第2回 EUV-FEL WORKSHOP ワークショップ 開催 2017 12.12 Tue 10:00-17:00

QST

KPSI Kansai Photon Science Institute

Research on interaction of SXFEL with matter for EUV ultra-precision nano-fabrication

EUV微細加工技術に向けた SXFELと物質・材料の相互作用に関する研究

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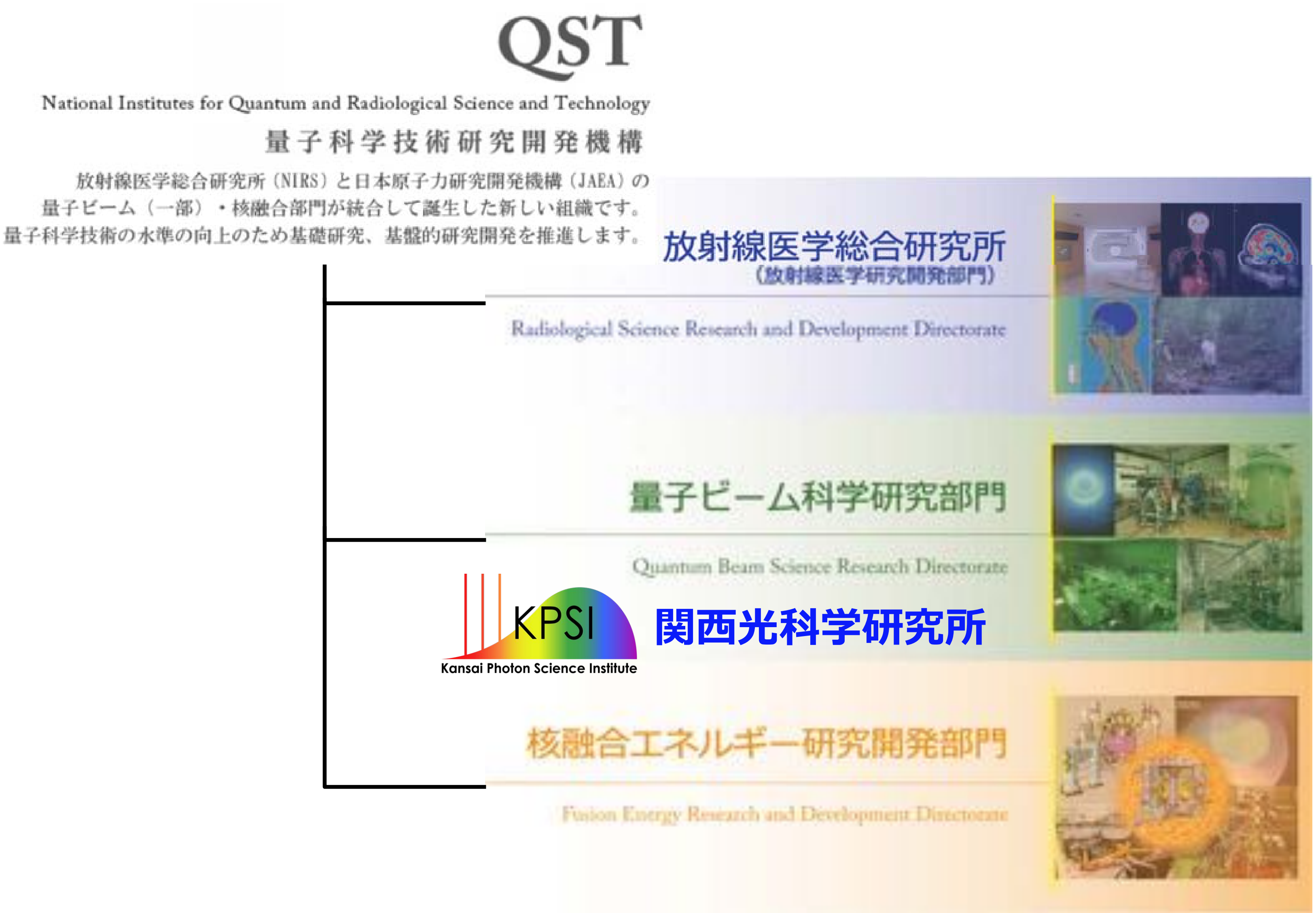
National Institutes for Quantum and Radiological Science and Technology (QST)



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The XFEL experiments were performed at the BL1 of SACLA with the approval of JASRI (Proposal No. 2016B8006, 2017A8026, and 2017B8004).

Contents

1. Introduction

- Motivation for the understanding of EUV laser ablation

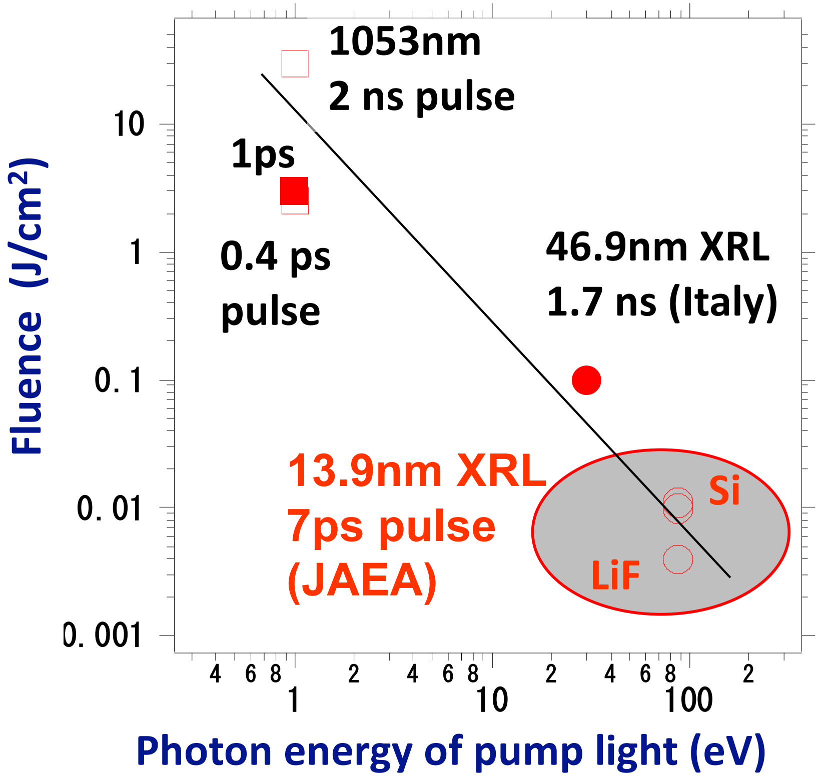
2. Interaction with SXFEL

- SXFEL ablation (Al & Si)
- SXFEL damage (Mo/Si & Resist)
- SXFEL exposure and SXFEL direct processing

