Electron Beam Lithography

Marco Salerno
Outline

• general lithographic concepts
• EBL extensions to SEM
• SEM imaging issues
• EBL stage motion & calibration
• EBL exposure & specific issues
Types of conventional lithography

- **Photo-** (UV-vis) 
  \[ \lambda = 0.2-0.4 \, \mu m \]

- **EUV** 
  \[ \lambda = 40-5 \, \text{nm} \] (Intel)

- **XRL** 
  \[ \lambda = \frac{h}{p} \] 
  \( \lambda(E), \ [\text{nm, eV}] \) 
  \| 
  \hline
  \( \gamma \) & 1240 / \( E \) \\
  \( e \) & 1.23 / \sqrt{E} \\
  \hline

- **EBL** 
  \( \lambda(\text{res}) \) 
  (30 nm res)

- **Ion-** 
  SCALPEL (Lucent Tech) 
  - 2 membrane mask (hi and low e diffusion) 
  - scaled down 
  (20 nm res)
Technical setup of EBL tools

Source: SPIE Handbook of Microlithography
www.cnf.cornell.edu/SPIEBook/SPIE1.HTM
Types of Electron Beam Columns

Typical Electron Beam Column

- no e- cross over $\rightarrow$ no Boersch-effect (additional energy spread)
- beam booster voltage of $8 \text{ kV}$ for $E<20 \text{ kV}$ (+ final retardation) $\rightarrow$ no stray field effects
- sample is not part of the column e-optics $\rightarrow$ feels low em field (ok for e.g. magnetic samples)
good in EBL means good in SEM!

adjust alignment – astigmatism by wobbling in-out of focus
Focussing - contamination dots

( far – but not too much far – from the region of exposure: 0.5-1 mm)
Fundamental rule for SEM imaging

Take always the LOW MAG images FIRST!!!
Types of coordinate systems

1. Stage
   - $(X,Y)$

2. Sample
   - $(U,V)$ - global
   - $(u,v)$ - local

3. Drawing
   - $(u,v)$ - local
   - repeated in position list: SPL

Beam:
- has to move according to $(u,v)$
- zoom, shift, rotation in both axis
- no specific labeling
Coordinate Transformations 1

Sample \((U,V)\) ↔ Transformation ↔ Drawing \((u,v)\)

Working area = area in layout used during overall exposure, \(WA \leq \text{(CAD) Layout}\)

- **case 1:** \(WA = \text{Complete Layout}\)
  - Complete Layout

- **case 2:** \(WA = \text{Part of Layout}\)
  - Part of Layout

- **case a:** \(WF = WA\)
  - \(WF = WA\)

- **case b:** \(WF < WA\)
  - \(WF < WA\)

Write Field = area in WA used in different exposure steps, \(WF \leq WA\)

\((U,V)\) coordinates (in SPL) = center of the first WF
Coordinate Transformations 2

Sample (U,V) — Transformation — Beam (zoom, shift, rot.)

necessary to avoid **Stitching** problems, e.g.: 

...why?

→ wrong beam movement, 
new calibration required
Self calibration technique using a particle and the stage: its motion assumed perfect, on nm scale

Procedure:
- choose WF
- find dust particle
- choose a point on it & move it to middle of image
Procedure:
- move stage so that particle appears in next corner of write field
- take small image with SEM
- measure offset

Coordinate Transformations 2

2. Sample (U,V) → Transformation → 4. Beam (zoom, shift, rot.)
Procedure:
- move stage so that particle appears in next corner of write field
- take small image with SEM
- measure offset
Transformations

2. Sample \((U,V)\) ← Transformation → 4. Beam (zoom, shift, rot.)

Procedure:

- move stage so that particle appears in next corner of write field
- take small image with SEM
- measure offset, calculate rotation, zoom
Stage Movement methods

moving stage

stationary stage

versus

stripes

fields

write “on-the-fly”

step & write
Writing methods

round (Gaussian) beam versus shaped beam

vector scan versus raster scan
Settling and flyback time

Settling time = waiting period at beginning of each element

Flyback time = waiting period between lines.

