Nanofabrication process using electron beam lithography

(AIPEL; Atomic Image Projection E-beam Lithography)

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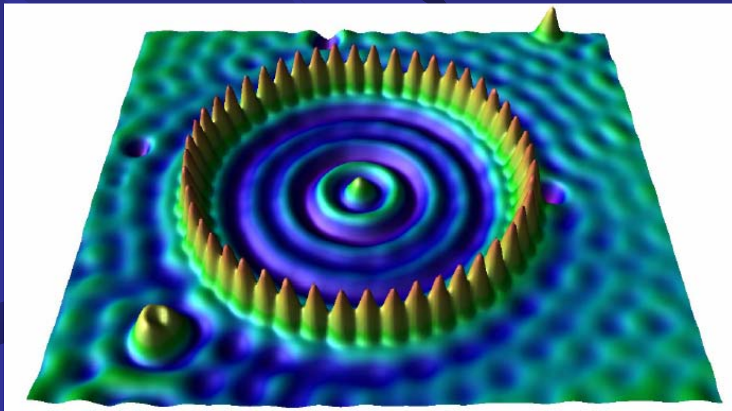
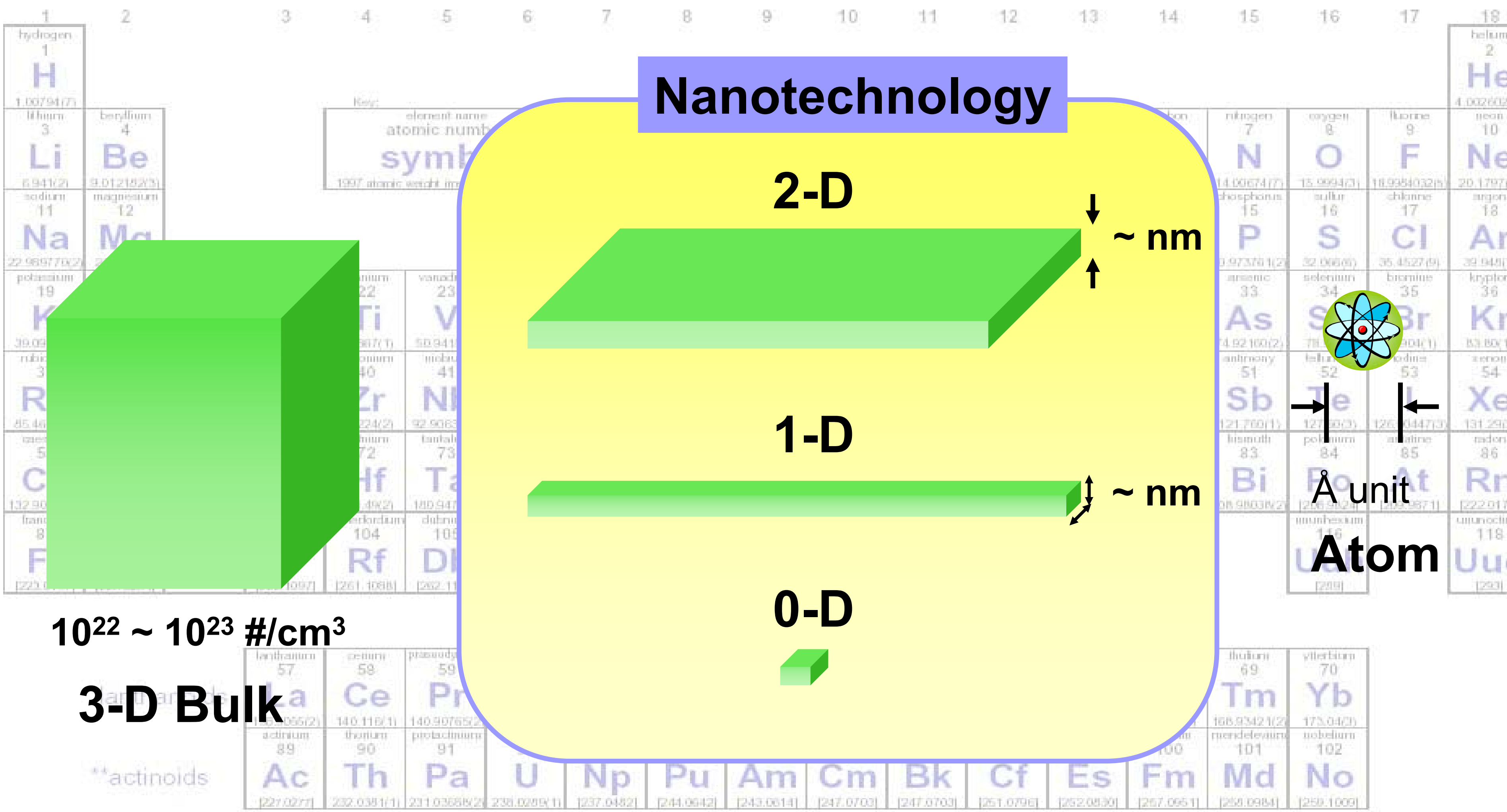
Nanotechnology;

The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization.

Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes due to their nanoscale size.

(*A report by the interagency working group on nanoscience, engineering and technology*, Feb., 2000)




Nanotechnology
2-D
~ nm
1-D
~ nm
0-D
10²² ~ 10²³ #/cm³
3-D Bulk
Å unit
Atom

Top-down approach

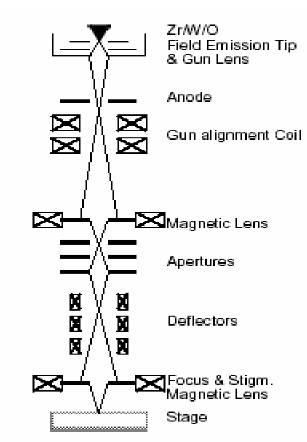
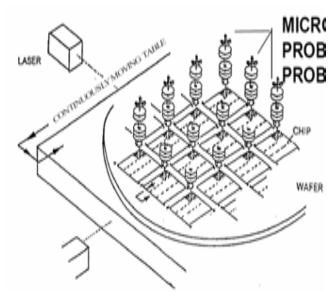
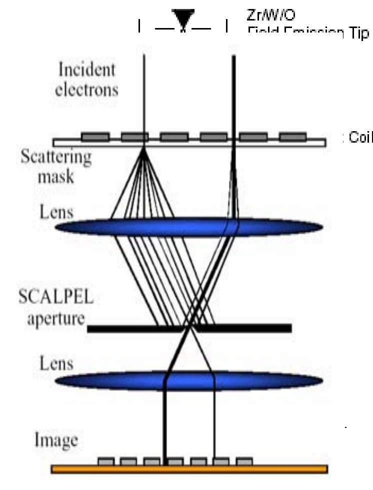
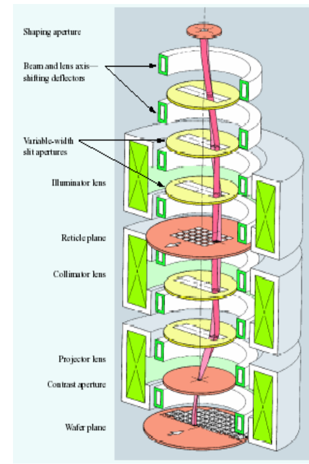
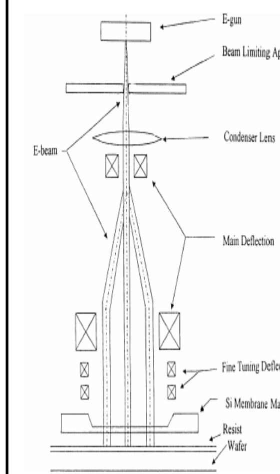
- E-beam lithography
- Nanoimprint Technology
- Probe technology

Nanotechnology

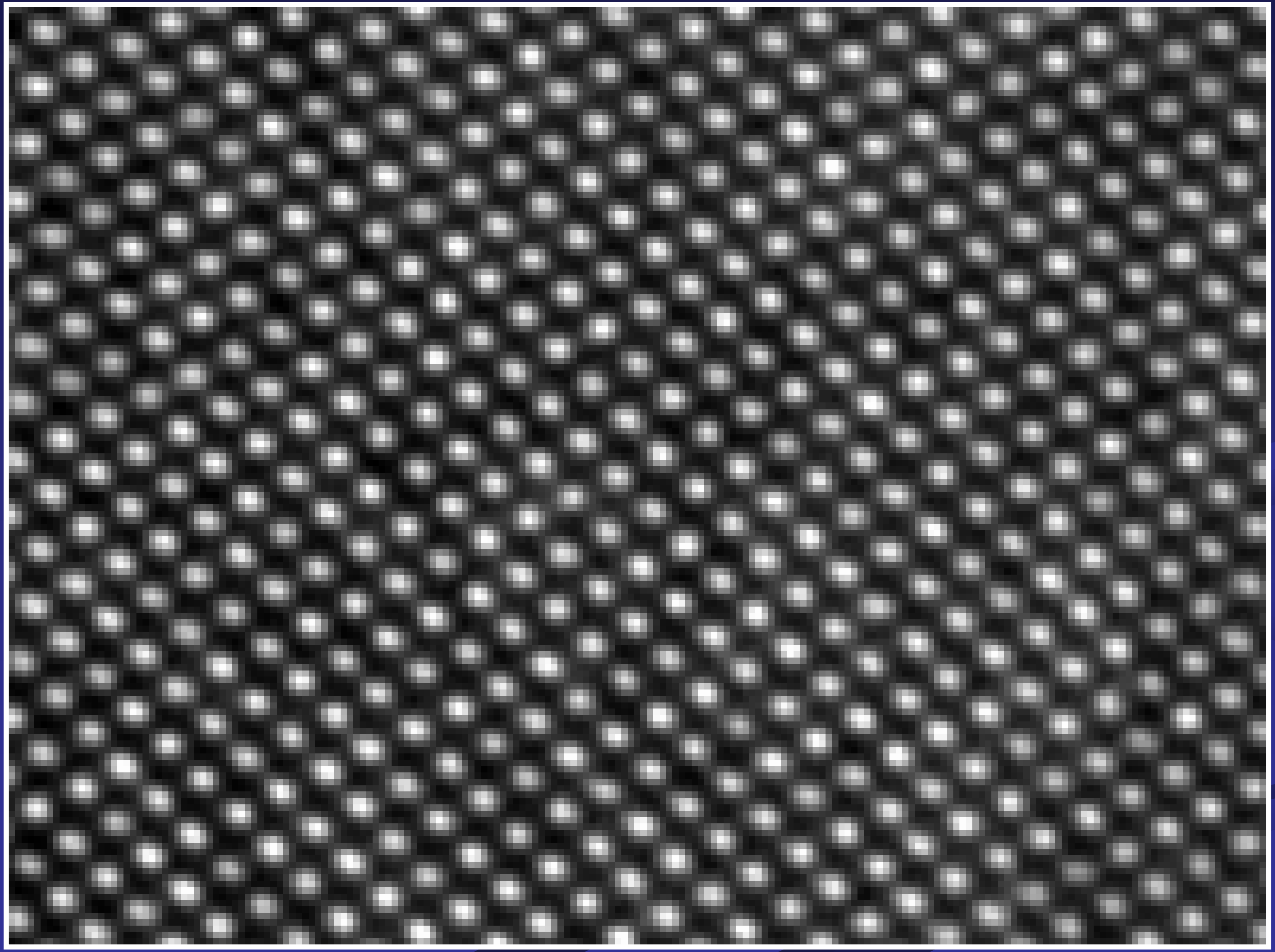
Bottom-up approach

- Probe technology
- Colloid process & self-assembly
- Thin film technology
- Gas phase nucleation

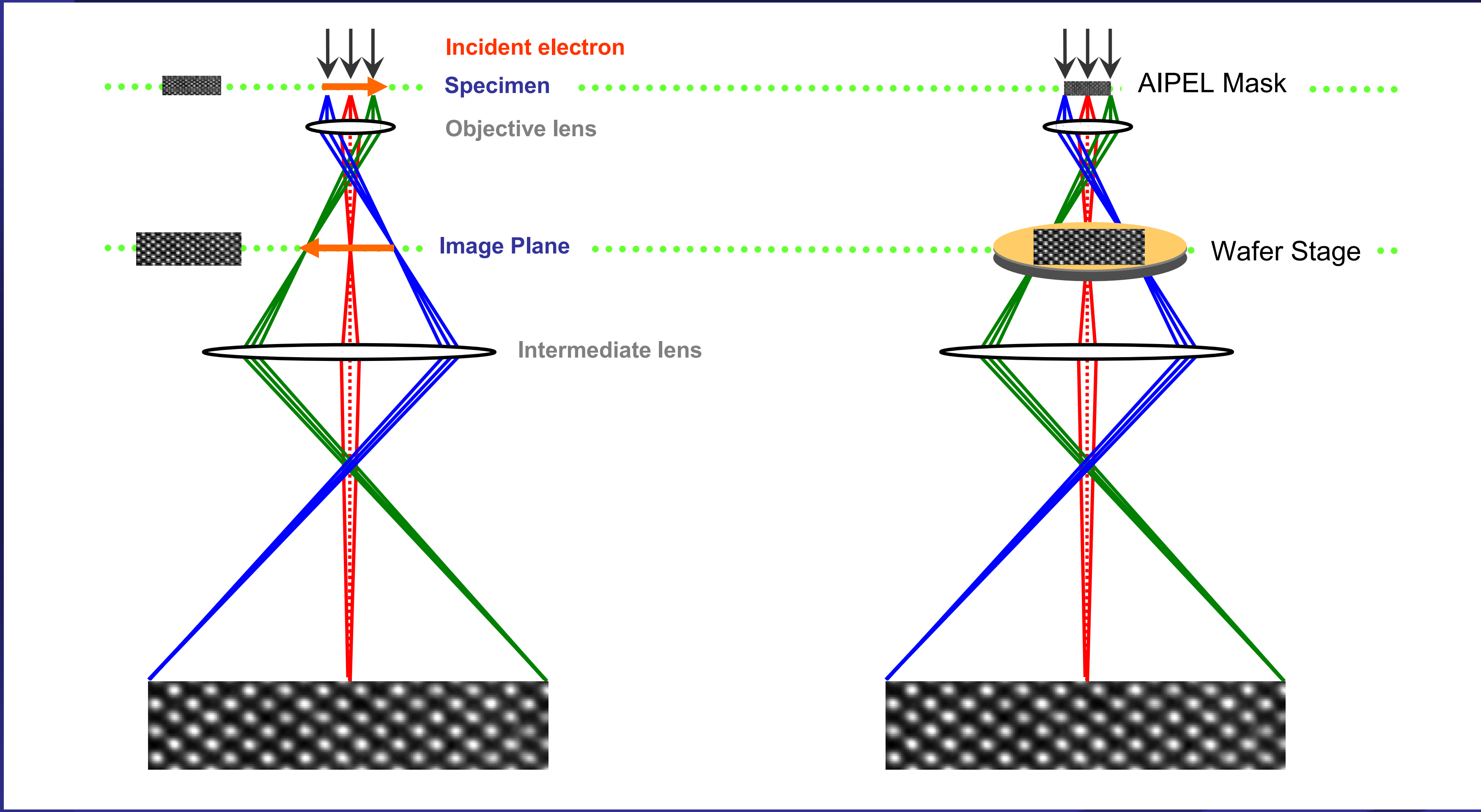
Top-down approach; E-beam lithography

	E-Beam Lithography; **Serial type**		E-beam Projection Lithography; **Projection type**		
	Conventional e-beam litho.	Multi e-beam lithography	SCALPEL **(e-Lith, Lucent, Applied materials, ASML)**	PREVAIL (IBM, Nikon)	LEEPL (LEEPL)
System Overview					
Resolution	~ 10 nm	~ 40 nm	< 100 nm	< 100 nm	< 100 nm
Throughput	**1.4 hr (100 cm^2)**		**25 (300 mm wafers / hr)**	**20 (300 mm wafers / hr)**	**40 (300 mm wafers hr)**
Mask	***No mask***		Membrane mask	Si stencil mask	
Advantage	***Resolution***	***Throughput***	***Throughput***		
Issue	***Throughput***	***Complex optics***	***Resolution vs. Throughput, Mask fabrication***		

Motivation

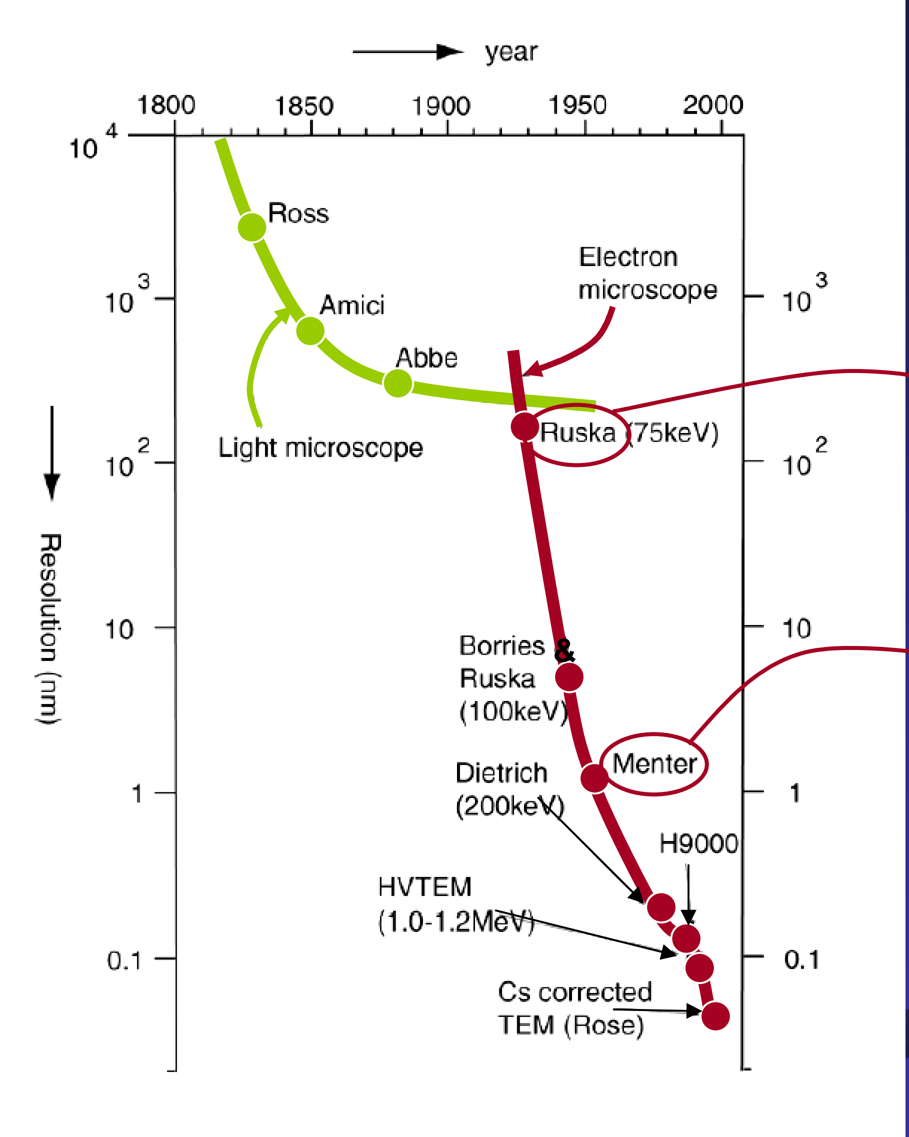


AIPEL (Atomic Image Projection E-beam Lithography)