3. Summary

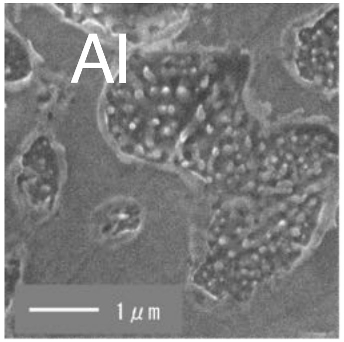
Motivation for the understanding of EUV laser ablation

Low ablation threshold

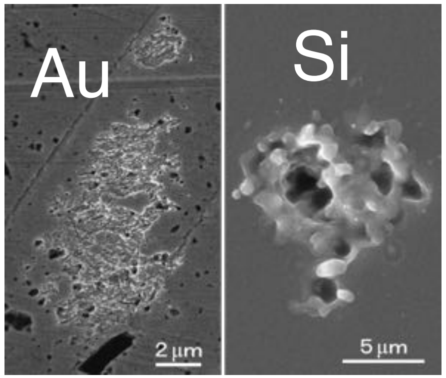


Faenov, Appl. Phys. Lett. 94, 231107 (2009)

Nano-scale surface structure



M. Ishino *et al.*, J. Appl. Phys. **109**, 013504 (2011).



M. Ishino *et al.*, Appl. Phys. A **110**, 179 (2013).

The law ablation threshold of a material for an XRL beam has a possibility of efficient machining by a lithography process and an ablation process.

Requirement for High power EUV source

EUV exposure system

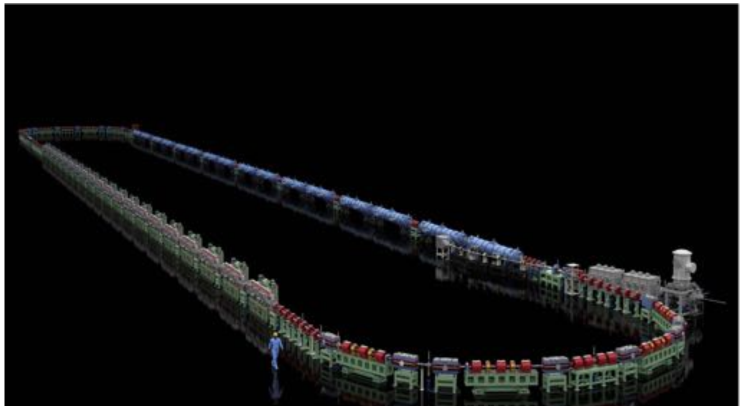
semiengineering.com

EUV source power

250~ W

500~1000 W
(for HVM)

Next generation photon source for EUVL ?

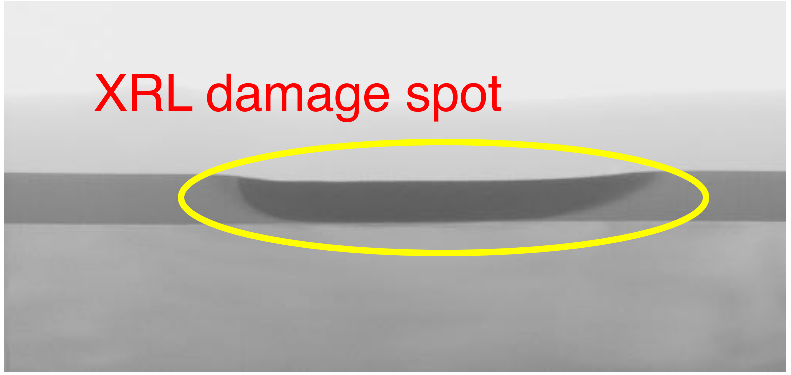


R. Kato, EUVL workshop 2016
"The Design and Development of a 10-kW Class EUV-FEL Project in Japan "

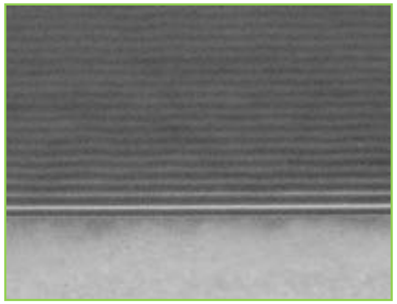
The EUV source power is need further improvement to HVM requirements.

Motivation for the understanding of EUV laser damage

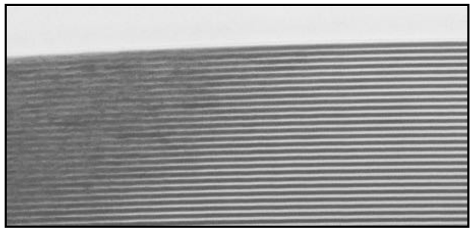
Mo/Si ML mirror ablation



Lurking structure in bottom



Compressed structure around damage



collaborated with NTT-AT

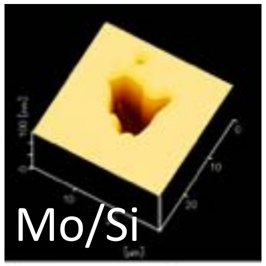
High power EUV source

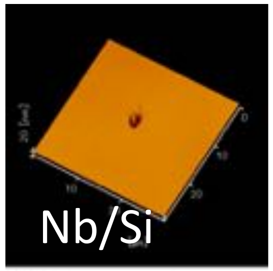
↓

Damage(ablation) risk
-Multilayer mirror-
-Pellicle-
-Resist-

↓

Highly-durable EUV optics





The Nb/Si multilayer has potential for higher resistance of High power EUV light source.

