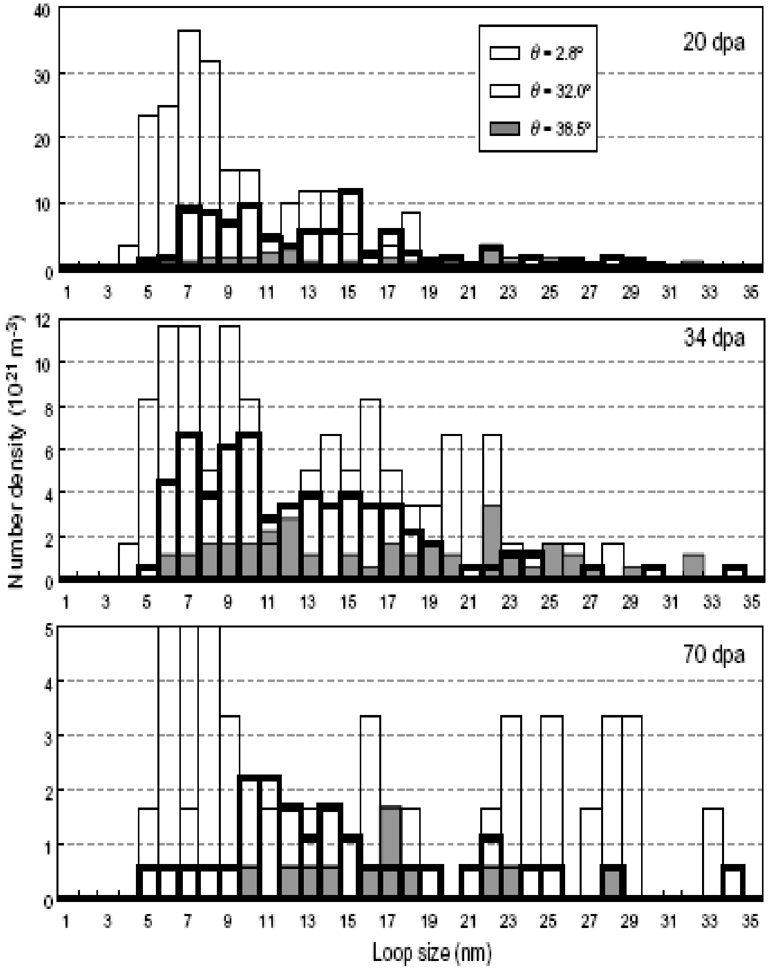


S.Kondo, A.Kohyama (2007)

TEM images of Frank loops in SiC under 5.1 MeV Si ion irradiation (DuET) at 1400 C

Dose~34 dpa





(A.Kohyama et al.,2007)

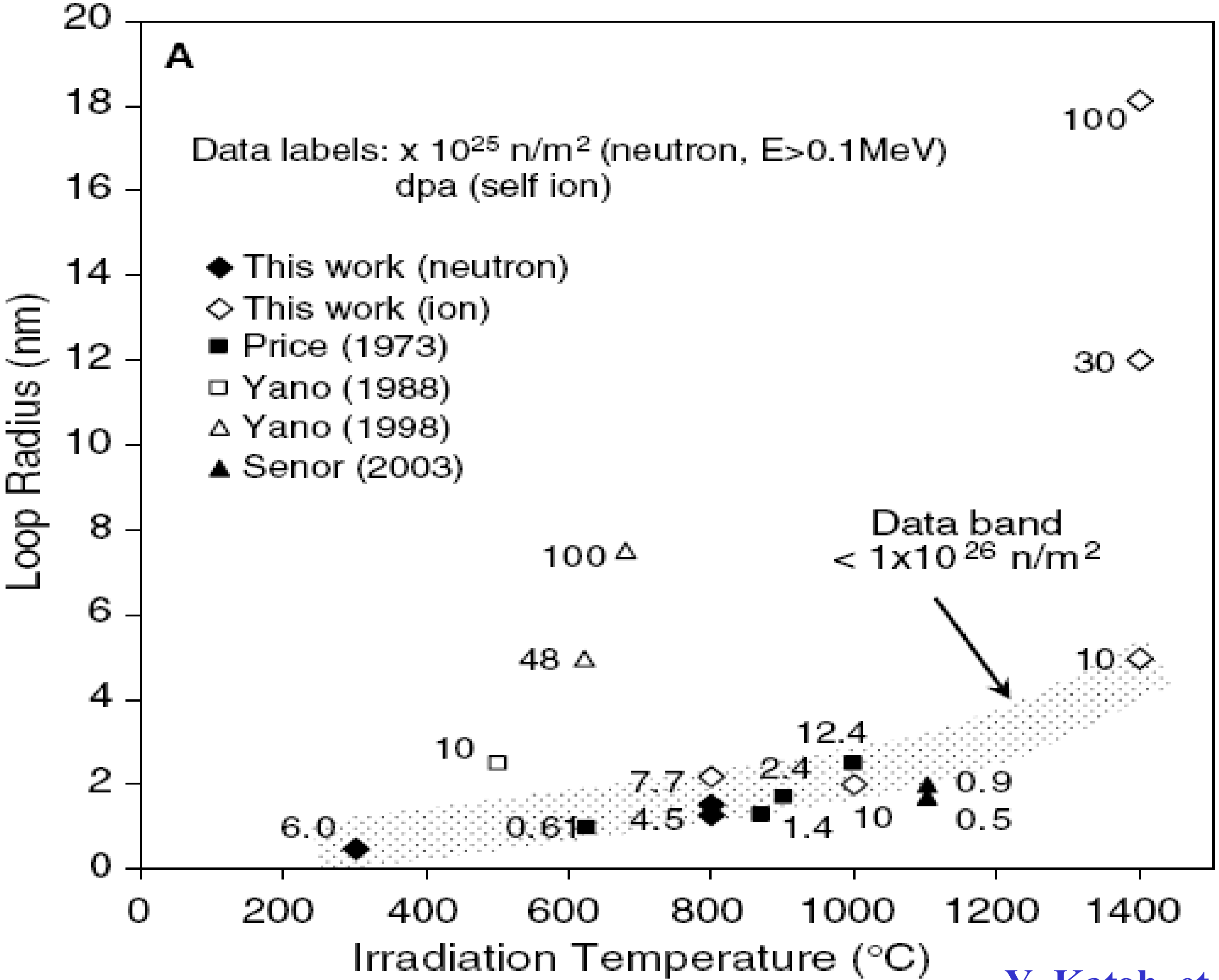
Microstructural data for irradiated cubic SiC

Irr. temp. (°C)	Dose ($\times 10^{25}$ n/m^2 or dpa)	Black spot/loops			Cavities	
		Type	Density (m^{-3})	Radius[a] (nm)	Density (m^{-3})	Radius (nm)
Neutron (0.5×10^{-6} dpa/s, HFIR, ORNL)						
300	6.0	Black spots	2.2×10^{24}	<0.5	Not detected	
800	4.5	Mix	2.6×10^{23}	1.3	Not detected	
800	7.7	Mix	3.3×10^{23}	1.5	Not detected	
Ion ($\sim 1 \times 10^{-3}$ dpa/s, 5.1 MeV Si^{2+}, DuET, Kyoto University)						
600	10	Black spots	n/m[b]	n/m	Not detected	
800	10	Mix	n/m	2.2	Not detected	
1000	10	Loops	2.6×10^{23}	~2	$<1 \times 10^{20}$	1.6[c]
1400	10	Loops	2.3×10^{21}	~5	2.0×10^{22} [d]	~ 2.0
1400	30	Loops	2.3×10^{21}	12.0	1.3×10^{24} [d]	~ 2.0
1400	100	Loops	5.2×10^{21}	18.1	1.8×10^{24} [d]	~ 2.0

[a] 1/2 of the approximate mean size for the black spot defects.
[b] Not measured.
[c] Grain boundary cavities.
[d] Local number density of grain/twin boundary cavities.

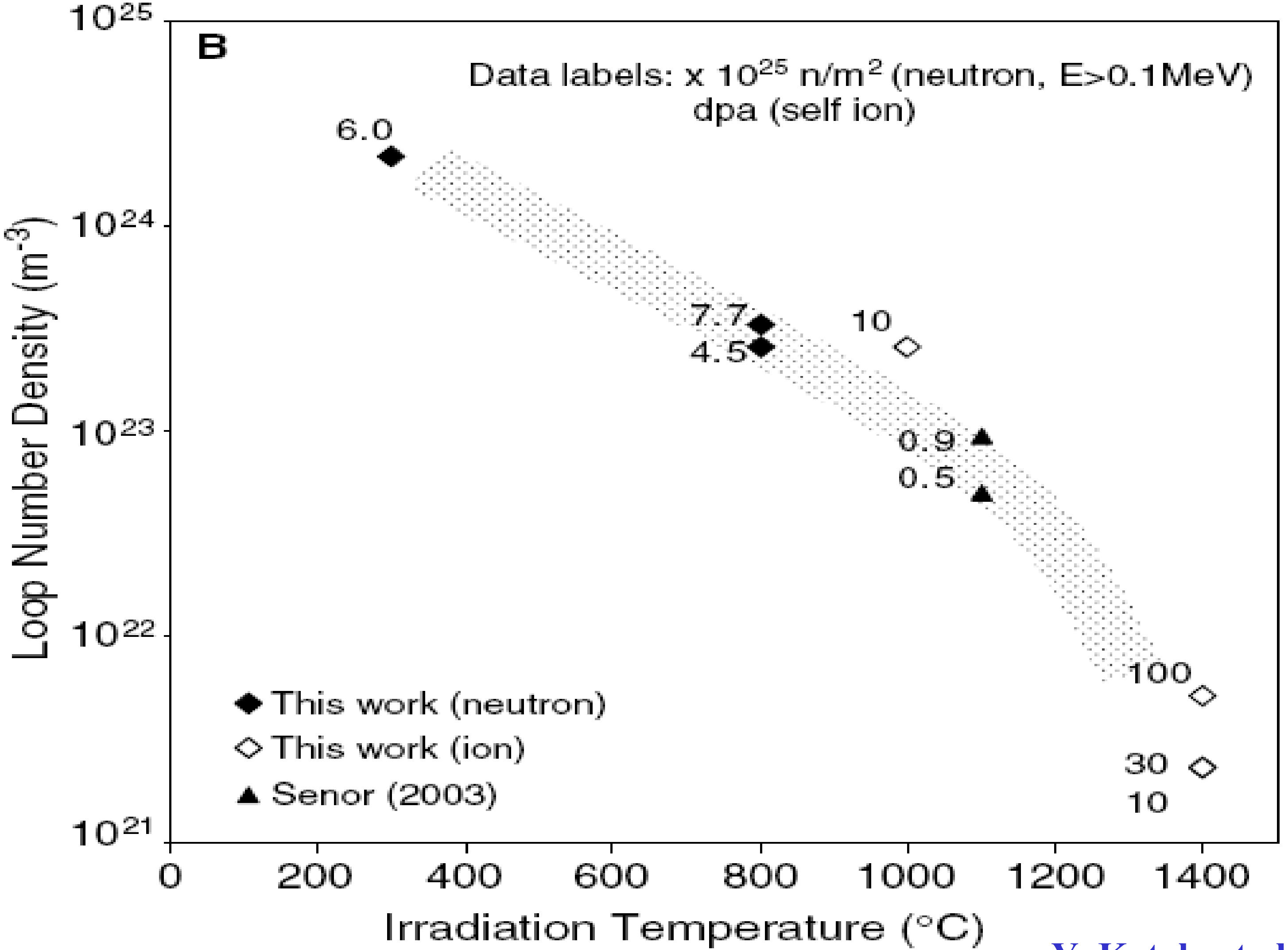
Y. Katoh, et al., ORNL, 2006

Temperature dependence of dislocation loop growth



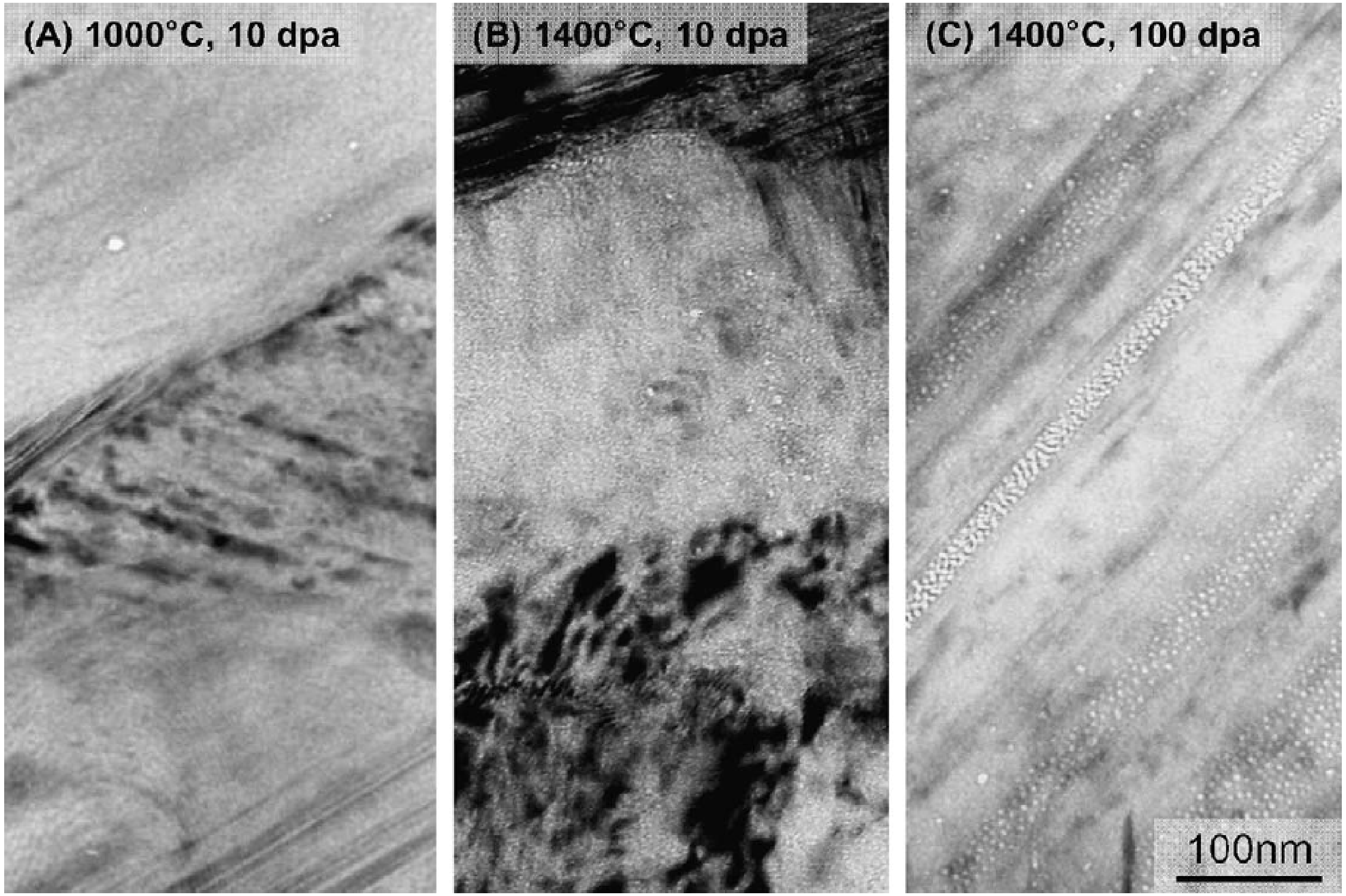
Y. Katoh, et al., ORNL, 2006

Temperature dependence of dislocation loop density



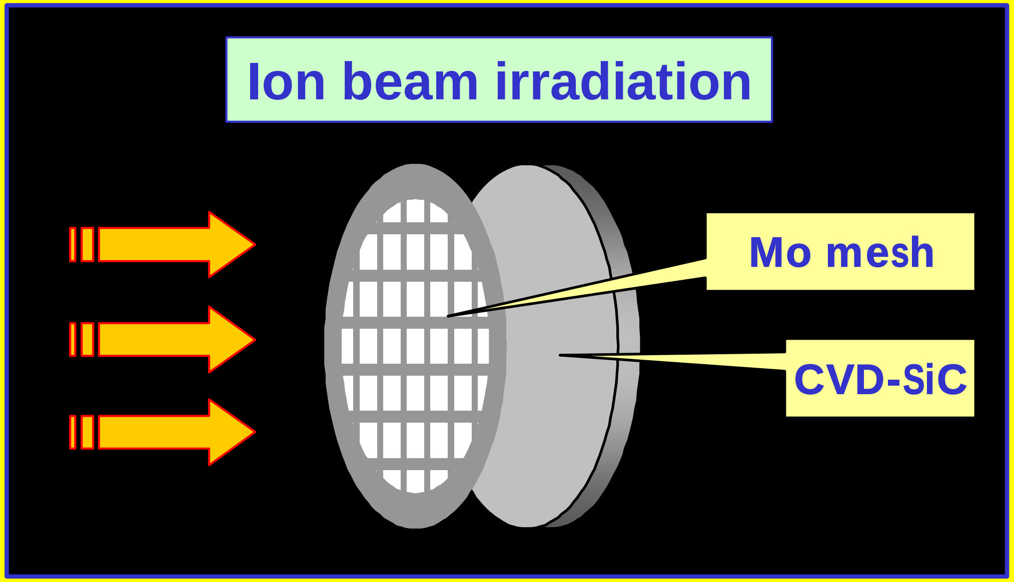
Y. Katoh, et al., ORNL, 2006

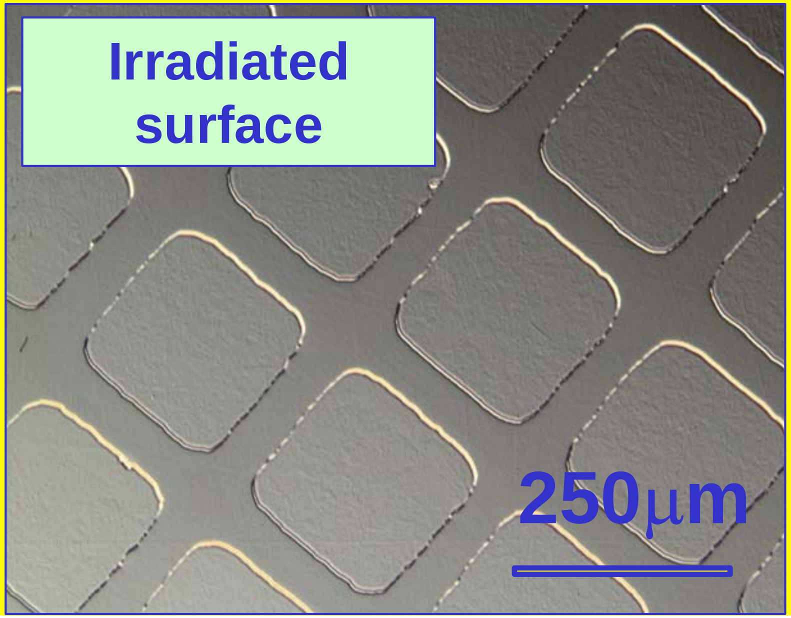
Cavity microstructure in cubic SiC irradiated by 5.1 MeV Si ions at high temperatures

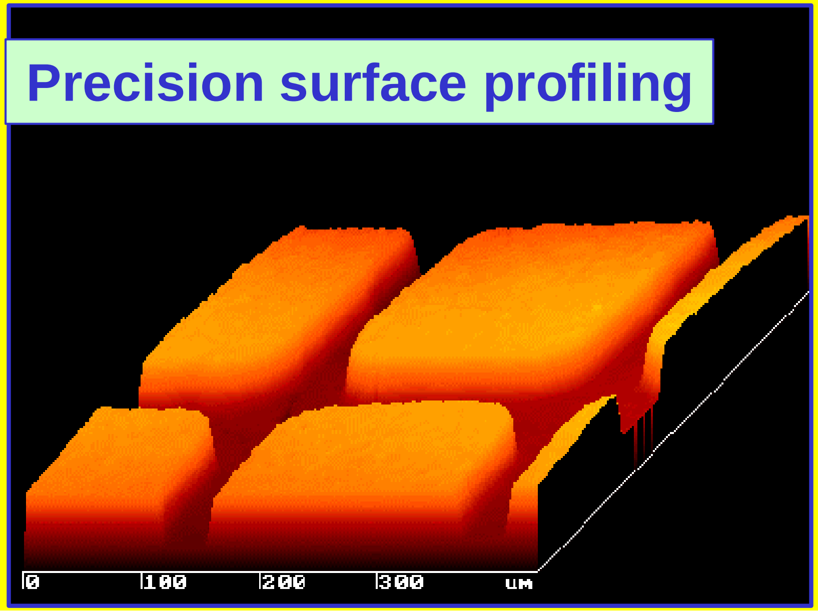


Y. Katoh, ORNL (2006)

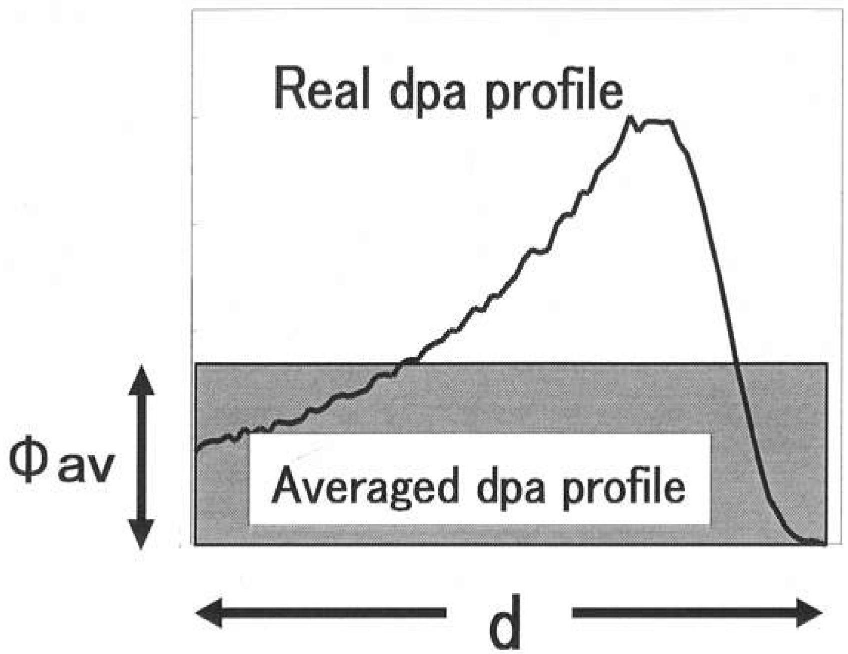
Ion beam irradiation and Surface profile characterization

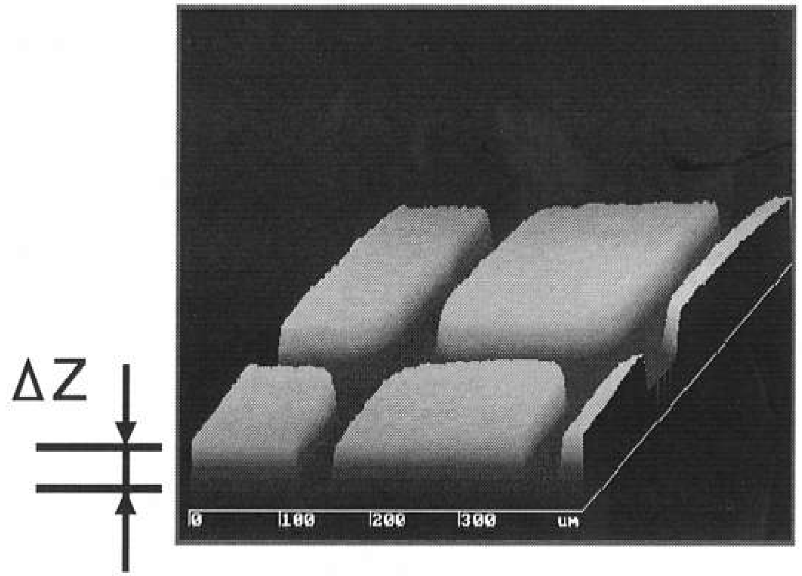






Experimental Measurement of Radiation Swelling





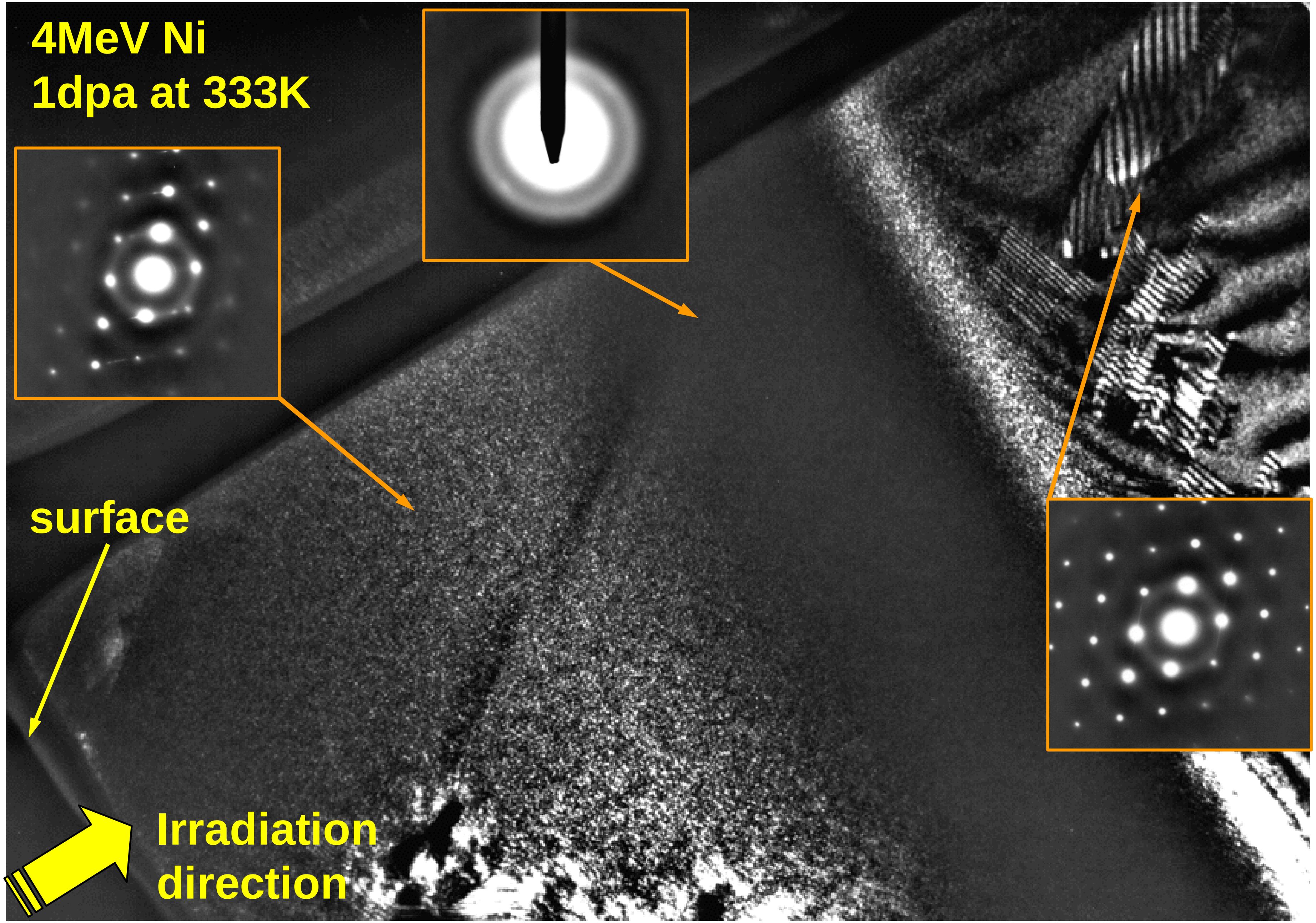
$$\Delta V / V\ (\Phi_{av}) \cong \Delta Z / d$$

Φ_{av} – Averaged dpa profile,

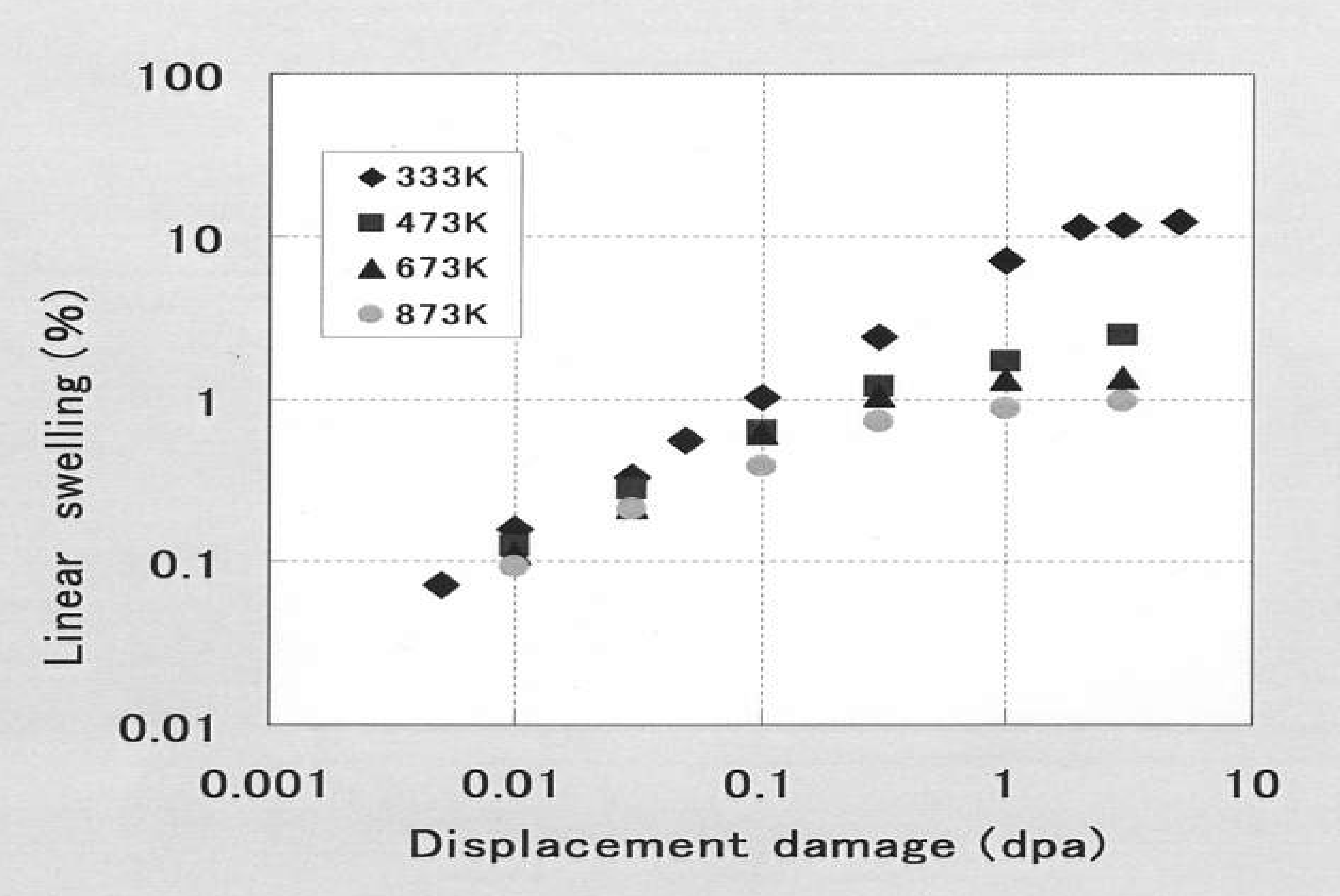
ΔZ - Height of step between irradiated and no irradiated area,

d - Penetration depth of irradiated sample.

