6th IEA & JUPITER Joint Workshop on Vanadium Alloys for Fusion Applications
Loews Ventana Canyon Resort
Tucson, Arizona
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Session II – Microstructural Evolution

Effect of impurities and alloying additions (binary V-X systems) on the formation of dislocation loops, voids, and precipitates during irradiation

IMR

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Contents

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Formation Energy *compiled by N. Nita*

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		Reference
Formation Energy [eV]		
n I-Cluster	$3.313n^{0.75}$	[237]
SIA	0.22, 4.58	[239][244]
n V-Cluster	$2.078n^{0.75}$	[237]
V	1.83, 1.2, 2.22, 2.2, 2.2, 2.1, 2.0, 2.1, 2.70-3.06, 3.07	[241][264][244][254][252][253][255][255][251][250]
2 V	3.99	[244]

Binding Energy

IMR

Binding Energy [eV]		
n I,V-Cluster	$E_{i,v}^{b}(n)=E_{i,v}^{f}(n-1)+E_{i,v}^{f}(1)-E_{i,v}^{f}(n)$	[237]
2 V	0.45	[244]
2 V	0.31	[263]
3 V	0.58	[263]
4 V	0.57	[263]
5 V	1.21	[263]
6 V	1.19	[263]
2 SIA	0.71	[262]
3 SIA	1.2	[262]
4 SIA	2.09	[262]
5 SIA	1.67	[262]
6 SIA	2.12	[262]
7 SIA	1.84	[262]
8 SIA	3.00	[262]
9 SIA	2.16	[262]
10 SIA	1.96	[262]

Migration Energy

IMR

Migration Energy [eV]		
SIA	0.116, 0.03, 0.13, 0.6, 0.21, 0.56, 0.62, 0.55, 0.06	[237][262][239][243][259][260][260][260][244]
2 SIA	0.139, 0.067	[237][262]
3 SIA	0.156, 0.17	[237][262]
4 SIA	0.335	[237]
7 SIA	0.069	[237]
V	0.763, 0.83, 1.2, 1.25, 1.4, 0.76, 1.57, 1.02, 0.72-1.3, 1.0, 1.5, 1.5, 0.81, 1.3, 1.2,	[237][266][246][240][265][241][260][260][243][244][255][261][259][255][254]
2 V	0.818	[237]
3 V	1.227	[237]
He	<0.1	[242]
O	1.21, 1.26, 1.26, 1.26-1.28	[245][246][268][249]
C	1.18	[267]

Other Parameters 1

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Self Diffusion Energy [eV]		
Vanadium	3.2, 2.65-3.2, 4.64, 4.26-5.96, <3.5	[244][244][244][244][261]
Damage Efficiency		
SDF	0.35	[269]
CDF_i	0.02	[238]
CDF_v	0.06	[238]

Other Parameters 2

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Stacking Fault Energy [J/m^2]		
	2.68	[237]
Surface Energy [erg/cm^2]		
100 loop	1743, 2589	[256][257]
110 loop	1473, 1822	[256][258]
Flat Lattice	2.62 eV	[261]
Void	1.2-1.6 eV	[261]
Dissociation Energy [eV]		
He_nVX	1.5	[247]
He_nVO	1.42	[248]

References

IMR

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Activation energies obtained from the HVEM experiment

specimen	Interstitial impurity level and solute concentration (at.%)	$E_{effec.M}^{I}$ (eV)	Possible physical significance
Pure V	High purity (HP)	0.24	$E_M^I + E_b$ b.w. a SIA and an impurity
	Nominal purity (NP)	0.22	$E_M^I + E_b$ b.w. a SIA and an impurity
V-xFe	NP (X= 0.1, 0.2, 0.3, 5)	0.81	E_M^I for solute dumbbells + E_b b.w. a SIA and an interstitial impurity
	HP (X= 0.1 and 5)	0.5 for V-5Fe	E_M^I for solute dumbbells
V-yCr	NP (Y= 0.1)	N.D.	E_M^I for solute dumbbells + E_b b.w. a SIA and an interstitial impurity
	NP (Y= 1 and 5)	0.65	E_M^I for solute dumbbells + E_b b.w. a SIA and an interstitial impurity
V-1Si	NP	0.99	?
V-5Ti	HP	0.38 in stage III'	$E_M^I + E_b$ b.w. a SIA and a solute (in concentrated alloy (?))
	NP	0.39 in stage III'	$E_M^I + E_b$ b.w. a SIA and a solute (in concentrated alloy (?))
V-4Cr-4Ti	NP	0.50 in stage III' 1.0 in stage IV	$E_M^I + E_b$ b.w. a SIA and a solute (in concentrated alloy (?)) ?
NIFS H-I	As-received	N.D.	Trapping by metal impurities
	HP	N.D.	Trapping by metal impurities

Mobility of Defects in V-alloys

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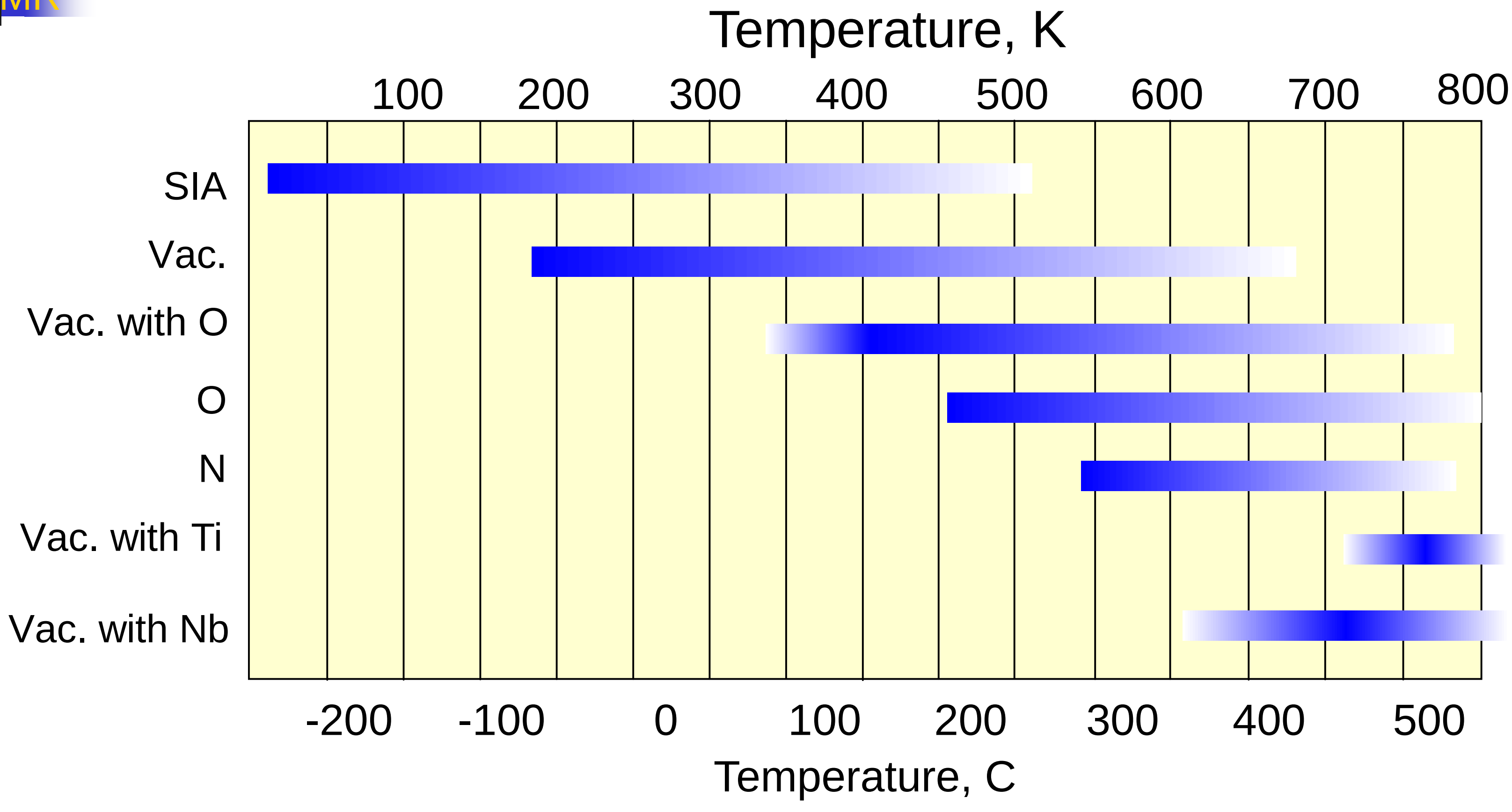
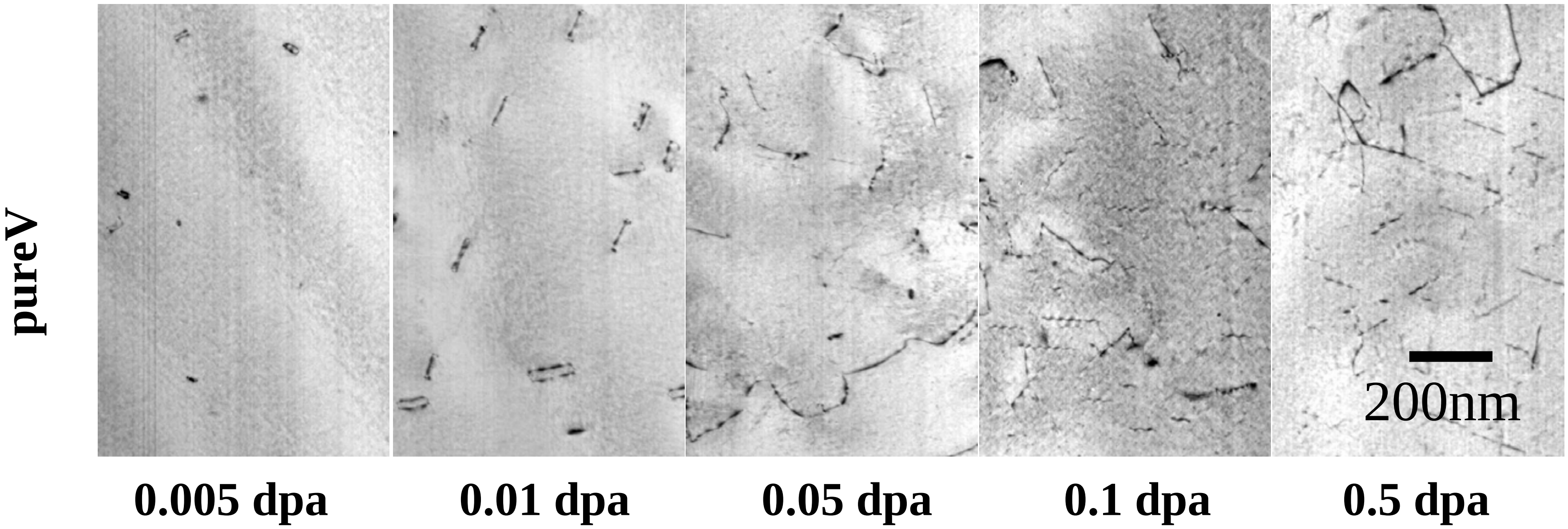