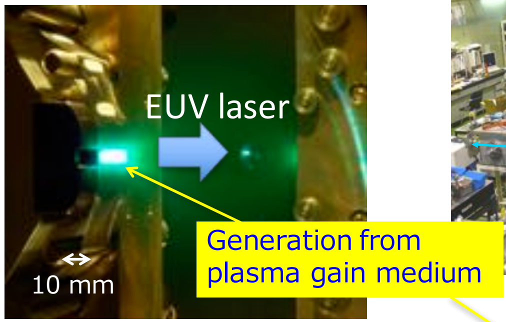
2. Interaction with SXFEL

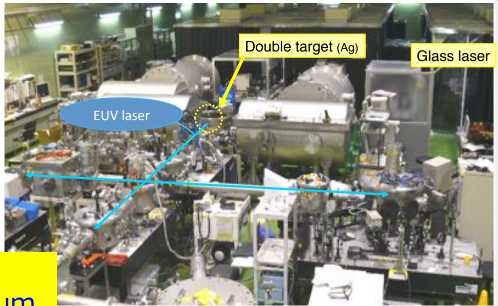
SXFEL ablation (Al & Si)

[2016B8006]
超短パルス高輝度コヒーレント軟X線レーザーによる超微細加工に向けたアブレーション現象の解明
Nanoscale surface modifications and formation induced by ultra-short soft x-ray laser pulse
[2017A8026]
SXFEL光源を用いた極端紫外線リソグラフィー技術の課題調査
Challenging survey of Extreme Ultraviolet Lithography Using SXFEL Source
[2017B8004]
EUV微細加工技術に向けたSXFELと物質・材料の相互作用に関する研究
Research on interaction of SXFEL with matter for EUV ultra-precision nano-fabrication

We have started the comparison study of pulse duration dependence using the two EUV lasers.

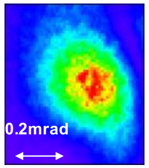
Plasma EUV laser

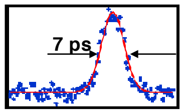


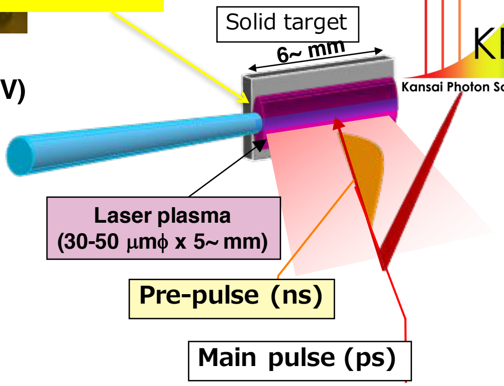


EUV laser

Wavelength : 13.9nm (89.2eV)
Energy: ~0.5 μJ
Pulse width : ~10 ps
Divergence: < 1mrad







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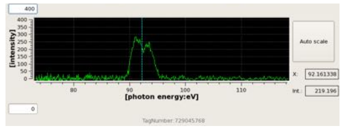
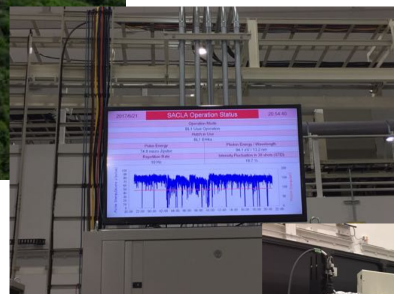
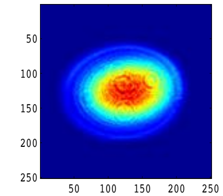
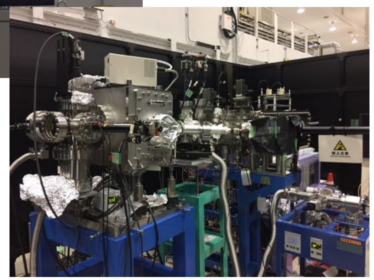
SXFEL









SACLA

SXFEL (SACLA BL-1)

Wavelength : 13.5nm (92eV)
Energy: ~80 μJ
Divergence: < 1mrad

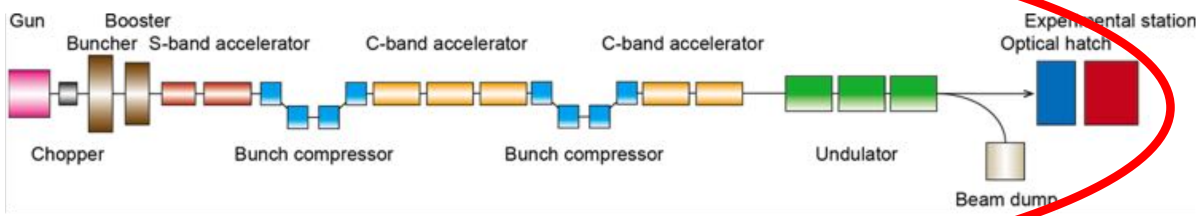
We have started the comparison study of pulse duration dependence using the two EUV lasers.

SXFEL at SACLA-Bl1

92 eV & 200~ fs

K. Togawa *et al.*, Proceedings of IPAC2017

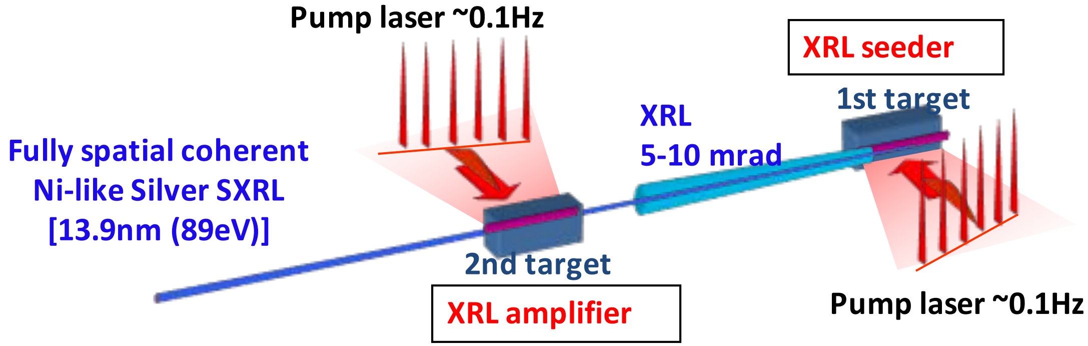
- Photon energy: 20 to 150 eV (soft x-ray region)
- Pulse energy: 100-μJ class
- Pulse width: 200 fs (100~300 fs)
- Repetition rate: 60 Hz



