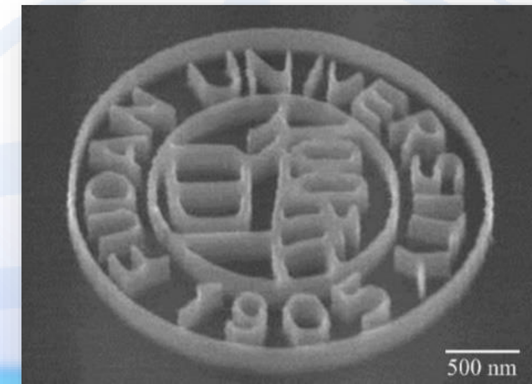
# Applications of 3D Grayscale Electron Beam Lithography in Nanofabrication

Nanofabrication

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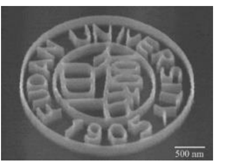
Nanolithography and application research group
Centre for micronano systems
School of Information Science and Technology
Fudan University, Shanghai, China

# Content






1. Introduction to Grayscale Electron Beam Lithography (EBL)
2. Fabrication of Kinoform zone plates
   - A. Grayscale EBL using Positive Resist
     - a. Methodology for Grayscale EBL
     - b. Result and Optimization
   - B. Grayscale EBL using Negative Resist
3. Other Grayscale Structures
   - A. High Electron Mobility Transistors (HEMTs)
   - B. Aztec Steps
   - C. Grayscale Ice Lithography Simulations

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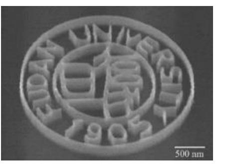



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# 1. Introduction to Grayscale Electron Beam Lithography (EBL)

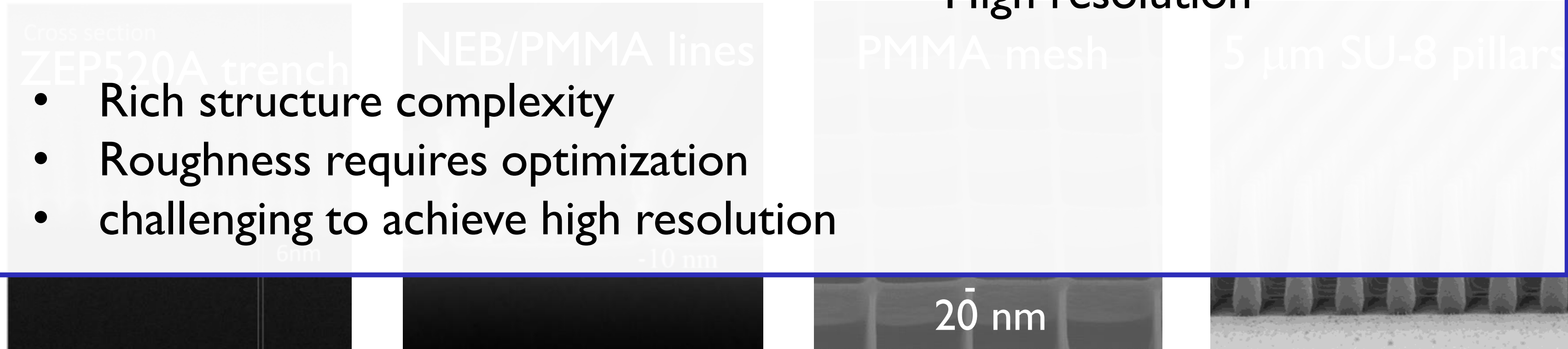
Voltage: 100 kV
Current: 500 pA
Spot size: 2 nm
Minimum linewidth: 6 nm
Field matching accuracy: ≤15 nm
Alignment accuracy: ≤15 nm
Stability: ≤ 2%

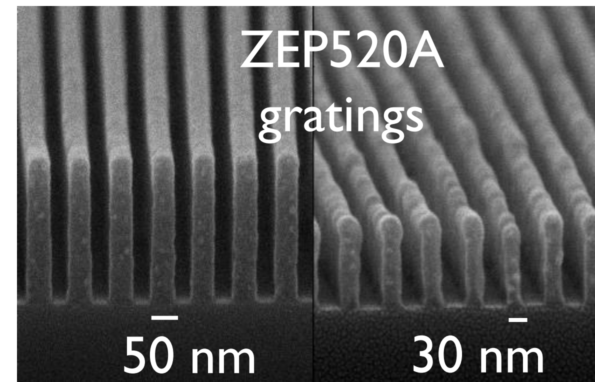
# 1. Introduction to Grayscale Electron Beam Lithography (EBL)



2D electron beam lithography Binary: 0 1 0 1

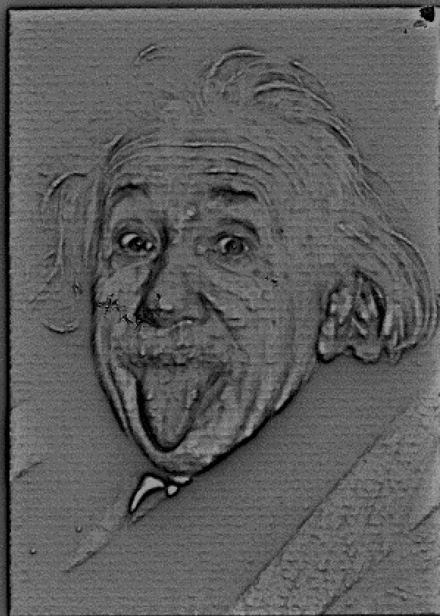
- Limited structure complexity
- High resolution

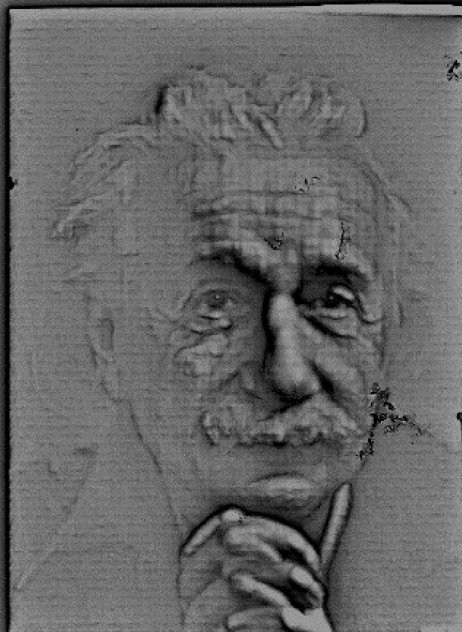



3D electron beam lithography Grayscale: 0 ~ 1

- Rich structure complexity
- Roughness requires optimization
- challenging to achieve high resolution



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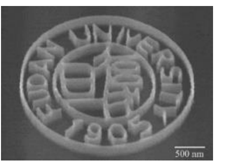





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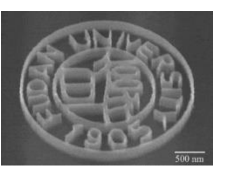
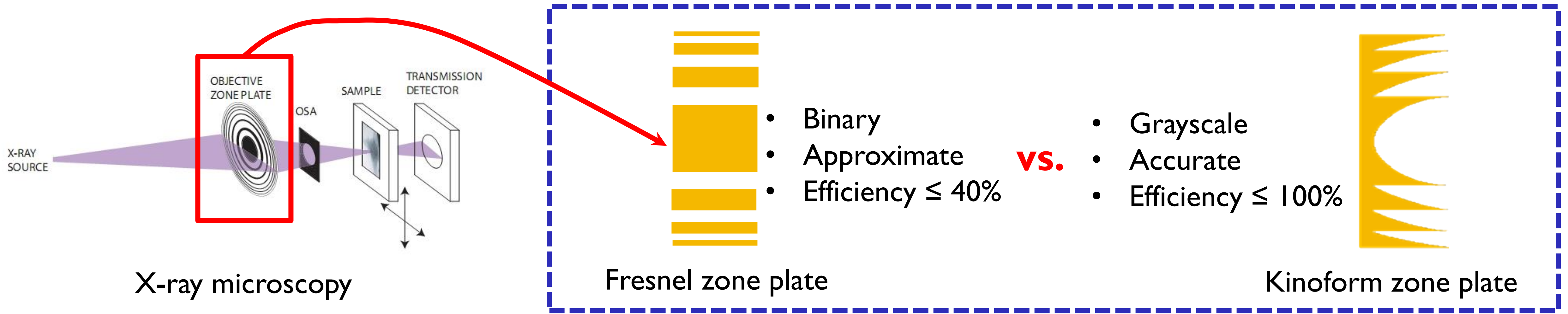
# 2. Fabrication of Kinoform zone plates

