Lithography-patterning-fidelity-aware electron-optical system design optimization by using COMSOL MULTIPHYSICS with MATLAB

藉由COMSOL MULTIPHYSICS結合MATLAB來達成基於圖案製作準確度之電子透鏡系統最佳化設計

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Outline

- Introduction to Lithography
- Traditional Electron-Optical System (EOS) Design Optimization
- Proposed Patterning-fidelity-aware Method
- Conclusions
VLSI Process Flow

1. Create n-well regions and channel-stop regions
2. Grow field oxide and gate oxide (thin oxide)
3. Deposit and pattern polysilicon layer
4. Implant source and drain regions, substrate contacts
5. Create contact windows, deposit and pattern metal layer

http://lsiwww.epfl.ch/LSI2001/teaching/webcourse/ch02/ch02.html#2.2
Limitations of Optical Lithography Systems

- **Pro**
  - Higher throughput

- **Con**
  - Low-resolution operation

Electron beam lithography is required in 2015 and beyond.

Electron beam lithography has issue of low throughput.

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**Optical lithography**

- **Illumination system** $J(x,y)$
- **Condenser pupil**
- **Condenser lens**
- **Projection system** $K(x,y)$
- **Projection pupil**
- **Projection lens**
- **Resist**

**Light source**

**Intensity** $I(x,y)$

**Mask** $f(x,y)$

**Projection system** $K(x,y)$

**Resist**

**Electron beam lithography is required in 2015 and beyond.**

**Electron beam lithography has issue of low throughput.**

**Ref:** R. F. Pease *et al.*, 1997 [1]

**Ref:** ITRS, 2011 [2]
Single- and Multiple-Electron-Beam Lithography Systems

Single-electron-beam lithography

- Electron Gun
- Source Lens
- Blanker
- Lens
- Limiting Aperture
- Stigmator
- Deflector
- Objective Lens
- Wafer

Refs: H. Xiao, 2001 [3]

Pros
- High-resolution operation
- Maskless operation

Cons
- Lower throughput
- Coulomb effect

Multiple-electron-beam lithography

- Retain pros of single electron beam lithography system
- Higher throughput

Pros
- Higher structure complexity, especially in electron-optical systems (EOSs) due to multiple beam nature

Cons
- Higher structure complexity, especially in electron-optical systems (EOSs) due to multiple beam nature

Several countries have been seriously involved with research in electron-beam-direct-write systems.

The main goal of the NTU team is to seamlessly develop equipment, process, and software technologies for MEMS-based maskless e-beam exposure systems.
To ensure a successful EOS design, many factors have to be considered.
- Focusing properties (FPs)
- Patterning fidelity (PF)

In traditional EOS optimization flow, FPs are typical performance indices selected when optimizing the EOS design parameters.

However, the performance indices related to FPs may have no direct relation to lithography PF, which is judged by the quality of the developed resist patterns.

A new EOS design methodology which directly incorporates lithography PF metrics into the optimization flow is proposed.

S.-Y. Chen et al., 2011 [14]
## Parameters and Values of the Demonstration EOS and the Optimization Setting

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Abbreviations</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing between substrate and gate electrode</td>
<td>( H_g )</td>
<td>1 µm</td>
</tr>
<tr>
<td>Spacing between gate and focus electrodes</td>
<td>( H_f )</td>
<td>1 µm</td>
</tr>
<tr>
<td>Thickness of the gate electrode</td>
<td>( T_g )</td>
<td>0.64 µm</td>
</tr>
<tr>
<td>Thickness of the focus electrode</td>
<td>( T_f )</td>
<td>0.64 µm</td>
</tr>
<tr>
<td>Work distance</td>
<td>( WD )</td>
<td>100 µm</td>
</tr>
<tr>
<td>Radius of the emission top</td>
<td>( r )</td>
<td>15 nm</td>
</tr>
<tr>
<td>Height of the emission top</td>
<td>( h )</td>
<td>0.4 µm</td>
</tr>
<tr>
<td>Weight of the emission top</td>
<td>( b )</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>Voltage of the wafer</td>
<td>( V_w )</td>
<td>5000 V</td>
</tr>
<tr>
<td>Voltage of the tip</td>
<td>( V_t )</td>
<td>0 V</td>
</tr>
<tr>
<td>Wafer per hour</td>
<td>( wph )</td>
<td>1</td>
</tr>
<tr>
<td>Voltage of the gate</td>
<td>( V_g )</td>
<td>–</td>
</tr>
<tr>
<td>Voltage of the focus</td>
<td>( V_f )</td>
<td>–</td>
</tr>
<tr>
<td>Diameter of the gate</td>
<td>( D_g )</td>
<td>–</td>
</tr>
<tr>
<td>Diameter of the focus</td>
<td>( D_f )</td>
<td>–</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>( D_{\text{max}} )</td>
<td>10 µm</td>
</tr>
<tr>
<td>Minimum diameter</td>
<td>( D_{\text{min}} )</td>
<td>0.45 µm</td>
</tr>
<tr>
<td>Minimum current required (for 1 wph)</td>
<td>( I_{\text{min}} )</td>
<td>0.076 nA</td>
</tr>
<tr>
<td>Beam current</td>
<td>( I_b )</td>
<td>–</td>
</tr>
<tr>
<td>Beam spot size</td>
<td>( B_{\text{ss}} )</td>
<td>–</td>
</tr>
</tbody>
</table>

