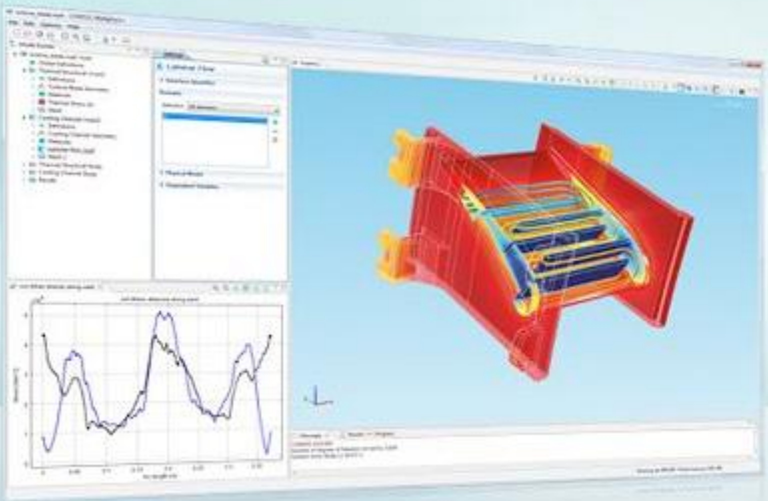


COMSOL CONFERENCE
Taiwan Taipei 2012

# 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真確度之電子透鏡系統最佳化設計

Presenter: Sheng-Yung Chen (陳勝勇)
Advisor: Prof. Kuen-Yu Tsai (蔡坤諭)
Dept. of Electrical Engineering, National Taiwan University

Nov. 2012

S.-Y. Chen, H.-T. Ng, S.-Y. Ma, H.-H. Chen, C.-H. Liu, and K.-Y. Tsai*,
*J. Vac. Sci. Technol. B* 29, 06FD04 (2011).

Nanoscale Design and Fabrication Systems Laboratory

# Outline

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

# VLSI Process Flow

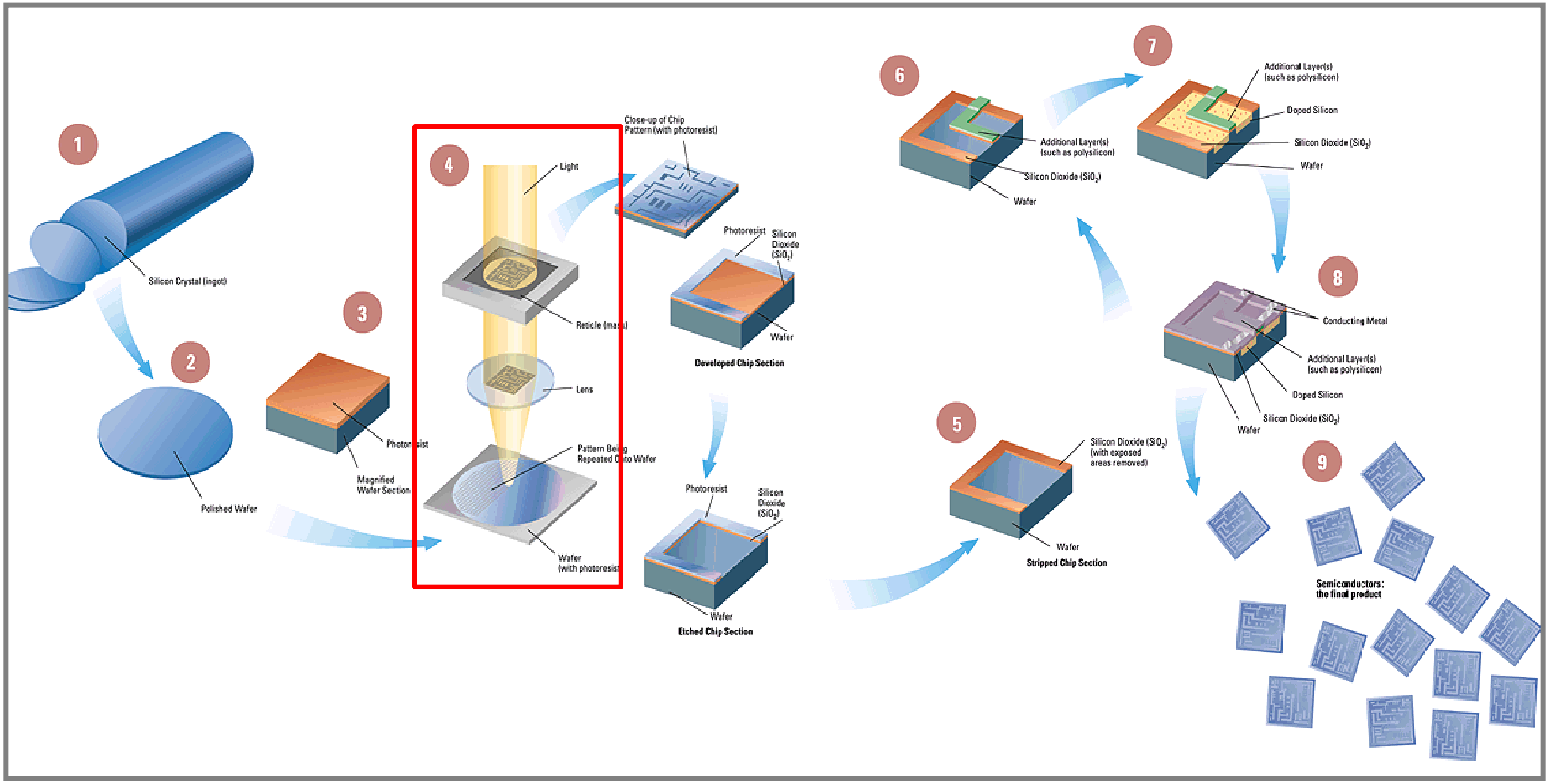
Create n-well regions and channel-stop regions

