Carbon Impurity Effects on Plasma Facing Wall

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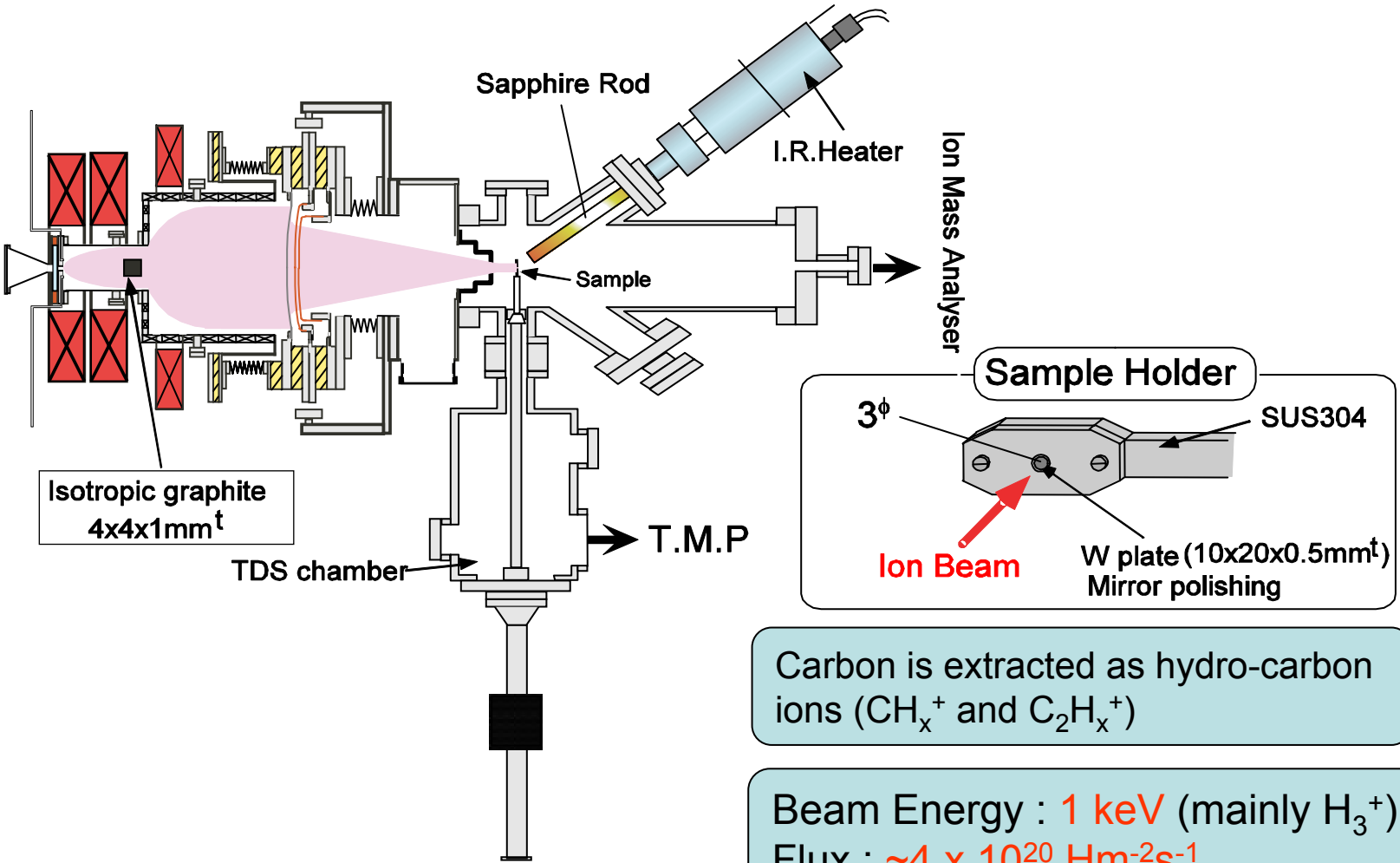
Outline

In this study, hydrogen and carbon mixed ion beam was irradiated to the first wall materials (W and RAF) to observe its effects on erosion and surface modification.

- Experimental : device, conditions
- Blistering on different W materials
- Carbon behavior in W : Experiment and Simulation
- Erosion of RAF (F82H) : Experiment and Simulation
- Summary

Experimental setup (HiFIT device)



Carbon is extracted as hydro-carbon ions (CH_x^+ and $C_2H_x^+$)

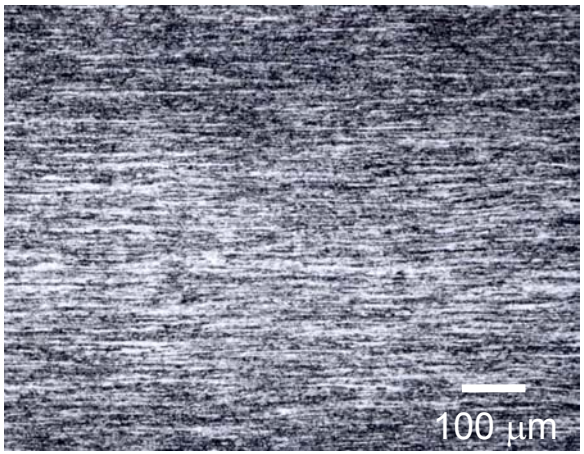
Beam Energy : 1 keV (mainly H_3^+)
Flux : ~4 x 10^{20} $Hm^{-2}s^{-1}$

HiFIT (High Flux Irradiation Test Device)

Blister characteristics for different W materials

Microstructure of pure W samples

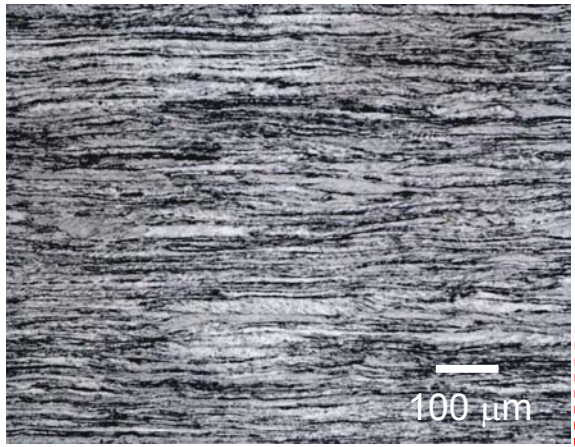
surface



W_0

Rolled to the thickness of 1 mm
No heat treatment
(Nilaco co.)

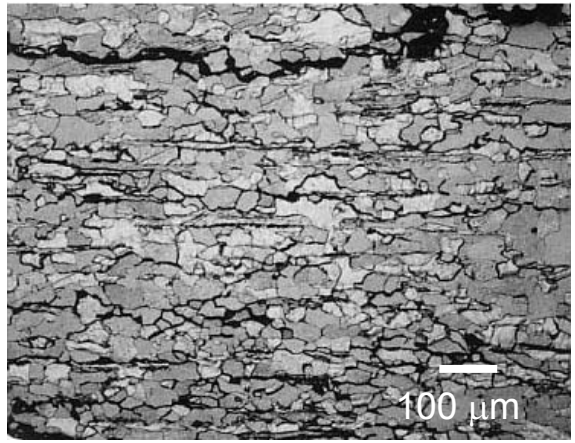
Laminar structure parallel to the surface with grains of high elongation.



W_{900} (Stress relieved)

Rolled to the thickness of 1 mm
Heat treatment at 900 °C
in hydrogen for 0.5 h.
(A.L.M.T. co.)

Laminar structure slightly recrystallized.

