Recent Progress of Tungsten R&D for Fusion Application in Japan

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13th International Workshop on Plasma-Facing Materials and Components for Fusion Applications and 1st International Conference on Fusion Energy Materials Science

May 09th - 13th, 2011 in Rosenheim, Germany

Outline

- Tungsten Materials Development
  - **TFGR (Toughened, Fine-Grained, Recrystallized) W-1.1%TiC**
    - H. Kurishita (Tohoku Univ.), et al.
  - **W coating on reduced activation materials**
    - A. Kimura, R. Kasada (Kyoto Univ.), et al.
- Neutron Effects
  - **Retention in neutron damaged W**
    - Y. Hatano (Toyama Univ.) et al. (**J-US collaboration project TITAN**)
  - **Mechanical and electrical properties of neutron irradiated W aloys (W-Re, W-Re-Os)**
    - A. Hasegawa (Tohoku Univ.), et al.
- Surface Modification Effects by Mixed Plasma Exposure
  - **D permeation by mixed ion exposure**
    - H.T.Lee, Y. Ueda (Osaka Univ.), et al.
  - **Mechanism of He induced nano-structure formation**
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- Summary and issues

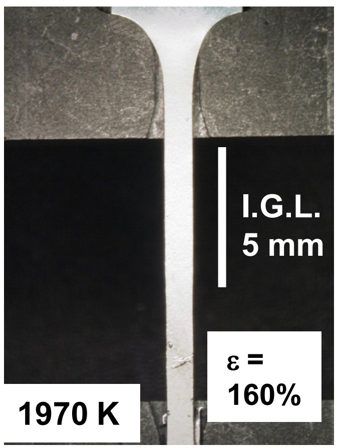
Tungsten Material Development

Conversion of UFG W-1.1TiC to TFGR W-1.1TiC by SPMM process

UFG W-1.1TiC compacts

H. KURISHITA (Tohoku Univ.)

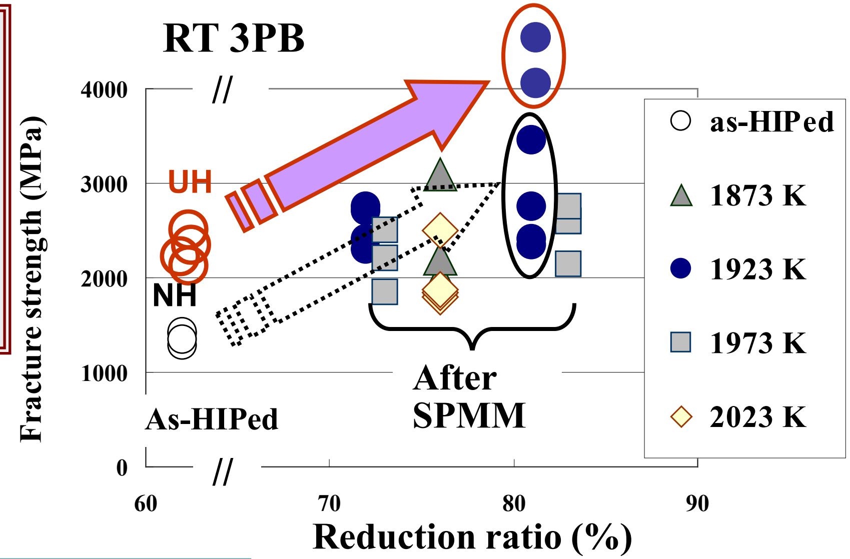
Gauge Size: 0.5 mm x 1.2 mm x 5 mm



super plasticity

SPMM process for significantly strengthening weak, high-energy grain boundaries (GBs) in UFG W-1.1TiC compacts

SPMM (<u>SuperPlasticity-based Microstructural Modification)</u>



H. Kurishita et al., JNM. 398 (2010)

TFGR W-1.1TiC compacts

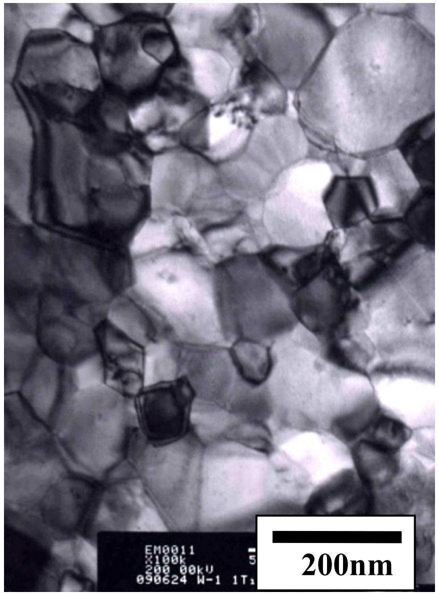
TFGR (<u>Toughened</u>, <u>Fine-Grained</u>, <u>Recrystallized</u>) W-1.1%TiC Compacts

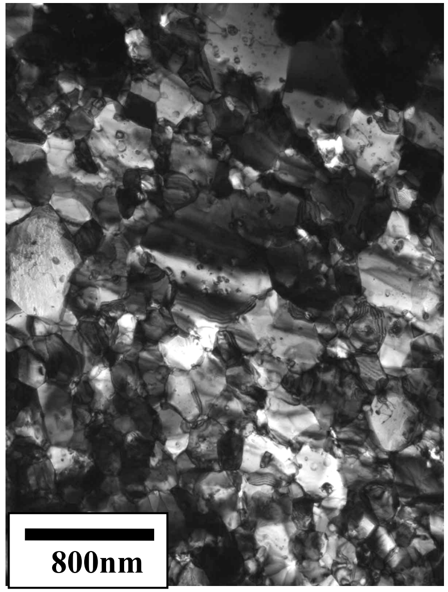
- Equiaxed grain structures with mostly random GBs and TiC dispersoids
- Very high fracture strength and appreciable bend ductility even at RT (DBTT: around RT)