- [Patent] Method for Forming a Pattern and a Semiconductor Device, Domestic(2001-1422), PCT (PCT/KR02/00043), Japan(2002-556925), EPO(2729593) application and USA (6767771 B2) registration
- [Patent] An Apparatus and a Method for Forming a pattern Using a Crystal Structure of Material, Domestic(2001-0017694), PCT(PCT/KR02/00109), Japan(2002-580390),EPO(2716458) application and USA registration (2004)

TEM Resolution from the Past



1926, Schrodinger, Schrodinger equation

1928, Bethe, Dynamical diffraction theory

1931, Ruska & Knoll, Invented TEM

1936, 1^{st} Commercial TEM (Siemens, German

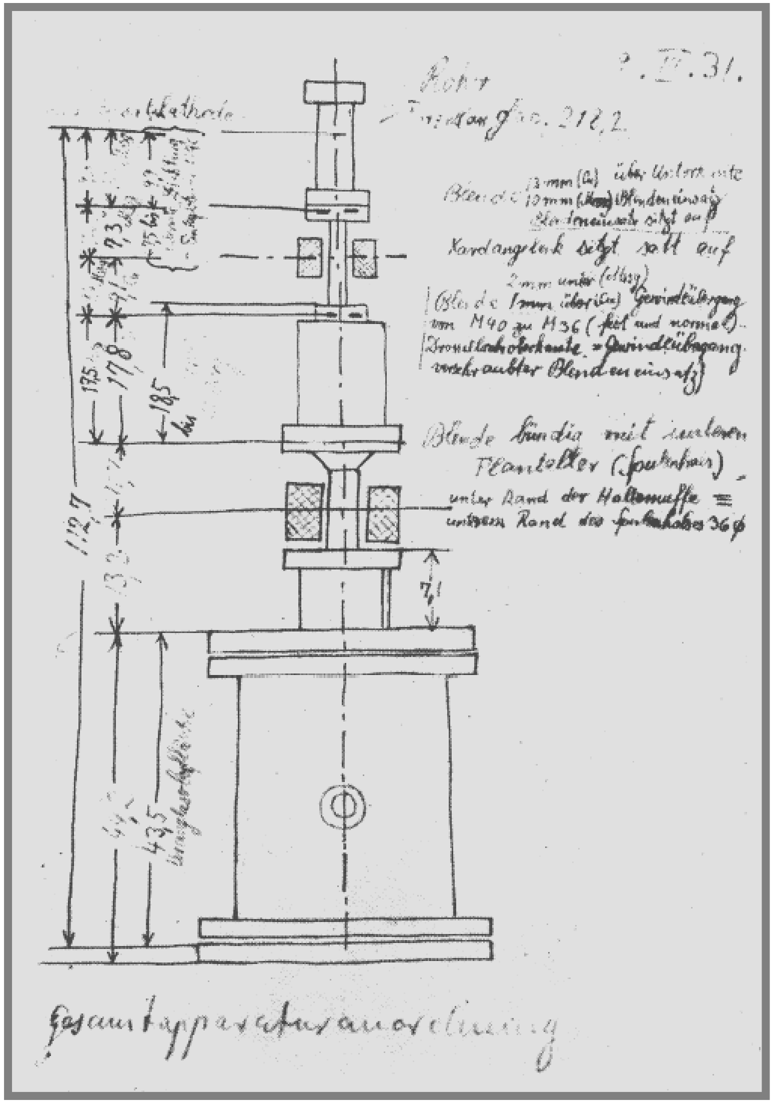
1939, Mollenstedt, CBED theory

1956, Menter, first observed lattice image (High Resolution)

1961, Howie & Whelan, Kinematical diffraction theory

1986, Ruska, Nobel prize winner

The first electron microscope, Ernst Ruska (1931)



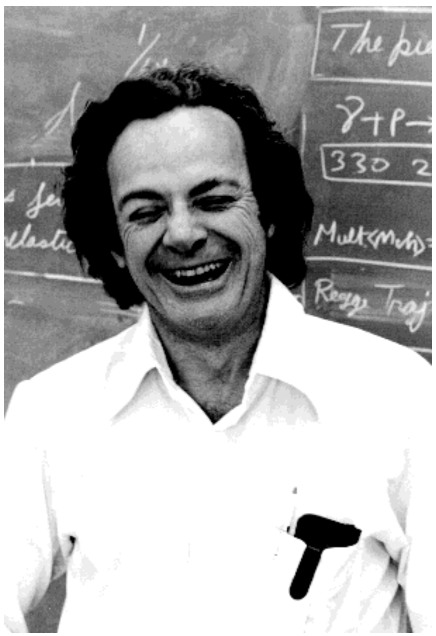
Total magnification; 3.6 X 4.8 = 17.4

Accelerating voltage; 50kV

Sketch by Ruska of the cathod-ray tube for testing the one-stage and two-stage electron-optical imaging by means of two magnetic electron lenses (9 March 1931)

There's Plenty of Room at the Bottom

An invitation to enter a new field of physics



Richard P. Feynman

- How do we write small ?
- Information on a small scale
- Better electron microscopes
- The marvelous biological system
- Miniaturizing the computer
- Miniaturization by evaporation
- Problems of lubrication
- A hundred tiny hands
- Rearranging the atoms
- Atoms in a small world
- High school competition

December 29th 1959 at the annual meeting of the American Physical Society at the California Institute of Technology

How do we write small?

The next question is: How do we write it? We have no standard technique to do this now. But let me argue that it is not as difficult as it first appears to be. We can reverse the lenses of the electron microscope in order to demagnify as well as magnify. A source of ions, sent through the microscope lenses in reverse, could be focused to a very small spot. We could write with that spot like we write in a TV cathode ray oscilloscope, by going across in lines, and having an adjustment which determines the amount of material which is going to be deposited as we scan in lines.

This method might be very slow because of space charge limitations. There will be more rapid methods. We could first make, perhaps by some photo process, a screen which has holes in it in the form of the letters. Then we would strike an arc behind the holes and draw metallic ions through the holes; then we could again use our system of lenses and make a small image in the form of ions, which would deposit the metal on the pin.

A simple way might be this (though I am not sure it would work): We take light and, through an optical microscope running backwards, we focus it onto a very small photoelectric screen. Then electrons come away from the screen where the light is shinning. These electrons are focused down in size by the electron microscope lenses to impinge directly upon the surface of the metal. Will such a beam etch away the metal if it is run long enough? I don't know. If it doesn't work for a metal surface, it must be possible to find some surface with which to coat the original pin so that, where the electrons bombard, a change is made which we could recognize later.

AIPEL Hardware

✓ **Specifications**

- **Accelerating voltage : 200 kV**
- **Electron gun type : Field emission gun**
- **Point-to-point resolution : 0.23 nm, Lattice resolution : 0.1 nm**
- **Patterning magnification : x20 ~ x300**
- **Lens system**

  Wafer stage

  OL – **IL1 – PL1** – OL2 – IL2 – PL2

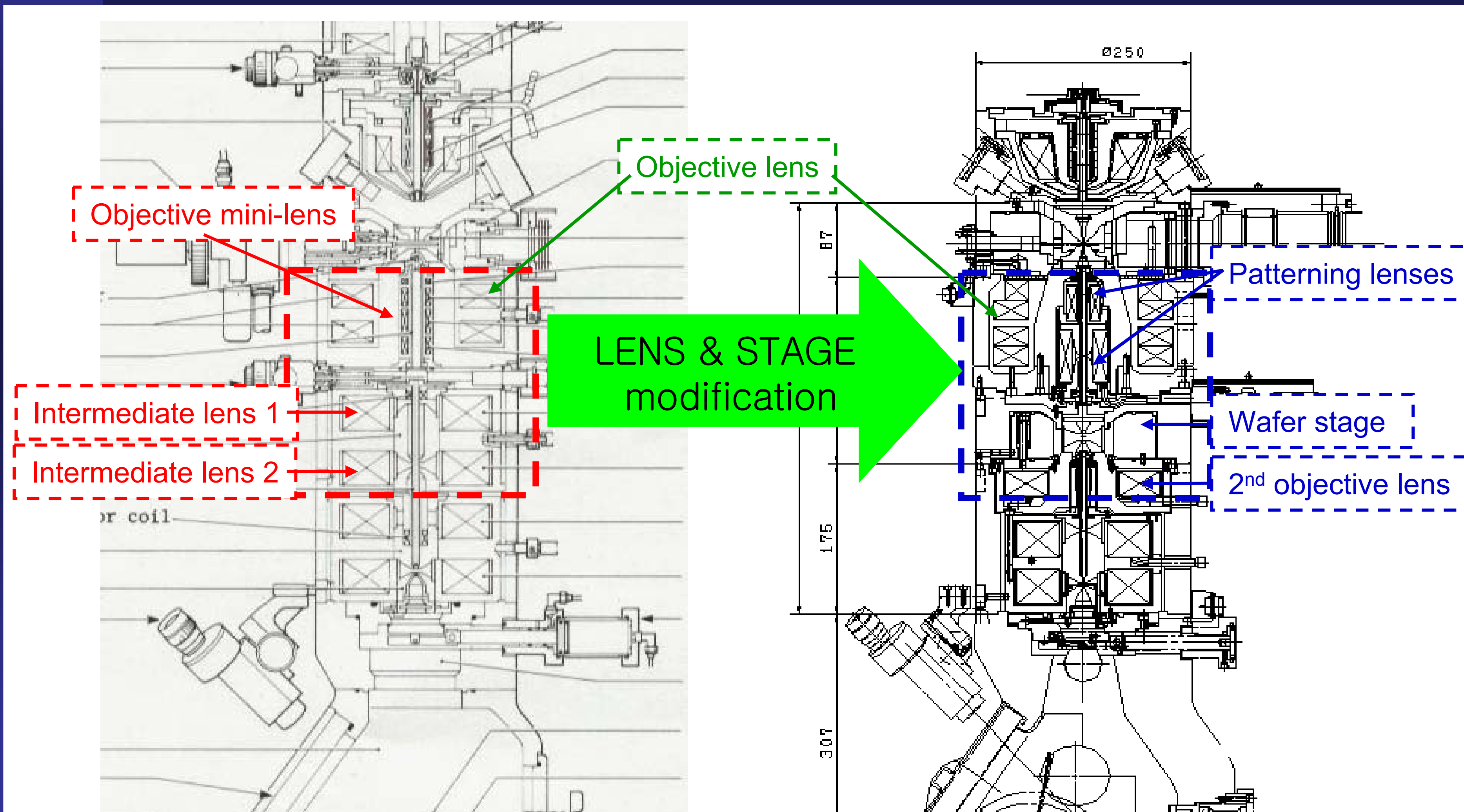
- **Wafer stage where resist coated wafer can be inserted**