Plasma-based x-ray laser

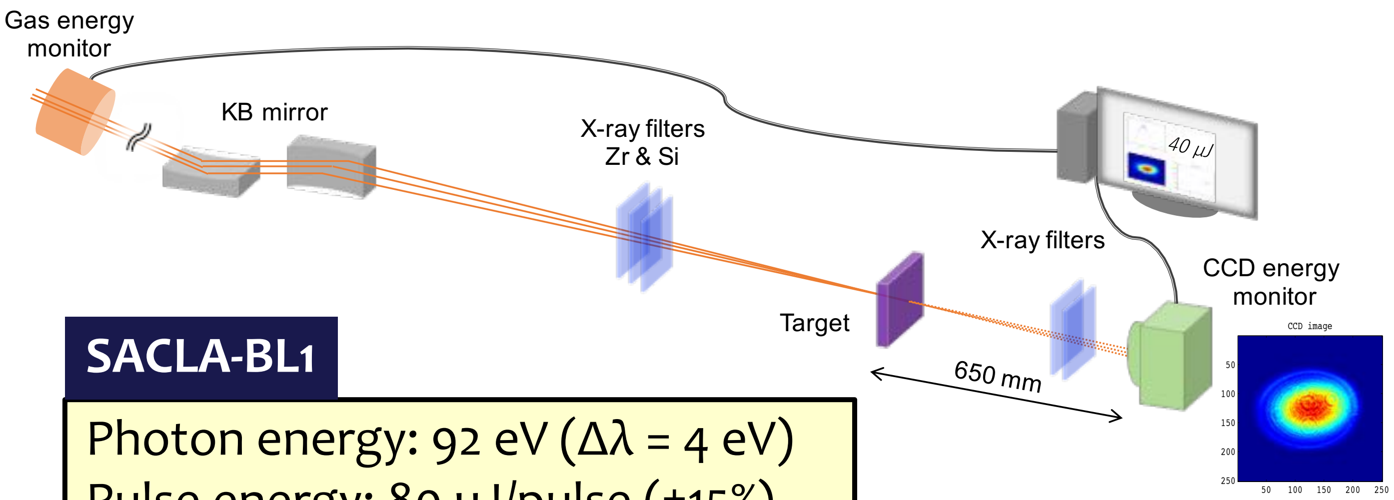
89 eV & ~10 ps

- Photon energy: 89 eV (13.9 nm)
- Pulse energy: 100-nJ class
- Pulse width: 7 ps
- Repetition rate: 0.1 Hz



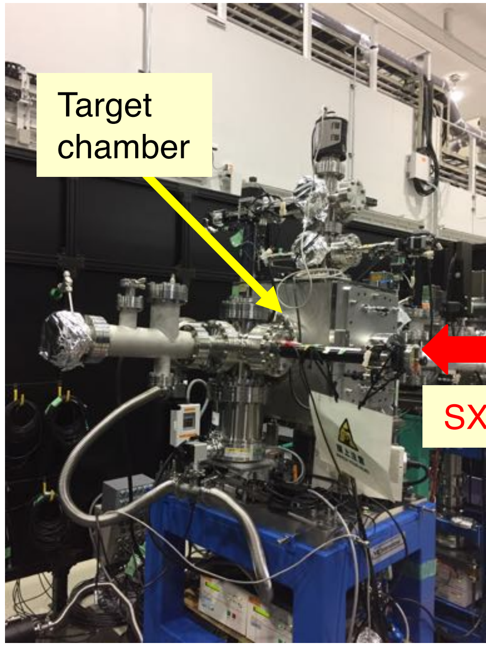
Study on dependence of pulse duration is enable

Experimental setup at SACLA-BL1



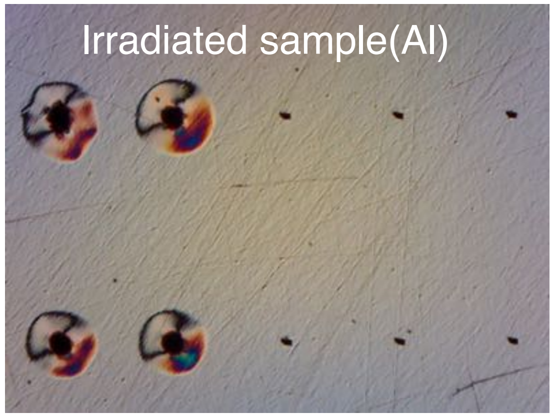
SACLA-BL1

Photon energy: 92 eV (Δλ = 4 eV)
Pulse energy: 80 μJ/pulse (±15%)
Pulse duration: 200 fs (100- 300 fs)

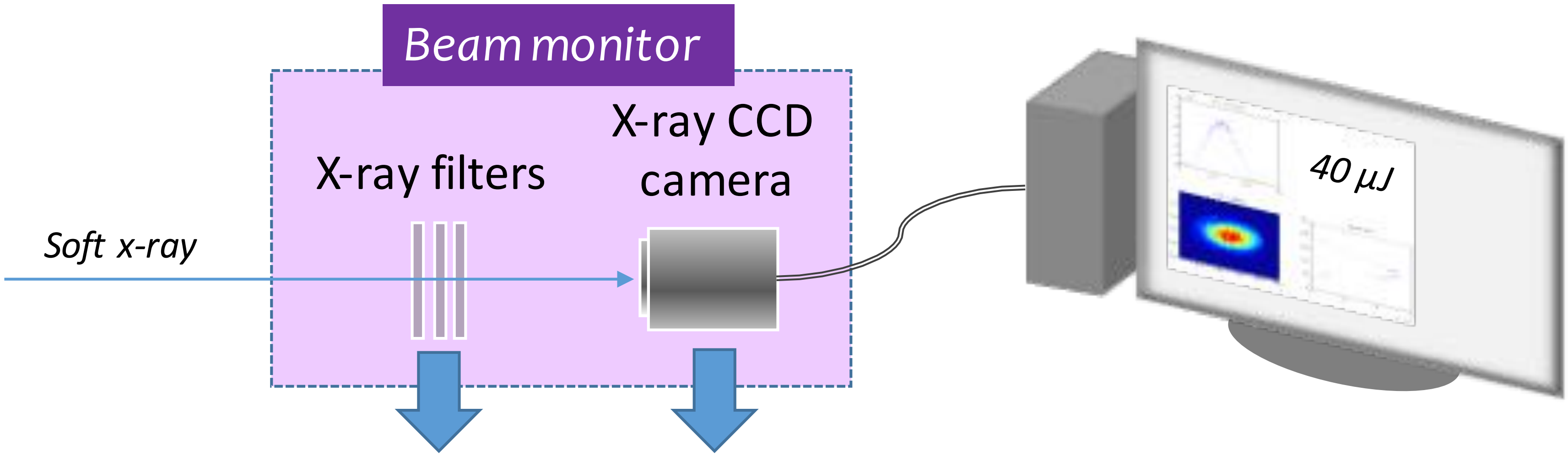


Irradiation condition

Focal spot size at FWHM (typical):
Horizontally: 10.5μm
Vertically: 8.5 μm
Fluence: 5 – 1000 mJ/cm^2
Target: Al, Si, Mo, Mo/Si, Resist etc…



X-ray filter & CCD camera were calibrated at KEK-PF BL11D.