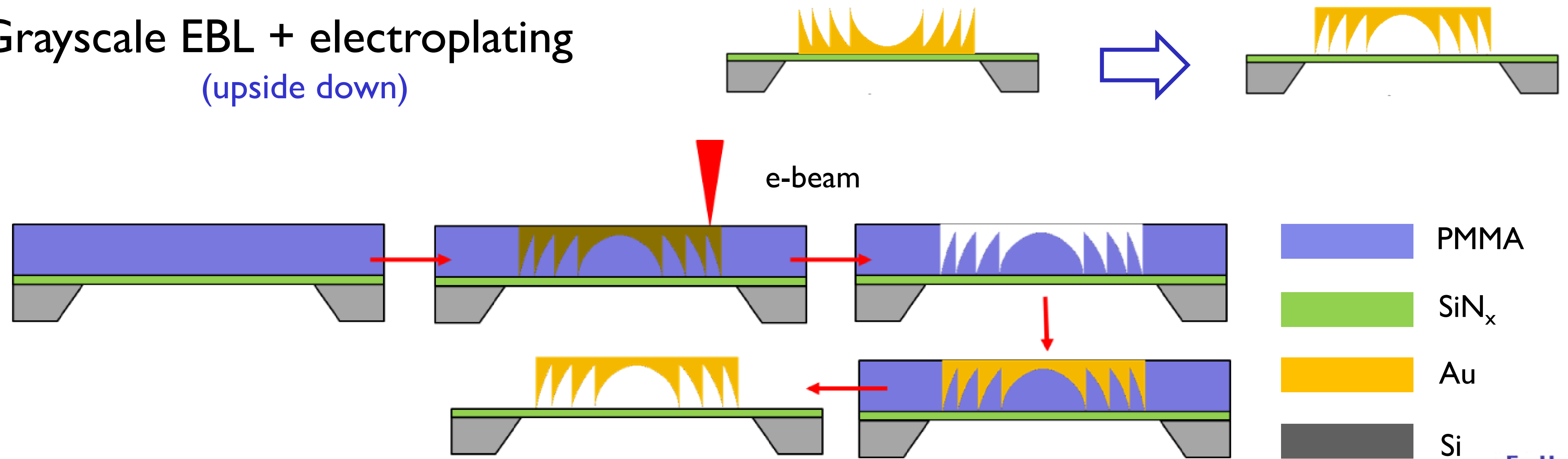
## A. Grayscale EBL using Positive Resist——*Introduction to Kinoform Zone Plate*






Grayscale EBL + electroplating

(upside down)



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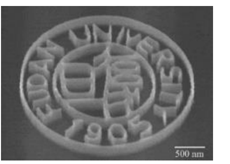



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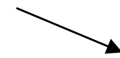
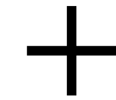
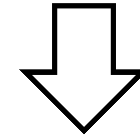


Exposure Dose Distribution



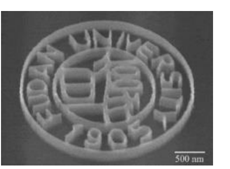
Development Conditions



Grayscale structure

# 2. Fabrication of Kinoform zone plates

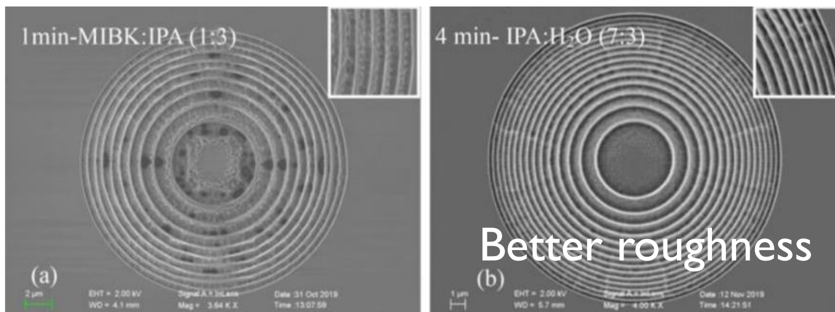
## A. Grayscale EBL using Positive Resist——*Development Conditions*



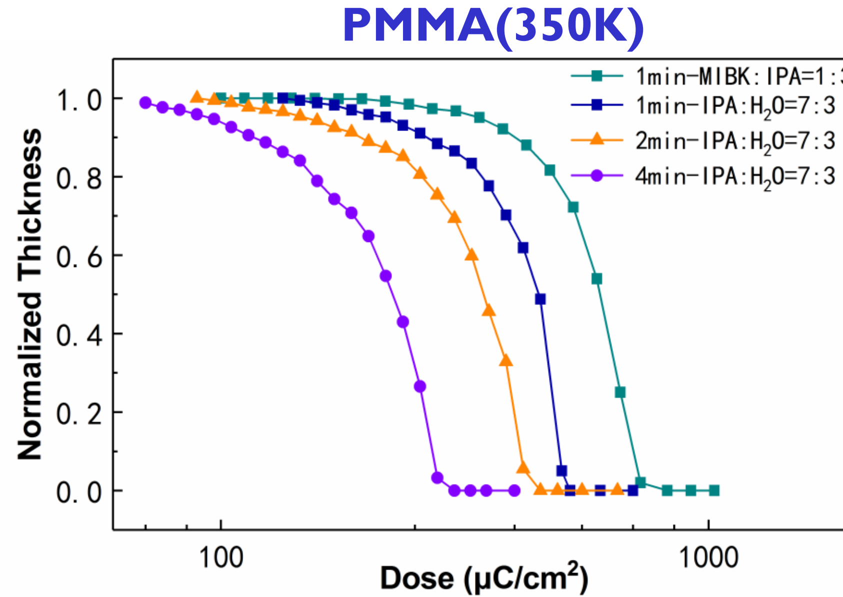


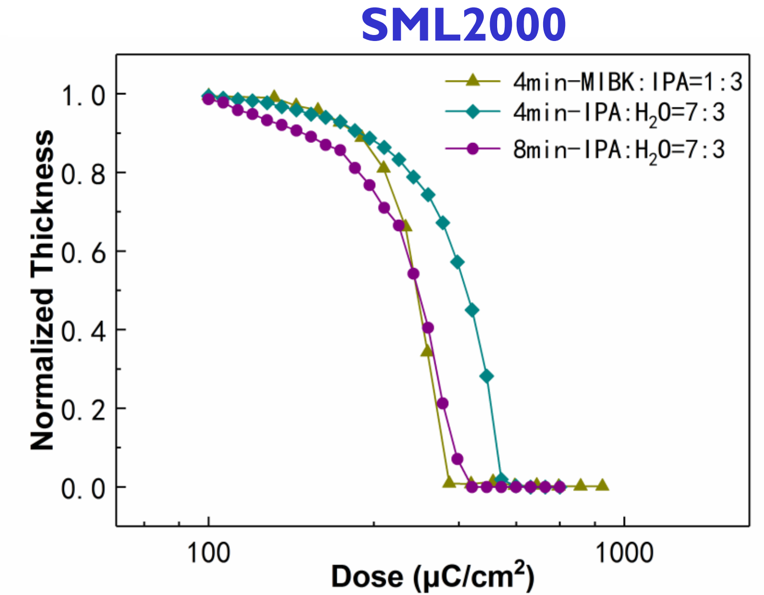
**The lower contrast the better**

1. Resist
   - PMMA(350K)
   - SML2000
2. Development solution
   - MIBK
   - IPA
   - $H_2O$




3. Development time
   - 1 min ~ 8 min




| | PMMA(350K) | | | | SML2000 | | |
|---|---|---|---|---|---|---|---|
| Developing Solution | MIBK:IPA(1:3) | IPA:$H_2O$(7:3) | | | MIBK:IPA(1:3) | IPA:$H_2O$(7:3) | |
| Developing Time (min) | 1 | 1 | 2 | 4 | 4 | 4 | 8 |
| Contrast | 4.9 | 4.32 | 3.39 | 2.81 | 5.16 | 3.14 | 2.96 |
| Sensitivity ($\mu C/cm^2$) | 741 | 537 | 462 | 314 | 391 | 584 | 437 |

Xujie Tong, Microelectronic Engineering, 2020.

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      b. Result and Optimization

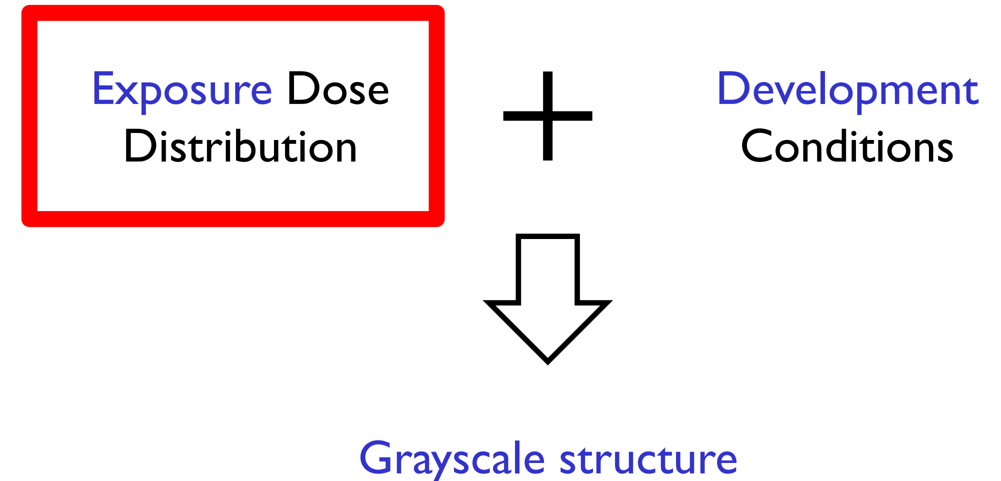
   B. Grayscale EBL using Negative Resist