Grow field oxide and gate oxide (thin oxide)

Deposit and pattern polysilicon layer

Implant source and drain regions, substrate contacts

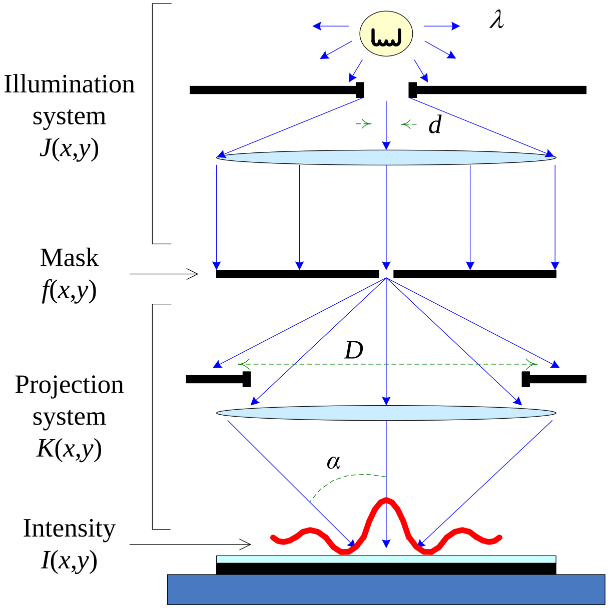
Create contact windows, deposit and pattern metal layer



http://lsiwww.epfl.ch/LSI2001/teaching/webcourse/ch02/ch02.html#2.2

# Limitations of Optical Lithography Systems

## Optical lithography

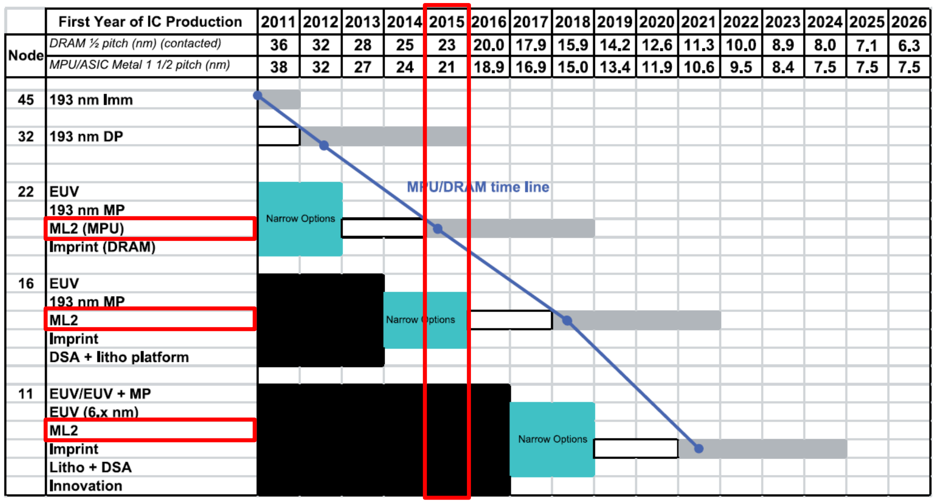


Ref: R. F. Pease *et al.*, 1997 [1]

- Pro
  - Higher throughput
- Con
  - Low-resolution operation

$$HP = k_1 \frac{\lambda}{NA}$$

## ITRS requirements



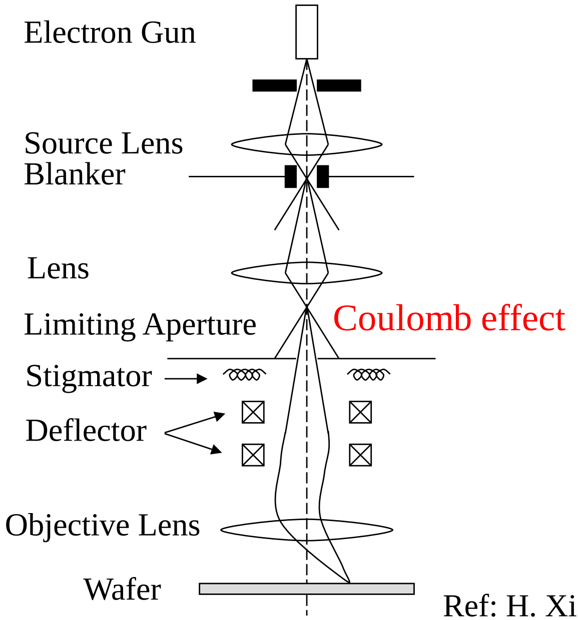
| Node | First Year of IC Production | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Node | *DRAM ½ pitch (nm) (contacted)* | 36 | 32 | 28 | 25 | 23 | 20.0 | 17.9 | 15.9 | 14.2 | 12.6 | 11.3 | 10.0 | 8.9 | 8.0 | 7.1 | 6.3 |
| | *MPU/ASIC Metal 1 1/2 pitch (nm)* | 38 | 32 | 27 | 24 | 21 | 18.9 | 16.9 | 15.0 | 13.4 | 11.9 | 10.6 | 9.5 | 8.4 | 7.5 | 7.5 | 7.5 |
| 45 | 193 nm Imm | | | | | | | | | | | | | | | | |
| 32 | 193 nm DP | | | | | | | | | | | | | | | | |
| 22 | EUV<br>193 nm MP<br>ML2 (MPU)<br>Imprint (DRAM) | | | | | | | | | | | | | | | | |
| 16 | EUV<br>193 nm MP<br>ML2<br>Imprint<br>DSA + litho platform | | | | | | | | | | | | | | | | |
| 11 | EUV/EUV + MP<br>EUV (6.x nm)<br>ML2<br>Imprint<br>Litho + DSA<br>Innovation | | | | | | | | | | | | | | | | |

Ref: ITRS, 2011 [2]

- Electron beam lithography is required in 2015 and beyond.
- Electron beam lithography has issue of low throughput.