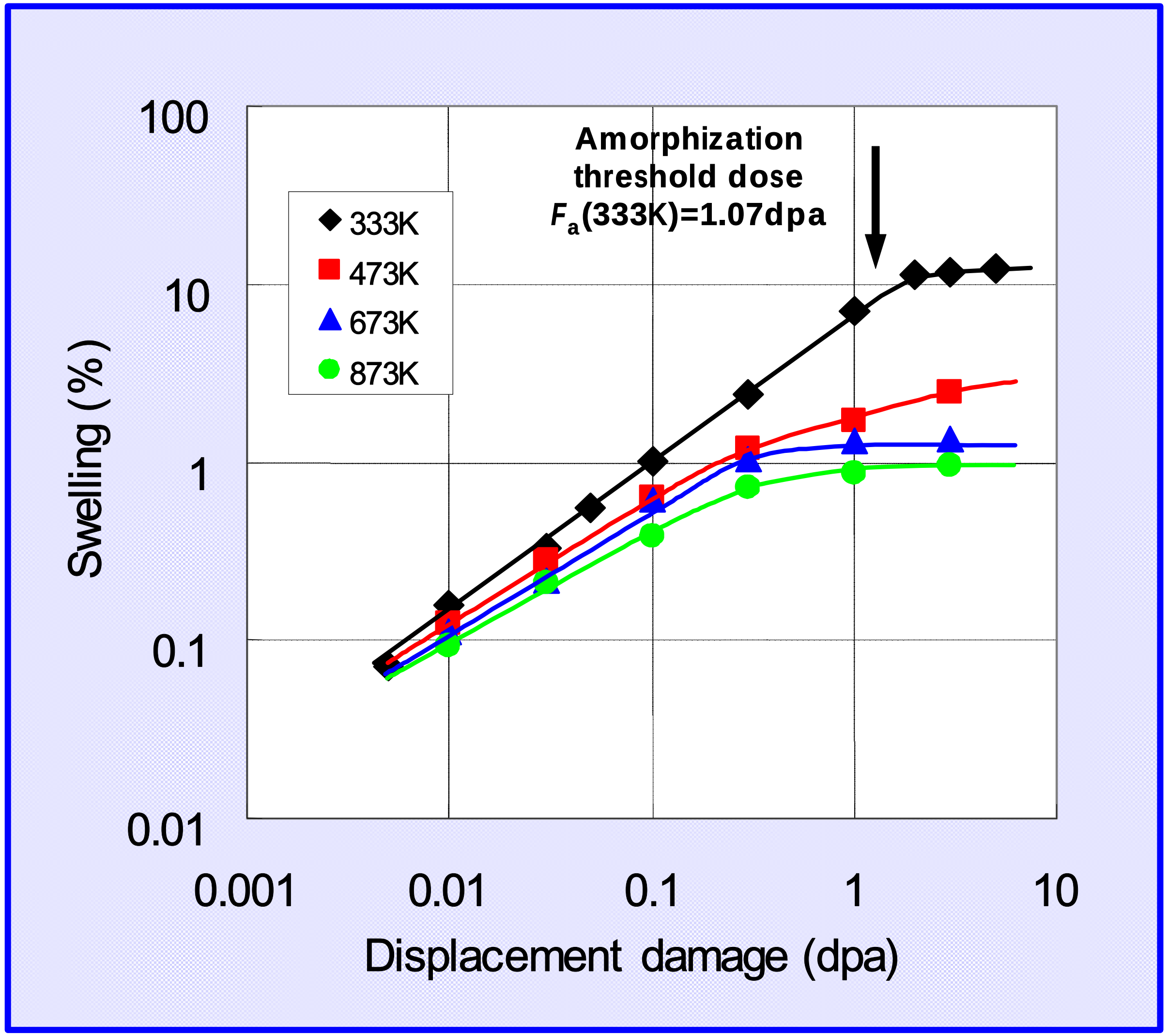
Cross-sectional TEM of ion-irradiated CVD-SiC



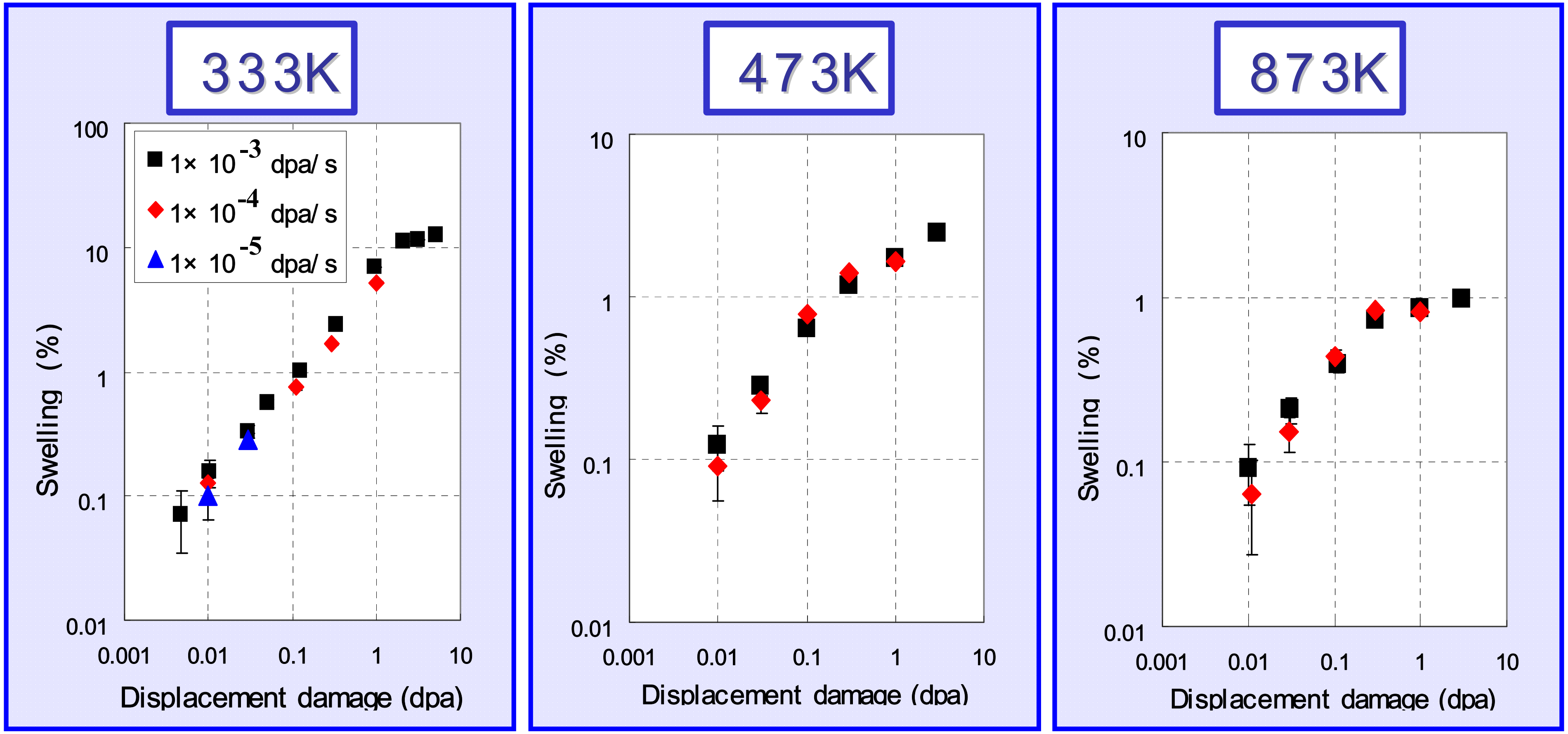
Dose dependence of radiation swelling in SiC



Temperature dependence of Ion-induced swelling in CVD-SiC

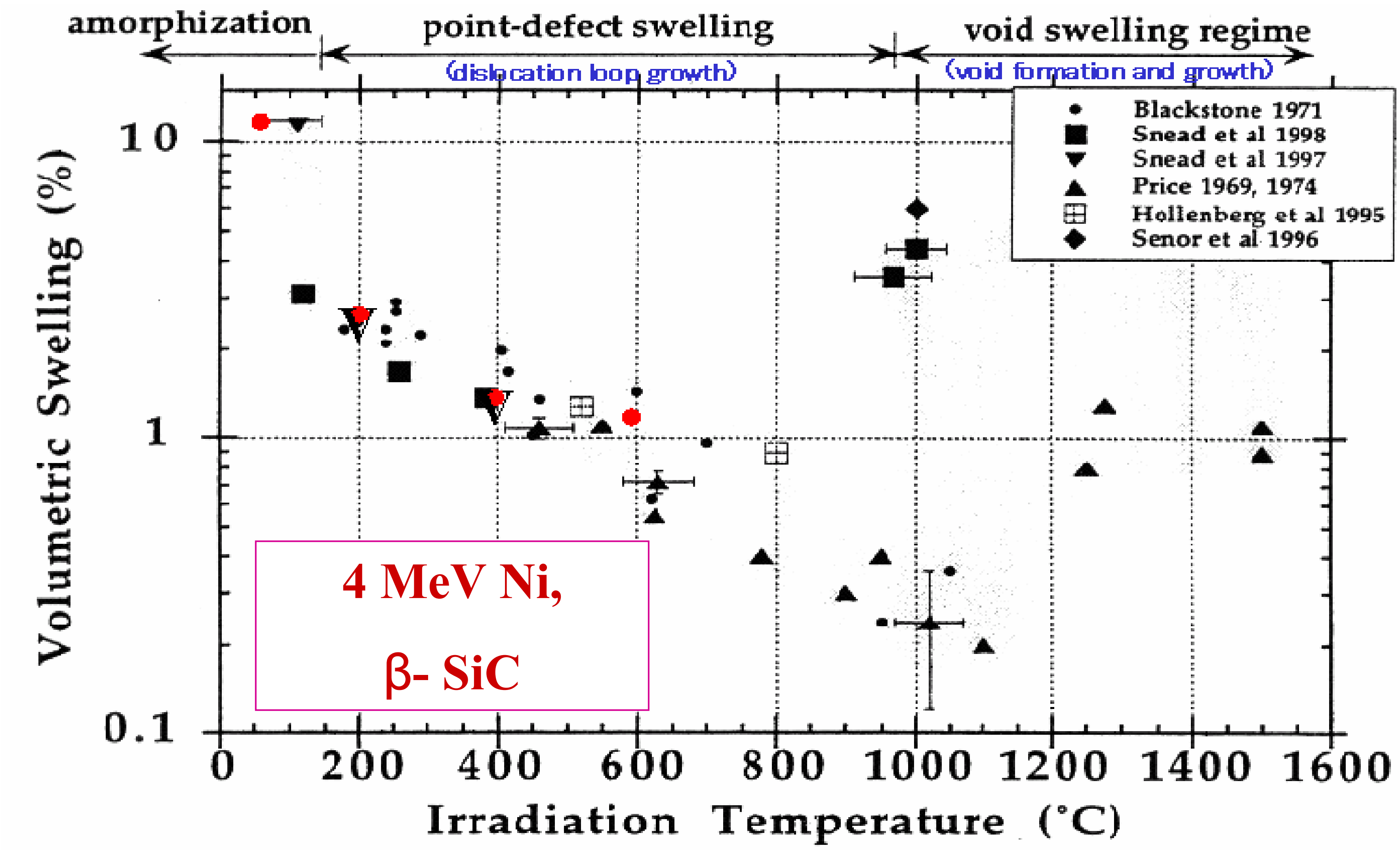


Dose rate dependence of Ion-induced swelling in CVD-SiC



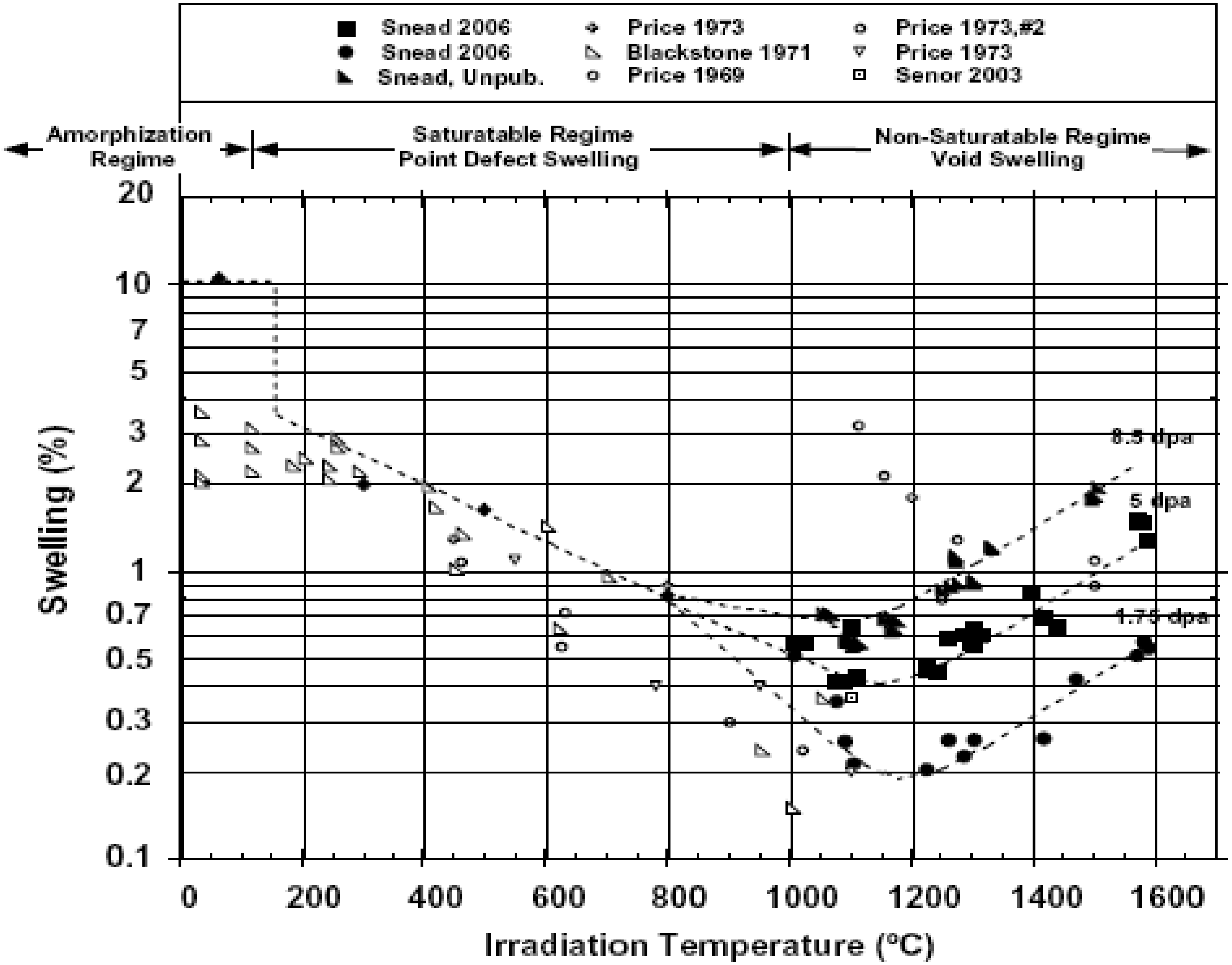
The displacement damage rates were 1× 10^{-4} and 1× 10^{-3} dpa/s at 333K-873K and 1× 10^{-5} dpa/s at 333K with single-beam irradiation. The error bars represent the 96% confidence limits for the Gaussian distribution.

Temperature dependence of swelling of SiC



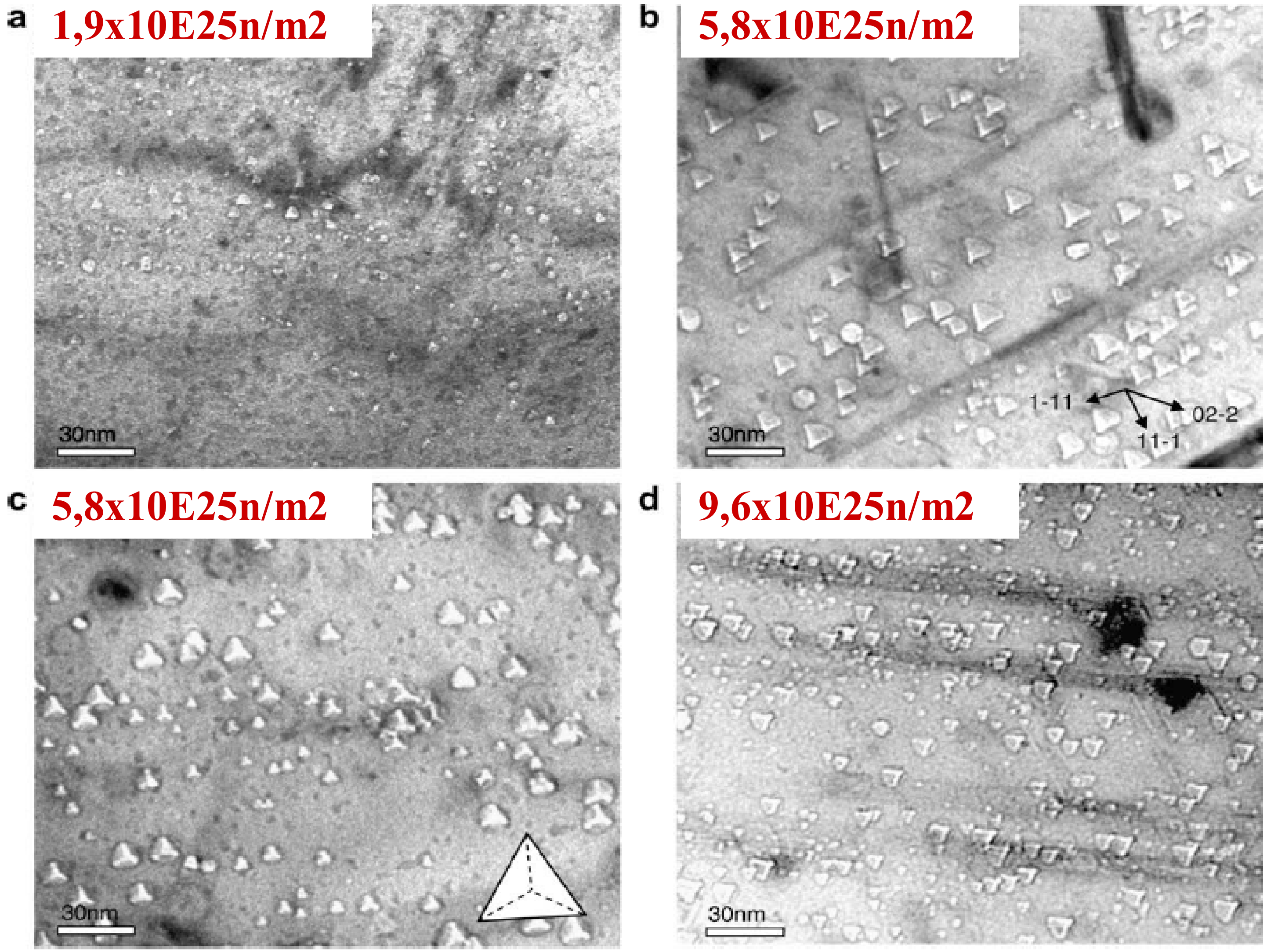
S.J.Zinkle and L.L.Snead, DOE/ER-0313/24 (1998) 93-114.

Temperature dependence of irradiation-induced swelling of SiC



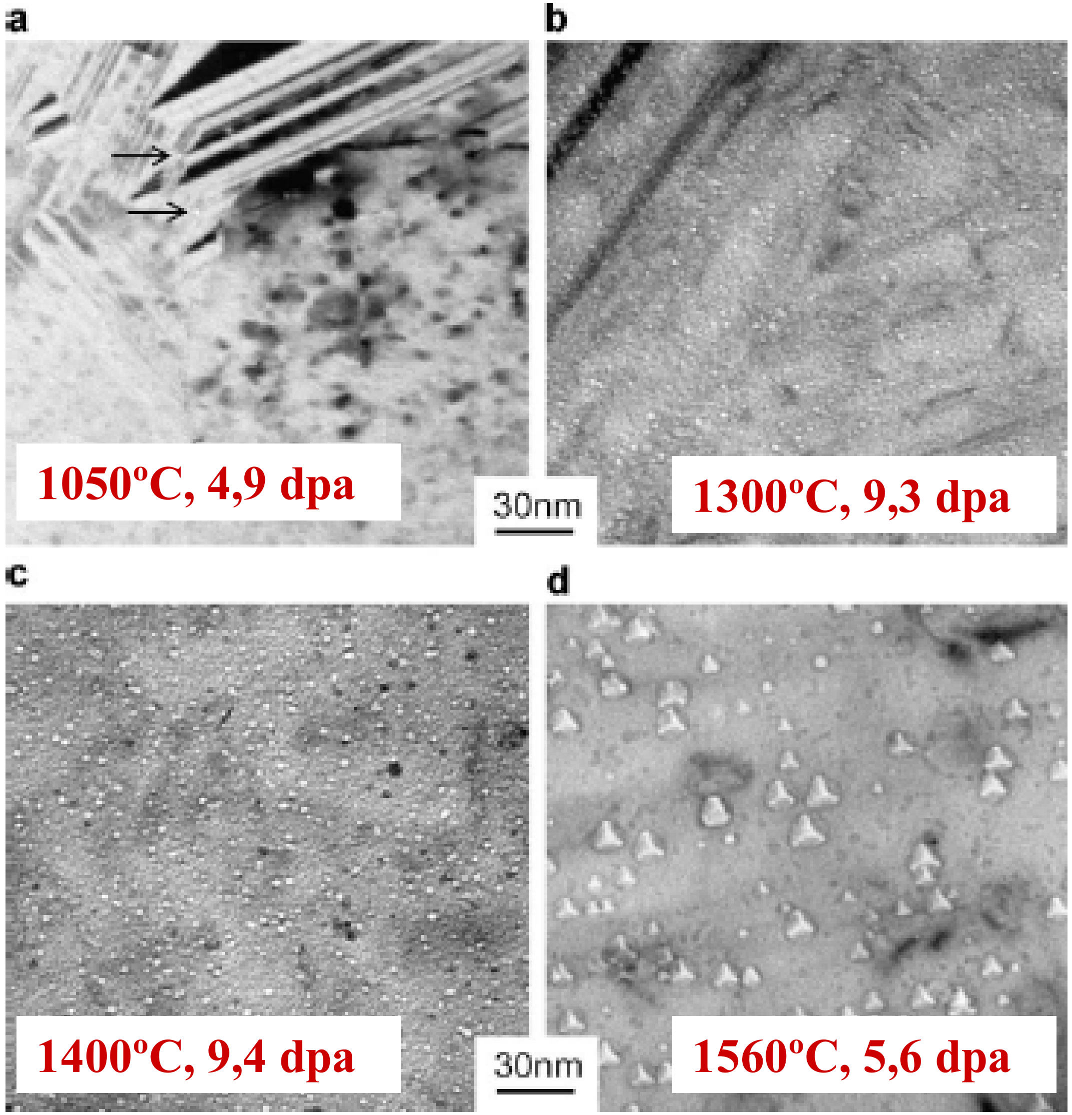
L. Snead, ORNL (2007)

Microstructure of irradiated SiC at different neutron doses: (1,9 - 9,6)x10E25n/cm2 at the temperature 1460^{o}C



S. Kondo, JNM, 2008

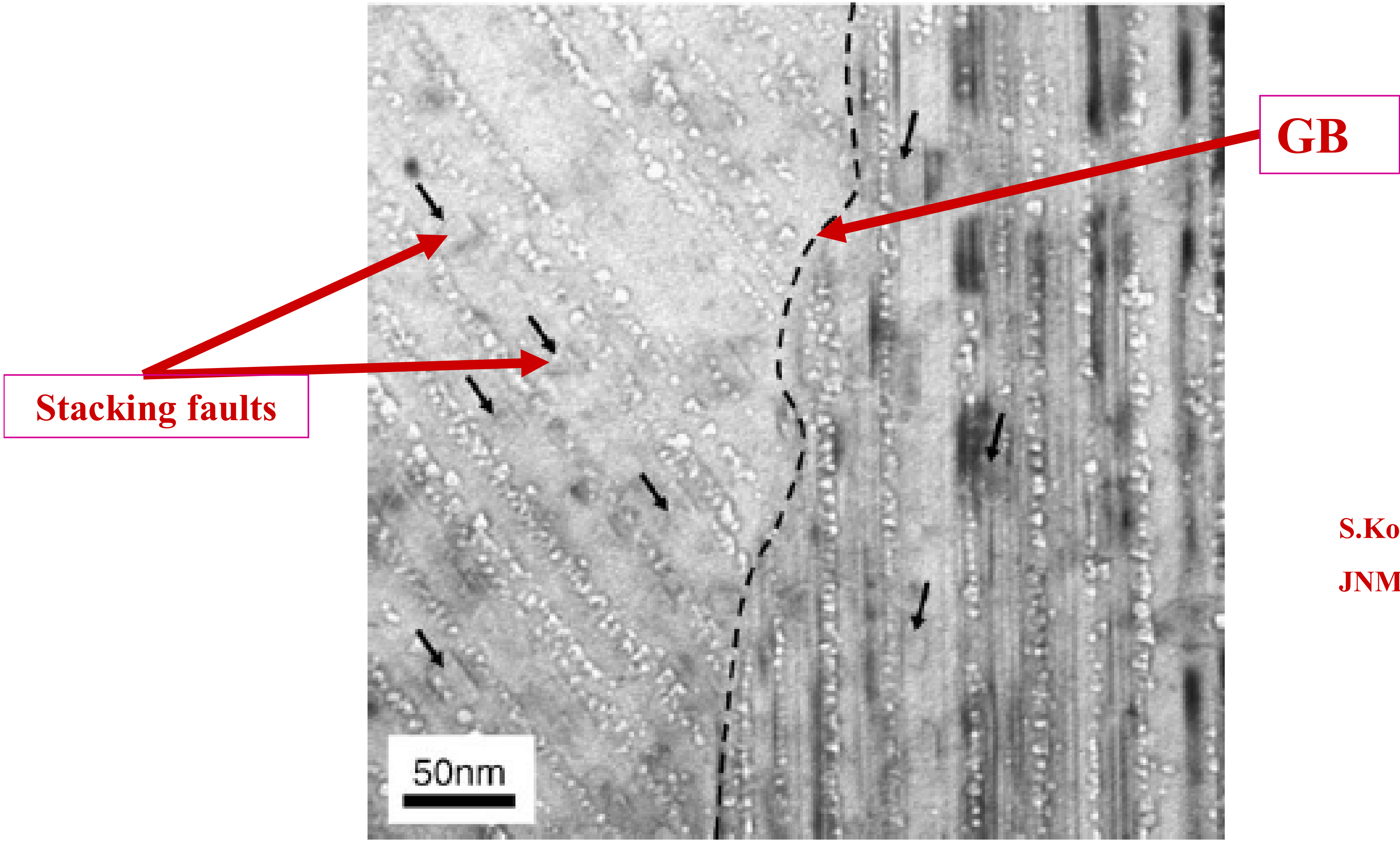
Microstructure of irradiated SiC at temperatures 1050°C - 1460°C