3. Other Grayscale Structures

   A. High Electron Mobility Transistors (HEMTs)

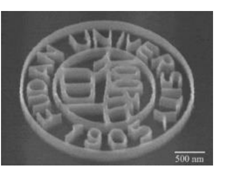
   B. Aztec Steps

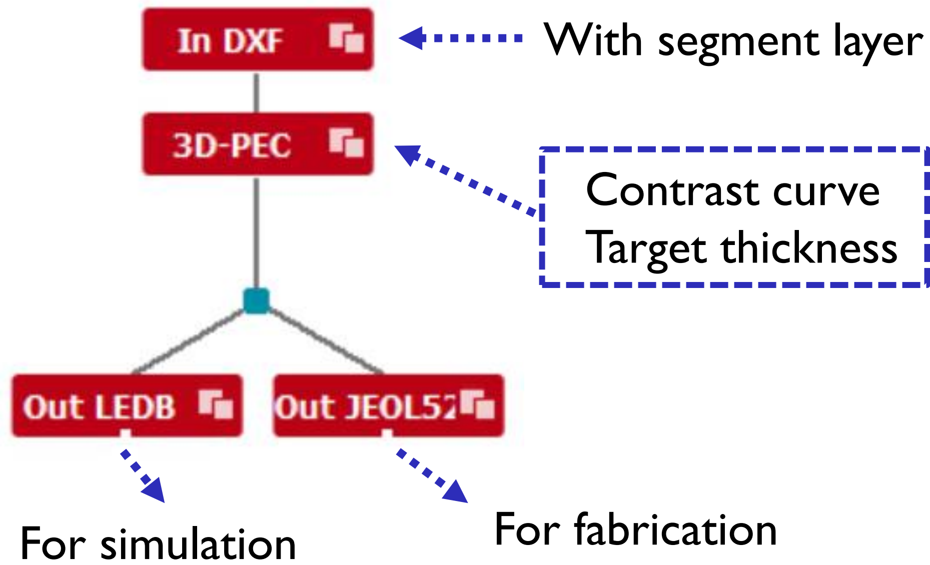
   C. Grayscale Ice Lithography Simulations



# 2. Fabrication of Kinoform zone plates

## A. Grayscale EBL using Positive Resist——*Exposure Dose Distribution*






With segment layer

Contrast curve
Target thickness

For simulation

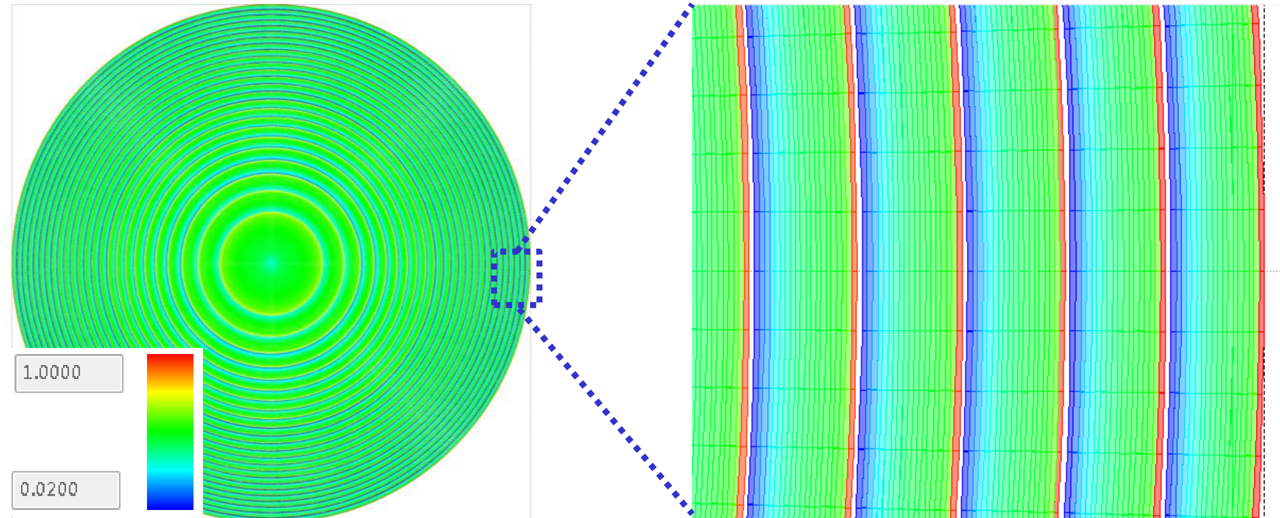
For fabrication

Further optimization:

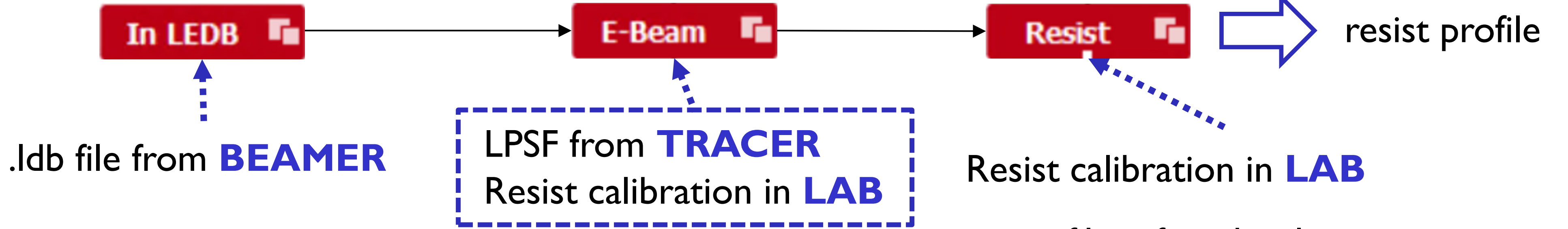
Kinoform zone plate parameters

| Energy | 8 | keV |
|---|---|---|
| Radius | 50 | μm |
| Number of zones | 25 | / |
| Focal Length | 323 | mm |
| Outmost zone width | 1010 | nm |
| Segment layer width | 50 | nm |

Exposure dose distribution



# Simulations : Optimization of Dose Distribution




resist profile

.ldb file from **BEAMER**

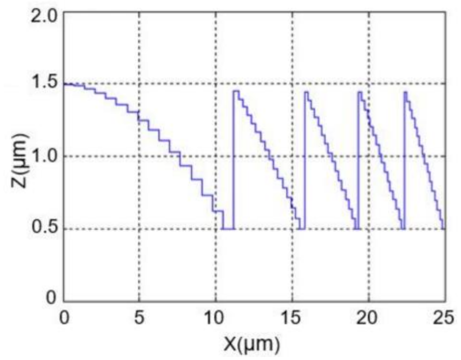
LPSF from **TRACER**
Resist calibration in **LAB**

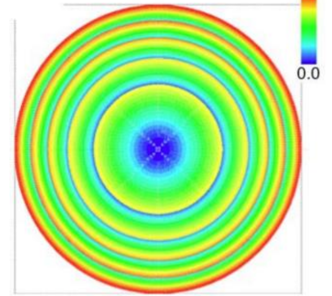
Resist calibration in **LAB**

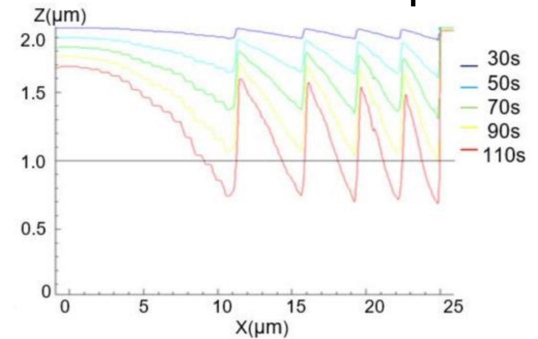
dose distributions

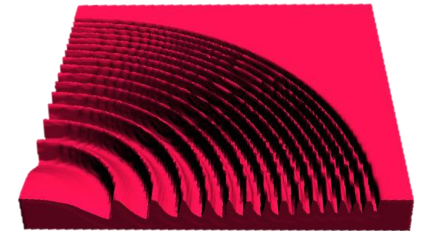
profiles after development

Designed height: 0.5~1μm

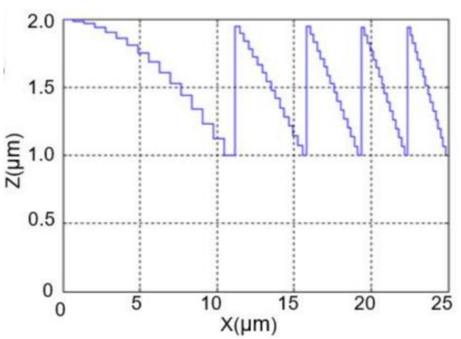


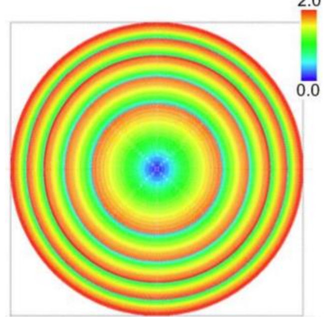



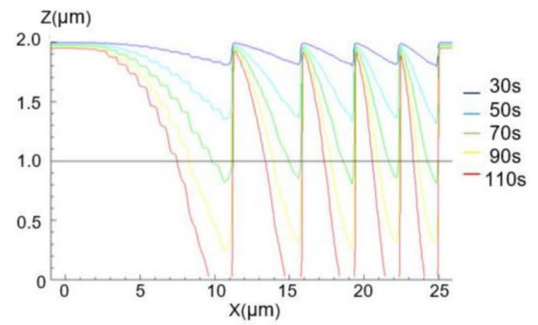



Designed height: 1~2μm



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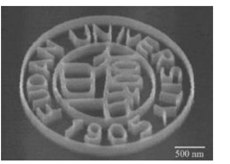