Effects of SPMM temperature on microstructures

W-1.1TiC/Ar-UH

As-HIPed → SPMM : 1650 C



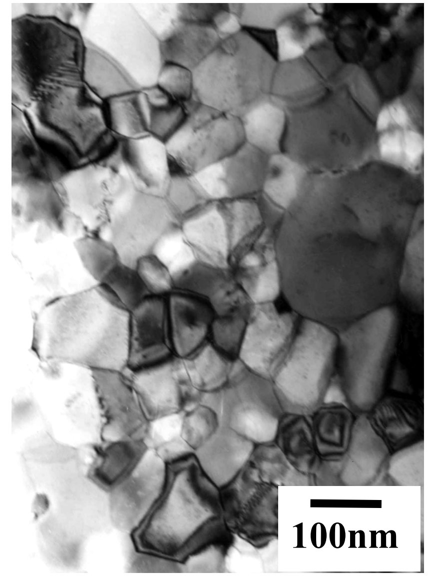


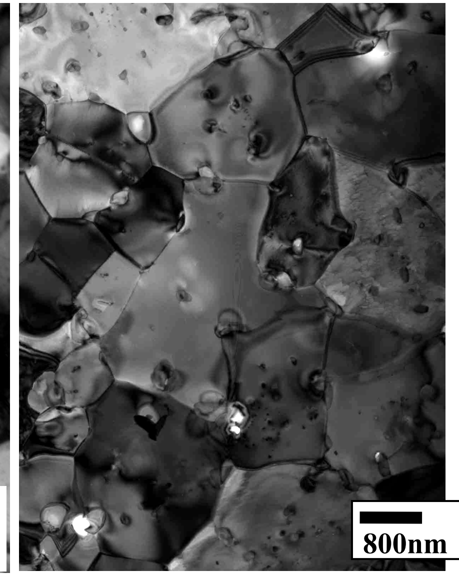
Grain size : 60 nm

Grain size : 520 nm

W-1.1TiC/H_2-NH

As-HIPed → SPMM : 1650 C



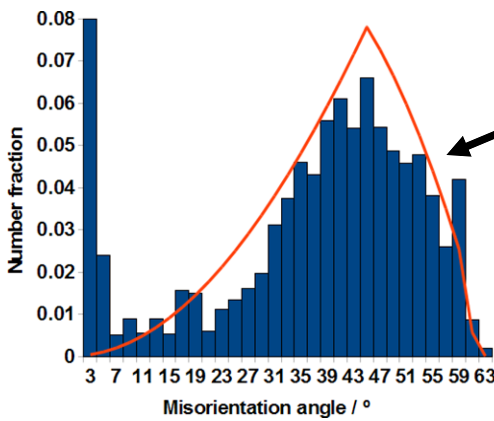


Grain size : 90 nm

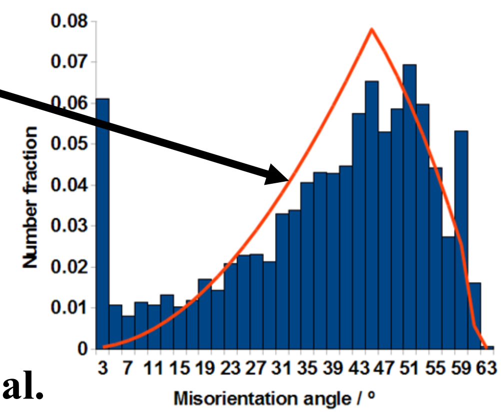
Grain size : 1480 nm

- -Recrystallized grain structures
- -Mostly high-energy random GBs

T. Sakamoto et al.

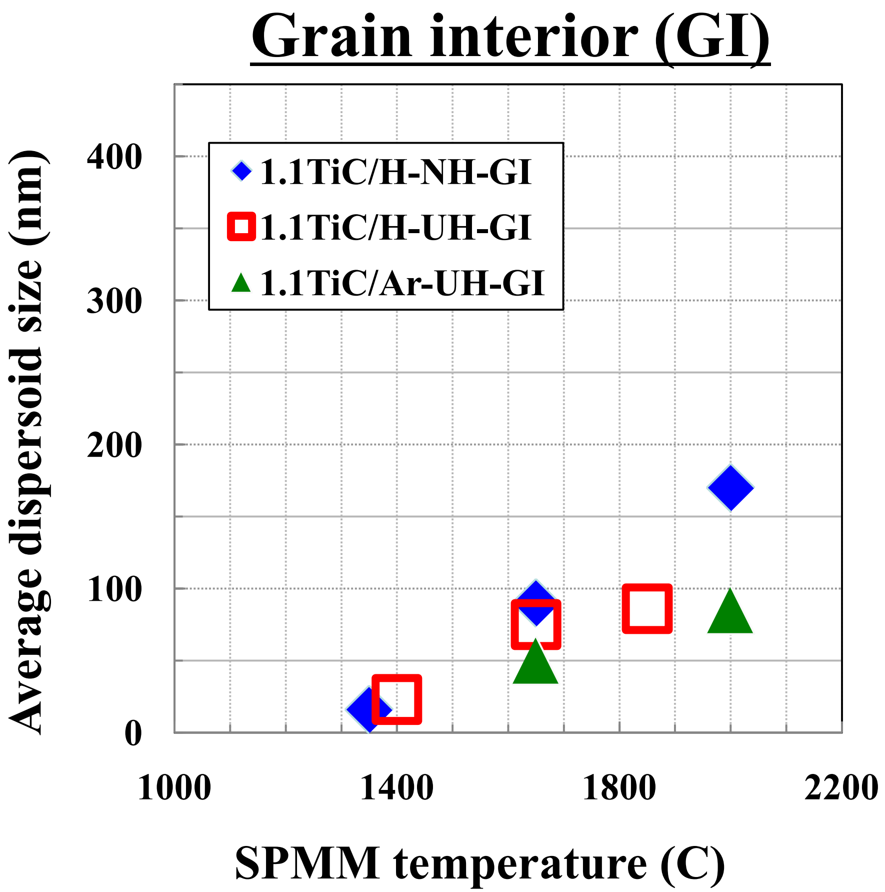


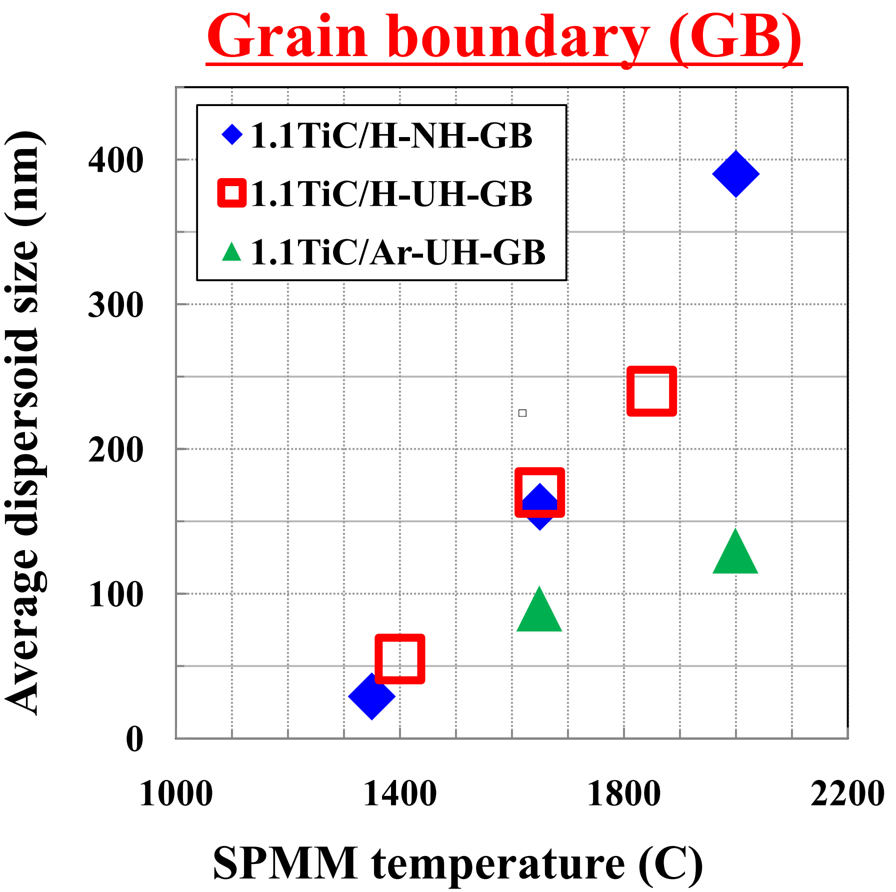
Random (Mackenzie curve)



S. Tsurekawa et al.

Effect of SPMM temp. on TiC dispersoid size

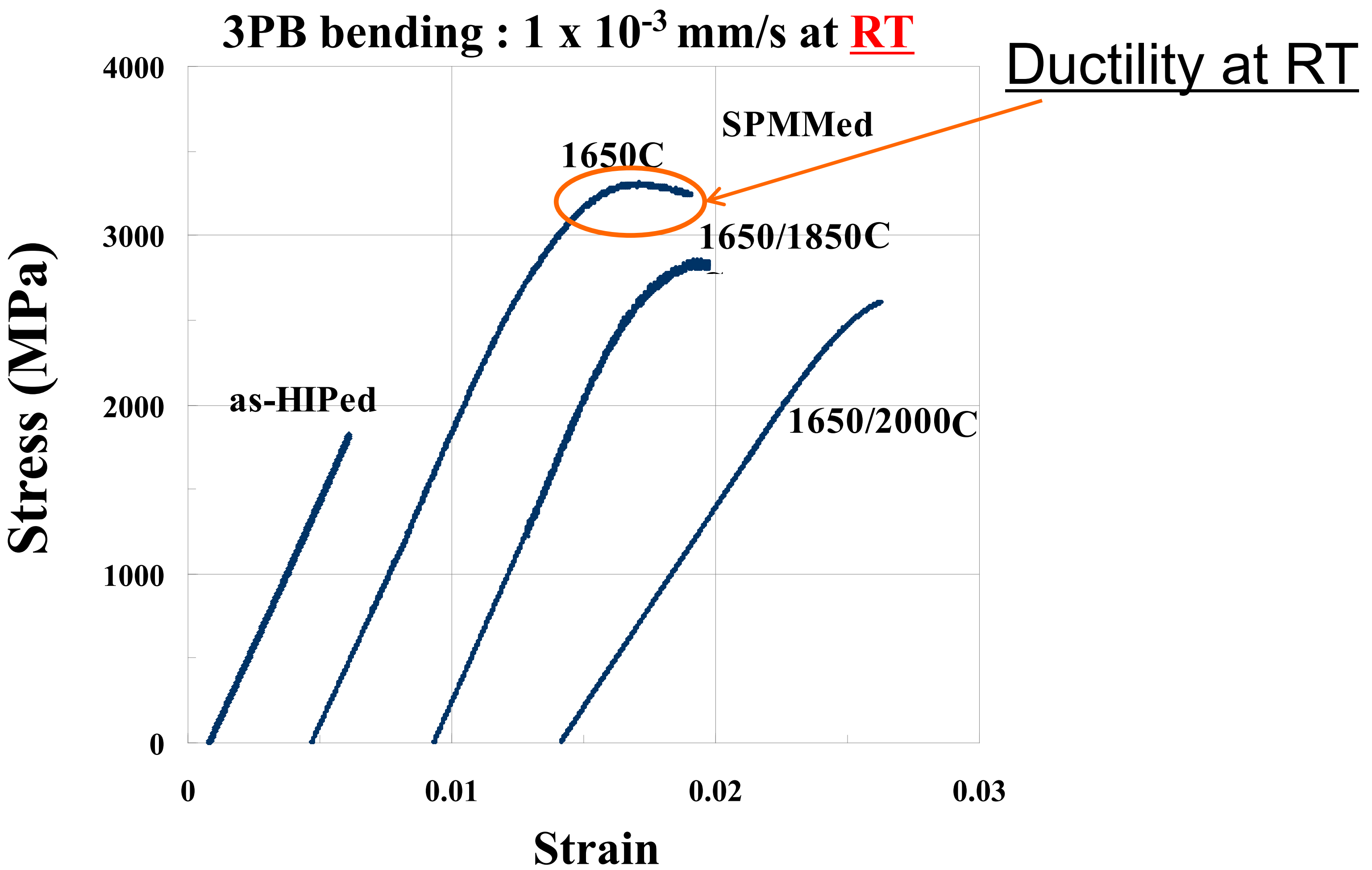




- The size of TiC dispersoids in grain interior and GBs increases with increasing SPMM temperature.
- W-1.1TiC/Ar exhibits much lower TiC growth rate than W-1.1TiC/H_2.

T. Sakamoto et al.

Effect of SPMM temperature on stress strain curve at RT for W-1.1TiC/H_2-NH

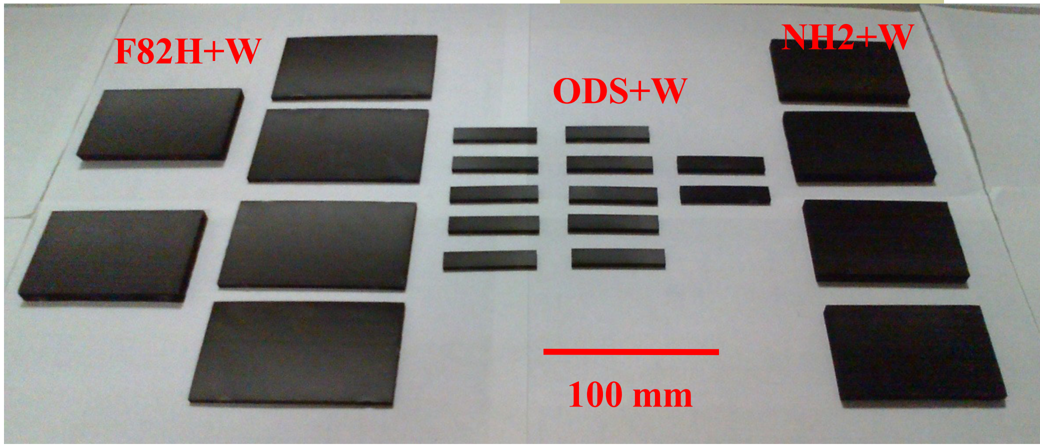


The samples exposed to 1850 and 2000C still exhibit slight ductility at RT and much higher strength than the as-HIPed, UFG sample.