S. Kondo,

JNM, 2009

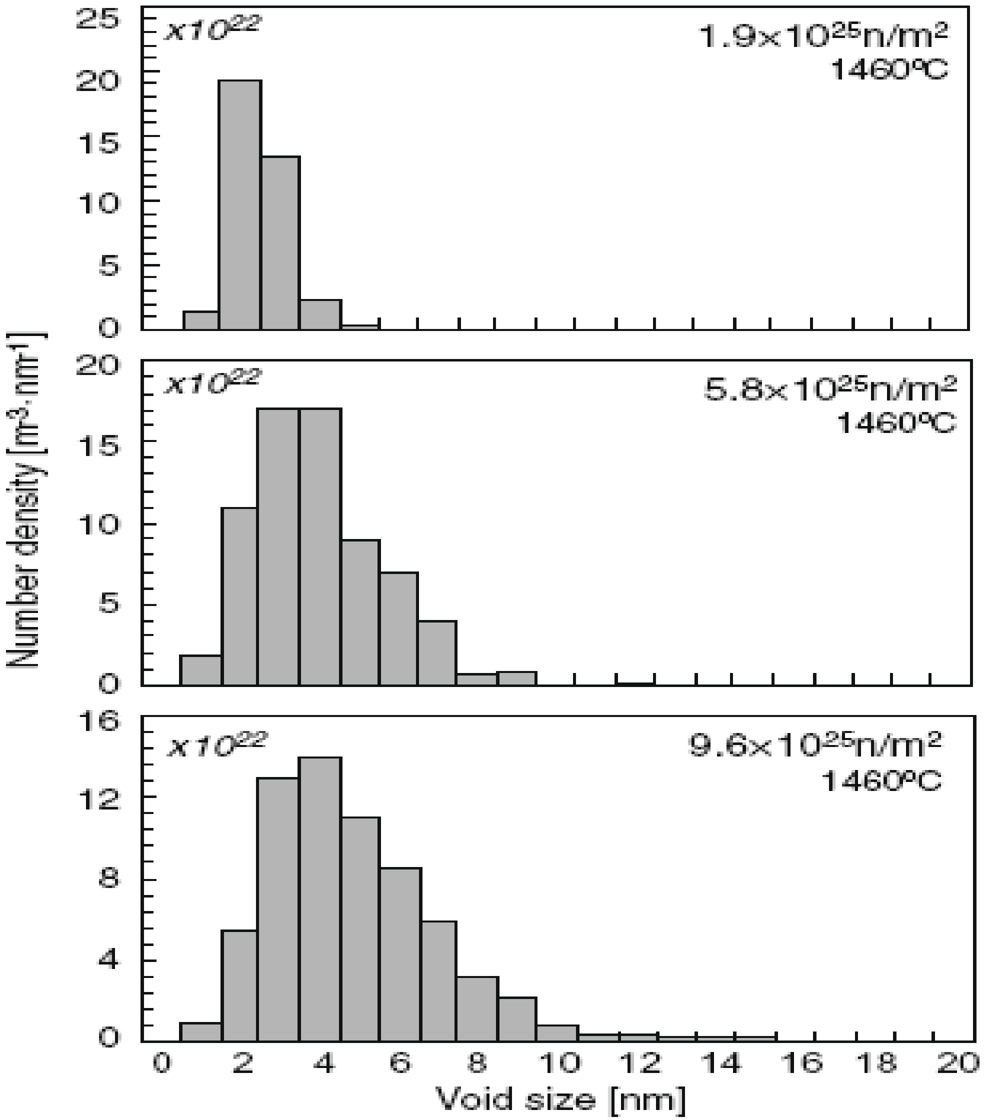
Preferential nucleation of faced voids in neutron irradiated β-SiC at 1460ºC temperature



S.Kondo,

JNM, 2008

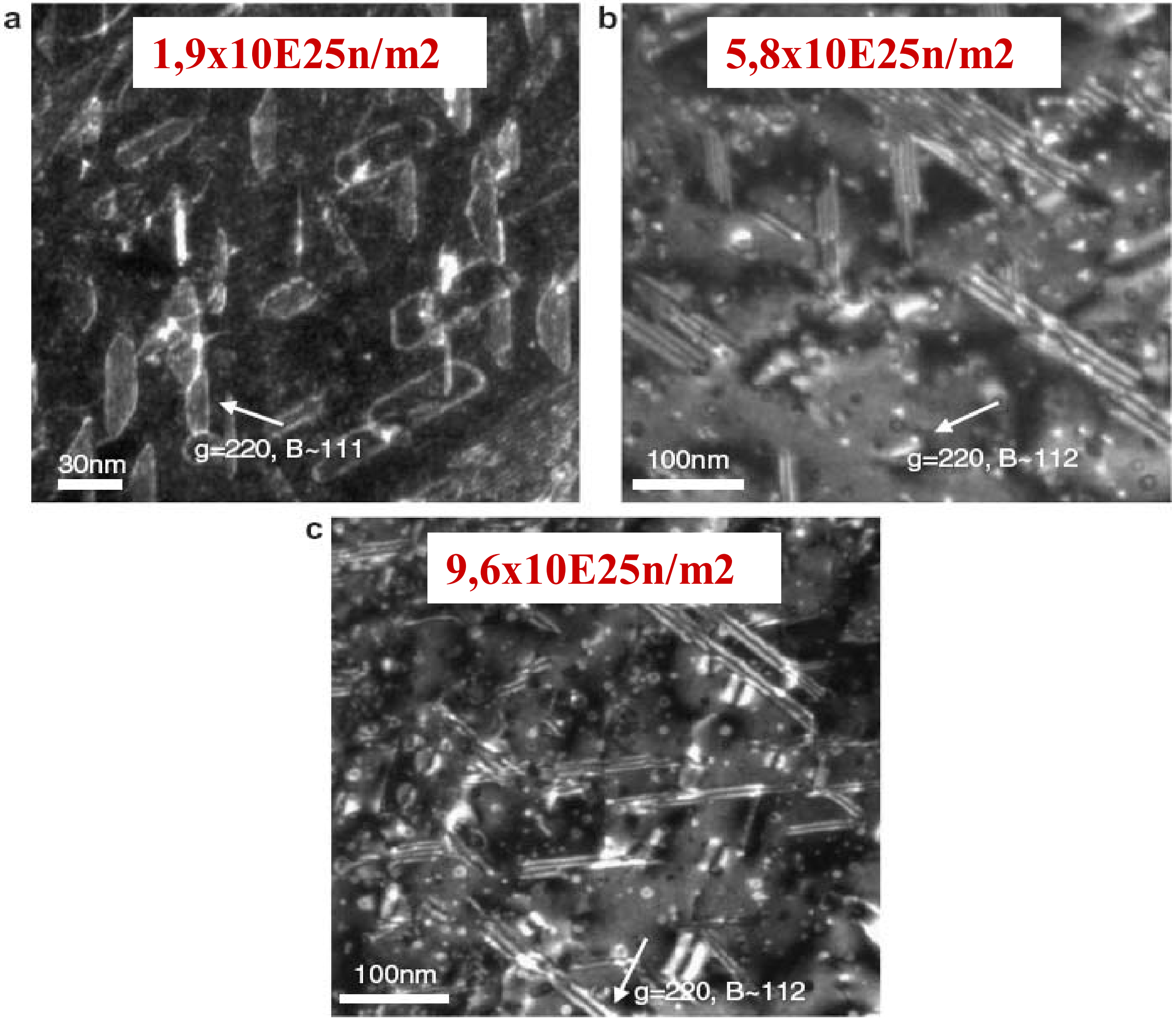
Size distribution of faceted voids in neutron irradiated β-SiC at 1460ºC temperature



S.Kondo,

JNM, 2008

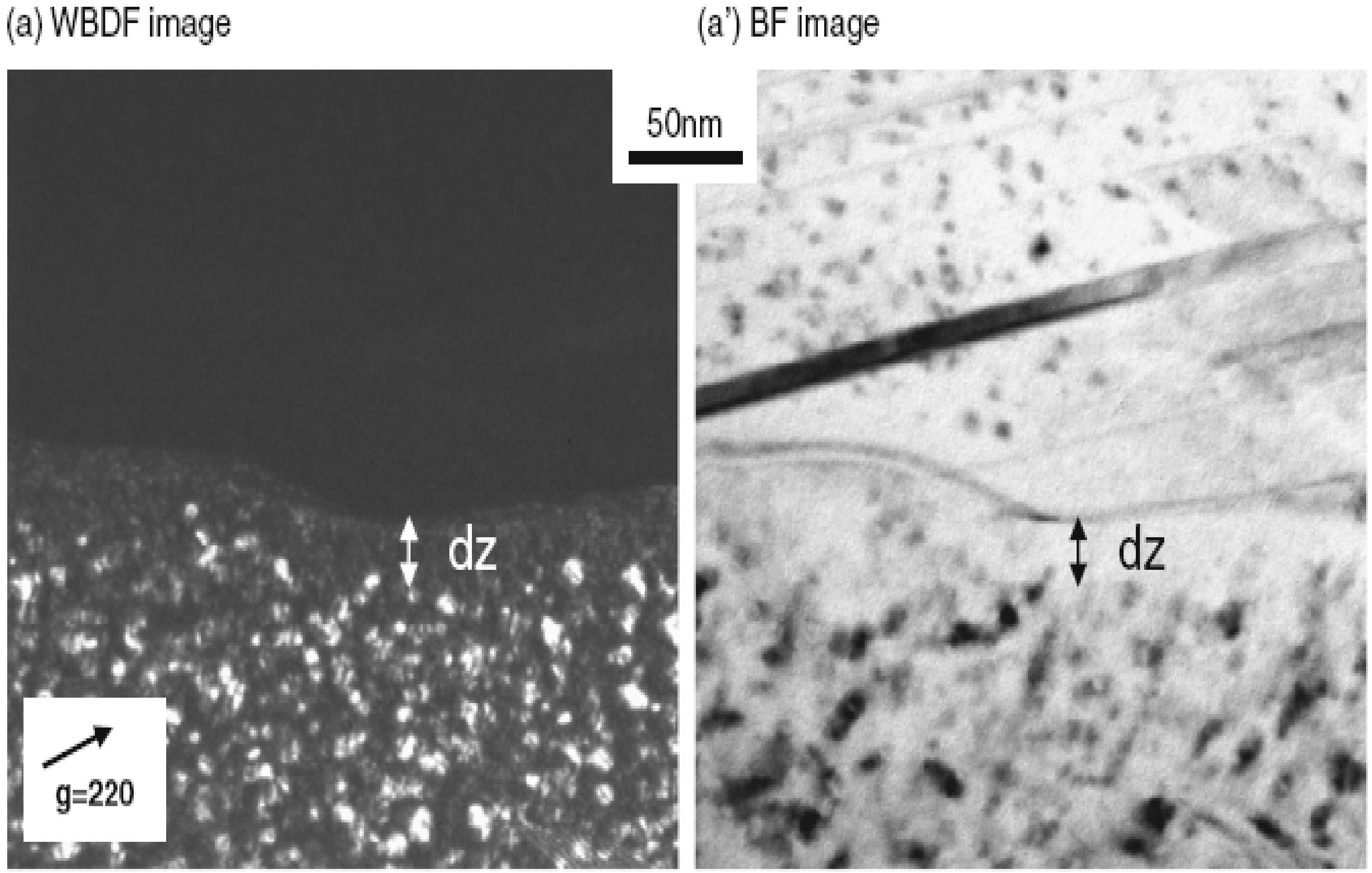
Weak beam dark field images of Frank loops in neutron irradiated β-SiC at 1460ºC temperature



S.Kondo,

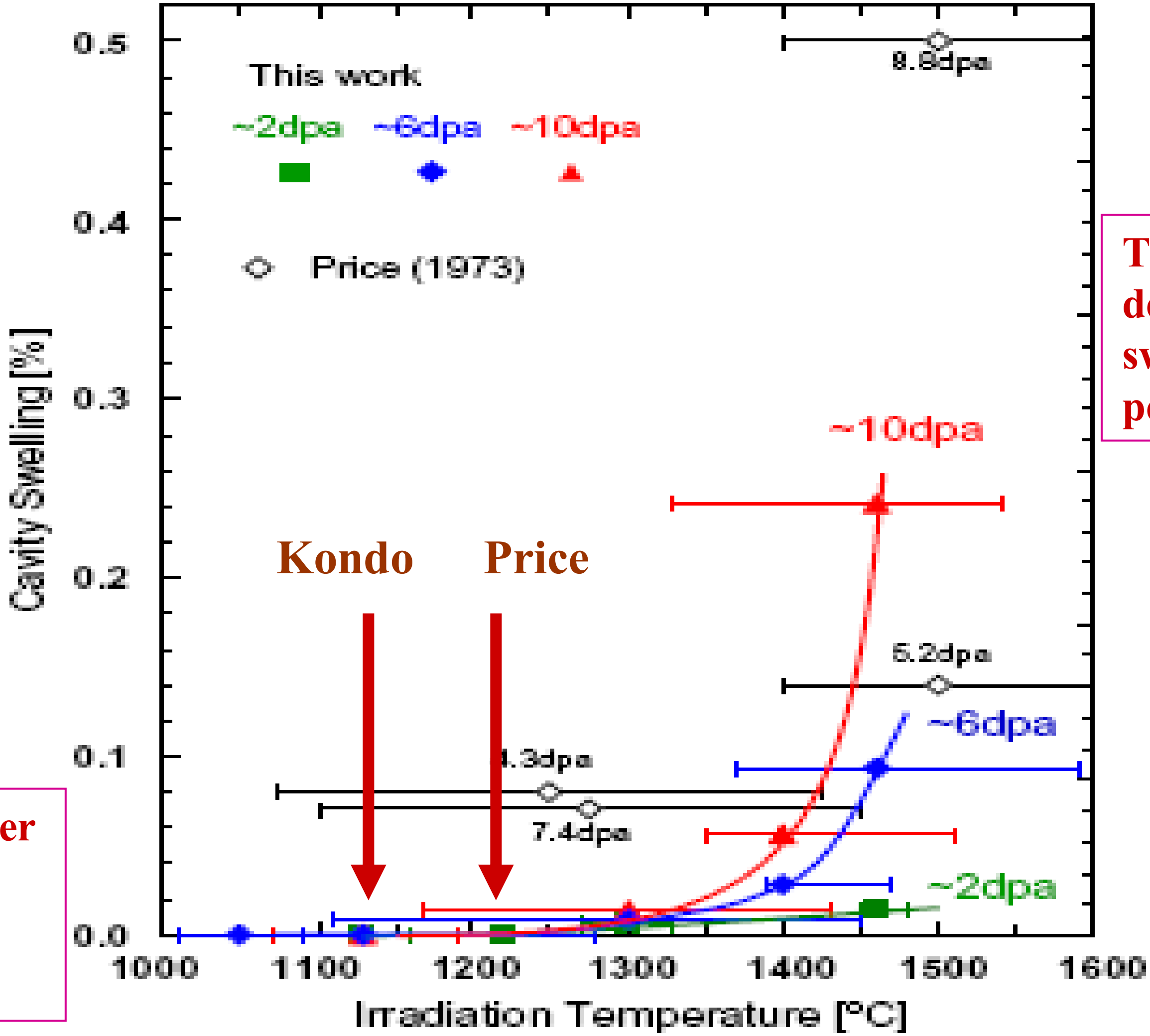
JNM, 2008

Denuded zone (dz) formation for dislocation loops along grain boundary in neutron irradiated (1,5x10E25n/m2) β-SiC at 1130ºC temperature



S.Kondo, JNM, 2008

Radiation cavity swelling in β-SiC at high temperatures

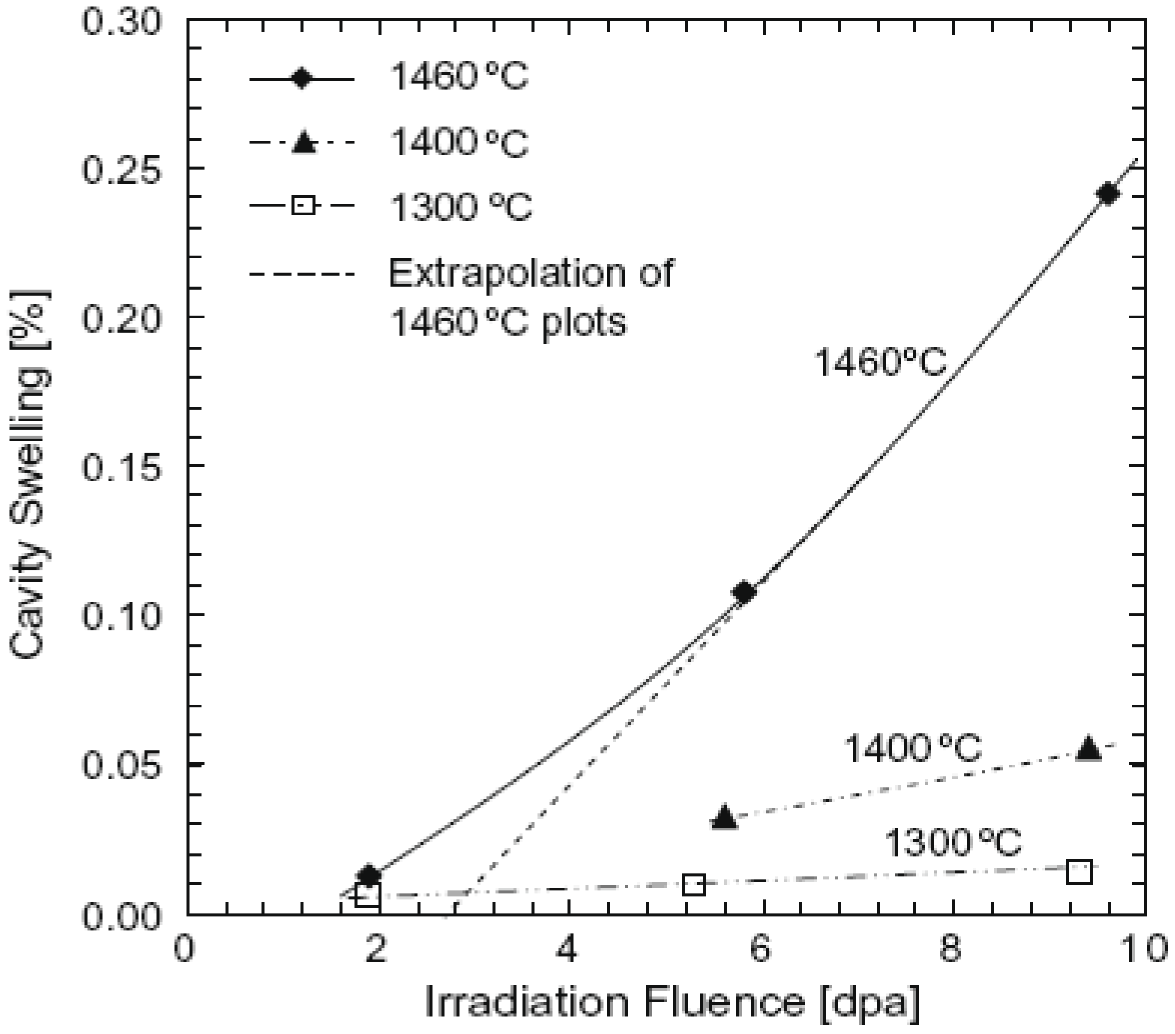


Temperature dependence of swelling without a peak

S. Kondo (2009)

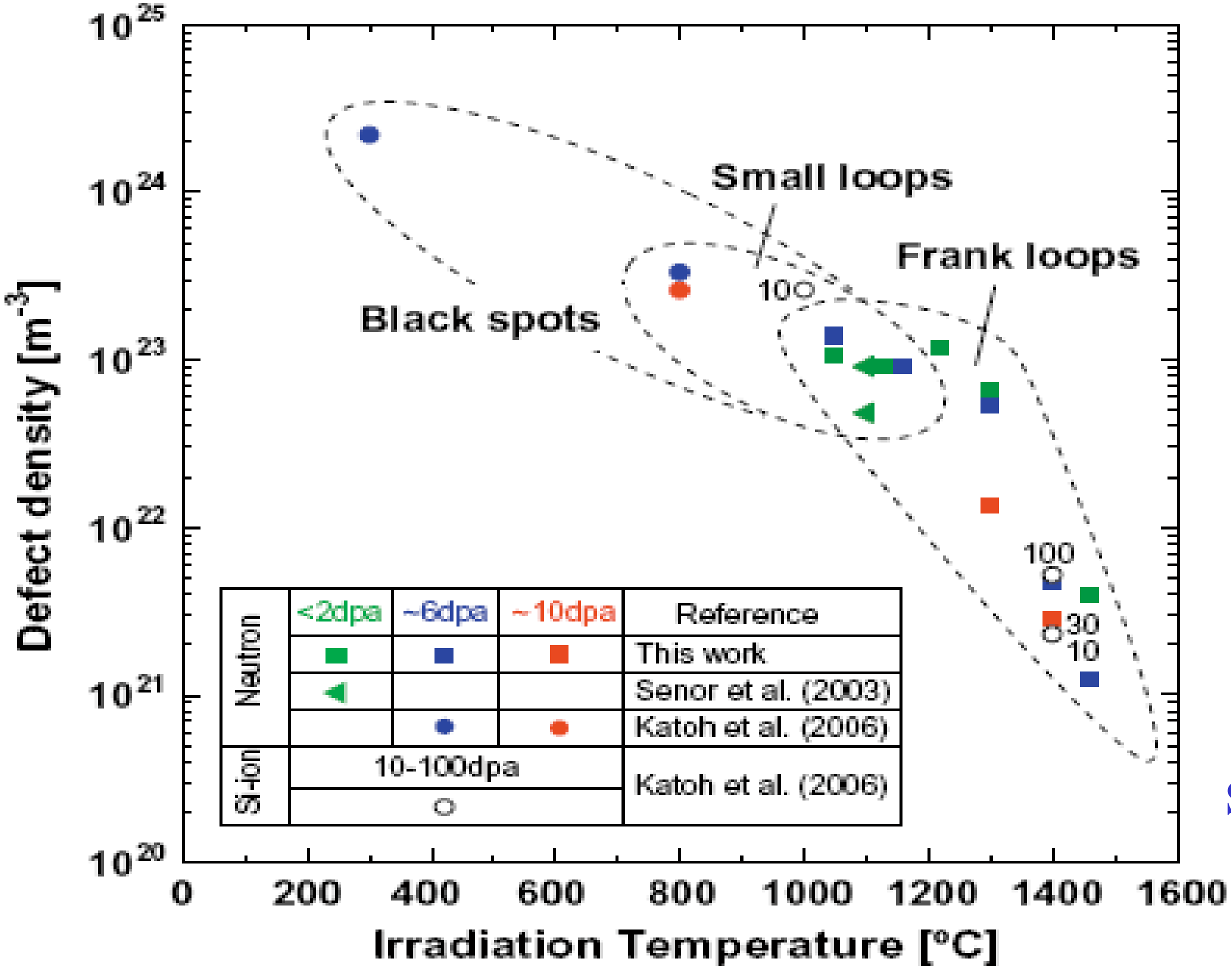
Void swelling is lower than macroscopic density swelling by factor of ~10

Irradiation fluence dependence of cavity swelling in neutron irradiated β-SiC at three temperatures



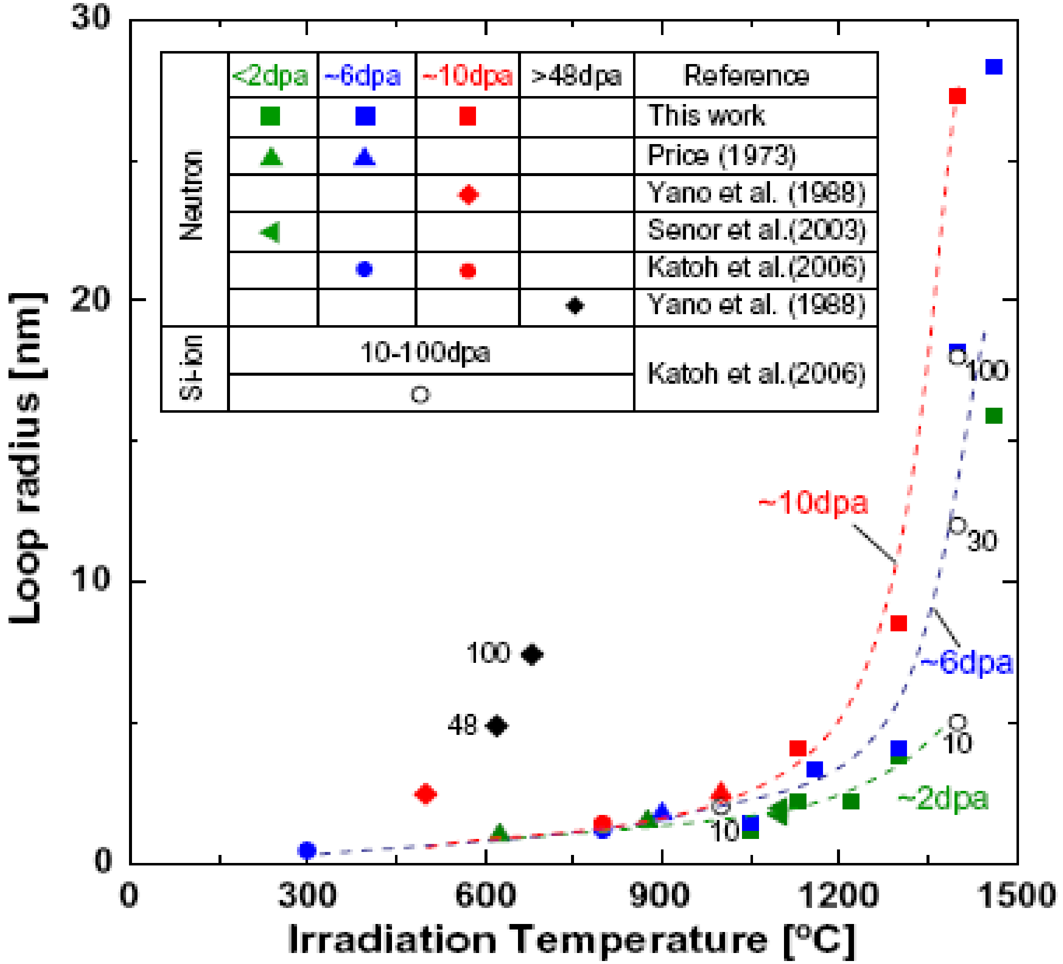
S. Kondo (2009)

Irradiation temperature dependence of defect number density in neutron and ion irradiated β-SiC



S. Kondo (2009)

Irradiation temperature dependence of loop radius size in neutron and ion irradiated β-SiC



S. Kondo (2009)

Difference between metals and dielectrics

Metals:

- Point defects are neutral
- Electric field does not exist in the matrix

Dielectrics (Ceramic Materials):

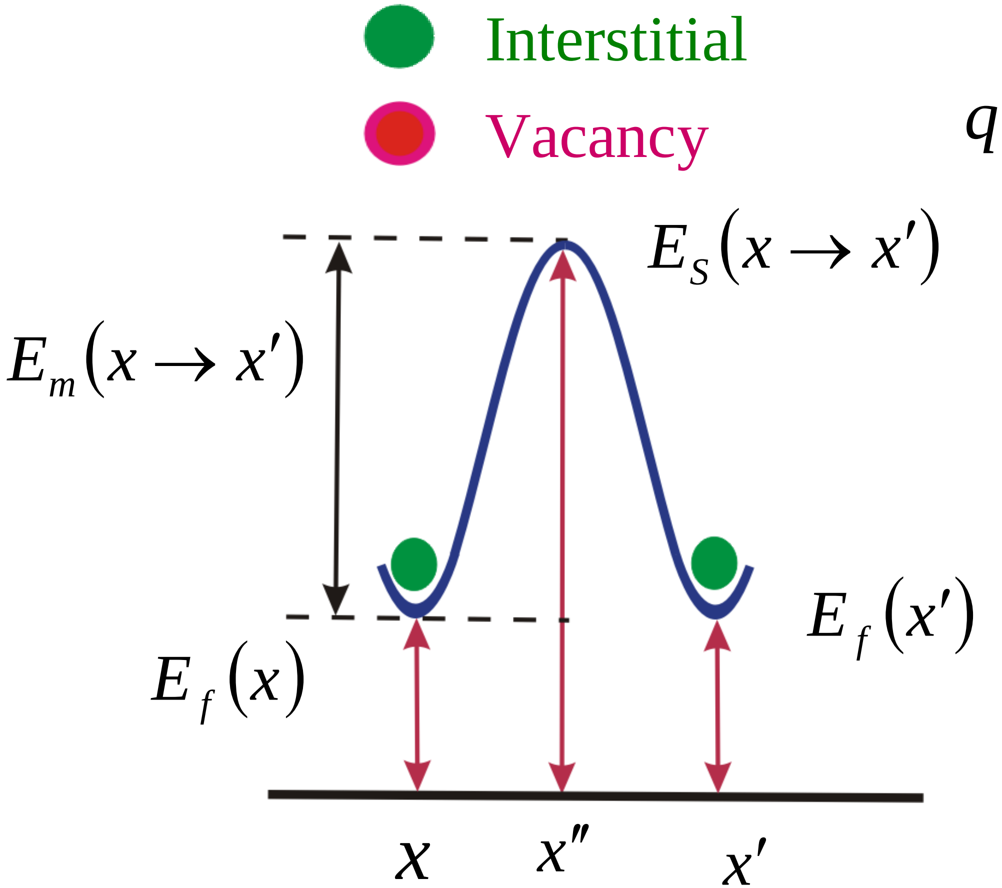
- Point defects can have effective charge
- Electric field exists in the matrix under the influence of an applied electric field
- Driving force due to an electric field can have a strong effect on diffusivity of charged point defects

Development of theoretical models for the calculations of radiation swelling in SiC materials.