  A-stage : 4 mm x17 mm wafer

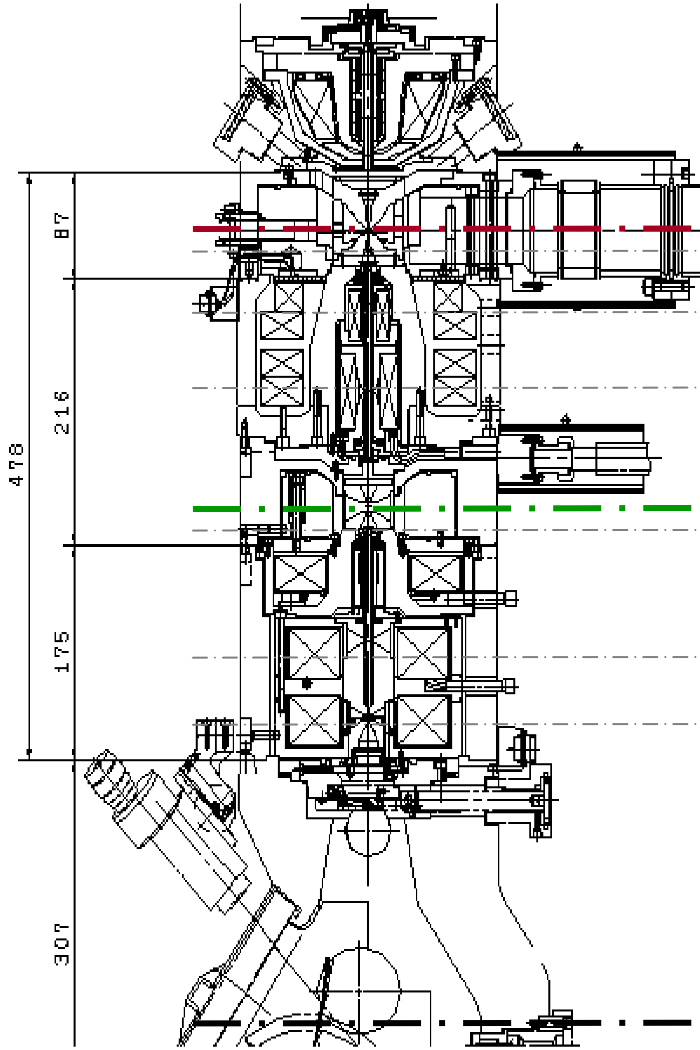
  B-stage : 25 mm x 25 mm wafer

Modification of JEOL 2010F TEM

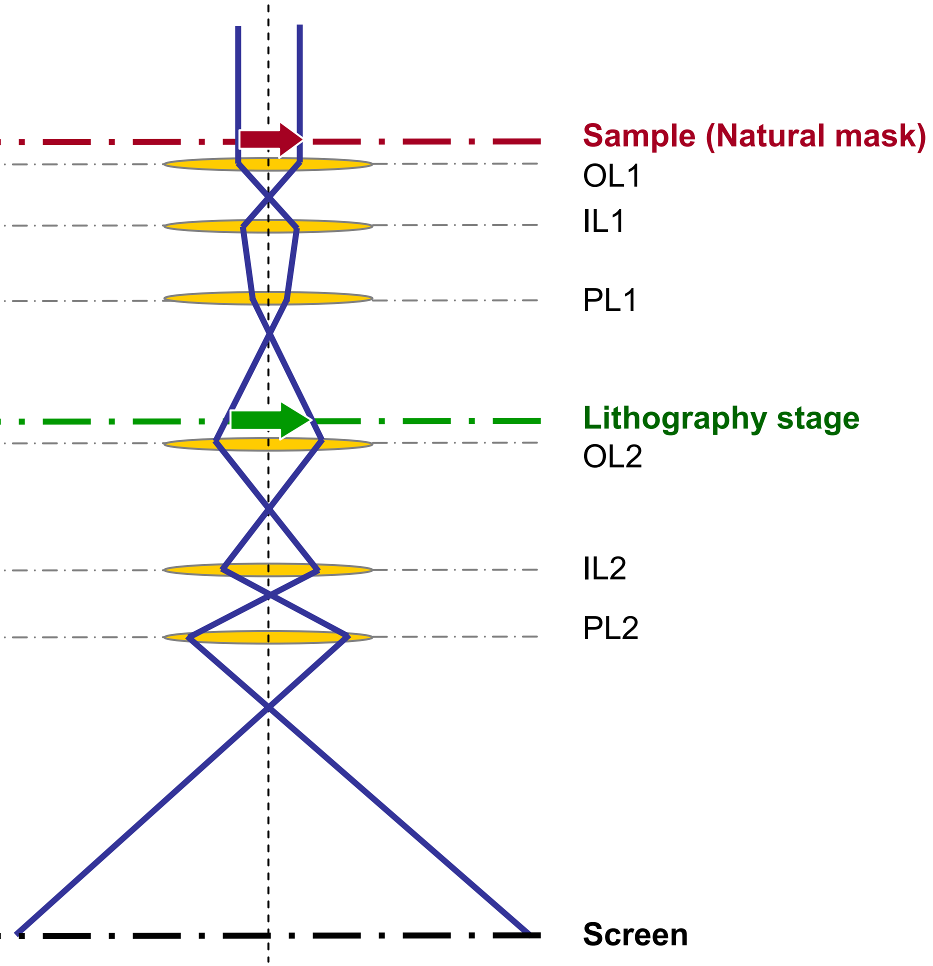
2010F AIPEL



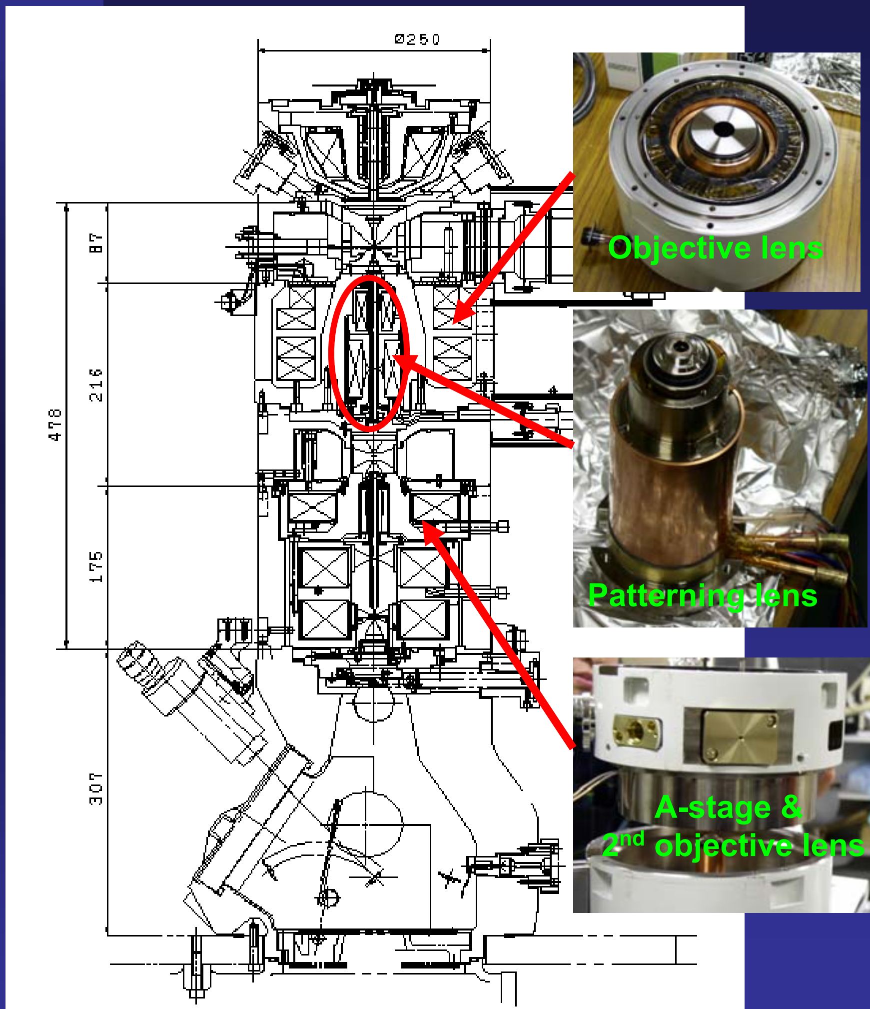
AIPEL hardware



Ray diagram



Modification of JEOL 2010F TEM



✓ **Modifications**

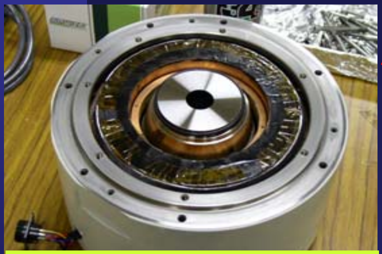
- **Objective lens :** Objective lens for 300 kV
- **Patterning lens 1 & 2**

  : New lenses for generating patterns at the stage

  : Magnification of objective lens and patterning lenses system : ×20 ~ ×300
- **Wafer stage**

  : Two types of stages : 4×17 mm^2 wafer stage(A-stage) and 25×25 mm^2 wafer stage(B-stage)
- **2nd objective lens**

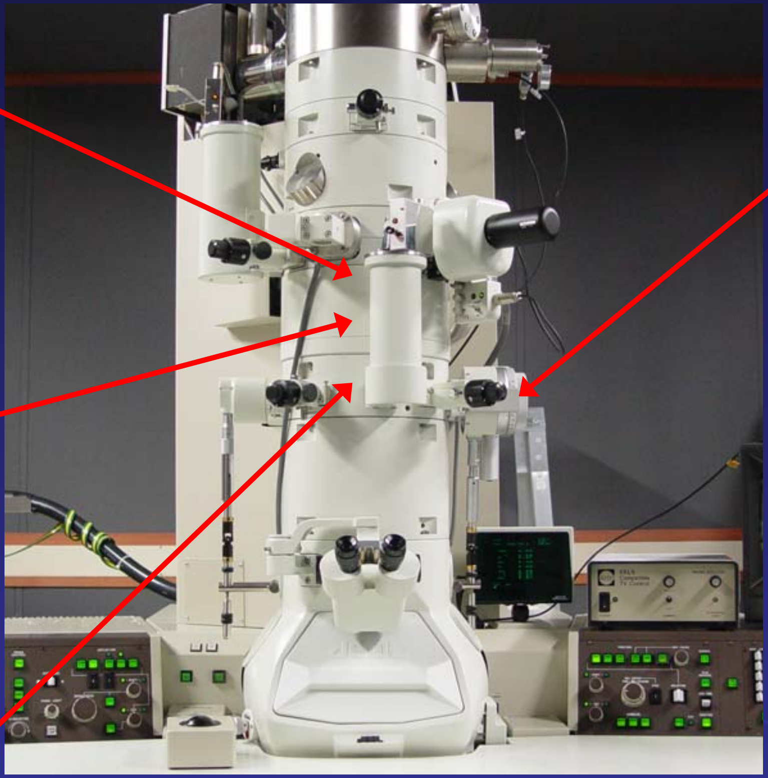
AIPEL system (Modified parts)



Objective lens

Patterning lens

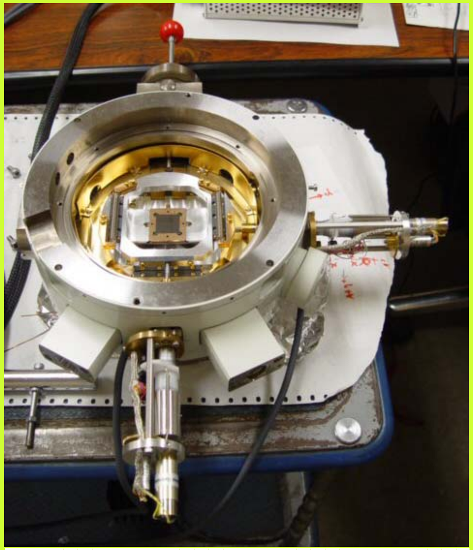
stage chamber



Patterning lens power supply

Control unit of wafer stage

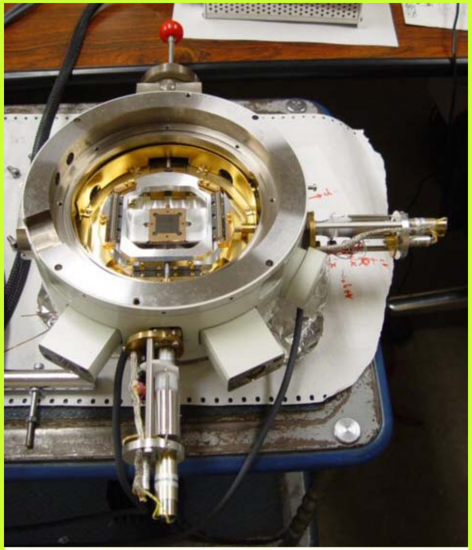
A - stage



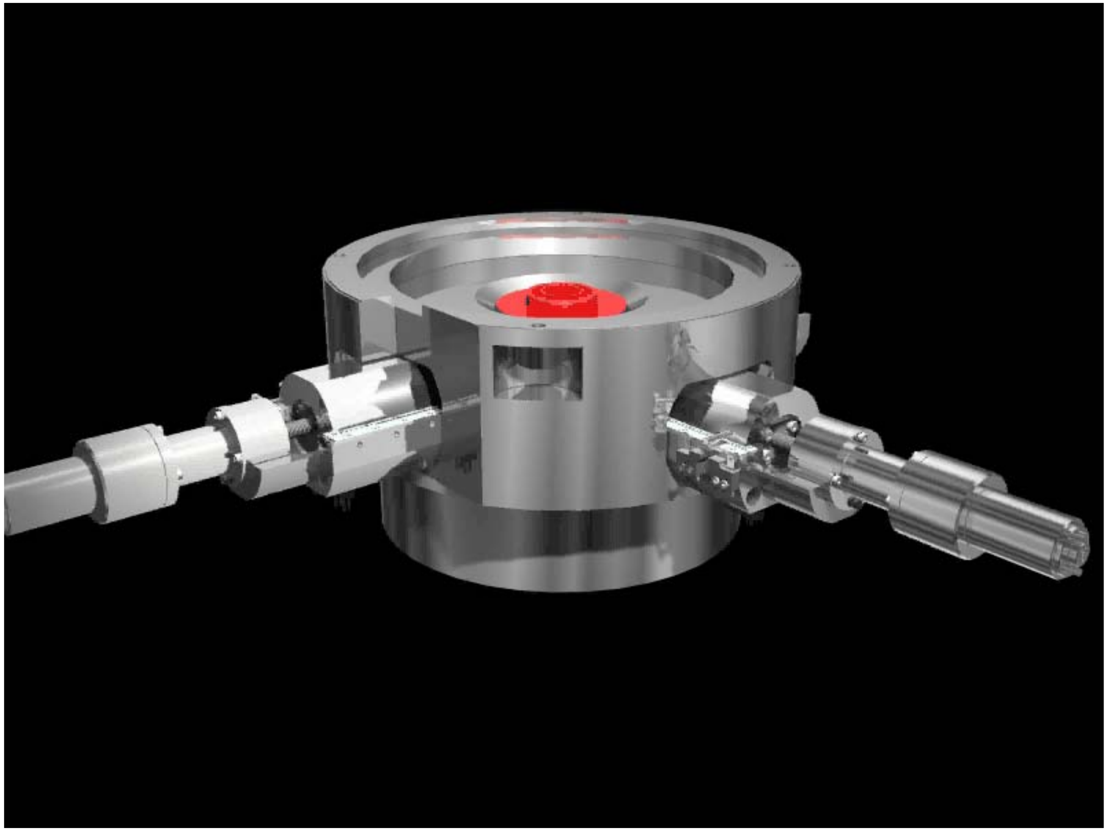
B - stage

AIPEL system (Modified parts)

✓ B - stage



B - stage



Collaboration with JEOL in JAPAN

Mr. Kim

"Hi, I am
an AIPEL
team
leader of
NFL."

Dr. Arai

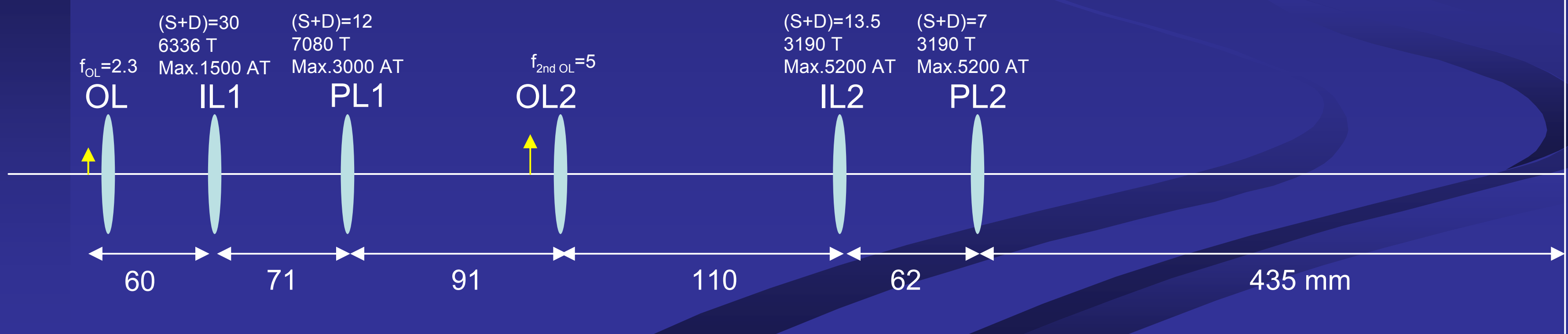
"Hello, I an
a principal
researcher
of JEOL."

AIPEL lens system

- ✓ **3-stage image forming system**
  - – **consists of OBJECTIVE(OL), INTERMEDIATE(IL), PROJECTOR LENS(PL)**
- ✓ **AIPEL lens system**
  - – **consists of two 3-stage image forming systems**
  - – **Mask stage-OL-IL1-PL1-wafer stage-OL2-IL2-PL2**

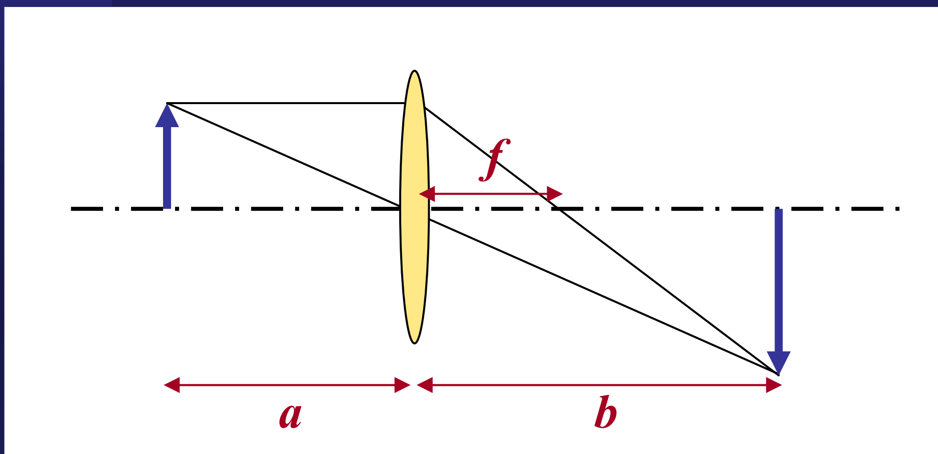
TEM1

TEM2



AIPEL lens system

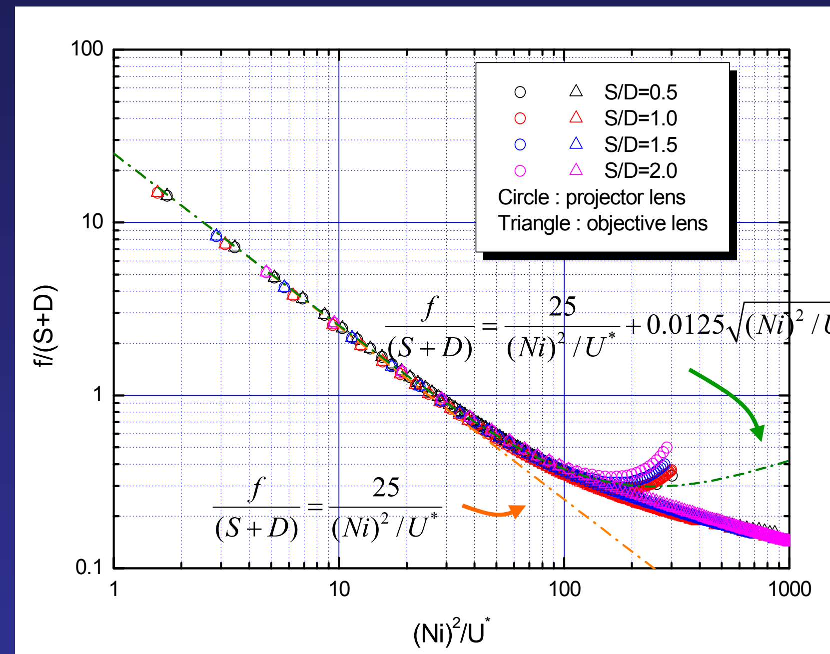
✓ Newton's Lens Equation



$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f}$$

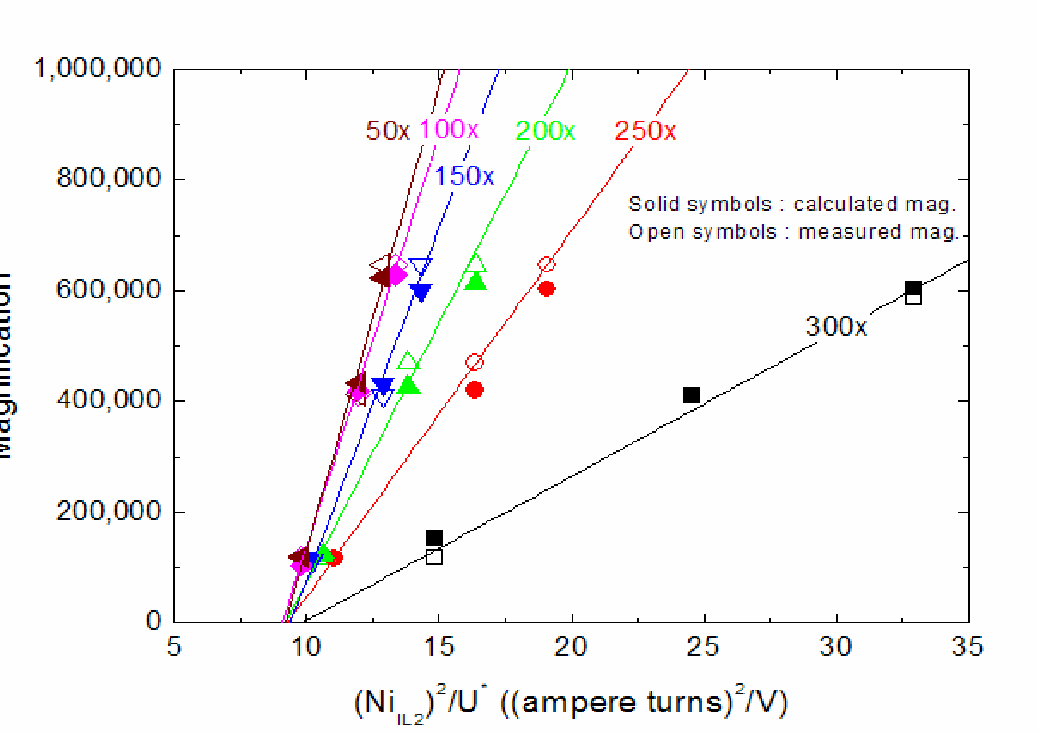
$$M=\left|\frac{b}{a}\right|$$

✓ Magnetic Lens



S: pole-piece gap
D : bore diameter
Ni : ampere turns
U^* : relativistic accelerating voltage