# Single- and Multiple-Electron-Beam Lithography Systems

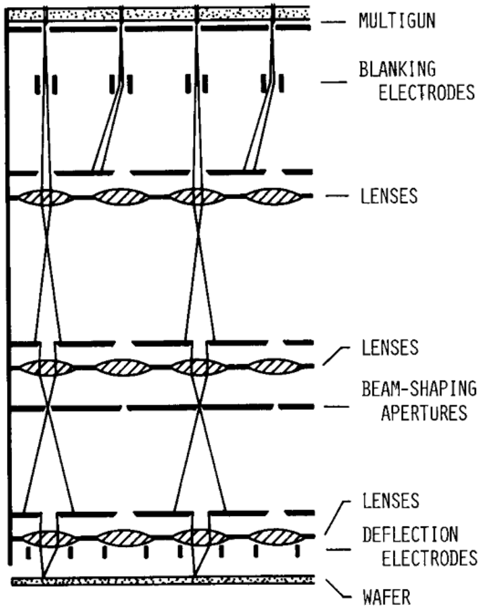
## Single-electron-beam lithography



Ref: H. Xiao, 2001 [3]

- Pros
  - High-resolution operation
  - Maskless operation
- Cons
  - Lower throughput
  - Coulomb effect

## Multiple-electron-beam lithography

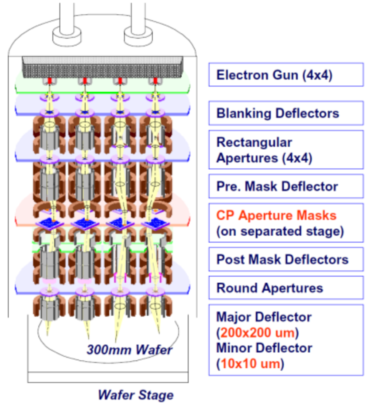


Ref: T. Sasaki, 1981 [4]

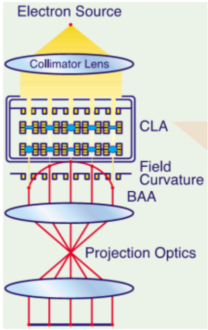
- Pros
  - Retain pros of single electron beam lithography system
  - Higher throughput
- Con
  - Higher structure complexity, especially in electron-optical systems (EOSs) due to multiple beam nature

# *Multiple-Electron-Beam–Direct-Write Lithography Systems*

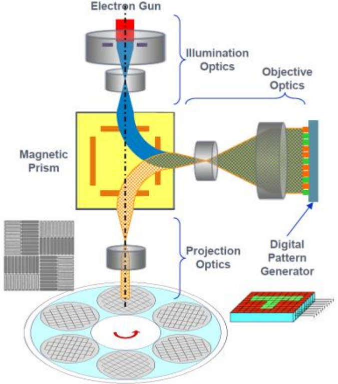
- Several countries have been seriously involved with research in electron-beam–direct-write systems.
- The main goal of the NTU team is to seamlessly develop equipment, process, and software technologies for MEMS-based maskless e-beam exposure systems.



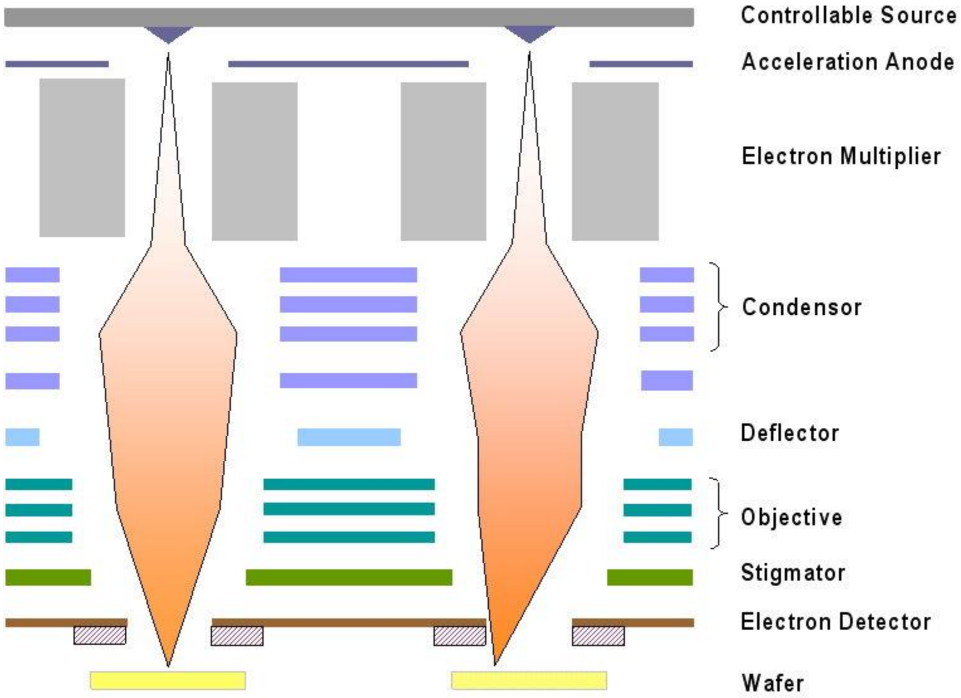
MCC, Advantest [5]