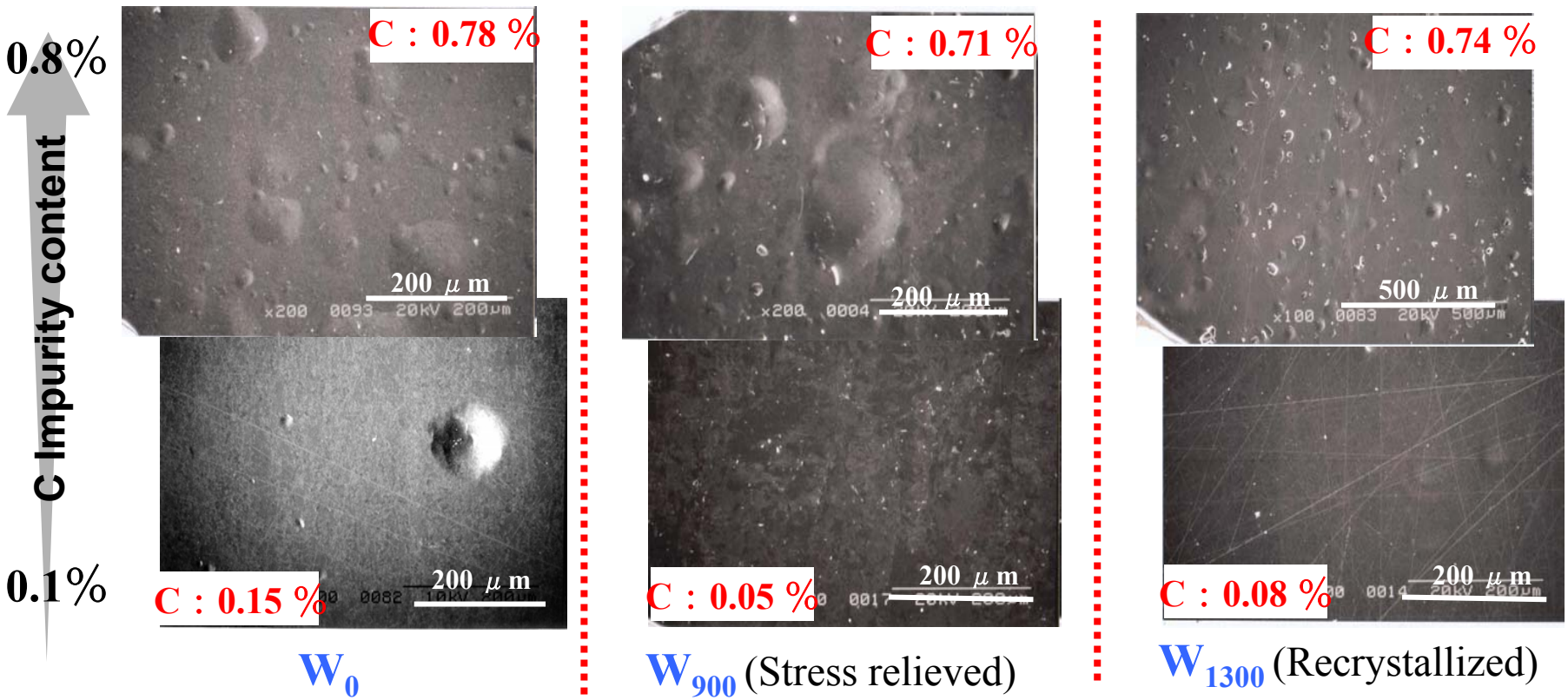


W_{1300} (Recrystallized)

Rolled to the thickness of 1 mm
Heat treatment at 1300 °C
in vacuum for 1 h.
(A.L.M.T. co.)

Recrystallized with average grain-size of 20-30 μm.

Dependence on C impurity content



W_0 | W_{900} (Stress relieved) | W_{1300} (Recrystallized)

Fluence: ~1.0×10^{25} H^+/m^2
Temperature : 653K

For all W materials, carbon impurity in ion beam enhanced blister formation.

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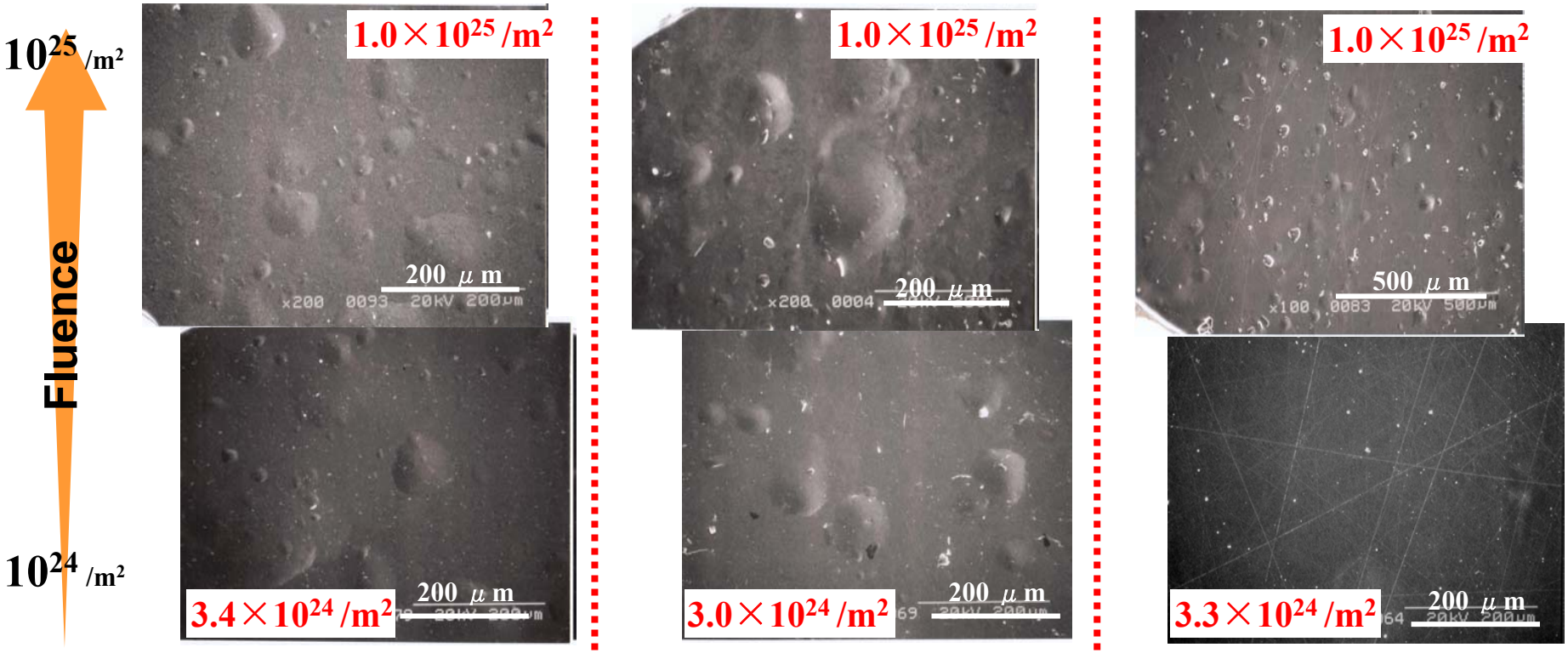
Dependence on Fluence



W_0 | W_{900} (Stress relieved) | W_{1300} (Recrystallized)

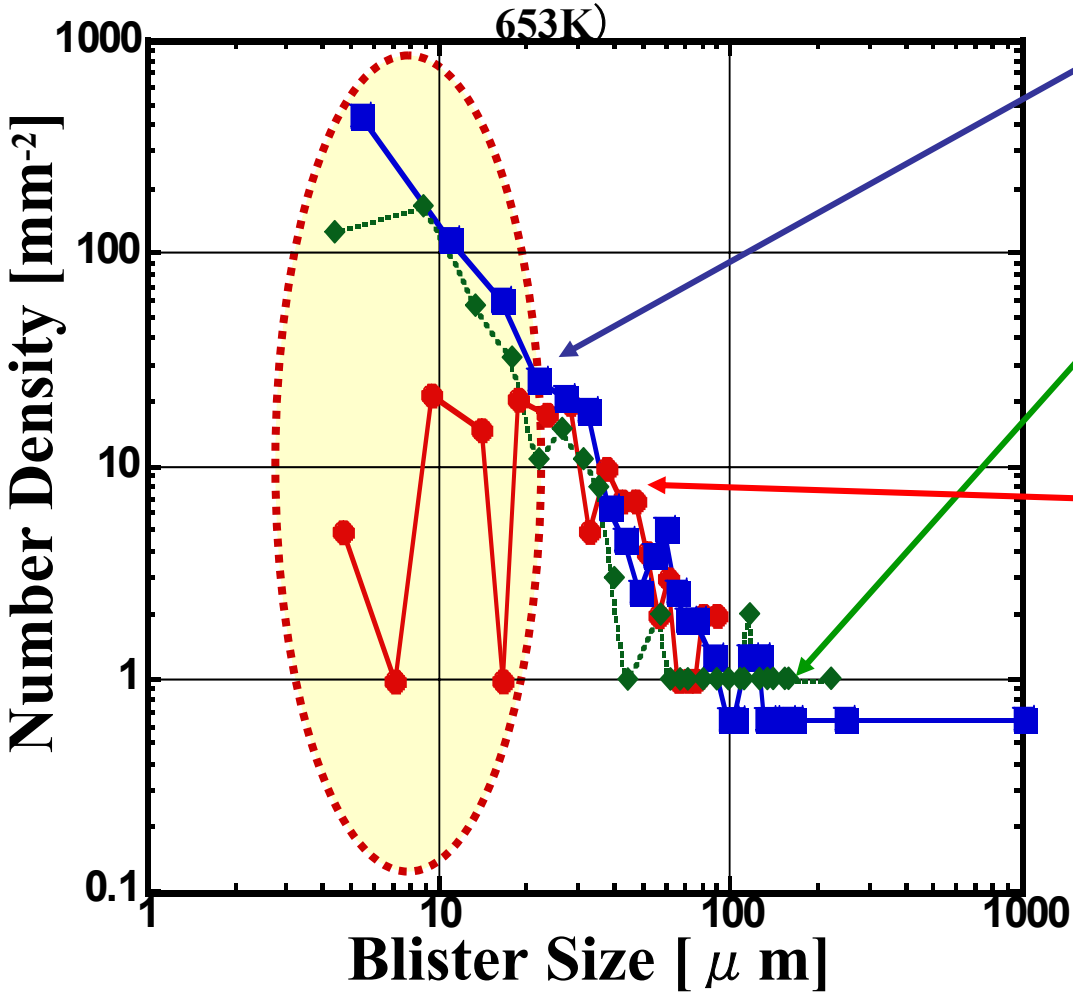
C: 0.7～0.8 %
Temperature : 653K

~3×10^{24} m^{-2} :Blisters appeared on W_0 and W_{900}.
No blisters on W_{1300}.
⇒~10^{25} m^{-2} :Blisters appeared on W_{1300}.

