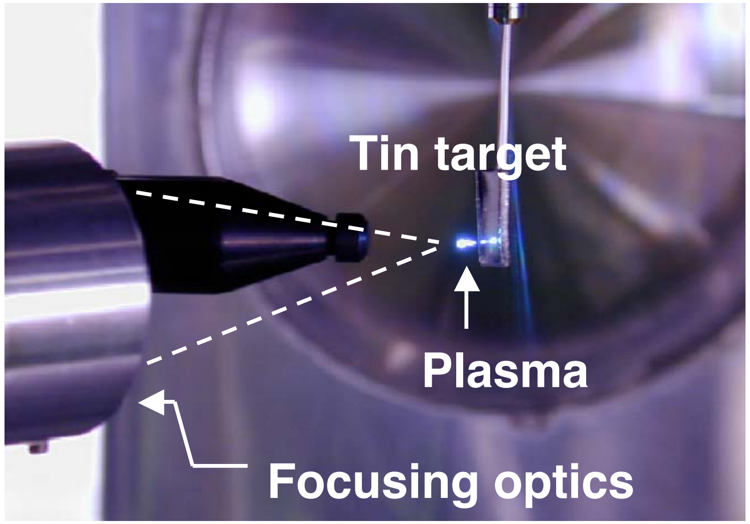
Low-density and nanostructured tin targets for high conversion efficiency of laser-produced-plasma extreme-ultraviolet (EUV) light generation and their high repletion supply



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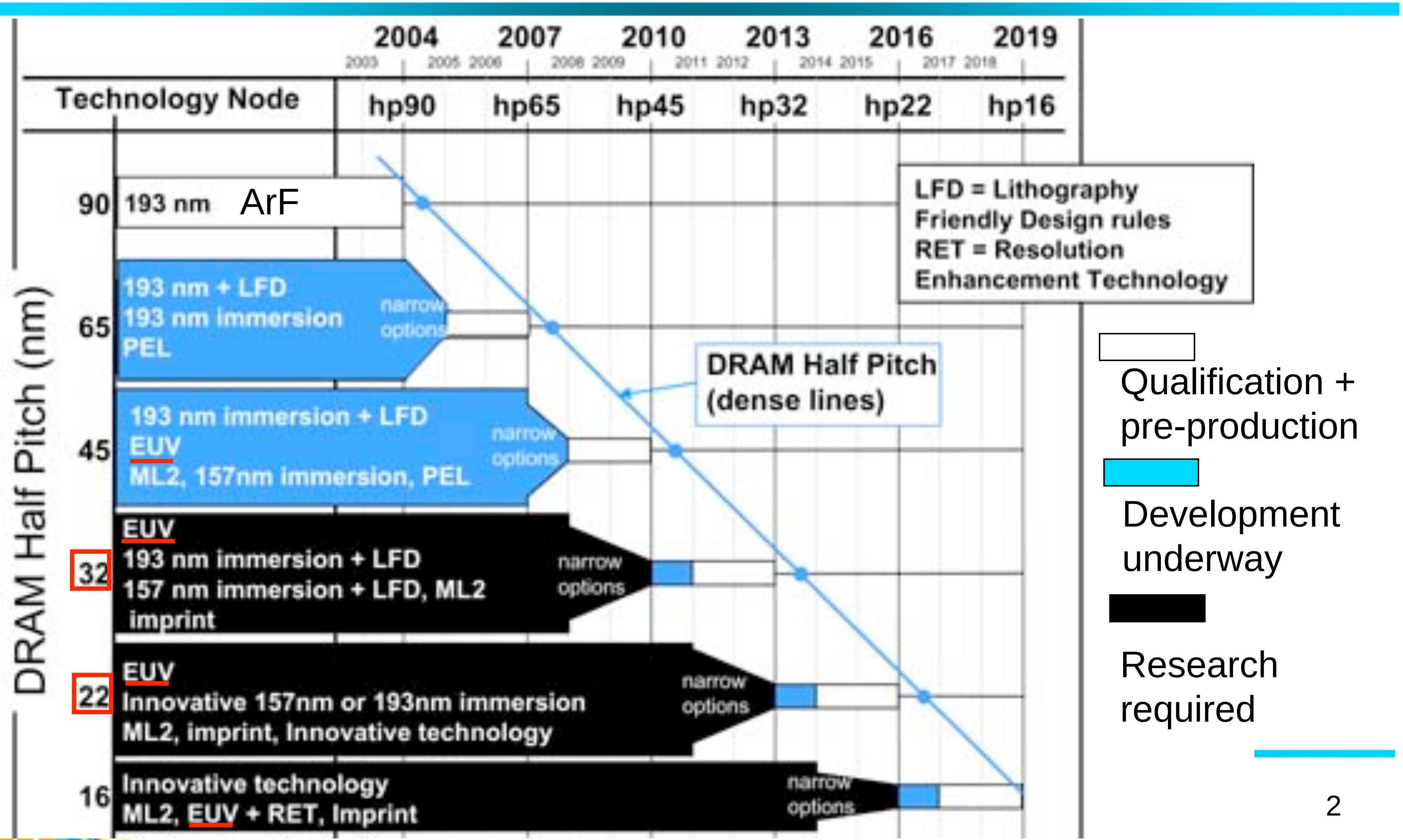
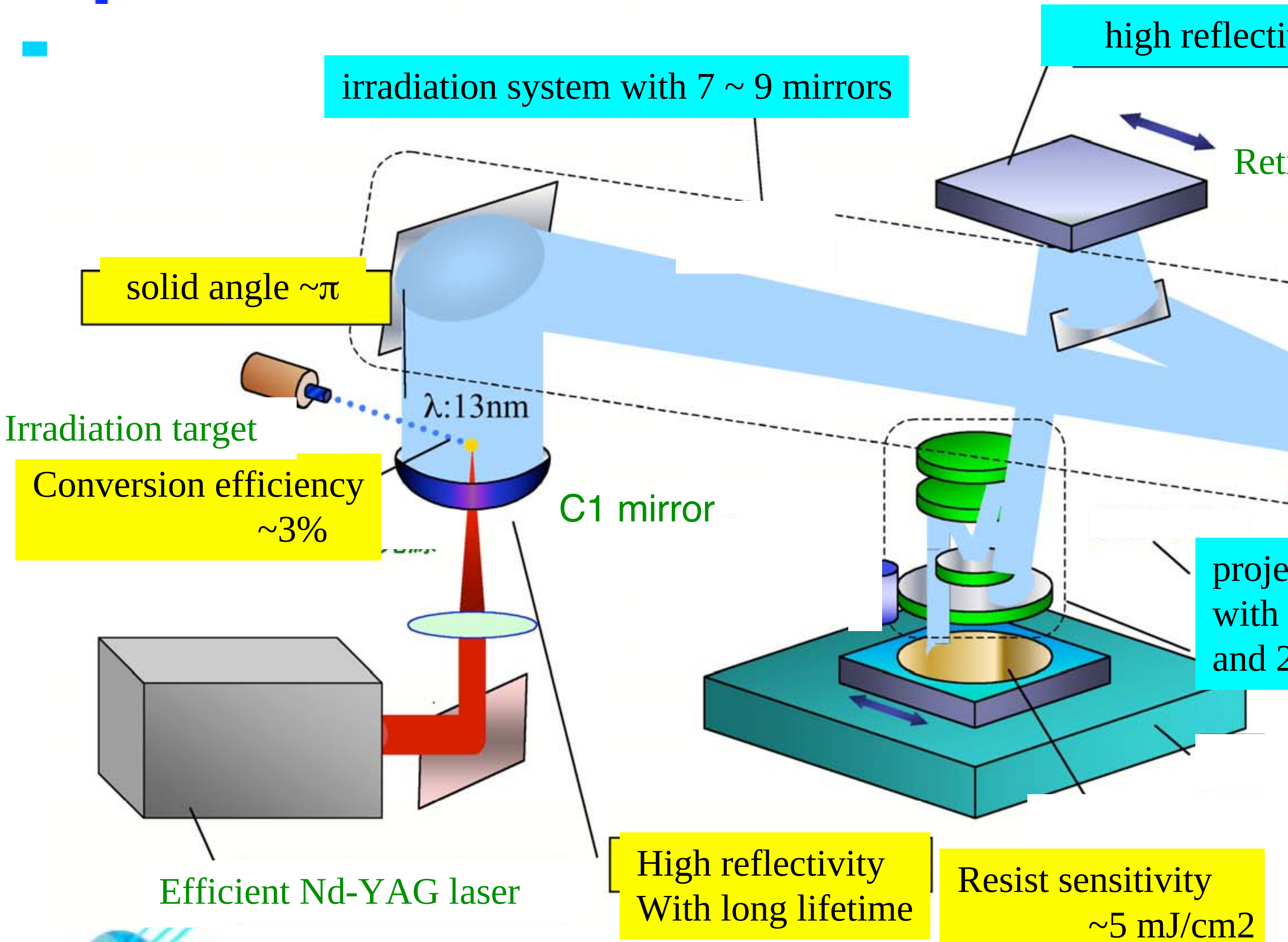
Institute of Laser Engineering (ILE)
Osaka University

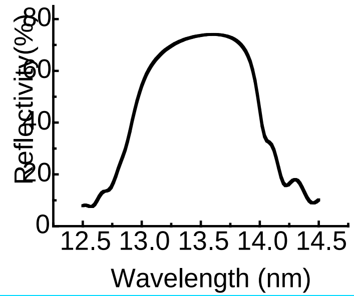
This work was performed under the auspices of Leading Project promoted by MEXT, JAPAN.

Lithography load map shown in ITRS 2004 update



Extreme UV (EUV) lithography system design





Reflection of Mo/Si mirror

In EUV lithography, efficient and clean EUV source is required.

- **Efficient and clean source by laser-produced tin plasma**

 # Efficient source: high conversion efficiency

High efficiency of 5 - 6 % will be available by low density plasma and long wavelength laser irradiation at low intensity.

 # Clean source: debris free

Ionization of all tin atoms in the target is important.