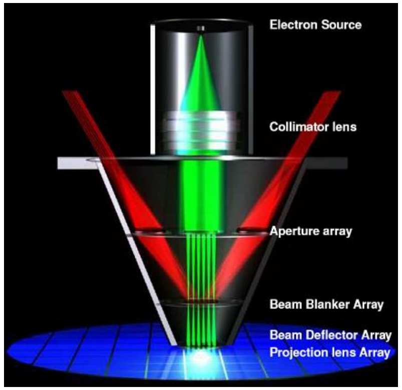
Canon [6]



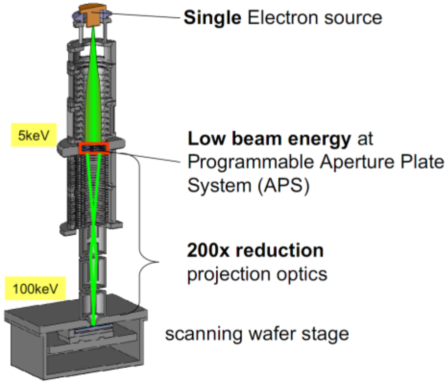
REBL, KLA [7]



MPML2, NTU [10]

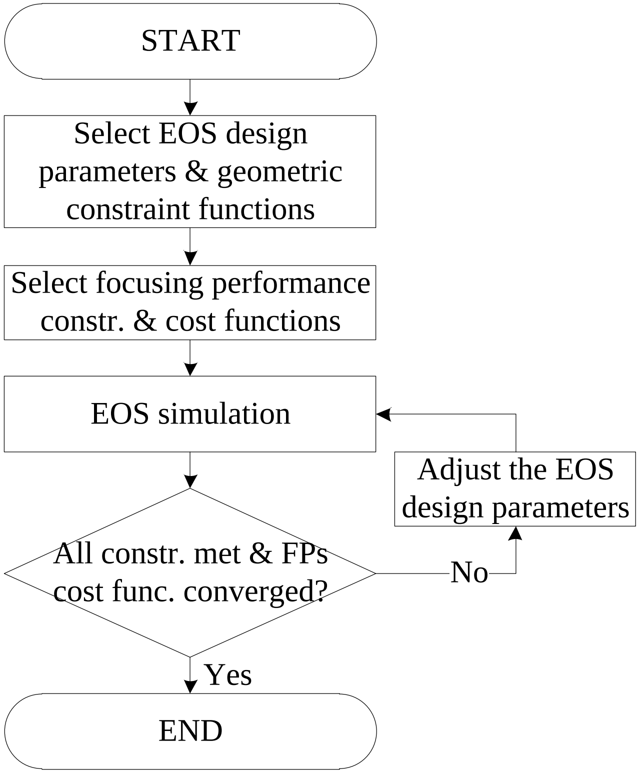


Mapper Lithography [8]



PML2, IMS [9]

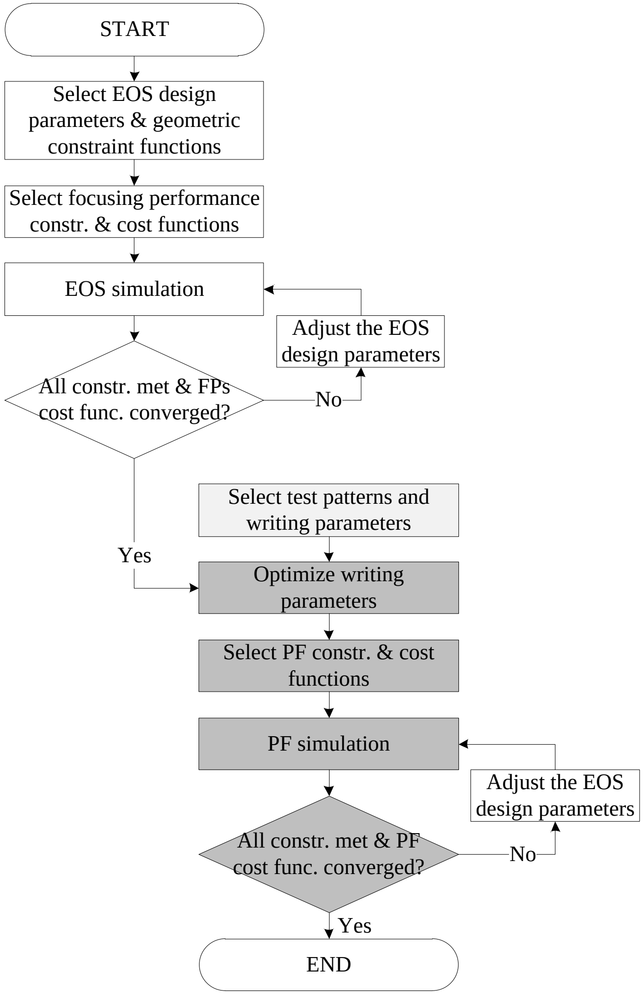
# Traditional EOS Design Optimization Flow