Flyback time = settling time $\times$ flyback factor
## Different Strategies

<table>
<thead>
<tr>
<th>company</th>
<th>beam</th>
<th>scan mode</th>
<th>stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raith</td>
<td>gaussian</td>
<td>vector</td>
<td>fixed</td>
</tr>
<tr>
<td>Etec</td>
<td>gaussian</td>
<td>raster</td>
<td>moving</td>
</tr>
<tr>
<td>Leica</td>
<td>shaped</td>
<td>---</td>
<td>fixed</td>
</tr>
</tbody>
</table>
1st Strategy (Raith)

gaussian beam, vector scan, fixed stage

- Fast writing of sparse patterns (unwritten areas are skipped)
- Easy dose variation from shape to shape
  - Settlement time & hysteresis
  - Calibration
  - Overhead time caused by stage settling

Apps: nano litho, R&D, …
2\textsuperscript{nd} Strategy (Etec)

\textbf{gaussian beam, raster scan, moving stage}

\begin{itemize}
  \item \textbf{stage motion}
  \item \textbf{beam motion}
\end{itemize}

+ very simple
+ very repeatable
  \begin{itemize}
    \item calibration possible
  \end{itemize}
  \begin{itemize}
    \item sparse patterns take as long as dense patterns
    \item difficult to adjust dose during writing
  \end{itemize}

Apps: mask making

(e.g. used by MEBES (Etec Systems Inc.))
3rd Strategy (Leica)

shaped beam, moving stage

+ ≈ 10 x faster than equivalent gaussian beam machines
– extremely complex electron optical column
– complicated calibration routines
– resolution and focus varies with shape size

Apps: mask making, advanced chip development

~ Gaussian vector scan, but: an entire rectangle (up to 2x2 µm²) in a single "flash"
Coating or stripping step

Spin coating

Exposure

Developing

Etching

Remover

Lift-Off

Pattern Transfer

Remover

After x process steps

substrate

resist

Wafer

metal
Resist polarity

\[ \text{Resist polarity} \rightarrow \text{lower MW} \rightarrow \text{more soluble} \]

\[ \text{Resist polarity} \rightarrow \text{higher MW} \rightarrow \text{less soluble} \]
EBL resist contrast

Hurter-Driffield contrast curve (1890)

Contrast $\gamma = [\log_{10}(D_1) - \log_{10}(D_T)]^{-1}$

High contrast:  
+ Steeper side walls  
+ Greater process latitude  
+ Better resolution (not always)  
+ Less sensitivity to proximity effects

Low contrast:  
+ 3d lithography

COP
copolimero
glicedil
metacrilato-
etil acrilato
(neg.)

PMMA
PoliMetil-
MetAcrilato
(pos.)
Which resist for which application?

• positive or negative: depends on which will give a minimum area to be exposed

• literature and resist suppliers for resist performance with respect to e.g. resolution, sensitivity, etching stability

• check suitability for your lab, e.g. required baking steps and chemicals

• avoid Chemically Amplified Resists because of the critical Post Exposure Bake

• make tests with positive resist, as the same substrate can be used more times

⇒ use for example PMMA 950K
Forward scattering events

Properties
• very often
• small angles
• hence very inelastic
• generation of SE with a few eV
Properties

- occasionally
- large angles
- hence mainly elastic
- high kinetic energy, range of the PE
What leads to an exposure?

SE with few eV kinetic energy are responsible for most of the resist exposure.

Hence **forward scattering** within the resist is responsible for **exposure**.

And **backscattering** is responsible for **exposure far from incidence**.
Effect of Voltage on Dose

- Resist sensitivity increases when one goes down in kV.
- Can do faster exposures (but may lose resolution!)

At small kVs one should keep an eye on the penetration depth.

number of electrons $\propto T_{dwell} \times I_{beam}$

**Area Dose**

$$\text{Area Dose} = \frac{I_{beam} \cdot T_{dwell}}{s^2}$$  Unit is $\mu$As/cm$^2$

**Line Dose**

$$\text{Line Dose} = \frac{I_{beam} \cdot T_{dwell}}{s}$$  Unit is pAs/cm

**Dot Dose**

$$\text{Dot Dose} = I_{beam} \cdot T_{dwell}$$  Unit is pAs
Important note:
The used exposure step size has to be fit to the structure definition in the layout!