↓

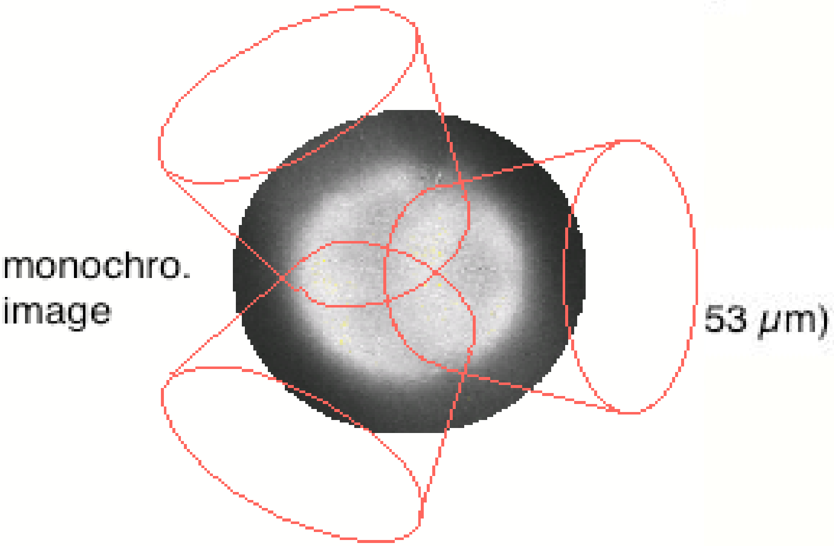
No neutral debris and enough EUV power by a minimum-mass target

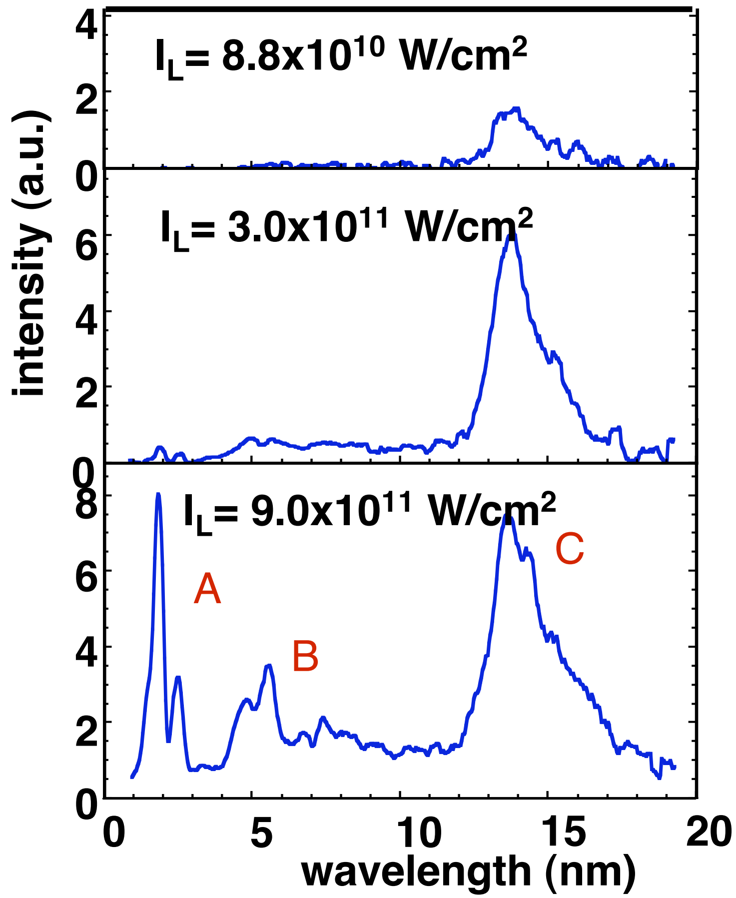
How many tin atoms are required in the minimum-mass target?

Ions will be mitigated by an electric or an magnetic field.

Ions with energy < 1 keV are easy to be mitigated by the magnetic field.

Tin (Sn) is one of attractive materials for creating highly efficient 13.5 nm radiator.





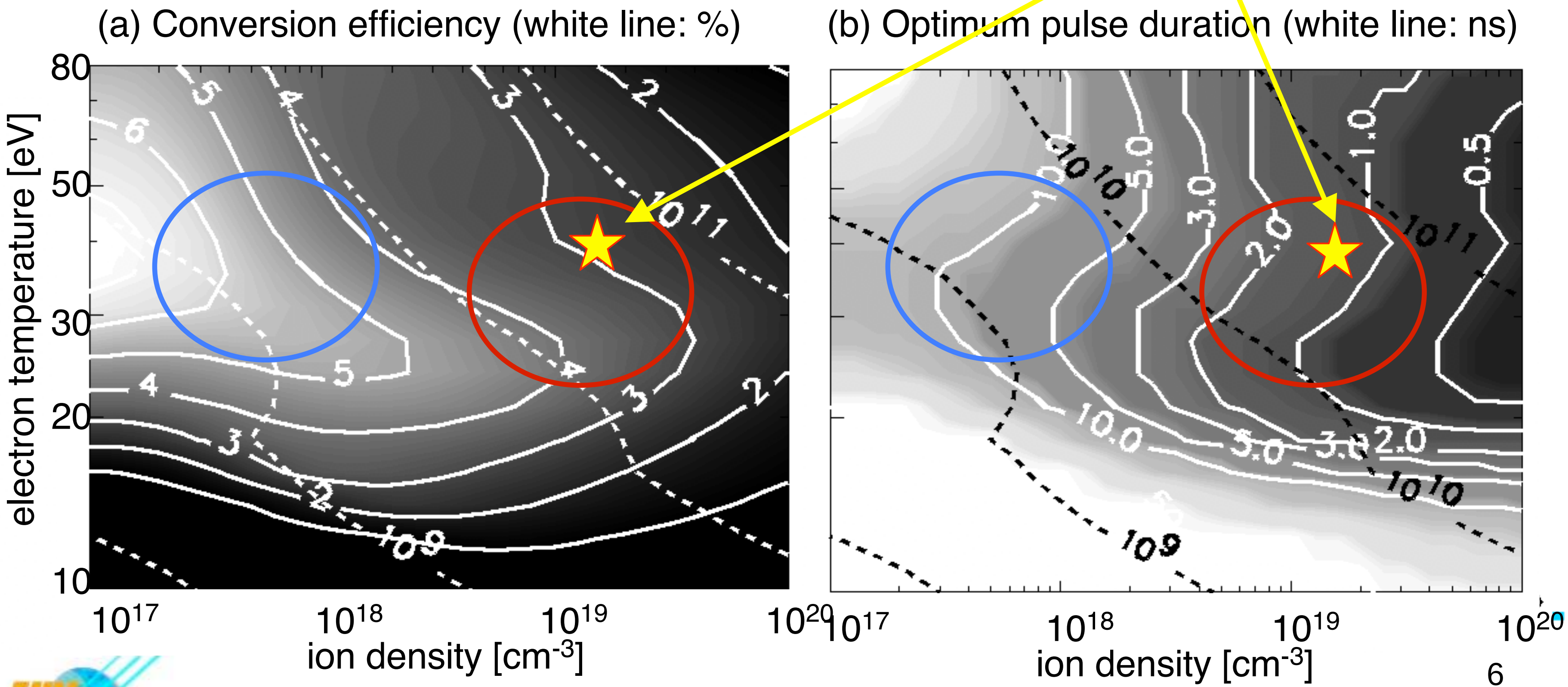
Y. Shimada *et al.*, APL Vol.86, 051501 (2005).

High conversion efficiency of 5 - 6 % is possible by long wavelength and low intensity laser.

Sn target

ILE (2003): 1.06 μm, 1.2 ns, 5 x 10^{10} W/cm^2 (spherical target), 3.0 %

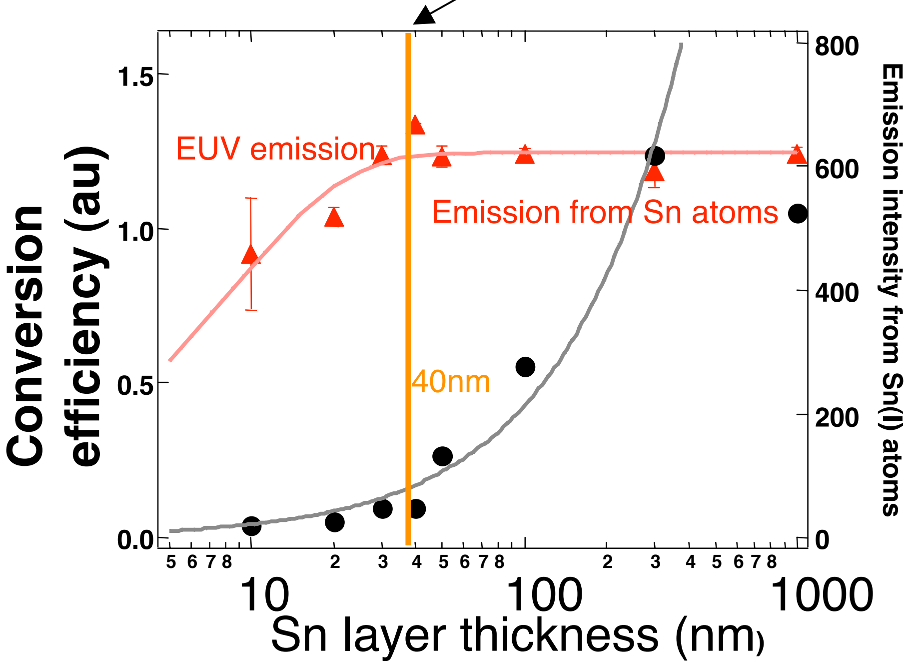
EUVA (2006): 10.6 μm, 11 ns, 3 x 10^{10} W/cm^2, 3.9 %



Minimum-mass target

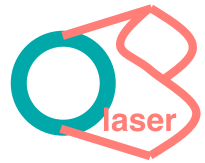
How many tin atoms are required for minimum-mass?

Ans. Coating thickness of **40 nm** is enough to produce high power EUV emission.

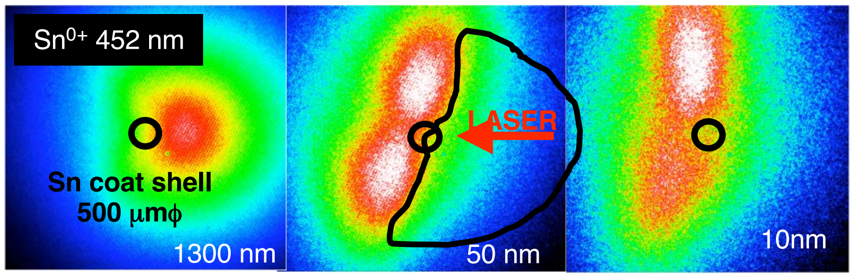


Emission from Sn neutrals linearly increases with coating thickness while keeping constant in EUV intensity.