Compiled from available data of TEM, positron, Q^{-1}

Dislocation Loops

- Based on TEM observation:
  - Neutron irradiated in JMTR

JMTR, 350C

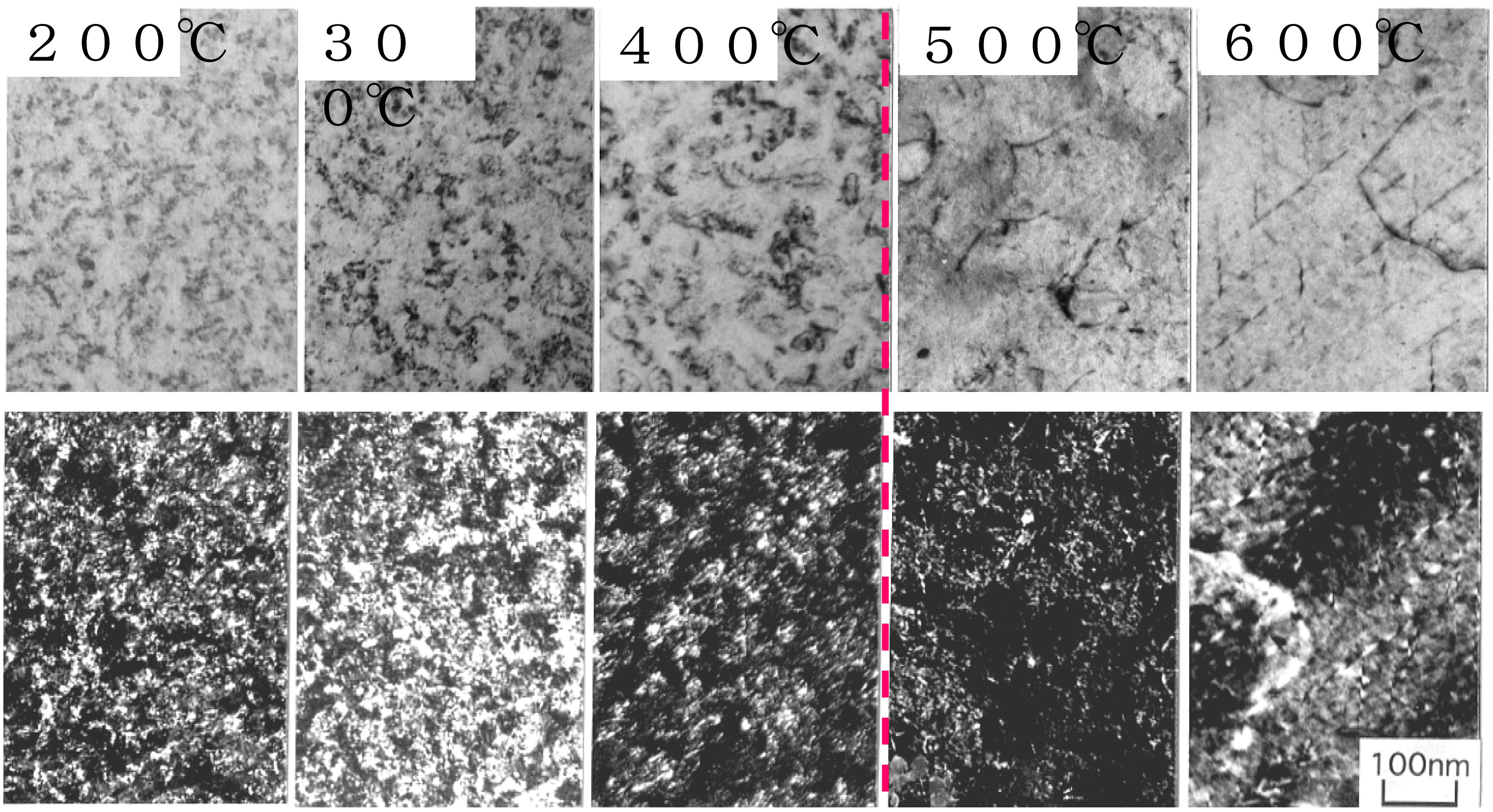


V: Temp. Dependence of Damage

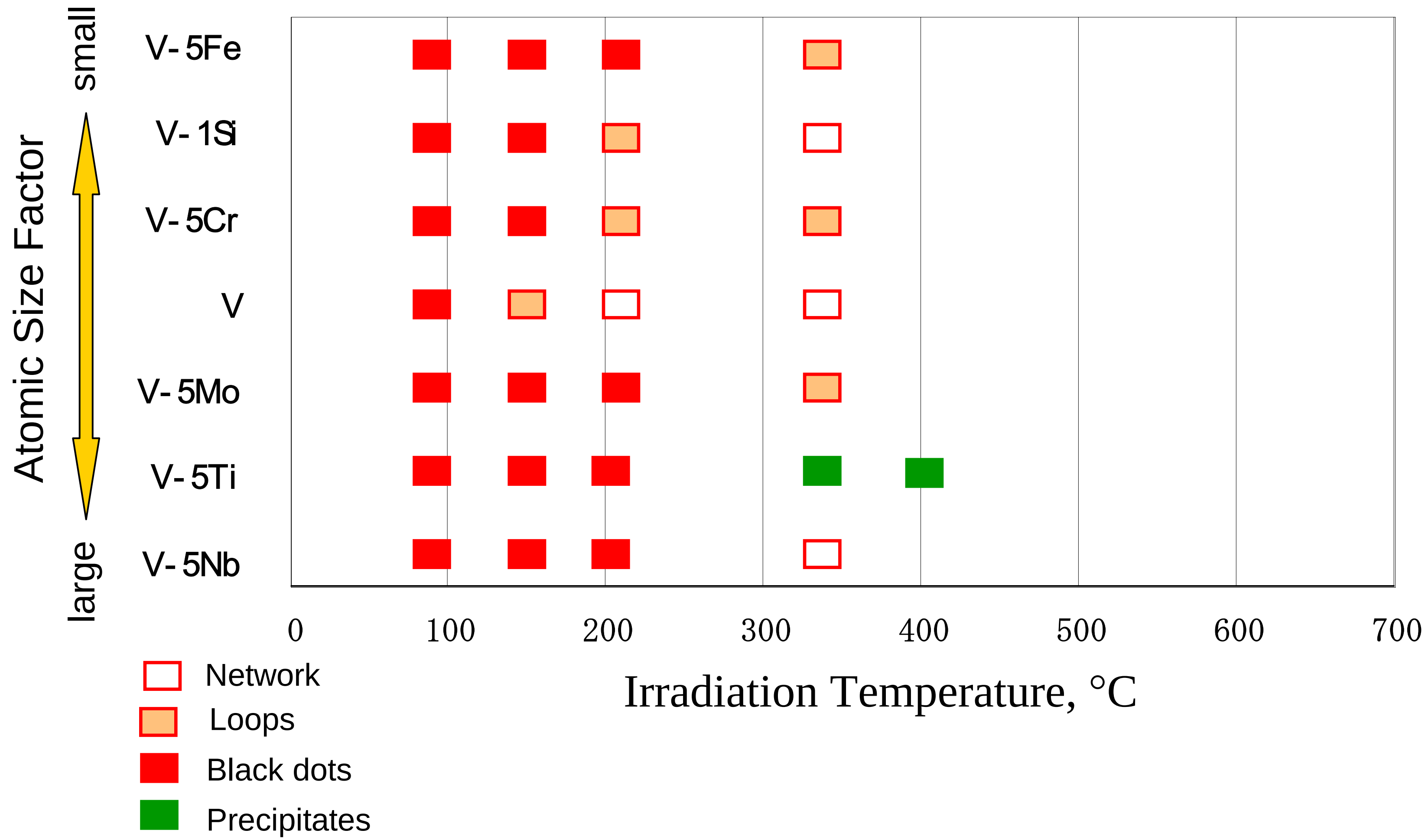
H. Watanabe & N. Yoshida

3MeV-Cu^{2+},0.75dpa, 200-600℃

- ***I-loops, V-clusters, precipitates, voids are formed depending on irradiation temperature.***