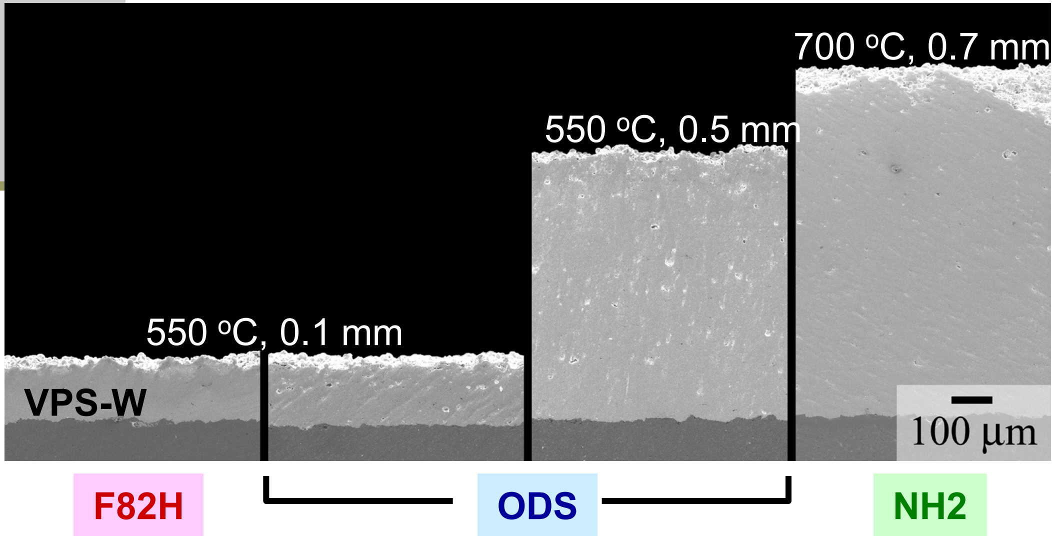
W coating on reduced activation materials by VPS (vacuum plasma spray)

Trade-off:
- Higher temperature is better for VPS coating
- Process temperature is limited by substrate materials

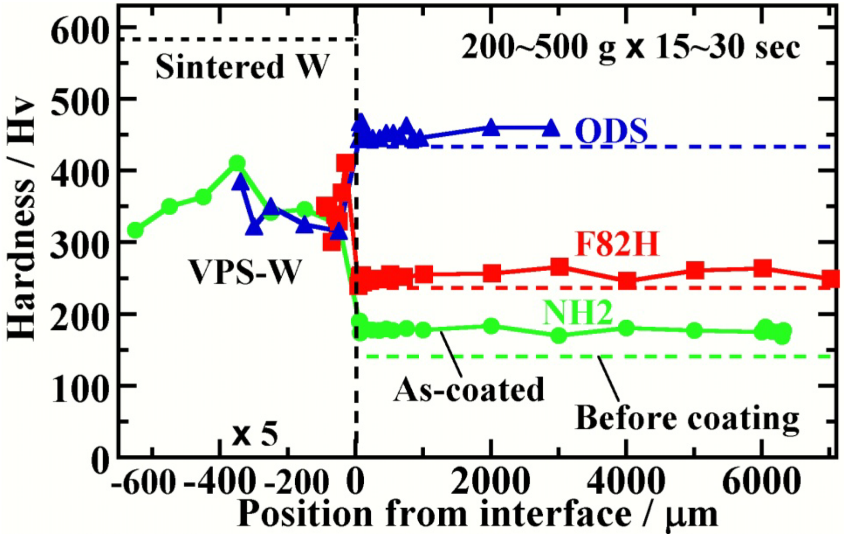
- VPS-W coating was successful for F82H, ODS, and NH2 (V-alloy).



W-coated low activation materials



Cross section of VPS-W coating

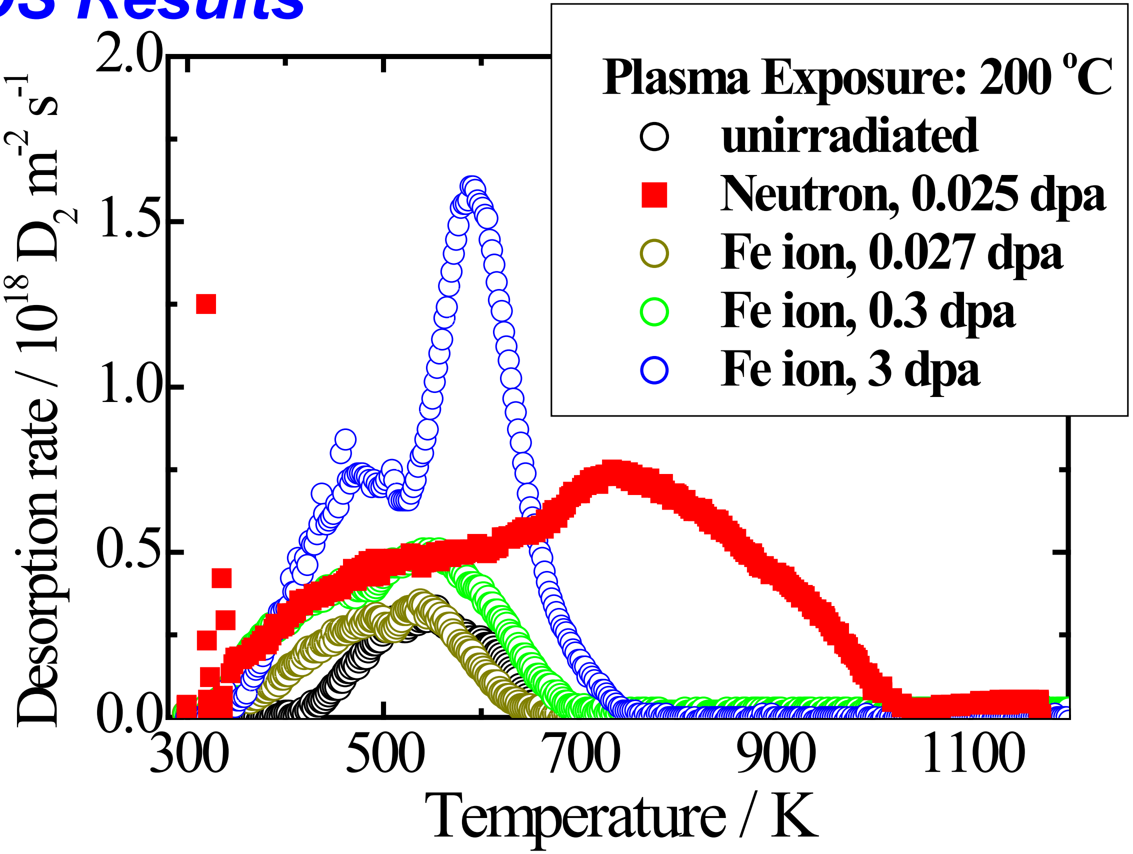


Hardness of cross section

Neutron Effects

T retention in neutron irradiated W

TDS Results



O-06, Y. Oya et al. (Tomorrow)
M. Shimada et al., PSI 2010

Broad peak for the n-irradiated sample suggests presence of several kinds of trapping sites (1 – 2 eV binding energy).

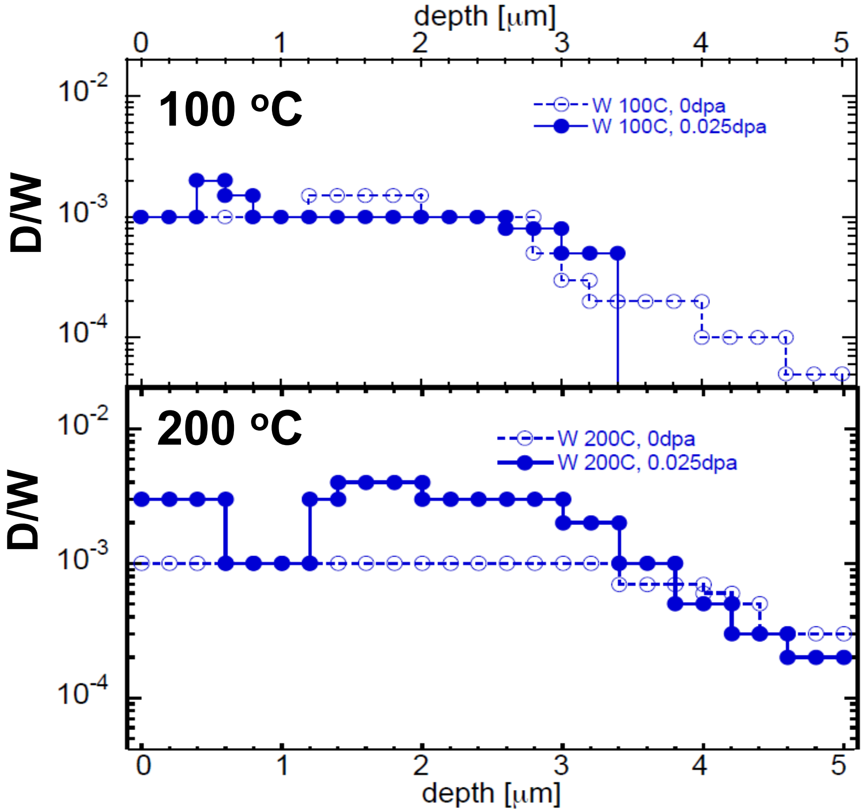
Comparison of TDS spectra from unirradiated, **neutron-irradiated**, and **2.8 MeV Fe^{2+} ion-irradiated** W specimens after plasma exposure at 200 °C.