Target: Sn coated sphere
Intensity : 10^{11}W/cm^2
Pulse width : 2ns



Emission from Sn atoms



With decrease of Sn thickness emission to laser direction decreases,

↓

Suppression of debris to C1 mirror

Number of EUV photon required ～number of ions: 40mJ/pulse ⟶ 3 x 10^{15} ions

S. Fujioka et al., Appl. Phys. Lett. 87, 241503 (2005),
S. Namba et al., Appl. Phys. Lett. 88, 171503 (2006).

Two ways for minimum-mass Sn target

1) **Double pulse irradiation**
2) **Low density target**

Double pulse irradiation

For 10 (100) kHz repetition

EUV energy / pulse : ~ 40 (4) mJ

Number of Sn atoms required : ~ 3×10^{15} (3×10^{14})

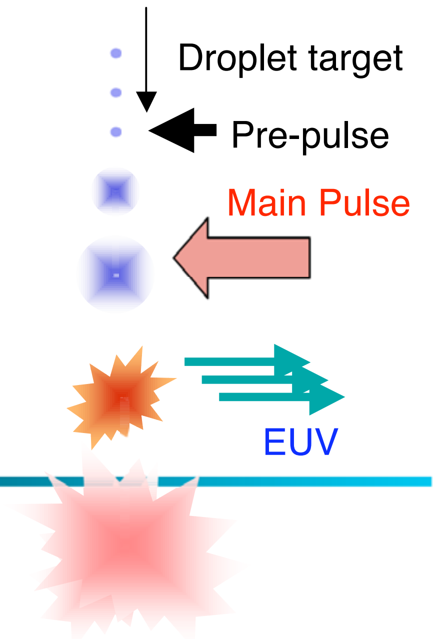
Diameter of droplet : ~ 50 (20) μm

↓ Pre-pulse irradiation and plasma expansion

Diameter of plasma : ~ 400 (150) μm

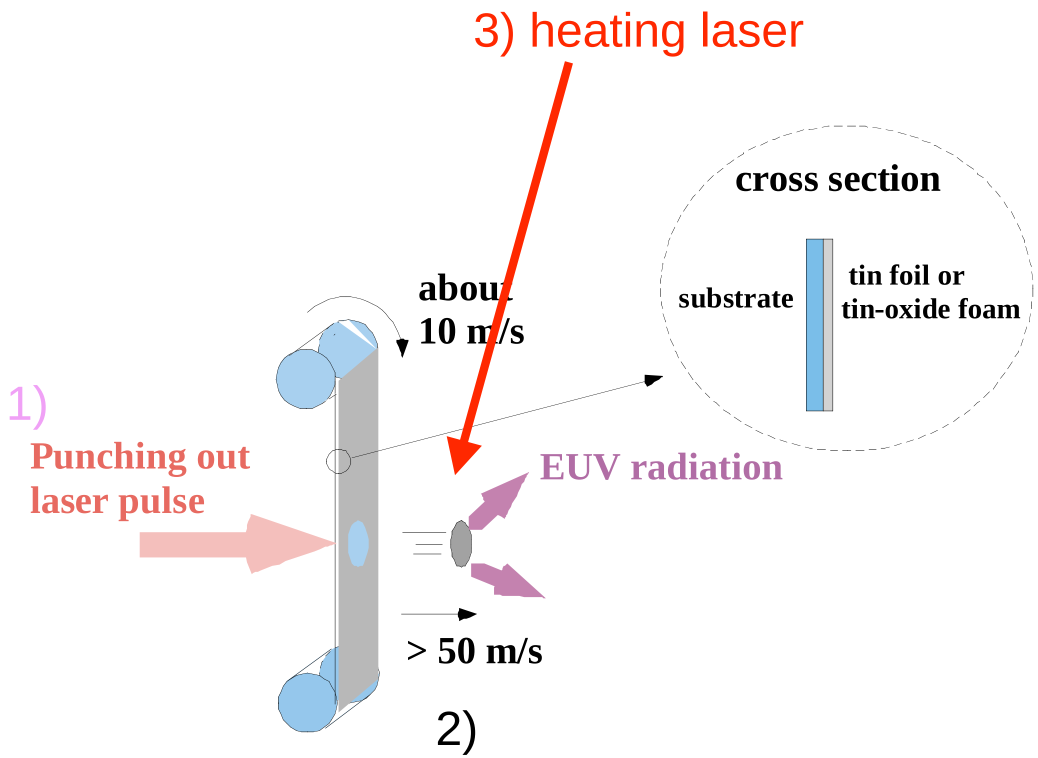
↓ Main pulse irradiation
Intensity: ~10^{11} W/cm^2
Pulse width: ~10 ns

EUV emission



Sn droplet

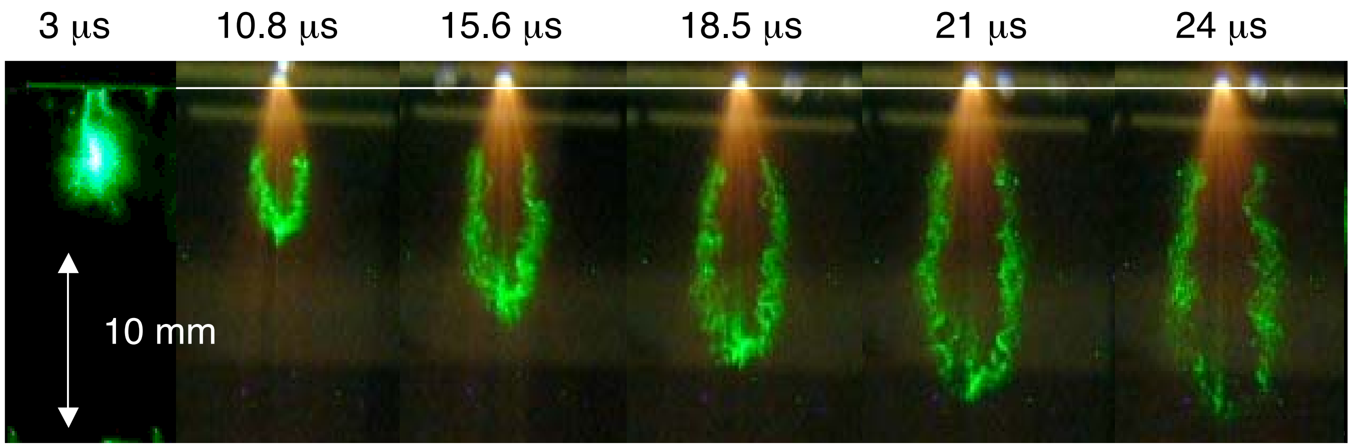
A novel target supplement, called the punch-out method, to supply mass-limited targets.



1) The punch-out laser (PoL) pulse is irradiated from the back surface of the substrate that is transparent to the pulse.
2) The tin-foil is ablated by the PoL pulse and produces a tin plasma at the boundary of the foil and substrate.
3) The rest of the tin-foil (mass-limited) is driven to a high velocity due to the expanding plasma.

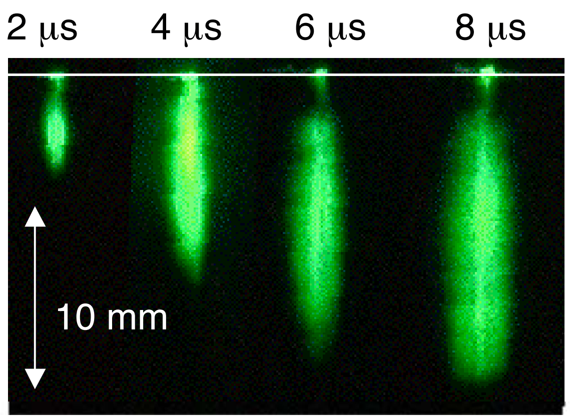
Shape and velocity of flying targets were observed by laser light scattering.