Magnification of AIPEL hardware



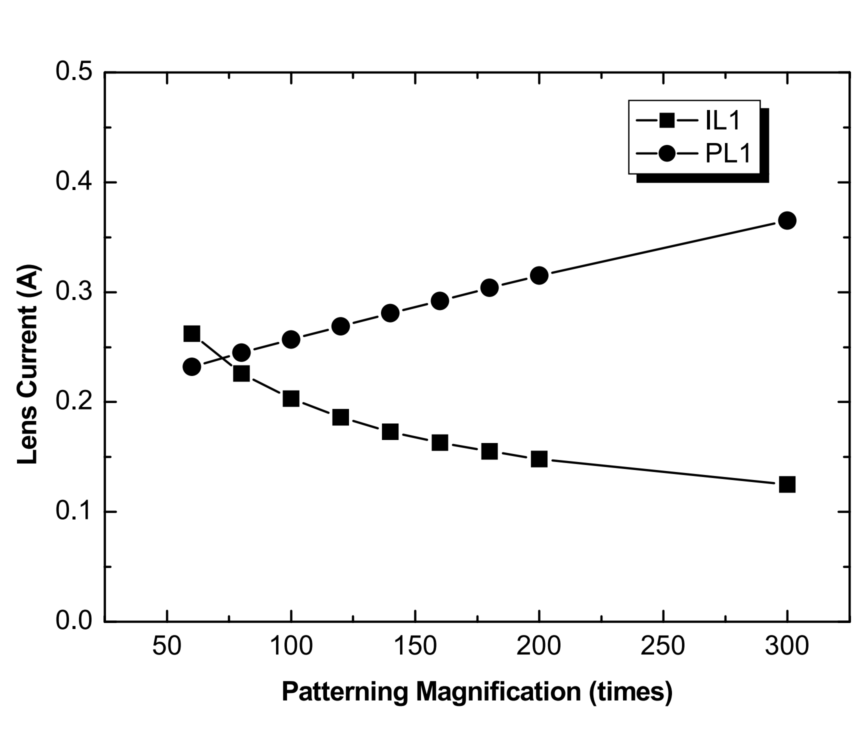
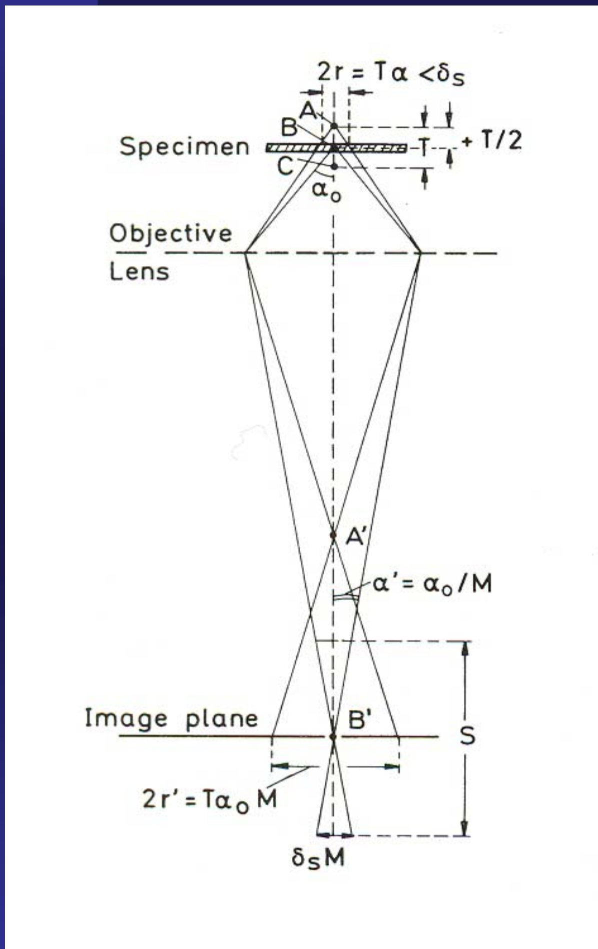


Fig.(a) Total magnification of AIPEL hardware as a function of the excitation of IL2

Fig. (b) Patterning magnification of AIPEL hardware as a function of the excitation of IL1 and PL1

Depth-of-focus at wafer stage



$$\delta_S M = \alpha' S; \qquad S = \frac{M}{\alpha'} = \frac{\delta_S M^2}{\alpha_o}$$

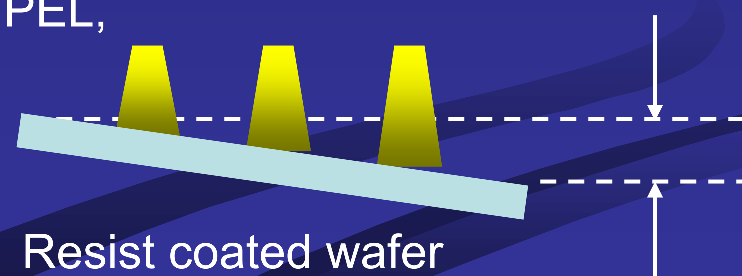
δ_S : resolution
α_o : beam semi-convergence angle
M : magnification

In TEM,

M=100,000 times, α_o = 10 mrad, δ_s = 0.3 nm

Depth-of-focus (S) = 300 m

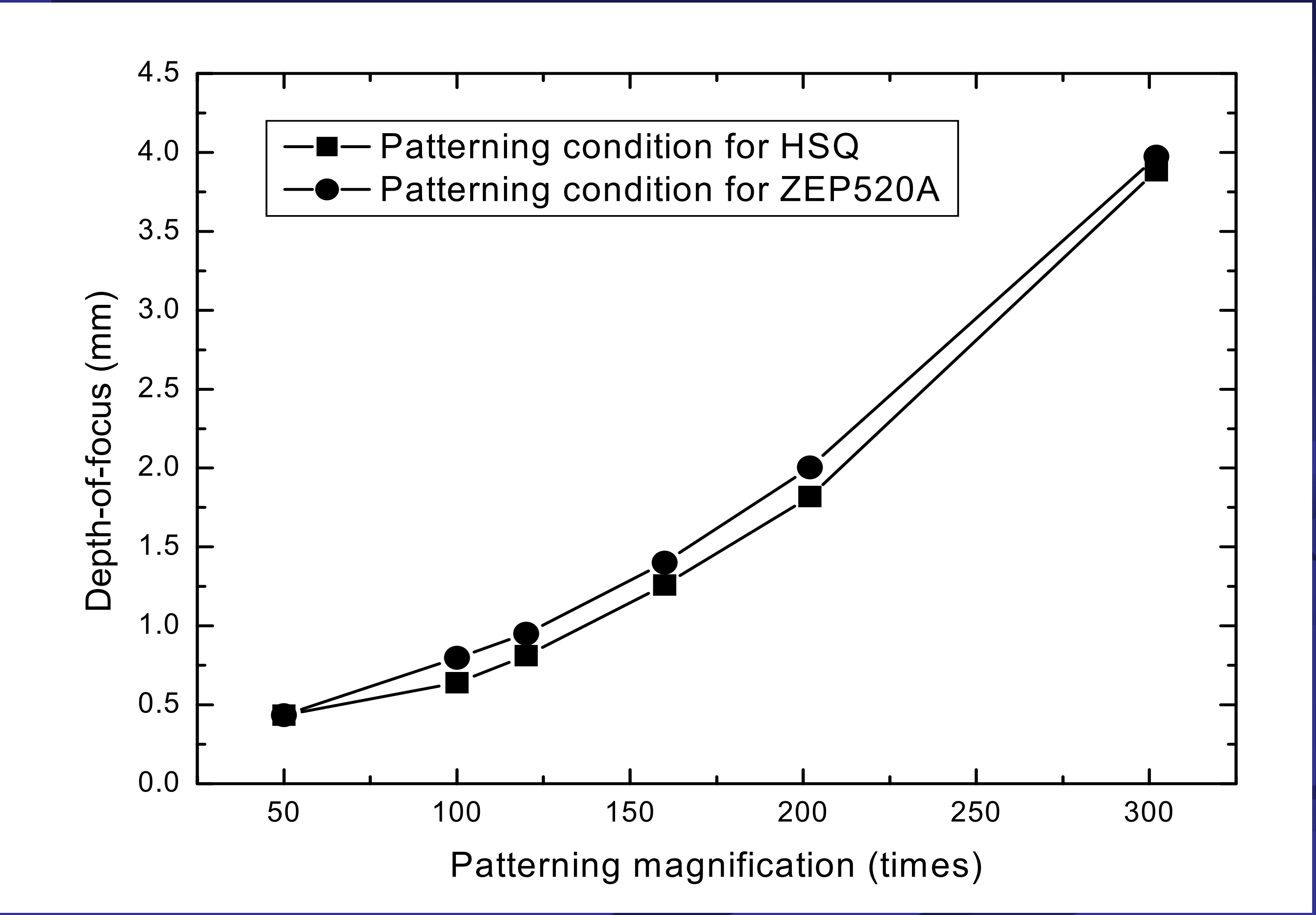
In AIPEL,



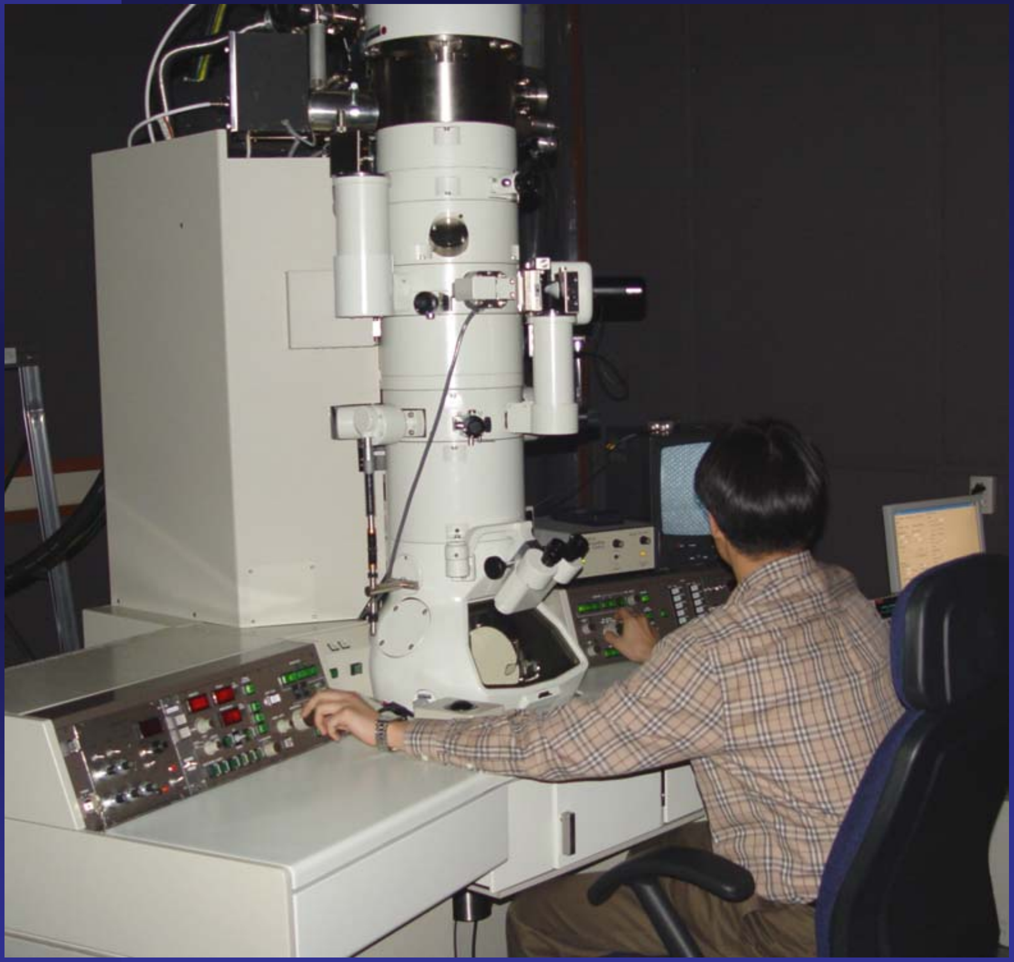
$<S_{wafer}$

Resist coated wafer

Depth-of-focus at wafer stage



AIPEL system specification

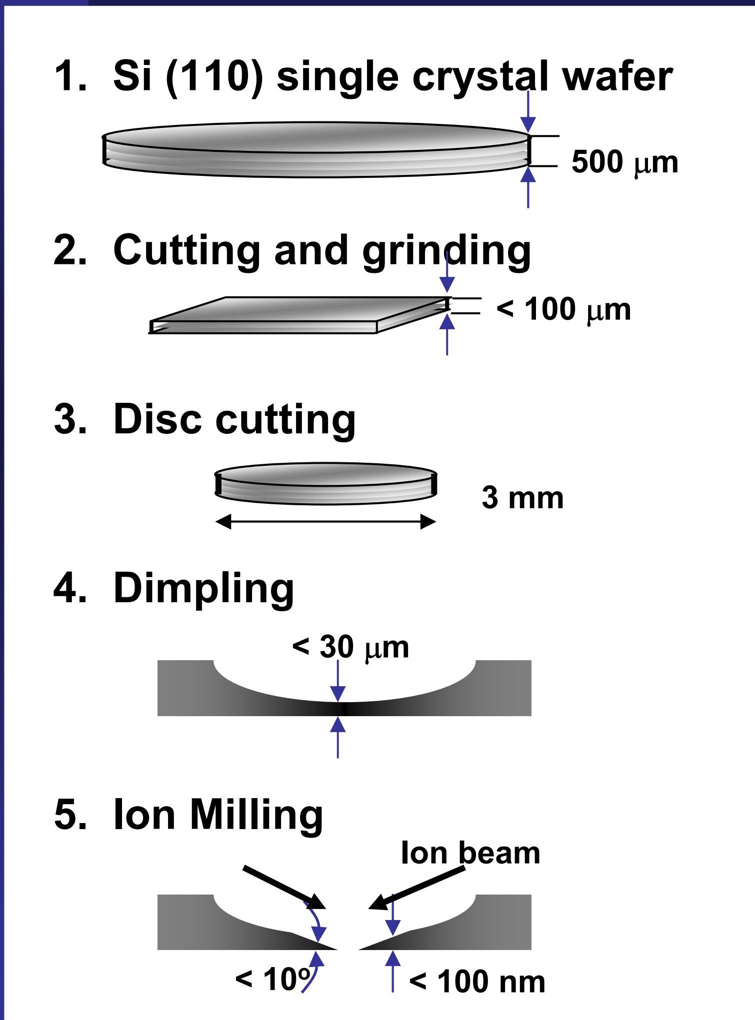


AIPEL System Installation in SNU

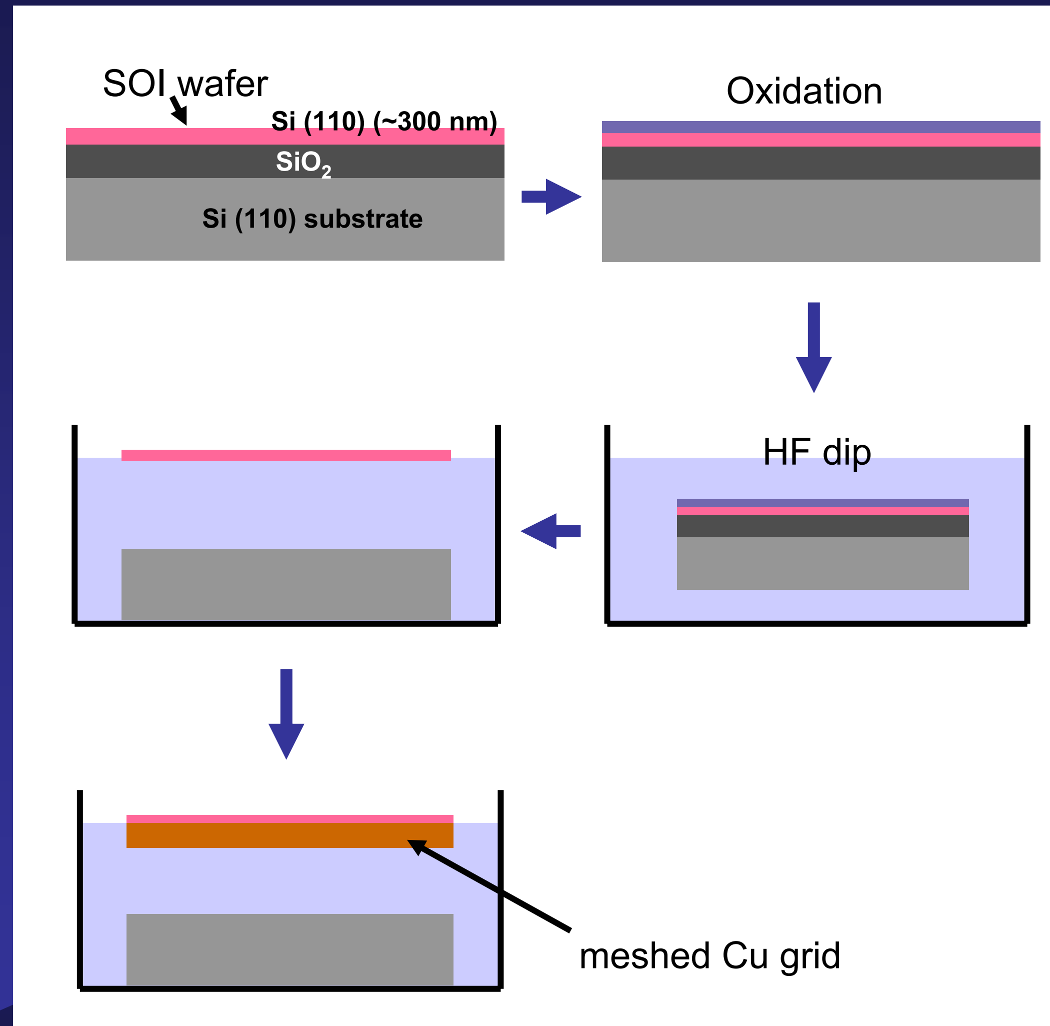
Specifications	AIPEL
Accelerating voltage	200 kV
Exposure current	~10 nA
Exposure area	Controllable
Electron gun	ZrO/W (Field emission)
Point-to-point resolution	0.23 nm
Depth-of-focus at wafer	0.4 ~ 4 mm
Pattering magnification	X20~300 magnification
Mask	Natural mask
Resist	ZEP-520A, HSQ, PMMA
Resist	30 ~ 300 nm
Target Throughput	5 wafer (8” wafer / hr)
Target resolution	10 nm

