#MS01.09.22

2019.12.1-12.6 Materials Research Society Fall Meeting and Exhibit

大阪大学 OSAKA UNIVERSITY

Mechanical Property Changes of Tungsten Thin Films due to Hydrogen or Helium Implantation

Y. Habu[1)], H. T. Lee[1)], A. Nagakubo[1)], H. Ogi[1)], K. Ibano[1)], and Y. Ueda[1)]

1) Graduate School of Engineering, Osaka University

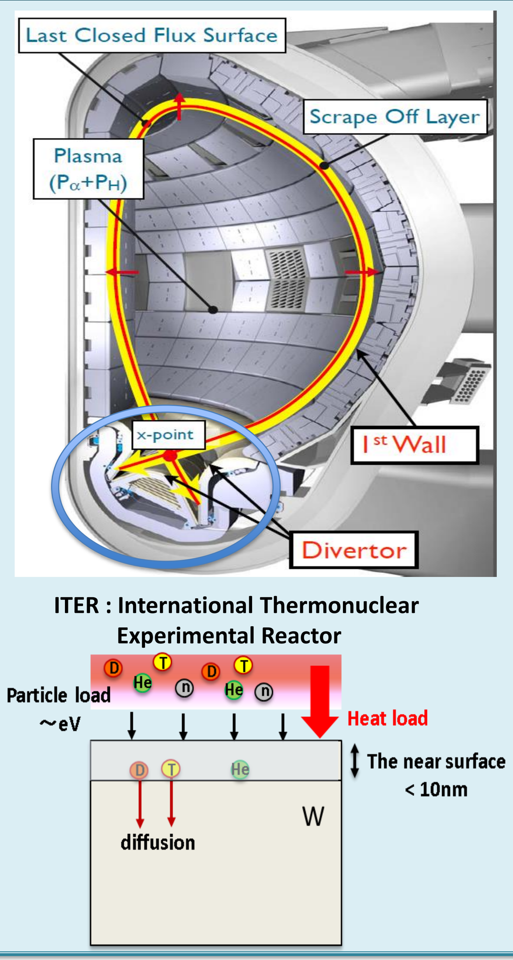
Presenter email : habu-y@st.eie.eng.osaka-u.ac.jp *Corresponding author email : heunlee@eei.eng.osaka-u.ac.jp

Background & Purpose

- Tungsten (W) plasma facing components in magnetic fusion devices experience extreme dynamical power (> 10 MW/m^2) and particle loads (>10^{24} m^{-2} s^{-1}) due to its interaction with the edge plasma [1].
- The large flux of implanted hydrogen or helium species result in large near-surface (< 10 nm) strain fields - driven by the low solubility of both hydrogen and helium in W.
- To date, the dynamical mechanical response of W under such non-equilibrium conditions far beyond its solubility limits is not well known due to the difficulty in probing the near-surface properties.

Purpose

To probe the near-surface mechanical property changes of W and it's dependence on hydrogen or helium implantation.



[1] R. A. Pitts et al., J. Nucl. Mater. 438 (2013) S48–56.

Conclusion

- In this study, the near-surface mechanical property of W thin film was probed by Picosecond Laser Ultrasonics.
- It was found that the elastic constant C_{33} decrease due to hydrogen or helium implantation. Such decrease in C_{33} is proportional to the square root of the implanted fluence. This suggests the increase in hydrogen or helium concentration by diffusion is responsible for the decrease in C_{33}.
- Such results suggest W plasma facing components be modelled as a two-layer structure (near-surface and bulk zones) with different mechanical properties due to hydrogen or helium implantation.
- Consequently, such two-layer structure can lead to larger cyclical strains during pulsed heat loads which can promote surface cracking.