Transmittance **measured at PF-BL11D & SACLA-BL1**

Responsivity **calibrated at PF-BL11D**

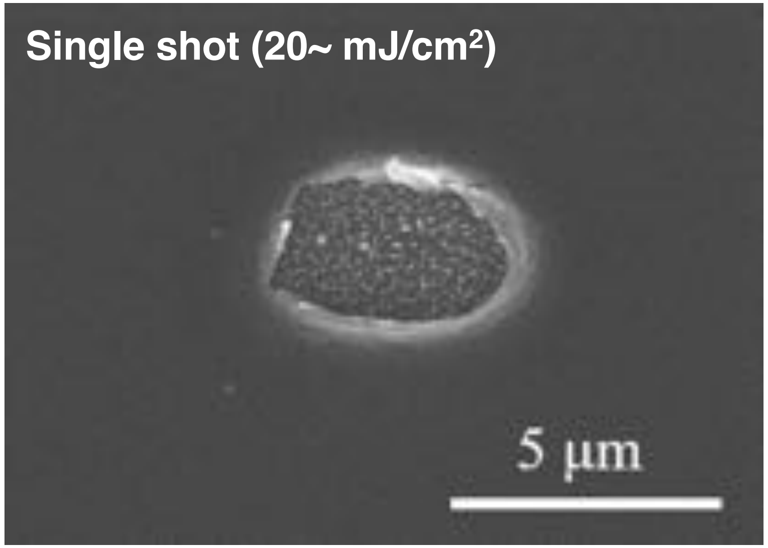
PF SACLA PF

SEM image

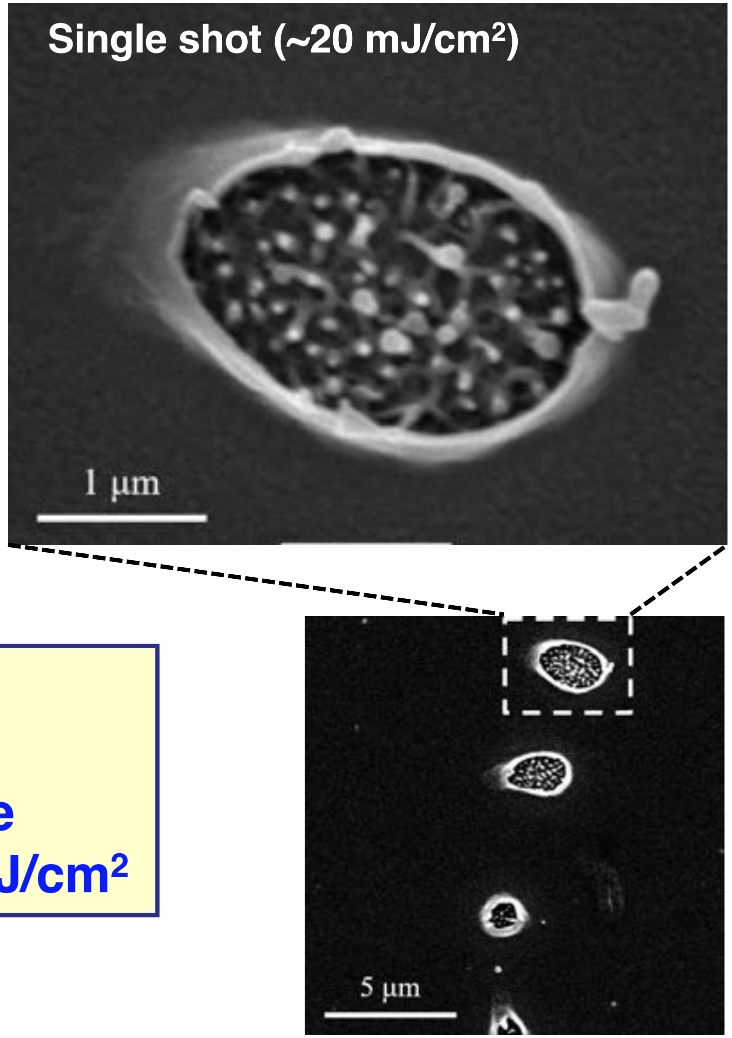
Spallative ablation structures on Al surfaces

QST

SXFEL: λ= 13.5 nm, τ = 100–300 fs



SXRL: λ = 13.9 nm, τ = 7 ps



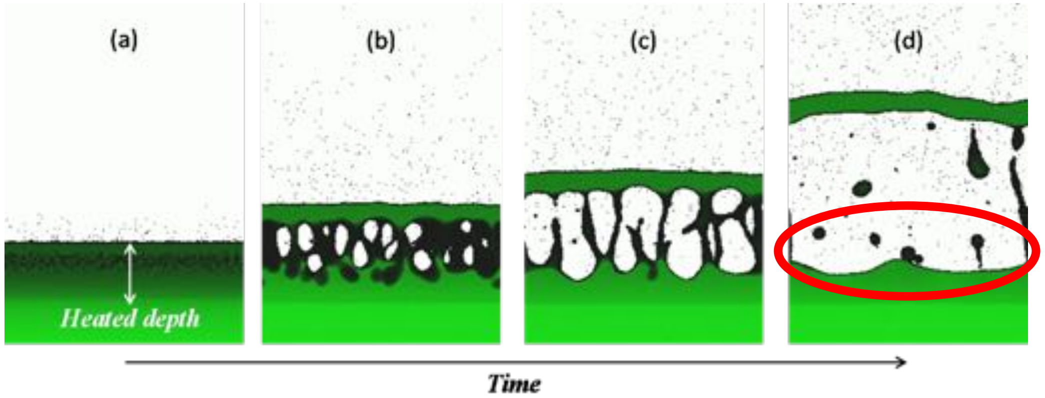
- **Attenuation length : ~40 nm**
- **Rim structure**
- **Nano scale conical structure**
- **Threshold fluence :15~20 mJ/cm²**

#ps-XRL results
M. Ishino et al., J. Appl Phys (2011)
S. V. Starikov *et al*., Appl. Phys. B 116, 1005 (2014).