[Diagram of EOS and optimization setting]

- **Wafer** (Anode)
- **Oxide**
- **Metal**
- **Focus**
- **Gate**
- **SiO\(_2\)**
- **Tip**
Field Solver (COMSOL MULTIPHYSICS)

- **Field solver**
  - COMSOL Multiphysics™
- **Space dimension**
  - 2D axial symmetry
- **Numerical method**
  - Finite element method (FEM)
- **Multiple scale mesh**

**Initial values**
- Electron trajectory
- Electron spot size
- Structure

**Electron initial position**

**Solve field**

**Electron spot size**

**COMSOL MATLAB**
**Electron Trajectory Simulator (MATLAB)**

- **Lorentz equation** – Charged particles motion in fields
  - Based on the *particle dynamics* of electrons
    - Newton’s laws of motion: \[ F = ma \]
    - Lorentz force: \[ F = q[E + (v \times B)] \]
    - Lorentz factor:
      \[
      m = \gamma m_0, \quad \gamma = \frac{1}{\sqrt{1 - (v/c)^2}}
      \]
  - Take \( r \)-direction for example
    \[
    a_r = \frac{d^2r}{dt^2}, \quad ma = qE_r \quad \Rightarrow \quad \gamma m_0 \cdot \frac{d^2r}{dt^2} = qE_r
    \]
    \[
    \frac{d^2r}{dt^2} = \frac{qE_r}{\gamma m_0}, \quad \frac{d^2z}{dt^2} = \frac{qE_z}{\gamma m_0}
    \]
  - Second order differential equation
  - Method: Runge-Kutta Method (RK)

\( F \): force  
\( E \): electric field  
\( B \): magnetic flux density  
\( m \): mass  
\( m_0 \): static mass of an electron  
\( v \): velocity  
\( c \): speed of light  
\( \gamma \): Lorentz factor  
\( q \): electric charge of a particle  
\( a \): acceleration
Schema of Electron Trajectory

- Emission tip
  - Electrons evenly distribute on tip
  - Current density \( J \) vary with field \( E \)
- Electron trajectory vary with field
- Beam spot size \( B_{ss} \)
  - Beam current rise from 10% to 90% at wafer plane
- Wafer plane
  - 10,000 electrons are plotted according to the current density
  - Each electron has the same current

Ref: L. P. Muray et. al., 2006 [16]
Proposed Method to Determine Optimal EOS Design Parameters

\[ X_0 = \begin{bmatrix} D_g & D_f - D_g & V_g & V_g - V_f \end{bmatrix} \]
\[ = \begin{bmatrix} 1.5 \text{ \( \mu \text{m} \)} & (3.6 - 1.5) \text{ \( \mu \text{m} \)} & 90 \text{ V} & 116 \text{ V} \end{bmatrix} \]

\[ X_{wp} = \begin{bmatrix} \text{pixel size} & \text{dosage} \end{bmatrix} \]
\[ = \begin{bmatrix} 1 \text{ nm} & 70 \text{ \( \mu \text{C/cm}^2 \)} \end{bmatrix} \]

Minimize: \( B_{ss} \)

Subject to: \( X \leq \begin{bmatrix} D_{\text{max}} & D_{\text{max}} & V_g & V_g - V_f \end{bmatrix} \)
\[ X \geq \begin{bmatrix} D_{\text{min}} & D_{\text{min}} & 0 \text{ V} & 0 \text{ V} \end{bmatrix} \]
\[ D_f \leq D_{\text{max}} \]
\[ I_b > I_{\text{min}} \]
\[ \text{LER} \leq \text{PF\_value} \]

Where: \( X = \begin{bmatrix} D_g & D_f - D_g & V_g & V_g - V \end{bmatrix} \)

\[ \text{Objective: } \text{NMSE}_i(x, y) = \frac{\sum_{x=0}^{n-1} \sum_{y=0}^{m-1} [L(x, y) - R_i(x, y)]^2}{\sum_{x=0}^{n-1} \sum_{y=0}^{m-1} L(x, y)^2}, \quad i = 1, \ldots, p. \]

where \( L(x, y) \) is the drawn layout, and \( R_i(x, y) \) is the each simulated resist pattern.
Preliminary Simulation Results

- Simulation environment
  - COMSOL with MATLAB

- After optimizing the design parameters for the traditional EOS design, the developed resist pattern is shown in the red contour.
  - Its corresponding value of critical dimension (CD) is 26 nm.

- The developed resist pattern after applying the proposed pattern-fidelity-aware method is shown in the blue contour.
  - Its corresponding value of CD is 22.68 nm.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CD (nm)</th>
<th>Error percentage (%)</th>
<th>Gate CD control (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawn layout</td>
<td>22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Before opt.</td>
<td>26</td>
<td>18.18</td>
<td>4.0</td>
</tr>
<tr>
<td>After opt.</td>
<td>22.68</td>
<td>3.09</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Conclusions

- A new EOS design methodology that directly incorporates lithography PF metrics into the optimization flow has been proposed.

- The results indicate that the value of corresponding CD and the value of gate CD control are more suitable for the ITRS specifications than before.

- This methodology can also be applied to many multiple-beam systems such as PML2, MAPPER, and other electron beam case.
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References


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