Thin film of tin
13 μm
9 x 10^8 W/cm^2



Tin dot 500 μmφ、thickness 1.3 μm
2 x 10^8 W/cm^2
Laser spot : ~ 970 μmφ

Dot target
Diameter : 500 μm

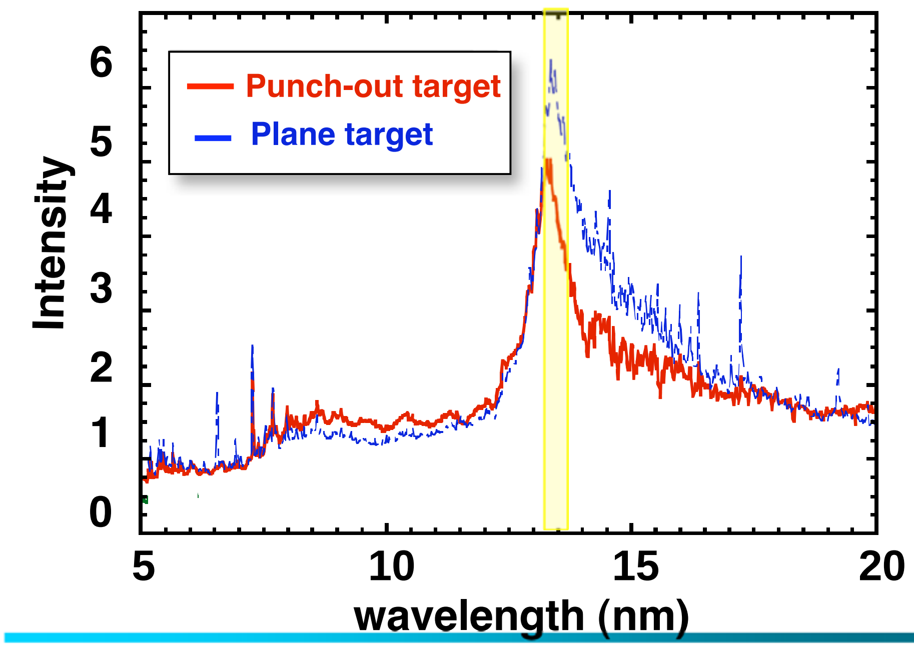


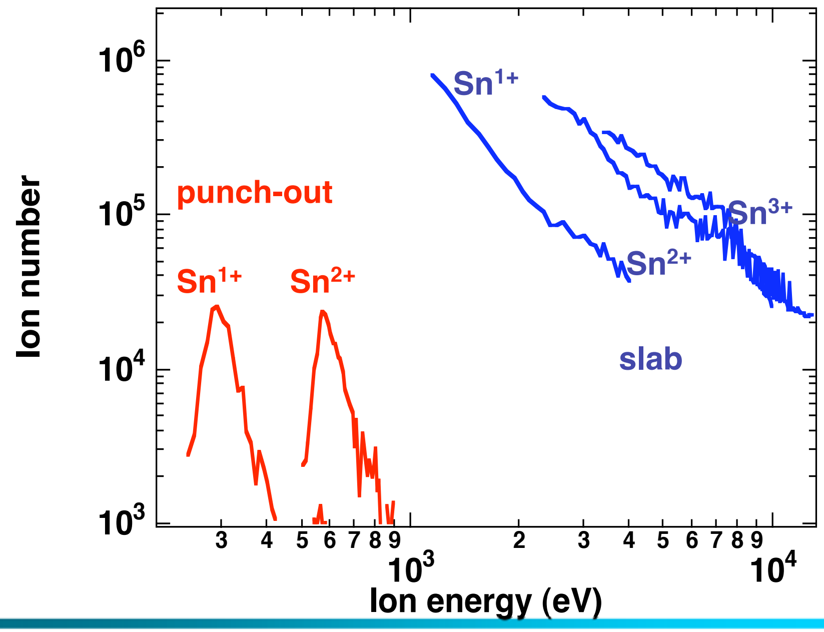
EUV emission and ion energy distribution from the punch-out target

In the punch-out target, the maximum ion energy and also the amount of ion emission drastically reduced, while the EUV emission was ~ 2/3 of that from the tin bulk target.

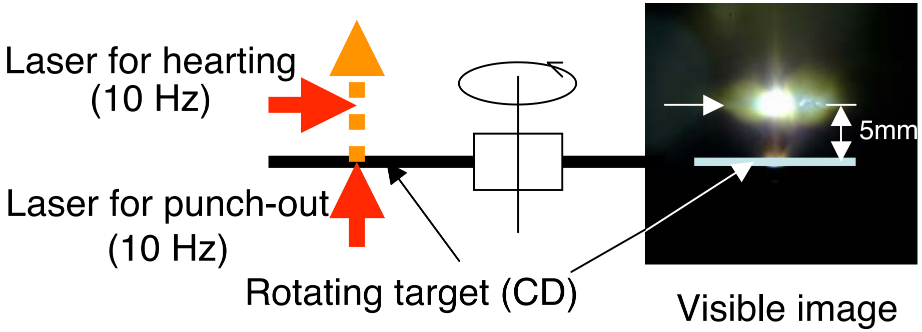
↓

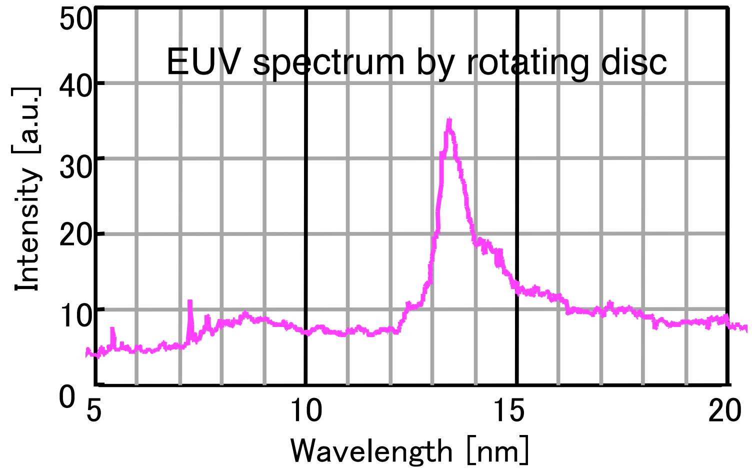
The protection of C1 mirror from ion bombardment will be easy by an magnetic field.

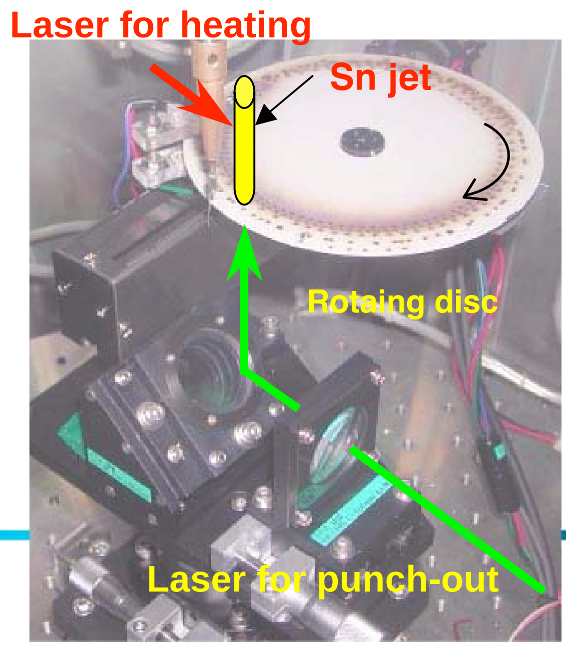


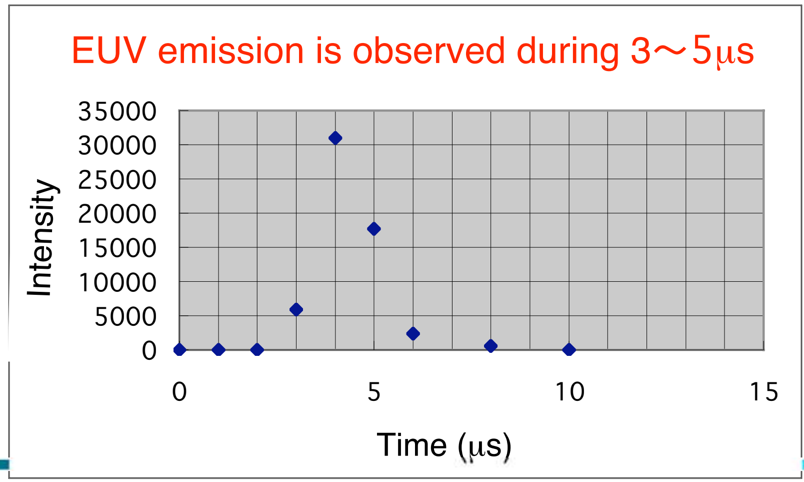


EUV experiments using a rotating punch-out target.





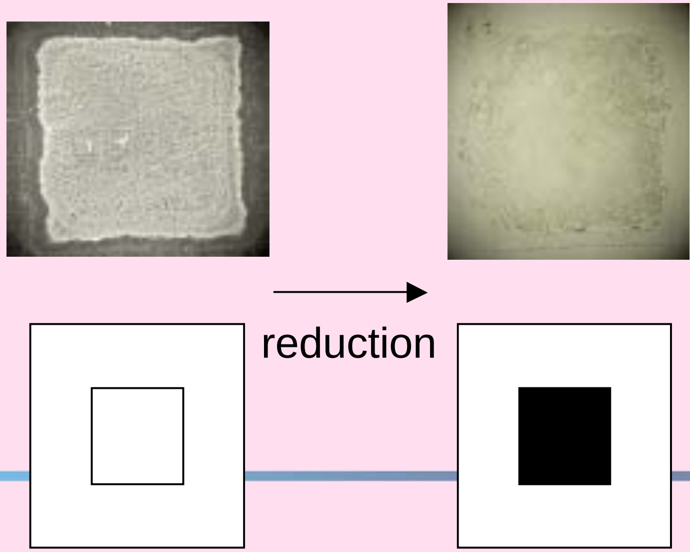




Sn dot films were fabricated using an inkjet printer.

The present method provides tin dots with low cost and high volume fabrication.

SnSO4 was printed on a transparent sheet, then it was reduced to metal tin.