Physical Processes:

- Generation of Point Defects
- Recombination of Point Defects
- Nucleation of Dislocation Loop
- Growth of Dislocation Loops
- Radiation Swelling

Metals $(\mathbf{E}_0 = 0)$



$$q_I = q_V = 0$$

$$W_\alpha(x \to x') \sim e^{-\frac{E_S(x \to x') - E_f(x)}{kT}},$$

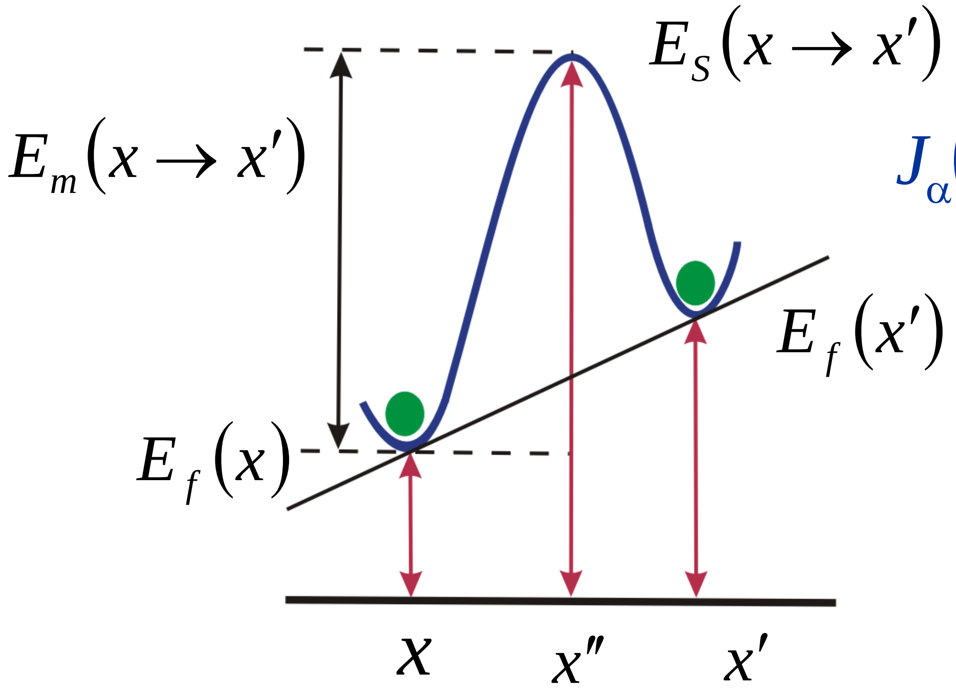
$$(\alpha = I, V)$$

$$J_\alpha(x) = C_\alpha(x) W_\alpha(x \to x') - C_\alpha(x') W_\alpha(x' \to x)$$

$$\mathbf{J}_\alpha = -D_\alpha \nabla C_\alpha, \quad (\alpha = I, V)$$

Dielectrics $(\mathbf{E}_0 \neq 0)$

Interstitial q_I Vacancy q_V



$$J_\alpha(x) = C_\alpha(x) W_\alpha(x \to x') - C_\alpha(x') W_\alpha(x' \to x)$$

$$W_\alpha(x \to x') \sim e^{-\frac{E_S(x \to x') - E_f(x)}{kT}},$$

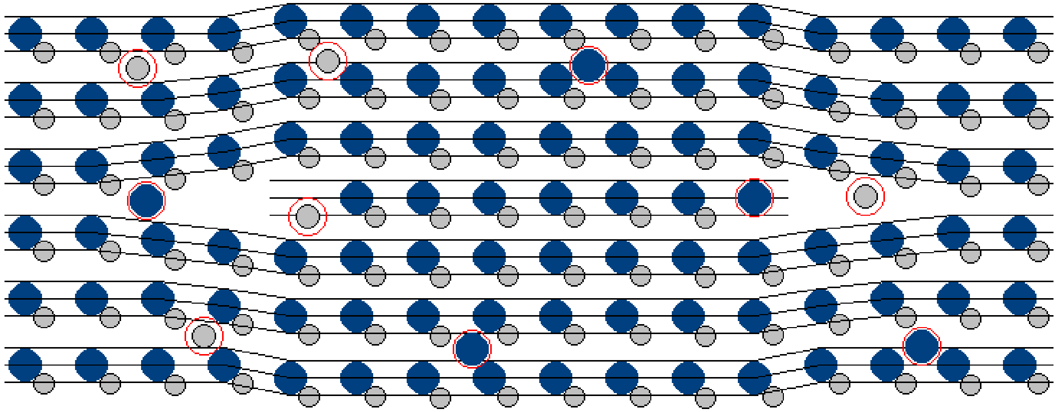
$$(\alpha = I, V)$$

$$E_{S\alpha}(x \to x') = E^0_{S\alpha} + q_\alpha \varphi(x) + q_\alpha (\mathbf{x}'' - \mathbf{x}) \nabla \varphi(x)$$

$$E_{f\alpha}(x) = E^0_{f\alpha} + q_\alpha \varphi(x)$$

$$\mathbf{J}_\alpha = -D_\alpha \nabla C_\alpha - \frac{q_\alpha}{kT} D_\alpha C_\alpha \nabla \varphi, \quad (\alpha = I, V)$$

Dislocation Loop in Dielectrics



System of Equations

$$D_m \Delta C_m + \frac{q\nu_m}{kT} D_m \nabla\left(C_m \nabla\varphi\right) = 0$$

$$\Delta\varphi = -\frac{4\pi}{\varepsilon\omega}\left(\sum_m q\nu_m C_m + \rho\right)$$

Boundary Conditions

$$C_m\big|_S = 0 \qquad C_m\left(r \to \infty\right) = C_{m0}$$

$$\varphi\left(r \to \infty\right) = 0 \qquad \sum_m \left(q\nu_m \mathbf{j}_m, \mathbf{n}\right)\Big|_S = 0$$

Theoretical model of radiation swelling in SiC

Radiation swelling (S_{tot}) is determined in ceramic materials by the following relation

$$S_{tot} = \sum_{K=1}^{2} C_{IK} e_{IK} + \sum_{K=1}^{2} C_{VK} e_{VK} + \omega \sum_{S,K} (n_{IK}^{S} e_{IK} + n_{VK}^{S} e_{VK})$$

e_{α} **is the dilatation of point defect type α (α = I for interstitial atoms, α = V for vacancies and α = He for helium atoms), ω is the atomic volume, $n_{\alpha k}^{S}$ is the total number of point defects of the type α absorbed by sinks of the type *s* (loops, voids) in an unit volume,**

$C_{\alpha k}$ **is the concentration of point defects for the two components: k=1=Si , k=2=C in SiC**

$$\frac{dC_{VK}}{dt} = G_{VK} - j_{VK}(\rho_D + \rho_L) - \alpha D_{IK} C_{IK} C_{VK}$$

$$\frac{dC_{IK}}{dt} = G_{IK} - j_{IK}(\rho_D + \rho_L) - \alpha D_{IK} C_{IK} C_{VK} - \mu\left(D_{I1} + D_{I2}\right) C_{I1} C_{I2}$$

G_{VK}, G_{IK} **are the generation rates of vacancies and interstitial atoms *k*-th components,**

D_{IK}, D_{VK} **are the diffusion coefficients of interstitial atoms and vacancies *k*-th component,**

ρ_d **is the dislocation density,** ρ_L **is the dislocation loop density** ($\rho_L = 2\pi R_L N_L$).

The dislocation loop density is determined from the following relation

$$\omega \frac{dN_L}{dt} = \mu \left(D_{I1} + D_{I2} \right) C_{I1} C_{I2}$$

The growth rate of dislocation loop with loop radius *R* in ceramic materials taking into account the absorption of two types of interstitial atoms and vacancies and remaining of stoichiometric of two components in dislocation loop is given by the following relation

$$\frac{dR_L}{dt} = \frac{\pi r_0}{b} \sum_K \left(j_{IK}^n - j_{VK}^n \right) = \frac{4\pi}{b \ln\left(\frac{8R}{r_0}\right)} \frac{D_{I1}C_{I1}D_{I2}C_{I2} - D_{V1}C_{V1}D_{V2}C_{V2}}{D_{I1}C_{I1} + D_{I2}C_{I2} + D_{V1}C_{V1} + D_{V2}C_{V2}}$$

The initial conditions (at t = 0):

$$C_{IK}(t=0) = 0 \qquad C_{VK}(t=0) = 0 \qquad R_L(t=0) = a$$

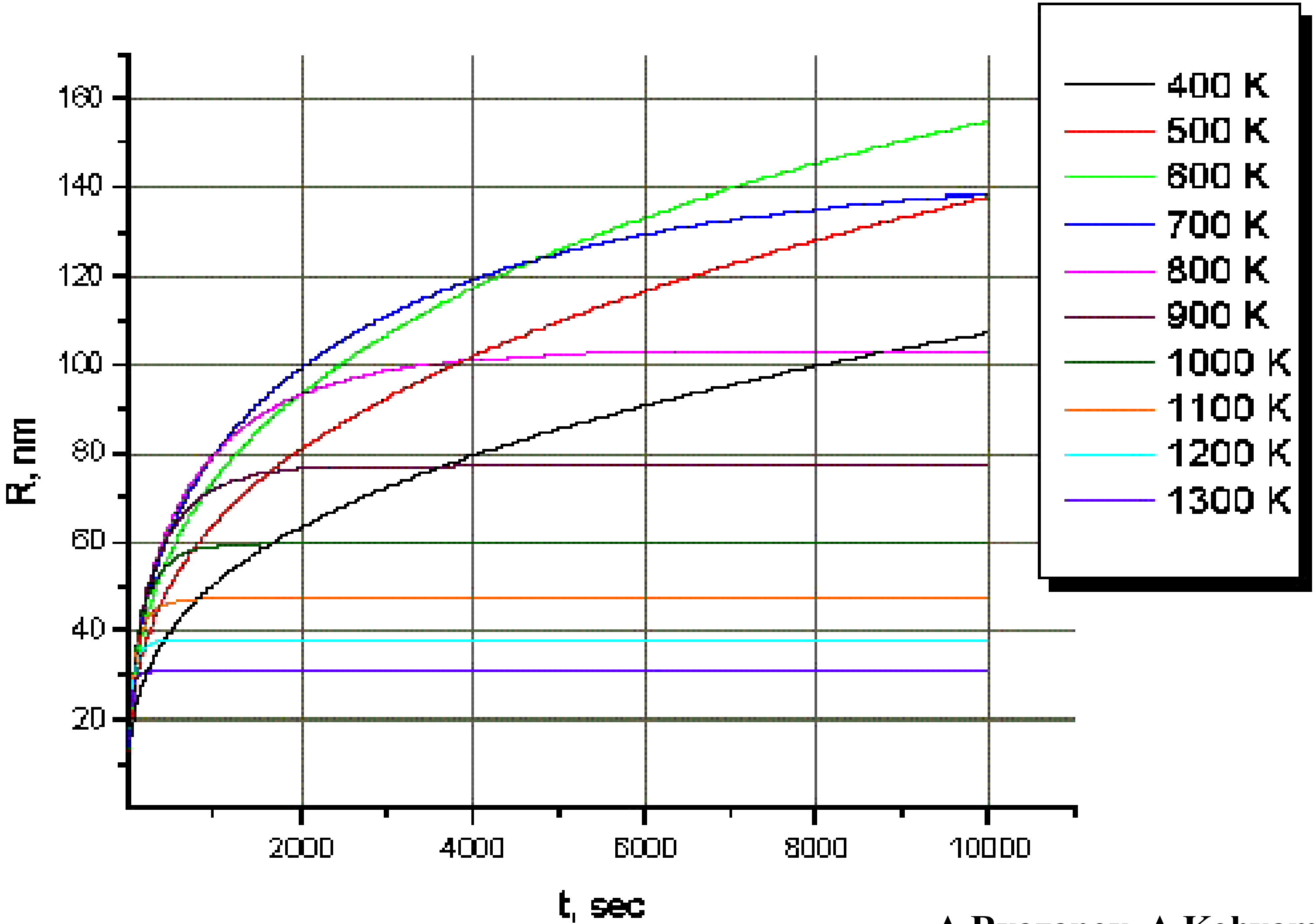
Main parameter values used for numerical calculations of radiation swelling in SiC

$G_1 = G_{Si}$	Point defect generation rate of Si atoms	3.10^{-3} dpa/s
$G_2 - G_C$	Point defect generation rate of C atoms	1.10^{-3} dpa/s
E_{mV}^{Si}	Silicon vacancy migration energy	2.3 eV
E_{mV}^{C}	Carbon vacancy migration energy	2.0 eV
E_{mI}^{Si}	Silicon interstitial migration energy	0.4 eV
E_{mI}^{C}	Carbon interstitial migration energy	0.3 eV
E_{FV}^{Si}	Silicon vacancy formation energy	2.5 eV
E_{FV}^{C}	Carbon vacancy formation energy	2.4 eV
ρ_D	Network dislocation density	10^{10} cm^{-2}
$e_{V1} = e_{V2}$	Vacancy dilatation	-0.1
a	Lattice parameter	5.14×10^{-8} cm

$D_{VK} = D_{VK}^O \exp(-E_{mV}^K / T)$,(where $D_{V1}^O = D_{V2}^O = 10^{-2} cm^{-2}$).

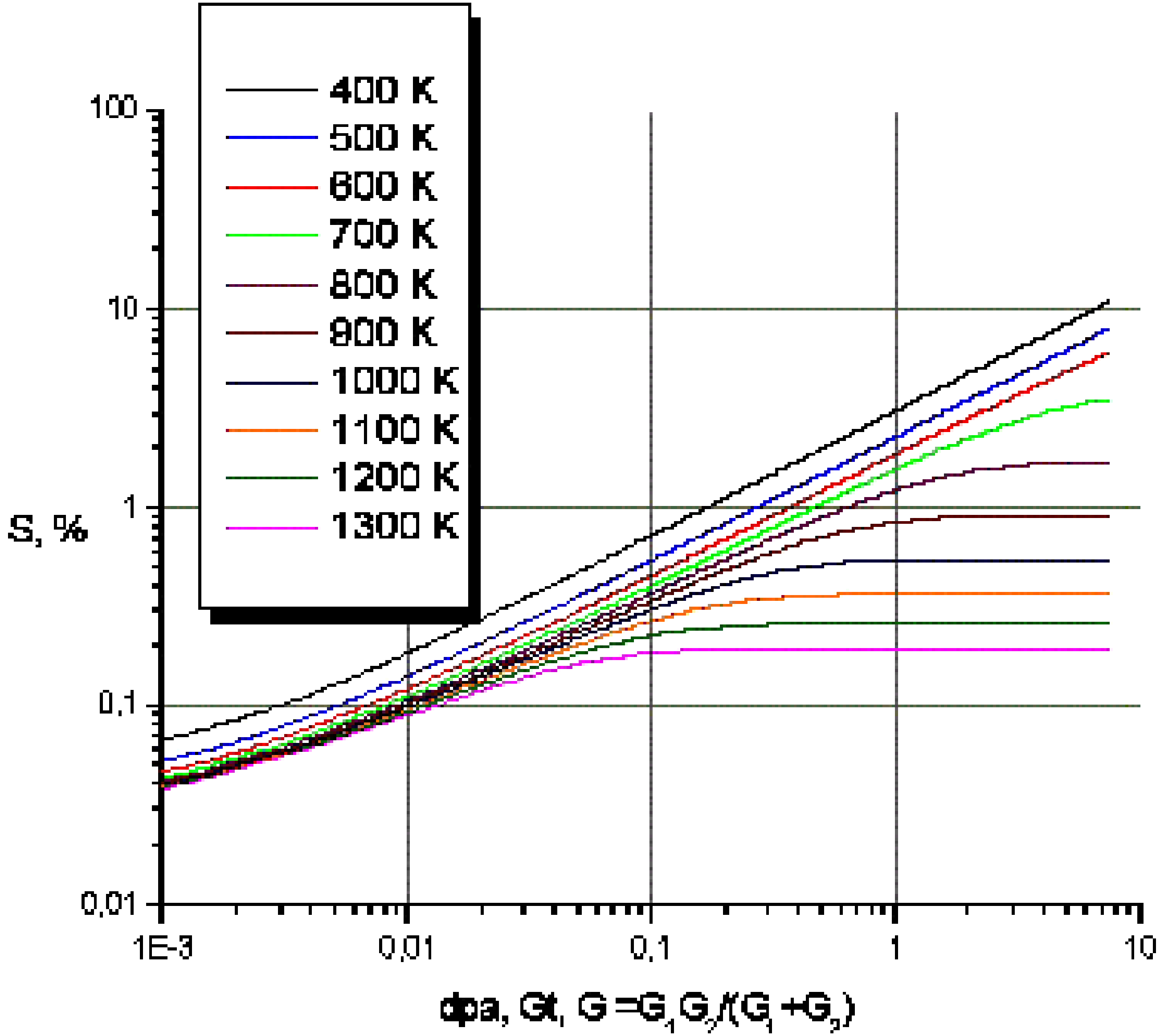
$N_I = N_I^O [\exp(E_{m1}^1 / T) + \exp(E_{mI}^2 / T)]^{1/2}$, (where $N_I^O = 3.10^{12} cm^{-3}$).

The time dependence of dislocation loop growth at different irradiation temperatures



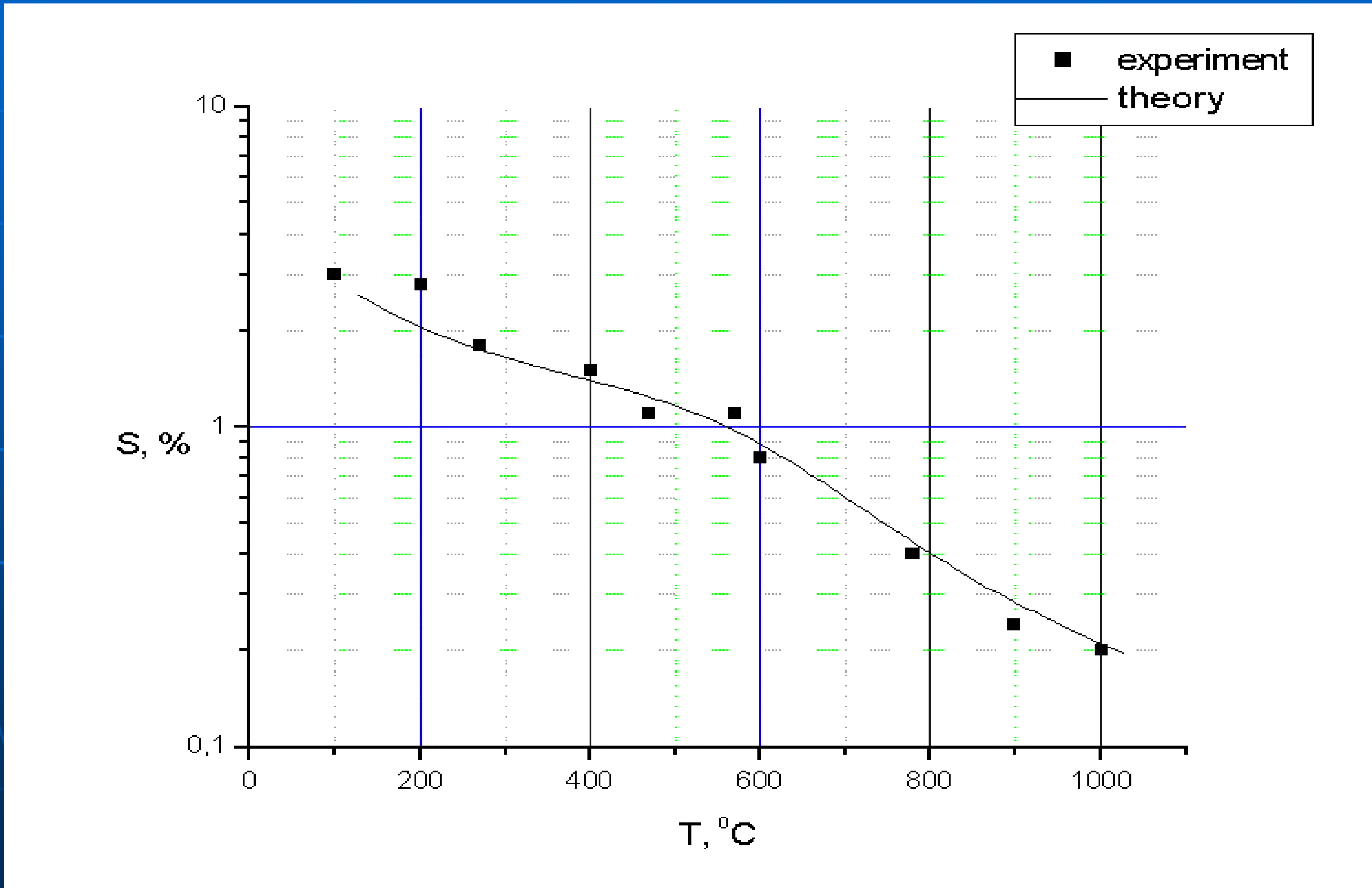
A.Ryazanov, A.Kohyama, 2002

Dose dependence of radiation swelling in SiC at different irradiation temperatures



A.Ryazanov, A.Kohyama, 2002

The comparison of experimental and theoretical temperature dependencies of radiation swelling in SiC.

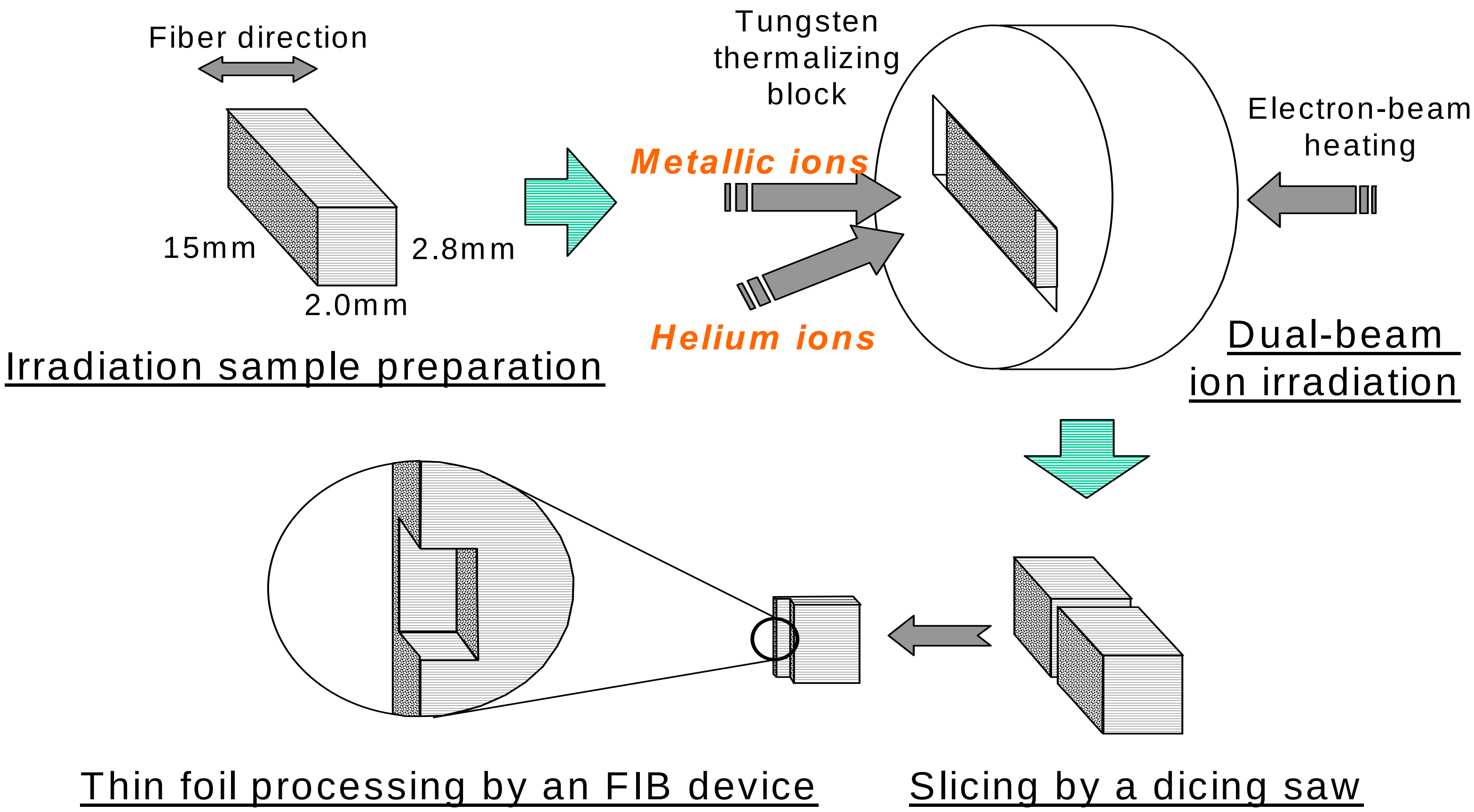


A.Ryazanov, A.Kohyama, 2002

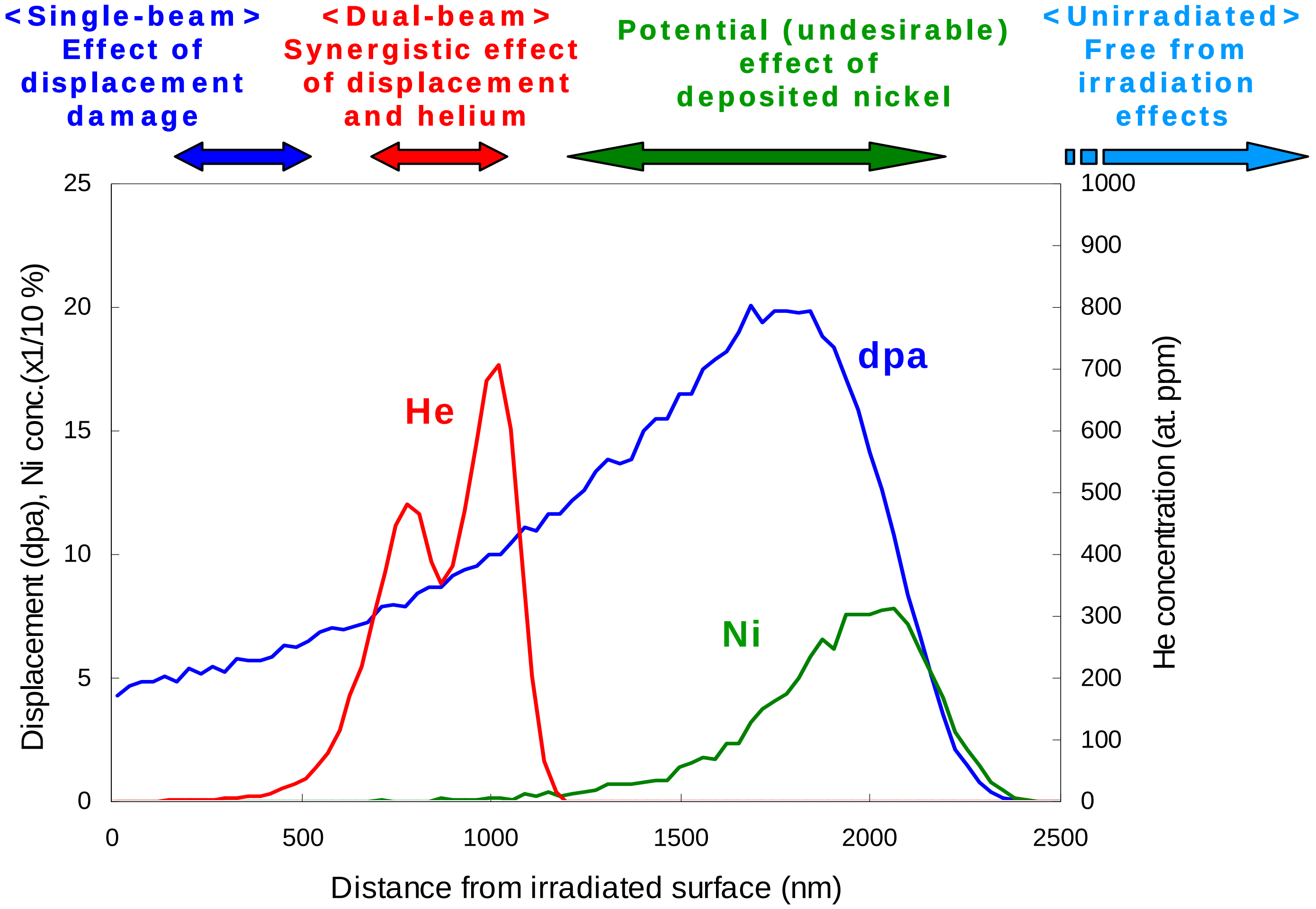
Helium Effect on Radiation Swelling of SiC

Experimental procedure illustrated

Institute of Advanced Energy
Kyoto University



Profiles of displacement damage and deposited Ni in irradiated monolithic SiC. Calculated by TRIM-92 assuming Ed=35eV, ρ=3.21g/cm^3.