Example:
Exposure of gratings:
step size (s) does not match grating period (g)

\[
e.g. \ s = 8 \text{ nm}, \ g = 10 \text{ nm}
\]
## Dose table for PMMA (950k)

<table>
<thead>
<tr>
<th></th>
<th>10 kV</th>
<th>20 kV</th>
<th>30 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Areas</strong></td>
<td>100 µC/cm²</td>
<td>200 µC/cm²</td>
<td>300 µC/cm²</td>
</tr>
<tr>
<td><strong>Lines</strong></td>
<td>300 pC/cm</td>
<td>600 pC/cm</td>
<td>900 pC/cm</td>
</tr>
<tr>
<td><strong>Dots</strong></td>
<td>0.1 pC</td>
<td>0.2 pC</td>
<td>0.3 pC</td>
</tr>
</tbody>
</table>

(developer: MIBK + IPA, 1:3)

Above values are good starting points.

Best way to get optimum results:

→ **Dose Scaling:**

SPL Dose Factor 0.5 – 5, (for Dots: 0.1 – 10)
Dose scaling

test structures
with different Dose Factors

(or e.g. taxi-checkers)
## Influence of operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration</strong></td>
<td>+ Clear surface structures</td>
<td>+ Higher resolution</td>
</tr>
<tr>
<td>Voltage</td>
<td>+ Less damage</td>
<td>– Unclear surface structures</td>
</tr>
<tr>
<td>(penetration</td>
<td>+ Less charge up</td>
<td>– More edge effects</td>
</tr>
<tr>
<td>depth)</td>
<td>+ Less edge effect</td>
<td>– More sample damage</td>
</tr>
<tr>
<td></td>
<td>– Lower resolution</td>
<td><em>(heating)</em></td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>+ Higher resolution</td>
<td>+ Smooth image</td>
</tr>
<tr>
<td><em>(I₀</em>beam)</td>
<td>+ Less damage <em>(heating)</em></td>
<td>+ Good Signal to noise</td>
</tr>
<tr>
<td></td>
<td>+ Larger depth of focus</td>
<td>– More damage <em>(heating)</em></td>
</tr>
<tr>
<td></td>
<td>– Grainy image</td>
<td>– Lower resolution</td>
</tr>
<tr>
<td><strong>WD</strong></td>
<td>+ Higher resolution</td>
<td>– Smaller depth of focus</td>
</tr>
<tr>
<td></td>
<td>– Smaller depth of focus</td>
<td></td>
</tr>
</tbody>
</table>

*(A guide to Scanning Microscope Observation, Jeol web page 1999)*
Resolution limits

beam:
- Thick resists (forward scattering)
- Thin resists (~0.5 nm by diffraction, de Broglie wavelength)
- SE range (5-10 nm)

resist:
- Polymer size (5-10 nm)
- Chemically Amplified Resists (acid diffusion ~50 nm)

In practice, best achievable resolution:
in polymer resists ~ 20 nm
(in inorganic resists, currently impractical, ~ 5 nm)

Ultra high resolution in PMMA (45 nm thickness): 16 nm line width (in resist)
Design must be adapted to dose

AZ PN114 (CAR negative)
Dense Lines (Distance 3x Linewidth)

Johannes Kretz, Infineon, Munich
Proximity effect

e trajectories for:
• 1.5 μm thick resist on Si wafer
• 50 trajectories, 25 keV beam energy

(Kyser, Viswanathan, "Monte Carlo simulation of spatially distributed beams in EBL", J. Vac. Sci. Technol. 12(6), 1305 ('75))
Proximity Effect Correction software

Each pattern element needs a different dose - here shown by colors -
Conclusions

• still a Top-down approach

• planar technique: possibly repeated, but no real 3-D outcome

• carries all limitations of SEM: slow, invasive, need vacuum, problems with insulators, ...

• ok for research, prototyping, R&D, not for mass production