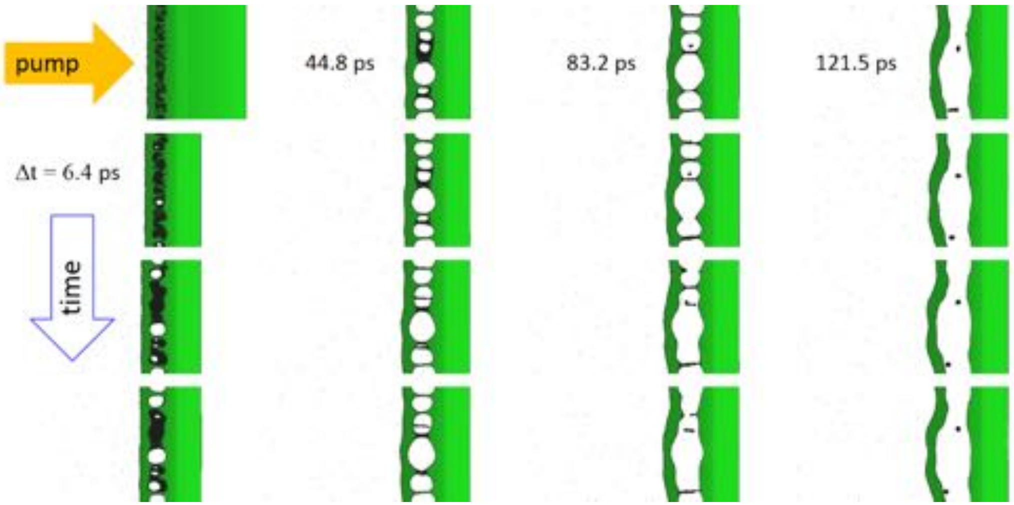
M. Ishino et al.,JSAP Meeting（2017)

Theoretical calculation of spallation process

Al attenuation length: ~40 nm



(a)	Nucleation of interatomic size form
(b) + (c)	Inflation of the foams
(d)	Run away of the spallative layer
Finally	Appearance of surface nano-relief



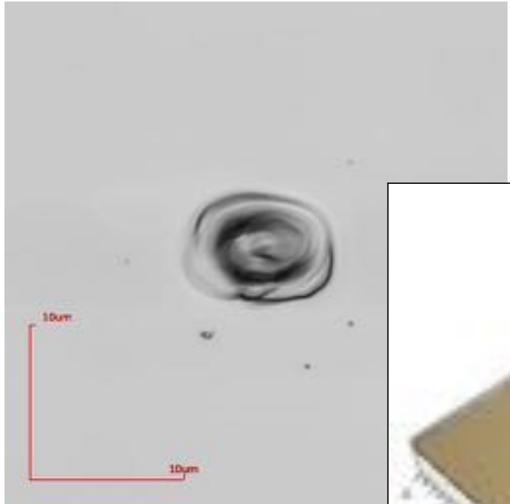
Spallation is long term process in comparison with SXRL pulse width.

Process duration >> Pulse width
(more than 100 ps)   (7 ps)

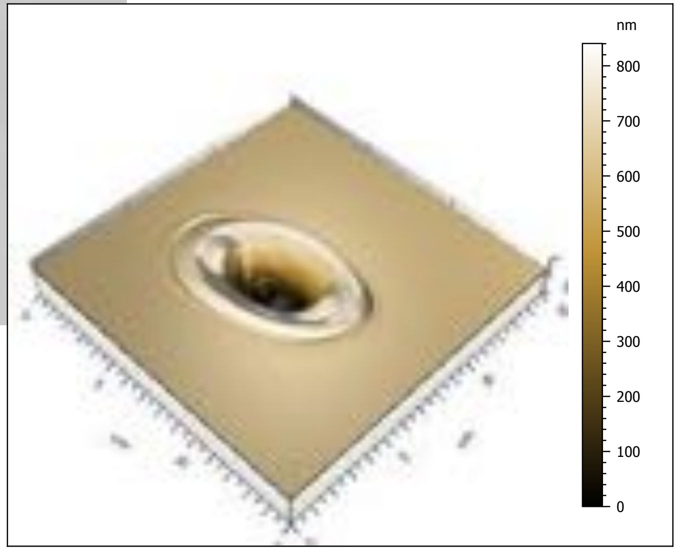
M. Ishino *et al.*, J. Appl. Phys. 109, 013504 (2011).

Deep hole on Si surfaces

SXFEL: λ = 13.5 nm, τ = 100–300 fs

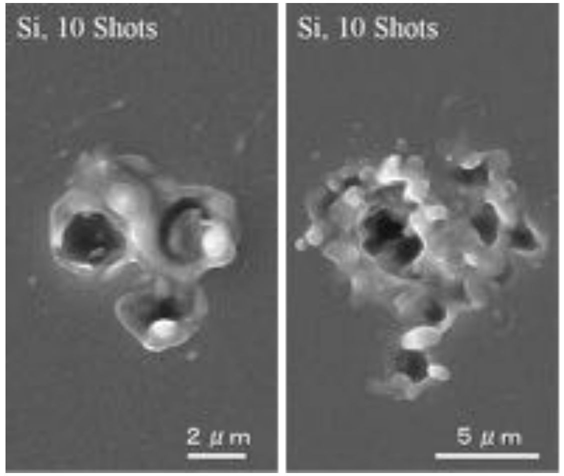


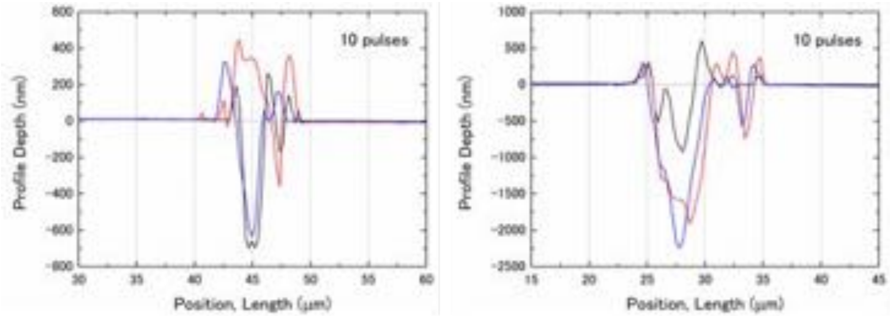
1shot (~500 mJ/cm²)



- **Attenuation lengty : ~600 nm**
- **Melting-like deep hole**
- **Threshold fluence :300~400 mJ/cm²**

SXRL: λ = 13.9 nm, τ = 7 ps





#ps-XRL results
M. Ishino et al., Appl Phys A(2013)