Reduction of SnO_2

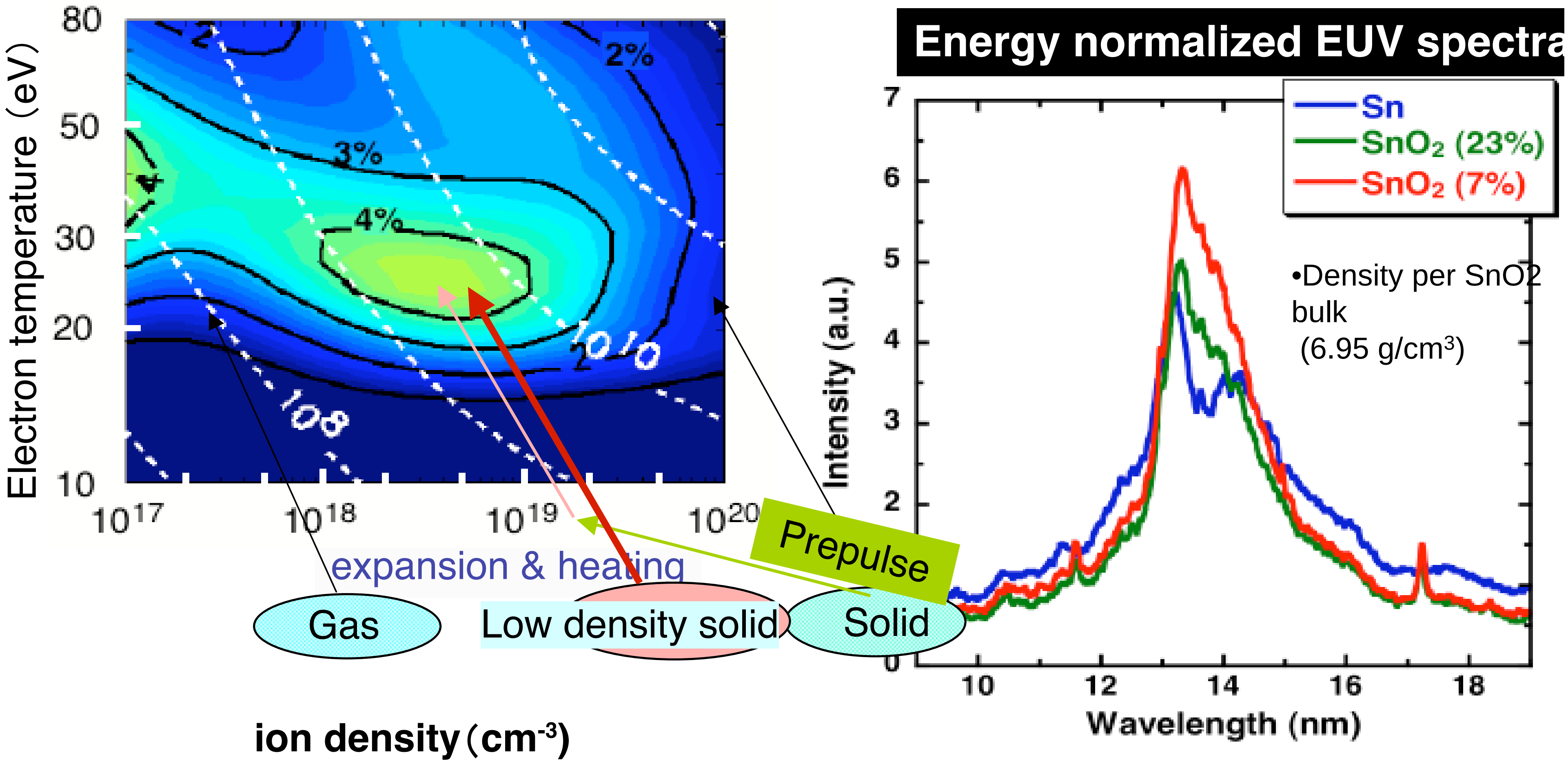
Reducer: sodium tetrahydroborate

Solution : 1,2-dimethoxyethane

Temperature : 70 °C

Fusion Sci. Technol., **51** (4), 769-771, (2007).

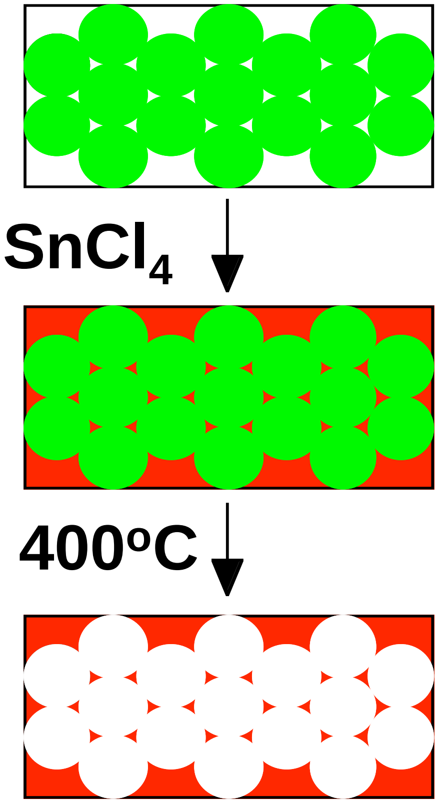
Low density targets gave fundamental information and possibility to be mass-limited targets



10 ns, 1064 nm

Appl. Phys. Lett., **88** (16), 161501 (2006).

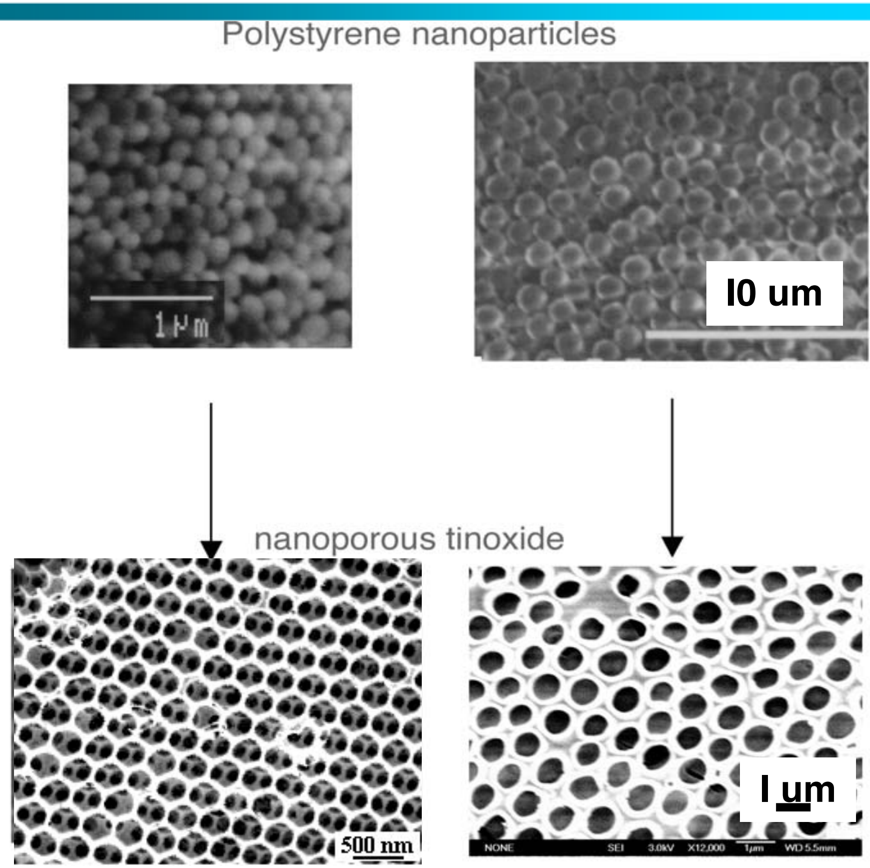
Low density tin oxide (d=1.5g/cm^3) using nanotemplate
(23 % of bulk crystal)



Polystyrene particles were aligned to be closed packing.

PS particles were immersed in liquid tin chloride.
Tin chloride was hydrolyzed to be tin oxide.

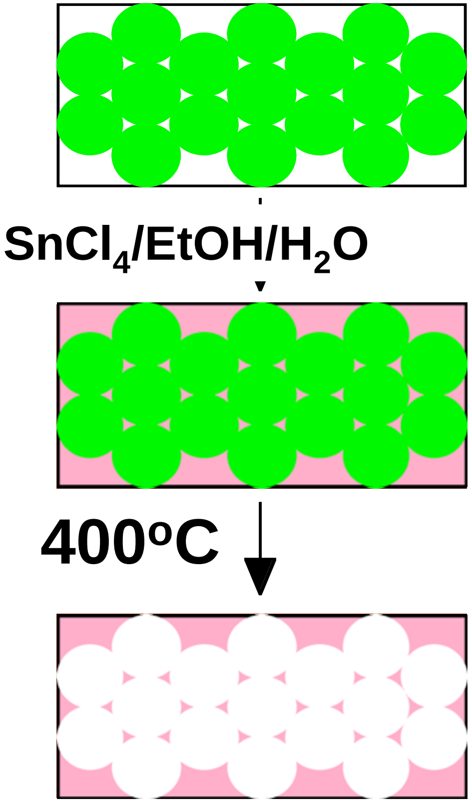
PS particles were decomposed by heating.
Porous tin oxide film was obtained.



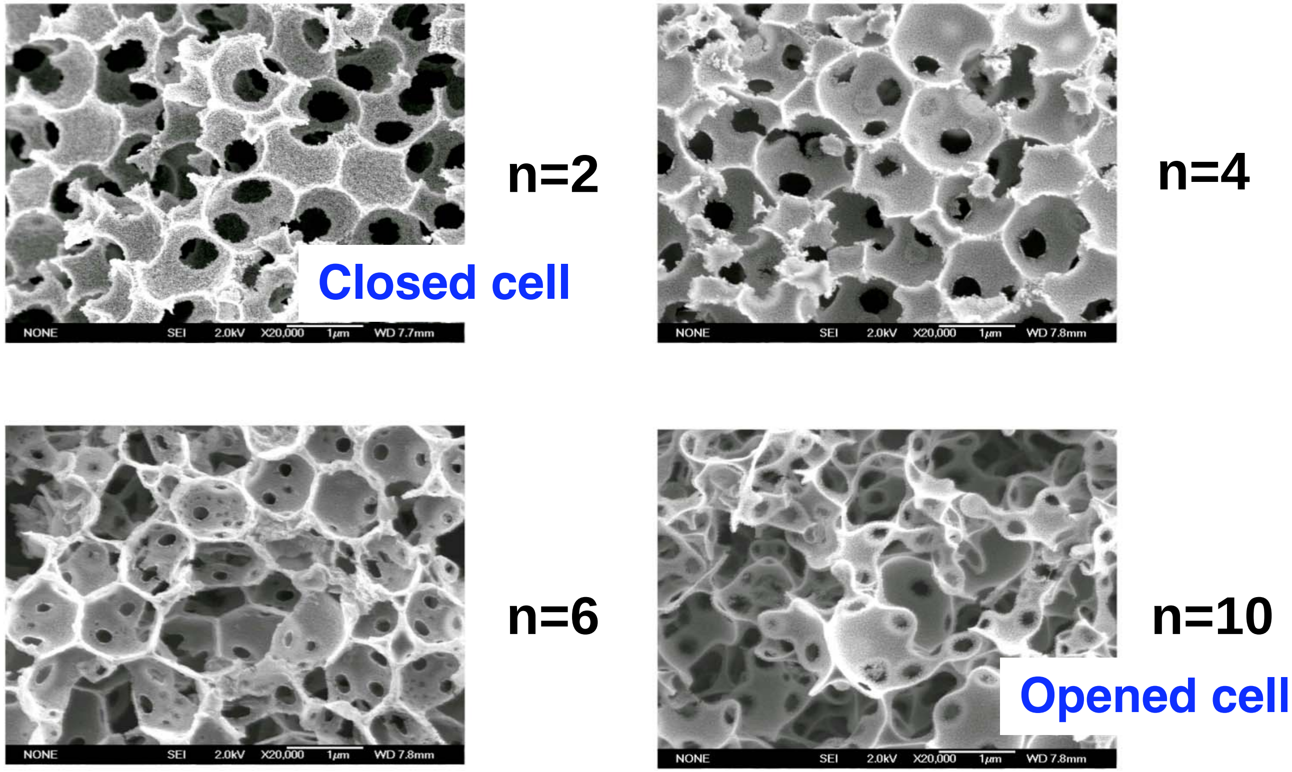
Pore size was well controlled by the template spheres.