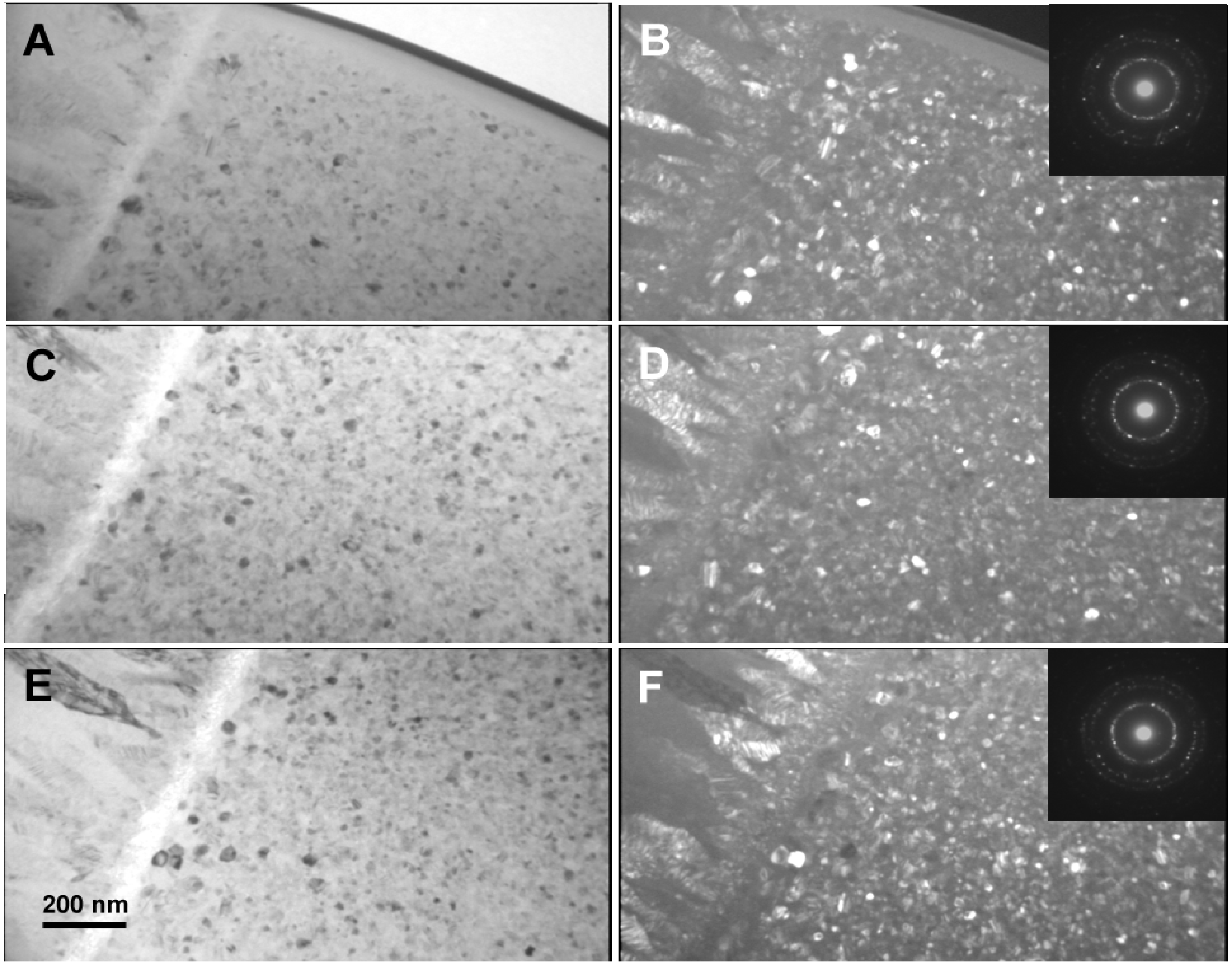
Depth-profiles of atomic displacement damage, deposited He and Ni ions in dual-beam irradiated randomly oriented micro-crystalline SiC calculated by TRIM-92 assuming target mass density of 3.21g/cm^3 and average displacement threshold energy of 35eV.

TEM images and SAD patterns for single-beam (A,B), dual-beam (C,D) and unirradiated (E,F) regions of Hi-Nicalon® Type-S/C/SiC composite

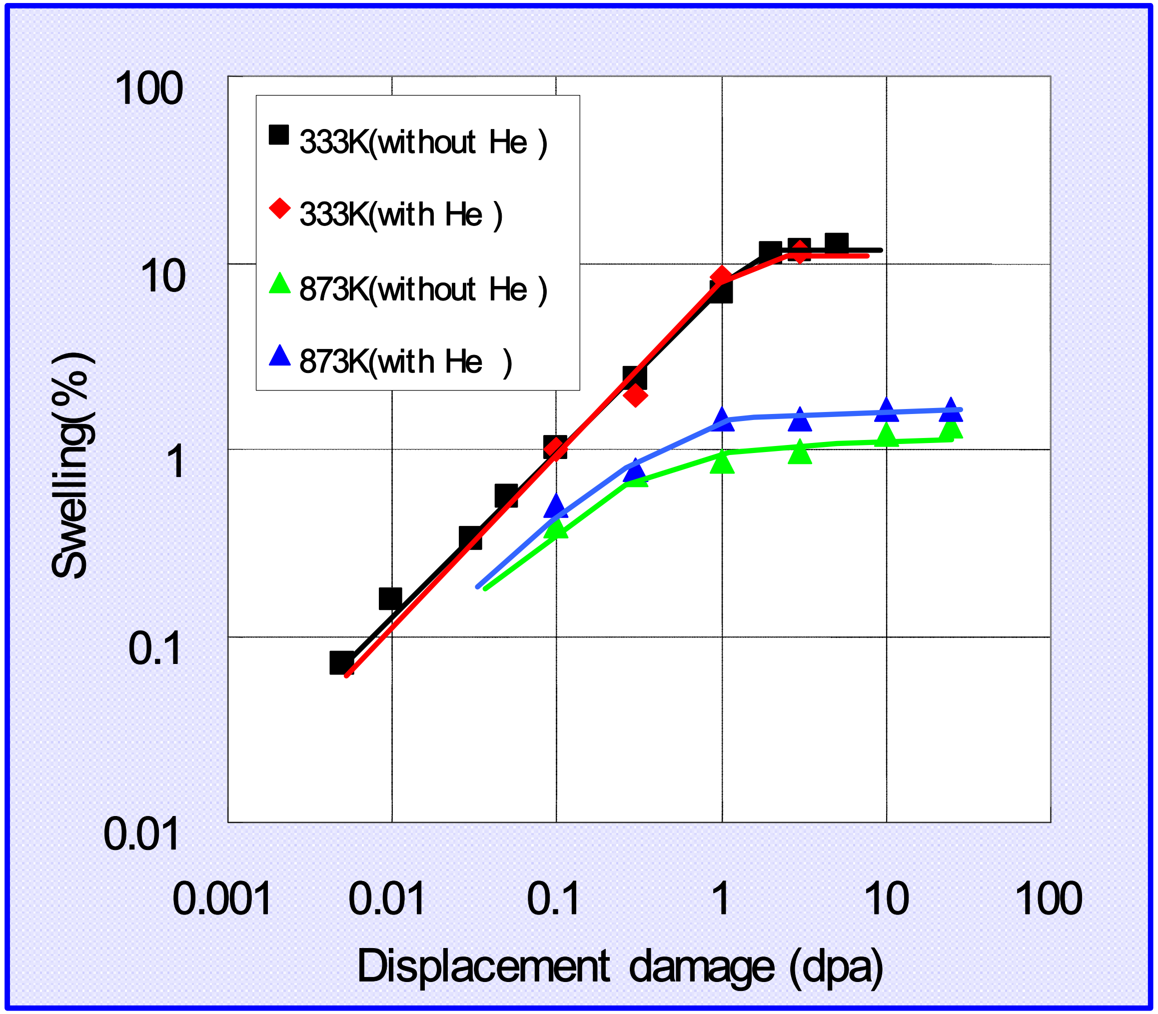
Single-beam
10 dpa
873 K
$1x10^{-3}$dpa/s

Dual-beam
10 dpa
873 K
$1x10^{-3}$dpa/s
60appm-He/dpa

Unirradiated
Dark field images from SiC <111> diffraction rings.

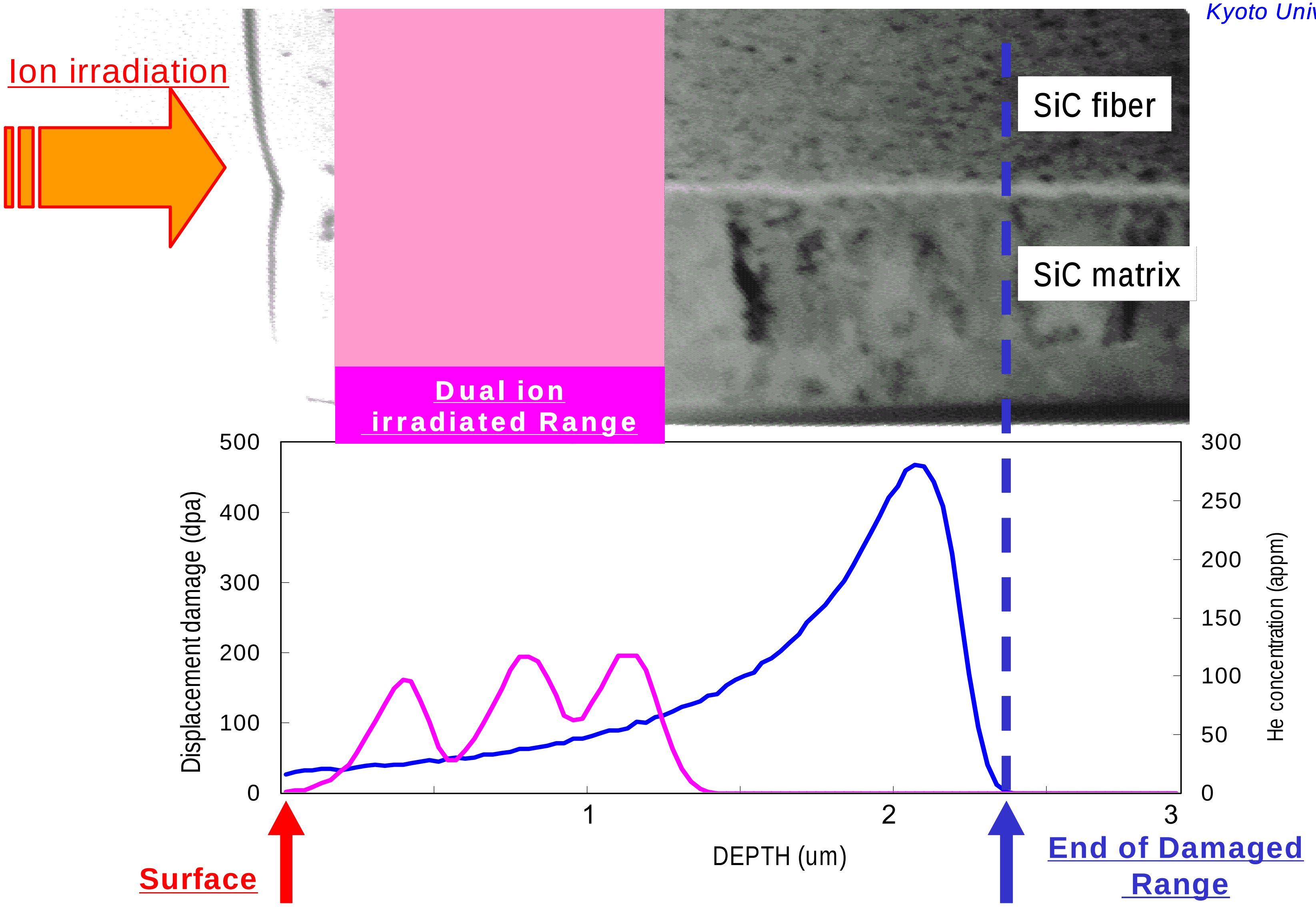


Dual ion beam irradiation-induced swelling in CVD-SiC

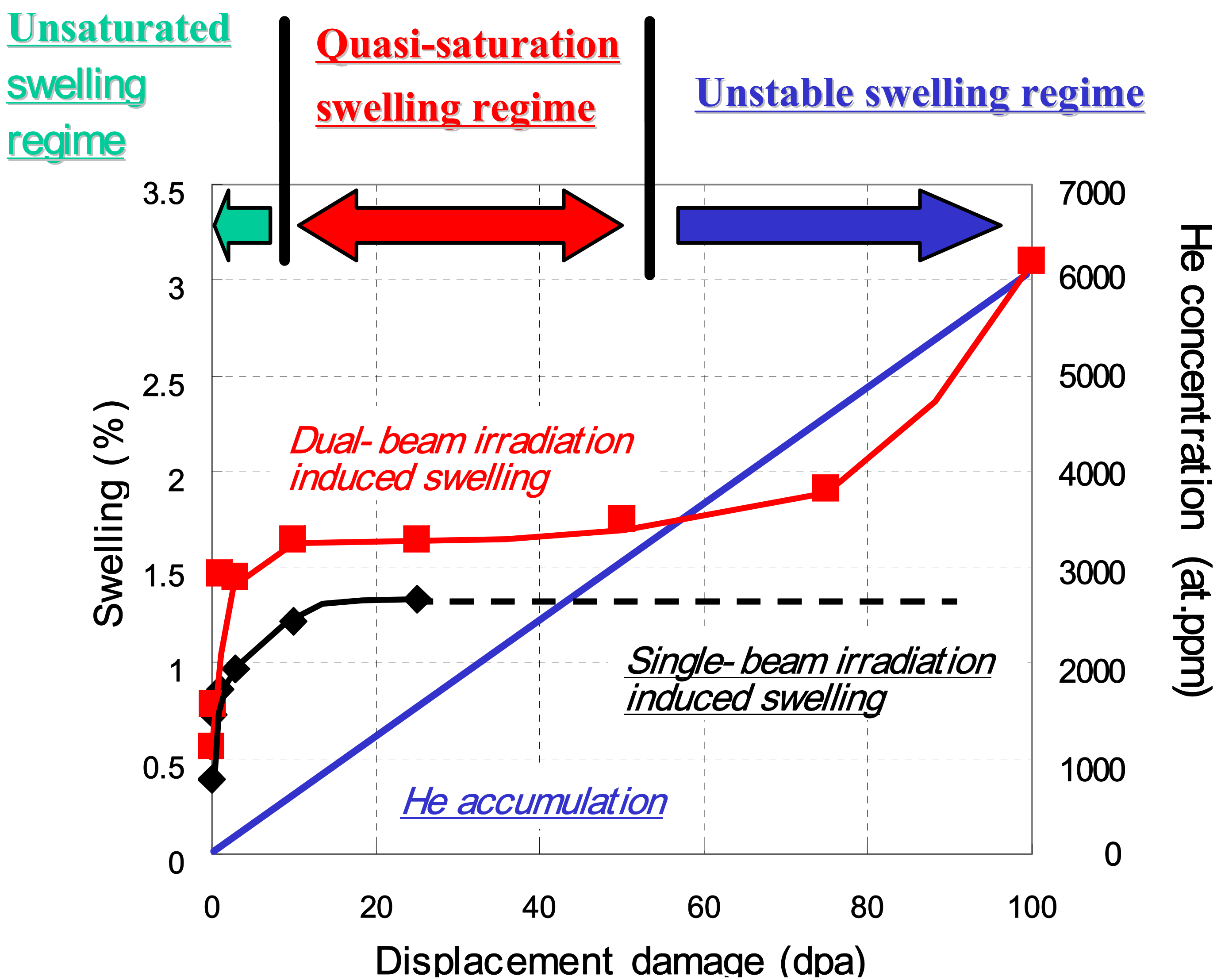


Profiles of irradiation induced displacement damage by 5.1 MeV Si^{2+} ion in SiC. SRIM Calculated by SRIM-98 assuming Ed=35eV, ρ=3.21g/cm^3.

Institute of Advanced Energy
Kyoto University



He accumulation and irradiation-induced swelling in dual- and single-ion irradiated CVD-SiC at 873K



Theoretical model of helium influence on radiation swelling in SiC

Radiation swelling (S_{tot}) is determined in ceramic materials by the following relation

$$S_{tot} = \sum_{K=1}^{2} C_{IK} e_{IK} + \sum_{K=1}^{2} C_{VK} e_{VK} + C_{He} e_{He} + \sum_{K=1}^{2} C_{HeV\,K}\, e_{HeVK} + \omega \sum_{S,K} (n_{IK}^{S} e_{IK} + n_{VK}^{S} e_{VK})$$

e_{α} is the dilatation of point defect type α (α = I for interstitial atoms, α = V for vacancies and α = He for helium atoms), ω is the atomic volume.

$C_{\alpha k}$ is the concentration of point defects for the two components: k=1=Si , k=2=C in SiC

C_{He} is the concentration of helium atoms.

$$\frac{dC_{VK}}{dt} = G_{VK} - j_{VK}(\rho_D + \rho_L) - \alpha D_{IK} C_{IK} C_{VK} - \nu D_{He} C_{He} C_{VK}$$

$$\frac{dC_{IK}}{dt} = G_{IK} - j_{IK}(\rho_D + \rho_L) - \alpha D_{IK} C_{IK} C_{VK} - \mu\left(D_{I1} + D_{I2}\right) C_{I1} C_{I2} - \gamma\left(D_{IK} + D_{He}\right) C_{IK} C_{He}$$

$$\frac{dC_{He}}{dt} = G_{He} - \nu D_{He} C_{He} C_{V1} - \nu D_{He} C_{He} C_{V2} - \gamma\left(D_{I1} + D_{He}\right) C_{I1} C_{He} - \gamma\left(D_{I2} + D_{He}\right) C_{I2} C_{He}$$

G_{VK}, G_{IK}, G_{He} are the generation rates of vacancies, interstitial atoms *k*-th components and helium atoms respectively, D_{IK} D_{VK} are the diffusion coefficients of interstitial atoms and vacancies *k*-th component respectively

$$\omega \frac{dN_L}{dt} = \mu\left(D_{I1} + D_{I2}\right)C_{I1}C_{I2} + \gamma\left(D_{I1} + D_{He}\right)C_{I1}C_{He} + \gamma\left(D_{I2} + D_{He}\right)C_{I2}C_{He}$$

The growth rate of dislocation loop with loop radius *R* in ceramic materials taking into account the absorption of two types of interstitial atoms and vacancies and remaining of stoichiometric of two components in dislocation loop is given by the following relation

$$\frac{dR_L}{dt} = \frac{\pi r_0}{b}\sum_K \left(j_{IK}^n - j_{VK}^n\right) = \frac{4\pi}{b\ln\left(\frac{8R}{r_0}\right)} \frac{D_{I1}C_{I1}D_{I2}C_{I2} - D_{V1}C_{V1}D_{V2}C_{V2}}{D_{I1}C_{I1} + D_{I2}C_{I2} + D_{V1}C_{V1} + D_{V2}C_{V2}}$$

The initial conditions (at t = 0):

$$C_{IK}(t=0) = 0 \qquad C_{VK}(t=0) = 0 \qquad R_L(t=0) = a \qquad C_{He}\left(t=0\right) = 0$$

The concentration of vacancy-helium atom compounds is determined by solving the following equation

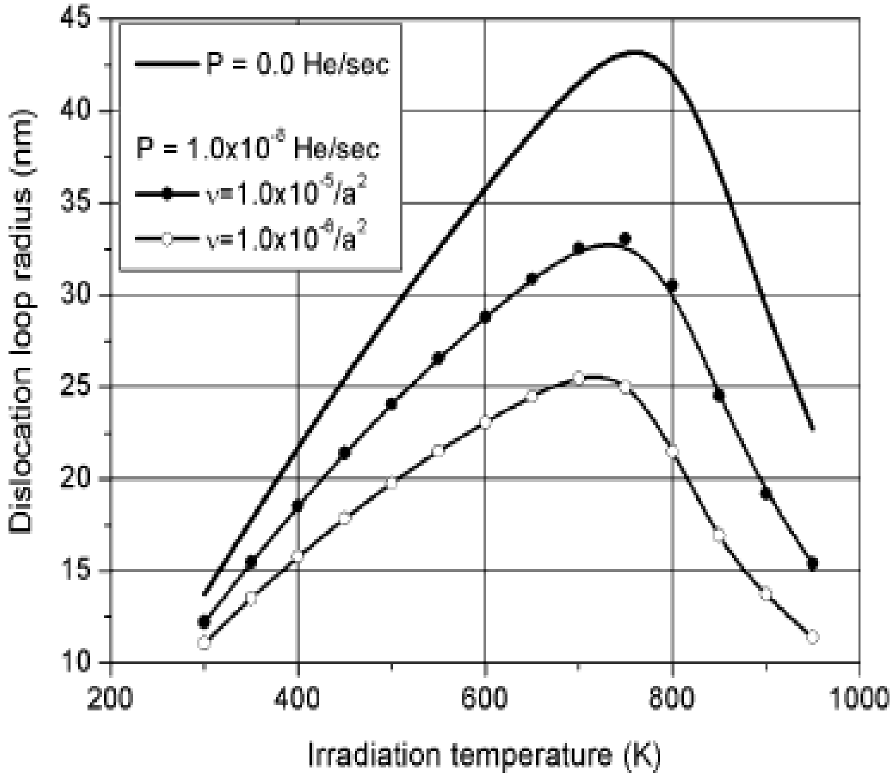
$$\frac{dC_{HeV1}}{dt} = \nu D_{He}C_{He}C_{V1}, \qquad \frac{dC_{HeV2}}{dt} = \nu D_{He}C_{He}C_{V2}$$

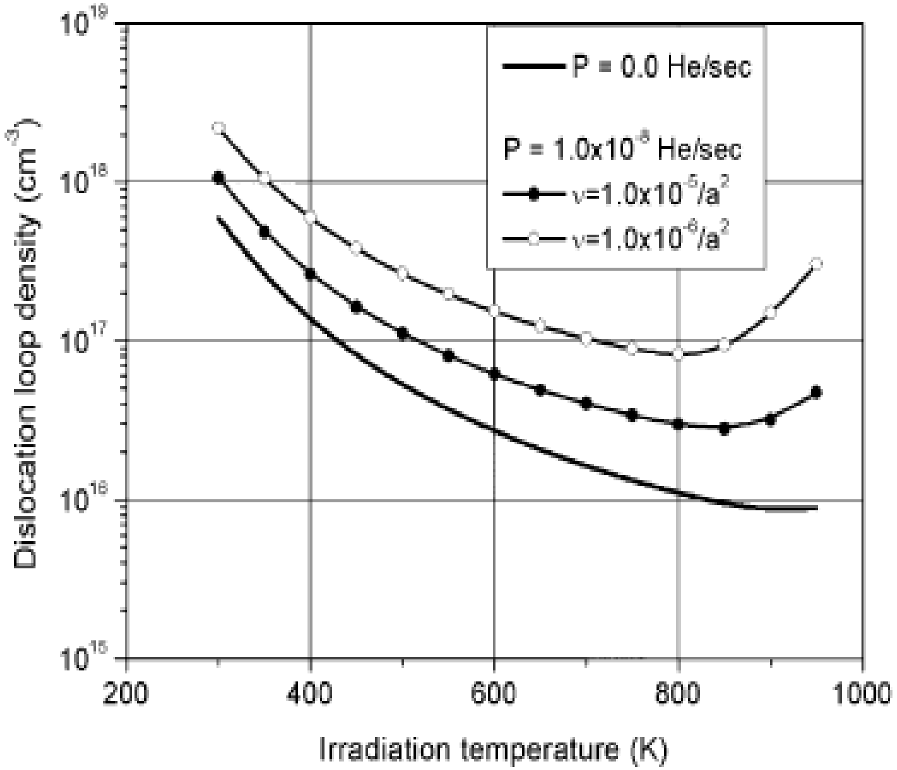
Main parameter values used for numerical calculations of radiation swelling in SiC

$G_1 = G_{Si}$	Point defect generation rate of Si atoms	1.0×10^{-3} dpa/s
$G_2 = G_C$	Point defect generation rate of C atoms	2.5×10^{-3} dpa/s
G_{He}	Helium atom generation rate	6.0×10^{-8} He/s
E_{mV}^{Si}	Silicon vacancy migration energy	2.9 eV
E_{mV}^{C}	Carbon vacancy migration energy	2.4 eV
E_{mI}^{Si}	Silicon interstitial migration energy	0.8 eV
E_{mI}^{C}	Carbon interstitial migration energy	0.7 eV
E_{m}^{He}	Helium atom migration energy	0.3 eV
$e_{I1} = e_{I2}$	Interstitial dilatation	1.2
$e_{V1} = e_{V2}$	Vacancy dilatation	-0.1
e_{He}	Helium atom dilatation	1.2
$e_{HeV1} = e_{HeV2}$	Helium atom–vacancy complex dilatation	1.1
ρ_D	Network dislocation density	10^{-10} cm^{-2}
a	Lattice parameter	3.0×10^{-8} cm

$$D_{\alpha K} = D_{\alpha K}^{O} \exp(-E_{m\alpha}^{K} / T), \text{ (where } D_{\alpha K}^{O} = 1 \ cm^{-2})$$