Si ablation

Comparison of Simulation result

Evaluation from simulation result

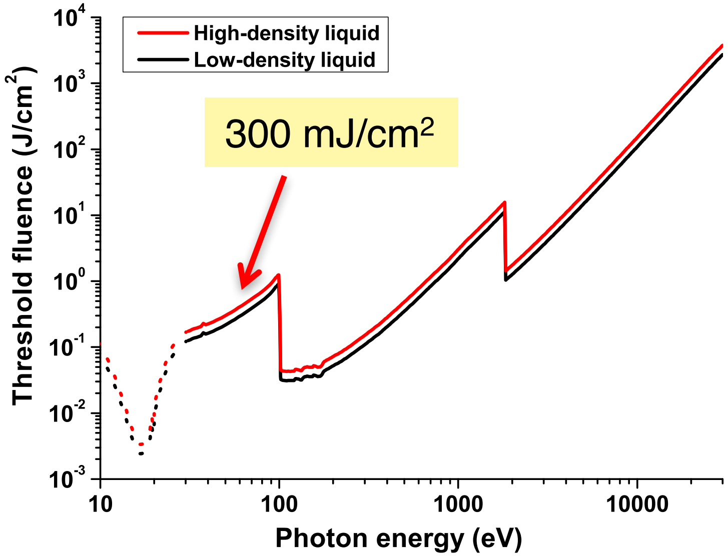


FIG. 10. (Color online) Damage threshold fluences for silicon corresponding to the low-density liquid and high-density liquid formation as a function of photon energy.

MD simulation

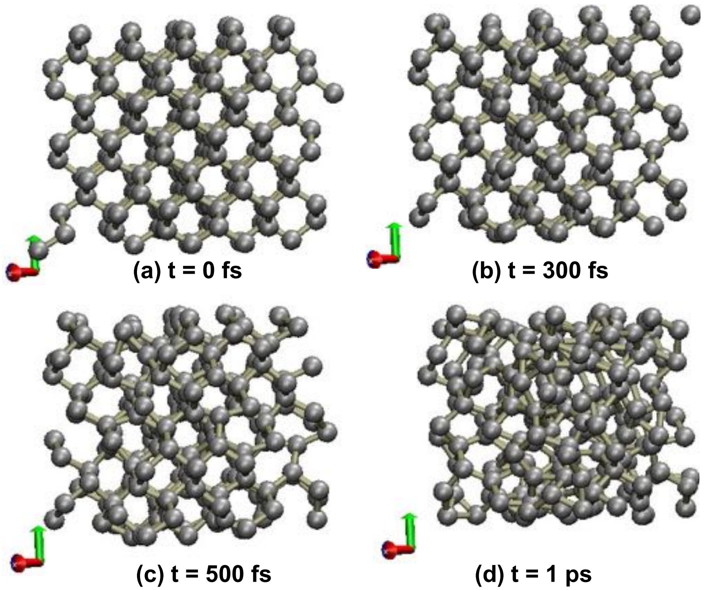


FIG. 11. (Color online) Nonthermal phase transition: snapshots of atomic positions in silicon irradiated with 10 fs laser pulse of $\hbar\omega = 1$ keV photon energy at the absorbed dose of 2.5 eV/atom: (a) $t = 0$ fs, (b) $t = 300$ fs, (c) $t = 0.5$ ps, and (d) $t = 1$ ps. X, Y, and Z axes are shown (left bottom of each panel).

N. Medvedev PRB91, 054113 (2015)

2. Interaction with SXFEL

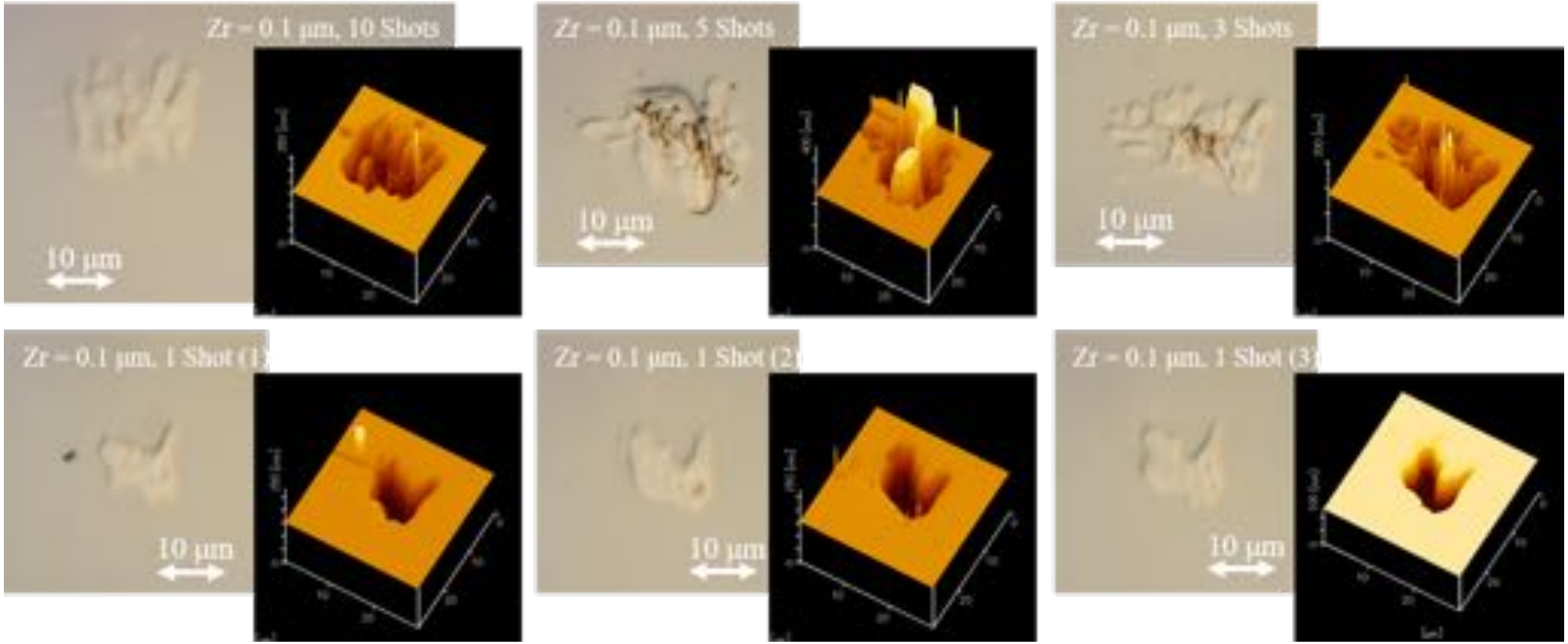
SXFEL ablation (Mo/Si & Resist)