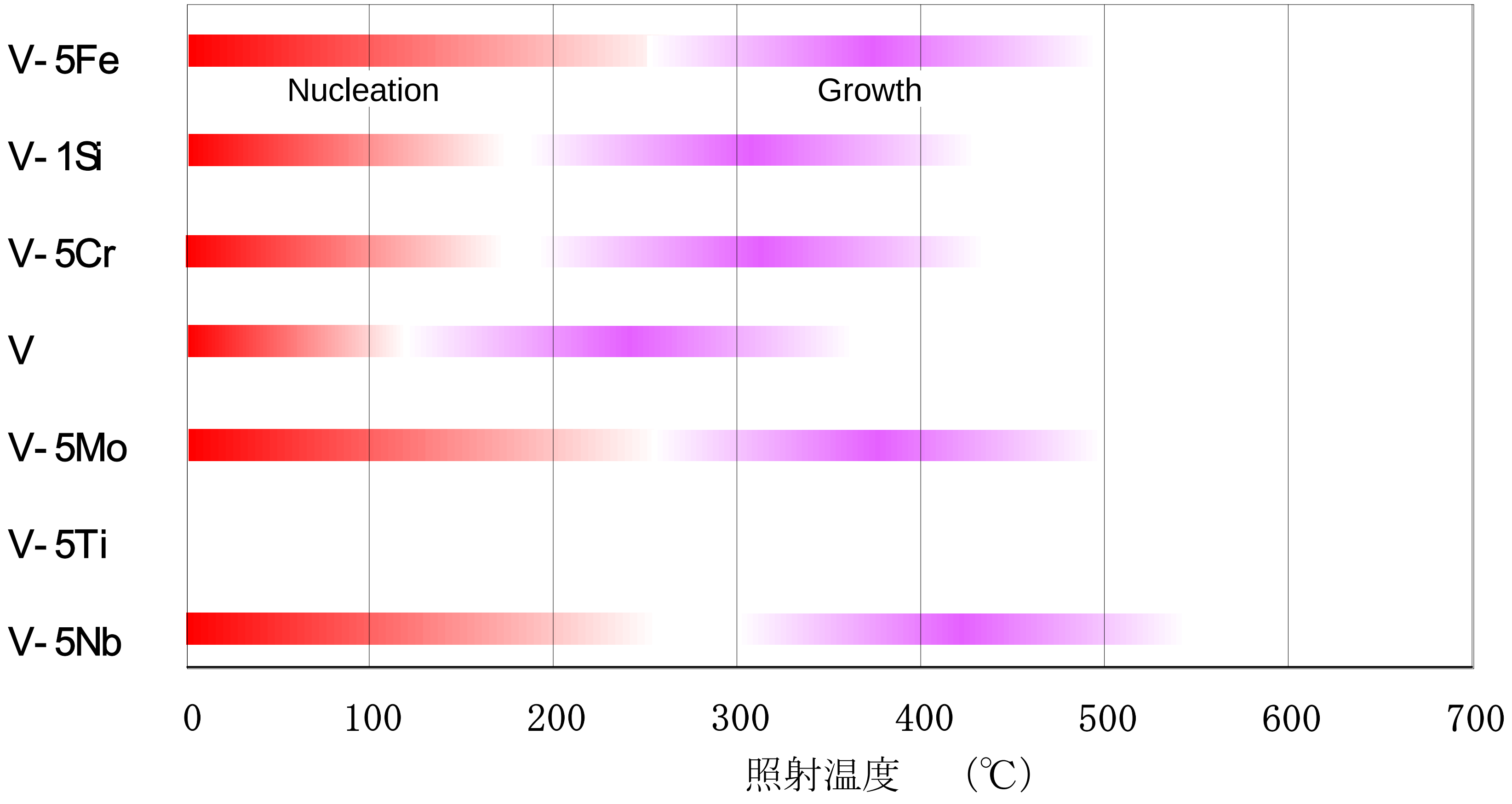


Temp. Dependence of Dislocations



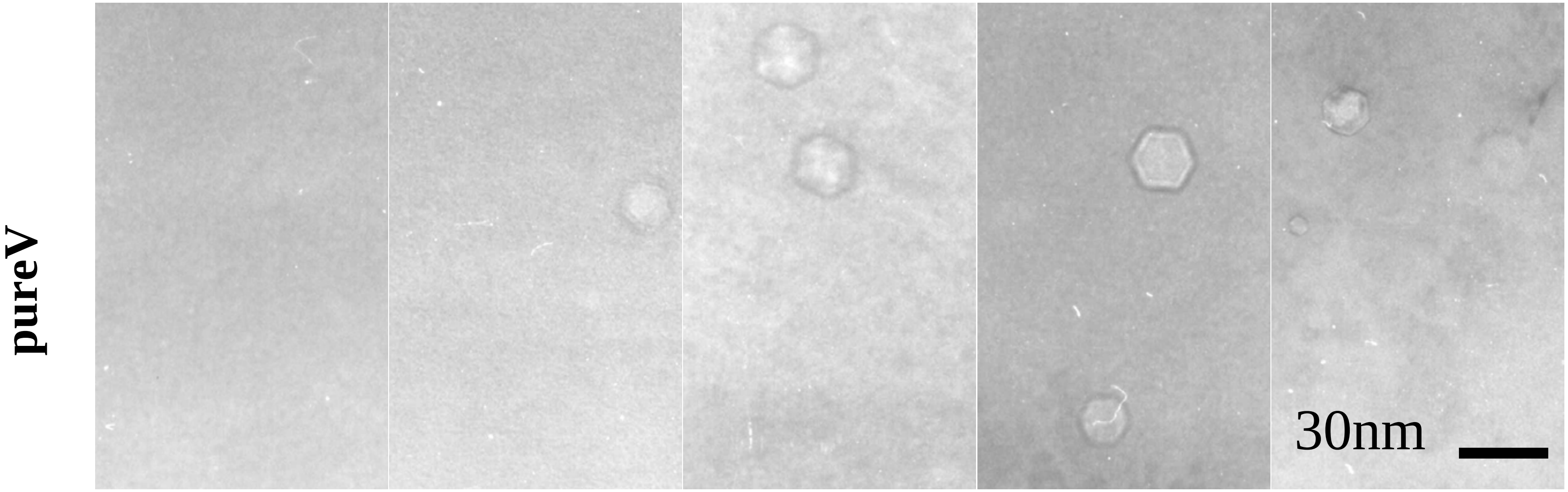
Nucleation and Growth of Dislocation Structure

IMR



Cavities

- TEM Observation



0.01 dpa **0.03 dpa** **0.1 dpa** **0.3 dpa** **1 dpa**

Positron Lifetime

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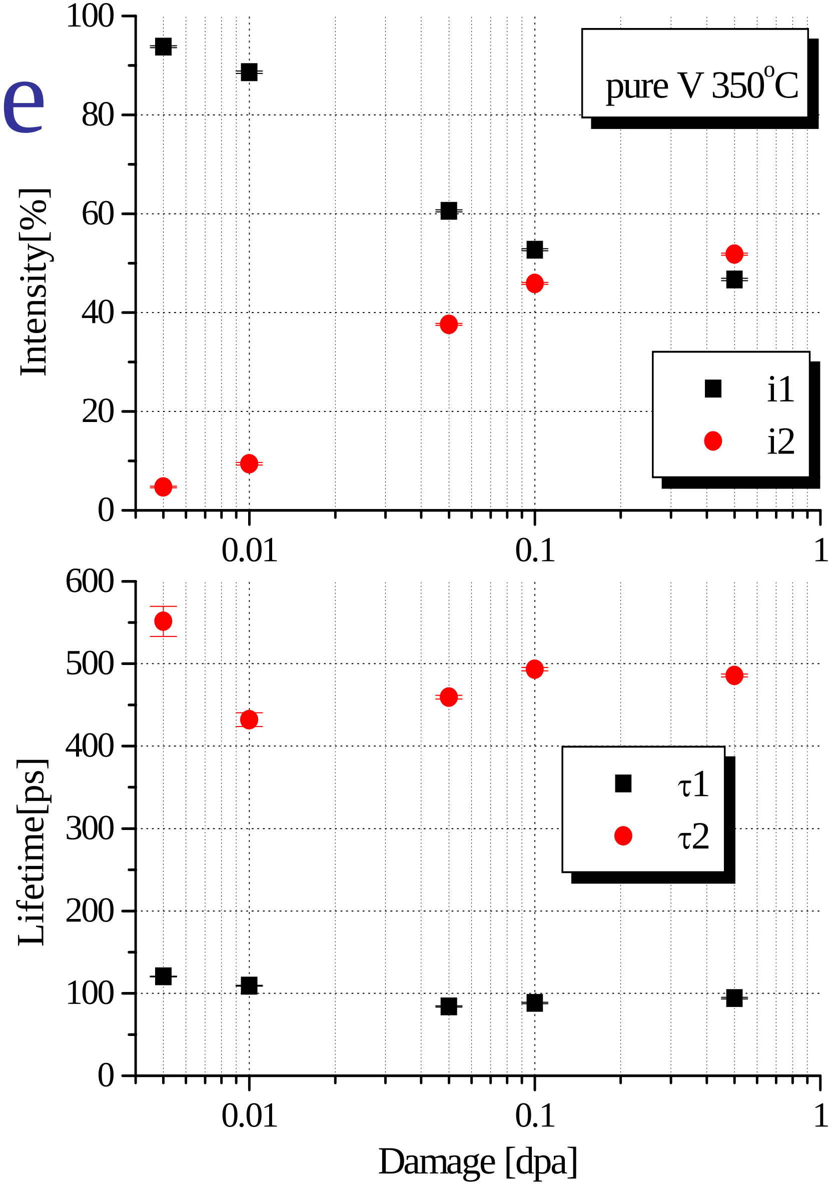
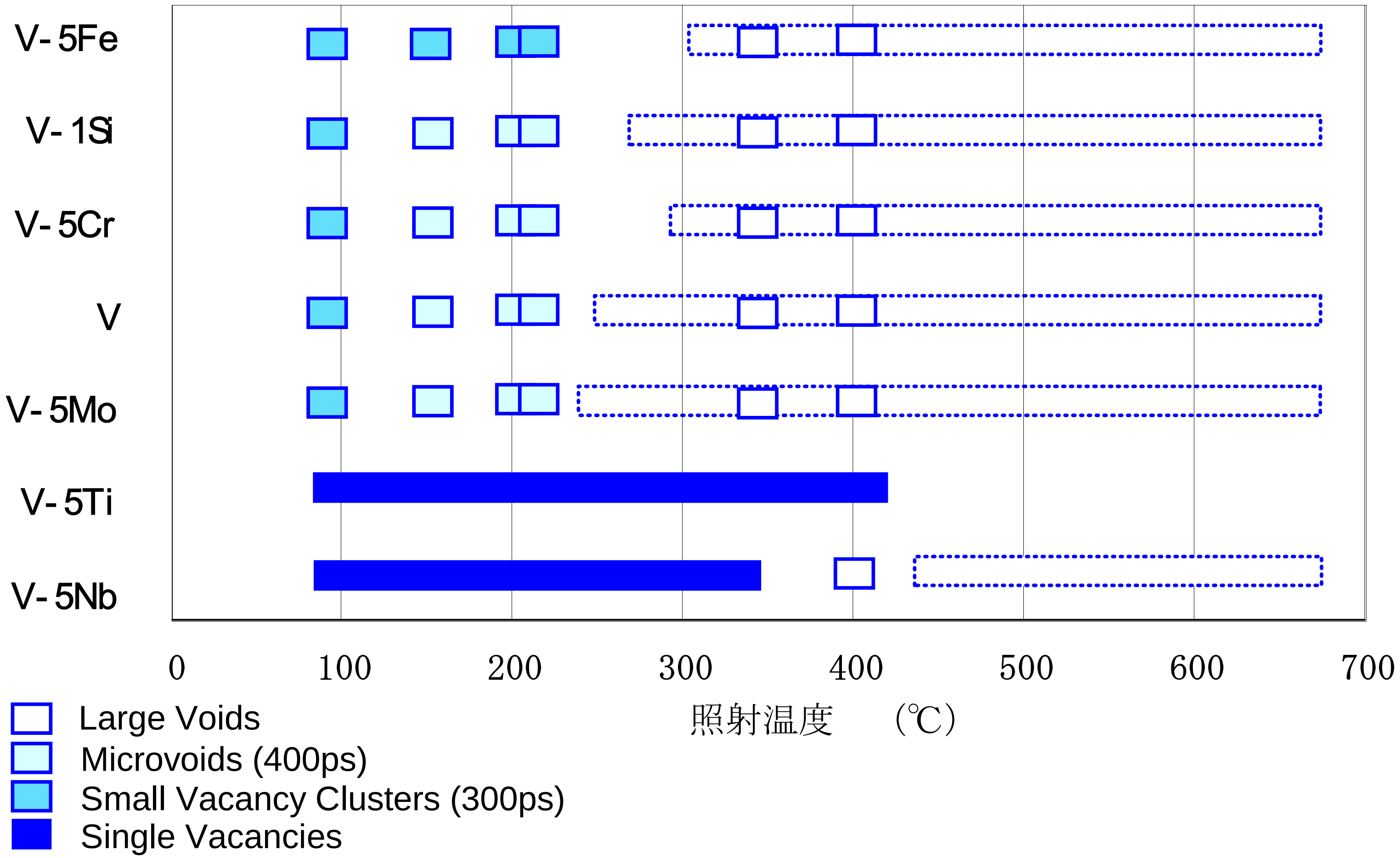
- Sensitive to V-type clusters