Distribution of blister size

≪Number density of blister on the surface≫

（C：0.7～0.8 %、1.0×10^{25}/m^2、653K）



W_0 (no heat treatment)

~717 blisters/mm^2

（largest blister：～1.0mm）

W_{900} (stress relieved)

~445 blisters/mm^2

（largest blister：～0.2mm）

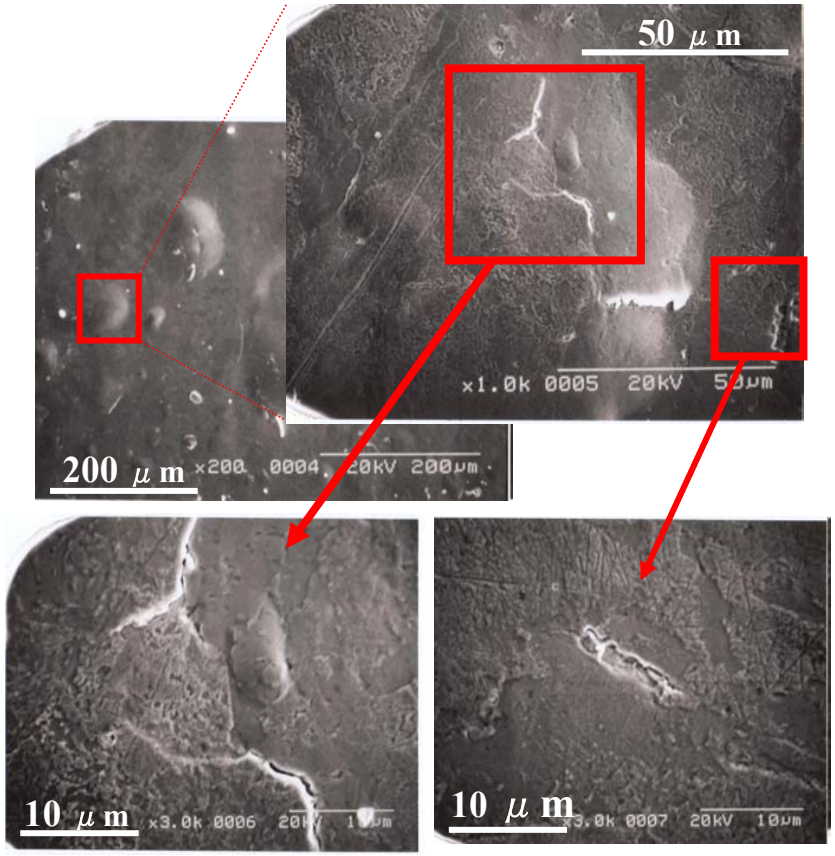
W_{1300} (recrystallized)

~144 blisters/mm^2

（largest blister：～0.1mm）

For W_{1300} (recrystallized), the size of blisters are distributed mainly between 20 μm and 100 μm.

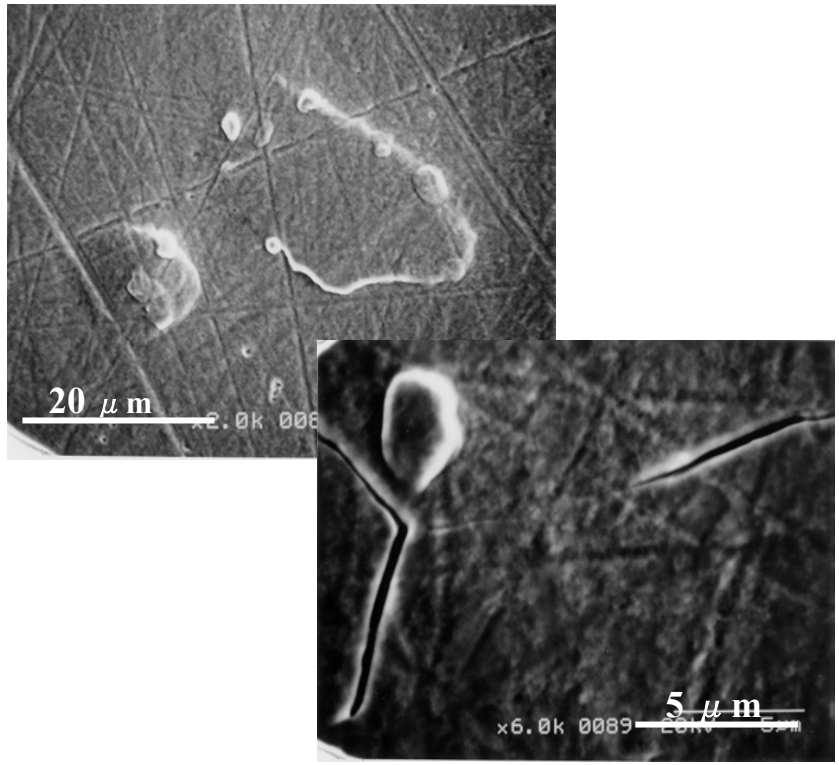
Cracking of blisters



W_{900} (Stress Relieved)

（C：0.71 %、1.0×10^{25} /m^2 、

Some of the blisters showed cracking.
Many cracks were found on the surface.



W_{1300} (Recrystallized)

（C：0.74 %、1.0×10^{25} /m^2 、

Many cracks were found on the surface.
All blisters did not grow beyond ~100 μm in diam. due to cracking.

It is noted that no cracks were observed for W_0.

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Characteristics of doped W

Atomic Composition

lot.	La_2O_3(%)	K	Al	Ca	Cr	Cu	Fe	Mg	Mn	Mo	Ni	Si	Sn
K-doped W	—	28	22	1	11	<1	26	<1	<1	25	12	<5	<2
La_2O_3 doped W	0.96	<5	6	2	7	2	41	<1	<1	40	4	<5	<2

ppm

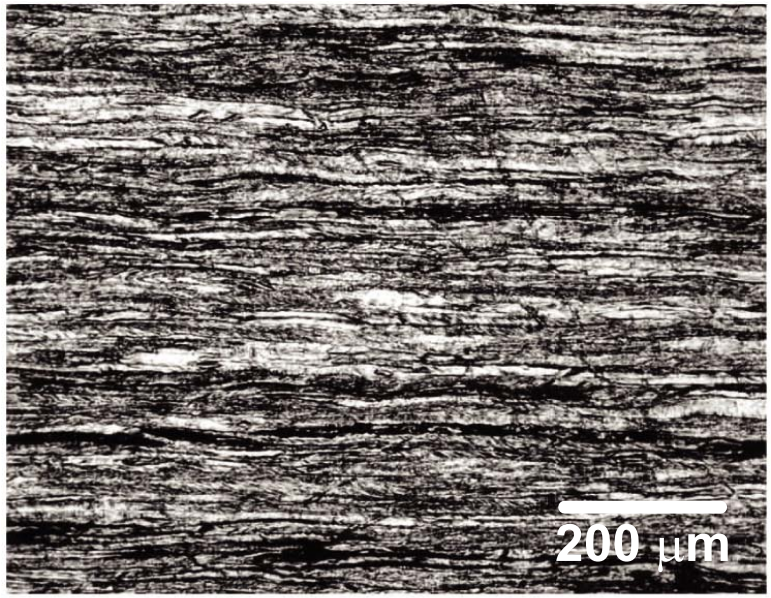
Advantages for K-doped W :

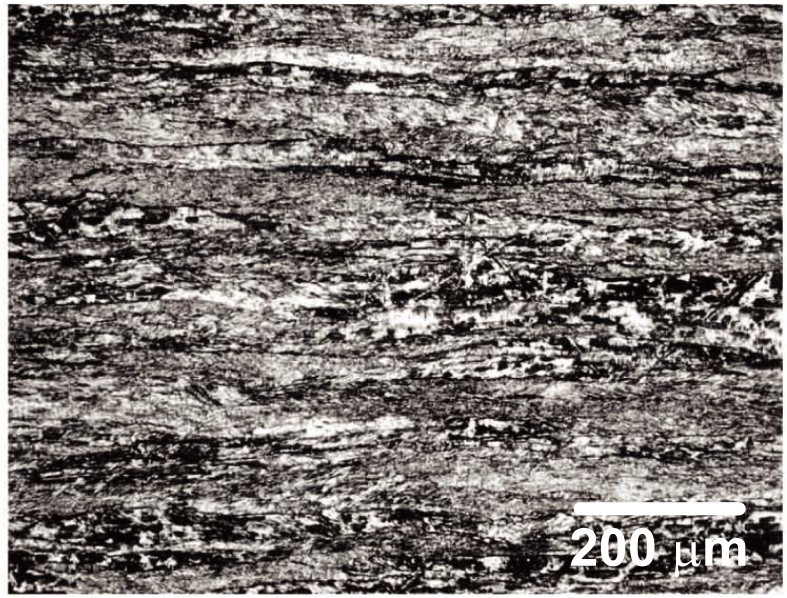
higher recrystallization temperature
grain stability
higher creep stability

Advantages for La_2O_3-doped W:

better creep resistance
higher recrystallization temperature
better high-temperature strength
higher ductility (better machinability)

Microstructure of doped W





K-doped W

Heat treatment at 900 °C
in hydrogen for 0.5 h.
(A.L.M.T. co.)