Experimental method

W thin film sample

- Film thickness : 45±0.5 nm
- Density : 18.5±0.1 g/cm^3
- Substrate : Si <111> (10 × 10 ×0.02^t mm)

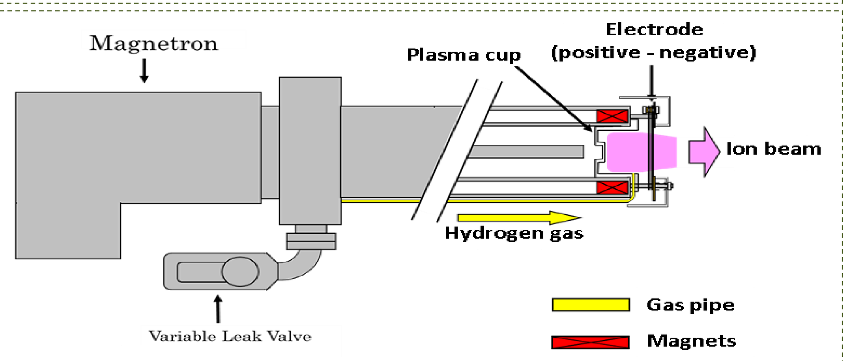
【Magnetron Sputtering】

- Voltage : 350 V, Current : 200 mA
- P_{Ar} : 2.0mTorr
- Temperature : 573K

Hydrogen plasma ion beam

Plasma Parameters

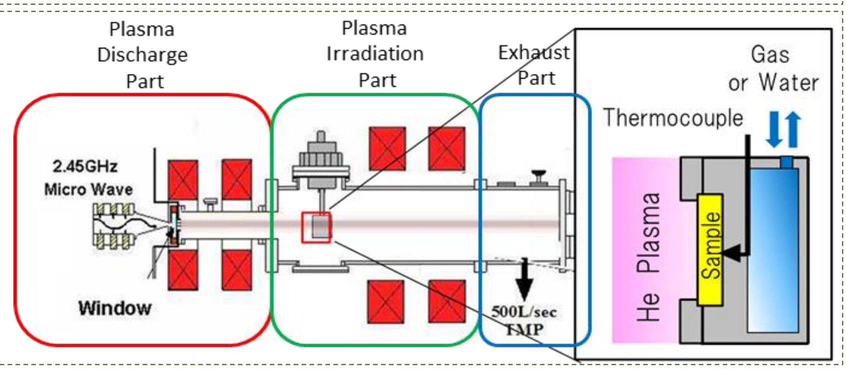
- ECR plasma ion source
- Ion energy : 1.0 keV
- Flux : 7.8×10^{15} H m^{-2}s^{-1}
- Fluence : 1.0×10^{18}, 10^{19}, 10^{20} H m^{-2}
- Sample temperature : 300 K



Helium plasma exposure

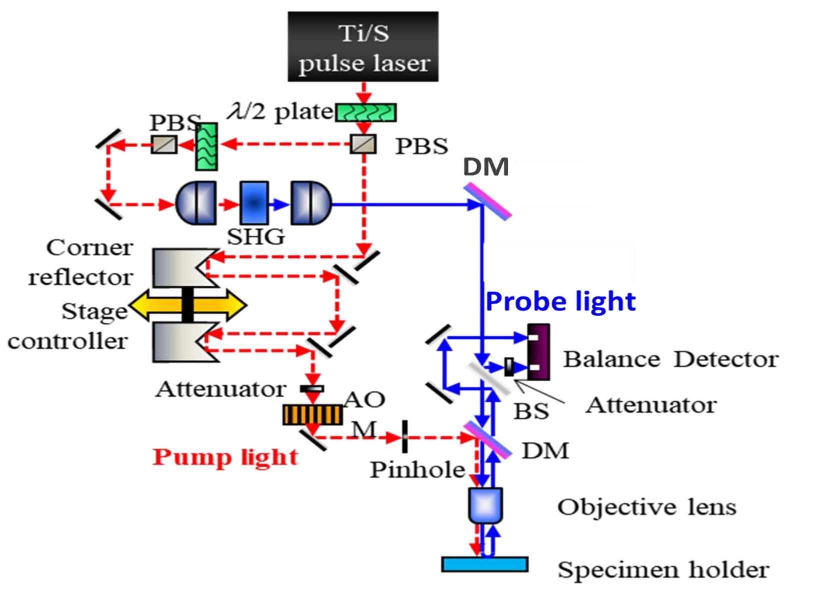
Plasma Parameters

- ECR plasma source
- Ion energy : 200 eV
- Flux : 1.0×10^{22} He m^{-2}s^{-1}
- Fluence : 1.0×10^{24}, 10^{25} He m^{-2}
- Sample temperature : 350 K