V-clusters under Constant Temp. Irradiation

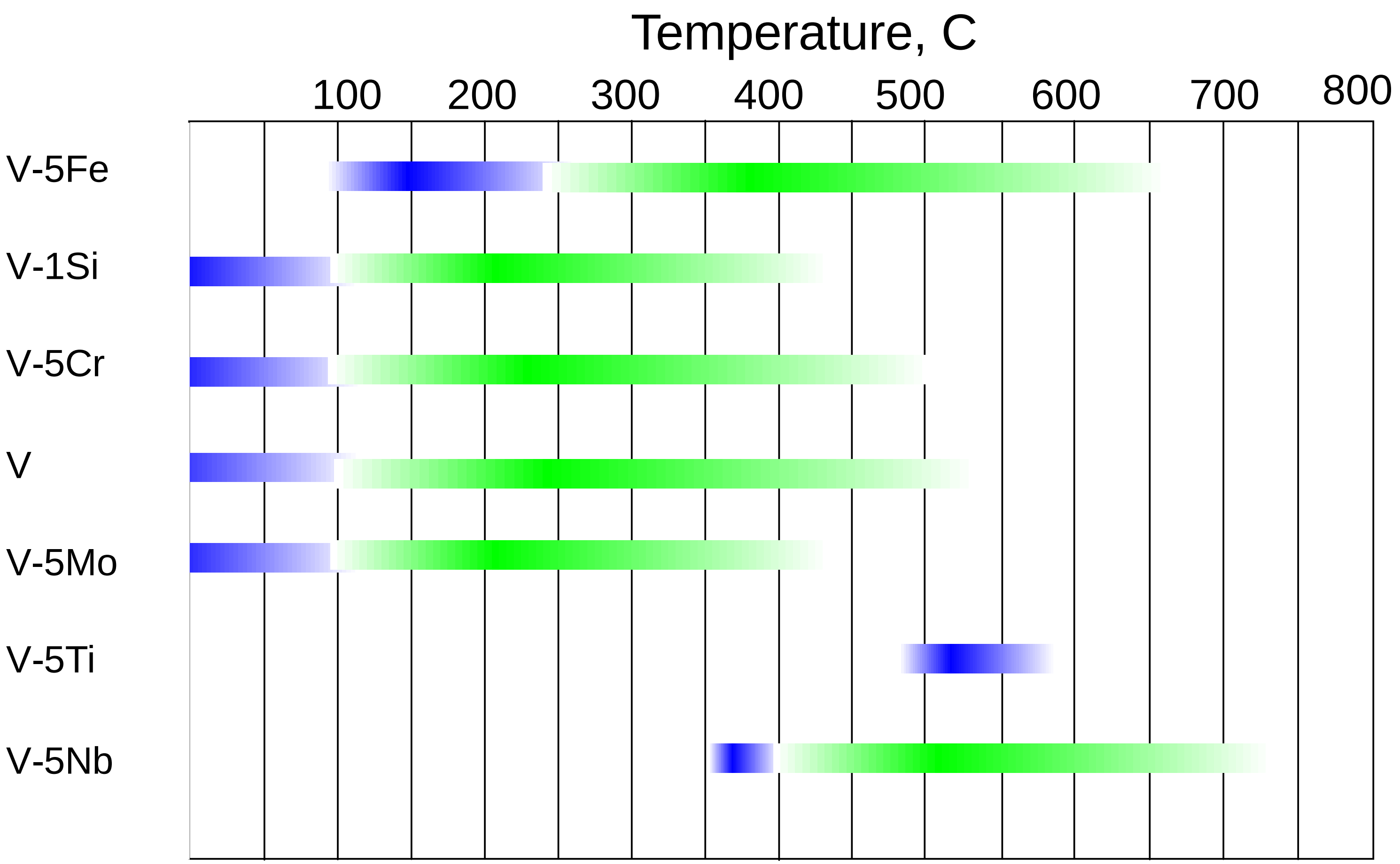
IMR



Data: Based on TEM and positron annihilation lifetime measurements

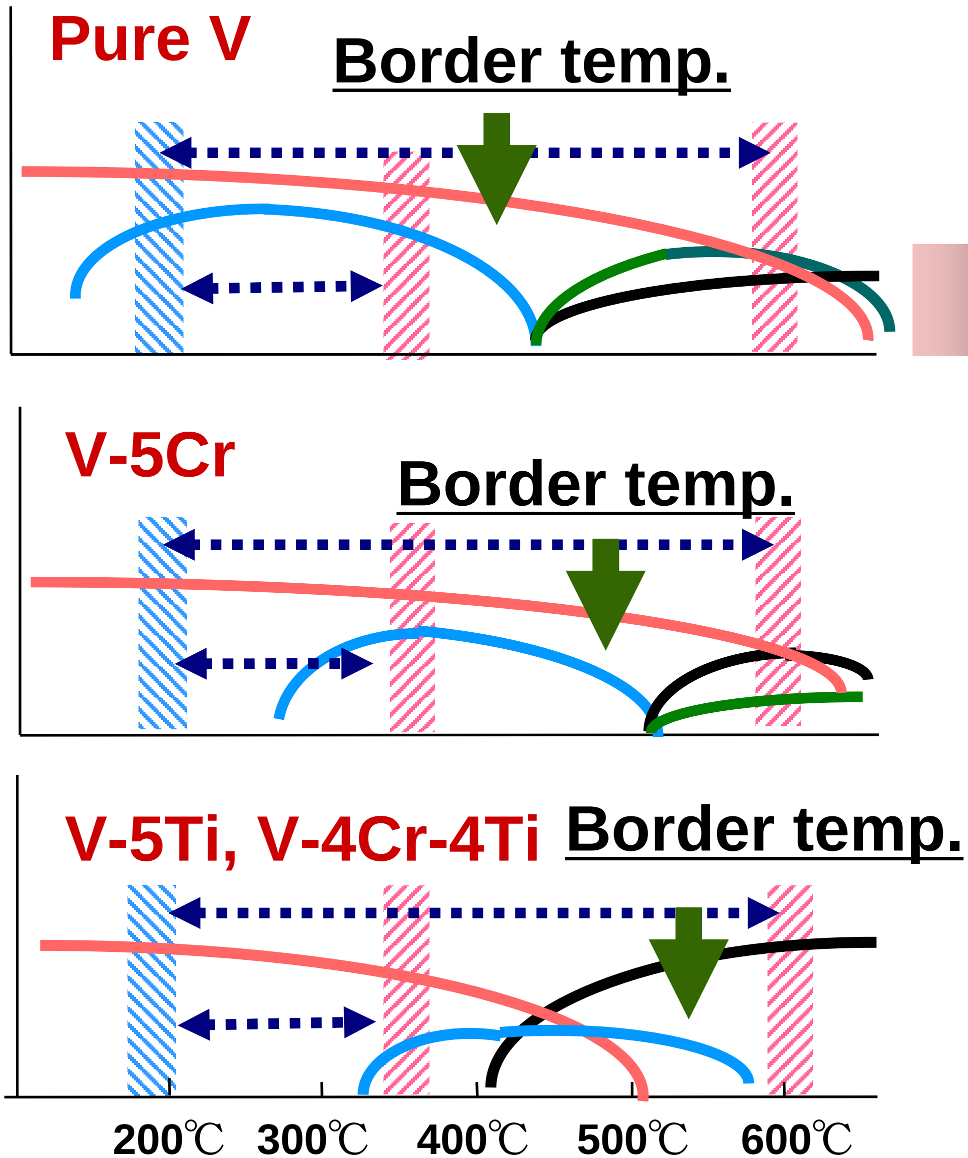
Nucleation and Growth of V-clusters

IMR



Temp. Depend. of Defect Formation in V and V-Alloys

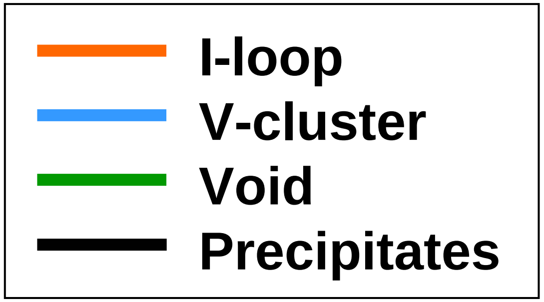
H. Watanabe & N. Yoshida



3MeV-Cu^{2+},
0.75dpa, 200-600℃

Border temp.
(Namely,Stage V)

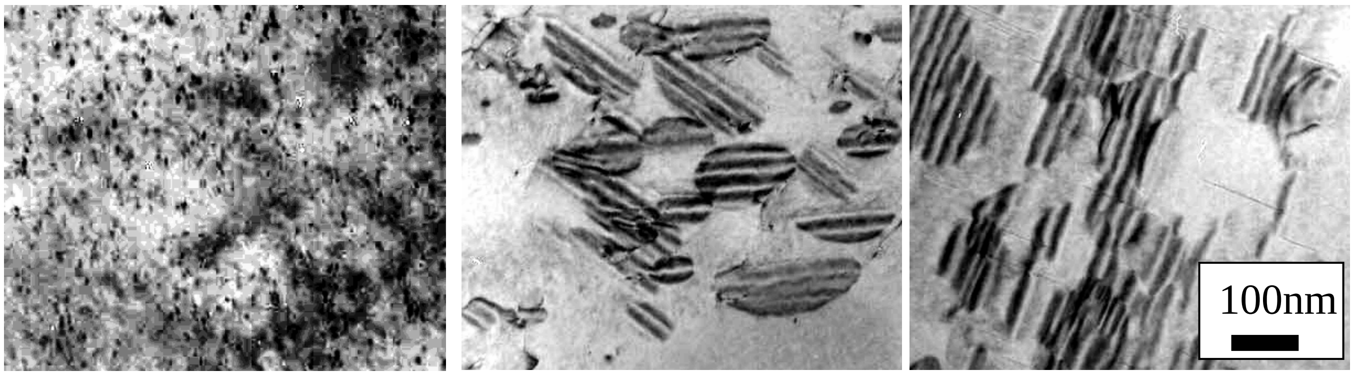
Dissociation of small V cluster
Significant effects on microstructure



Precipitates

- "Pure V"
  - VC
- V-5%Ti
  - Ti_2O, TiO, TiO_2
- V-Cr-Ti(-Si)
  - TiO, Ti(O,C,N) , Ti_5Si_3, etc.

V-5Ti



400(0.1dpa) 500(0.1dpa) 600(0.1dpa)

Precipitates

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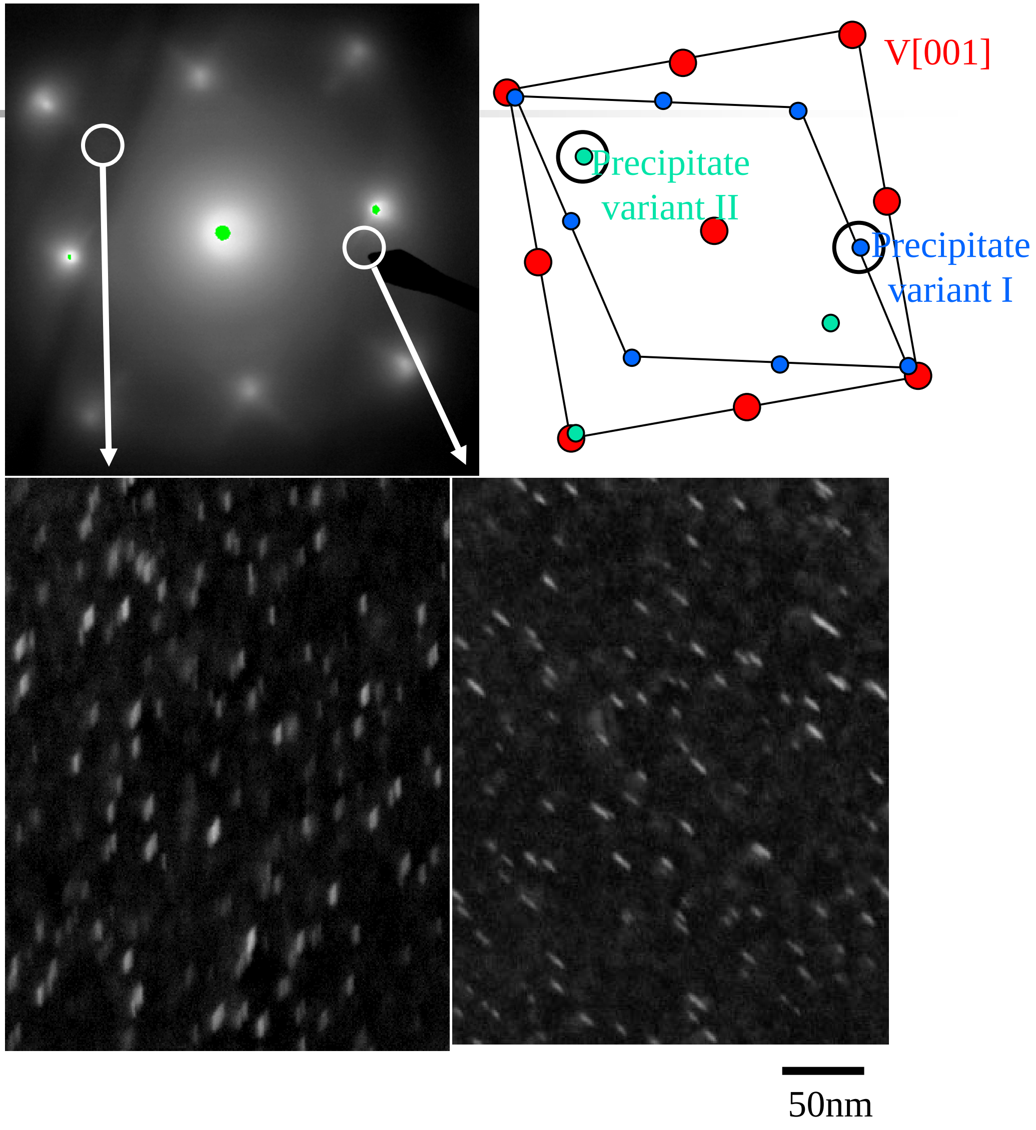
- TiO precipitates
  - Needle like, along <100>