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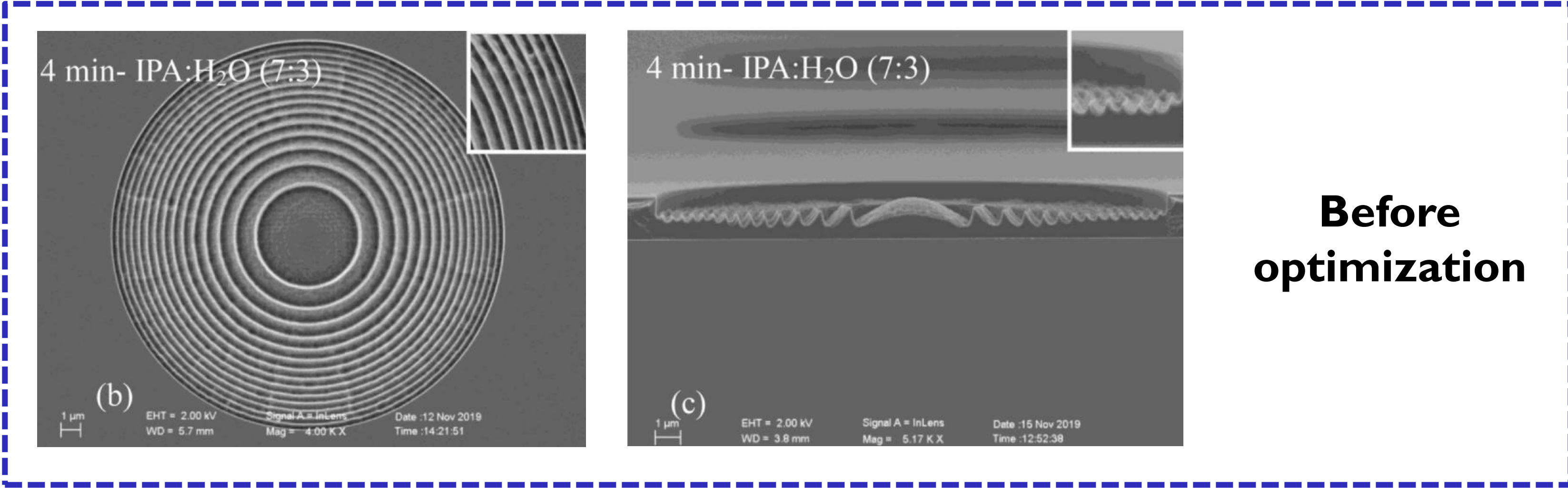
# 2. Fabrication of Kinoform zone plates

## A. Grayscale EBL using Positive Resist——*Result and Optimization*

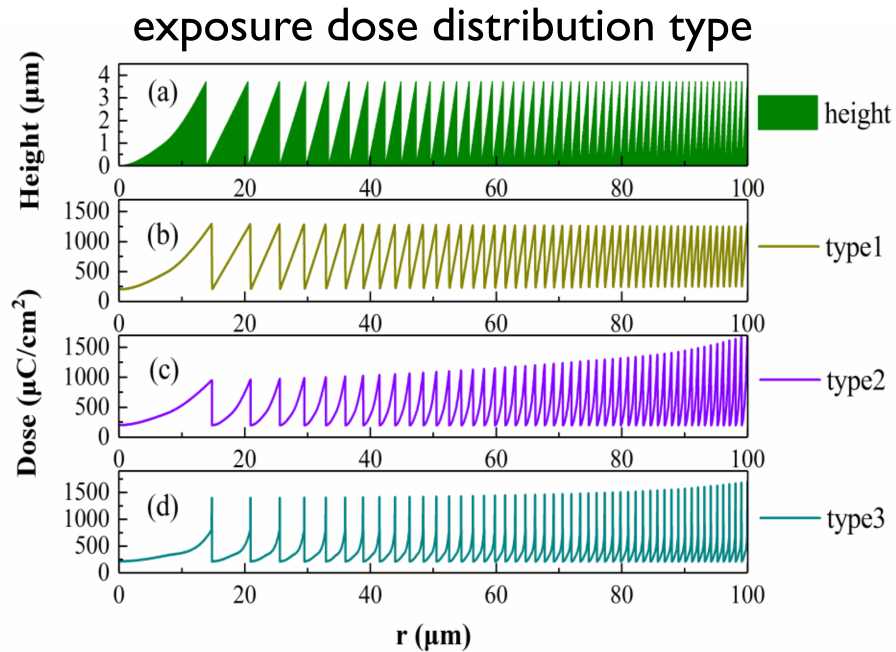


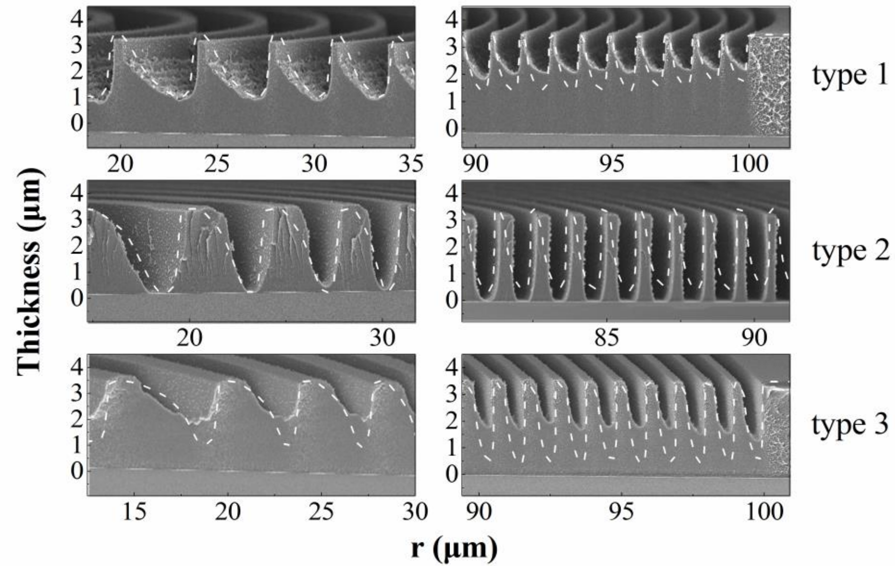

**Before optimization**

### Principle of optimization

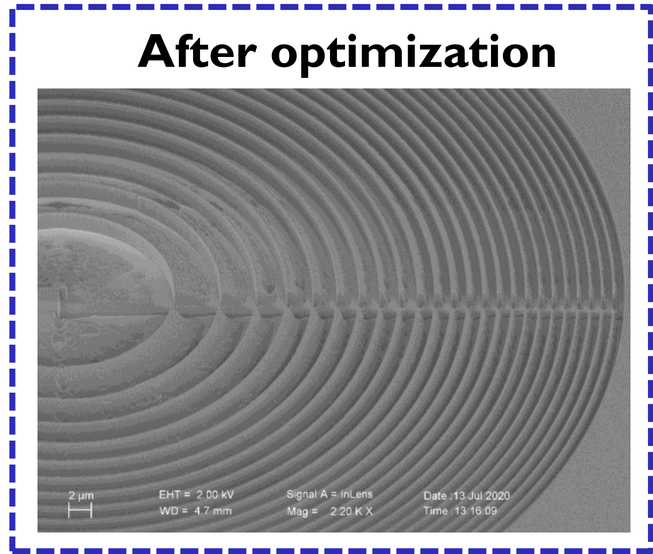
1. Trenches touch substrate (to electroplate)
2. Kinoform profile