K. Nagai et al., Trans. Mater. Res. Soc. Jpn., 29 (3) 943 (2004)

Low density tin oxide (d=0.5g/cm^3) using nanotemplate (7 % of bulk crystal)



$$n = EtOH_{mol} / SnCl_{4\ mol}$$

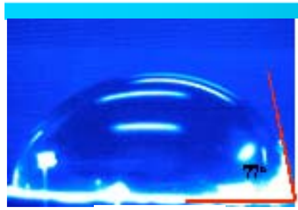


There were various morphologies.

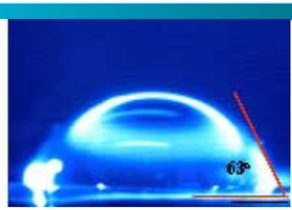
Q.C.Gu et al., Chem. Mater., **17** (5), 1115-1122, (2005).

Volume template vs. Surface template

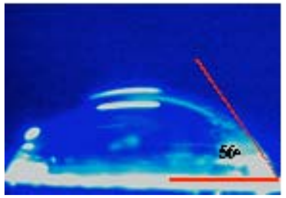
Contact angle on polystyrene film



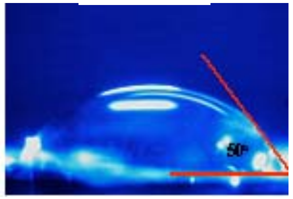
n=2



n=4



n=6



n=10

More EtOH (n), lower contact angle (higher affinity for PS)

SEM images before heating at 400 °C

n=2

Volume template

-> Closed cell

n=10

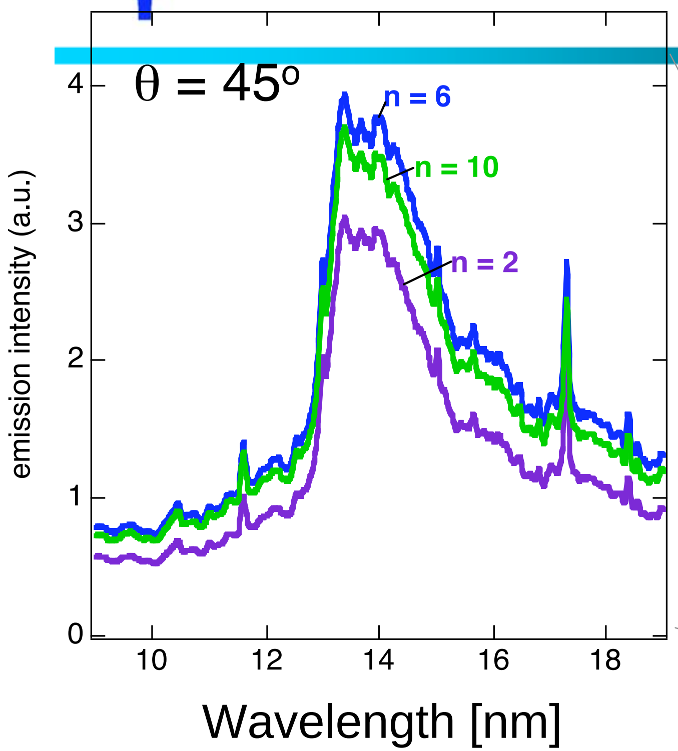
Surface template

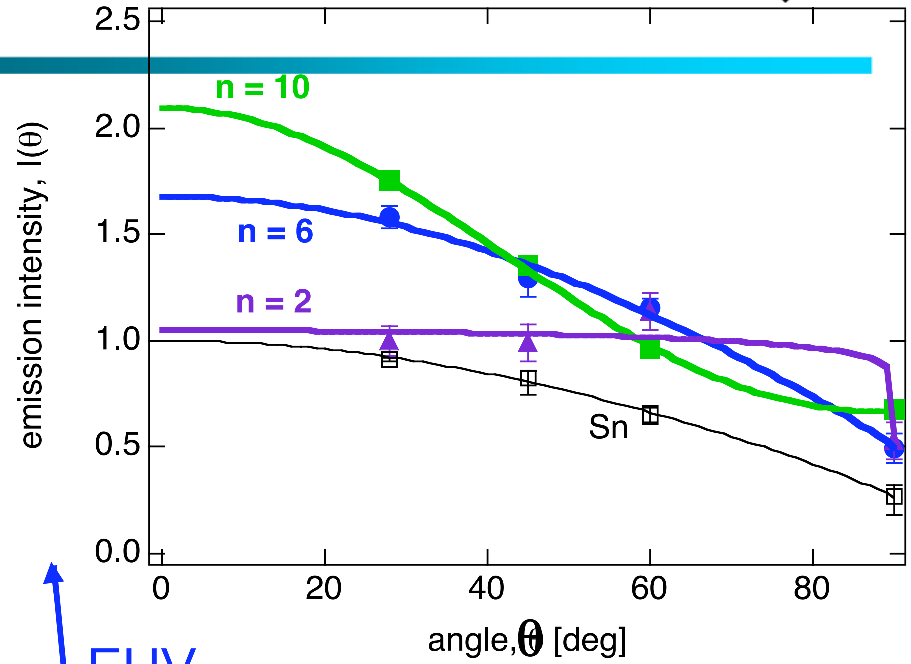
-> Opened cell

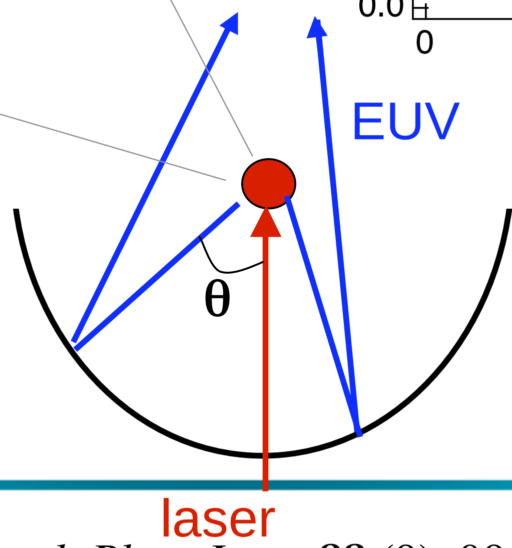
$n = EtOH_{mol} / SnCl_{4\ mol}$

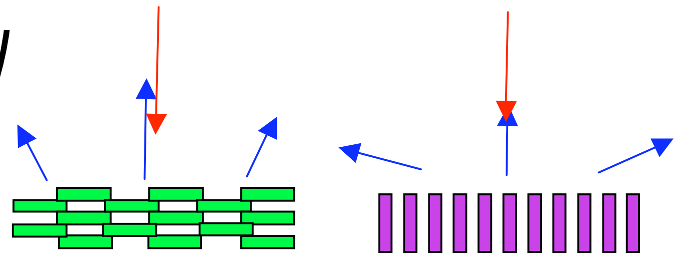
Q.C.Gu et al., Chem. Mater., **17** (5), 1115-1122, (2005).