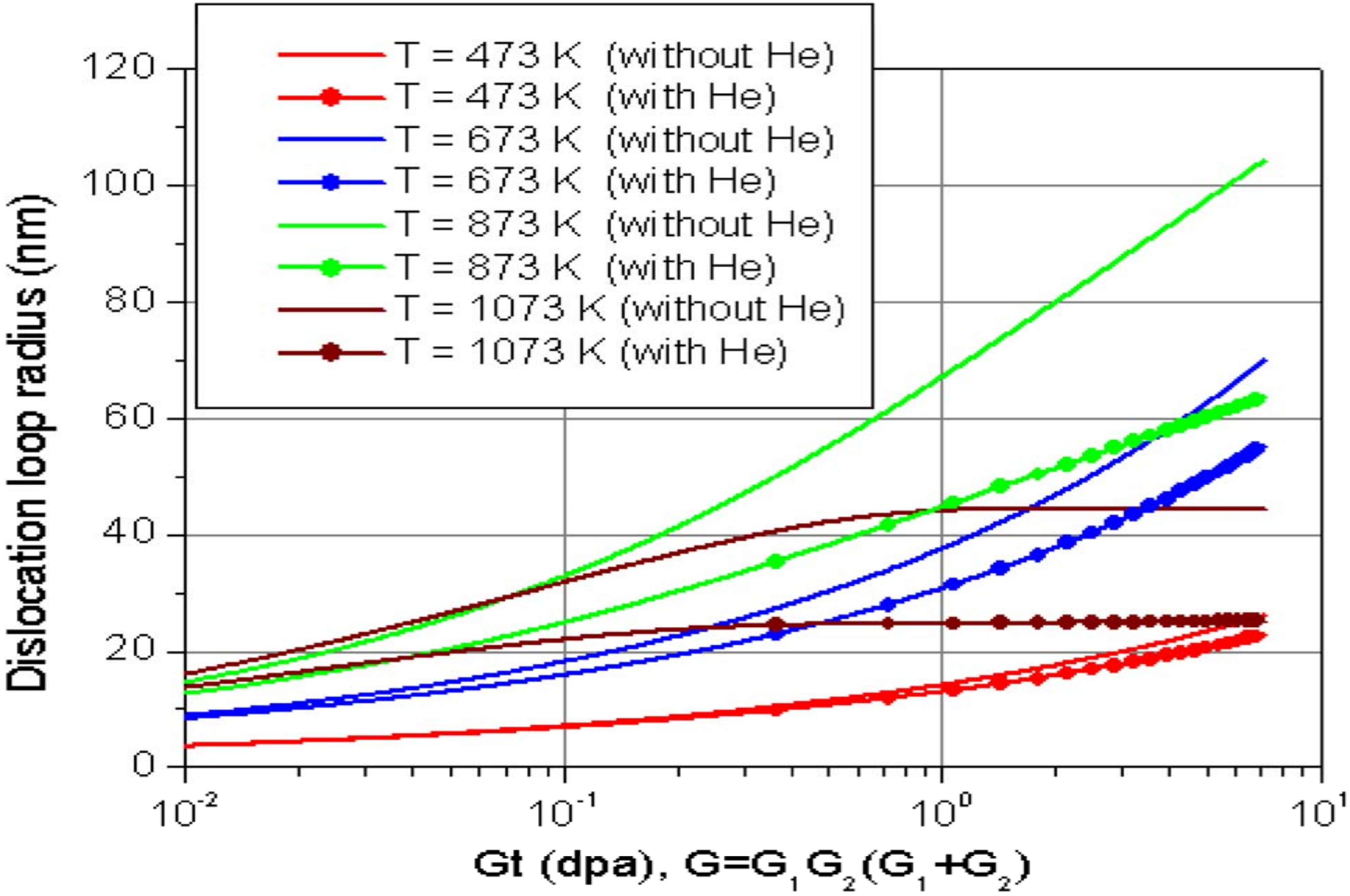
Temperature dependencies of dislocation loop radius and density



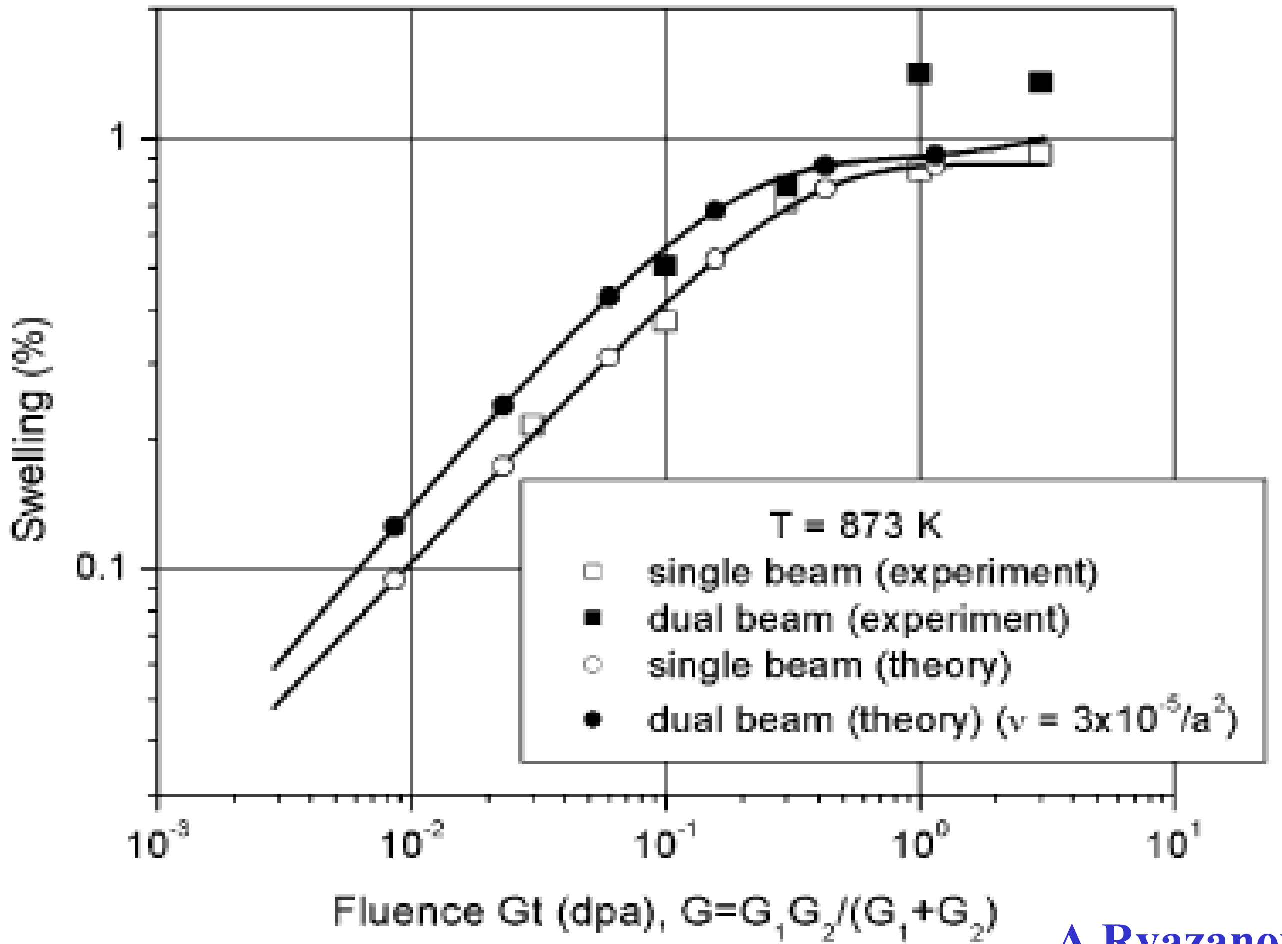


A.Ryazanov, A.Kohyama,Y.Katoh, 2004

Dose dependence of dislocation loop growth in SiC with helium effect (theory)

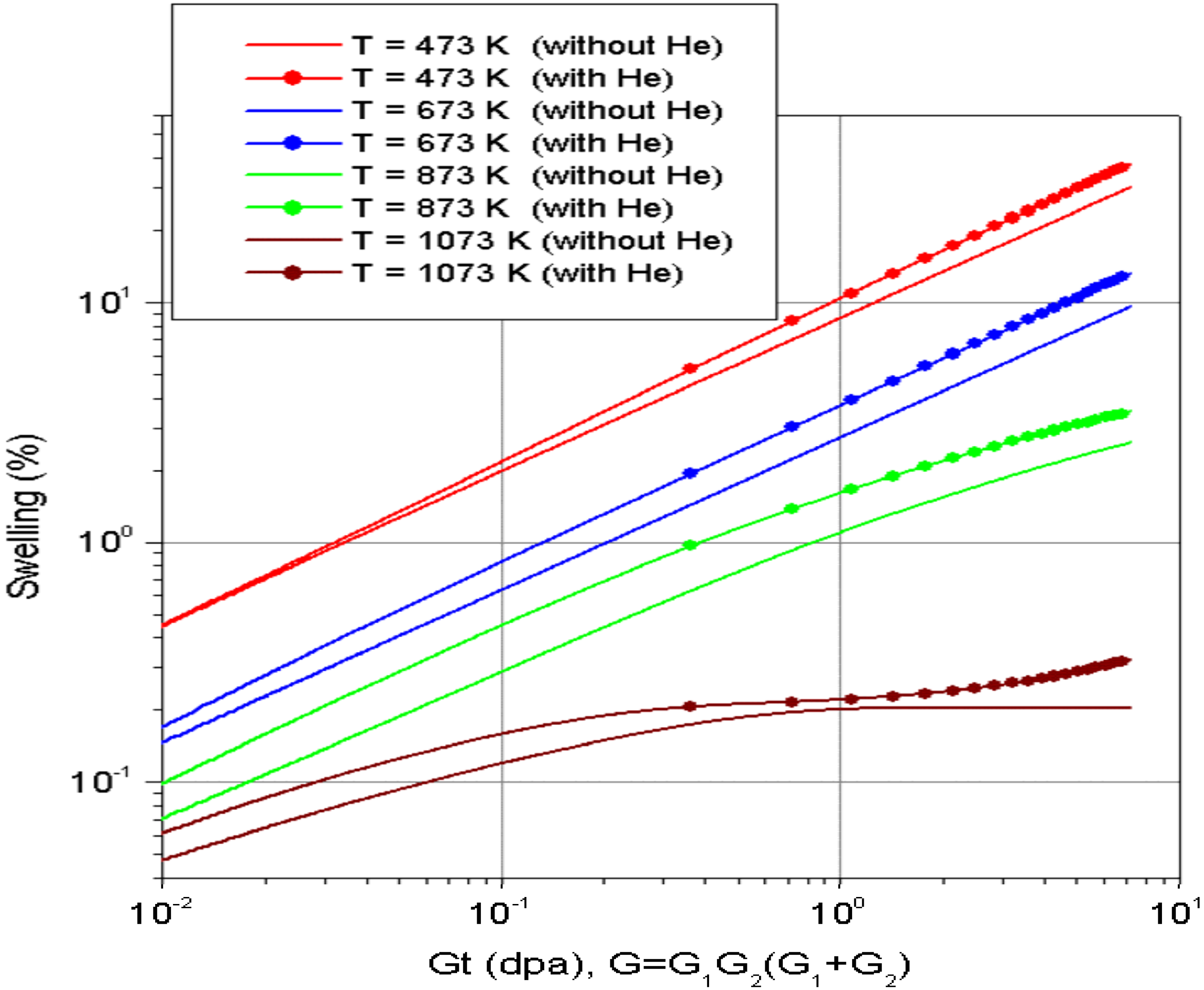


Dose dependence of radiation swelling in SiC under ion irradiatiation

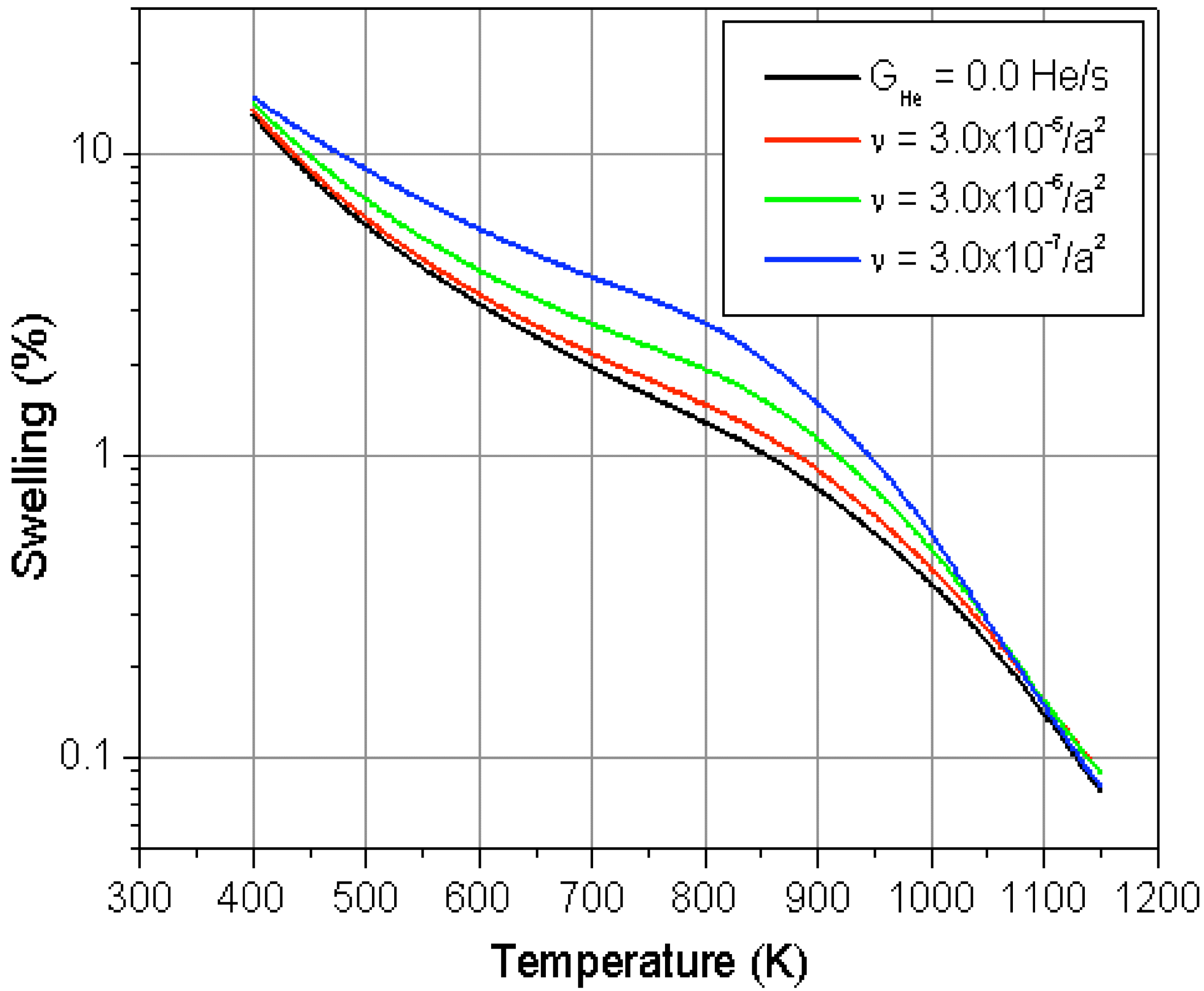


A.Ryazanov, Y.Katoh, A.Kohyama, (2004)

Dose dependence of radiation swelling in SiC at different temperatures with the helium effect



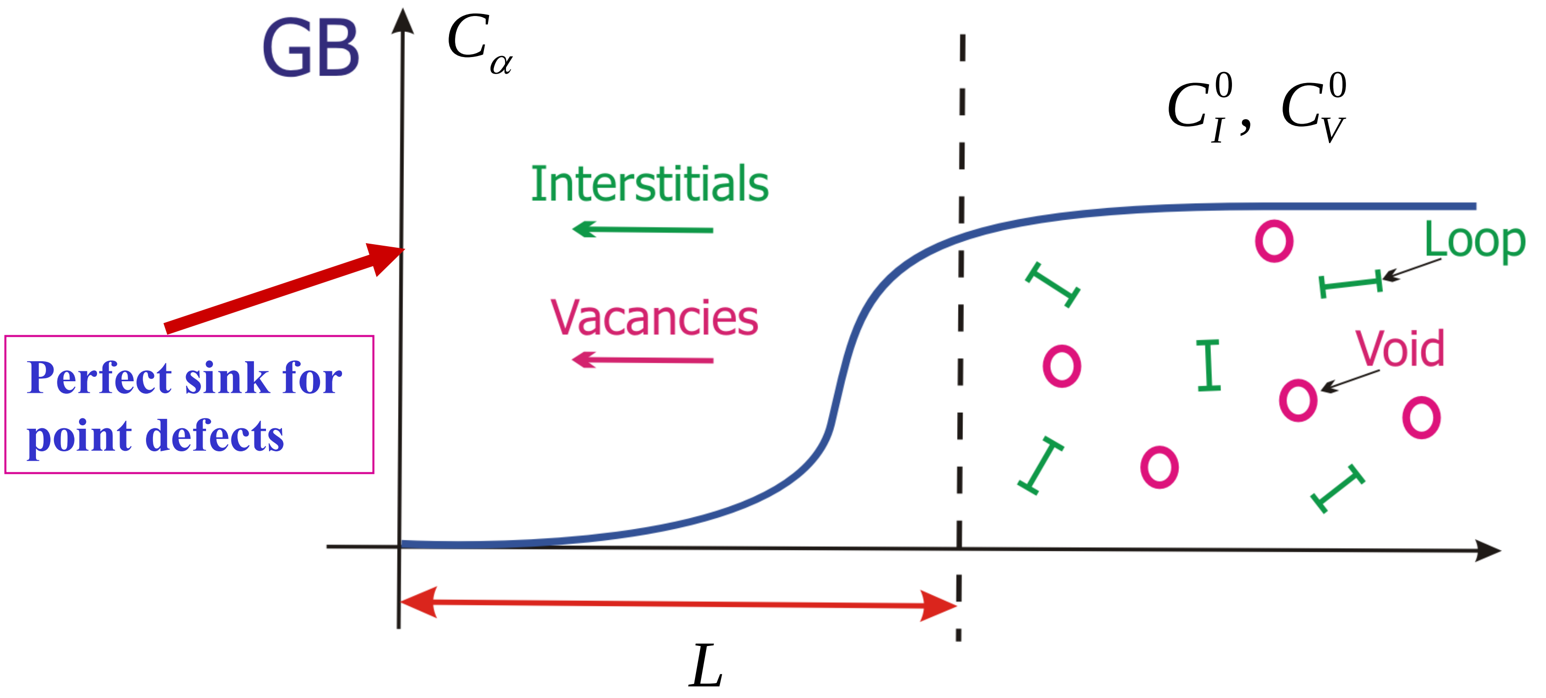
Temperature dependence of radiation swelling in SiC at 0.7 dpa and at different coefficient of helium atom capture by vacancy



A.Ryazanov, A.Kohyama,Y.Katoh, 2004

Physical model for determination of effective charge of point defects in ceramic materials

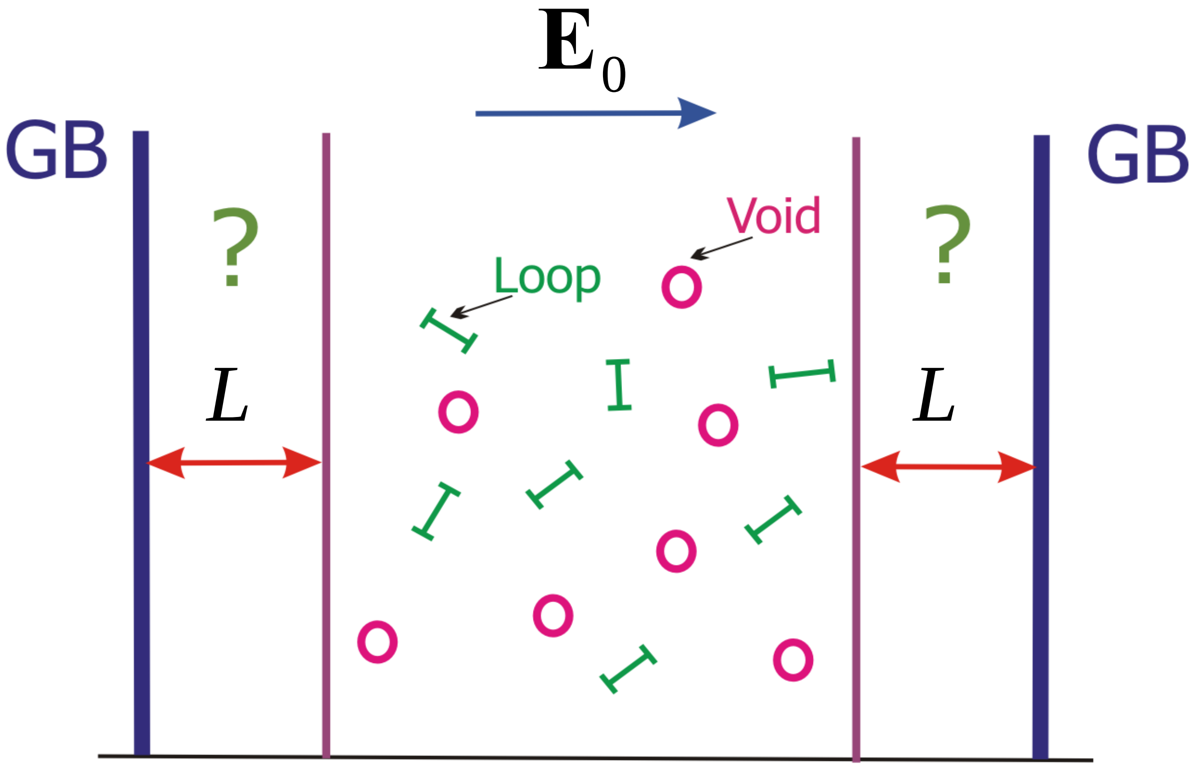
Denuded zone $(E_0 = 0)$



L **is the size of denuded zone**

Effect of an Applied Electrical Field: $(\mathbf{E}_0 \neq 0)$

A.I. Ryazanov, A.V. Klaptsov*, K.Yasuda**,
C. Kinoshita**, JNM, 2004



$$L = L(q, \mathbf{E}_0) = ?$$

Main Equations:

Diffusion equations for point defects

$$G - \alpha C_I C_V - \frac{dj_I}{dz} = 0, \quad G - \alpha C_I C_V - \frac{dj_V}{dz} = 0, \qquad \textbf{(1)}$$

G **is the generation rate of point defects under irradiation,**

α **is the recombination coefficient,** $\alpha = \mu(D_I + D_V)$

D_I, D_V **are diffusion coefficients of intestinal atoms and vacancies**

Diffusion currents of point defects

$$j_I = -D_I \frac{dC_I}{dz} + \frac{qD_I C_I}{kT}\frac{d\varphi}{dz}, \quad j_V = -D_V \frac{dC_V}{dz} - \frac{qD_V C_V}{kT}\frac{d\varphi}{dz} \qquad \textbf{(2)}$$

φ **is the potential of internal electric field ,** $E = -\nabla \varphi$

kT **is the temperature**

Poisson equation

$$\Delta\varphi = -\frac{4\pi}{\varepsilon\omega}\left(qC_V - qC_I + eC_h - eC_e\right) \qquad \textbf{(3)}$$

Total electric current

$$J = -q\left(j_I - j_V\right) = q\left(D_I\frac{dC_I}{dz} - D_V\frac{dC_V}{dz}\right) + \frac{q^2}{kT}\left(D_I C_I + D_V C_V\right)E = J_0 \qquad \textbf{(4)}$$

Boundary conditions:

$$C_I(z=0)=0,\quad C_I(z\to\infty)=C_I^0,\quad C_V(z=0)=0,\quad C_V(z\to\infty)=C_V^0 \qquad \textbf{(5)}$$

$$J_0 = \left.\left(q\left(D_I\frac{dC_I}{dz} - D_V\frac{dC_V}{dz}\right) + \frac{q^2}{kT}\left(D_I C_I + D_V C_V\right)E\right)\right|_{z=0} = \sigma\omega E_0$$

Assumption:

$$C_I \approx C_I^0 + C_I^1 \left(|C_I^1| << C_I^0\right), \quad C_V \approx C_V^0 + C_V^1 \left(|C_V^1| << C_V^0\right) \qquad \textbf{(6)}$$

Equations (1)-(3) have the following form

$$\frac{d^2 C_I^1}{dz^2} + \frac{qE_0}{\varepsilon kT}\frac{dC_I^1}{dz} - \left[\frac{\alpha C_V^0}{D_I} + \frac{4\pi q^2 C_I^0}{\varepsilon \alpha kT}\right] C_I^1 - \left[\frac{\alpha C_I^0}{D_I} - \frac{4\pi q^2 C_V^0}{\varepsilon \alpha kT}\right] C_V^1 = 0,$$

$$\frac{d^2 C_V^1}{dz^2} - \frac{qE_0}{\varepsilon kT}\frac{dC_V^1}{dz} - \left[\frac{\alpha C_I^0}{D_V} + \frac{4\pi q^2 C_V^0}{\varepsilon \alpha kT}\right] C_V^1 - \left[\frac{\alpha C_V^0}{D_V} - \frac{4\pi q^2 C_I^0}{\varepsilon \alpha kT}\right] C_I^1 = 0 \qquad \textbf{(7)}$$

Solutions of equations (7) have the following form

$$C_I^1, C_V^1 \sim \exp(-\lambda_{\min} z) \qquad \textbf{(8)}$$

$\lambda_{\min}$ **is the minimum positive roots of the equation:**

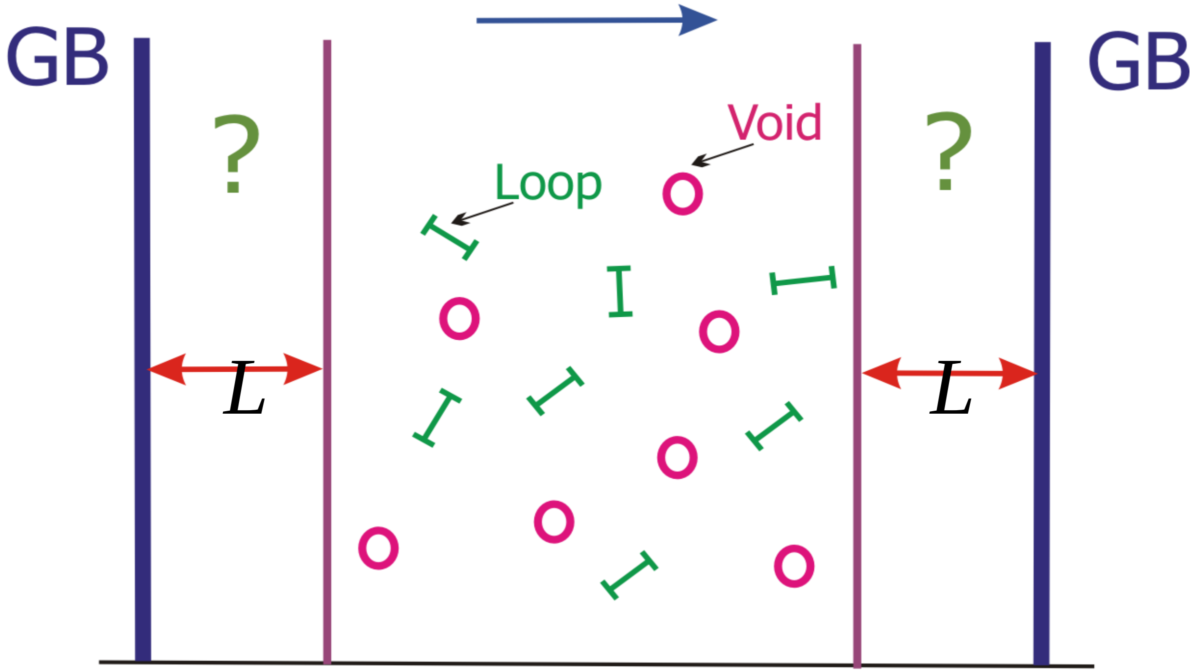
$$\left(\lambda^2 - \frac{qE_0}{\varepsilon kT}\lambda - \frac{\alpha C_V^0}{D_I} - \frac{4\pi q^2 C_I^0}{\varepsilon\omega kT}\right)\left(\lambda^2 + \frac{qE_0}{\varepsilon kT}\lambda - \frac{\alpha C_I^0}{D_V} - \frac{4\pi q^2 C_V^0}{\varepsilon\omega kT}\right) = \tag{9}$$

$$= \left(\frac{\alpha C_I^0}{D_I} - \frac{4\pi q^2 C_V^0}{\varepsilon\omega kT}\right)\left(\frac{\alpha C_V^0}{D_V} - \frac{4\pi q^2 C_I^0}{\varepsilon\omega kT}\right).$$