exposure dose distribution type




**After optimization**



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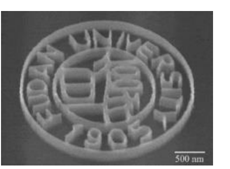
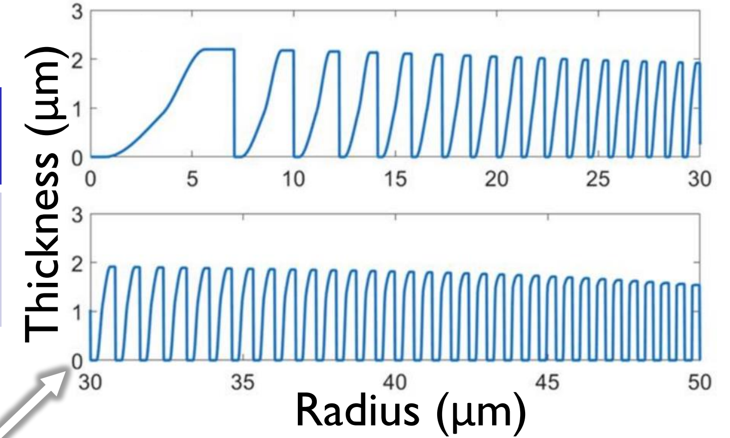
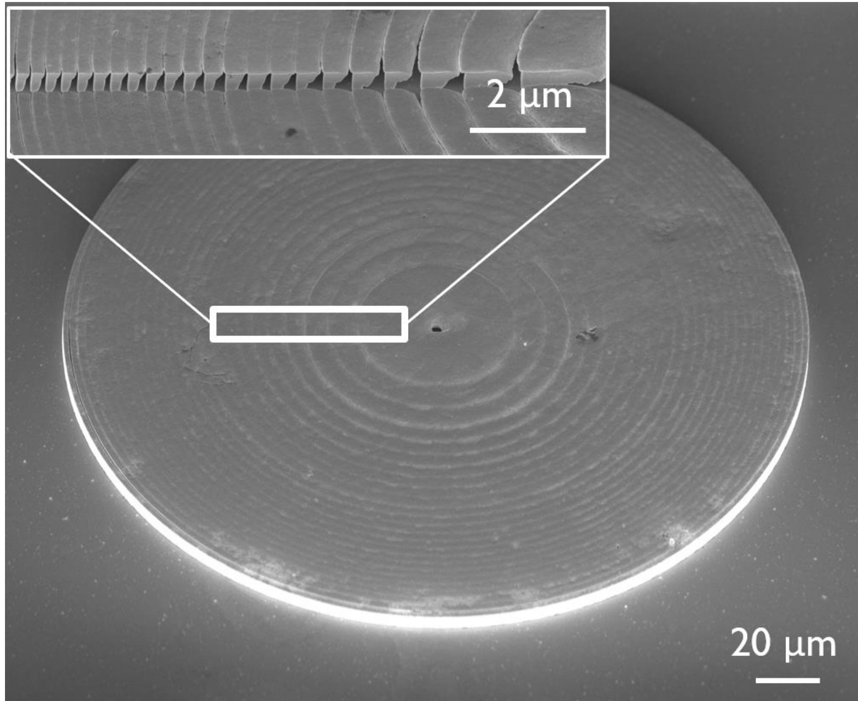
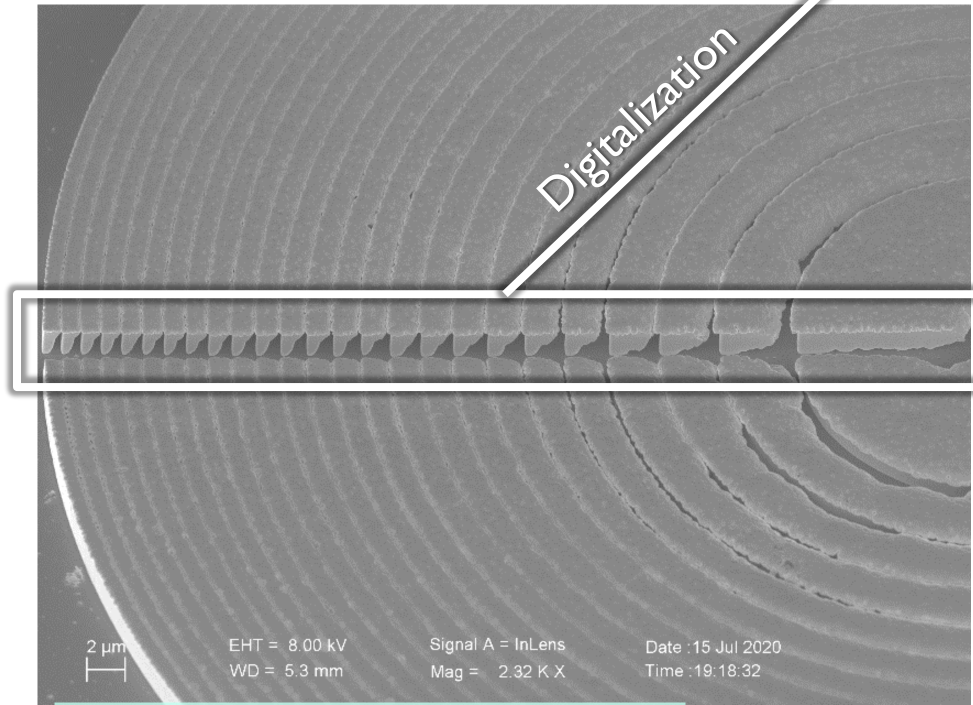


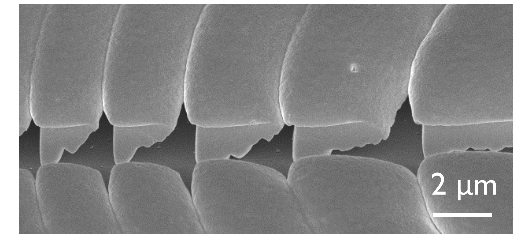
electroplating parameters

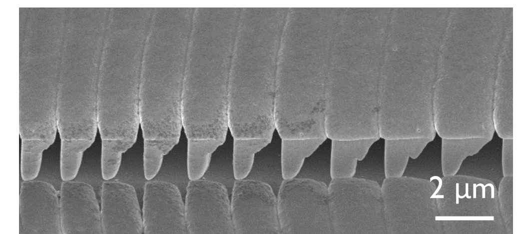
| Temperature | Electroplating solution | Time | Current | Thickness |
|---|---|---|---|---|
| 50 ℃ | $K_3[Au(SO_3)_2]$ | 20 min | 1 µA | 2100 nm |

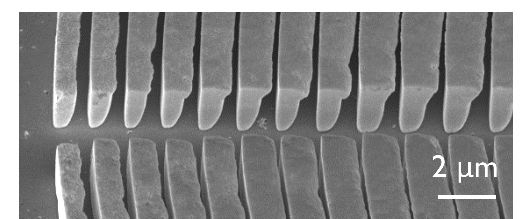
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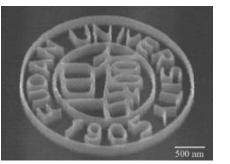



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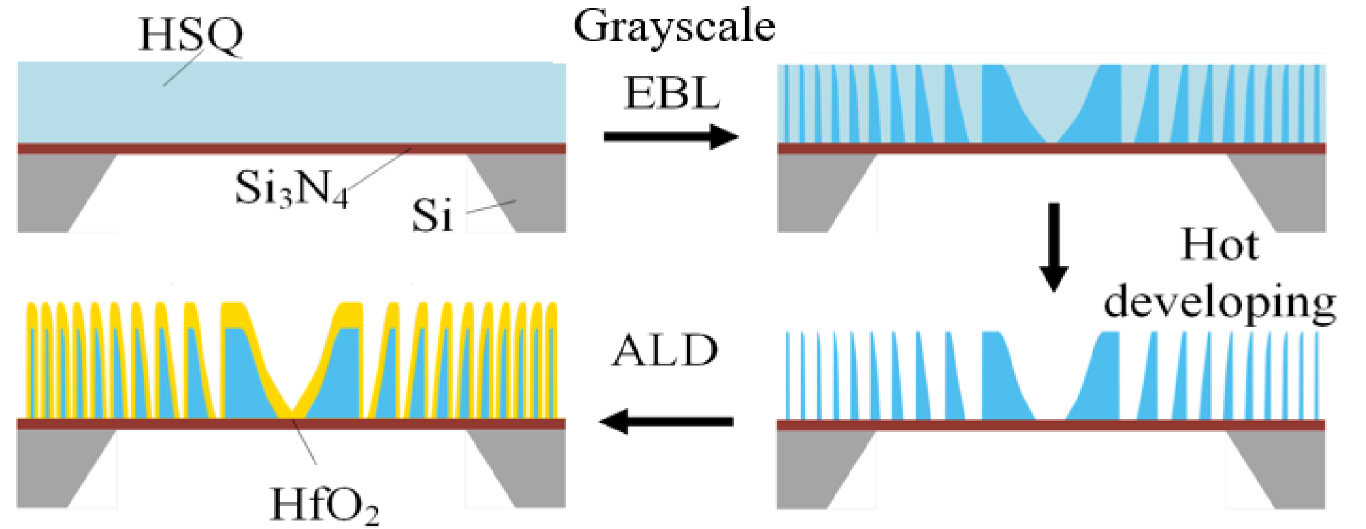
## Kinoform zone plate for soft X-ray