V-3Fe-4Ti-0.1Si, 340℃, 0.061dpa



Precipitates in V-4Cr-4Ti

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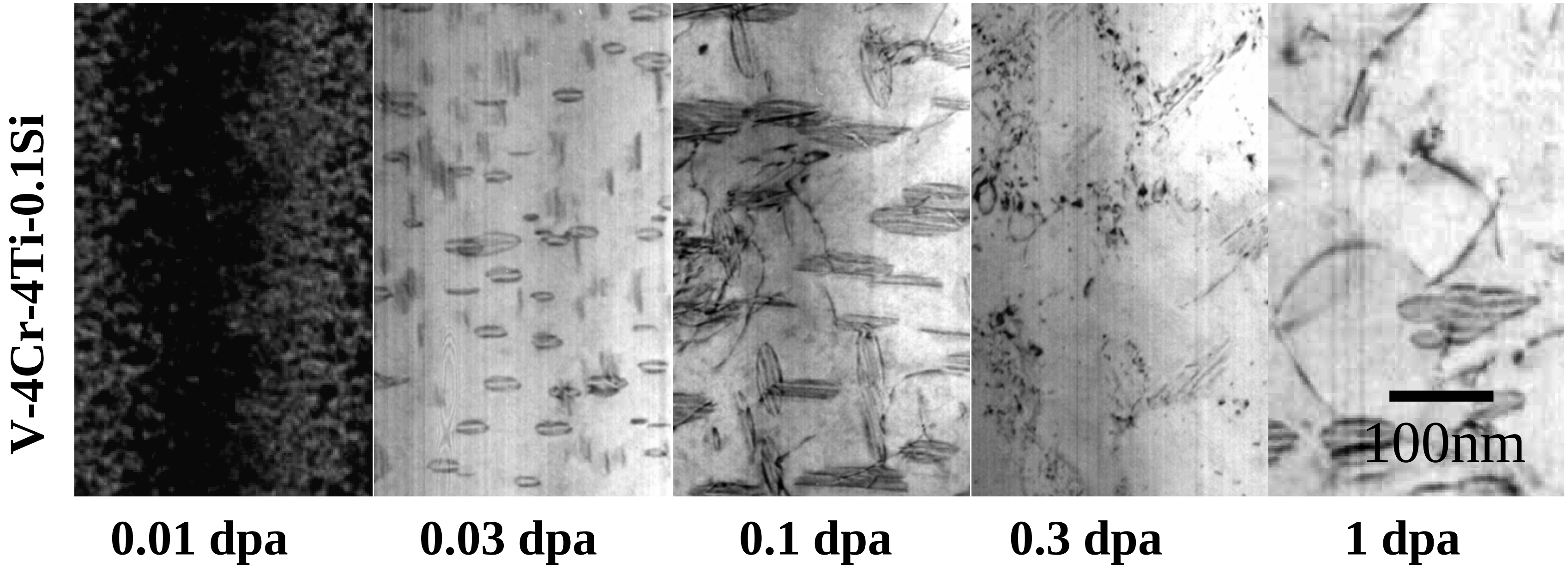
- Mostly TiO precipitates
- TiSiO

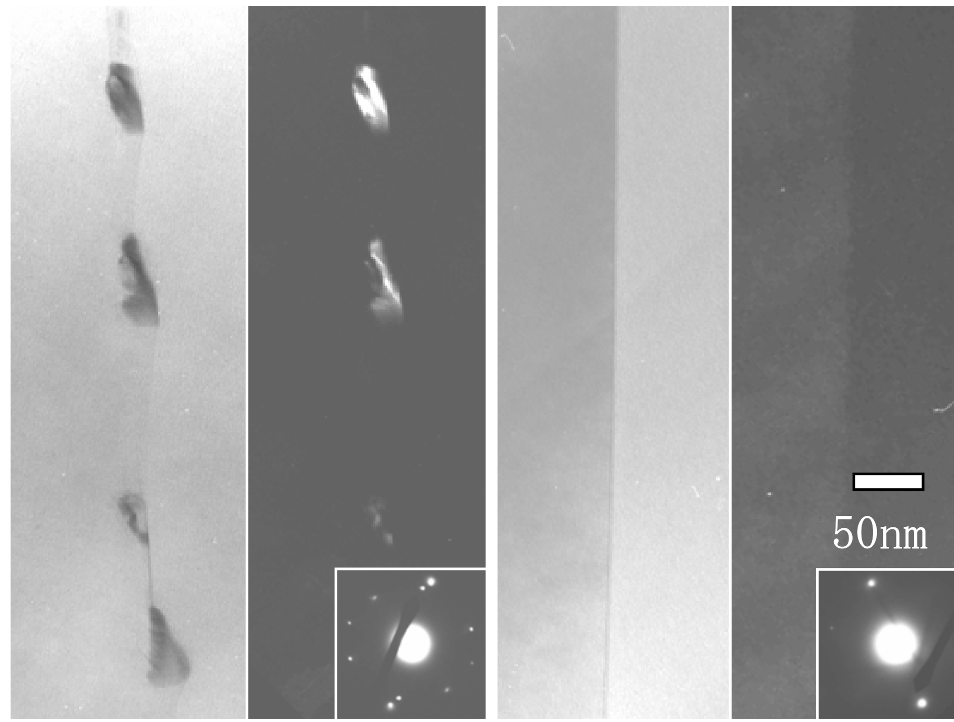
500°C



IMR

Effects of Purification

- V-4Cr-4Ti
  - Grain boundary precipitates disappear by purification



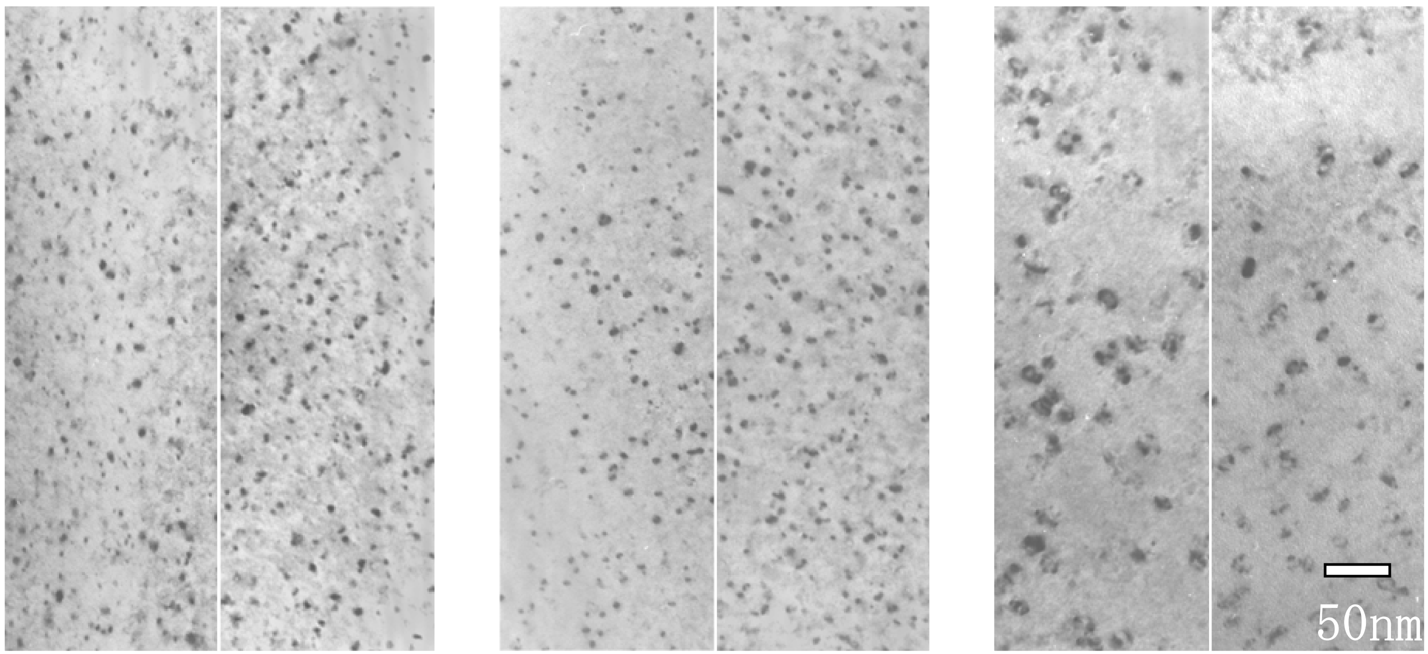
as-received

Zr-

t

O	144	wppm 2
N	124	6
C	54	3

Effect of Purification on Loops



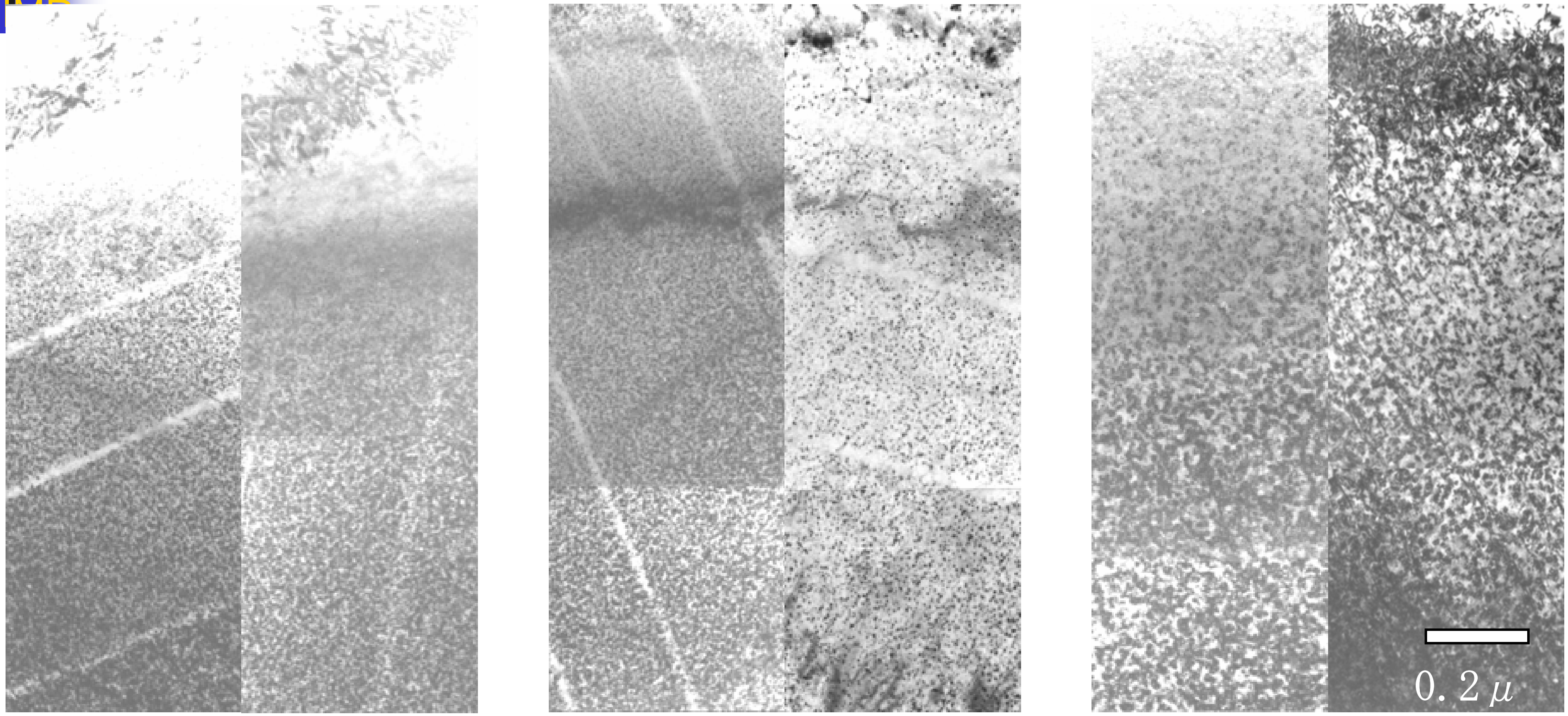
as-rcved Zr-treated as-rcved Zr-treated as-rcved Zr-treated