AIPEL mask preparation

I. TEM specimen type

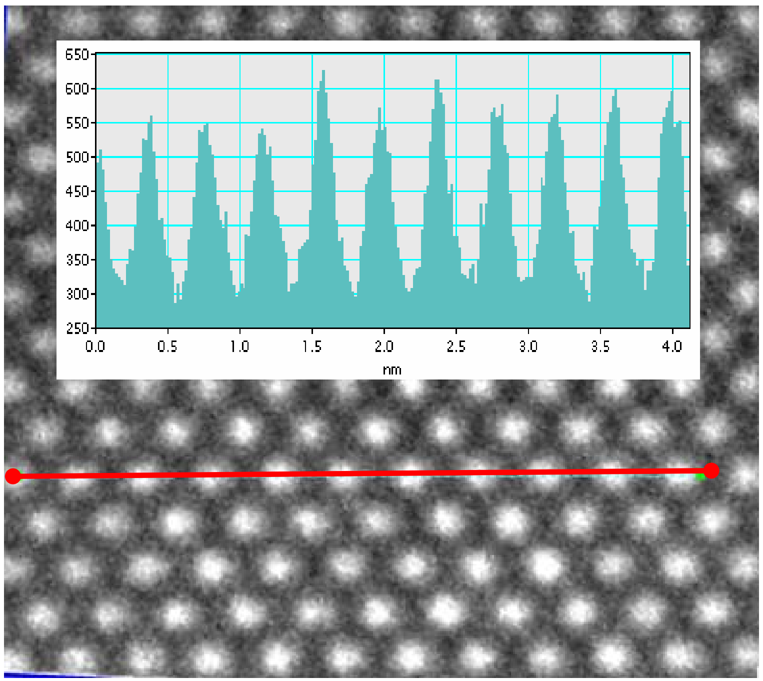


II. SOI wafer type

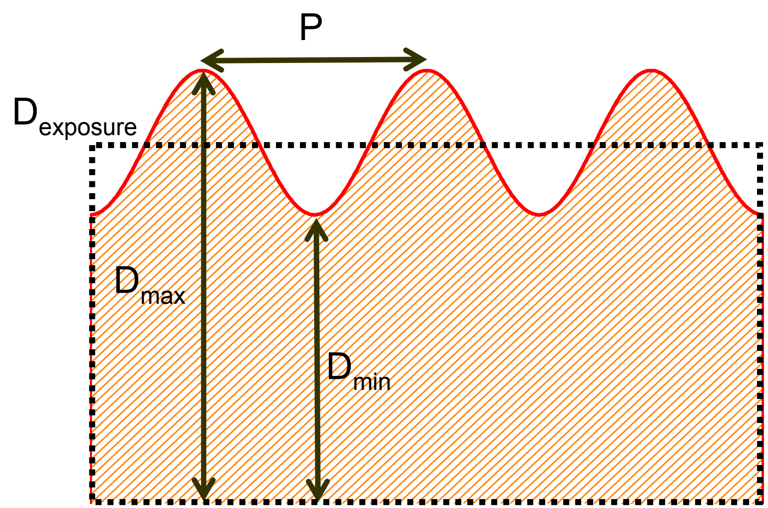


Electron signal from AIPEL mask

- Dose distribution modeling



$$\mathrm{MTF} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} = 0.25$$



$$D = \frac{D_{\max} - D_{\min}}{2}\left(\cos\frac{2\pi}{P}x + 1\right) + D_{\min}$$

When MTF is 0.25,

$$D_{max} = 1.366 \times D_{exposure}$$

$$D_{min} = 0.819 \times D_{exposure}$$

AIPEL patterning ; Experimental condition

– Mask : Si single crystal

– Beam current : 3.3 nA

– Patterning magnification : x100 ~ x200

– Resist : 100 nm-thick-**HSQ (Hydrogen silsesquioxane)**

– Exposure conditions :

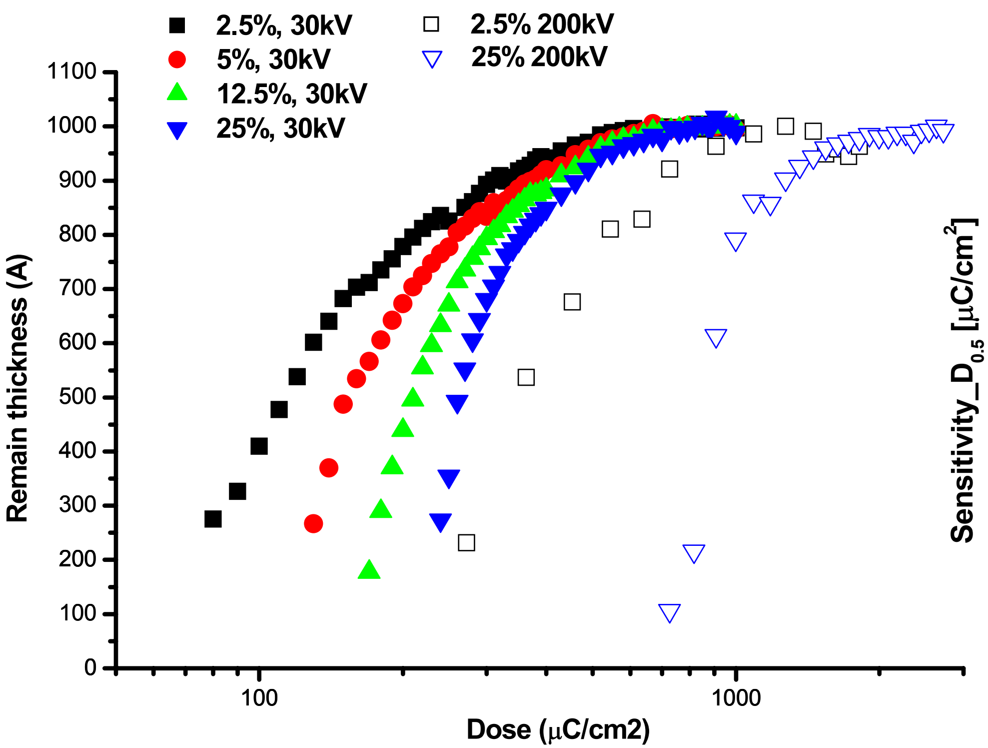
  Dose : 1000 ~ 1700 $\mu C/cm^2$, Exposure time : 1.0 ~ 1.5 sec

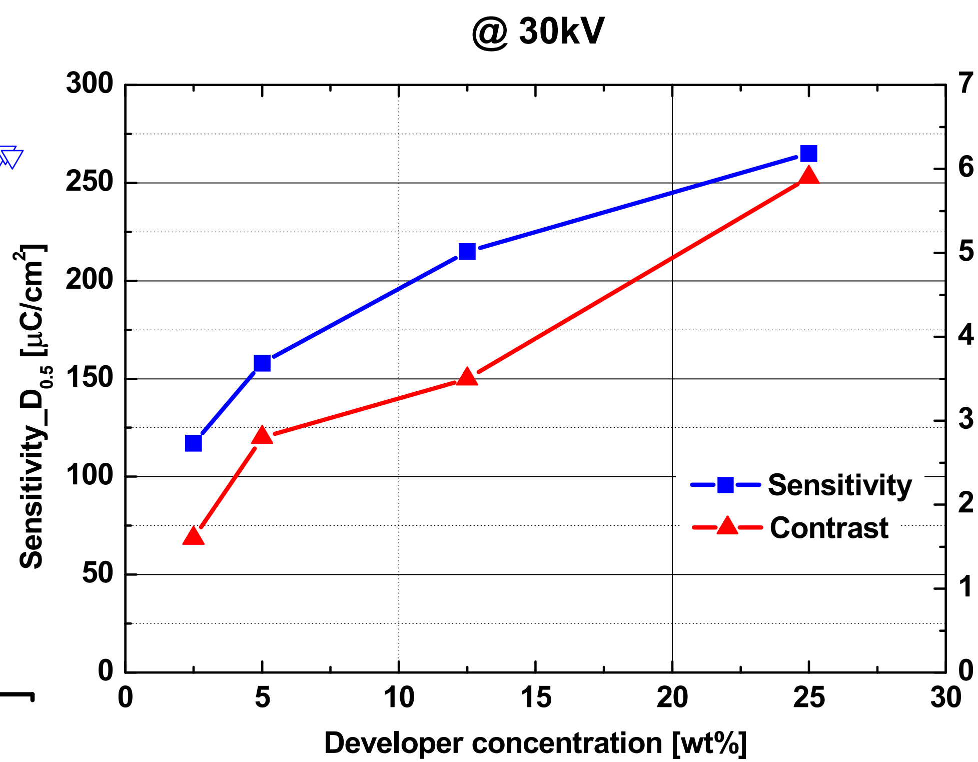
– Development condition;

  TMAH 25% (in water) 60 sec, D.I. water rinse 120 sec

Resist; Contrast curve of HSQ

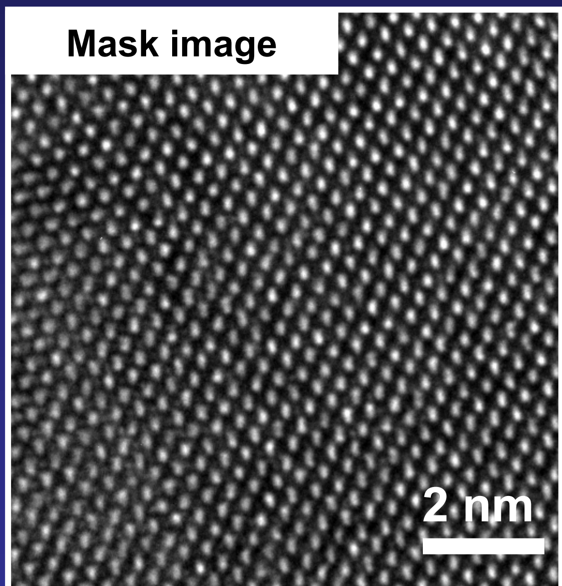
➢ Developer Concentration Dependency (30, 200 keV exposure)



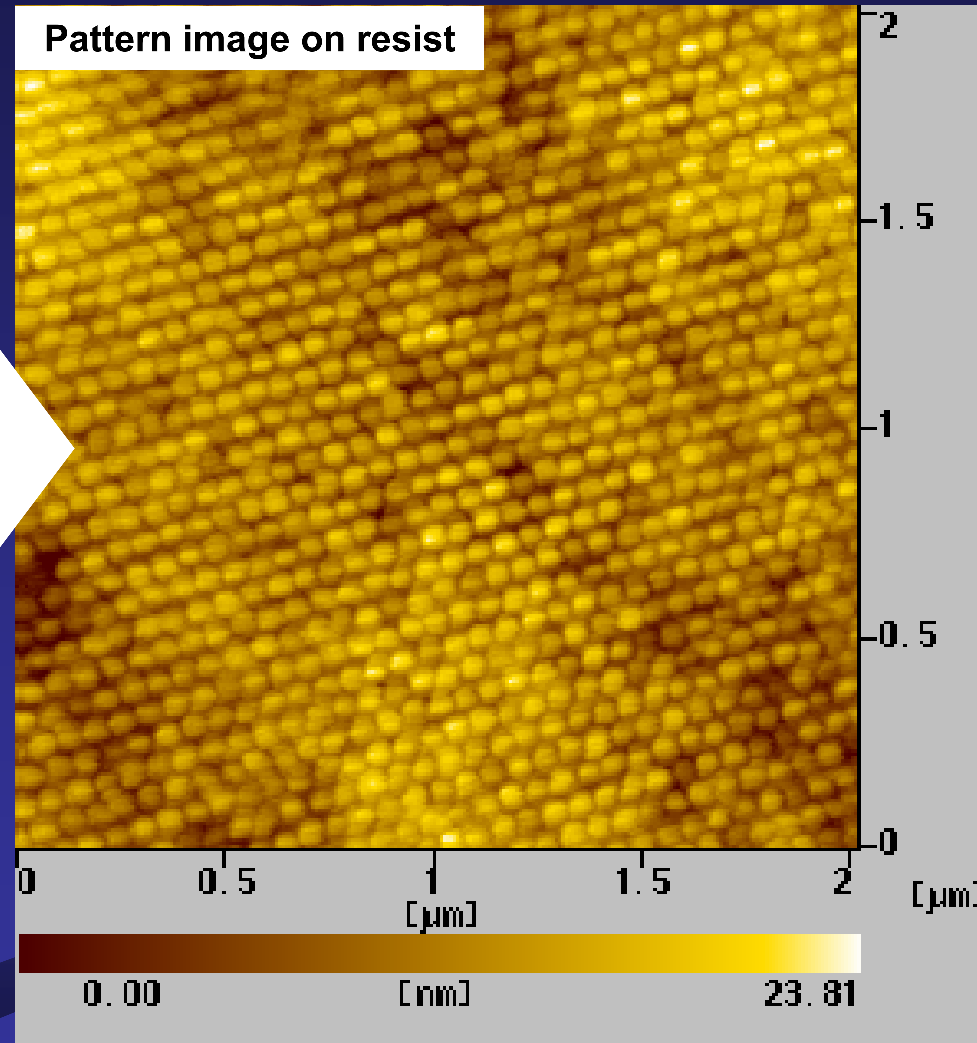


AIPEL patterning ; Experimental results (HSQ)

Dot patterns: 180^x, Pitch 65nm



180^X



Resist : **HSQ**,

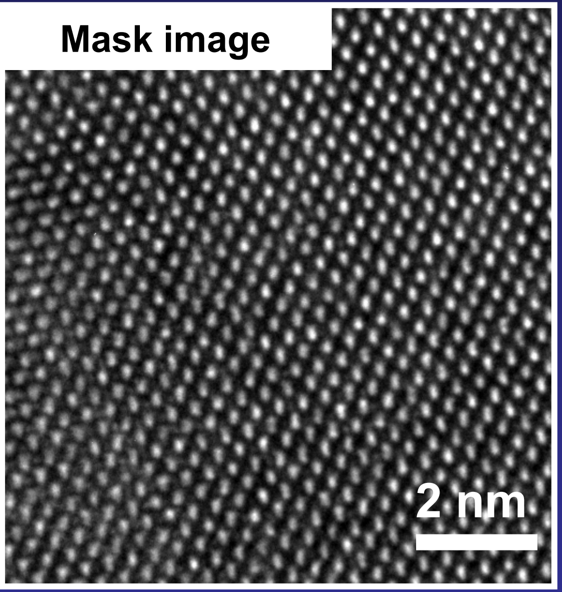
Dose : 1039 μC/cm^2,

Exposure time : 1.2 sec

AIPEL patterning ; Experimental results (HSQ)