Size *(L)* of denuded zone is equal

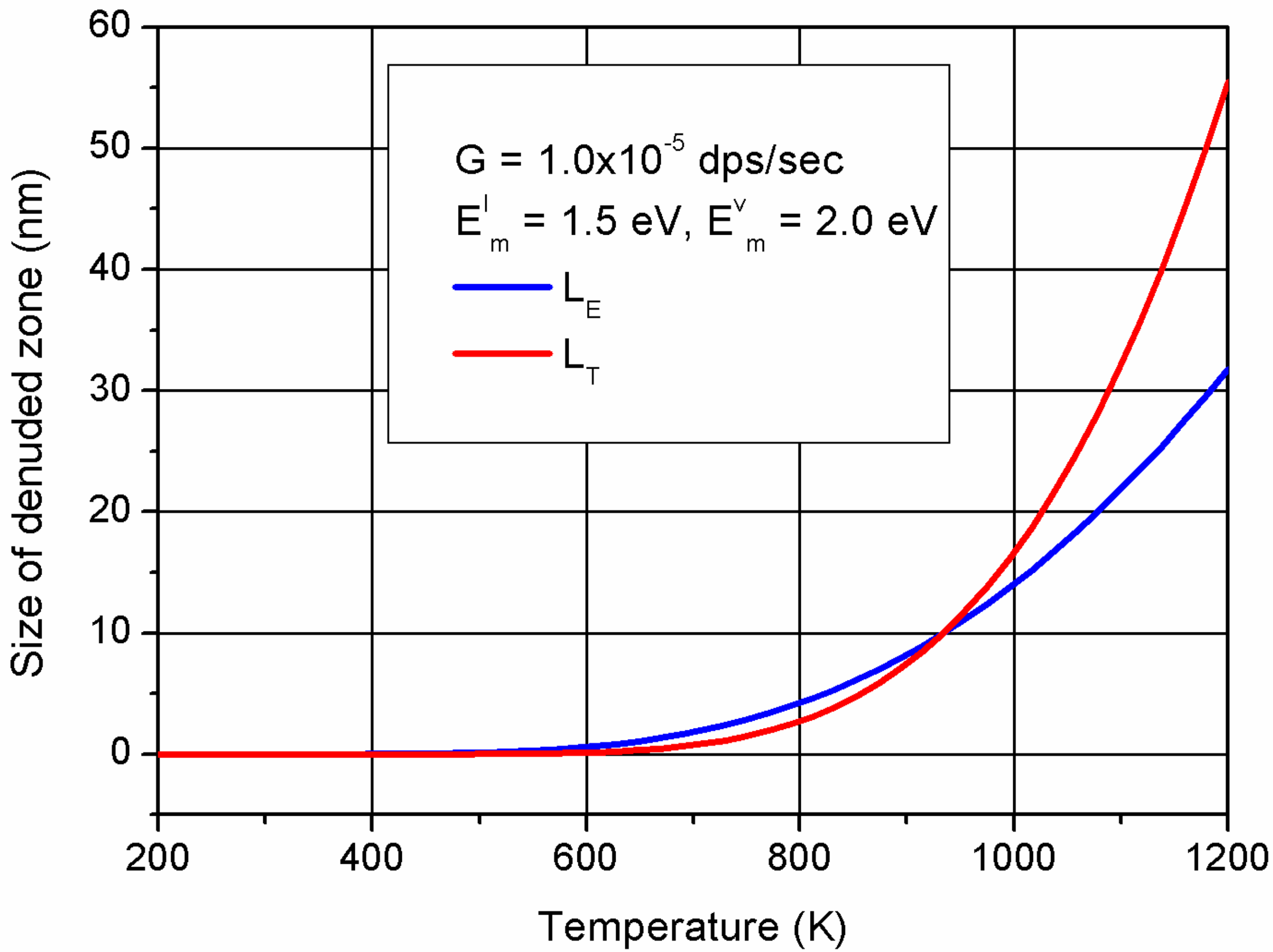
$$L = 1/\lambda_{\min} \tag{10}$$

1.Absence of an external electric field ($E_0 = 0$)

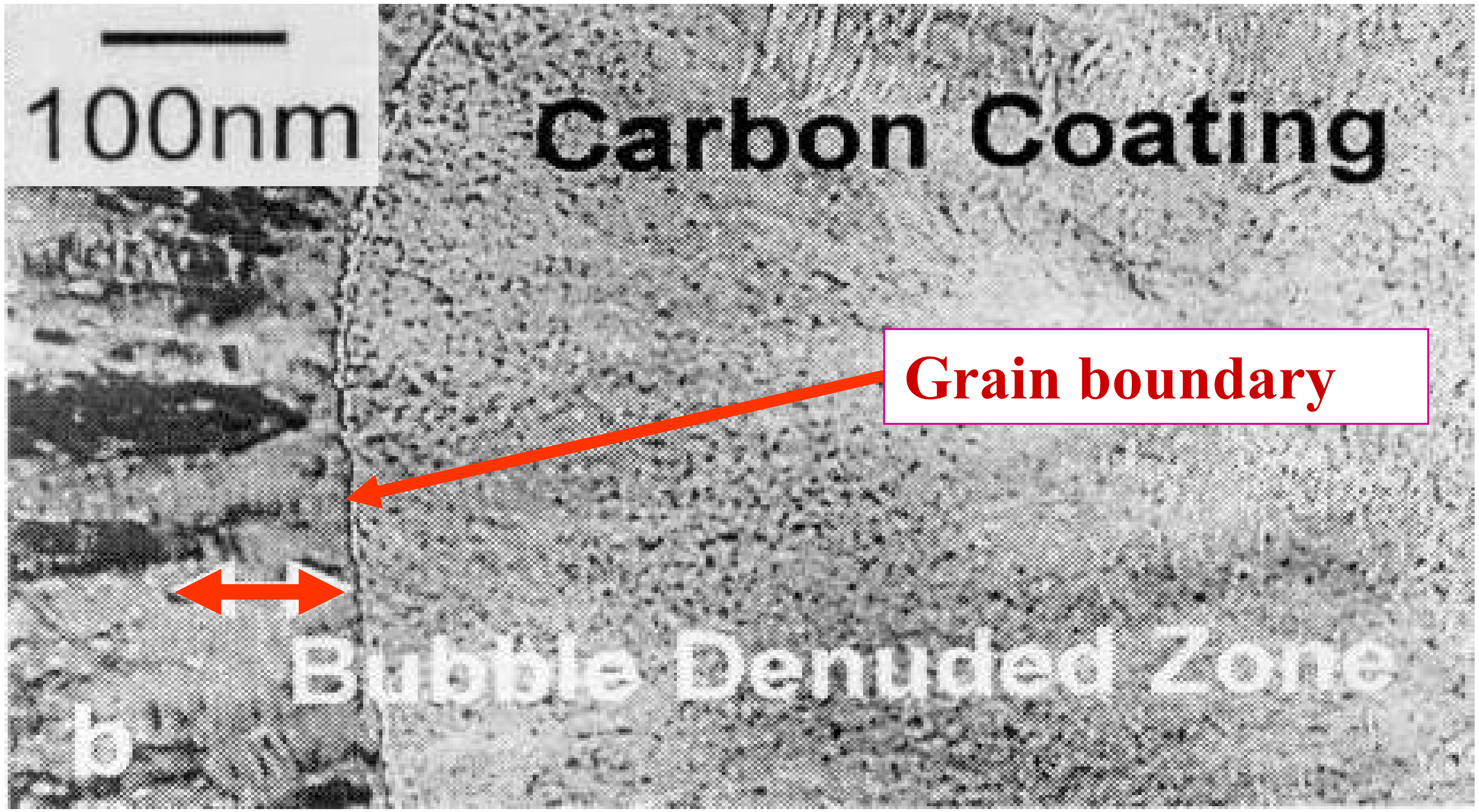


$$L_E \approx \sqrt{\frac{\varepsilon\omega kT}{8\pi q^2}}\left(\frac{\mu D_I}{G}\right)^{1/4}, \quad L_T \approx \left(\frac{D_V^2}{\mu D_I G}\right)^{1/4}$$

Temperature dependence of denuded zone size



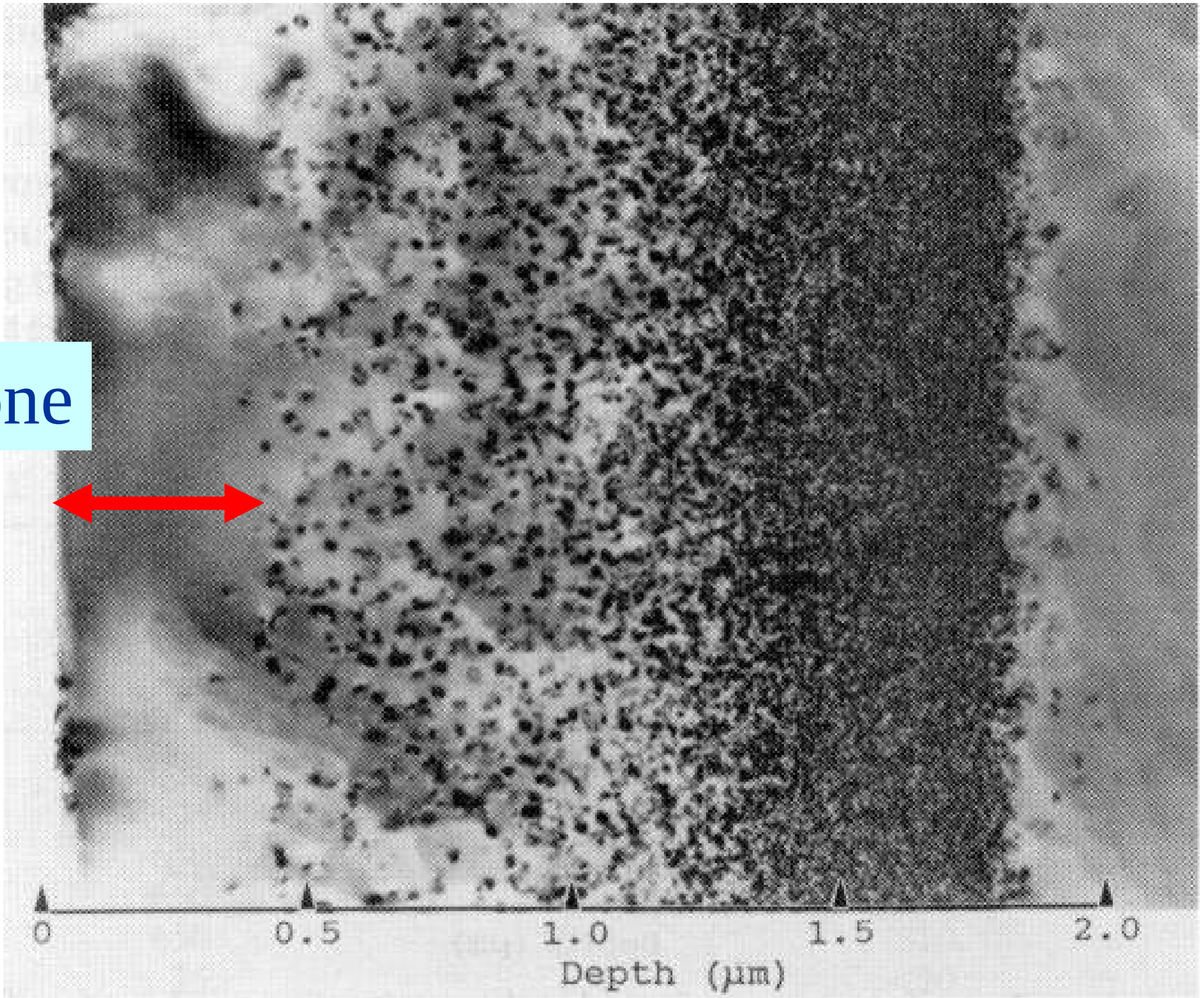
TEM micrograph of SiCf/SiC composites after implantation with 3 MeV helium and annealing at T = 1673 K for 1 h
(A.Hasegawa et. al. 1999)



Depth-dependent microstructure of $MgAl_2O_4$ (spinel) irradiated by 2 MeV Al^+ at 650 C to a peak damage 14 dpa

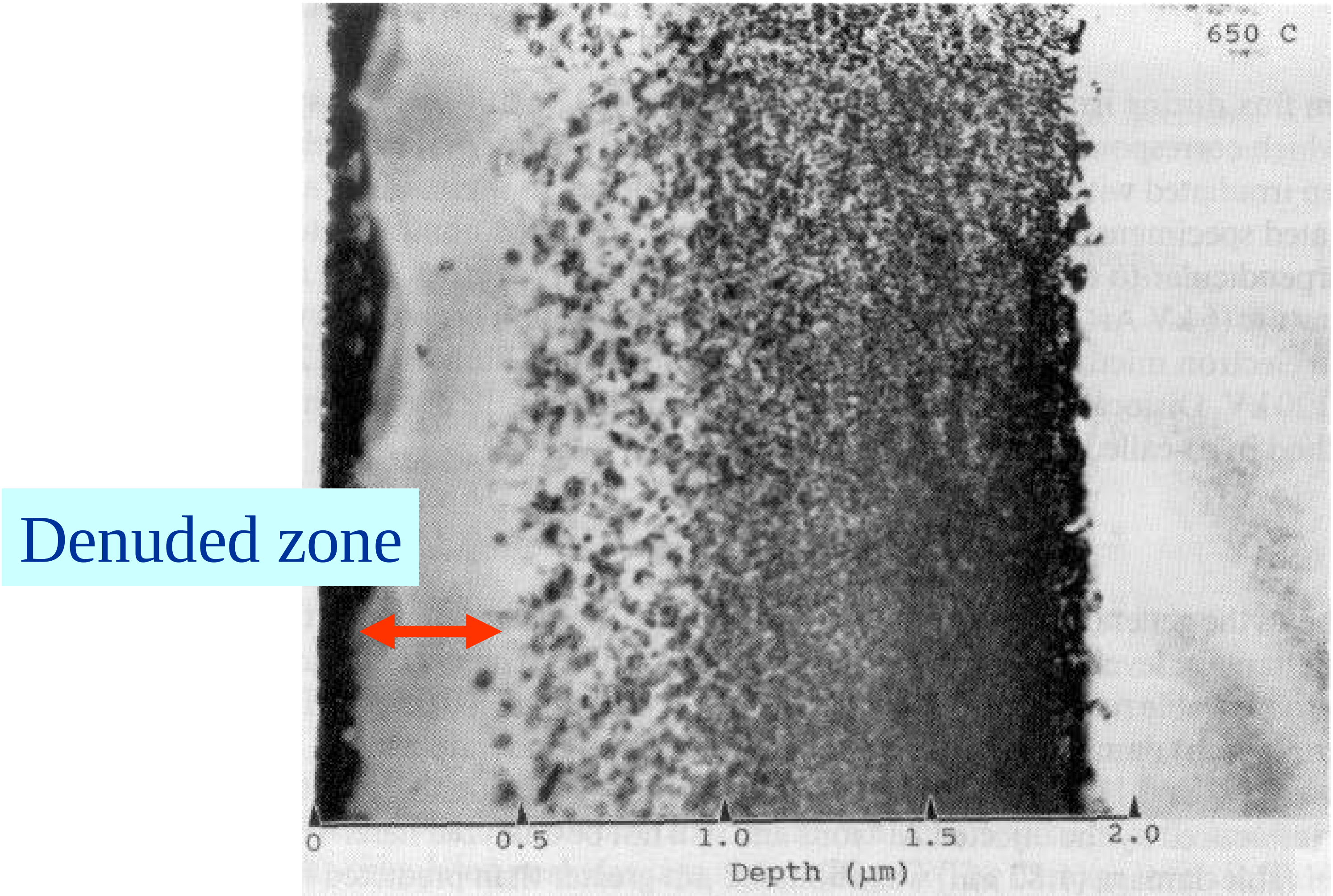
(S.J.Zinkle 1992)

Denuded zone

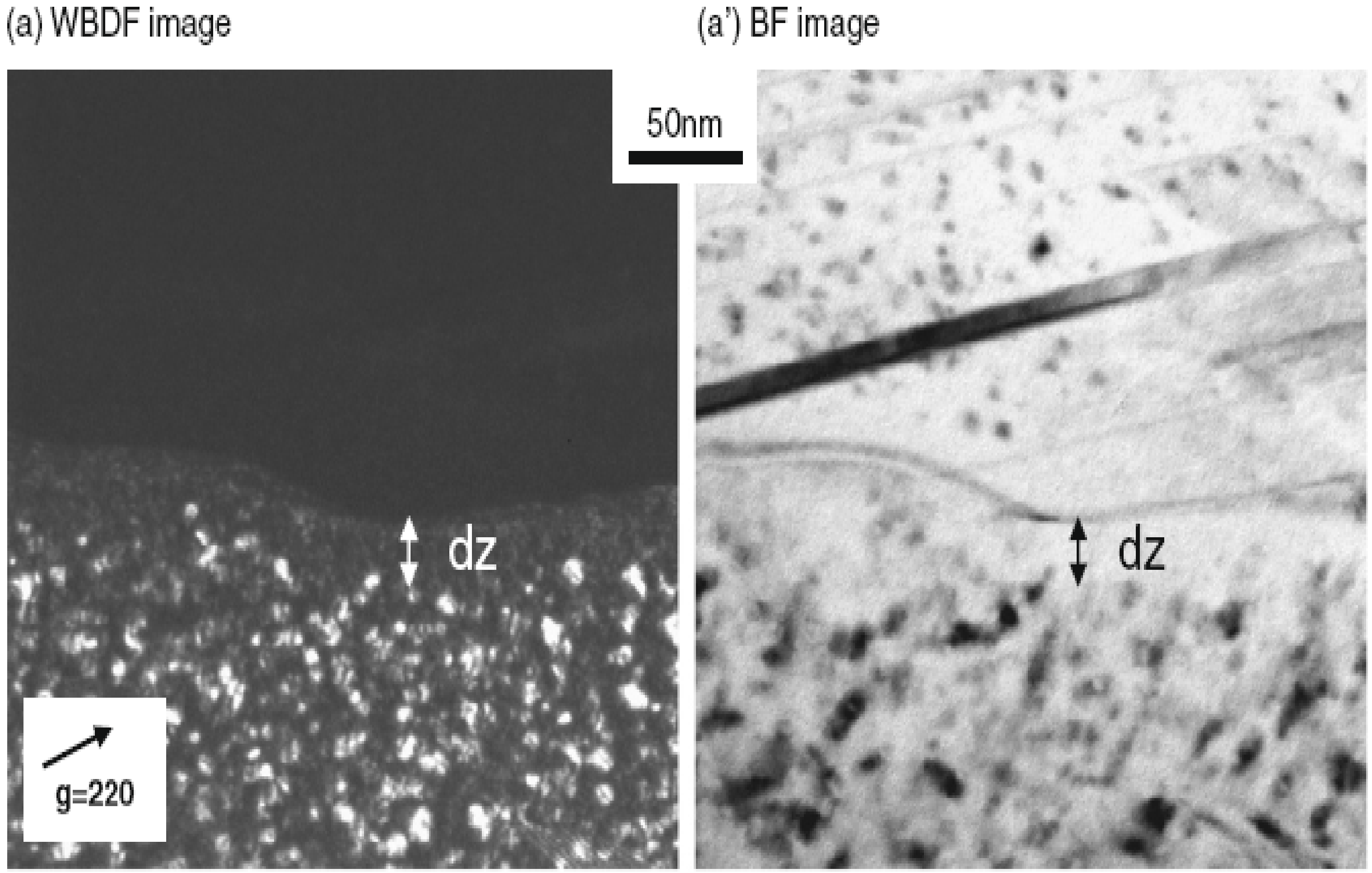


Depth-dependent microstructure of $MgAl_2O_4$ irradiated by 2 MeV Al^+ at 650 C to a peak damage 100 dpa

(S.J.Zinkle 1992)

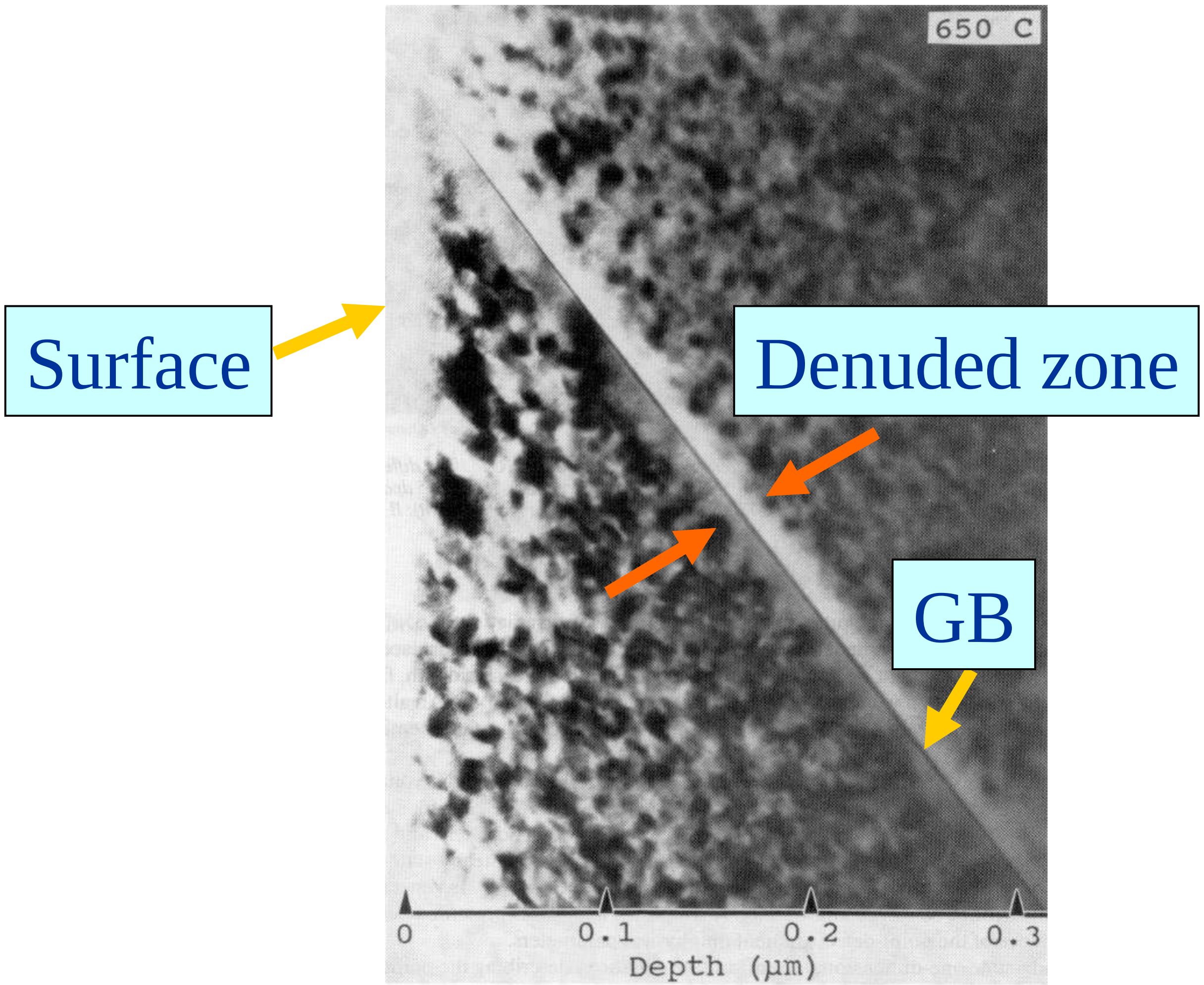


Denuded zone (dz) formation for dislocation loops along grain boundary in neutron irradiated (1,5x10E25n/m2) β-SiC at 1130ºC temperature

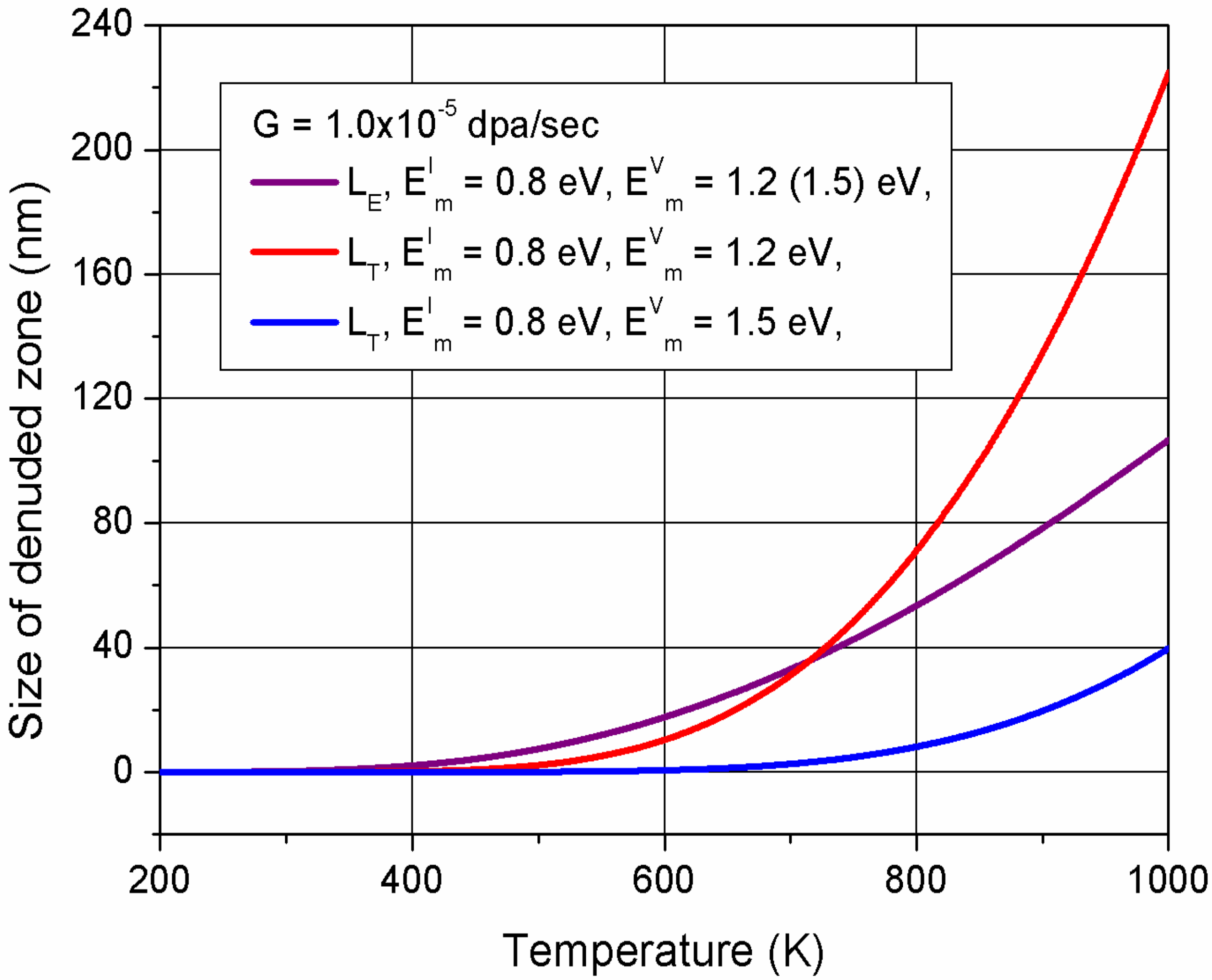


S.Kondo,
JNM, 2008

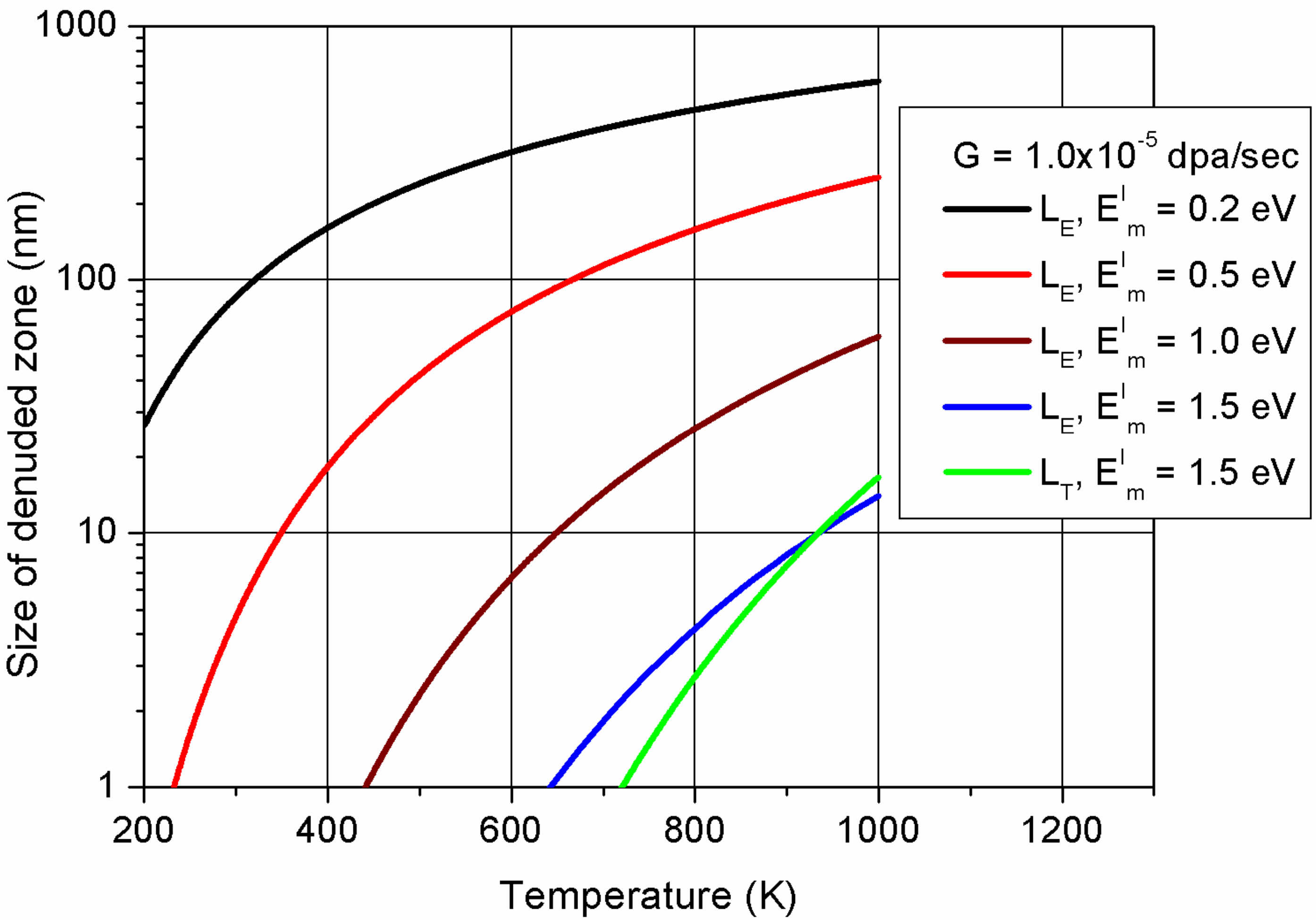
Microstructure of Al_2O_3 in the vicinity of surface and grain boundary irradiated by 2 MeV Al^+ at 650 C to a peak damage 1 dpa (S.J.Zinkle 1992)