1dpa at: 200℃ 300℃ 400℃

- No significant effects of purification is observed

Effects of Purification on Channeling

V-4Cr-4Ti



as-received Zr-treated as-received Zr-treated as-received Zr-treated

200℃ 300℃ 400℃

- Frequency of dislocation channeling is higher in as-received material, despite no apparent difference in dot density.

Variable Temperature Irradiation

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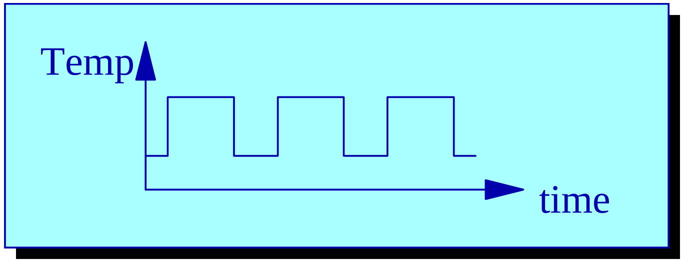
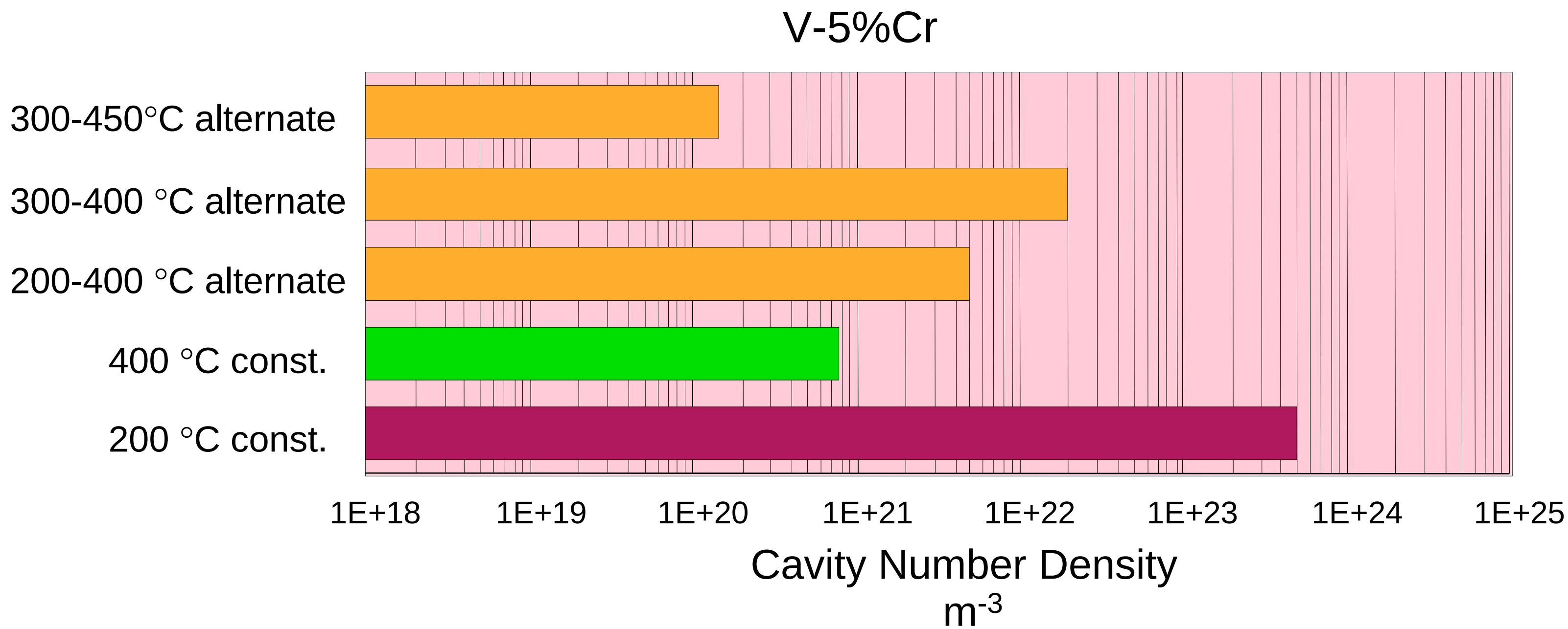
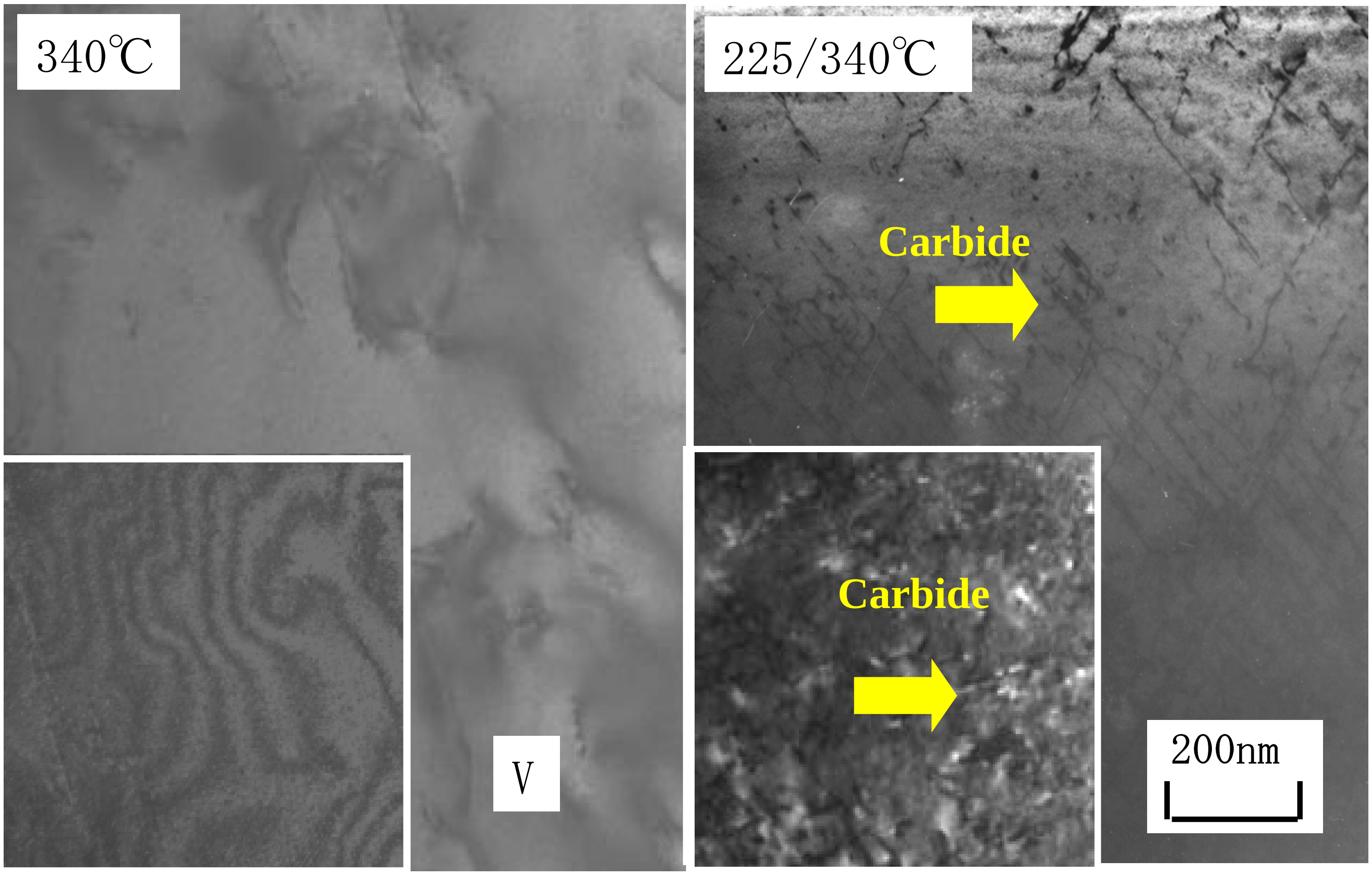
- Variable Temp. Irradiation:
  - Sometimes defect number density becomes more than an order of magnitude greater than constant temperature irradiation
  - Embrittlement, swelling, etc. will be also affected accordingly.