Picosecond Laser Ultrasonics [2][3]

Chameleon : Femto second Laser system



Measurement condition

- Ti/S pulse laser (wavelength : 800 nm)
- Period : 80 MHz, pulse width : ~140 fs
- Pump/Probe light : 20/10 mW
- Objective lens : 20, 50 times (Spot diameter : ~10 μm)

Theory

- This method is able to measure the longitudinal elastic constant C_{33} of thin film accurately using Pump pulse and Probe pulse.
- Pump pulse causes the acoustic pulse through thermal expansion.
- Probe pulse (time-delayed light pulse) can detect the reflectance change due to resonance vibration.
- The elastic constant C_{33} is obtained by

$$C_{33} = \rho v_l^2 = \rho (2fd)^2 \text{ [GPa]} \quad (1)$$

where ρ is density, v_l is longitudinal wave velocity, f is fundamental resonance frequency, d is film thickness.

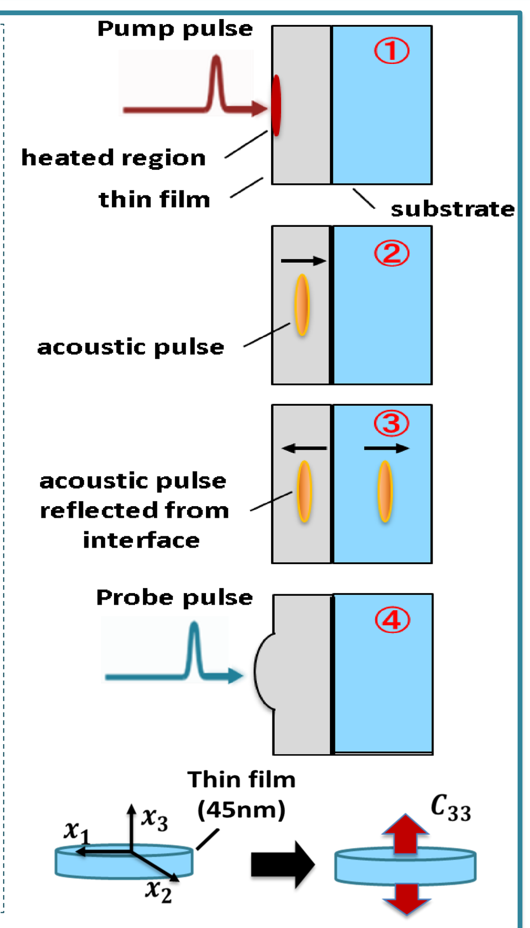
- For bulk W, C_{33} is expressed by

$$C_{33} = \frac{1-\nu}{(1+\nu)(1-2\nu)} E \quad (2)$$

where ν is Poisson ratio, E is Young's modulus

- Since Poisson's ratio does not change much,

$$\Delta C_{33} \propto \Delta E$$



[2] C. Thomsen et al., Phys. Rev. B 34 (1986) 4129. [3] H. Ogi et al., Phys. Rev. Lett. 98 (2007) 195503.

Results & Discussion

1)Elastic constant of W thin film

- In this study, the near-surface mechanical property of W thin film was determined.
- Fig. 1 shows the time-resolved reflectivity variation after pump pulse irradiation.
- We subtracted the decreasing reflectivity due to thermal diffusion as background.