X. Yang *et al.*, 2002 [11], 2004 [12], 2007 [13]

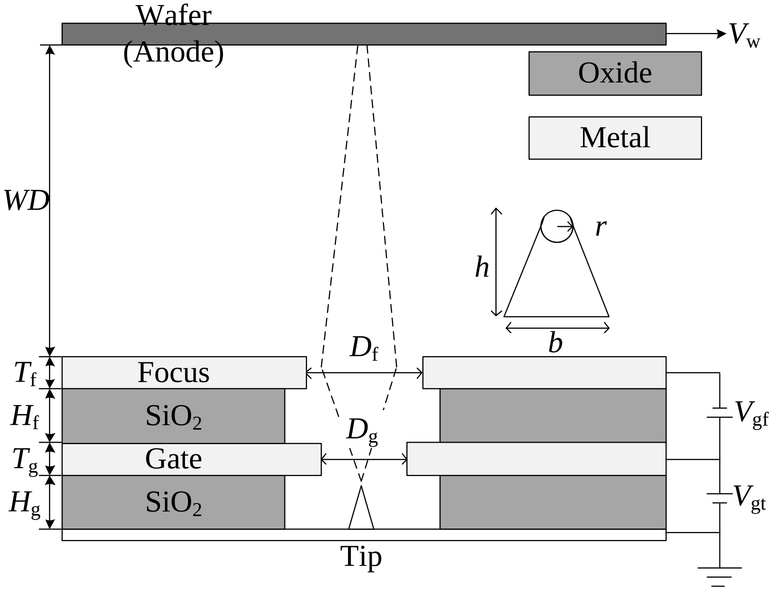
- To ensure a successful EOS design, many factors have to be considered.
  - Focusing properties (FPs)
  - Patterning fidelity (PF)
- In traditional EOS optimization flow, FPs are typical performance indices selected when optimizing the EOS design parameters.
- However, the performance indices related to FPs may have no direct relation to lithography PF, which is judged by the quality of the developed resist patterns.

# Proposed EOS Design Optimization Flow



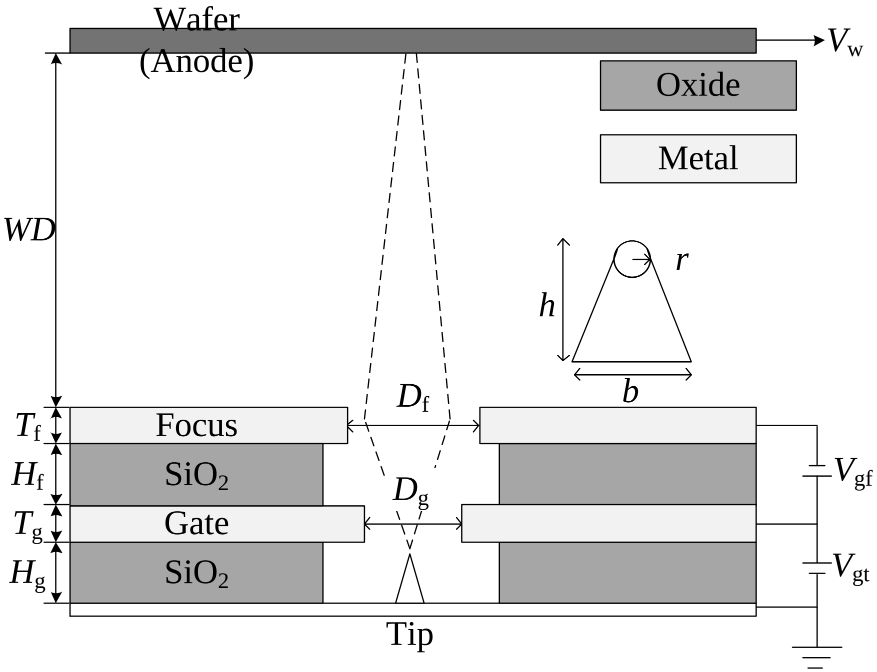
S.-Y. Chen *et al.*, 2011 [14]