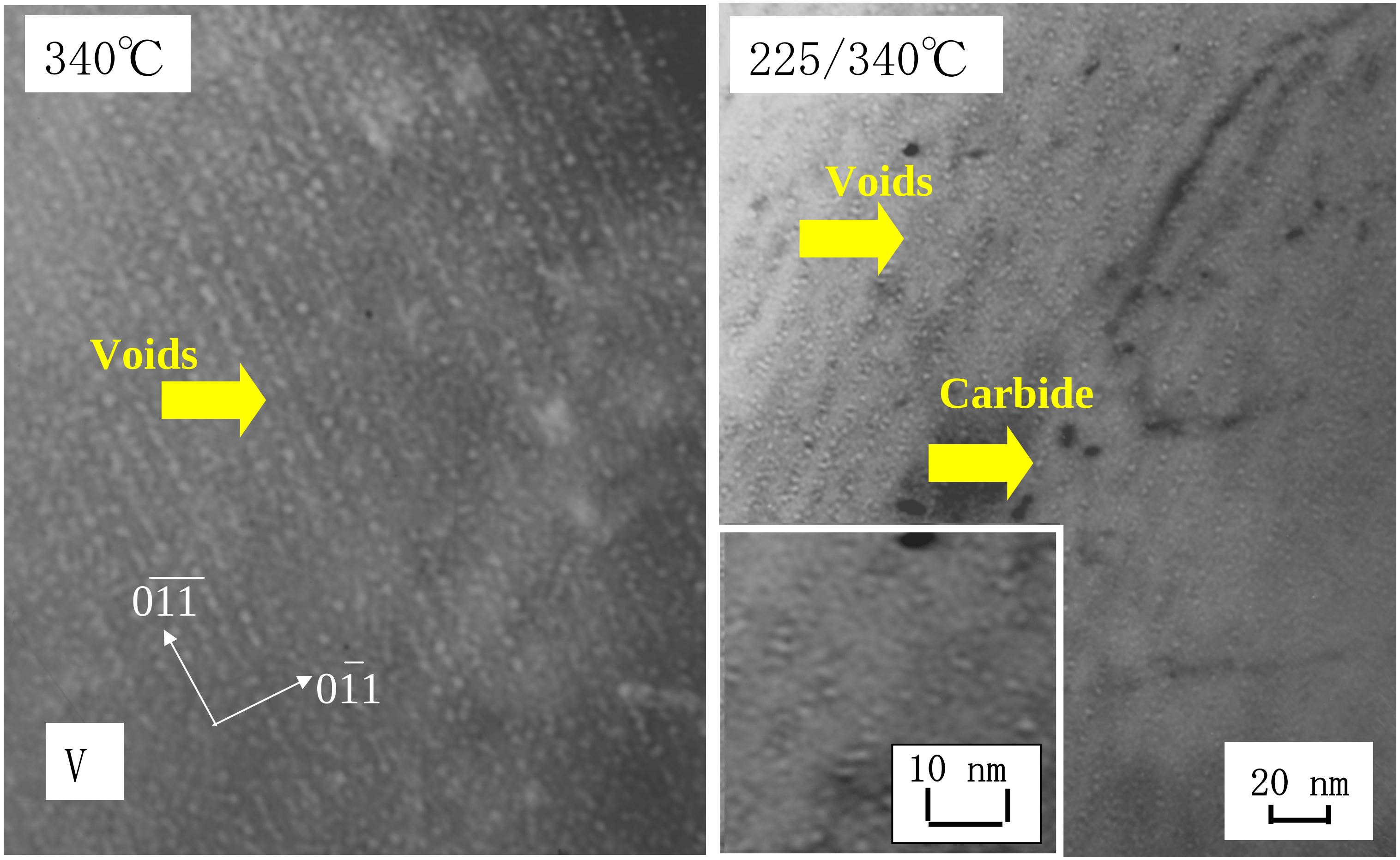


Enhanced Carbide Formation in V



Const. Temp.; Low dislocation density
Varying Temp.; They are oriented <100> direction, Carbide formation

Void Lattice Formation in V

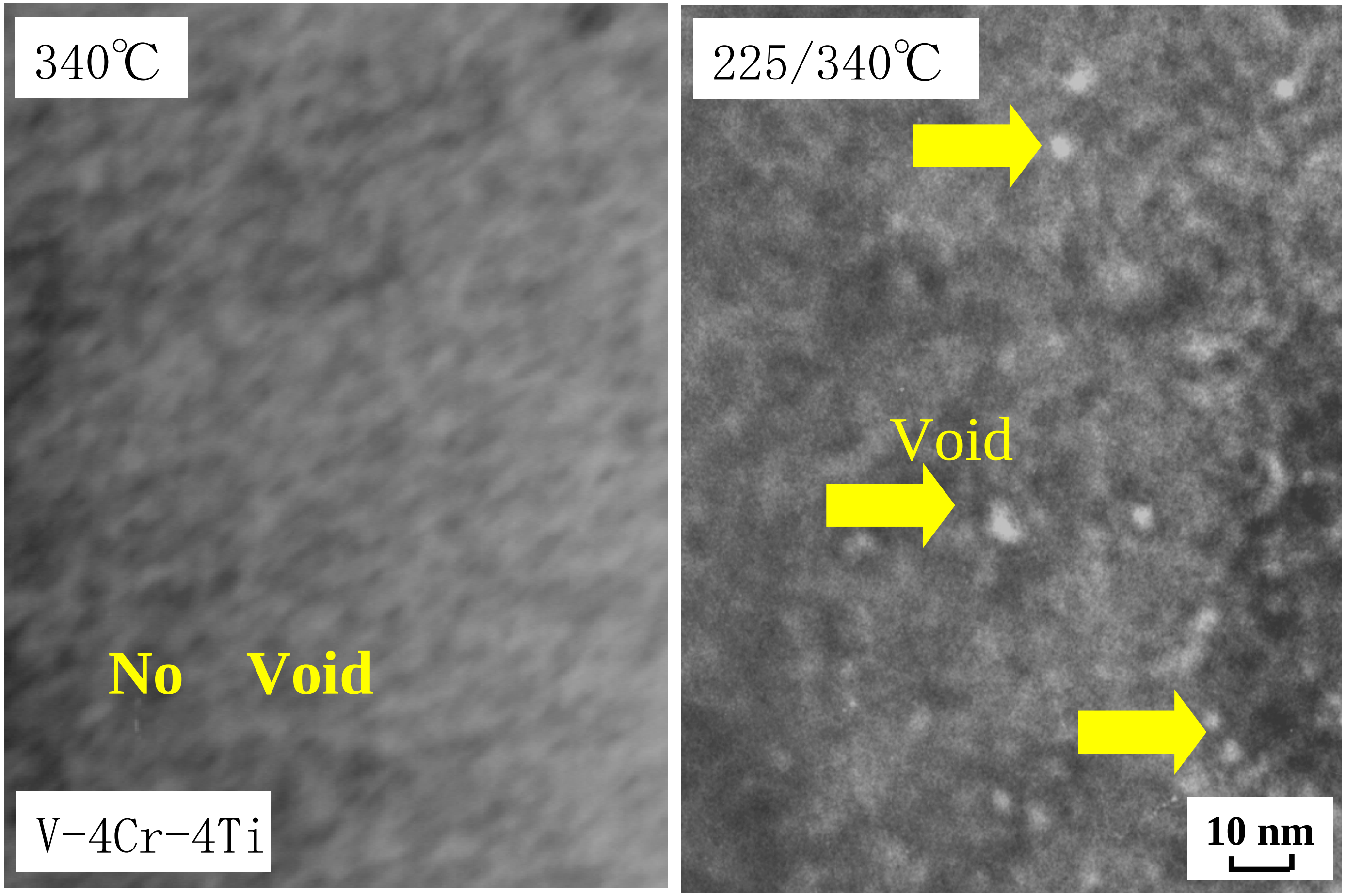


Const. Temp.; Formation of Void lattice (Effects of O?)

Size;2.8(nm) Density; 1.1 x 10^{24} (m^{-3})

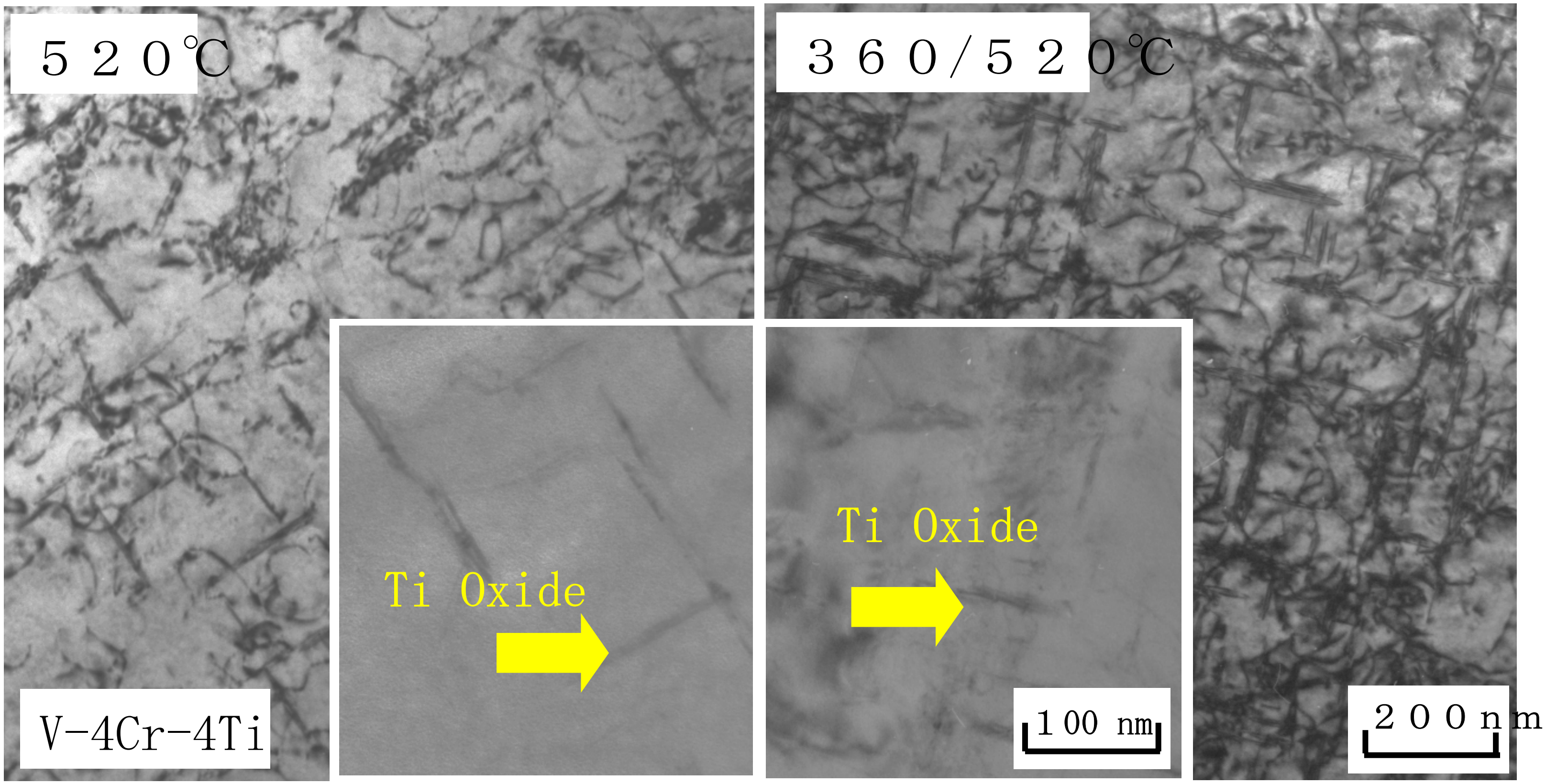
Varying Temp.; Random distribution (1.8nm, 1.4 x 10^{24} (m^{-3}))

Void Contrast Image of V-4Cr-4Ti



Small voids were observed at varying temp. condition.
→ Enhanced nucleation of Void, Oxide related?.
→ Unstable at higher dose levels?

Microstructure of V-4Cr-4Ti



- 360/520℃ irrad. produced higher Ti oxide number density
- Size of oxide; 250 → 160 (nm)

Variable Temperature Irradiation

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- Theory and Modeling of temperature variation is necessary:
  - -to make planning of irradiation experiments
  - -to understand the mechanism.
- To be fully covered in the swelling session.

Summary

IMR

- Temperature ranges of loop and void formation are relatively well understood.
- Fundamental parameters of point defects are known in pure vanadium, while the effects of alloying and impurity elements are less well known.
- Precipitates are mainly originated from interstitial impurities, and are not controlled well.
  - Tests on low oxygen materials are necessary since oxygen will be eventually re-distributed to lithium. To narrow down oxygen concentration range will be beneficial in building up database.

Summary -2

IMR

- High dose irradiation tests are lacking.
- He and H effects are still need to be addressed intensely.
  - to be covered in the swelling session.
  - Qualitative understanding has been obtained, while quantitative evaluation is not possible with high accuracy.
  - Fusion neutron source is awaited; simulation technique, e.g. DHCE may be useful.