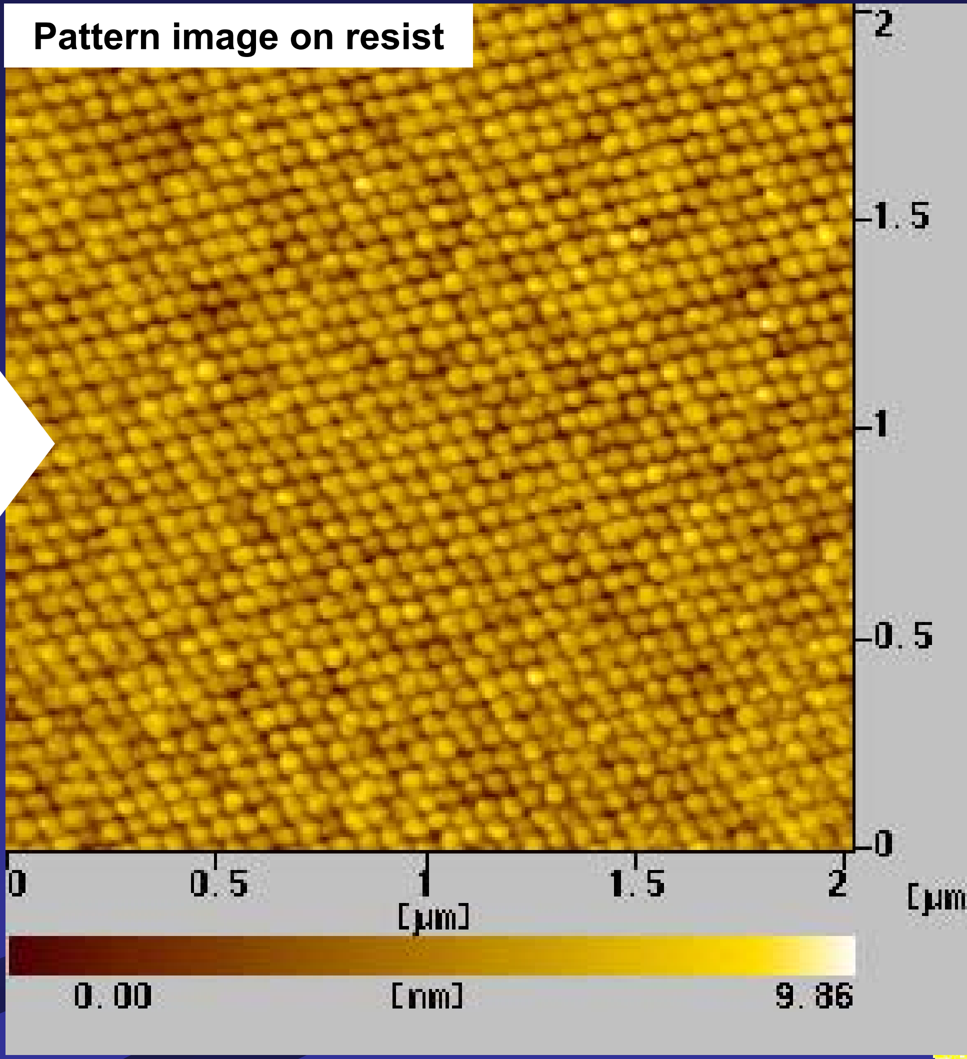
Dot patterns: 160^x, Pitch 55nm

Mask image



160^X

Pattern image on resist



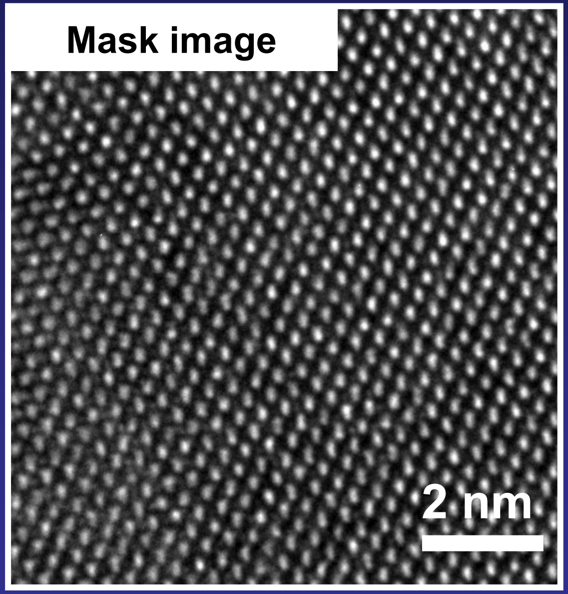
Resist : **HSQ**,

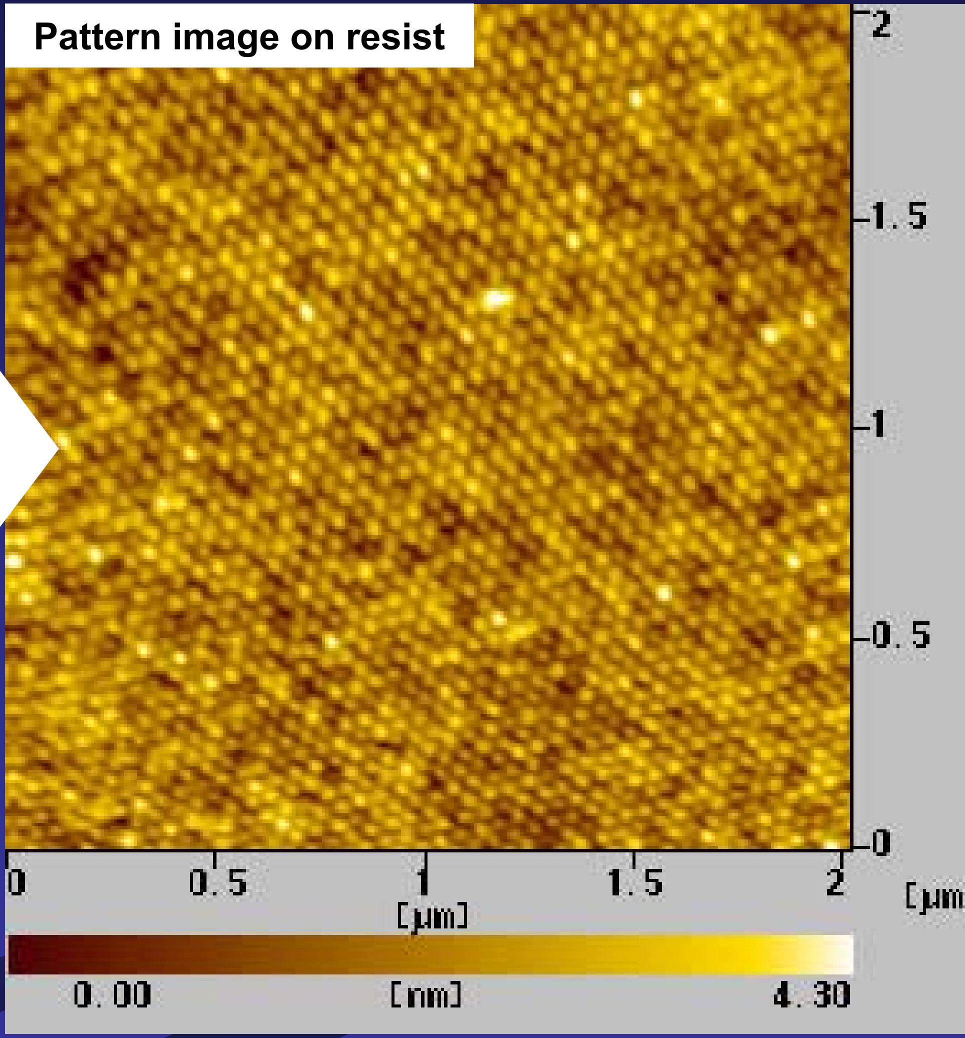
Dose : 1263 μC/cm^2,

Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (HSQ)

Dot patterns: 140^x, Pitch 45nm





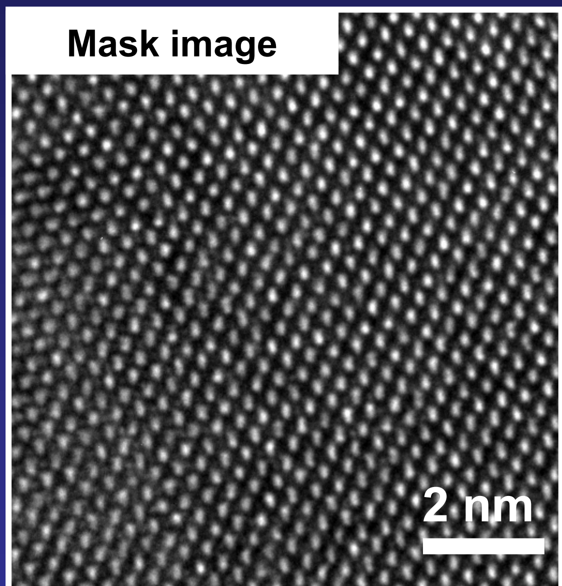
Resist : **HSQ**,

Dose : 1488 μC/cm^2,

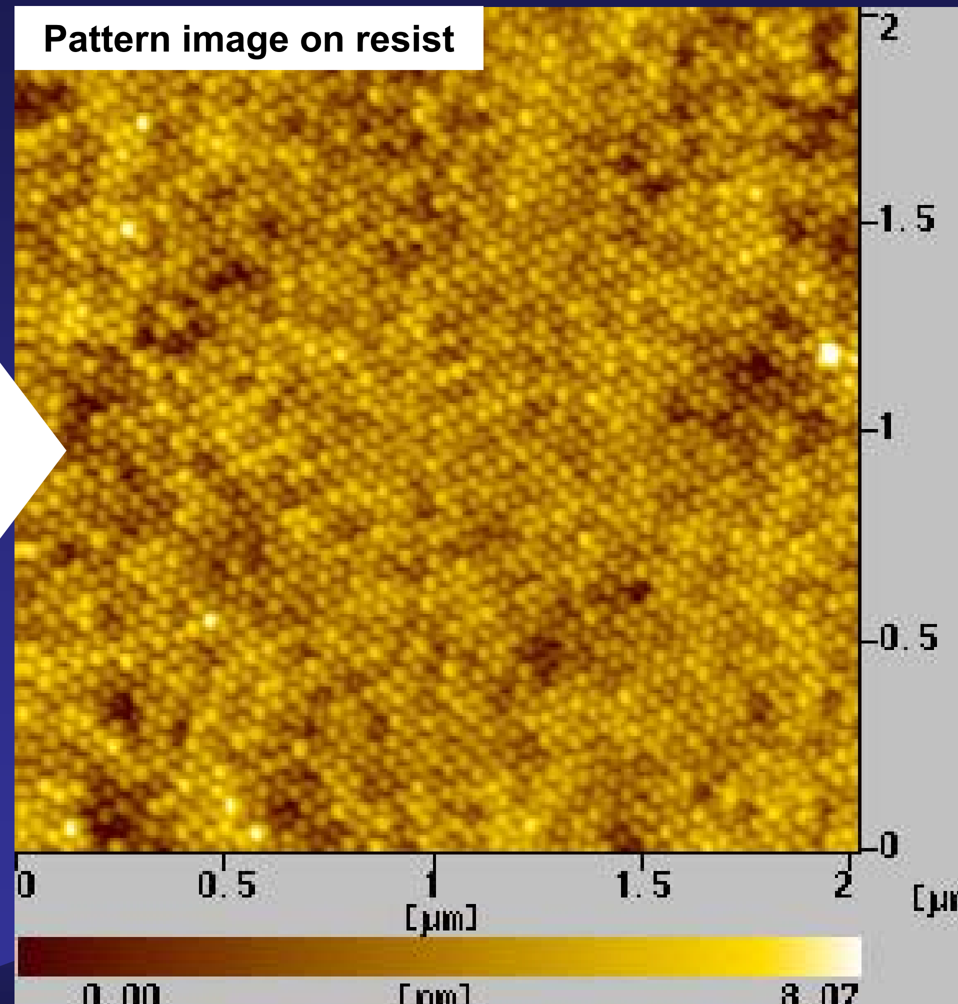
Exposure time : 1.6 sec

AIPEL patterning ; Experimental results (HSQ)

Dot patterns: 120^x, Pitch 40nm



120^X



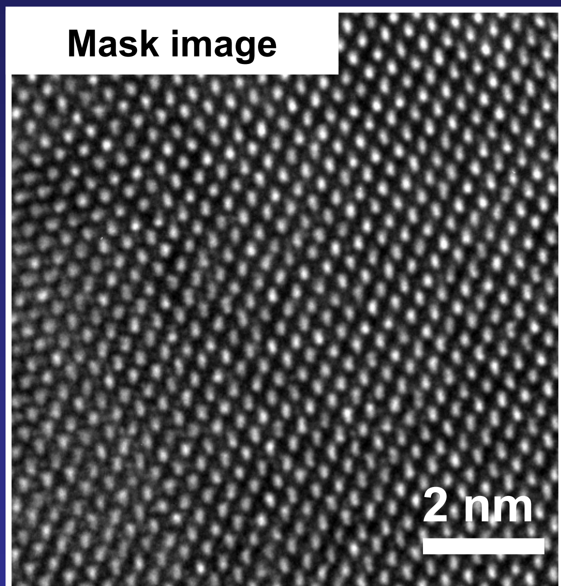
Resist : **HSQ**,

Dose : 1416 $\mu C/cm^2$,

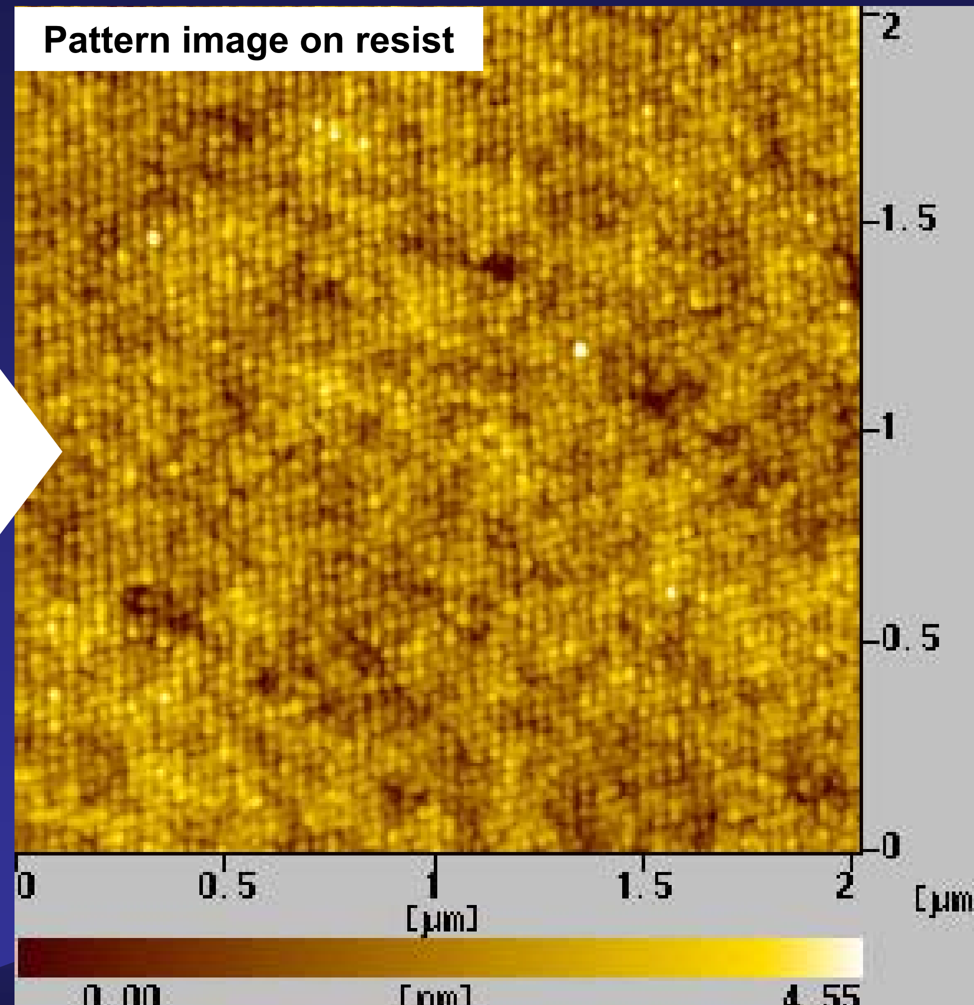
Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (HSQ)

Dot patterns: 100^{x}, Pitch 35nm



100^{X}



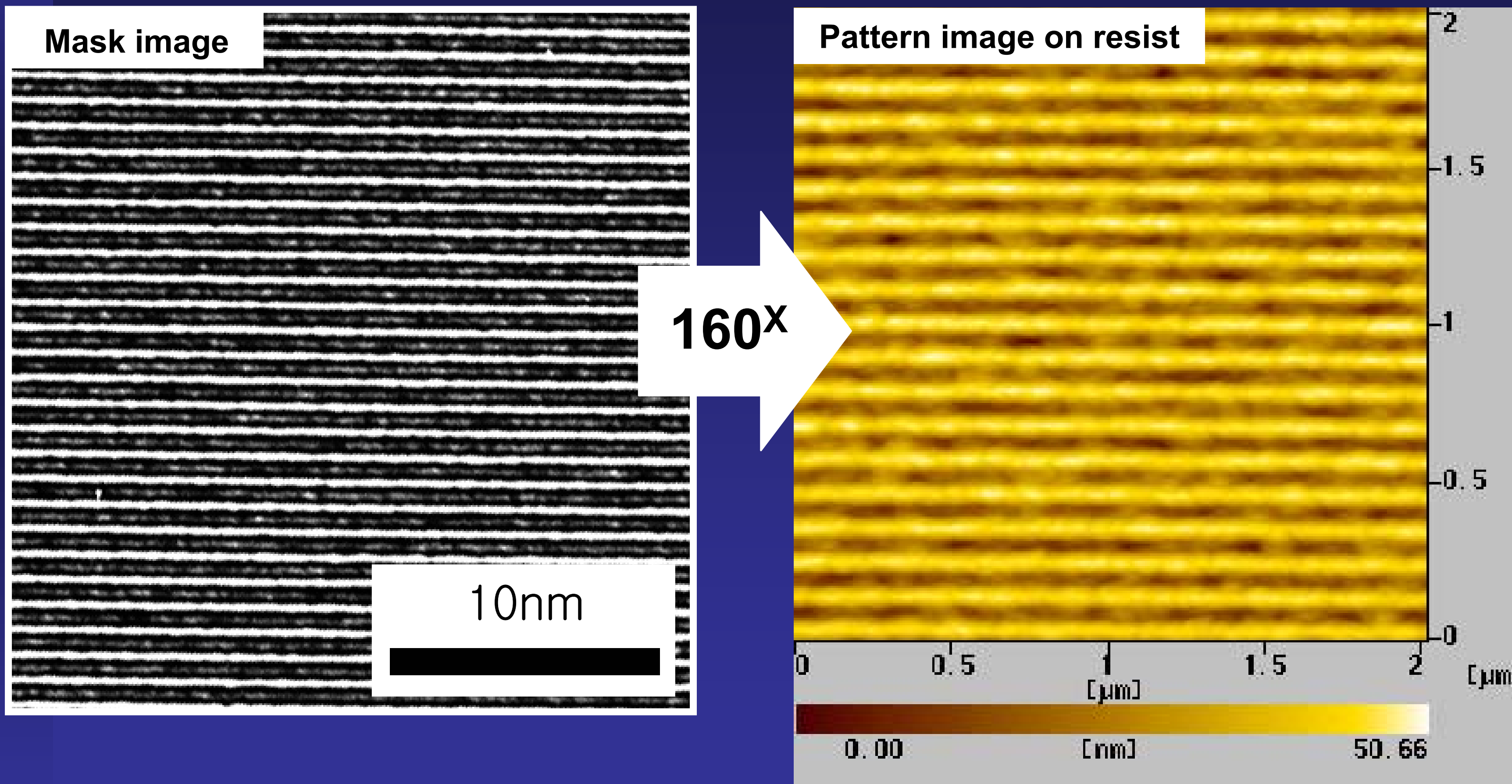
Resist : **HSQ**,

Dose : 1260 µC/cm^2,

Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (Si_3N_4 mask)