Laminar structure

La_2O_3-doped W

Heat treatment at 900 °C
in hydrogen for 0.5 h.
(A.L.M.T. co.)

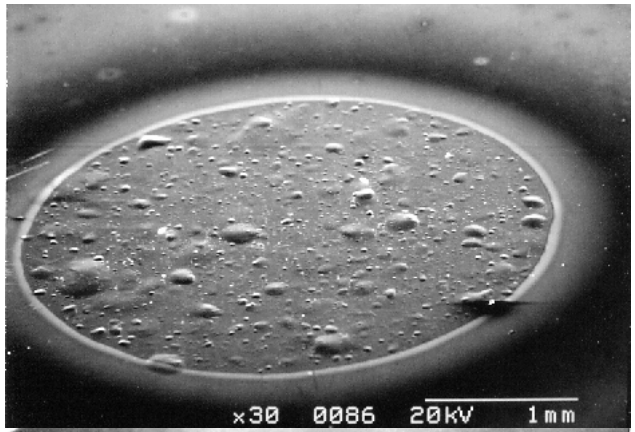
Disordered structure
(slightly laminar)

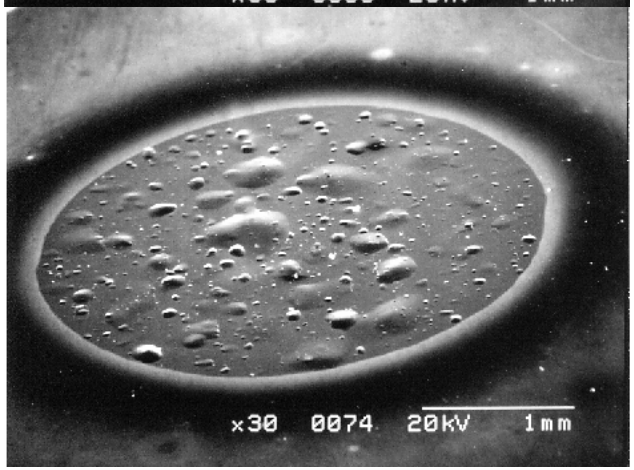
Blister Formation for Doped W

Fluence
1.0×10^{25} m^{-2}

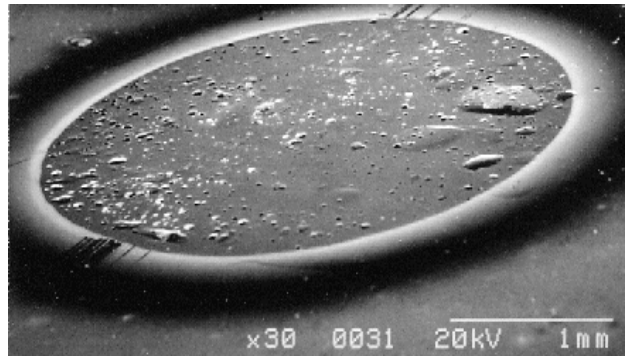
1 keV H_3^+
C: 0.8%
653 K

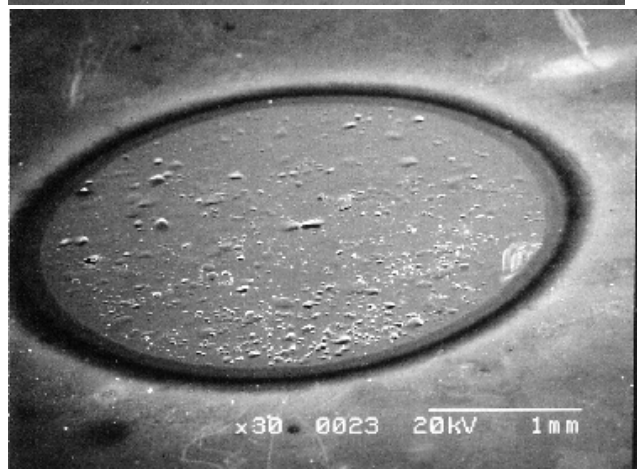
Fluence
3.0×10^{24} m^{-2}





K doped W_{900}





La_2O_3 doped W_{900}

For K-doped W, large blisters with some cracks.
For La_2O_3-doped W, small blisters with many cracks.

Summary of blistering on W samples

	C : 0.8%	C:0.1%	Fluence of blister appearance	Blister size (~10^{25} m^{-2})	Cracking (~10^{25} m^{-2})
	1.0×10^{25} /m^2 ,653K				
W_0 (no heat treatment)	○	○	~10^{24} m^{-2}	Max ~1.0 mm	**None**
W_{900} (stress relieved at 900°C)	○	×	~10^{24} m^{-2}	Max ~0.2 mm	**Observed**
W_{1300} (recrystallized at 1300°C)	○	×	~10^{25} m^{-2}	Max ~0.1 mm	**Observed**
K-Doped W_{900}	○			Max ~0.5 mm	**Observed**
La_2O_3-Doped W_{900}	○			< 0.1 mm (a few ~1mm blisters)	**Observed**

In terms of blister size and number,

K-doped W_{900} is similar to W_{900}. -> laminar grain structure

La_2O_3-doped W_{900} is similar to W_{1300}. -> non-laminar structure

W_0 did not show cracking in this experiments.
Is this advantageous for fusion FW?

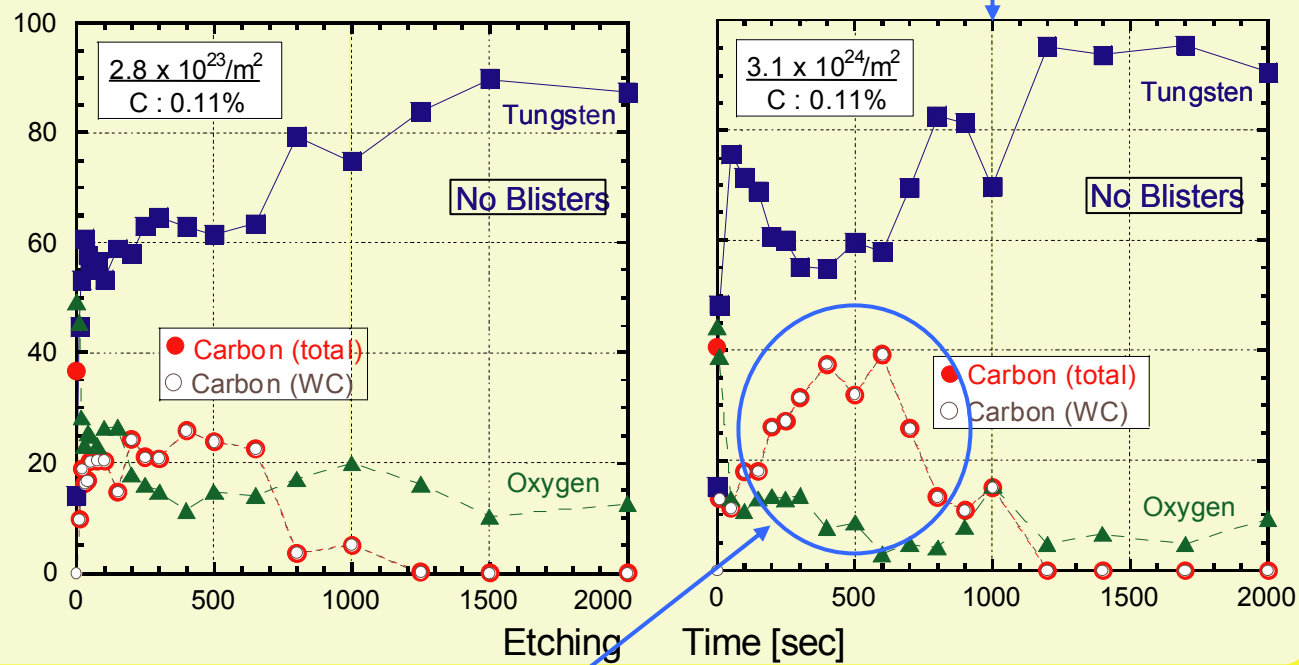
Carbon behavior in W

Atomic composition in tungsten (0.11 %C)