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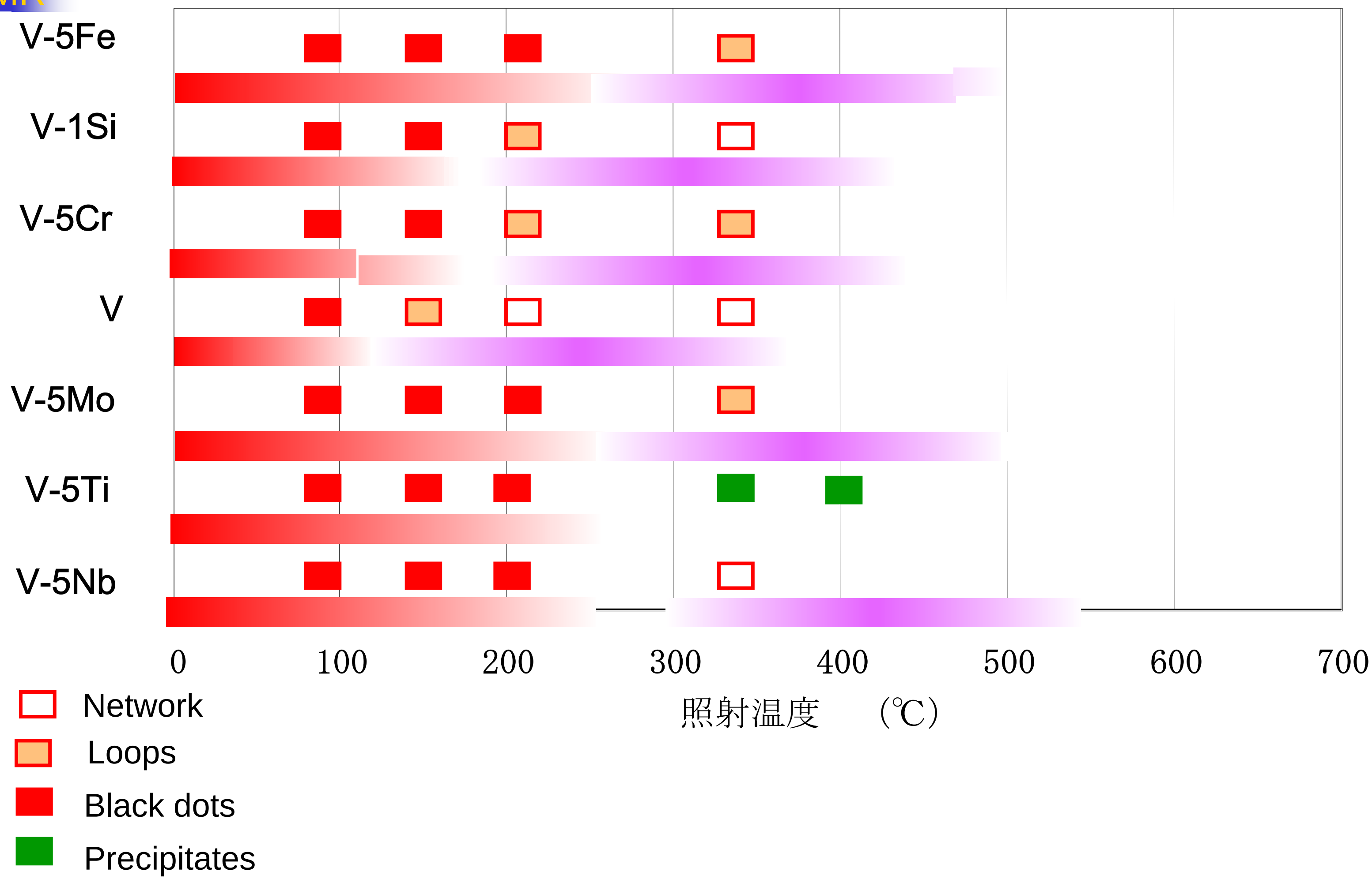
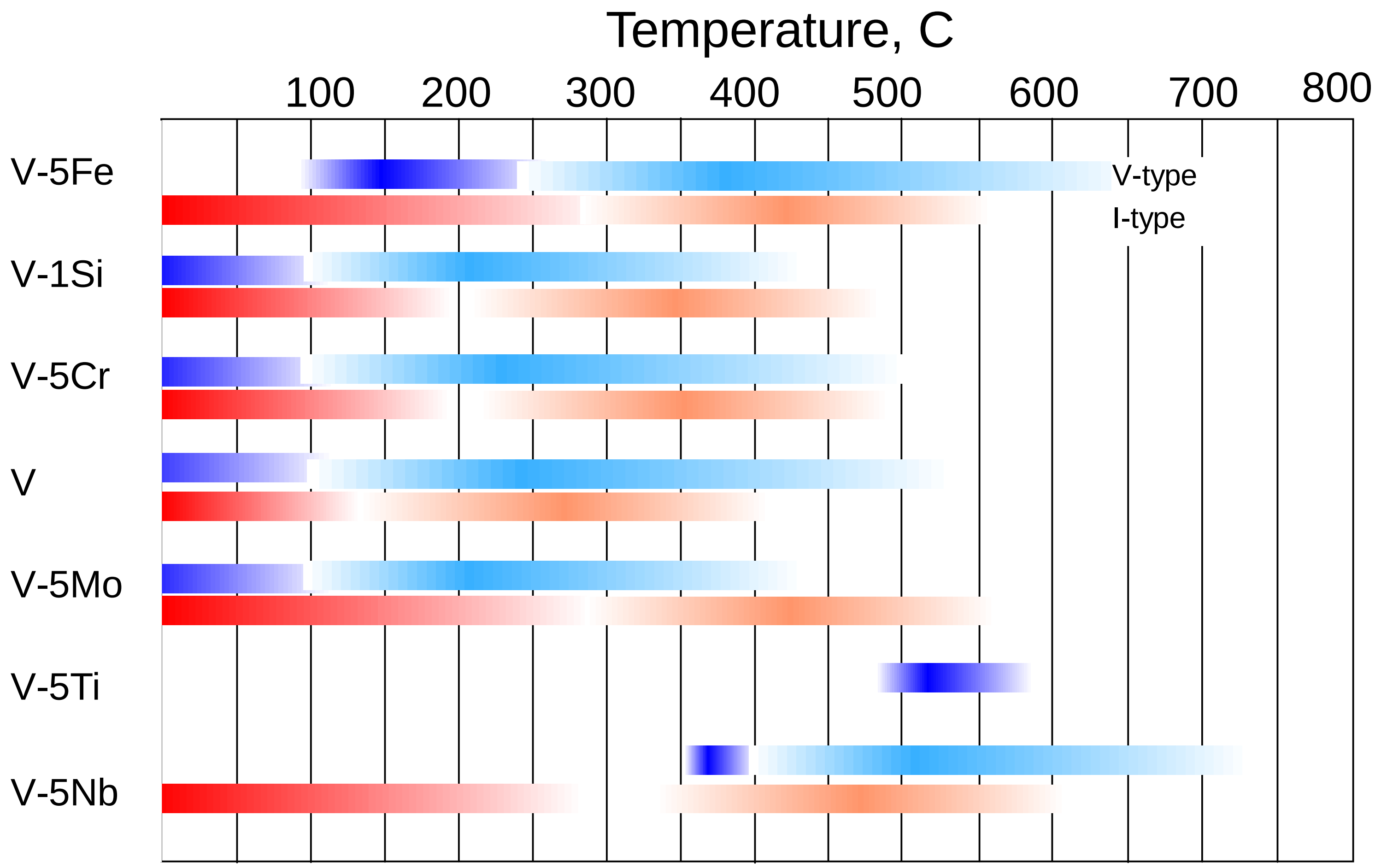
Temp. Dependence of Dislocation Structure

IMR



Nucleation and Growth of Clusters



Effects of Oxygen Reduction

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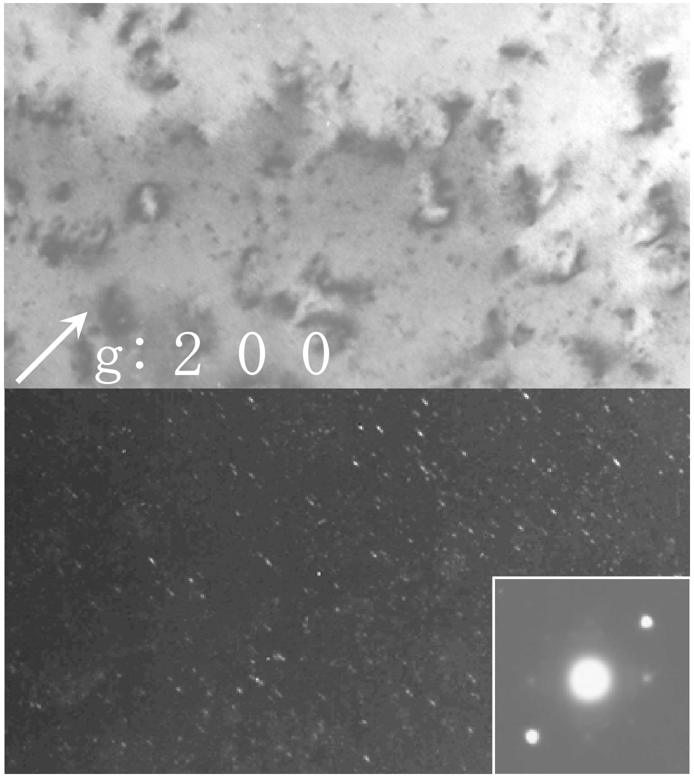
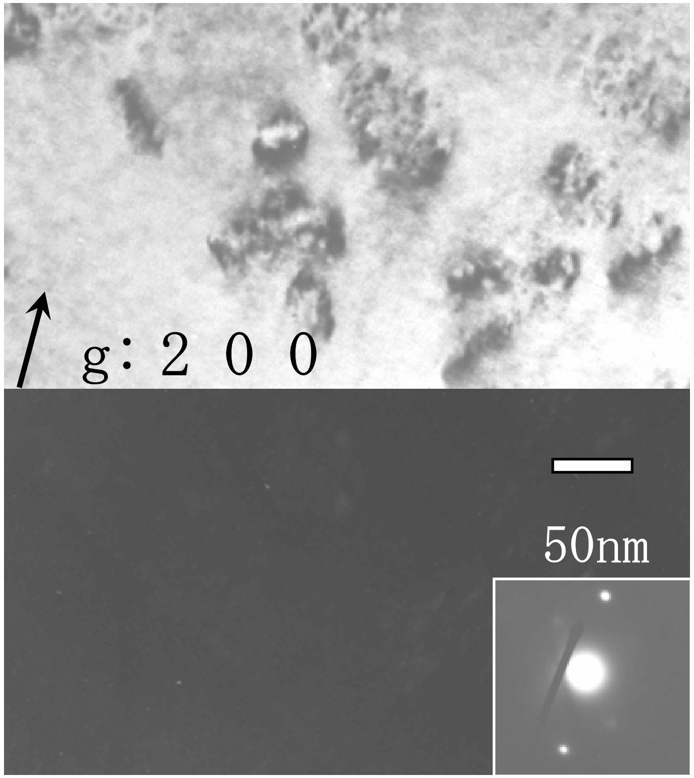
- Fine precipitates disappear by reducing oxygen

V-5%Ti
400C, 1dpa





as-received (C_0=400wppm)

Zr-treated (C_0=33wppm)