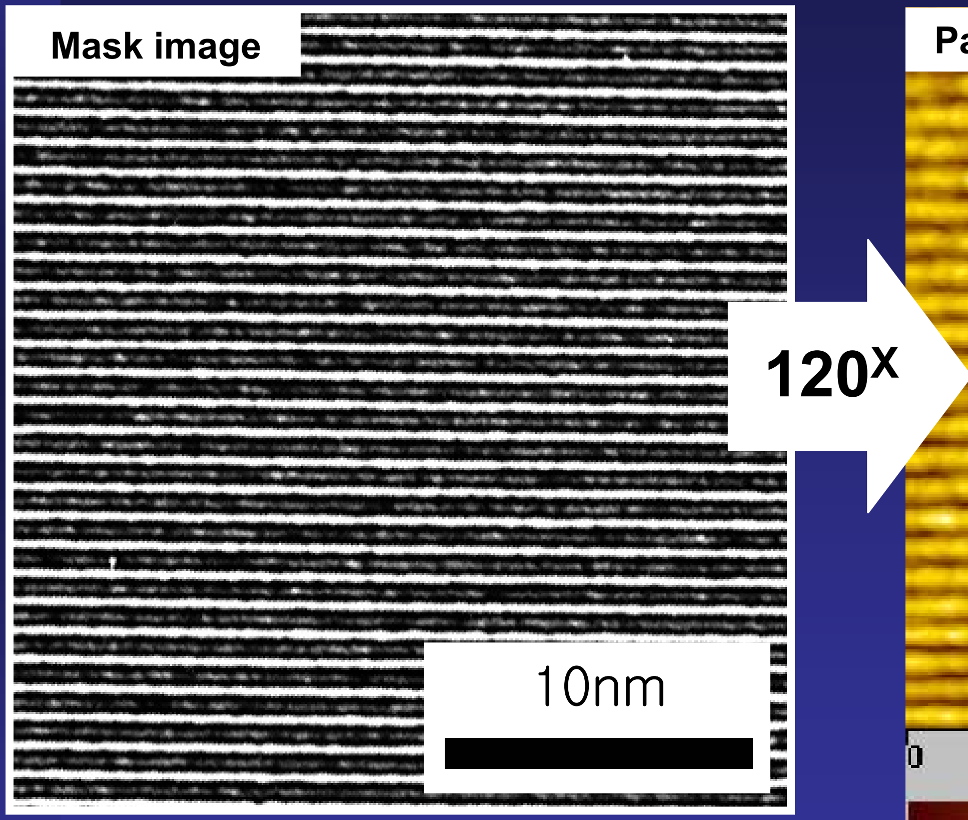
Line patterns: 160^x, Pitch 105nm

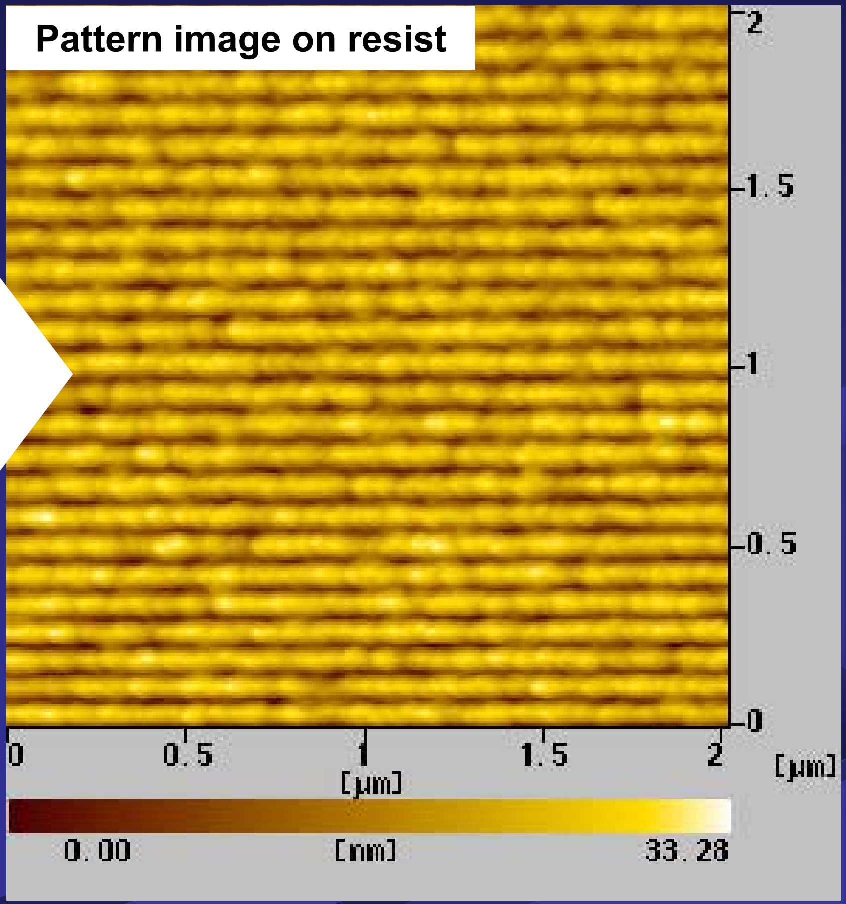


Resist : **HSQ**, Dose : 1260 $\mu C/cm^2$, Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (Si_3N_4 mask)

Line patterns: 120^x, Pitch 90nm

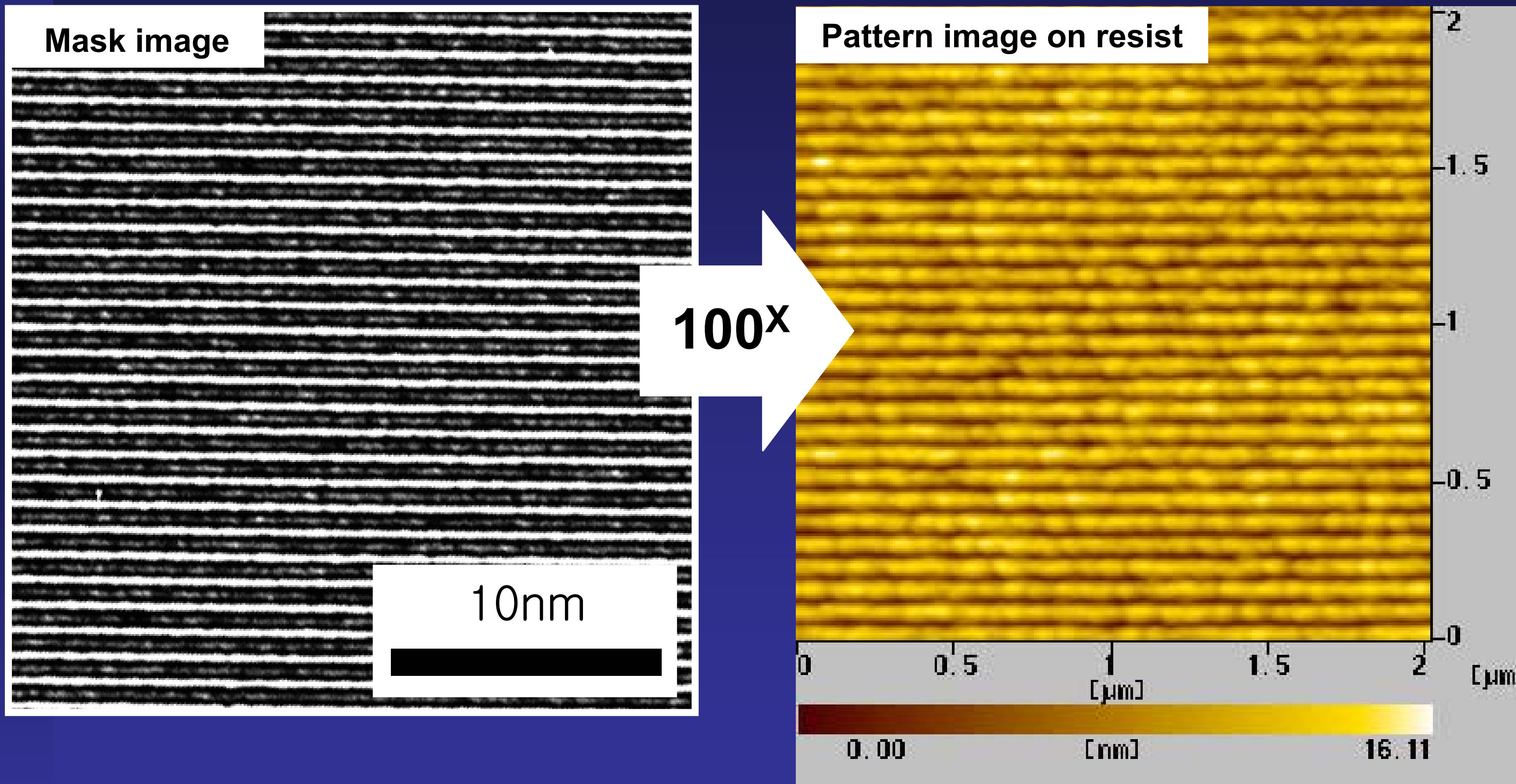




Resist : **HSQ**, Dose : 1260 μC/cm^2, Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (Si_3N_4 mask)

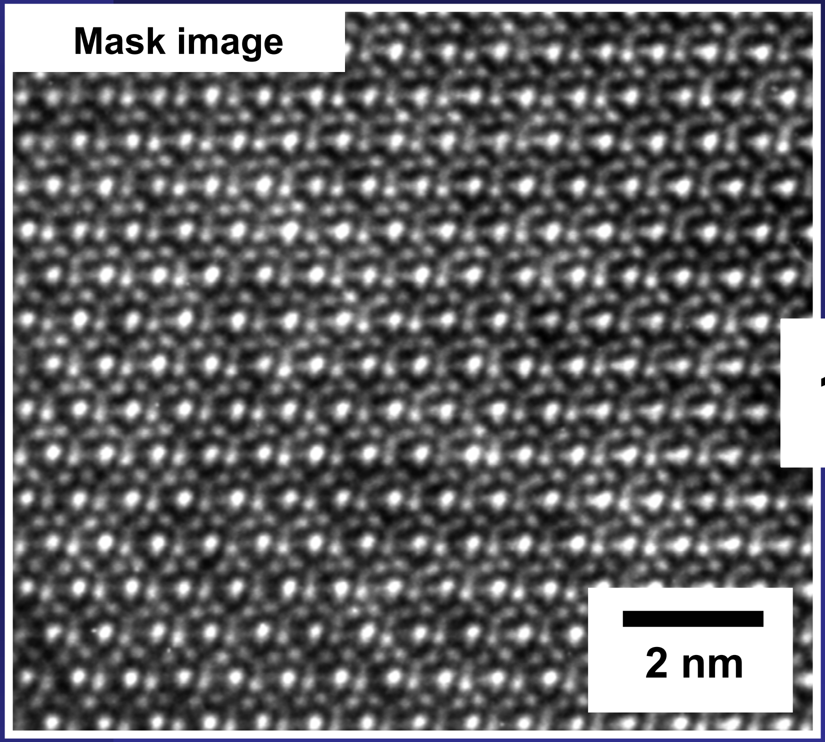
Line patterns: 100^x, Pitch 70nm



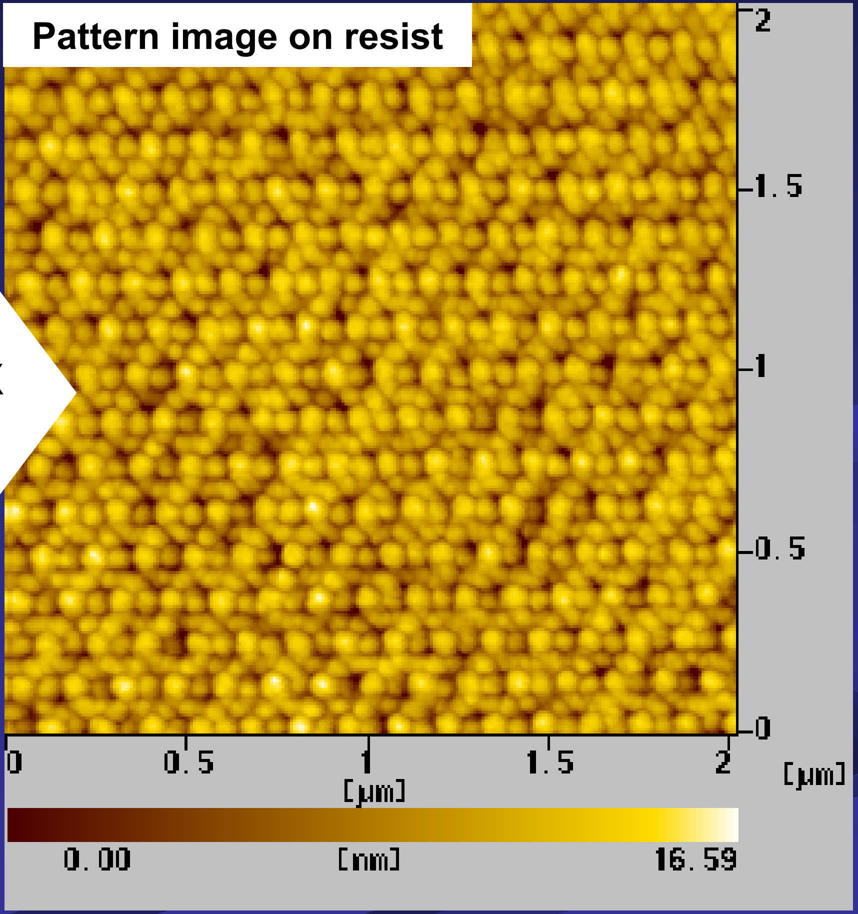
Resist : **HSQ**, Dose : 1260 μC/cm^2, Exposure time : 1.5 sec

AIPEL patterning ; Experimental results (Si_3N_4 mask)

Complicate (6-fold symmetry) patterns: 160^x (HSQ)