Temperature : 653 K, Energy : 1 keV

~30 nm for pure W

C : 0.11%



Top surface was partly covered by C (10-20%)

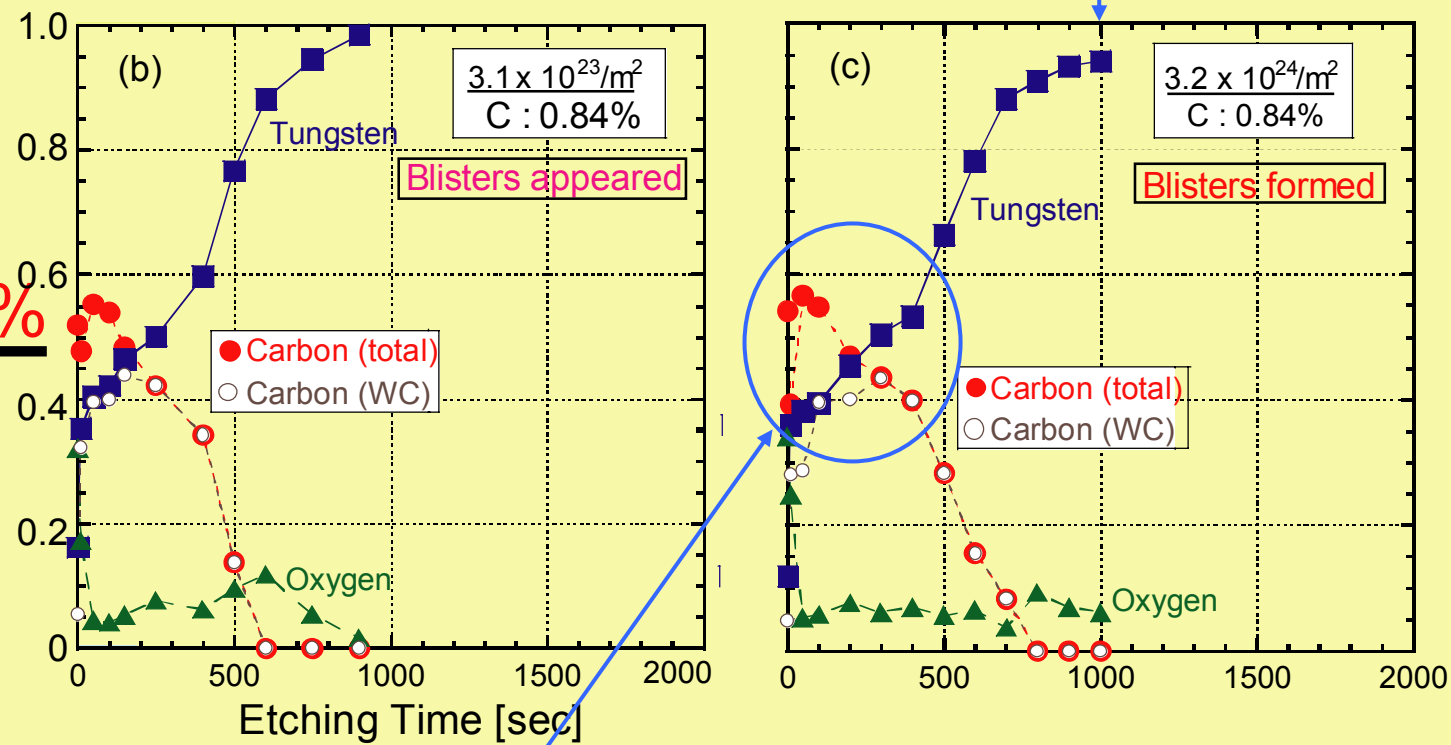
C concentration took a local max. around 500s (~15 nm) in ~3x10^{24} m^{-2}.

Atomic composition in tungsten (0.84 %C)

653 K, 1 keV

~30 nm for pure W

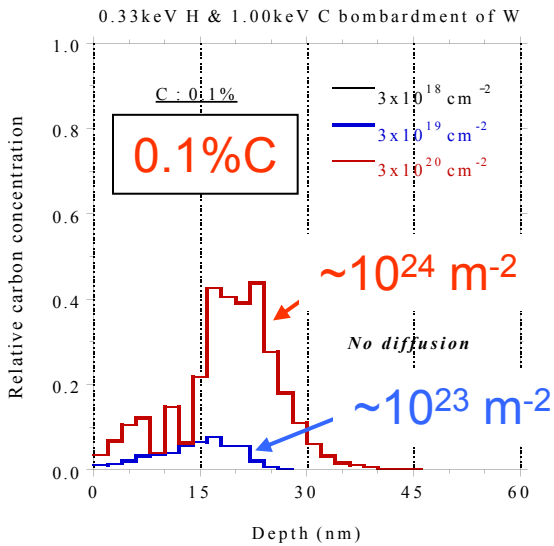
C : 0.84%

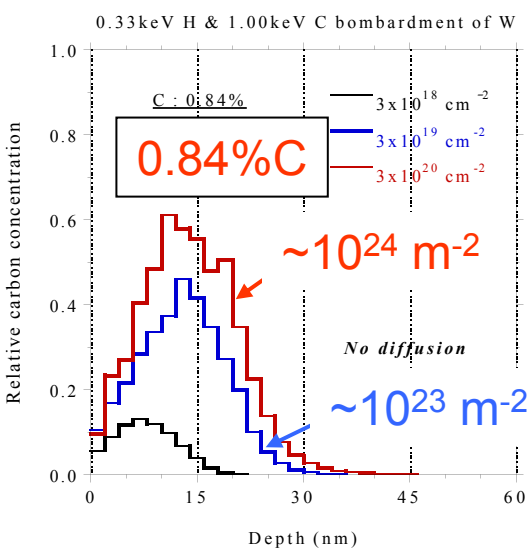


Top surface was covered by WC (and C) (50-60% C), which could be a barrier for H diffusion.

Simulation results by EDDY code (TRYDYN-like)

Collision cascade and composition change is calculated by Monte-Carlo method.





For C:0.1%, local peak appeared around 20 nm due to recoil implantation (carbon range is ~5nm), which agrees well with experiments.
But C concentration at the surface (<0.1) is lower than that of the experiments (~0.2).

For C:0.84%, local peak appeared around 15 nm, which was not observed by the experiments.
C concentration at the surface (~0.1) is lower than that of the experiments (~0.6).

Radiation-enhanced segregation and/or radiation-enhanced diffusion (not included in the simulation) could affect carbon depth profiles.

By R. Kawakami and K. Ohya.

Erosion and carbon behavior of Ferritic Steel

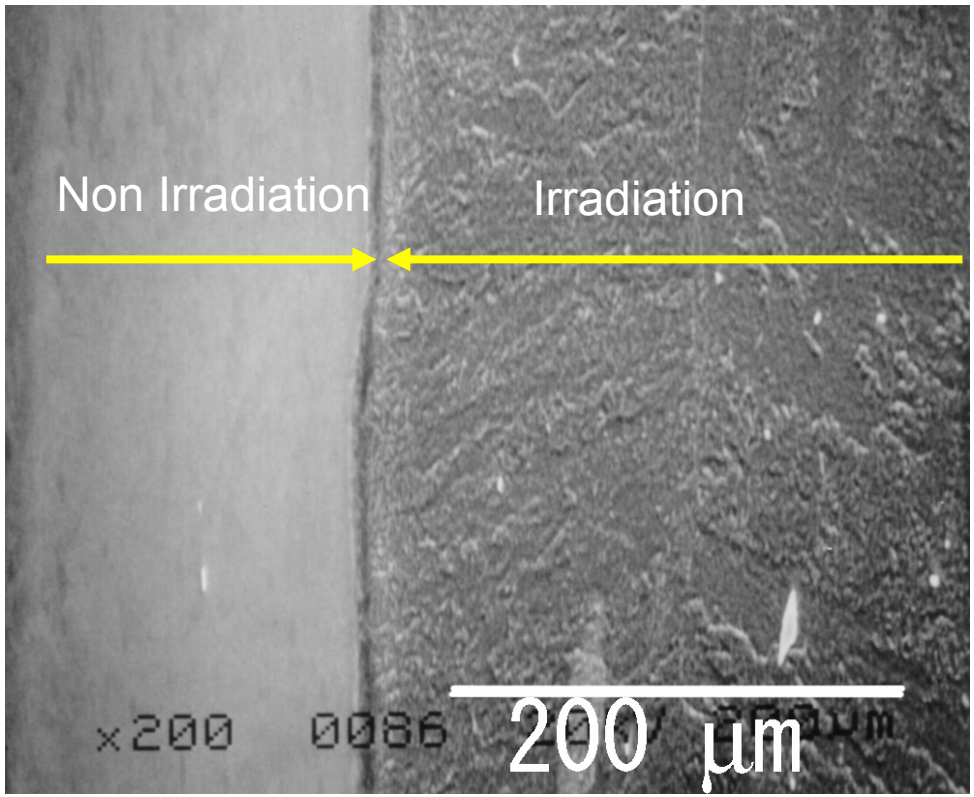
Experimental

- Irradiation Sample : RAF (Reduced Activation Ferritic steel, F82H)
- Atomic Composition of F82H (supplied from JAERI)

Cr	W	C	Si	Mn	Ni	V	Fe	
7.7	2.0	0.09	0.11	0.16	0.02	0.16	Balance	%

- Irradiation Condition
  - Beam Energy : 1 keV (mainly H_3^+)
  - Flux : ~4 x 10^{20} $m^{-2}s^{-1}$
  - C : 0.1%~1.0%
  - Fluence : ~4 x 10^{24} m^{-2}

Irradiation Surface of RAF



Irradiated surface became very rough.

