Nanofabrication process using electron beam lithography

(AIPEL; Atomic Image Projection E-beam Lithography)

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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

1-D

0-D

$10^{22} \sim 10^{23}$ #/cm$^3$

3-D Bulk

~ nm

~ nm

A unit

Atom
Nano Fabrication Laboratory

**Top-down approach**
- E-beam lithography
- Nanoimprint Technology
- Probe technology

**Bottom-up approach**
- Probe technology
- Colloid process & self-assembly
- Thin film technology
- Gas phase nucleation
### E-Beam Lithography: Serial Type

<table>
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<tr>
<th>System Overview</th>
<th>Conventional e-beam litho.</th>
<th>Multi e-beam lithography</th>
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<tr>
<td>Resolution</td>
<td>~ 10 nm</td>
<td>~ 40 nm</td>
</tr>
<tr>
<td>Throughput</td>
<td>1.4 hr (100 cm²)</td>
<td></td>
</tr>
<tr>
<td>Mask</td>
<td>No mask</td>
<td></td>
</tr>
<tr>
<td>Advantage</td>
<td>Resolution</td>
<td>Throughput</td>
</tr>
<tr>
<td>Issue</td>
<td>Throughput</td>
<td>Complex optics</td>
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### E-beam Projection Lithography: Projection Type

<table>
<thead>
<tr>
<th>Method</th>
<th>Throughput</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>SCALPEL</td>
<td>25 (300 mm wafers / hr)</td>
<td>&lt; 100 nm</td>
</tr>
<tr>
<td>PREVAIL</td>
<td>20 (300 mm wafers / hr)</td>
<td>&lt; 100 nm</td>
</tr>
<tr>
<td>LEEPL</td>
<td>40 (300 mm wafers / hr)</td>
<td>&lt; 100 nm</td>
</tr>
</tbody>
</table>

- **Throughput**
  - SCALPEL: 25 (300 mm wafers / hr)
  - PREVAIL: 20 (300 mm wafers / hr)
  - LEEPL: 40 (300 mm wafers / hr)

- **Resolution**
  - SCALPEL: < 100 nm
  - PREVAIL: < 100 nm
  - LEEPL: < 100 nm

- **Mask**
  - SCALPEL: Membrane mask
  - PREVAIL: Si stencil mask

- **Advantage**
  - Resolution
  - Throughput

- **Issue**
  - Throughput
  - Complex optics

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**Top-down approach; E-beam lithography**

**SCALPEL**
- (e-Lith, Lucent, Applied materials, ASML)
- Throughput: 25 (300 mm wafers / hr)
- Resolution: < 100 nm

**PREVAIL**
- (IBM, Nikon)
- Throughput: 20 (300 mm wafers / hr)
- Resolution: < 100 nm

**LEEPL**
- (LEEPL)
- Throughput: 40 (300 mm wafers / hr)
- Resolution: < 100 nm

**Advantage**
- Resolution
- Throughput

**Issue**
- Throughput
- Complex optics
Motivation
AIPEL (Atomic Image Projection E-beam Lithography)

1926, Schrodinger, Schrodinger equation
1928, Bethe, Dynamical diffraction theory
1931, Ruska & Knoll, Invented TEM
1936, 1st Commercial TEM (Siemens, Germany)
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 = \textbf{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

• 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

Richard P. Feynman

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 shining. 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
  \[ \text{OL} \rightarrow \text{IL1} \rightarrow \text{PL1} \rightarrow \text{OL2} \rightarrow \text{IL2} \rightarrow \text{PL2} \]
- Wafer stage where resist coated wafer can be inserted
  - A-stage: 4 mm x 17 mm wafer
  - B-stage: 25 mm x 25 mm wafer

Wafer stage
Modification of JEOL 2010F TEM

LENS & STAGE modification

Objective mini-lens
Intermediate lens 1
Intermediate lens 2
Objective lens
Patterning lenses
Wafer stage
2nd objective lens
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: \( \times 20 \sim \times 300 \)

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

- **2\(^{nd}\) 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
Collaboration with JEOL in JAPAN

Mr. Kim
“Hi, I am an AIPEL team leader of NFL.”