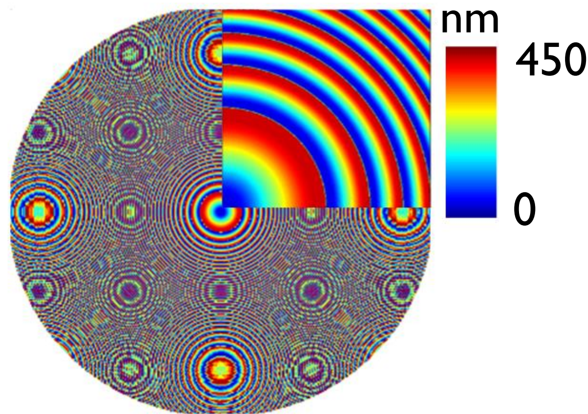
**Negative resist :**

HSQ (Hydrogen silsesquioxane)

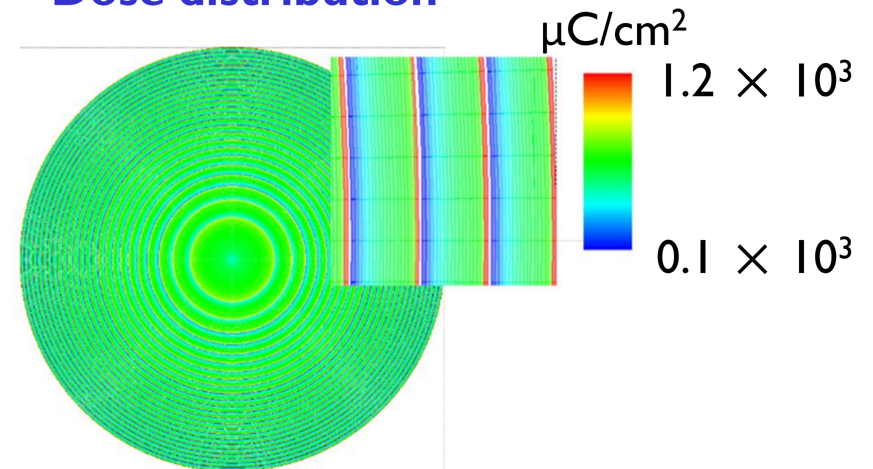
- low contrast
- high resolution




**Height distribution**

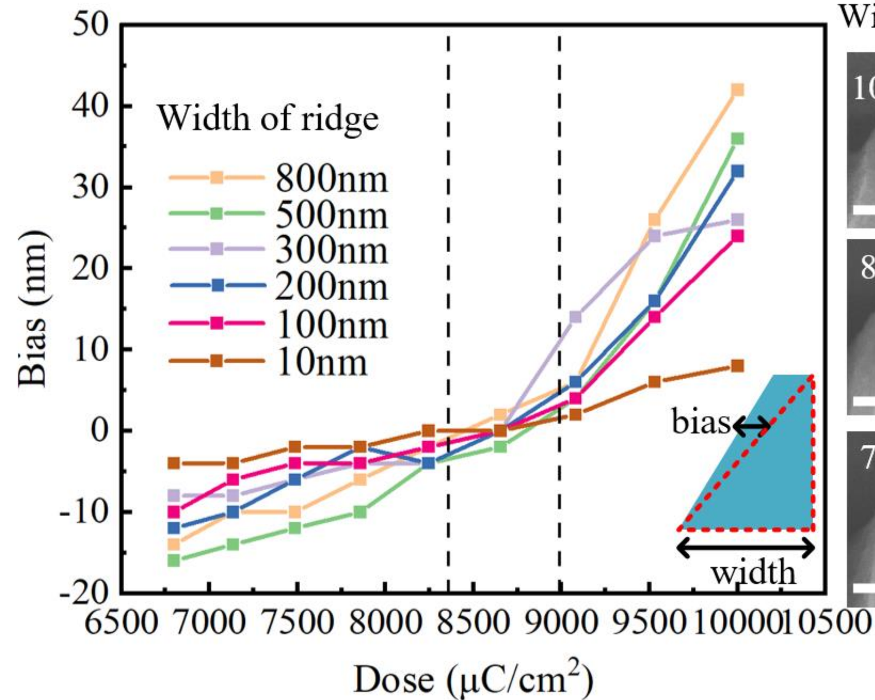


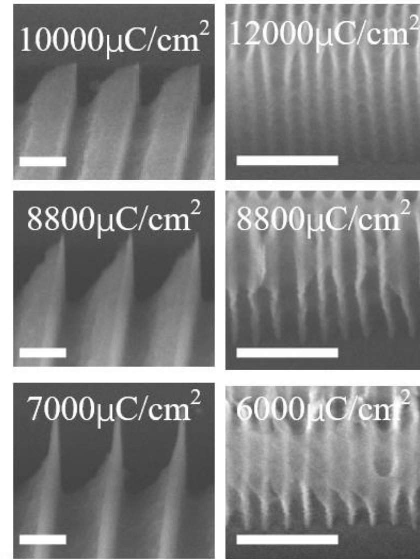
**Dose distribution**

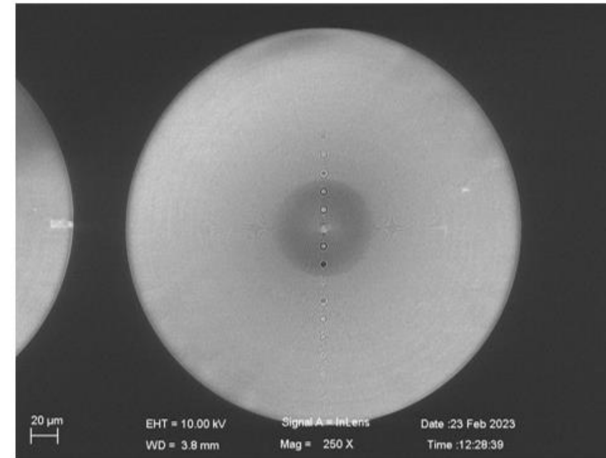


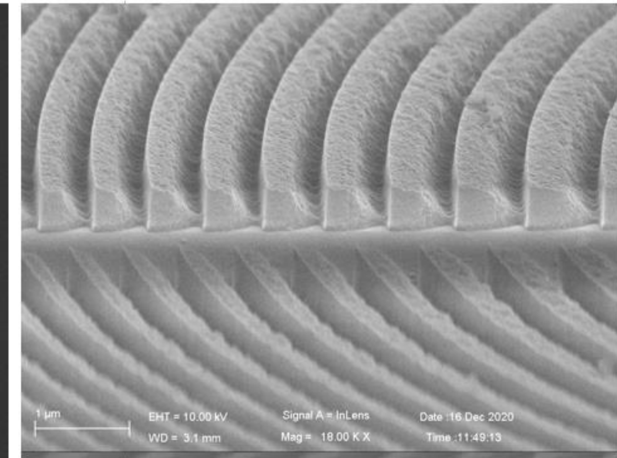
### Principle of optimization

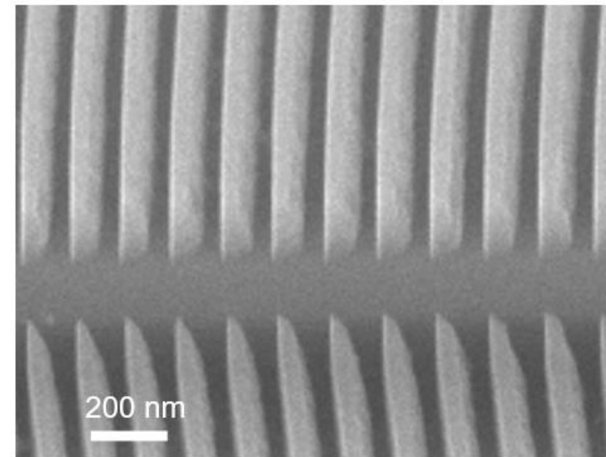
1. Minimum HSQ residue
2. Kinoform profile

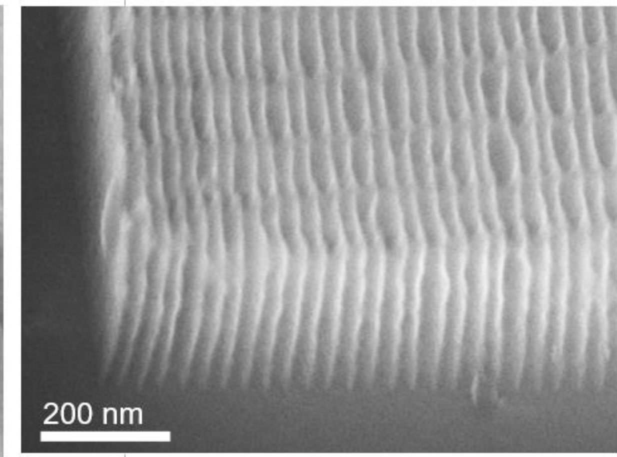






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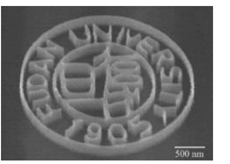