Control of angular distribution depending on target surface morphology



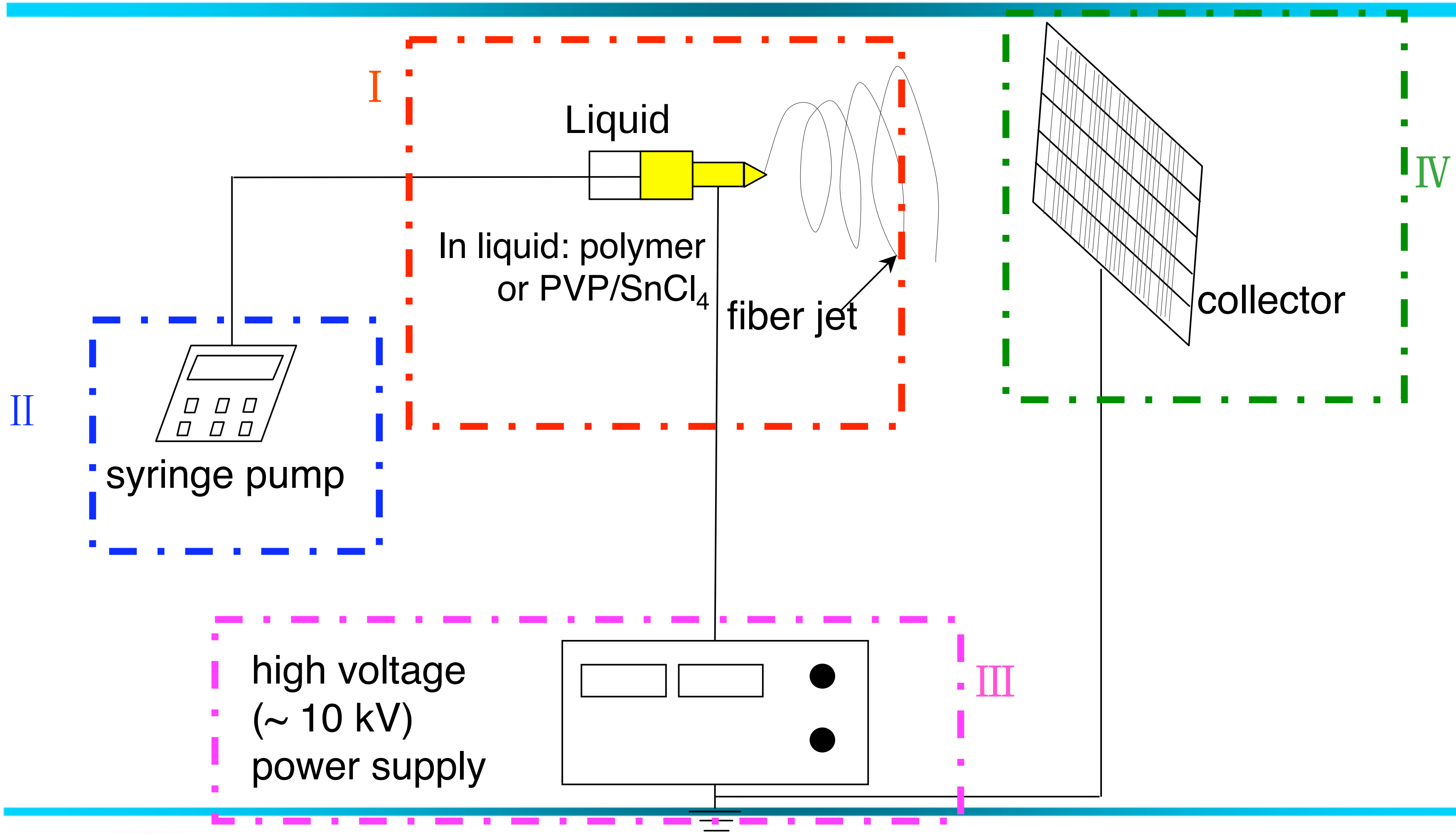




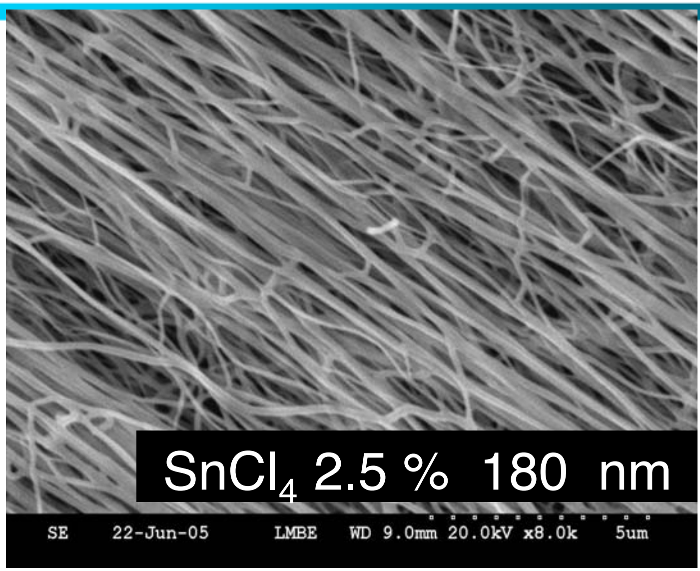


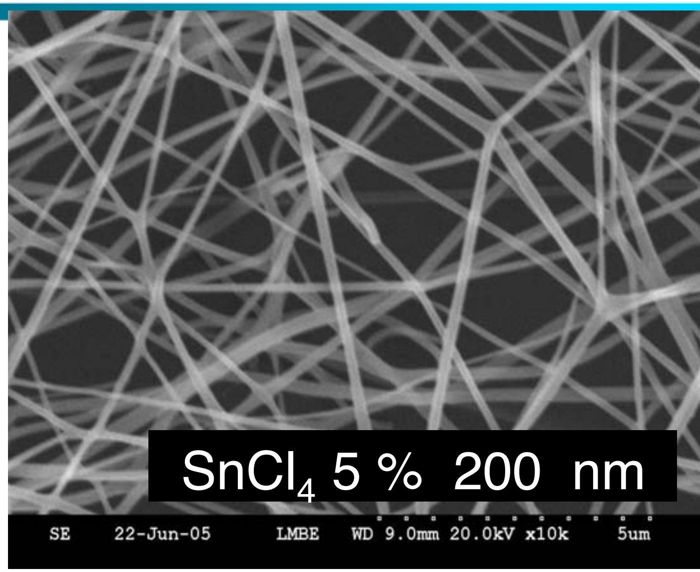
K. Nagai et al., *Appl. Phys. Lett.*, **88** (9), 094102, (2006).

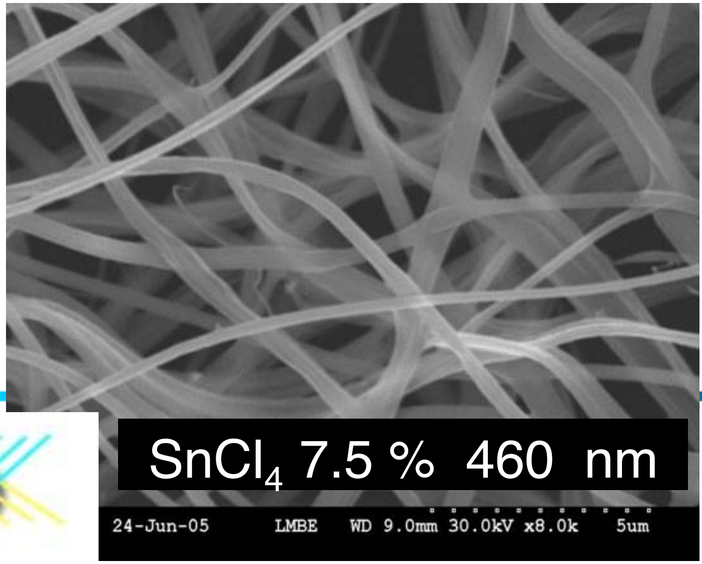
Oriented low density materials electrospinning nanofiber



SnO2 fibriformic film with controllable morphology

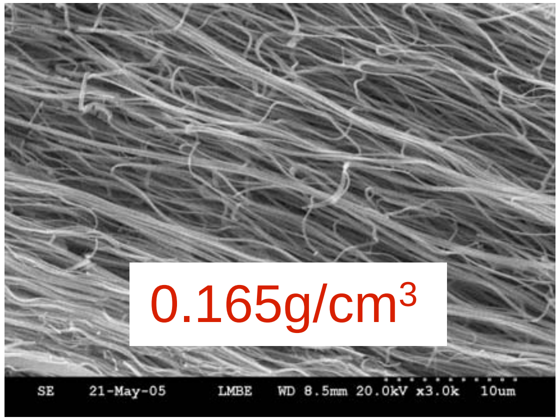


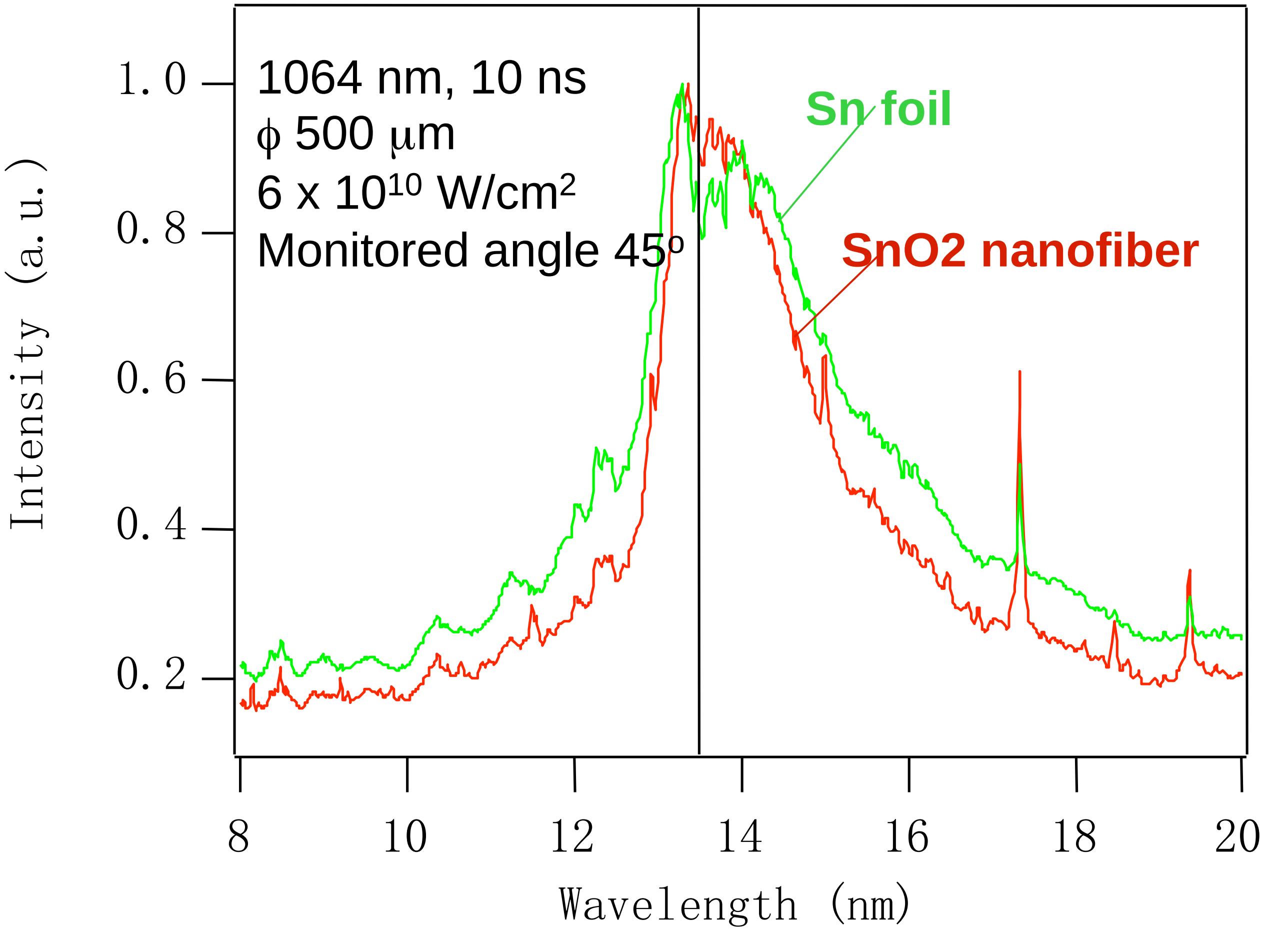




C. Pan, Z.-Z. Gu, K. Nagai, T. Norimatsu, et al., *J. Appl. Phys.*, **100** (1), 016104, (2006).

EUV emission spectra

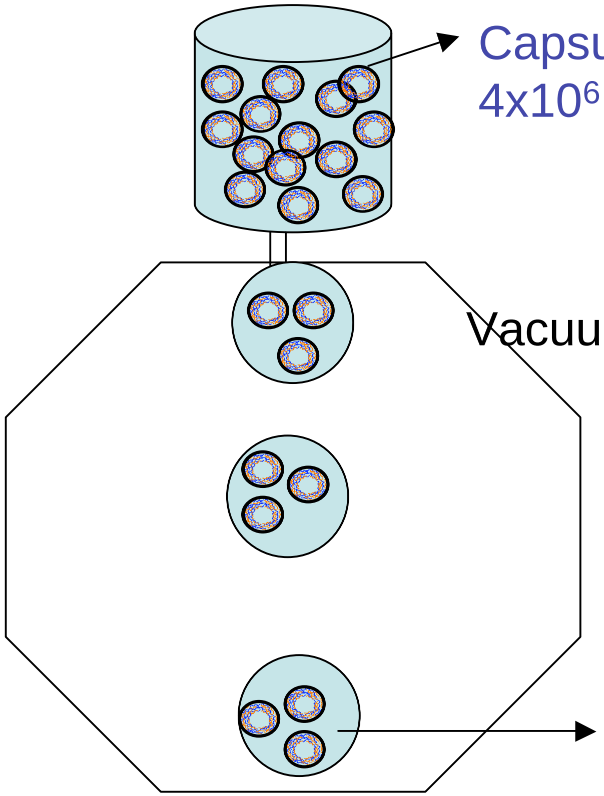




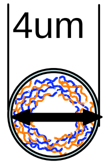
C. Pan, Z.-Z. Gu, K. Nagai, T. Norimatsu, et al., *J. Appl. Phys.*, **100** (1), 016104, (2006).