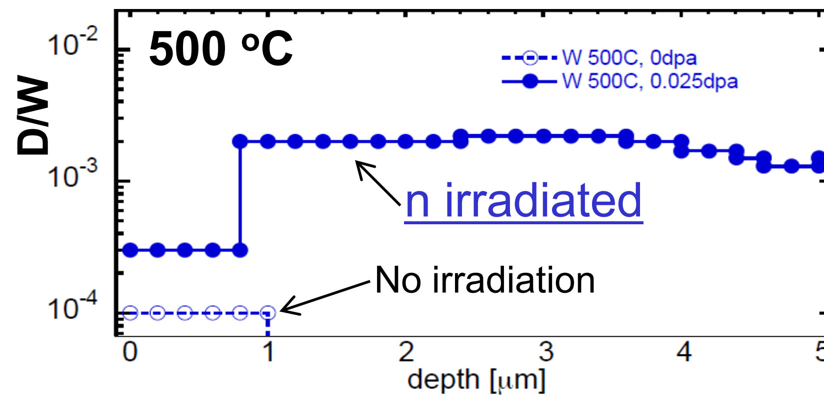
Difference between Neutron and Ion Irradiation

- Distribution of defects (uniform vs. near surface)
- PKA energy spectrum (uniform vs. exponential)
- Damage rate (10^{-7} vs. 10^{-4} – 10^{-3} dpa s^{-1})

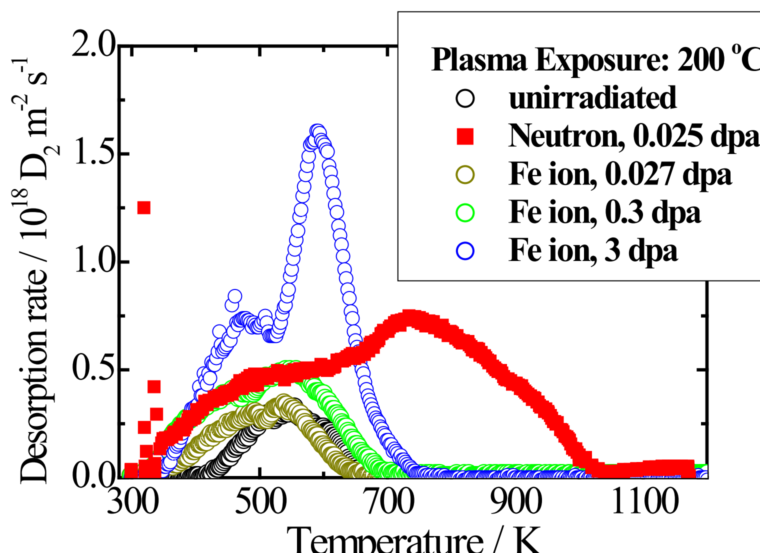
Simulation study is required to understand the difference between neutron and ion irradiation.

NRA Results (Neutron-irradiated & unirradiated W)





Depth profiles of deuterium measured by NRA after TPE plasma exposure at indicated temperatures.



Good quantitative agreement between TDS and NRA results.

Trap density: 0.2-0.3 at% at 0.025 dpa.

Strong trapping even at 500 °C.

M. Shimada, Poster Presentation, P50B (Today)

Irradiation Hardening of W-Re alloys

Dept. Quantum Science & Energy Engineering, Tohoku University

■Lower dpa region (<0.37dpa) :

Irradiation hardening (ΔHv) of W-Re alloys was smaller than that of W.

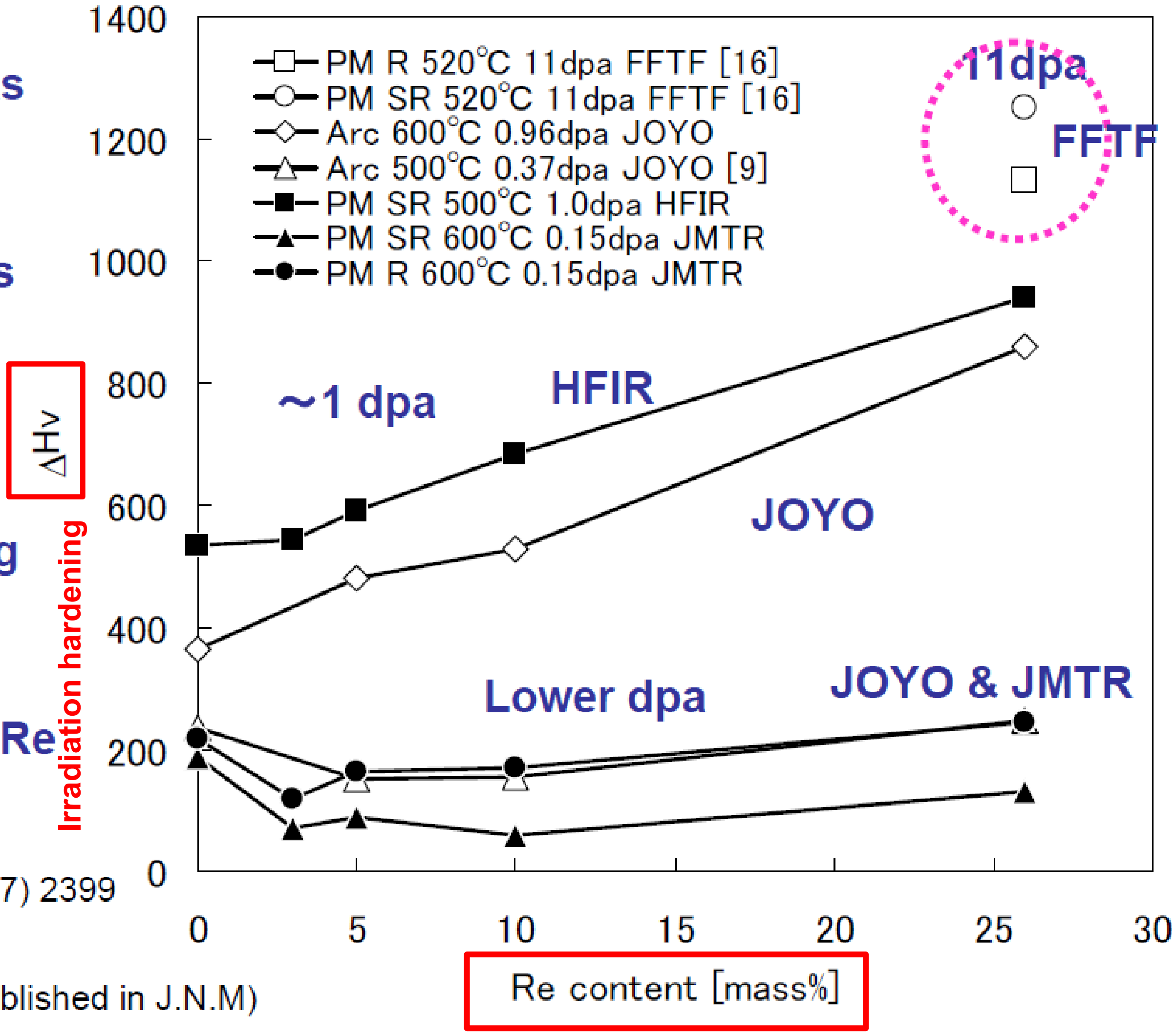
Re concentration dependence on ΔHv was not significant.

■Medium dpa region: (about 1dpa:

The irradiation hardening became larger.

The magnitude of the hardening depended on Re content.

Hardening of the W and W-Re alloys irradiated at 500 oC and 600 oC as a function of Re contents



[9]Tanno et.al. Mater. Trans. 48(2007) 2399
[16] Ueda et al. unpublishted data
Hasegawa et.al. ICFRM-14(to be published in J.N.M)

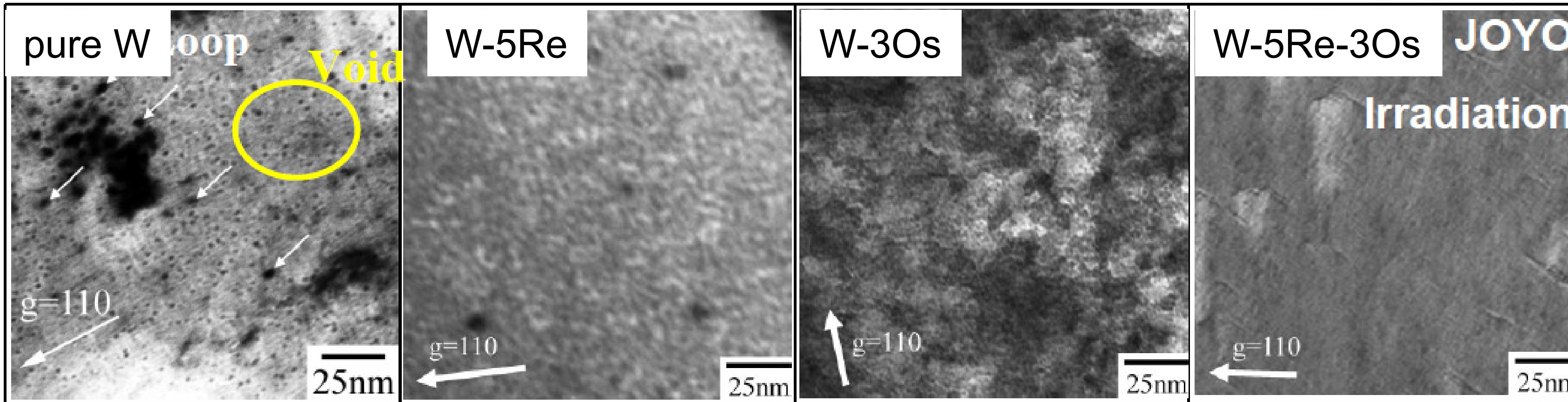
Microstructure of Irradiated W and W-Re-Os Alloys

Dept. Quantum Science & Energy Engineering, Tohoku University

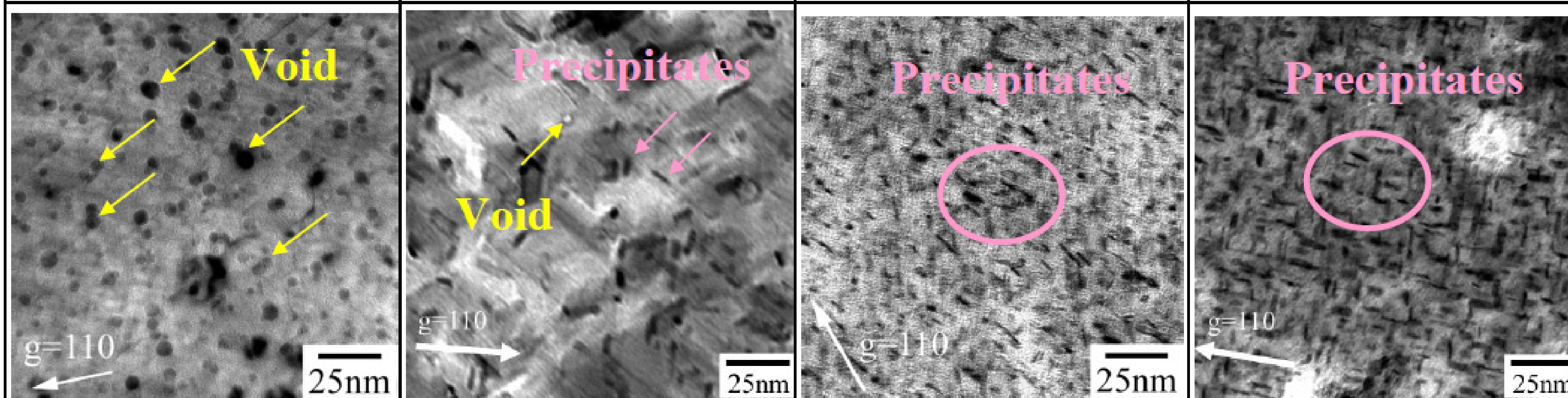
- Void and loop formation were suppressed by Re and Os addition and fine and dense precipitates were formed after irradiation in the alloys.