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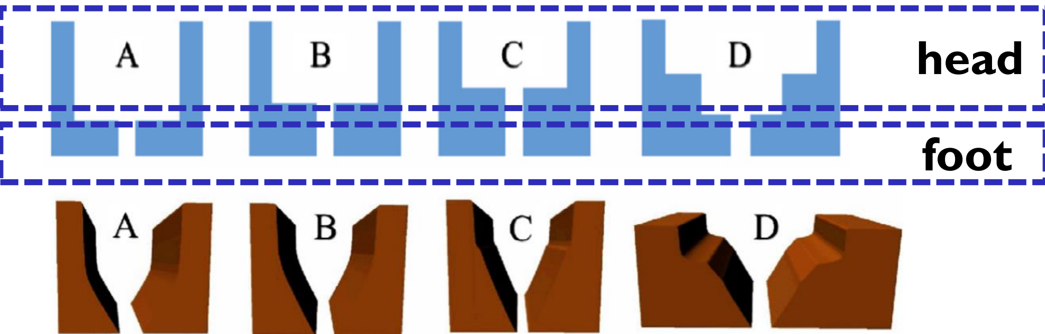
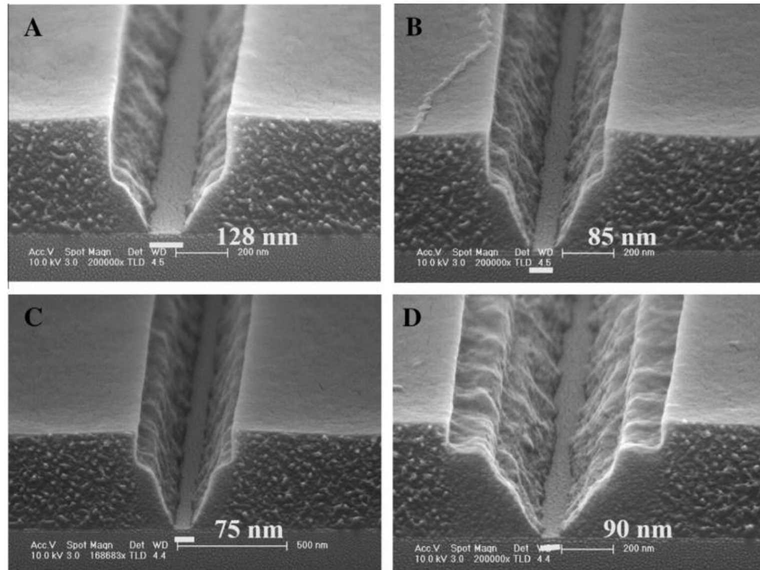
## Y shape gate

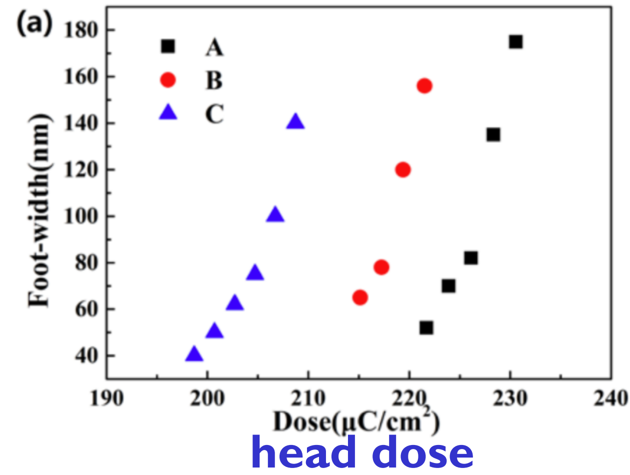
—mechanical strength ⤴ Resist: ZEP520A

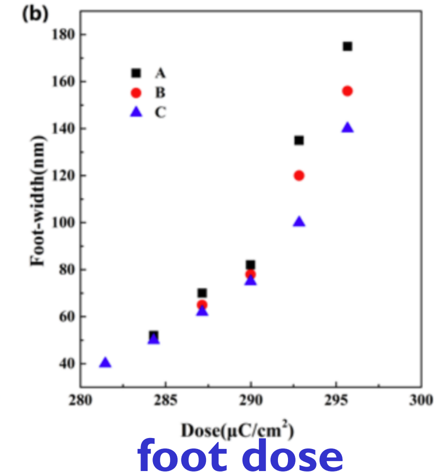
Different configuration




**To achieve thinner foot-width:**

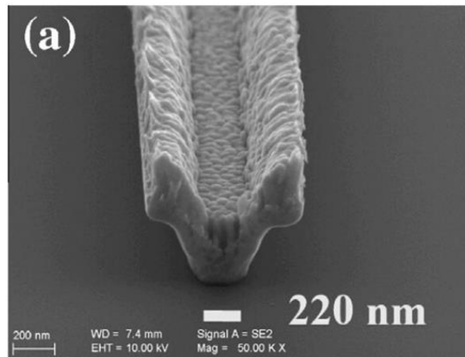


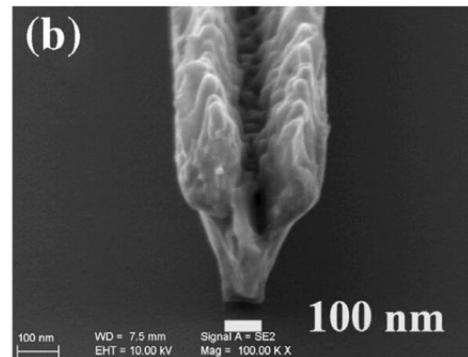



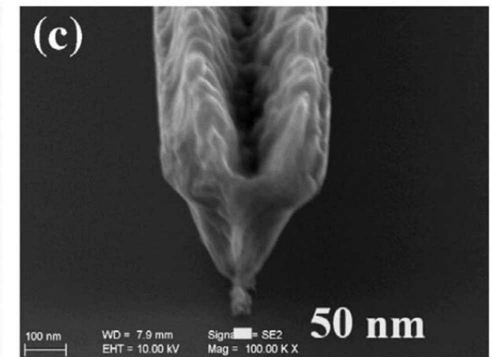

head dose foot dose

Conclusion

1. Lower head dose → thinner foot-with, C is the best
2. Lower foot dose → thinner foot-with, A B C are similar




Jinhai Shao, Microelectronic Engineering, 2015.

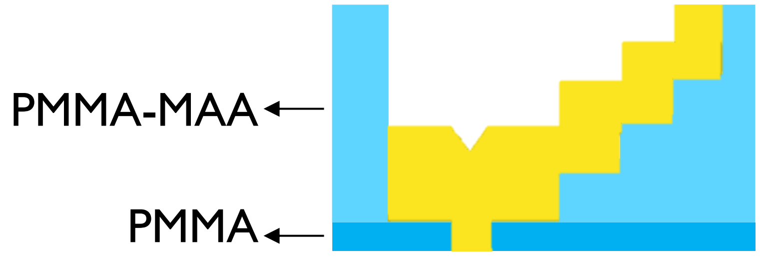
# 3. Other Grayscale Structures

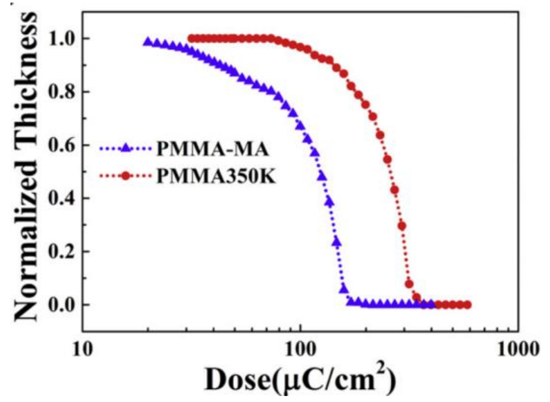
## A. High Electron Mobility Transistors (HEMTs)——*Asymmetric T Shape Gate* & B. Aztec Steps