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

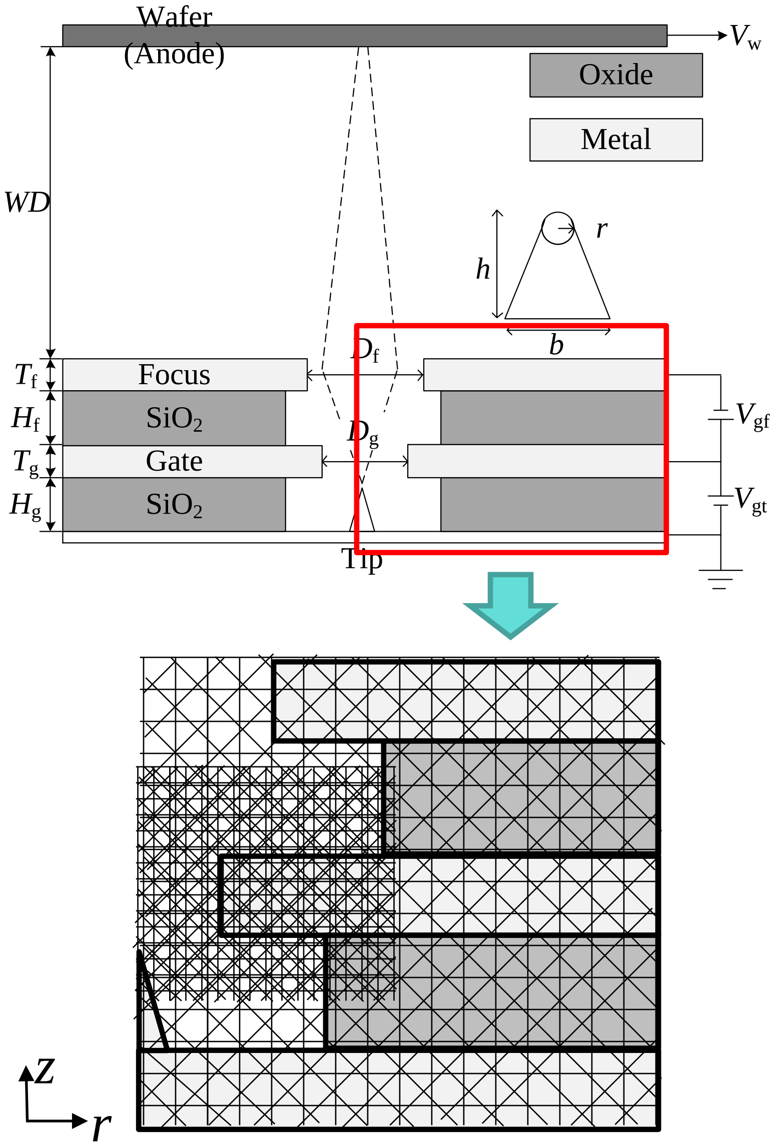


# Parameters and Values of the Demonstration EOS and the Optimization Setting

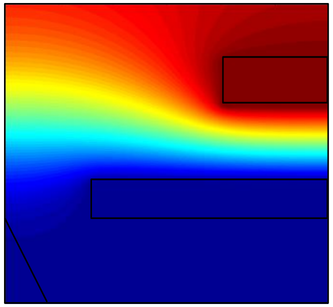
| **Parameters** | **Abbreviations** | **Values** |
|---|---|---|
| Spacing between substrate and gate electrode | $H_g$ | 1 μm |
| Spacing between gate and focus electrodes | $H_f$ | 1 μm |
| Thickness of the gate electrode | $T_g$ | 0.64 μm |
| Thickness of the focus electrode | $T_f$ | 0.64 μm |
|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



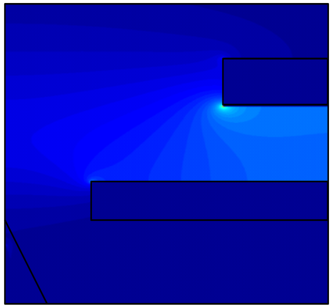
# Field Solver (COMSOL MULTIPHYSICS)



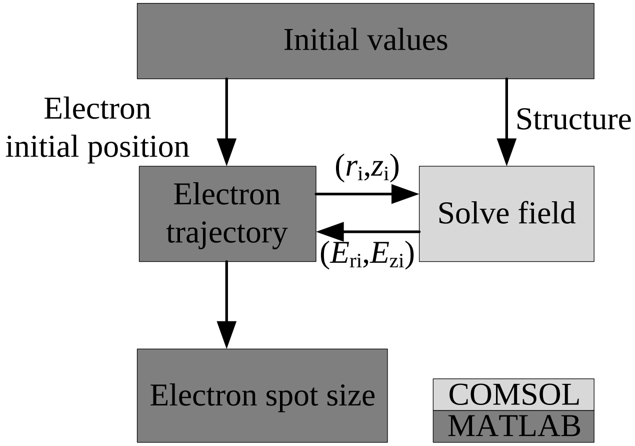
- Field solver
  - COMSOL Multiphysics$^{TM}$
- Space dimension
  - 2D axial symmetry
- Numerical method
  - Finite element method (FEM)
    - Multiple scale mesh



Potential distribution



Field distribution



# 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:

$$m = \gamma m_0, \quad \gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

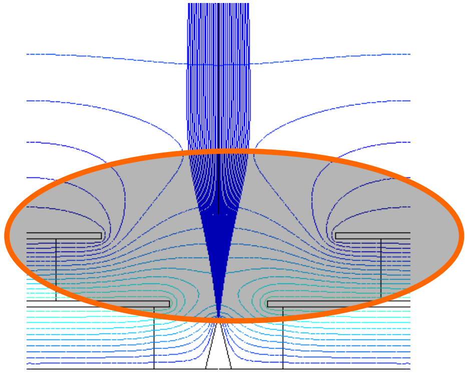
    - Take *r*-direction for example

$$a_r = \frac{d^2r}{dt^2}, \; ma = qE_r \;\Rightarrow\; \gamma m_0 \cdot \frac{d^2r}{dt^2} = qE_r$$

$$\frac{d^2r}{dt^2} = \frac{qE_r}{\gamma m_0} \qquad \frac{d^2z}{dt^2} = \frac{qE_z}{\gamma m_0}$$