Bubble targets as a minimum mass targets

microbubble targets



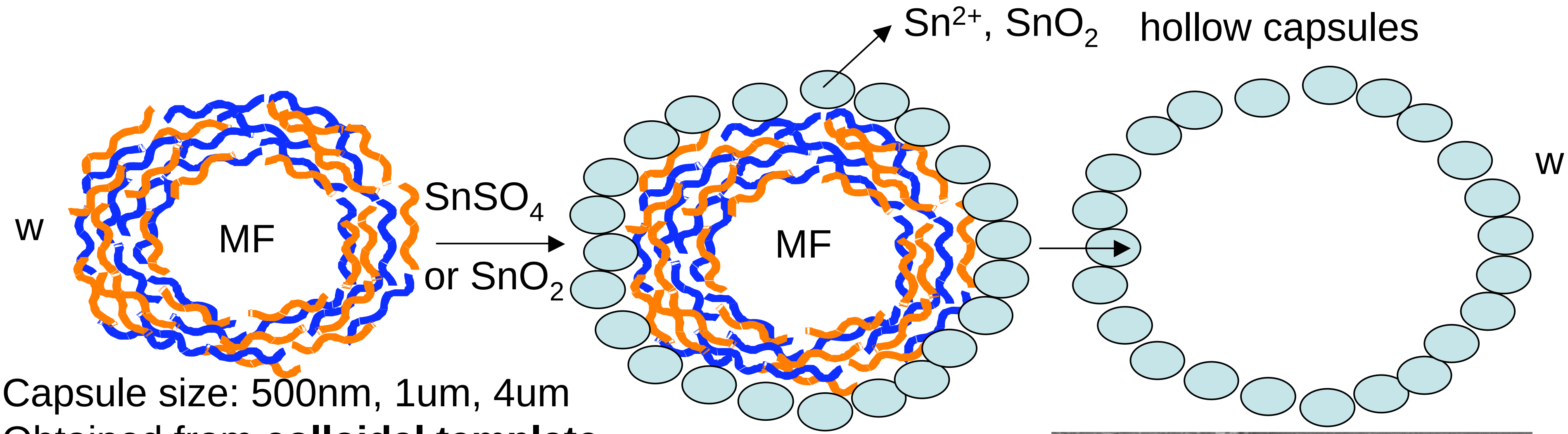
Capsule concentration:
4×10^6 pieces/ml



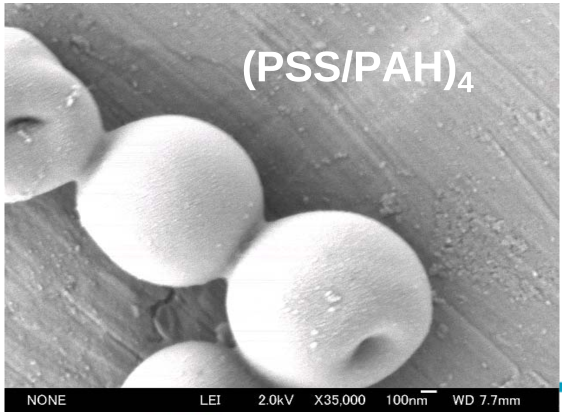
Tin containing bubble is prepared layer-by-layer coating technique

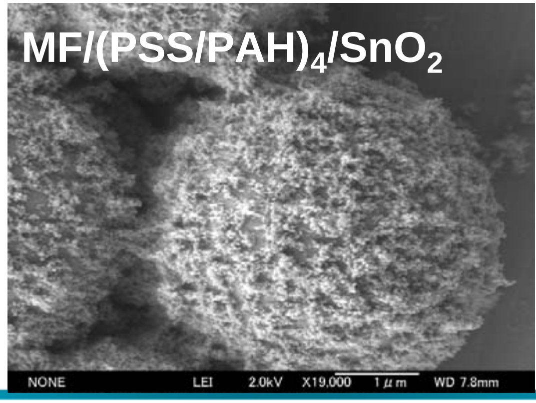
the thickness of the tin on the capsules is about 2.13 um. In every droplet, there should contain $2X10^5$ capsules (size 4um) for EUV mass-limit target.

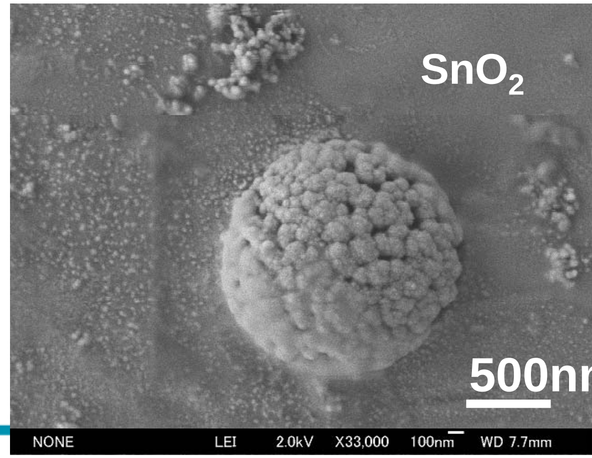
Microbubble targets using a template



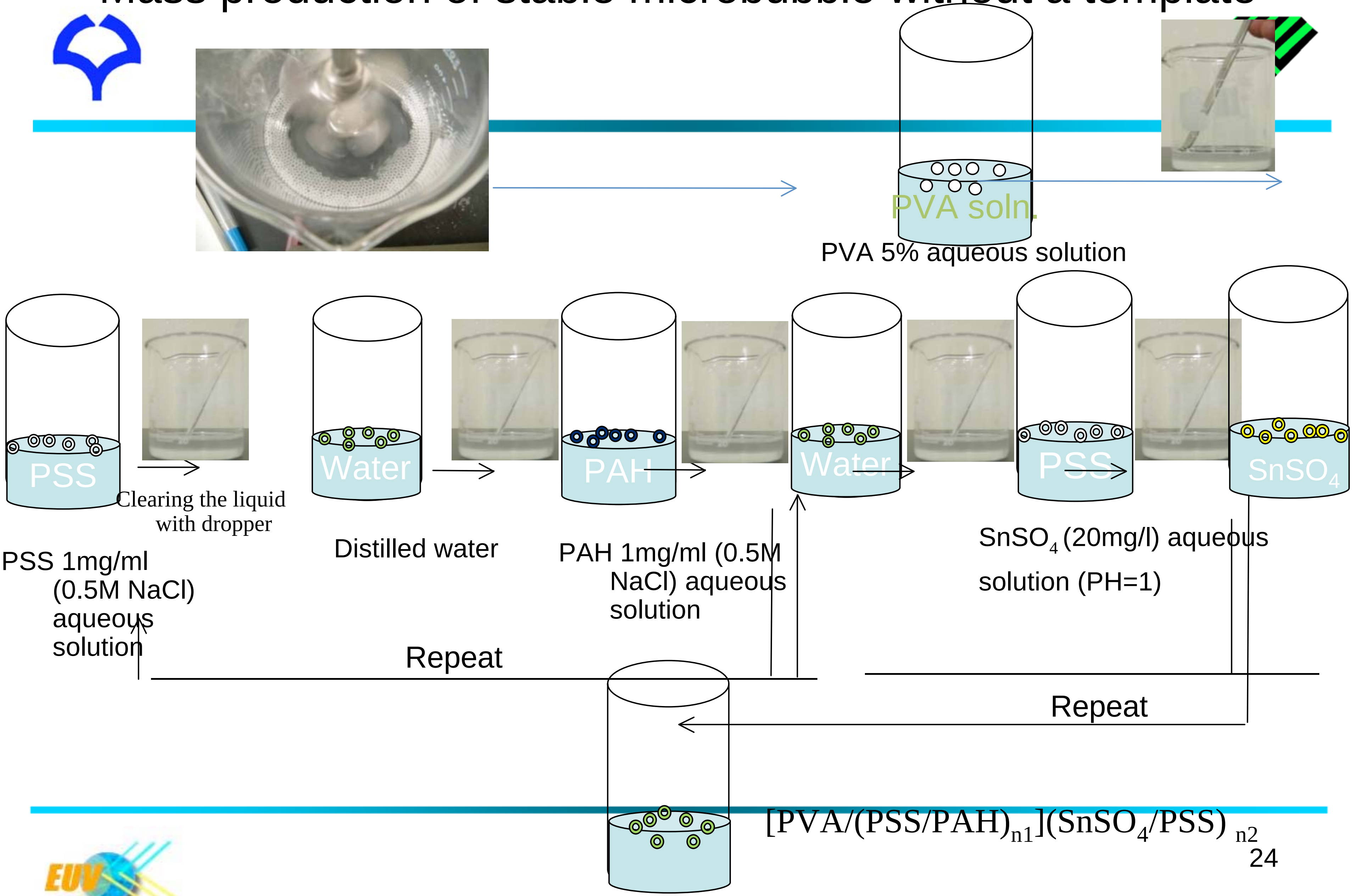
Capsule size: 500nm, 1um, 4um
Obtained from **colloidal template**







Mass production of stable microbubble without a template



Summary

1) High conversion efficiency (CE) was achieved using tin target.
2) According to theoretical analysis, longer wavelength (CO_2) will exhibit highest CE.

3) Required mass not to decrease CE is 3×10^{15} tin atom/target, which is called to be minimum-mass target.

4) To supply minimum-mass target, double pulse method and low density targets are investigating.

Keiji Nagai