Irradiation Condition

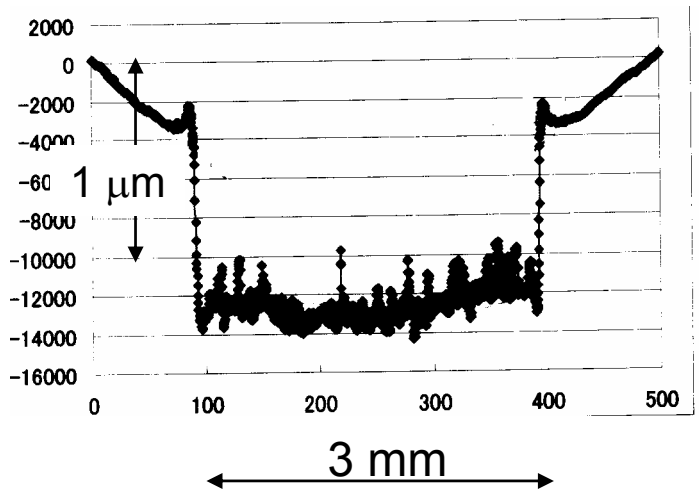
Energy: 1keV H_3^+ (mainly)

Fluence: 4.3×10^{24} m^{-2}

Temperature: 653 K

C content :1.0 %

Sample: mechanically polished



Surface Profile

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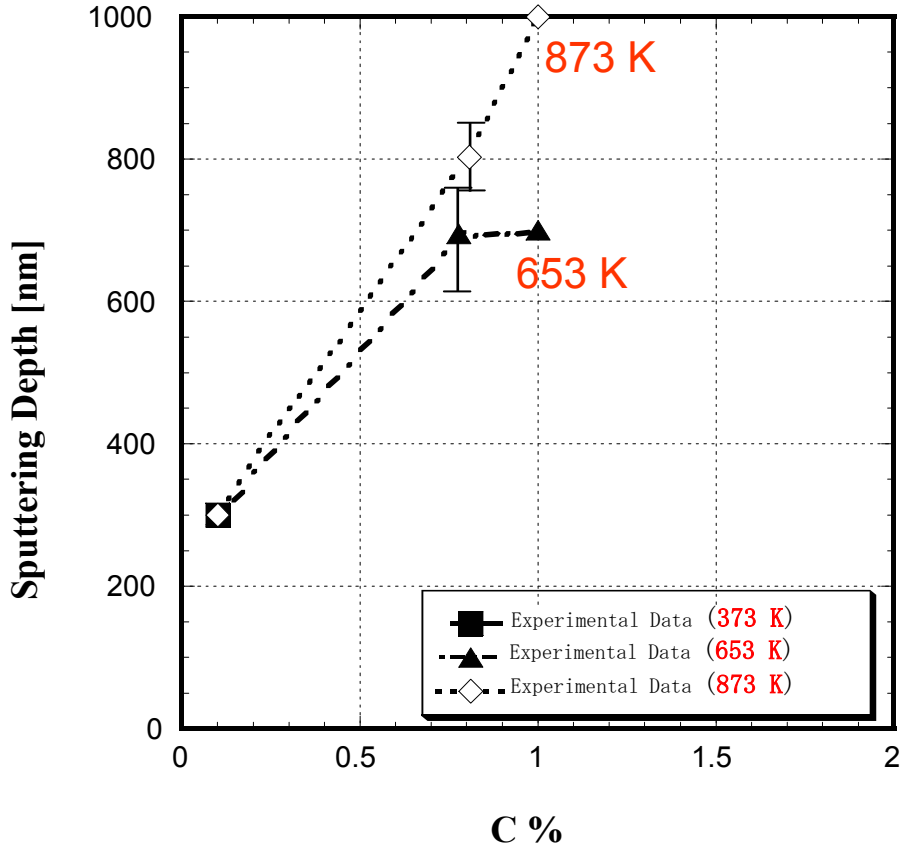
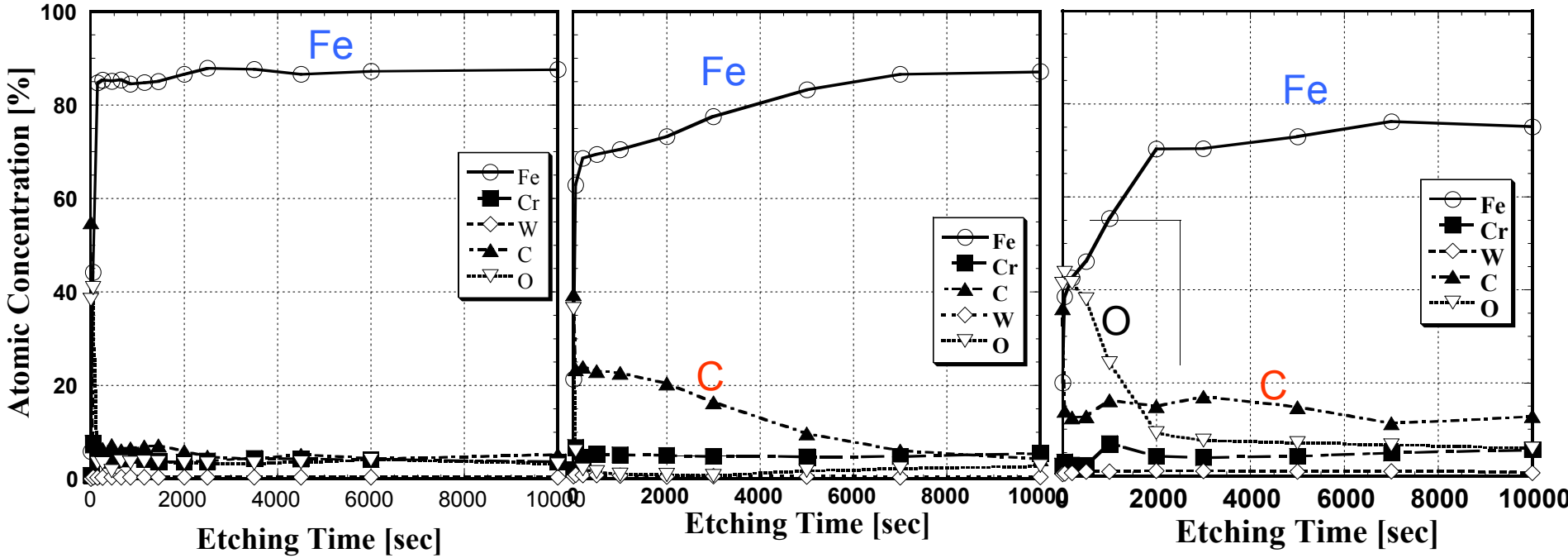
Erosion Depth of RAF



Erosion depth could be temperature-dependent.

Carbon depth profile in RAF



No Irradiation

C : 1.0% , 373 K

C : 1.0% , 873 K

Carbon atoms diffuses deeper into the bulk in 873 K.