Collaboration with
NTT-AT, Waseda Univ., Utsunomiya Univ., and EIDEC

Damage induced by ps-XRL

QST

ps-XRL: Single shot (20~ mJ/cm²) Normal incidence

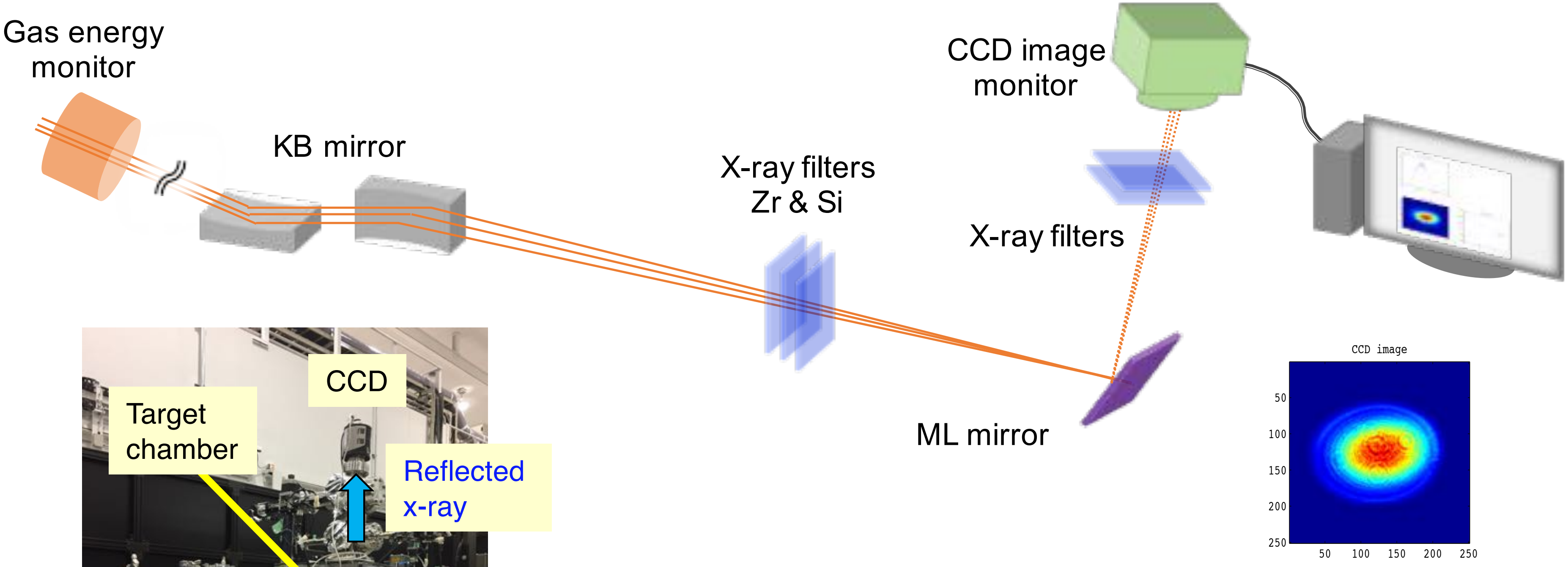


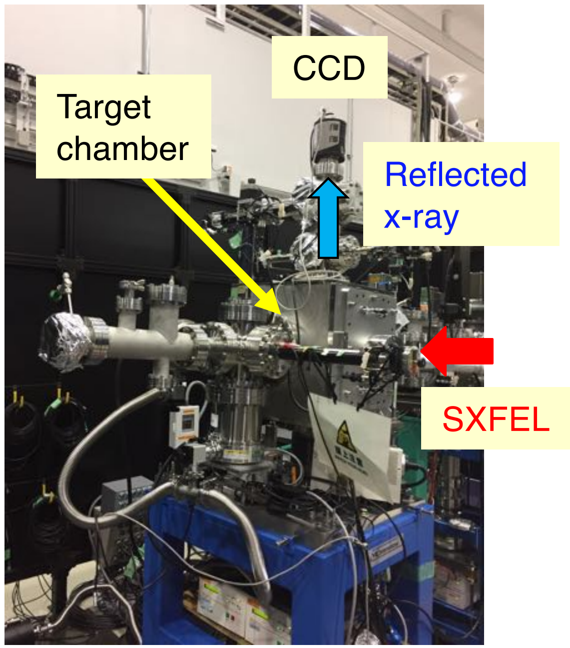
S. Ichimaru *et al.*, Proc. ICXRL 2016 (will be published).

Ablation threshold of Mo/Si multilayers evaluated by EUV lights

- **~45 mJ/cm^2: FEL (FLASH), λ = 13.5 nm, τ = 10 fs [A. R. Khorsand *et al.*, Opt. Express 18, 700 (2010).]**
- **~200 mJ/cm^2: Plasma source, λ = 13.5 nm, τ = 8.8 ns [M. Müller *et al.*, Appl. Phys. A 108, 263 (2012).]**

Experimental setup at SACLA-BL1





S. Ichimaru et al.,JSAP Meeting（2017)

Summary

Nano-scale surface modifications

- We show the surface ablation/modifications formed on Al and Si induced by single or multiple SXFEL pulse irradiations.
- Surface modification thresholds of SXFEL pulse for materials are essentially lower than those of optical lasers.
- The MD simulation developed for soft x-ray ablation reveals the spallation process for surface modifications.

EUV lithography components test

- We started the EUV damage test on multi-layered mirrors and EUV lithography components.
- The surface damage are occurred in essentially *lower* fluence than those of ns-plasma x-ray source.
- There is a possibility that the exposure sensitivity is also lower than a ablation threshold.

ACKNOWLEDGEMENTS

This work was partly supported by Grant-in Aid for Scientific Research (25390103, 25289244, 26286078 16K04989, 16K05030 and 16F16019) from the Japan Society for the Promotion of Science and the Russian Foundation for Basic Research (RFBR) Grant No. 12-02-00947a. This work was also supported by the Japan Society for the Promotion of Science (JSPA) and Russian Academy of Sciences (RAS) under the JSPS-RAS Joint Research Program (RFBR Grant No. 14-02-92107).