Tanno, et.al. J.N.M. 386-388(2009) p.218

Tanno et al. Mater. Trans.,10(2008) p.2259



W 400℃ 0.17dpa	W-5Re 400℃ 0.17dpa	W-3Os 400℃ 0.17dpa	W-5Re-3Os 400℃ 0.17dpa



W 750℃ 1.54dpa	W-5Re 750℃ 1.54dpa	W-3Os 750℃ 1.54dpa	W-5Re-3Os 750℃ 1.54dpa

Effects of Re and Os Contents on Change of Electrical Resistivity of W by Irradiation

Dept. Quantum Science & Energy Engineering, Tohoku University

■W and W-Re alloys

・JOYO Irradiation:

Significant change by irradiation was not observed.

・HFIR Irradiation:

Increase of resistivity was observed.

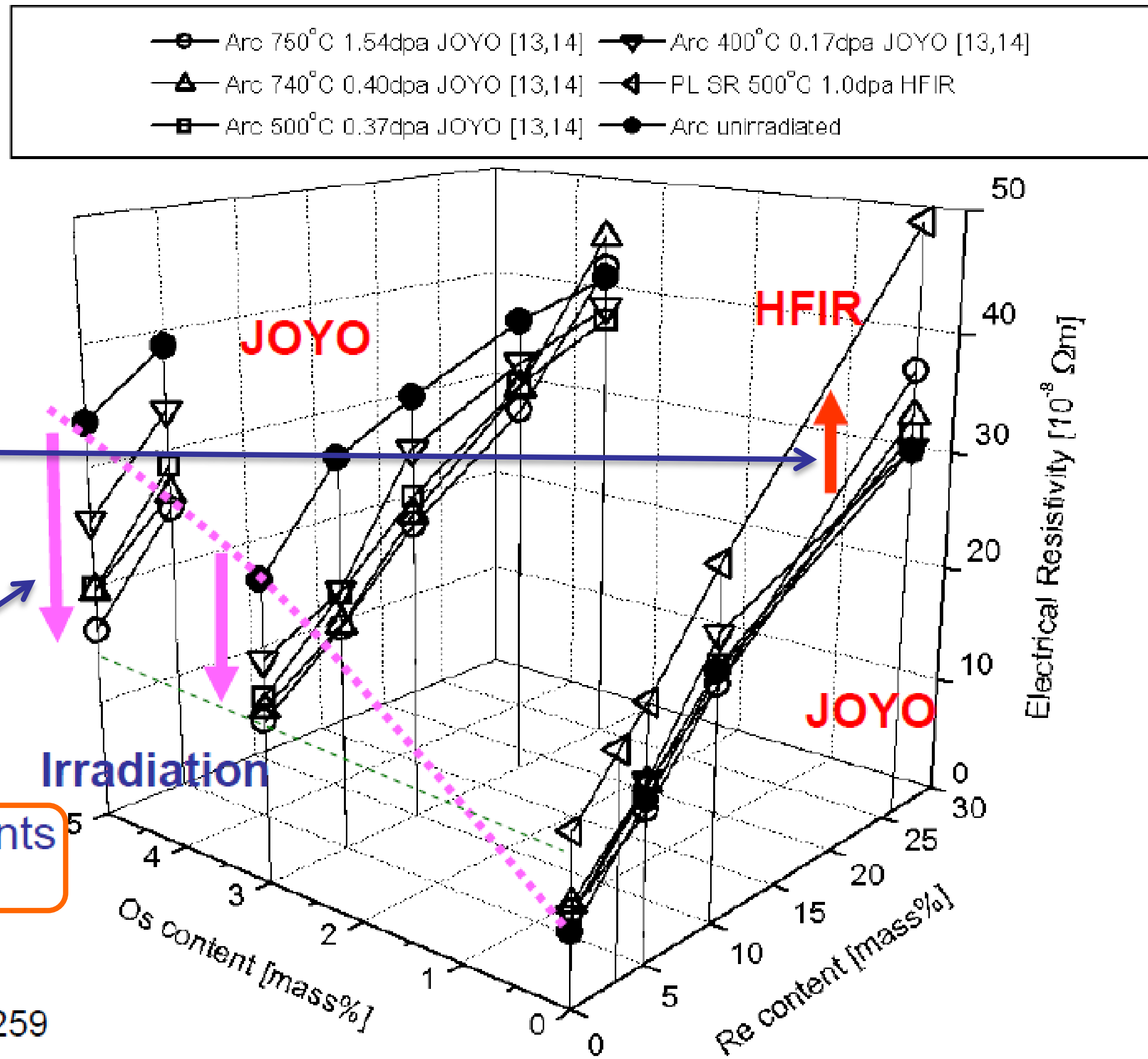
→Re production effects

■W-Re−Os alloys

・JOYO Irradiation:

Decrease of resistivity was observed.

→Reduction of solute elements in the matrix by precipitation.



[13] Tanno et.al. Mater. Trans.49(2008) 2259

[14] Tanno et.al. J.N.M. 386-388(200) 218

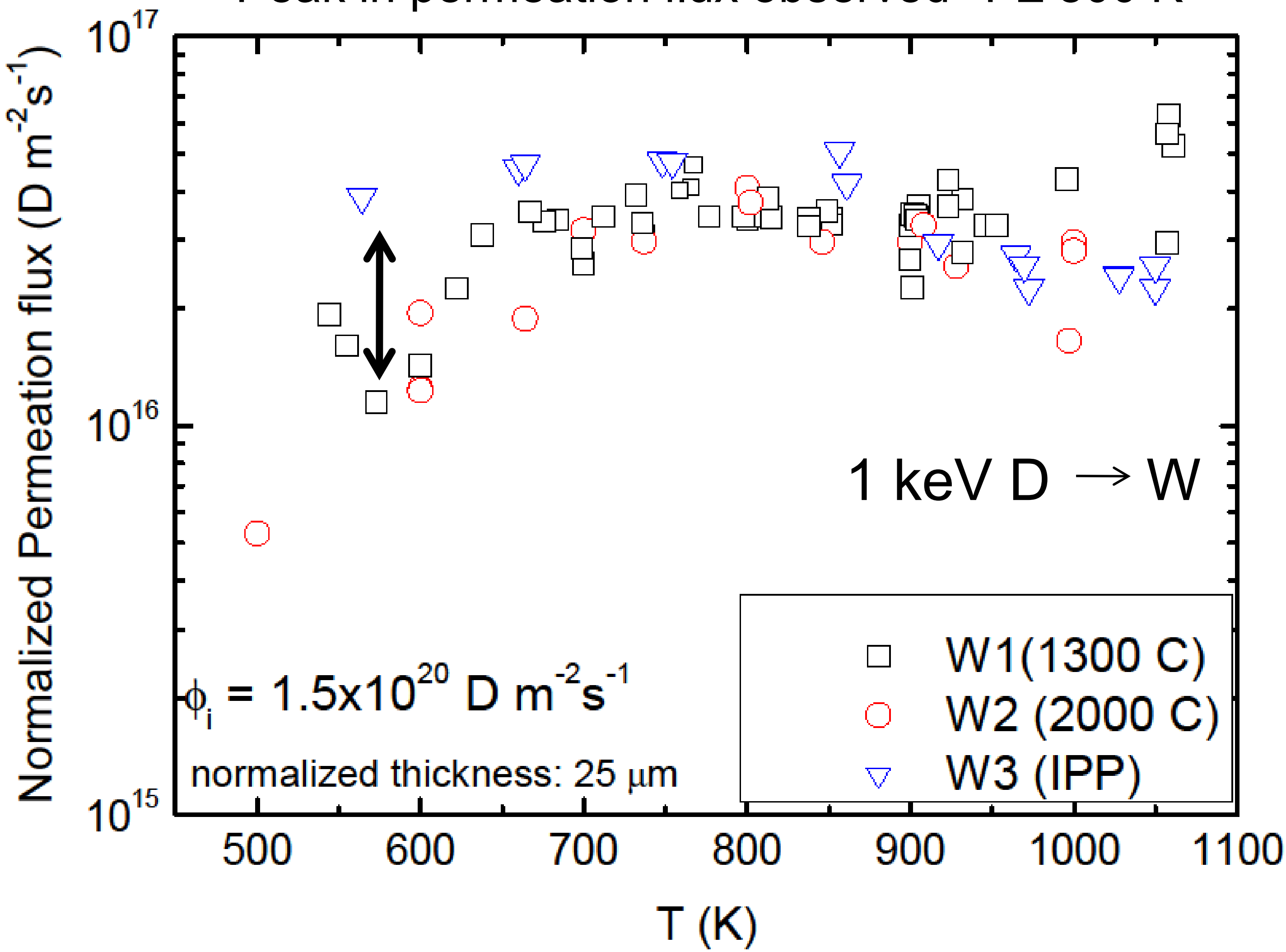
Hasegawa et.al. ICFRM-14(to be published in J.N.M)