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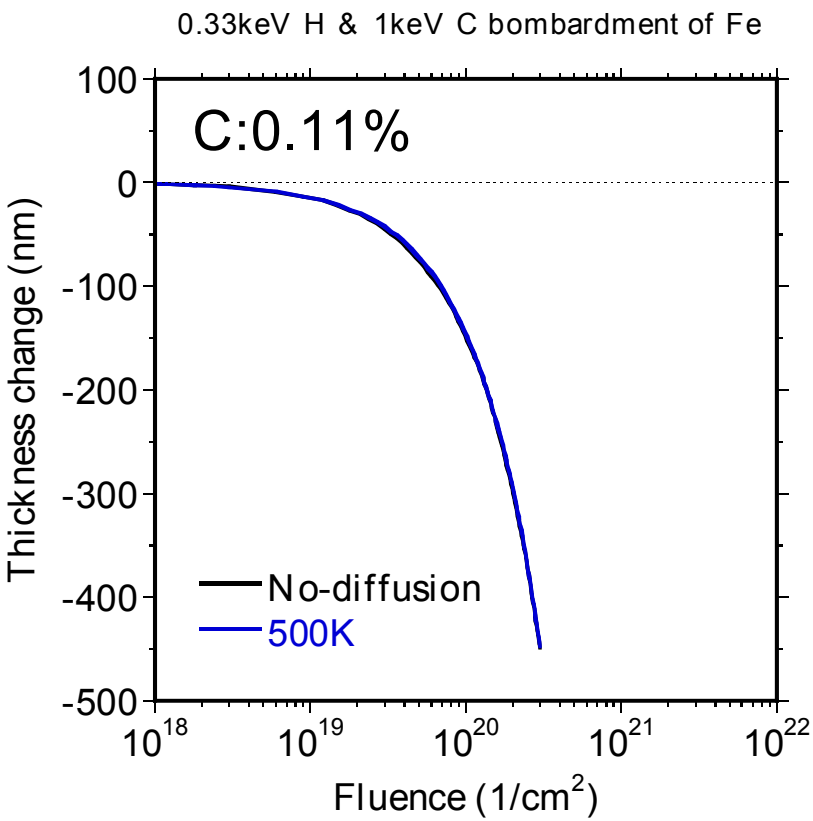
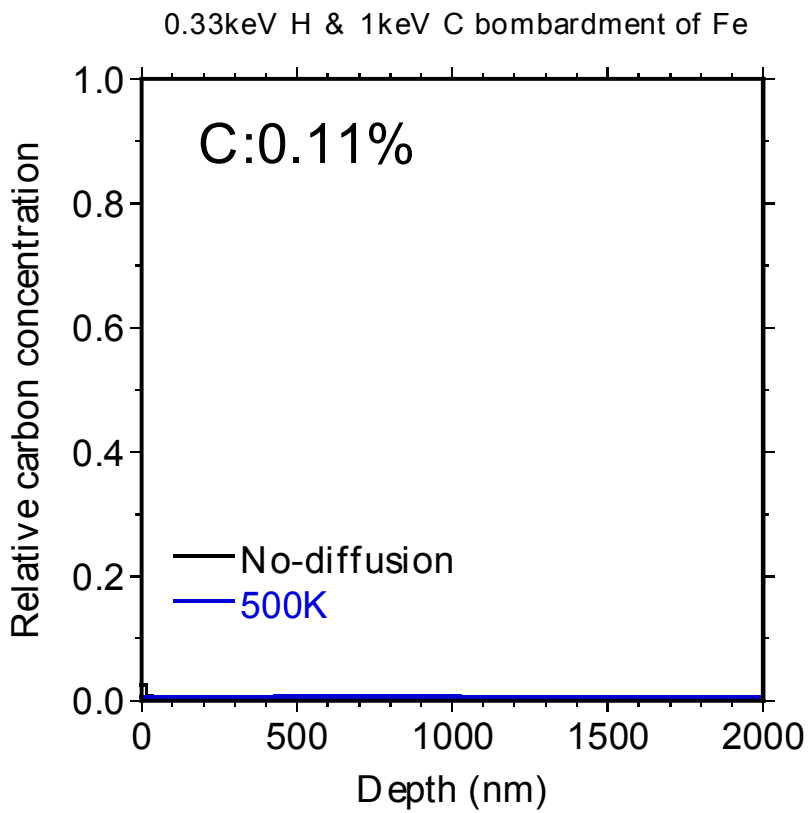
Erosion and C behavior in Fe (C:0.11%)

Simulation by the EDDY code with diffusion package

By R. Kawakami and K. Ohya.

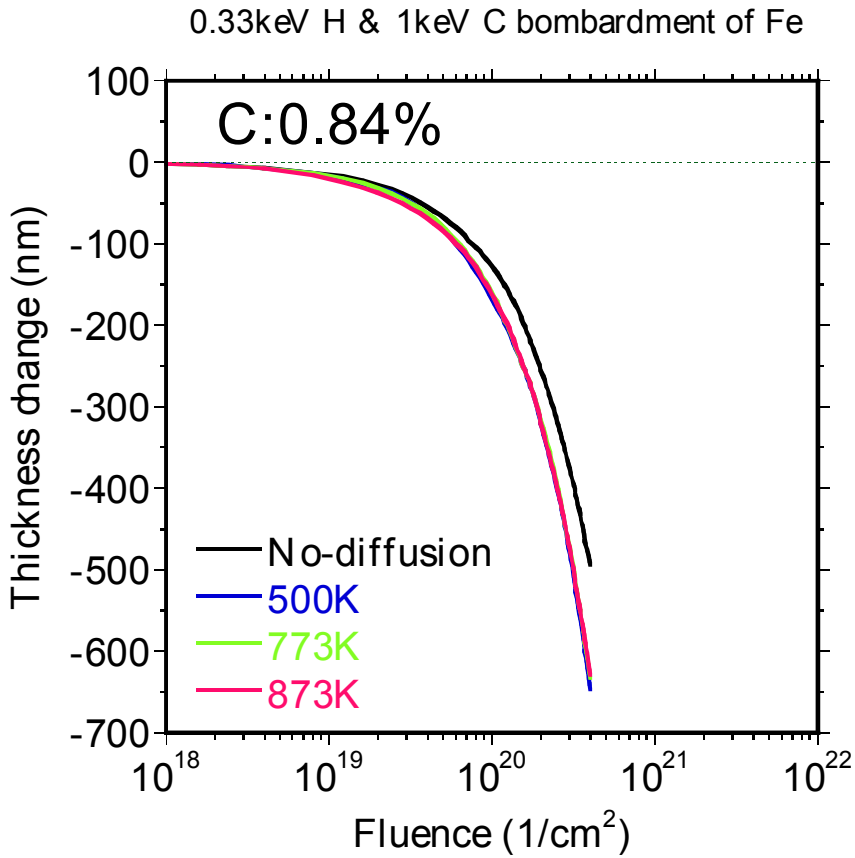


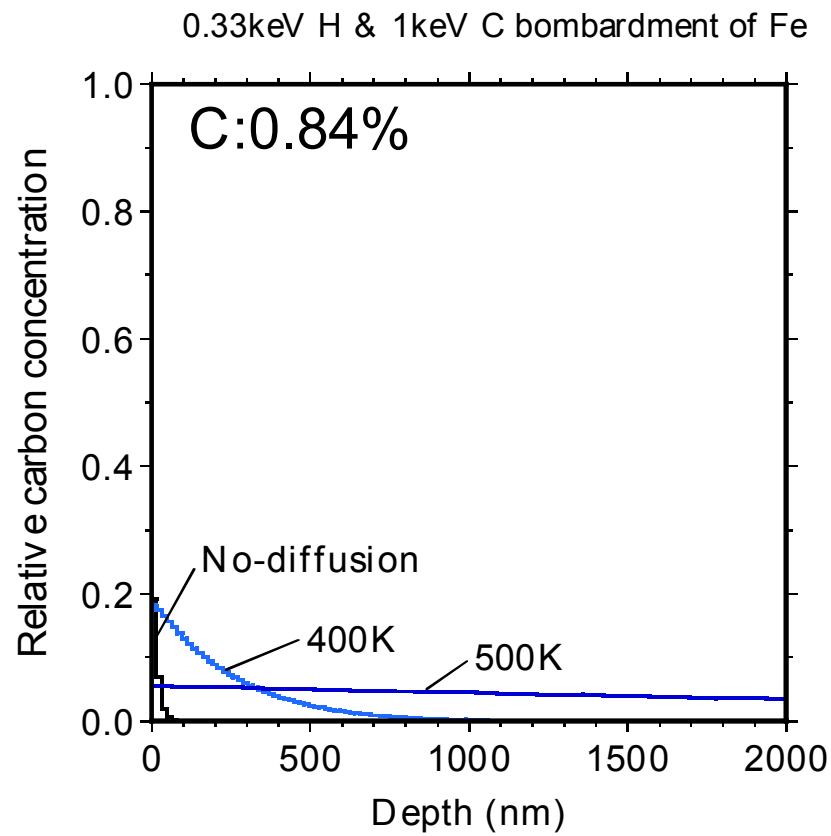


In the case of C:0.11%, surface concentration of C is very low.
Erosion depth is not temperature-dependent.

Erosion and C behavior in Fe (C:0.84%)

By R. Kawakami and K. Ohya.