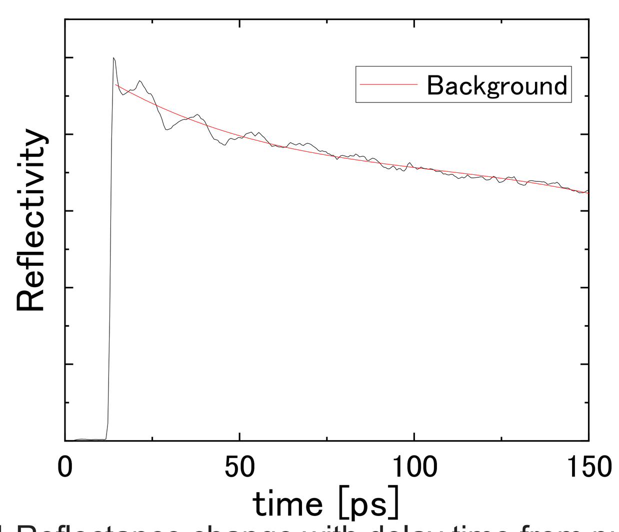


Fig.1 Reflectance change with delay time from pump pulse

- Fig. 2 shows the result of Fast Fourier Transform (FFT) of the reflectivity.
- The acoustic-phonon resonances up to the 3rd overtones were observed.

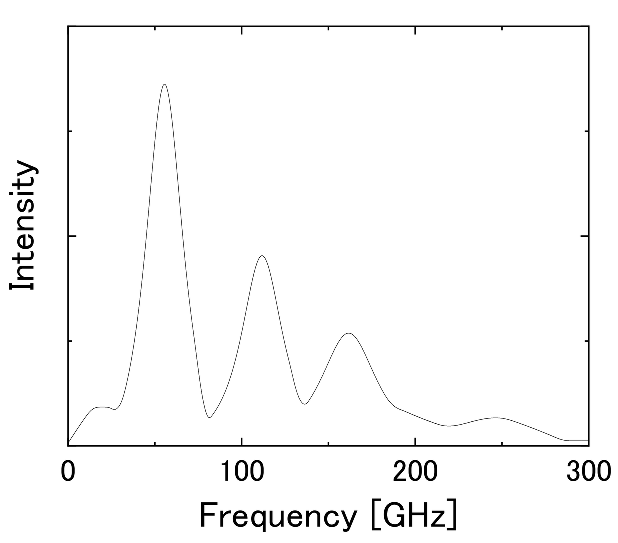


Fig. 2 The FFT spectrum, showing the acoustic-phonon resonances up to the 3rd overtones

- In this study, the elastic constant C_{33} of W thin films was 460±5 GPa.

2) Effects of hydrogen implantation on elastic constant

- We irradiated W thin films with hydrogen ion beam and measured the changes in elastic constant C_{33} before and after hydrogen irradiation.
- Fig. 3 shows changes in elastic constant C_{33} due to hydrogen ion beam irradiation.

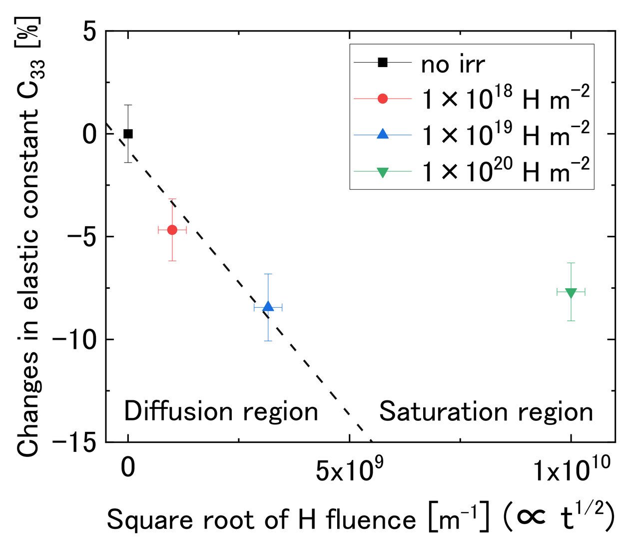


Fig.3 Changes in elastic constant due to hydrogen implantation

- The elastic constant C_{33} decreased linearly with respect to the square root of implanted hydrogen fluence (up to 1.0×10^{19} H m^{-2}) and then saturated.
- The relationship between the hydrogen diffusion distance x and the diffusion coefficient D is:

$$x \propto \sqrt{Dt} \quad (3)$$

- The diffusion coefficient is approximated to be:

$$D \cong O(10^{-18})\ m^2 s^{-1}$$

3) Effects of helium implantation on elastic constant

- We irradiated W thin films with helium plasma and measured the changes in elastic constant C_{33} before and after helium irradiation.
- Fig. 4 shows changes in elastic constant C_{33} due to helium plasma irradiation.