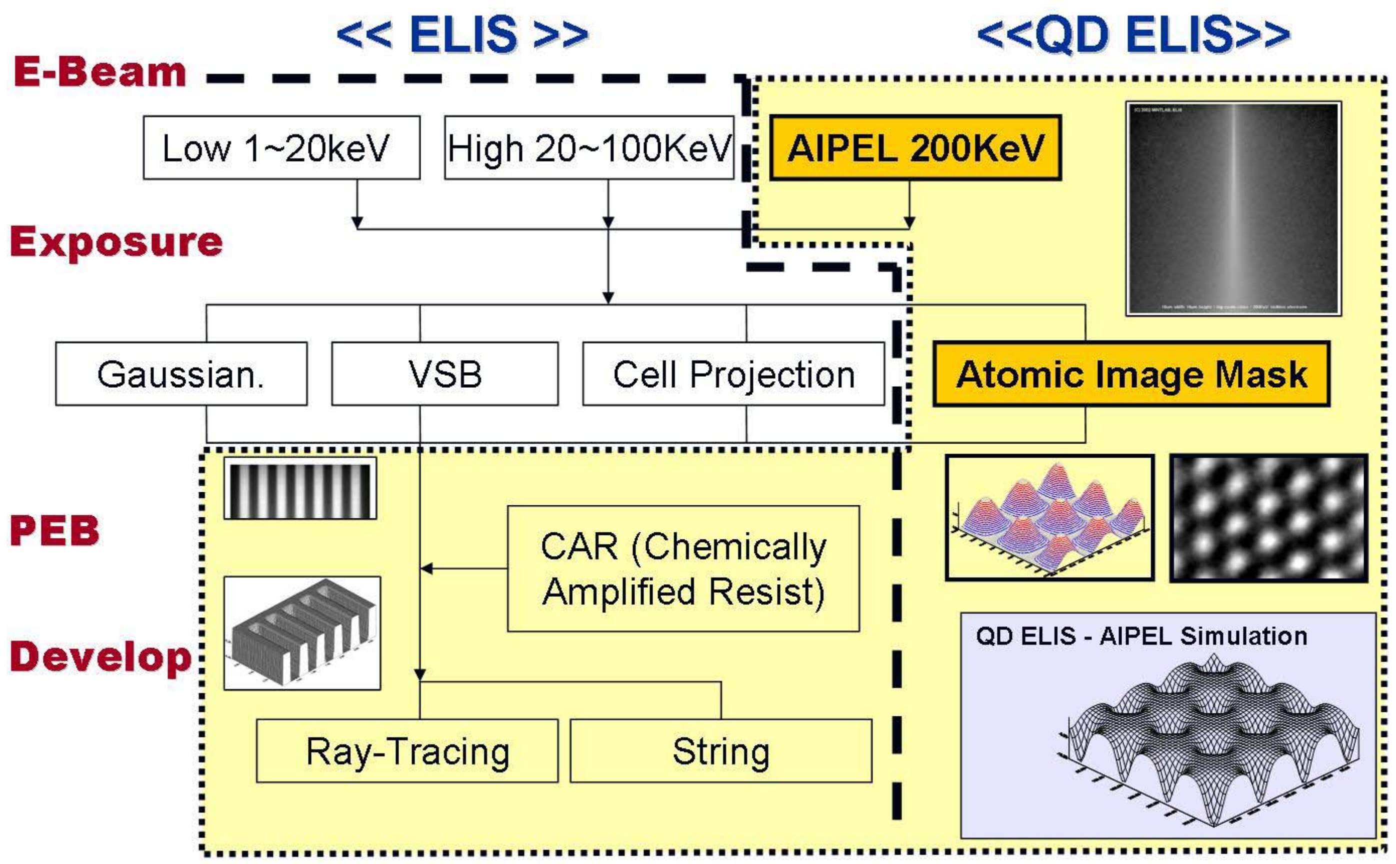
160^X



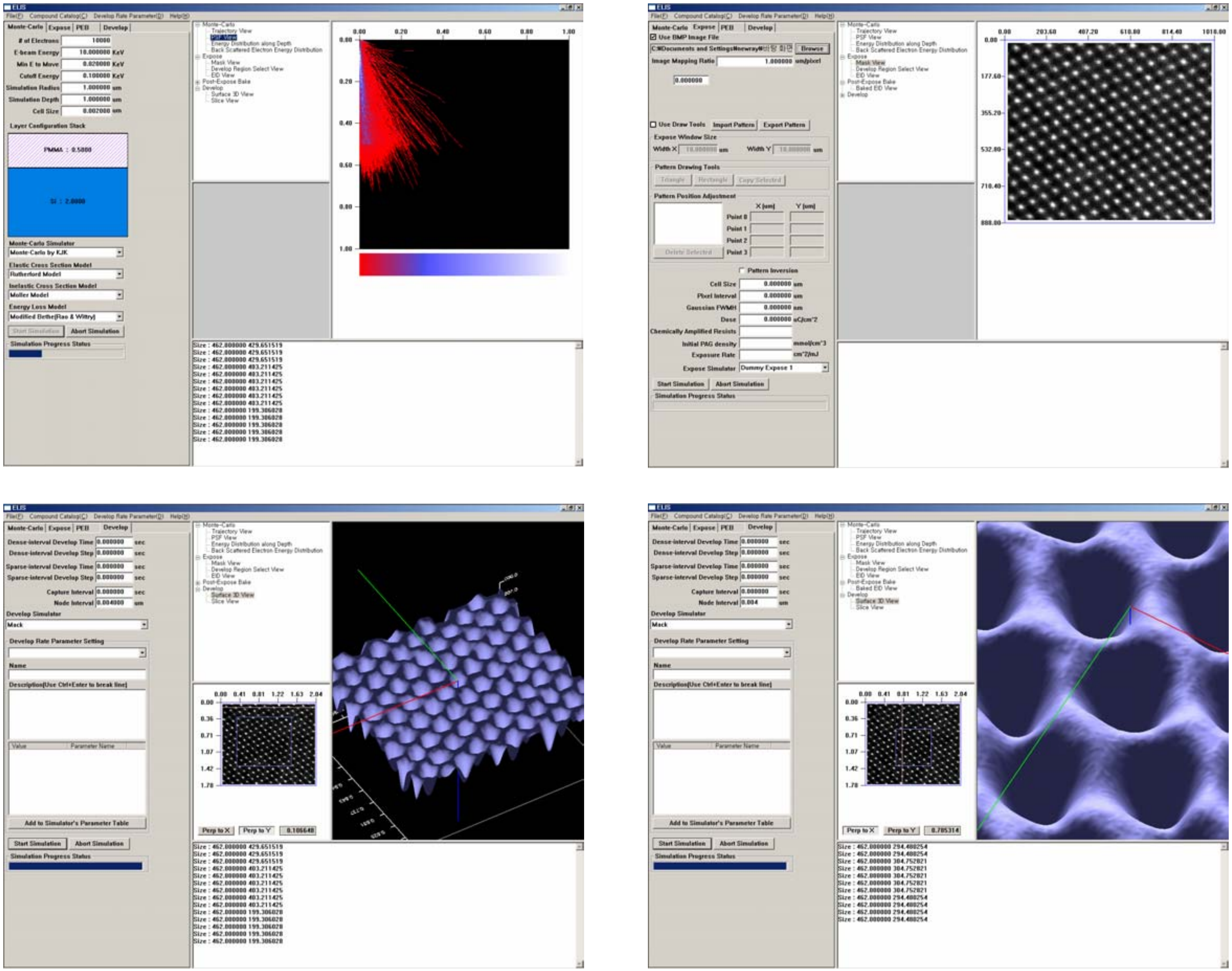
Resist : **HSQ**, Dose : 1260 μC/cm^2, Exposure time : 1.5 sec

AIPEL Simulation

- ELIS (E-Beam Lithography Simulator)



ELIS simulator



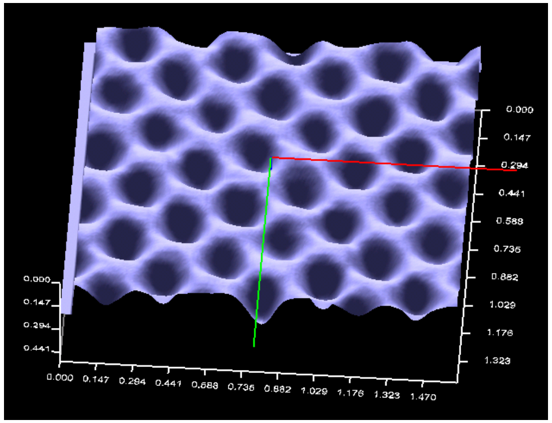
Simulation results

Mask image

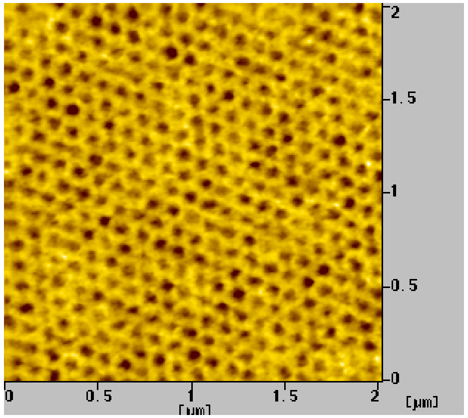
Mag. X300

ZEP520A

Simulation results



Experimental results

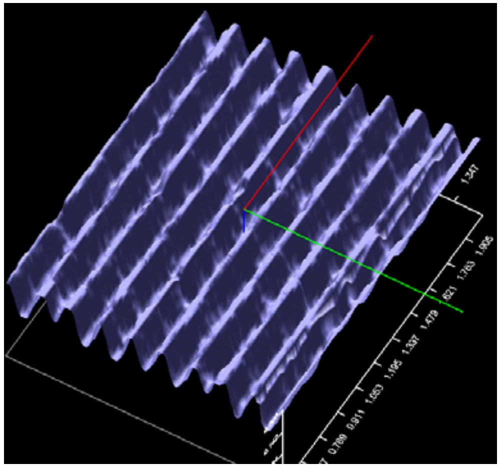


Mask image

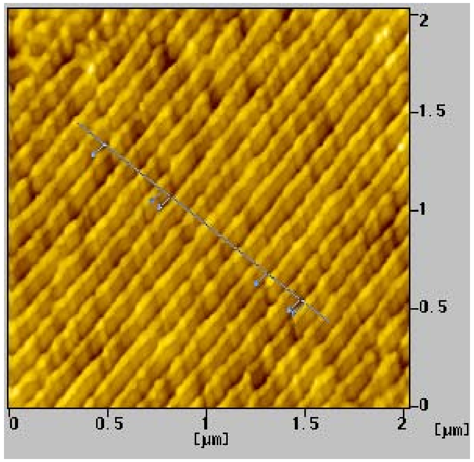
Mag. X300

ZEP520A

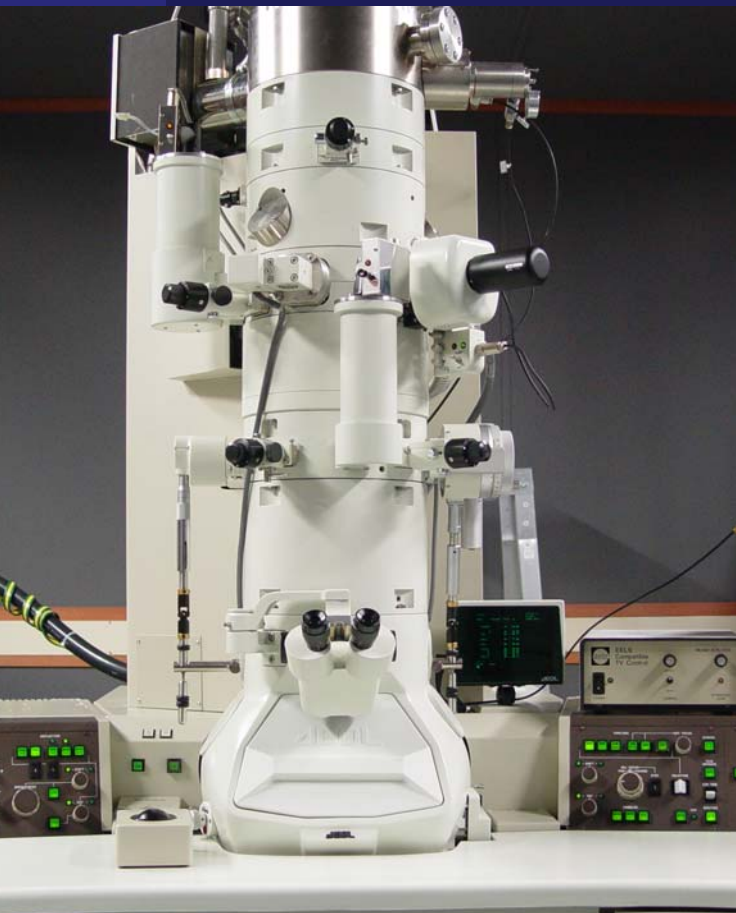
Simulation results

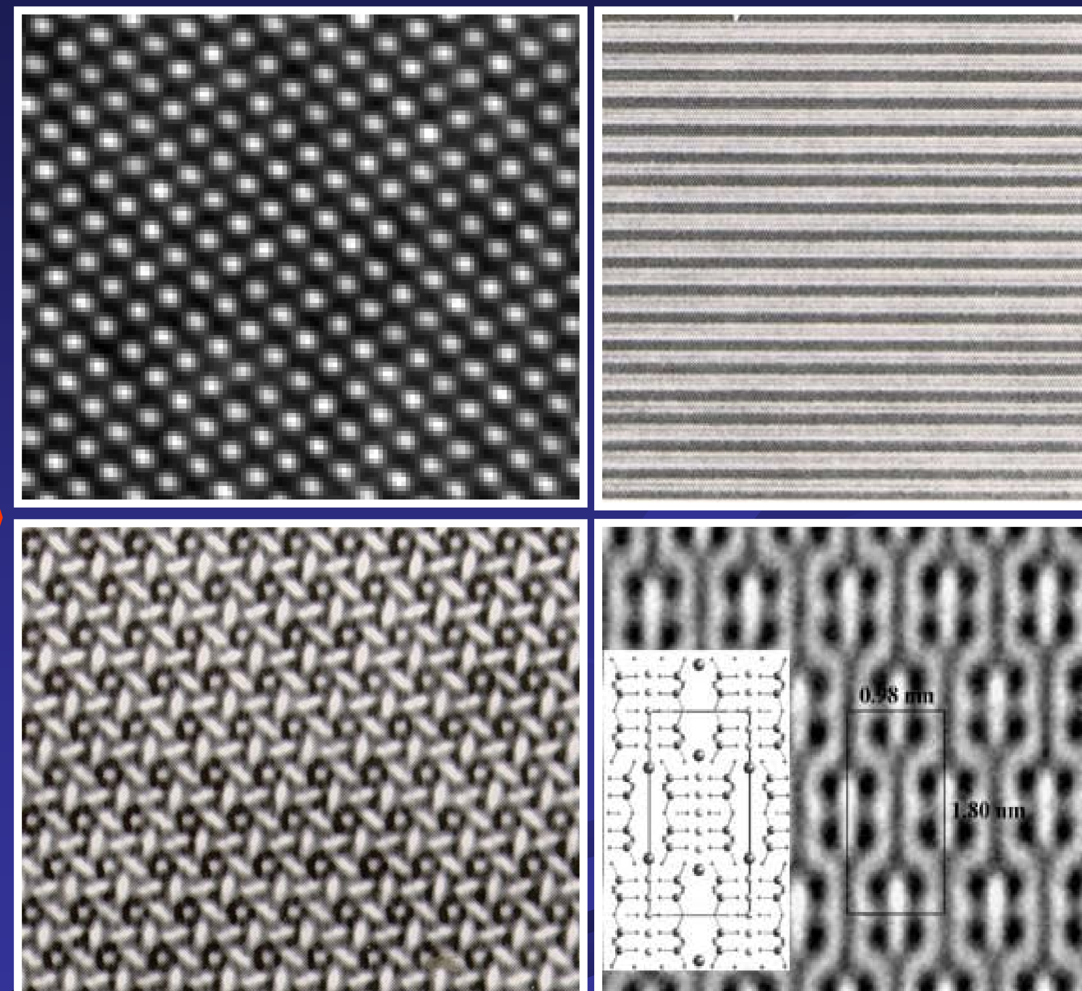


Experimental results

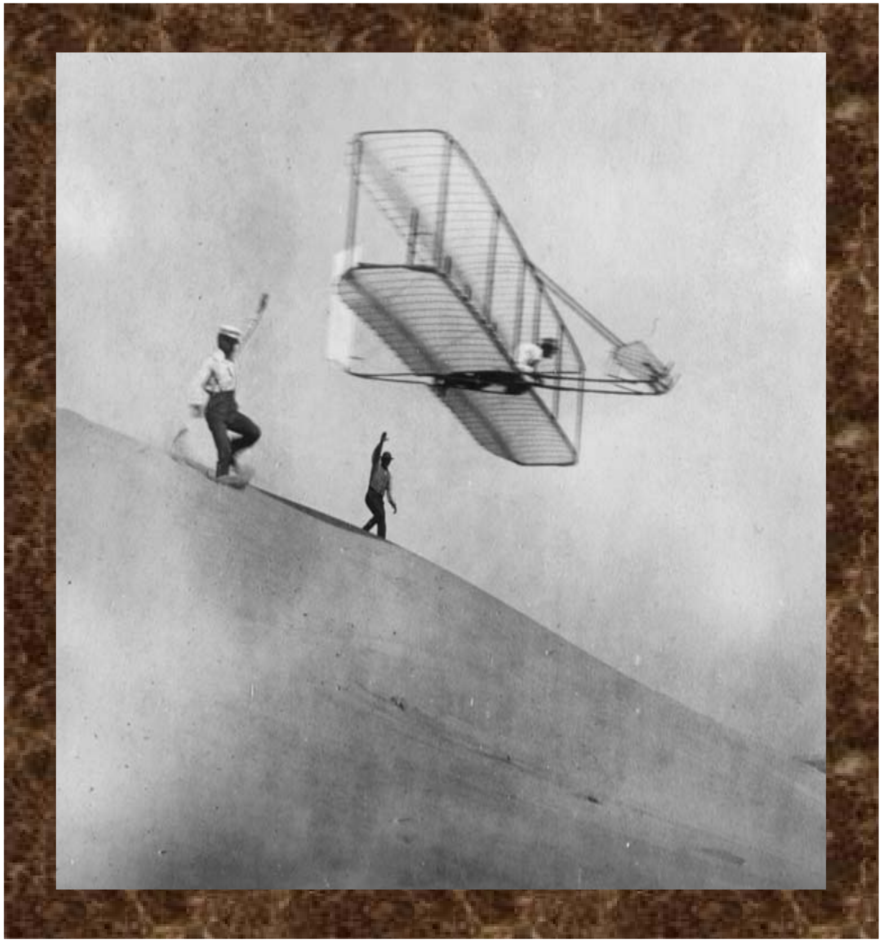


Patterns from Nature





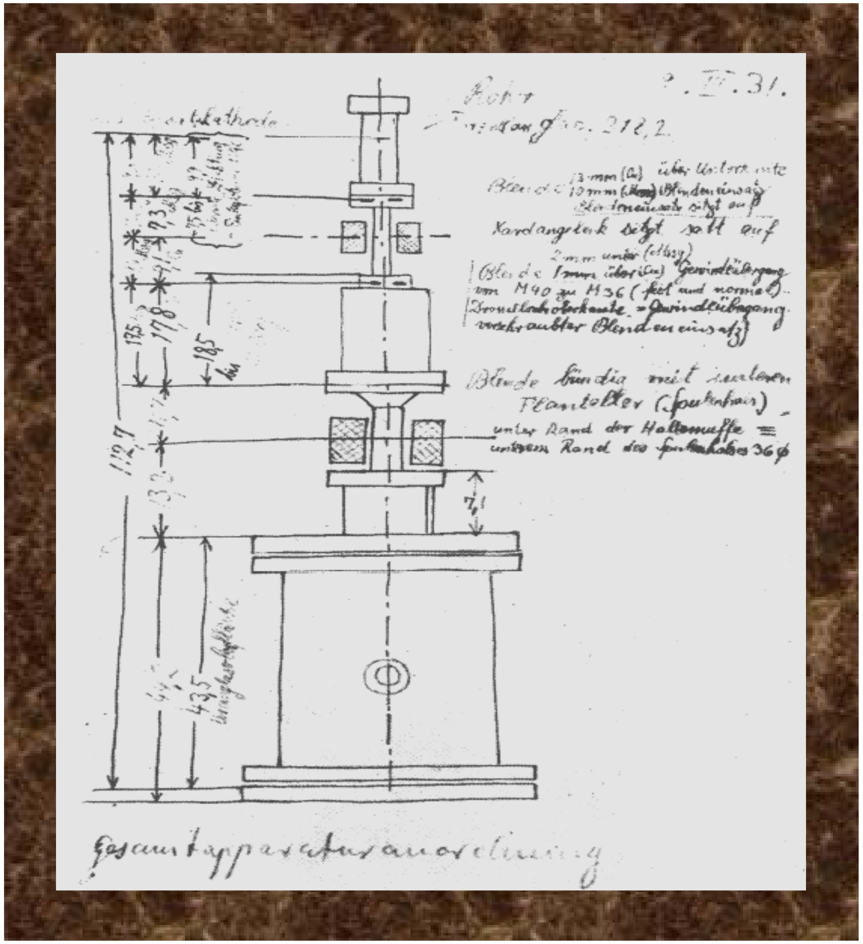
The First Flight, Wright brothers (1903)



Flight time ; 12 sec

Flight distance ; 36 m

The First Electron Microscope, Ruska (1931)



Magnification ; X 17.5

Accelerating voltage ; 50 kV

Acknowledgement

Tera-Level Nanoelectronics Program (Dr. Jo-Won Lee)

Nano Fabrication Laboratory at SNU:

Byung-Sung Kim (Ph.D. AIPEL project initiation)

Hyun-Mi Kim (Post doc. New mask process)

Hyo-Sung Lee (AIPEL process improvement)

Jung-Sub Yi (Mix and match process)

Kyung-Bae Jin (Etch process)

Elecron-Beam Lithography Simulation at SNU:

Prof. Kuk-Jin Jun

KRISS (Dr. Yang-Koo Cho): Stage Design

JEOL. Ltd.; Yoshihiro Arai