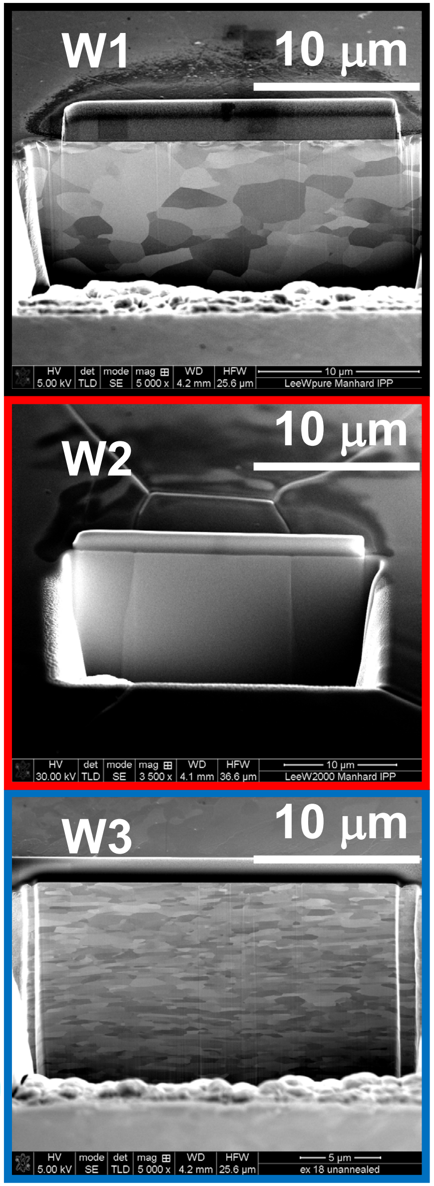
Surface Modification effects by Mixed Plasma Exposure

pure D permeation study in tungsten

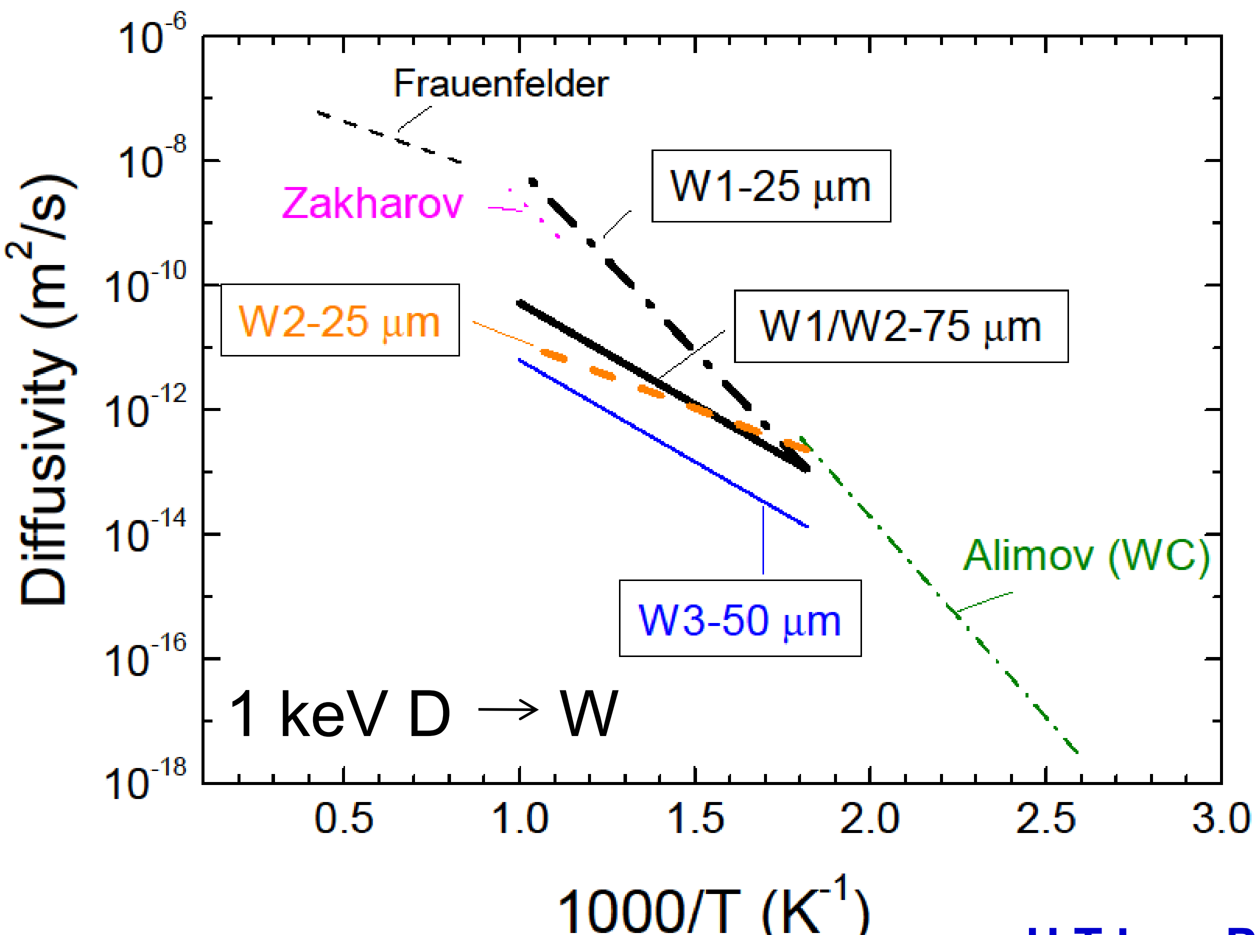
Microstructure dependence
--Steady state permeation--

- Weak grain boundary dependence (factor of two)
- Peak in permeation flux observed T ≅ 800 K





Microstructure dependence --Effective diffusivity--



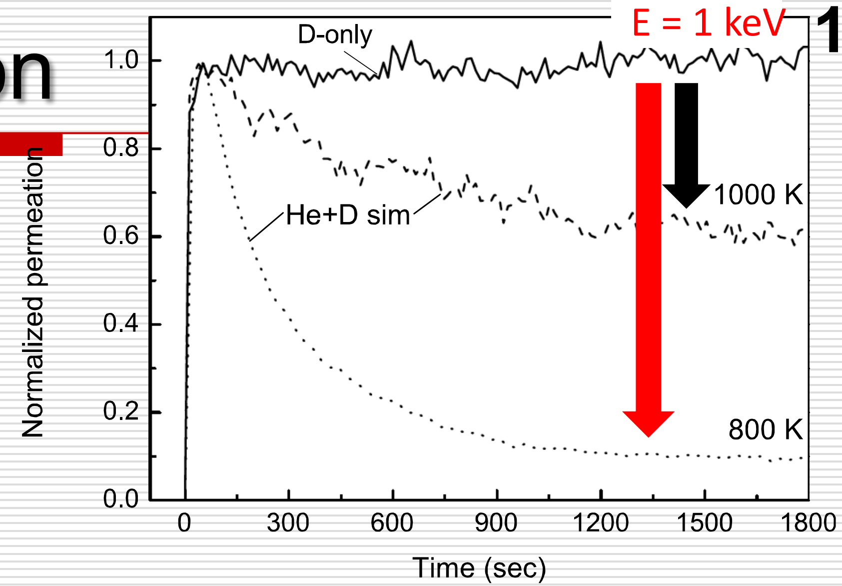
- Effective diffusivity values determined from lag time measurements.
- Thickness dependence was observed.
- The activation energy was ~0.65 eV for “thick” samples (50 and 75 μm) with difference only in the diffusion constant.

H.T Lee, Poster Presentation, P42B

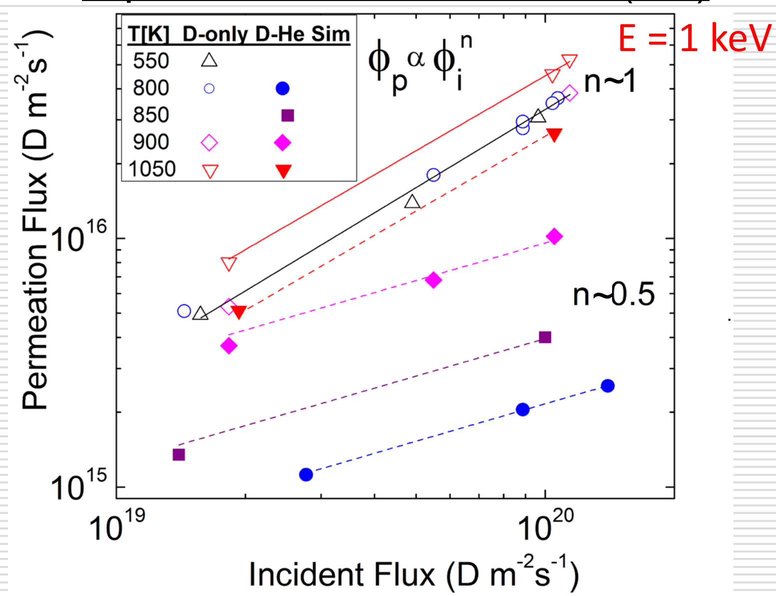
R. Frauenfelder, J. Vac. Sci. Techn. 6 (1969) 388.
A.P. Zakharov, E.I. Evko. Fiz. Khim. Mekh. Mater. 9 (1973) 29.
V. Kh. Alimov, Problems of Atomic Science and Technology, Series Nuclear Fusion. 4 (2008) 31 (In Russian).

He effects on permeation

- D permeation greatly reduced with He (5%) in ion beam.
- $\phi_p \sim \phi_i$ (<u>D only</u> irradiation)
- $\phi_p \sim \phi_i^{1/2}$ (<u>D/He</u> irradiation)
  - ϕ_p : Permeation flux
  - ϕ_i : Incident flux
- Change of flux dependence suggests D release from the front surface could change from diffusion limited (D) to recombination limited (D/He).