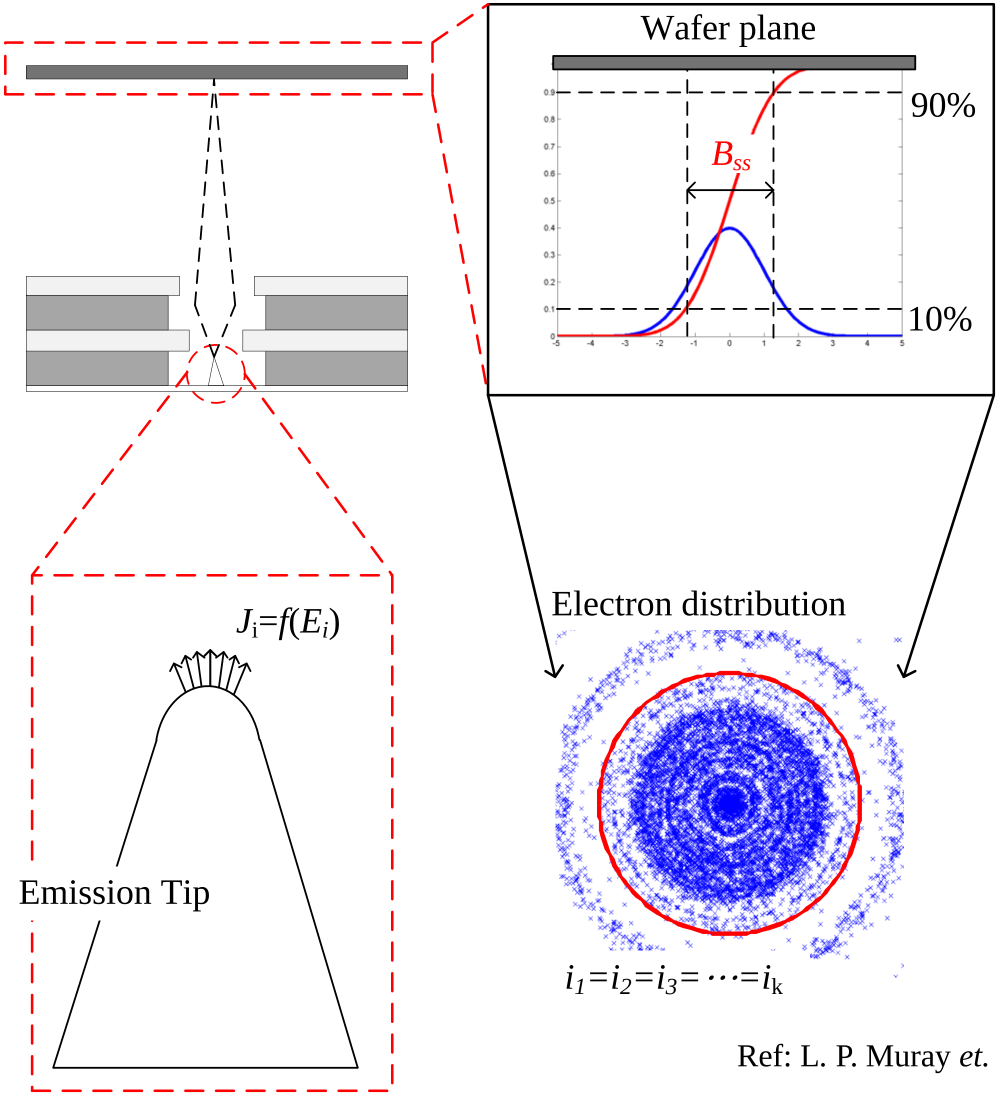
Second order differential equation
Method: Runge-Kutta Method (RK)

Ref: P. W. Hawkes *et. al.*, 1996 [15]



$F$: 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



Ref: L. P. Muray *et. al.*, 2006 [16]

- 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

# Proposed Method to Determine Optimal EOS Design Parameters

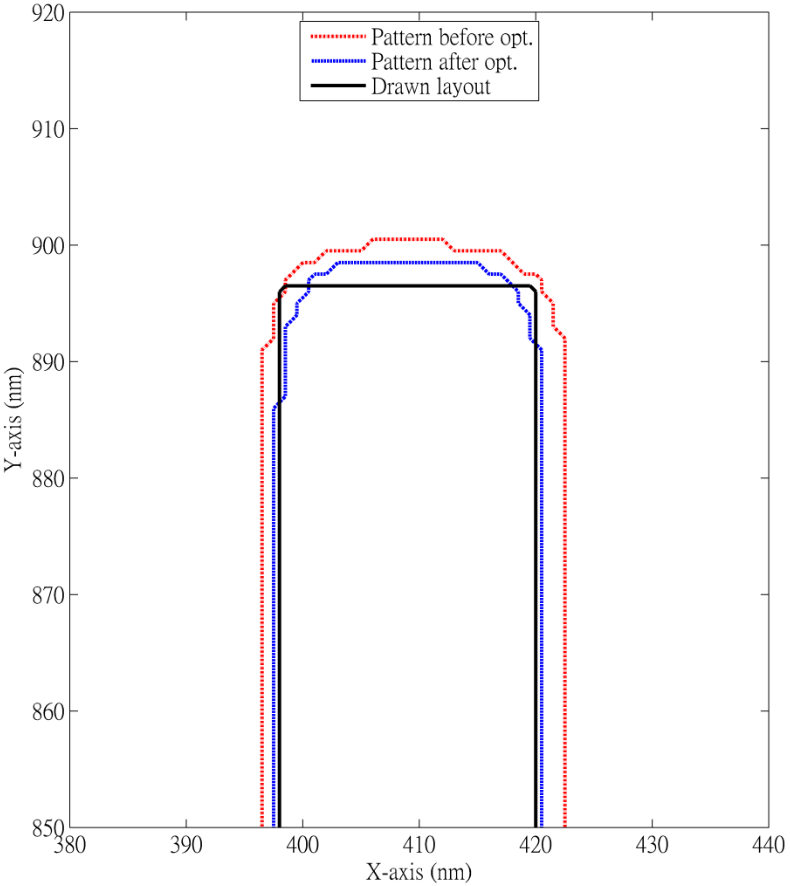
$$
\begin{aligned}
X_0 &= \begin{bmatrix} D_\mathrm{g} & D_\mathrm{f}-D_\mathrm{g} & V_\mathrm{g} & V_\mathrm{g}-V_\mathrm{f} \end{bmatrix} \\
&= \begin{bmatrix} 1.5\ \mu\mathrm{m} & (3.6-1.5)\ \mu\mathrm{m} & 90\ \mathrm{V} & 116\ \mathrm{V} \end{bmatrix} \\
X_\mathrm{wp} &= \begin{bmatrix} \text{pixel size} & \text{dosage} \end{bmatrix} \\
&= \begin{bmatrix} 1\ \mathrm{nm} & 70\ \mu\mathrm{C/cm}^2 \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
&\text{Minimize}: B_\mathrm{ss} \\
&\text{Subject to: } X \le \begin{bmatrix} D_\mathrm{max} & D_\mathrm{max} & V_g & V_\mathrm{g}-V_f \end{bmatrix} \\
&\qquad\qquad\quad X \ge \begin{bmatrix} D_\mathrm{min} & D_\mathrm{min} & 0\ \mathrm{V} & 0\ \mathrm{V} \end{bmatrix} \\
&\qquad\qquad\quad D_\mathrm{f} \le D_\mathrm{max} \\
&\qquad\qquad\quad I_\mathrm{b} > I_\mathrm{mmin} \\
&\qquad\qquad\quad \mathrm{LER} \le \mathrm{PF\_value} \\
&\text{Where: } X = \begin{bmatrix} D_\mathrm{g} & D_\mathrm{f}-D_\mathrm{g} & V_\mathrm{g} & V_\mathrm{g}-V \end{bmatrix}
\end{aligned}
$$