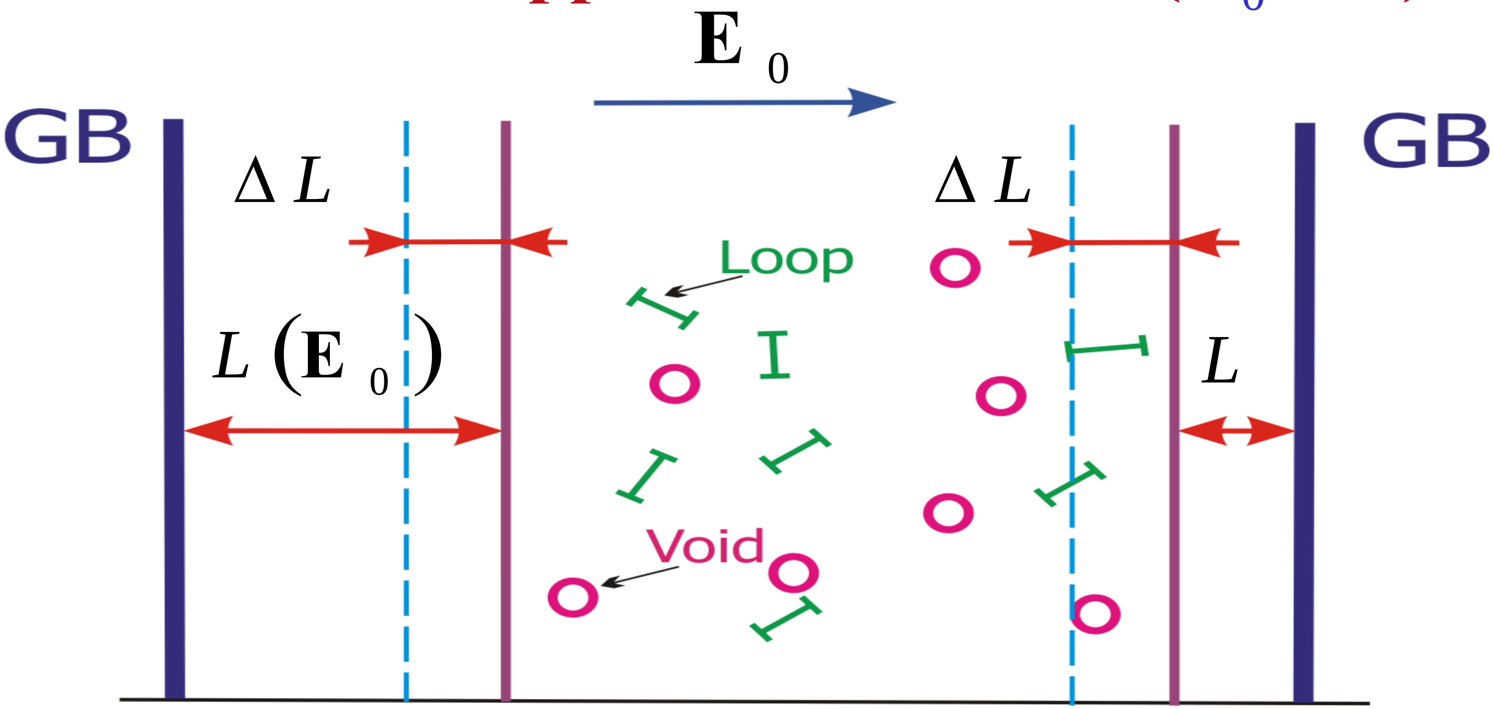
Temperature dependence of denuded zone size



Temperature dependence of denuded zone size



2.Effect of an applied electric field ($E_0 \neq 0$)

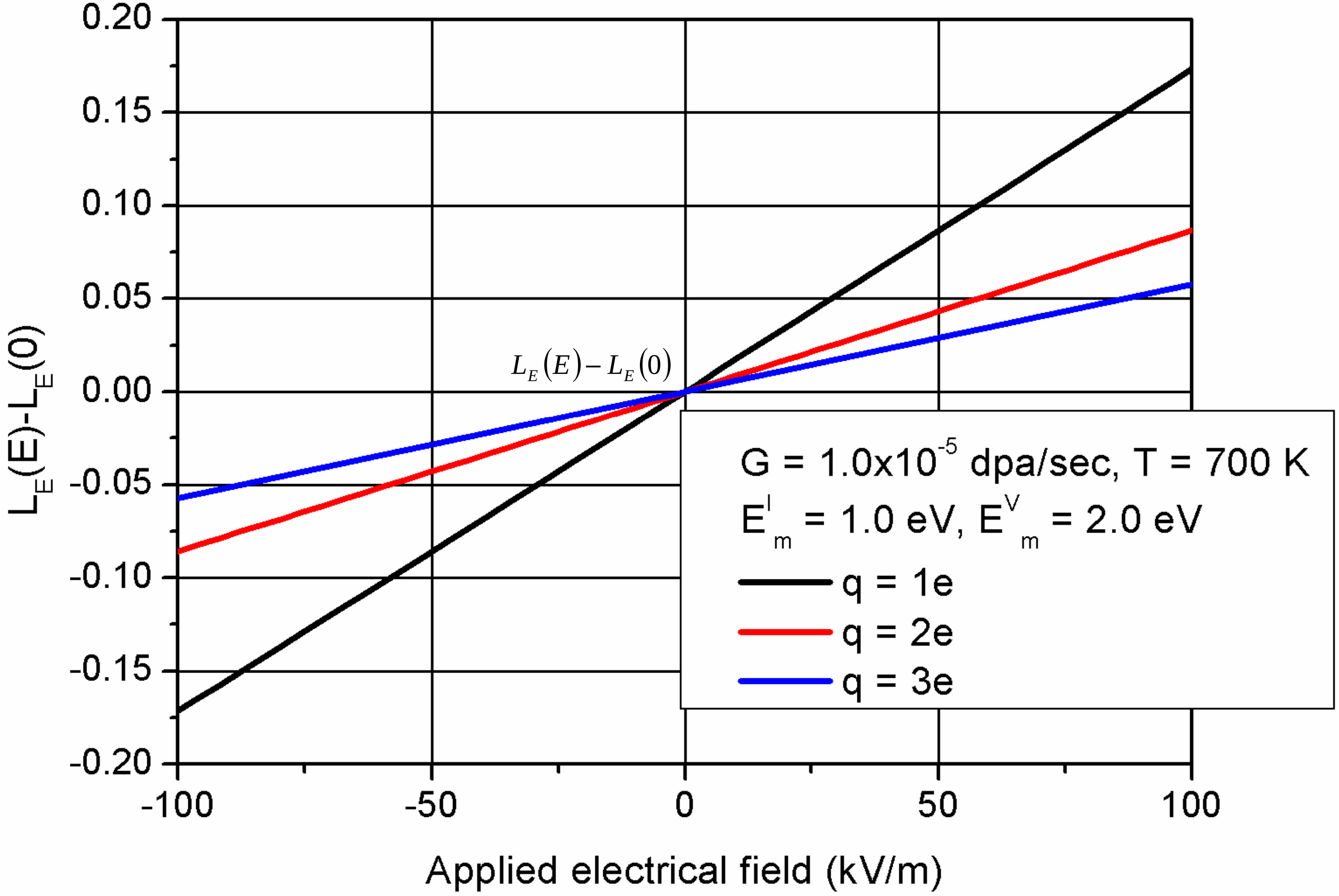


$$L \approx L_E(1-\alpha E_0 + \frac{1}{2}\alpha^2 E_0^2), L_E >> L_T$$

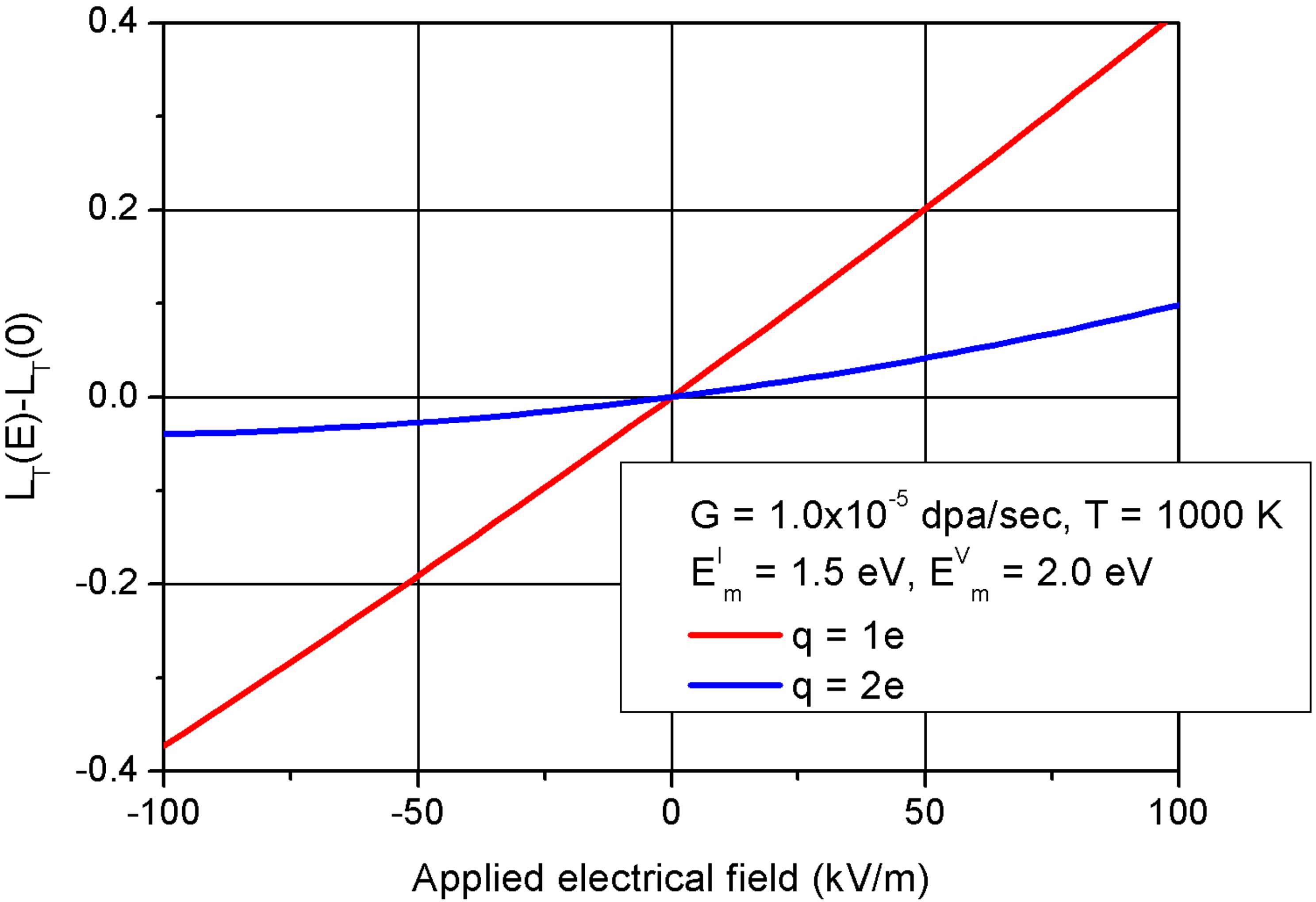
$$L \approx L_T(1-\beta E_0 + 2\alpha^2 E_0^2), \quad L_T >> L_E.$$

$$\Delta L(E_0) = -\frac{\omega}{16\pi q}\left(\frac{\mu D_I}{G}\right)^{1/2} E_0$$

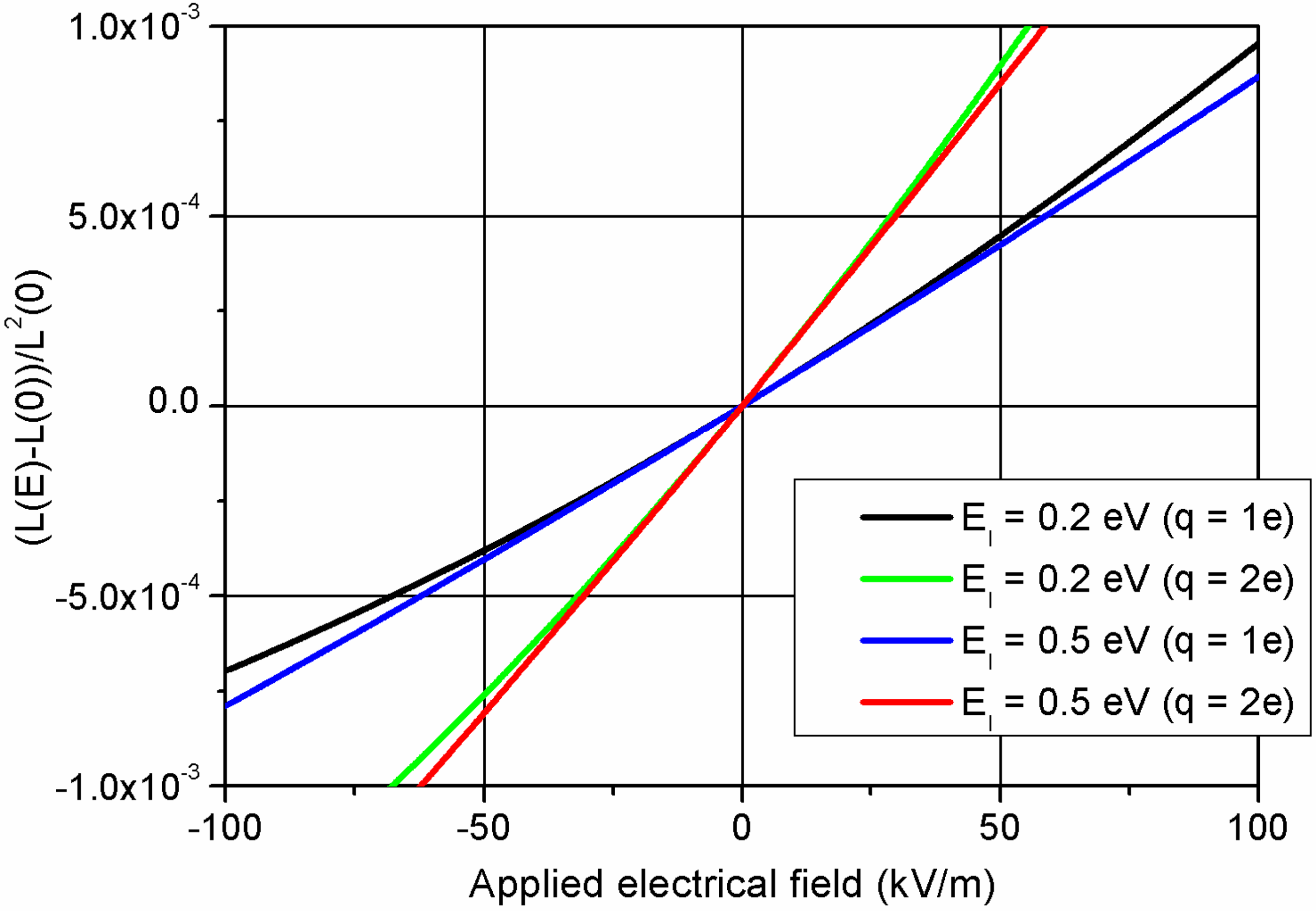
Dependence of $\Delta L_E(E)$ on an applied electric field



Dependence of $\Delta L_E(E)$ on an applied electric field

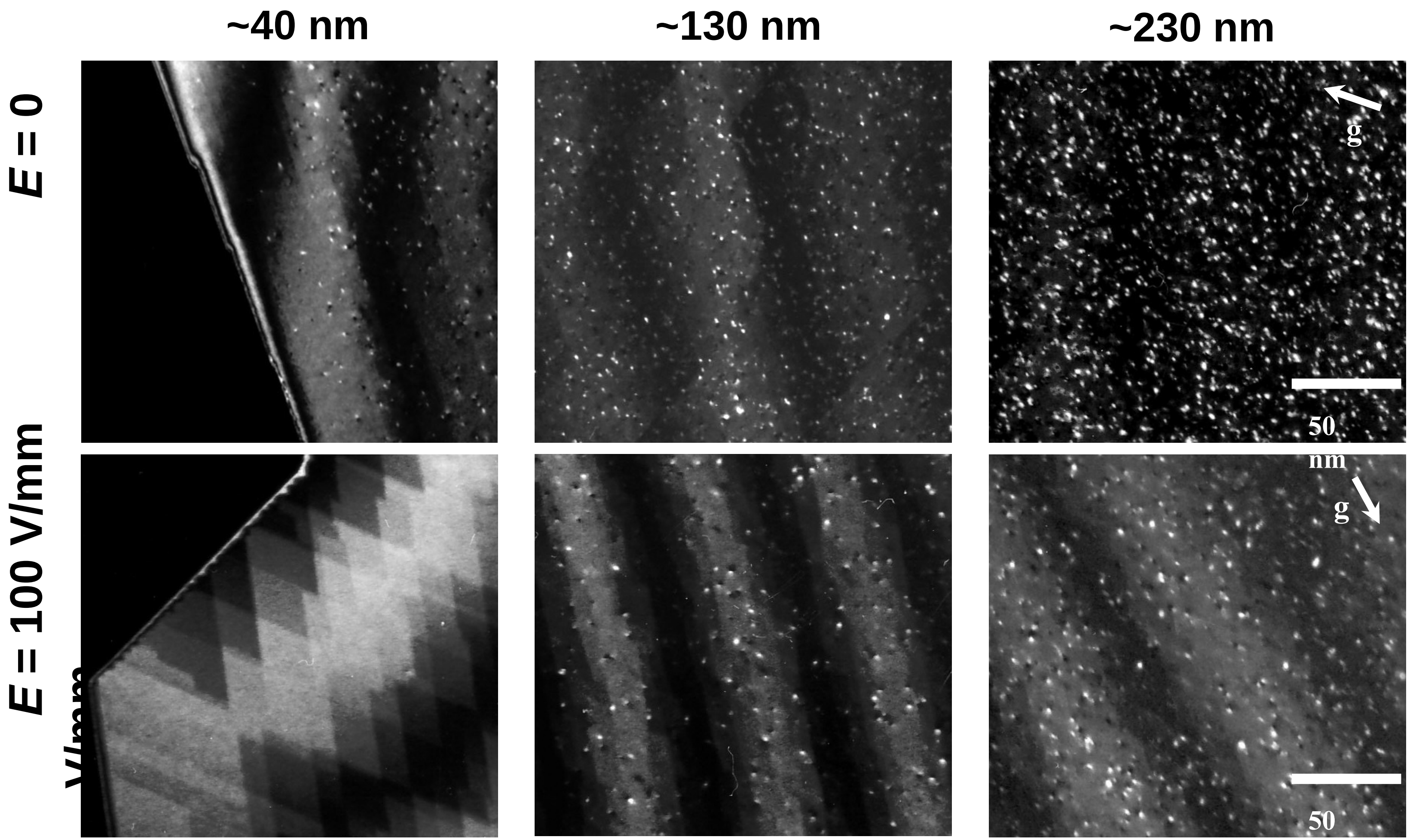


Dependence of $\Delta L_E / L_E^2$ on applied electrical field



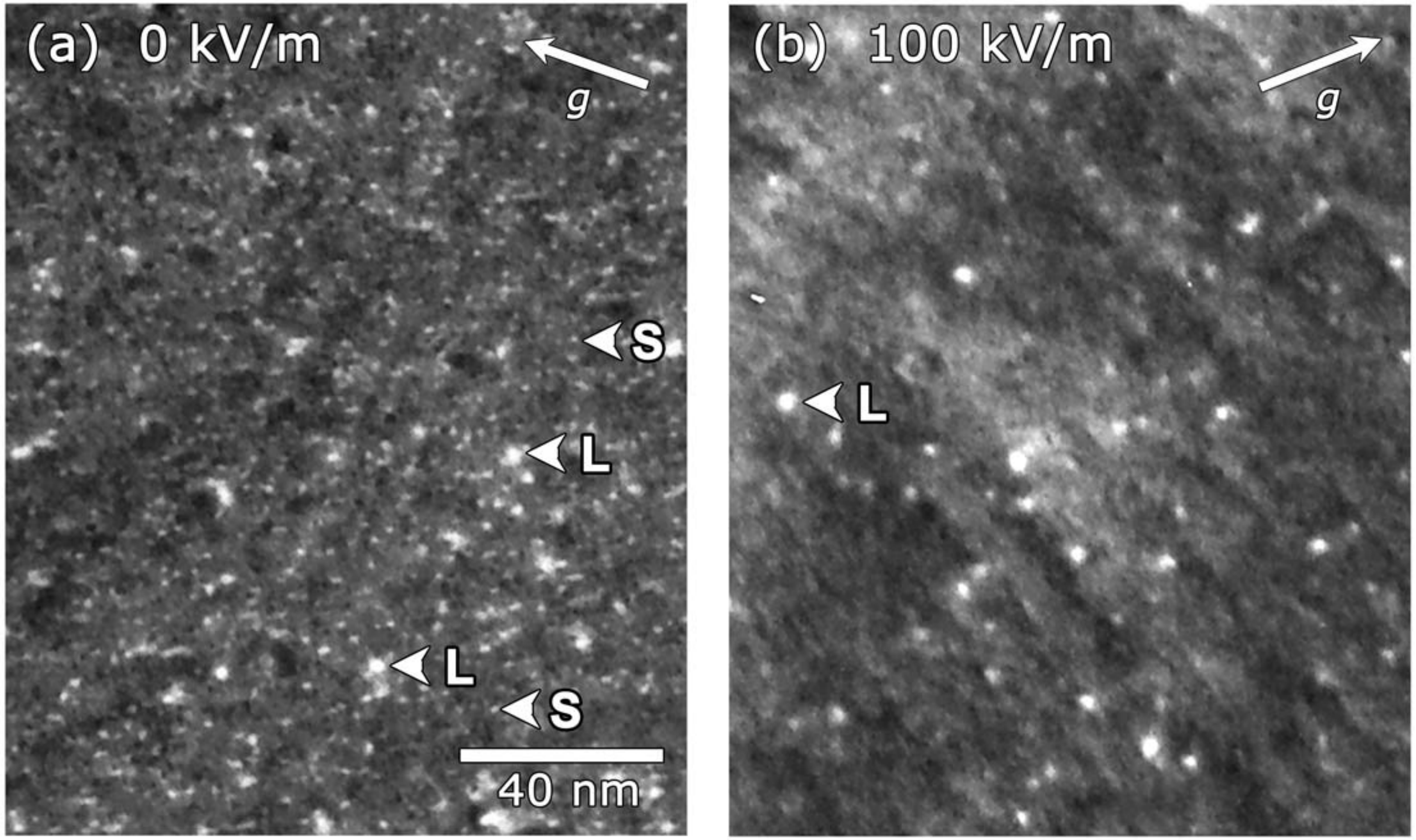
Experimental observation of dislocation loop density in Al_2O_3 irradiated at 760 K with 100keV He^+ ions to a fluence of $1x10^{20}$ m^{-2} with and without electric field of 100 kVm^{-1}

(K.Yasuda, K.Tanaka,C.Kinoshita 2002)



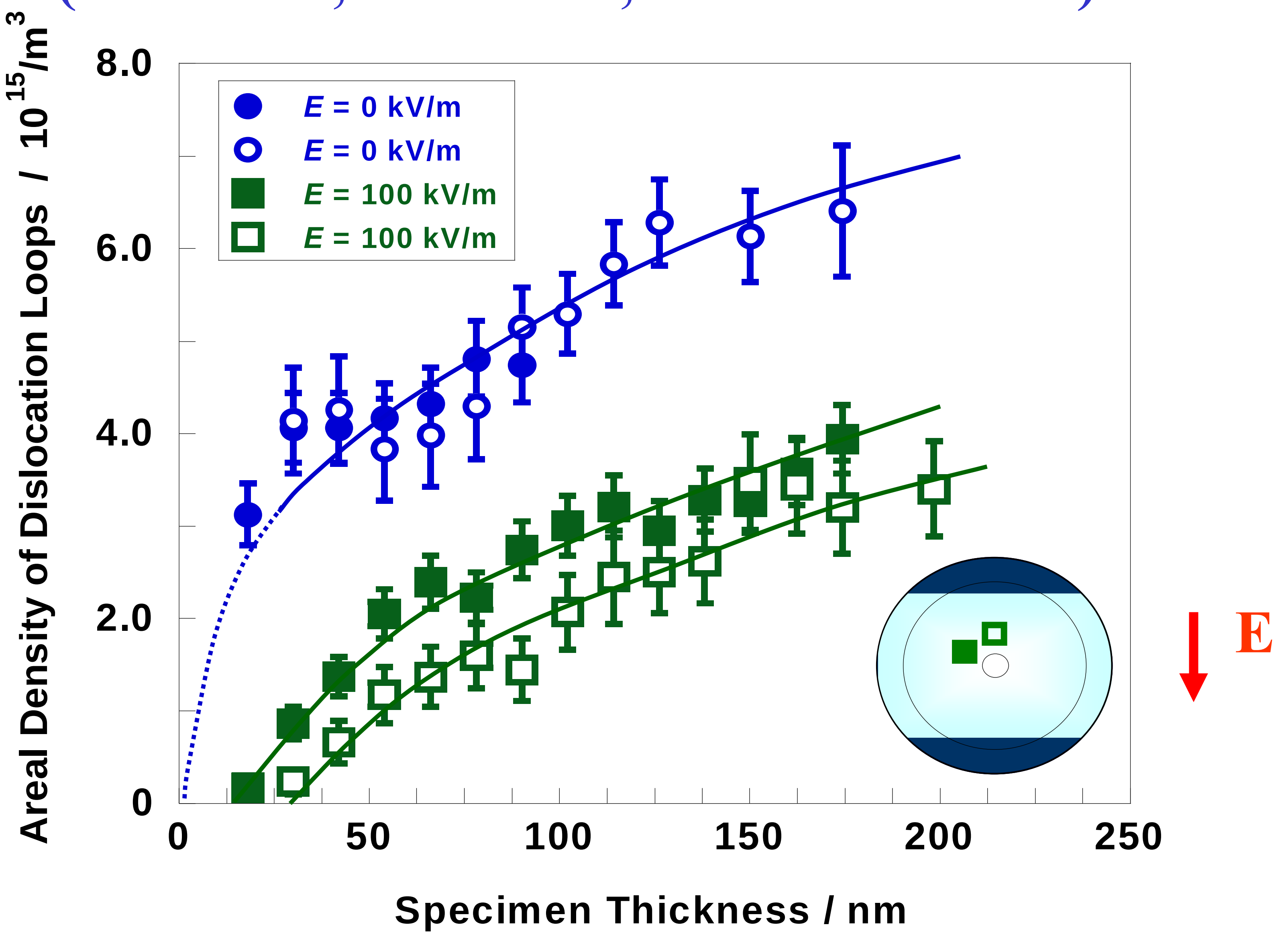
TEM data in α-Al_2O_3 irradiated with 100 keV He^+ ions at T = 870 K

(K.Yasuda, K.Tanaka,C.Kinoshita 2002)



Specimen thickness; 100 nm

(K.Yasuda, K.Tanaka,C.Kinoshita 2002)



Summary

- Low temperature swelling in SiC due to point defect accumulation in matrix exceeding 1% at temperatures below 673K, which is supported both by experiment and theoretical model.
- Low temperature swelling in SiC saturates in helium free conditions. Saturation behavior is highly predictable using the suggested theoretical model. Saturation of radiation swelling in SiC is determined based on the growth rate saturation of interstitial dislocation loops.
- The recent experimental data clearly demonstrate the strong monotonic decrease of radiation swelling in SiC up to 1000C. The theoretical calculations give the same temperature dependence for decreasing of radiation swelling in SiC with temperature increase.

- **Low temperature swelling in SiC containing He atoms due to point defect accumulation in matrix exceeding 1% at temperatures below 673K, which is supported both by experiment and theoretical model.**
- **Helium atoms increase the nucleation of interstitial dislocation loops and decrease an average radius of them. Helium atoms increase radiation swelling in temperature interval from 400 to 1000 K.**
- **The experimental data on dual-beam clearly demonstrate the strong temperature decrease of radiation swelling in SiC with helium up to 1000C. The theoretical calculations give the same temperature dependence for radiation swelling in SiC with temperature increase.**
- **Void swelling is observed in irradiated SiC at high temperatures T > 1050^{o}C under neutron and ion irradiations. The theoretical models for explanation of behavior void swelling and helium effect on swelling at high temperatures do not exist.**

Thank you for your attention!