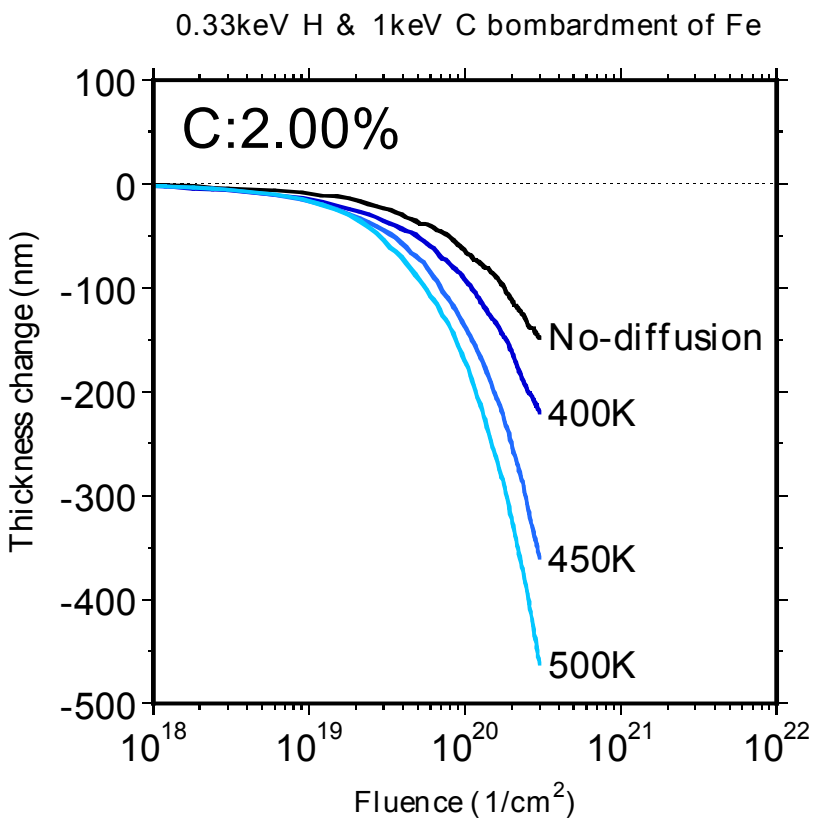


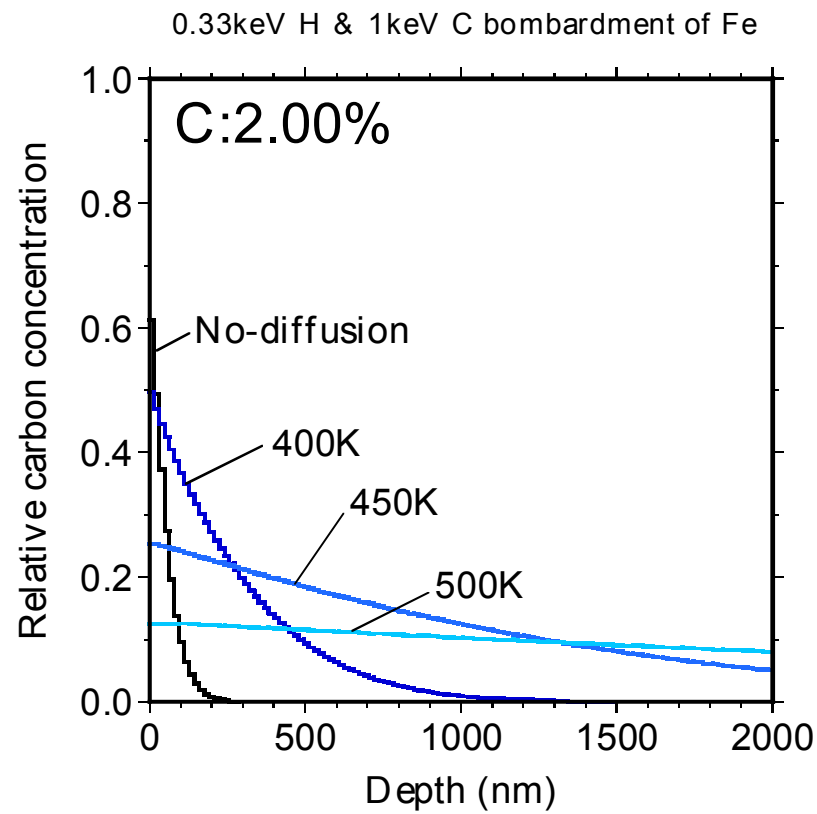


In the case of C:0.84%, surface concentration of C at low temp. is ~0.2.
Erosion depth is slightly temperature-dependent.

Erosion and C behavior in Fe (C:2.0%)

By R. Kawakami and K. Ohya.





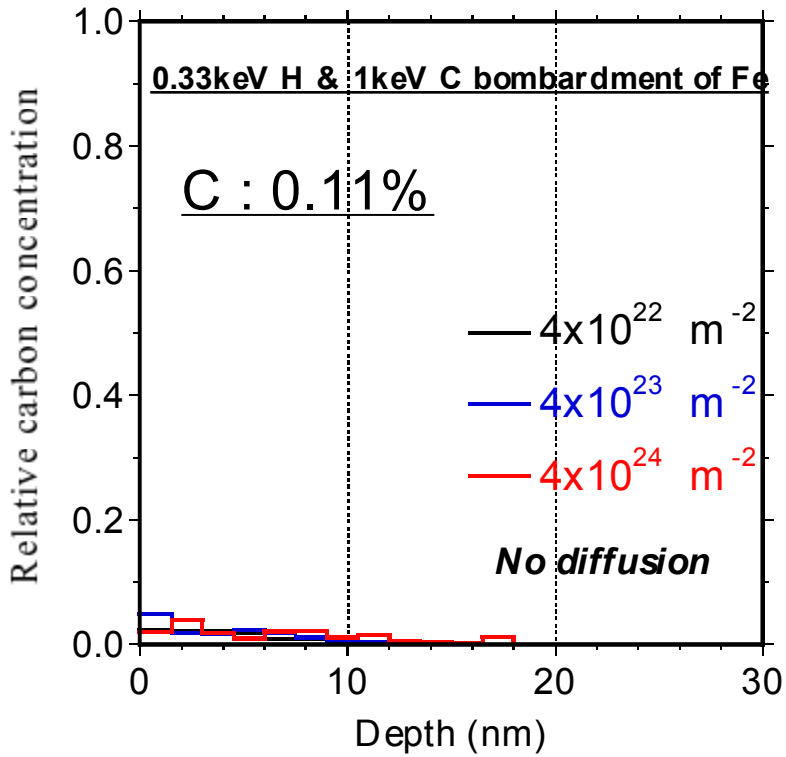
In the case of C:2.0%, surface concentration of C at low temp. is ~0.6.
Erosion depth is strongly temperature-dependent.

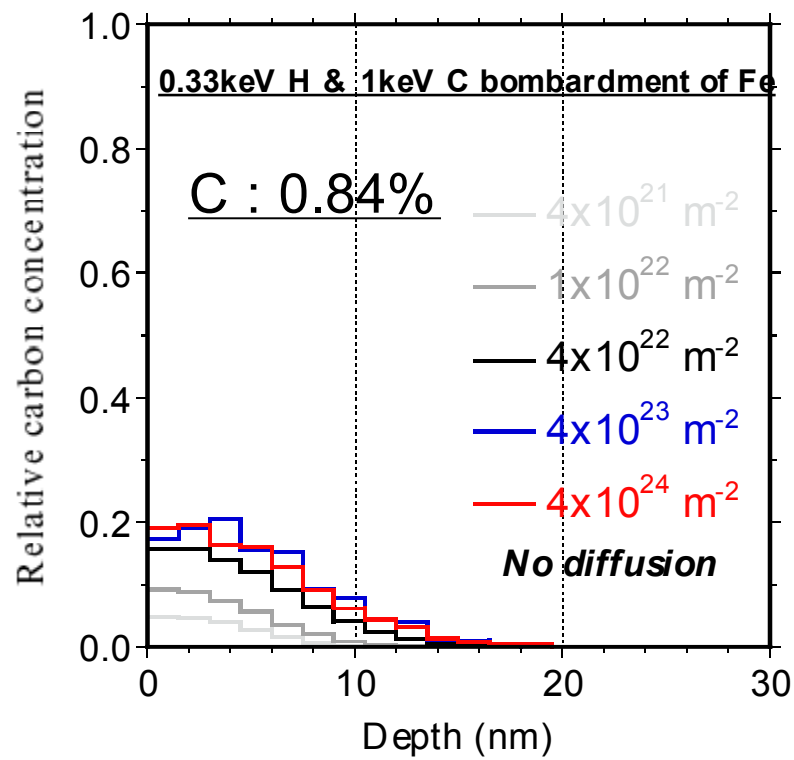
Summary

- Blister characteristics on W
  - Microstructure : Laminar → Disordered (Crystallized)
  - Blister size : Large → Small
  - Cracking : None → Many
- Carbon depth profile in W
  - Effects of recoil implantation and surface segregation observed.
- Carbon effects on F82H erosion
  - Temperature-dependent erosion probably occurred due to carbon diffusion.

Carbon depth profile in Fe

By R. Kawakami and K. Ohya.





No clear recoil implantation is observed for Fe. Because Fe has higher sputtering rate than W due to sputtering by H.