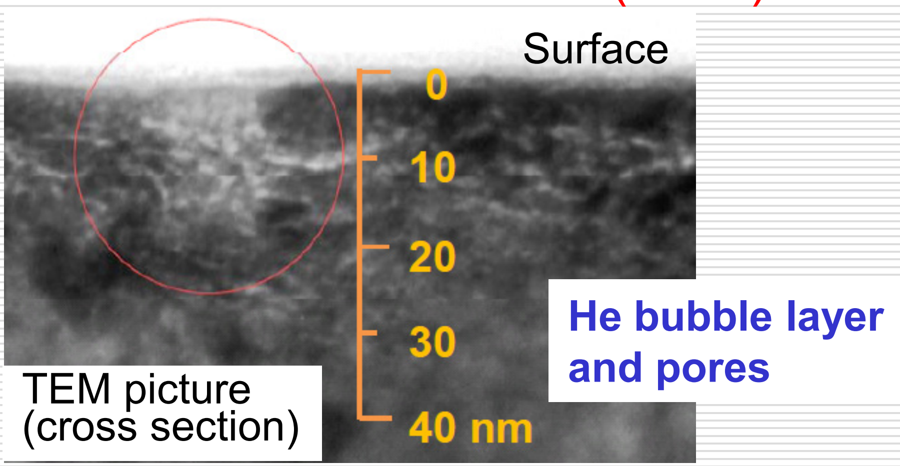


D permeation w/ and w/o He(5%)



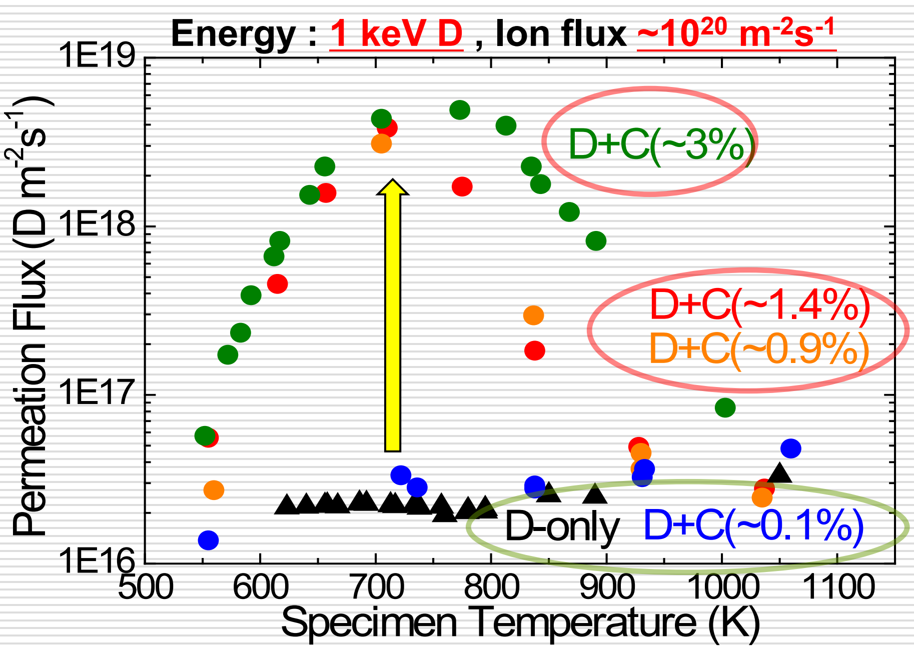
Flux dependence of D permeation

H.T.Lee et al. JNM in print (2011)

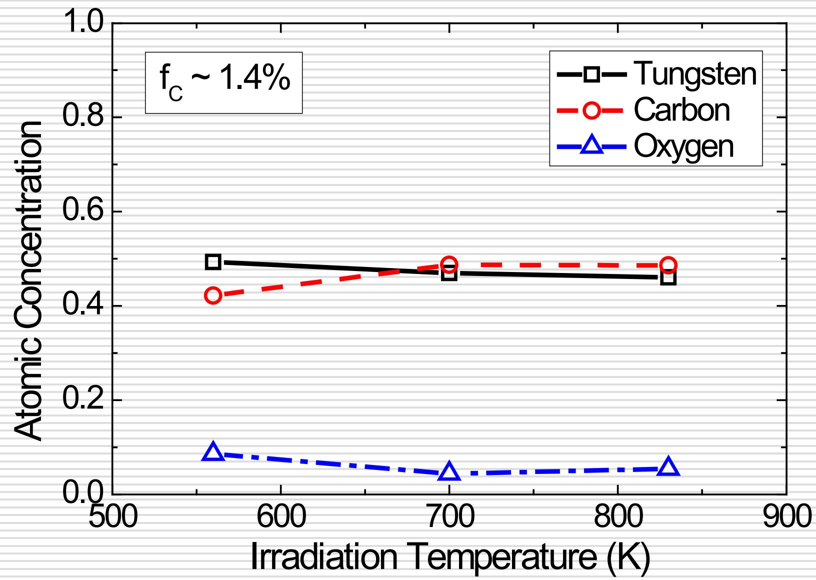


Carbon effect on D permeation

- D permeation greatly increased with C (>0.9%) in ion beam.
- Strong temperature dependence.
- Surface elemental composition shows little dependence on temperature (C:1.4%).



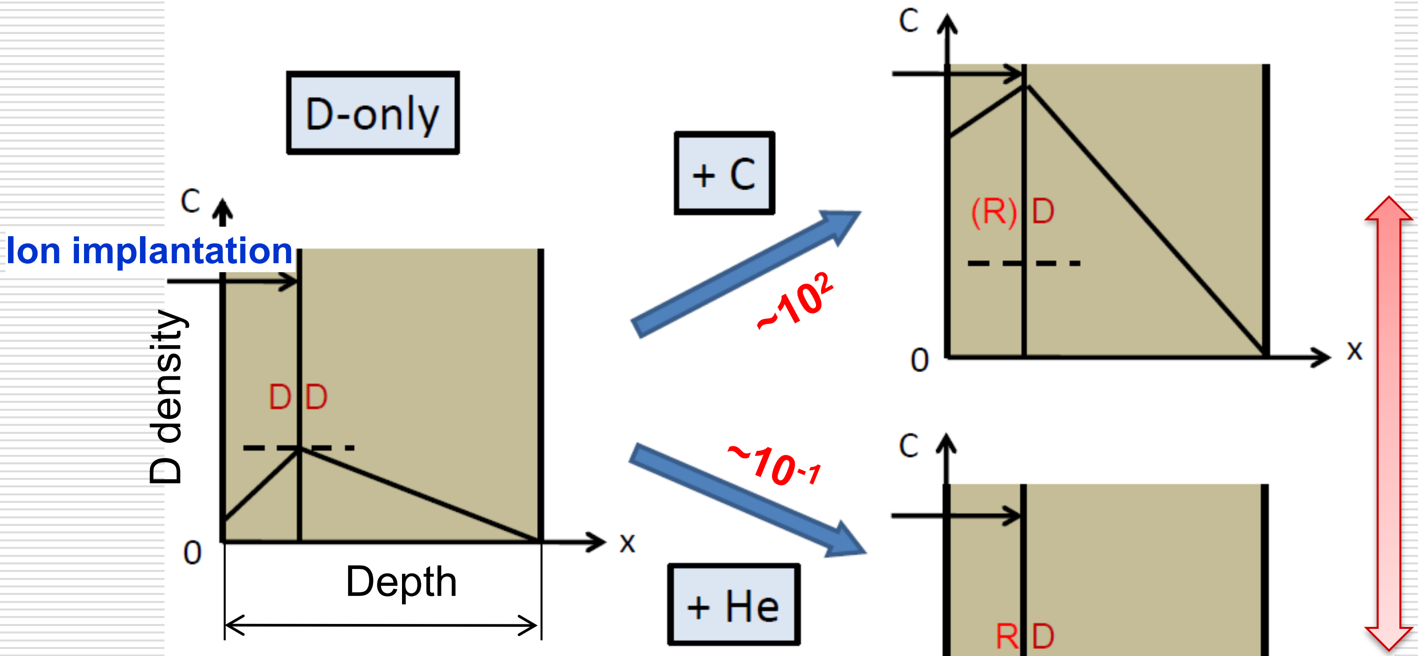
Temperature dependence of permeation



Near surface atomic composition

H.Y. Peng, Poster Presentation, P44B (Today)

Solute D behavior in tungsten



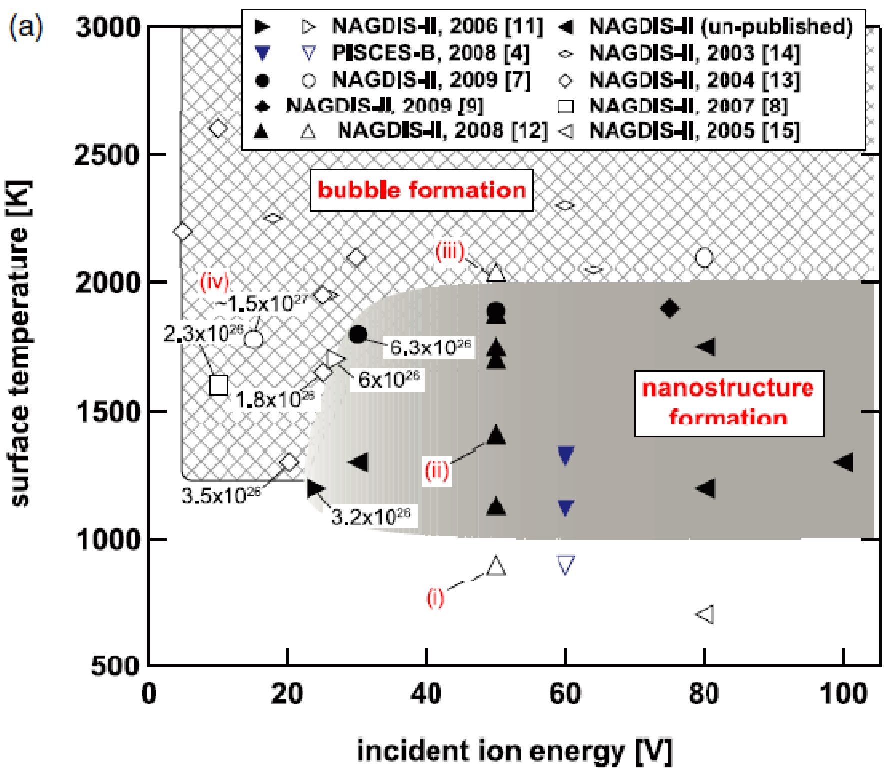
~10³ difference in permeation flux (solute D density) (at 700~800 K)