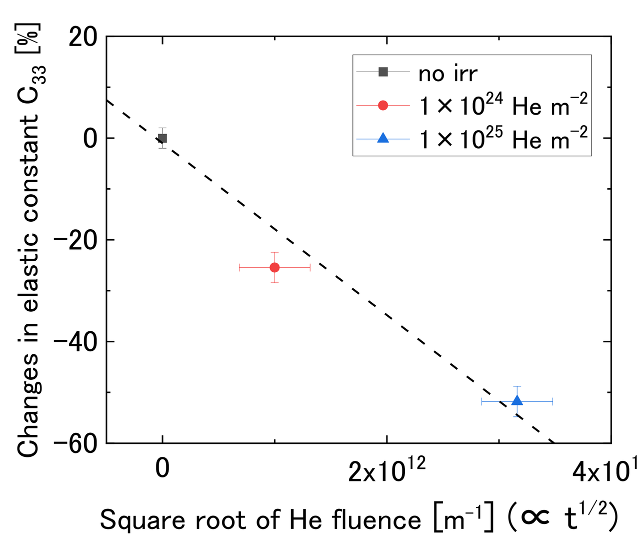


Fig.4 Changes in elastic constant due to helium implantation

- The elastic constant C_{33} decreased linearly with respect to the square root of implanted helium fluence.
- The relationship between the helium diffusion distance and the diffusion coefficient is expressed by Eq. (3).
- The diffusion coefficient is approximated to be

$$D \cong O(10^{-18})\ m^2 s^{-1}$$

4) Discussion

- The near-surface elastic constant C_{33} of W decrease due to H or He implantation.
- This suggests H and He weaken the bond energy of W atoms consistent with MD simulations. [4]
- The decrease in C_{33} is proportional to the rate of inward diffusion suggesting the decrease depends linearly on H or He concentrations.
- The diffusion coefficient of hydrogen at 300 K is [5]

$$D = 1.2 \times 10^{-13}\ \text{m}^2\text{s}^{-1}$$

and that of helium at 350 K is [6]

$$D = 5.5 \times 10^{-9}\ \text{m}^2\text{s}^{-1}$$

- These values correspond to diffusion without trapping. The much lower values from our experiments indicate significant trapping effects.

[4] X. Yu et al., J. of Nucl. Mater. 441 (2013) 324
[5] R. Frauenfelder et al., Journal of Vacuum Science and Technology 6 (1969)
[6] Xiaolin Shu et al., Nuclear Instruments and Methods in Physics Research B 303 (2013) 84–86
[7] C.S. Becquart, C. Domain, Phys. Rev. Lett., 97 (2006), p. 196402

- Such results suggest W plasma facing components be modelled as a two-layer structure (near-surface and bulk zones) with different mechanical properties due to H or He implantation. (Fig. 5)
- Pulsed heat loads generate periodic lateral stresses [8] (Fig. 6) and the near-surface strains of W can increase due to the decrease in C_{33}. (Fig. 7)
- We consider that such increase in cyclical strains can promote W surface cracking.

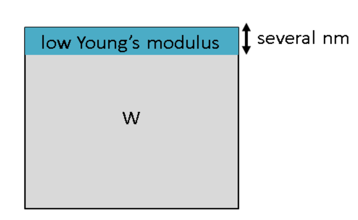


Fig. 5 two layer model

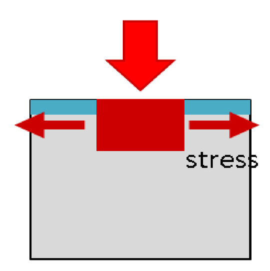


Fig. 6 thermal stress

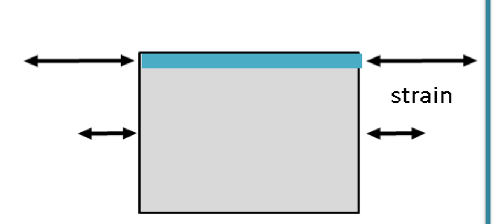


Fig. 7 different strain

[8]T.Hirai, Nuclear Materials and Energy, Volume 9, December 2016, Pages 616-622