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

where $L(x,y)$ is the drawn layout, and $R_i(x,y)$ is the each simulated resist pattern.

# Preliminary Simulation Results



| Parameters | CD (nm) | Error percentage (%) | Gate CD control (nm) |
|---|---|---|---|
| Drawn layout | 22 | – | – |
| Before opt. | 26 | 18.18 | 4.0 |
| After opt. | 22.68 | 3.09 | 0.68 |

- 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.

# 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.

# *Acknowledgements*

- Funding Support
  - Taiwan Semiconductor Manufacturing Company Limited
  - National Science Council, Taiwan

- Taiwan Semiconductor Manufacturing Company Limited
  - Dr. Burn J. Lin
  - Mr. Jeng-Horng Chen

- Nanoscale-Design and Fabrication Systems Laboratory
  - Prof. Kuen-Yu Tsai
  - Shiau-Yi Ma, Chun-Hung Liu, Philip C. W. Ng, and Yu-Tian Shen
  - Shin-Chuan Chen, Hsing-Hong Chen, and Hoi-Tou Ng

- National Taiwan University
  - Prof. Jia-Yush Yen, Prof. Chieh-Hsiung Kuan, Prof. Yung-Yaw Chen, Prof. Tien-Tung Chung, and Prof. Jia-Han Li
  - Ming-Shing Su

# References

[1] Y. C. Pati, A. A. Ghazanfarian, and R. F. Pease, *IEEE Trans. Semicond. Manuf.* **10**, 62 (1997).

[2] See: *International Technology Roadmap of Semiconductors*, available at http://www.itrs.net/.

[3] H. Xiao, *Introduction to Semiconductor Manufacturing Technology*, Prentice Hall, (2000).

[4] T. Sasaki, *J. Vac. Sci. Technol. B.* **19**, 963 (1981).

[5] A. Yamada, SEMATECH Maskless Workshop 2005, available at http://www.sematech.org/.

[6] P. Ware, *SPIE's OE Magazine* **2**, 26 (2002).

[7] KLA Tencor, SEMATECH ML2 Workshop, (2008).

[8] B. J. Kampherbeek and G. de Boer, SEMATECH ML2 Workshop, (2005).

[9] PML2, SEMATECH ML2 Workshop, (2005).

[10] M.-S. Su, K.-Y. Tsai, Y.-C. Lu, Y.-H. Kuo, T.-H. Pei, and J.-Y. Yen, *Proc. SPIE* **7637**, 76371Q (2010).

[11] L. R. Baylor, D. H. Lowndes, M. L. Simpson, C. E. Thomas, M. A. Guillorn, V. I. Merkulov, J. H. Whealton, E. D. Ellis, D. K. Hensley, and A. V. Melechko, *J. Vac. Sci. Technol. B* **20**, 2646 (2002).

[12] M. A. Guillorn1, X. Yang, A. V. Melechko, D. K. Hensley, M. D. Hale, V. I. Merkulov, M. L. Simpson, L. R. Baylor, W. L. Gardner, and D. H. Lowndes, *J. Vac. Sci. Technol. B* **22**, 35 (2004).

[13] X. Yang, W. L. Gardner, L. R. Baylor, H. Cui, and D. H. Lowndes, *J. Vac. Sci. Technol. B* **25**, 394 (2007).

[14] S.-Y. Chen, H.-T. Ng, S.-Y. Ma, H.-H. Chen, C.-H. Liu, and K.-Y. Tsai, *J. Vac. Sci. Technol. B* **29**, 06FD04 (2011).

[15] P.W. Hawkes and E. Kasper, *Principles of Electron Optics*, Vol. 1, Academic Press, (1996).

[16] L. P. Muray, C. S. Silver and J. P. Spallas, *J. Vac. Sci. Technol. B.* **24**, 2945 (2006).

***Thank you for your attention!***