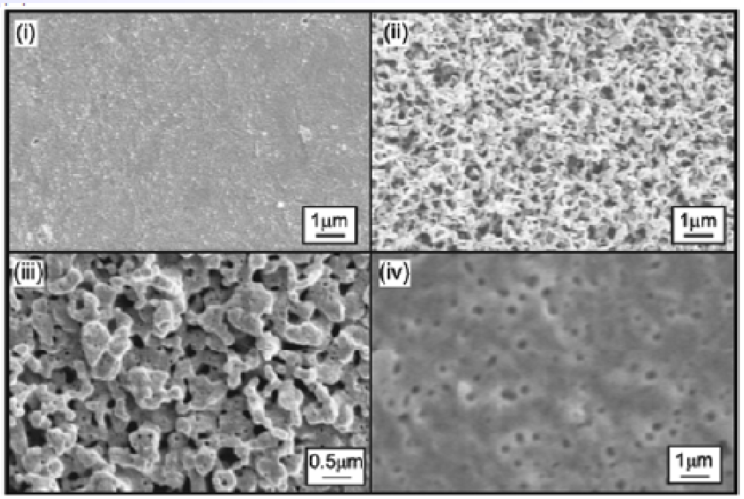
D: diffusion limited
R: recombination limited

- **Mixed irradiation (D/C, D/He) greatly changed diffusion and recombination near surface area**
  - **Addition of C→ Recombination or diffusion reduced : under investigation**
  - **Addition of He→ Effective diffusion near surface area increased.**

Summary of W fuzz formation condition

N. Ohno, S. Kajita (Nagoya Univ.)





- Closed markers with nanostructure
- open markers without nanostructure

Surface Temp: **1000 K < T < 2000 K**
Ion Incident Energy**>20 eV**

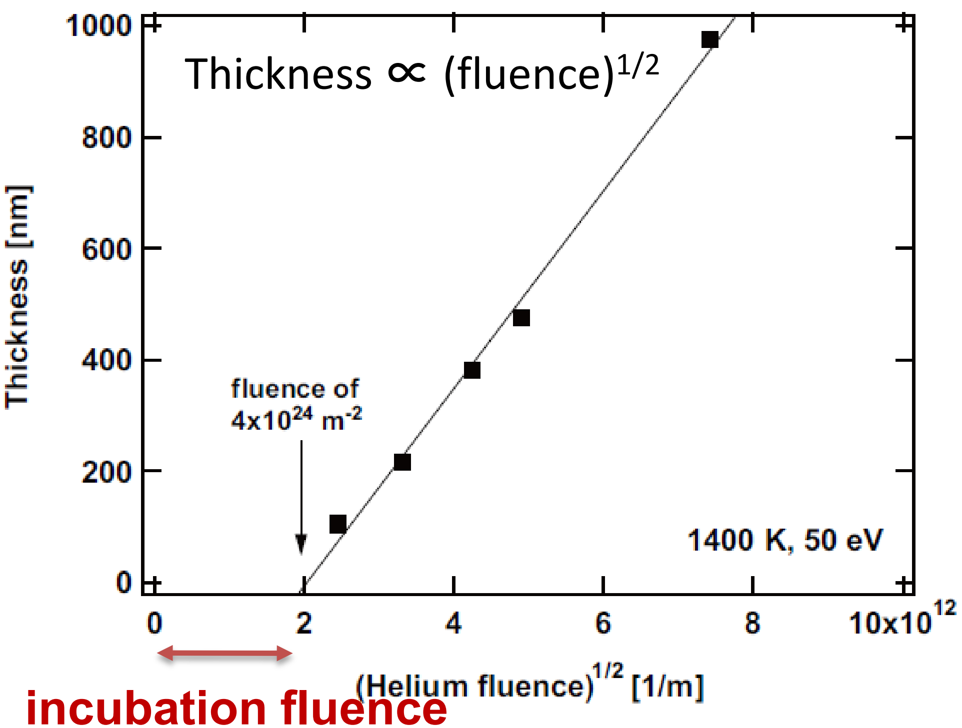
[4] M. Baldwin NF (2008).
[7] W. Sakaguchi JNM (2009)
[8] S. Kajita, NF (2007).
[9] S. Kajita, NF (2009).
[11] S. Kajita, J. Appl. Phys. (2006).
[12] W. Sakaguchi, Proc. 18th Int. Toki Conf. (2008).
[13] D. Nishijima, JNM (2004).
[14] D. Nishijima, JNM (2003).
[15] D. Nishijima, NF (2005).

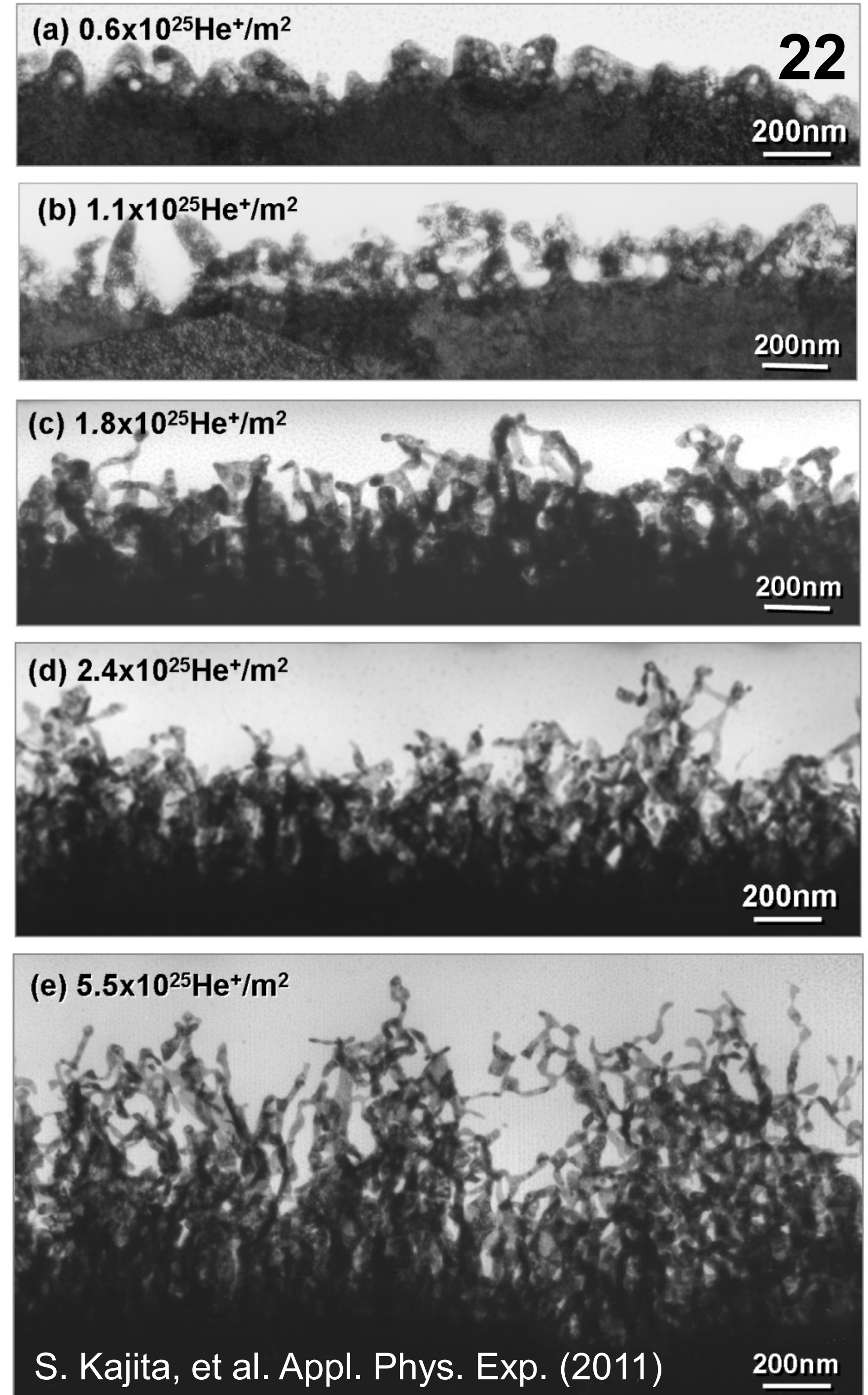
S. Kajita, et al., Nucl. Fusion, 49 (2009) 095005 (6pp)

Growth of protrusions by helium irradiation

Irradiation were performed in the divertor simulator NAGDIS-II. The samples were analyzed FIB-TEM analysis.

sample：W, 1400K, 50eV-He plasma





S. Kajita, et al. Appl. Phys. Exp. (2011)

Summary and future directions 1

- **Development of TFGR W-1.1TiC**
  - Superplasticity based process (SPMM) successfully demonstrated
  - High fracture strength and ductility even at RT
  - Issues : large size specimen, retention
- **W coating on reduced activation materials**
  - VPS-W successfully demonstrated on RAM
  - Issue: optimization of process, retention, heat flux
- **Neutron irradiation effects on T retention**
  - Difference from ion damaged W
  - Issues : trap site characterization, T behavior modeling

Summary and future directions 2

- **Property change of W alloys due to neutron irradiation**
  - Hardening : void formation (W), radiation induced precipitation (W alloy)
  - Electrical resistivity (thermal conductivity) change: low dpa→ damage, high dpa→ transmutation
  - Issues : more database, modeling
- **D permeation by mixed ion irradiation**
  - Weak dependence of SS permeation on microstructure
  - **D/C** mixed irradiation **increases** permeation
  - **D/He** mixed irradiation **reduces** permeation
  - Issues : parameter dependence, modeling
- **He induced nano-structure**
  - Detailed formation mechanism
  - Issues : impact on plasma operation