Dr. Arai
“Hello, I am 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

- $f_{OL} = 2.3$ (S+D) = 30
  6336 T Max. 1500 AT

- $f_{IL1} = 7080$ T Max. 3000 AT

- $f_{PL1} = 5$ (S+D) = 13.5
  3190 T Max. 5200 AT

- $f_{OL2} = 5$ (S+D) = 7
  3190 T Max. 5200 AT

- $f_{IL2} = 110$ T Max. 3000 AT

- $f_{PL2} = 62$ T Max. 2000 AT

- Distance: 435 mm
AIPEL lens system

✓ Newton’s Lens Equation

\[ \frac{1}{a} + \frac{1}{b} = \frac{1}{f} \]

\[ M = \left| \frac{b}{a} \right| \]

✓ Magnetic Lens

\[ f \left( \frac{S+D}{2} \right) = \frac{25}{(Ni)^2/U^*} + 0.0125 \left( (Ni)^2/U^* \right) \]

\( S \): 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


\[ \delta_s M = \alpha' S; \quad S = \frac{M}{\alpha'} = \frac{\delta_s M^2}{\alpha_o} \]

- \( \delta_s \): resolution
- \( \alpha_o \): beam semi-convergence angle
- \( M \): magnification

In TEM,

\( M=100,000 \) times, \( \alpha_o = 10 \) mrad, \( \delta_s = 0.3 \) nm

Depth-of-focus (S) = 300 m

In AIPEL,
Depth-of-focus at wafer stage

- Patterning condition for HSQ
- Patterning condition for ZEP520A

Depth-of-focus (mm) vs. Patterning magnification (times)
## AIPEL system specification

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

**AIPEL System Installation in SNU**

*Nano Fabrication Laboratory*
AIPEL mask preparation

I. TEM specimen type

1. Si (110) single crystal wafer
   - Thickness: 500 µm

2. Cutting and grinding
   - Thickness: < 100 µm

3. Disc cutting
   - Diameter: 3 mm

4. Dimpling
   - Depth: < 30 µm

5. Ion Milling
   - Ion beam: < 10 nm

II. SOI wafer type

- SOI wafer
  - Si (110) (~300 nm)
  - SiO₂
  - Si (110) substrate

- Oxidation

- HF dip

- Meshed Cu grid
Electron signal from AIPEL mask

- Dose distribution modeling

MTF = \[
\frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{D_{\text{max}} - D_{\text{min}}}{D_{\text{max}} + D_{\text{min}}} = 0.25
\]

When MTF is 0.25,

\[D_{\text{max}} = 1.366 \times D_{\text{exposure}}\]

\[D_{\text{min}} = 0.819 \times D_{\text{exposure}}\]
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 µC/cm², 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: $180^\times$, Pitch 65nm

Resist: HSQ,
Dose: 1039 $\mu$C/cm$^2$,
Exposure time: 1.2 sec
AIPEL patterning; Experimental results (HSQ)

Dot patterns: $160^x$, Pitch 55nm

- Resist: HSQ,
- Dose: 1263 $\mu$C/cm$^2$,
- Exposure time: 1.5 sec

Pattern image on resist

Mask image
AIPEL patterning; Experimental results (HSQ)

Dot patterns: $140^x$, Pitch 45nm

Resist: HSQ,
Dose: 1488 $\mu$C/cm$^2$,
Exposure time: 1.6 sec
AIPEL patterning; Experimental results (HSQ)

Dot patterns: 120x, Pitch 40nm

Resist: HSQ,
Dose: 1416 µC/cm²,
Exposure time: 1.5 sec

Pattern image on resist
AIPEL patterning; Experimental results (HSQ)

Dot patterns: $100^x$, Pitch 35nm

Resist: HSQ,
Dose: 1260 $\mu$C/cm$^2$,
Exposure time: 1.5 sec
AIPEL patterning; Experimental results (Si$_3$N$_4$ 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$_3$N$_4$ mask)

Line patterns: 120x, Pitch 90nm

Resist: HSQ, Dose: 1260 $\mu$C/cm$^2$, Exposure time: 1.5 sec
AIPEL patterning; Experimental results (Si$_3$N$_4$ mask)

Line patterns: $100^x$, Pitch 70nm

Resist: HSQ, Dose: 1260 $\mu$C/cm$^2$, Exposure time: 1.5 sec
AIPEL patterning; Experimental results (Si$_3$N$_4$ mask)

Complicate (6-fold symmetry) patterns: $160^\times$ (HSQ)

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

- ELIS (E-Beam Lithography Simulator)

E-Beam
- Low 1~20keV
- High 20~100KeV

Exposure
- Gaussian
- VSB
- Cell Projection

PEB

Develop
- CAR (Chemically Amplified Resist)
- Ray-Tracing
- String

AIPEL 200KeV

Atomic Image Mask

QD ELIS - AIPEL Simulation
ELIS simulator
Simulation results

Mask image

Simulation results

Experimental results

Mag. X300
ZEP520A

Mask image

Simulation results

Experimental results

Mag. X300
ZEP520A
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

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- Hyo-Sung Lee (AIPEL process improvement)
- Jung-Sub Yi (Mix and match process)
- Kyung-Bae Jin (Etch process)

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