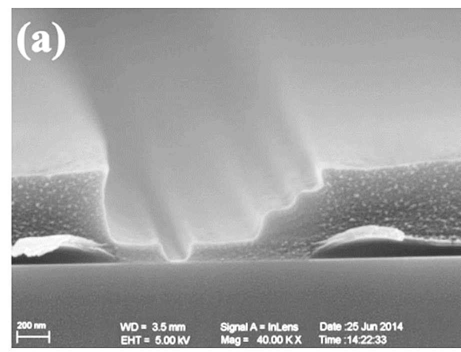
### Asymmetric T shape gate

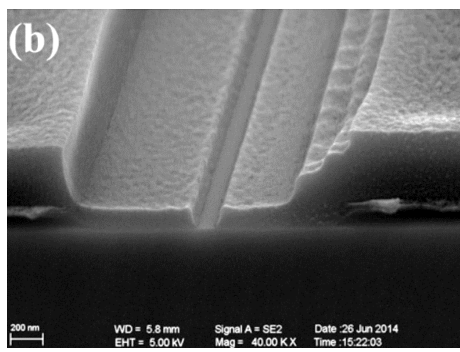
—high frequency performance ⤴

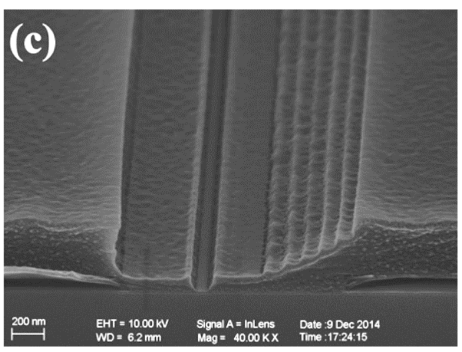
—breakdown voltage ⤴

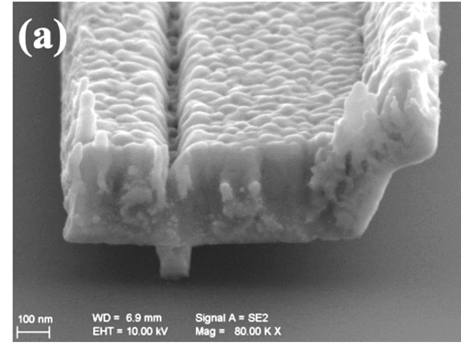


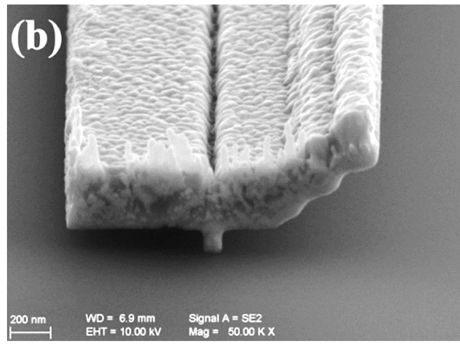



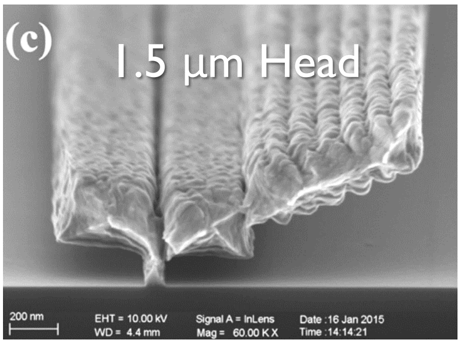



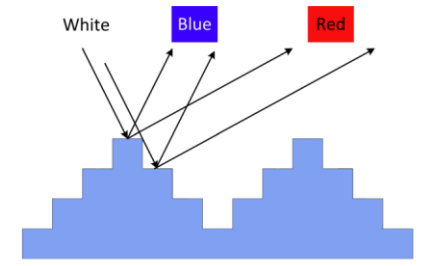



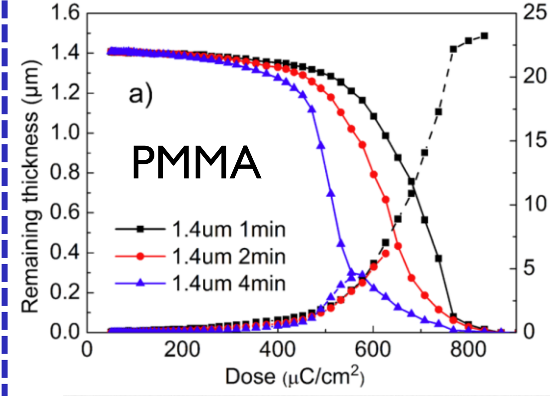



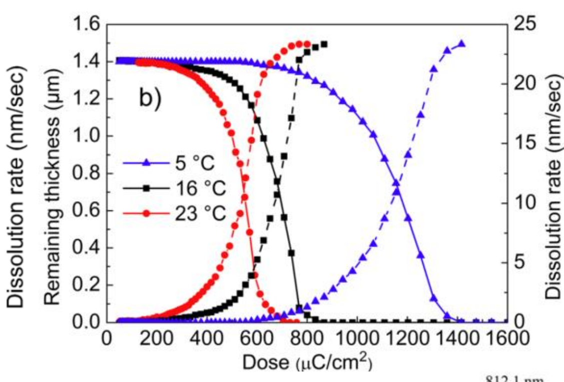

Jinhai Shao, Microelectronic Engineering, 2018.

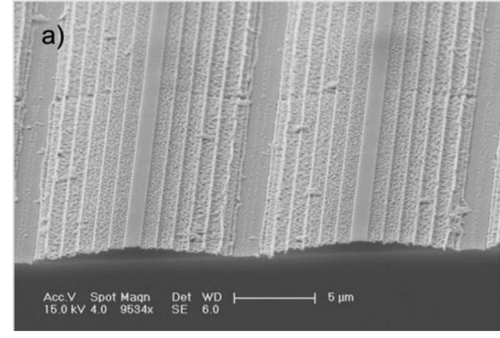
### Aztec steps

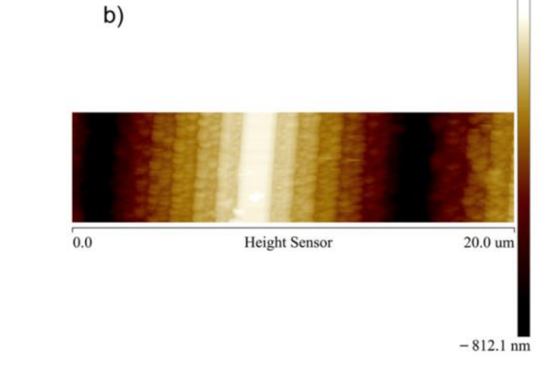
wavelength selector



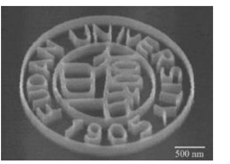




Sichao Zhang, Journal of Vacuum Science & Technology B, 2014.

# Content



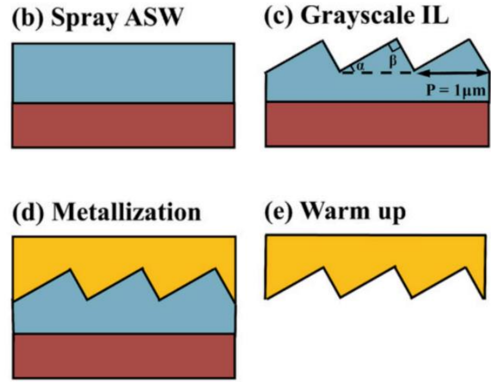


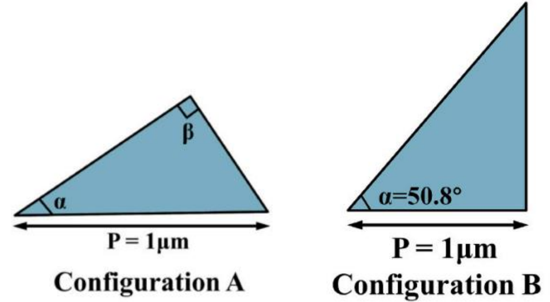
1. Introduction to Grayscale Electron Beam Lithography (EBL)
2. Fabrication of Kinoform zone plates
   A. Grayscale EBL using Positive Resist
      a. Methodology for Grayscale EBL
      b. Result and Optimization
   B. Grayscale EBL using Negative Resist
3. Other Grayscale Structures
   A. High Electron Mobility Transistors (HEMTs)
   B. Aztec Steps
   C. Grayscale Ice Lithography Simulations

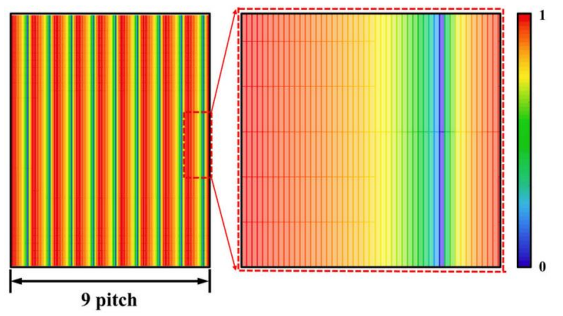
Resist : Amorphous Solid Water (ASW)

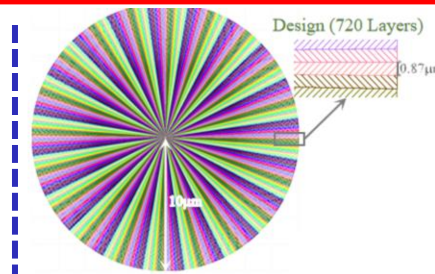


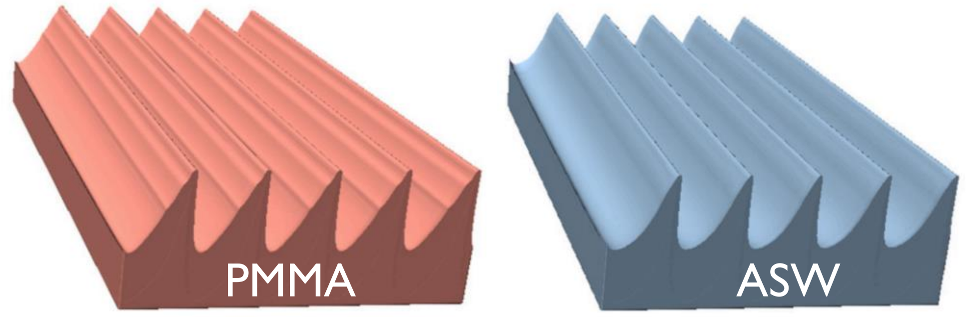
## Blazed gratings



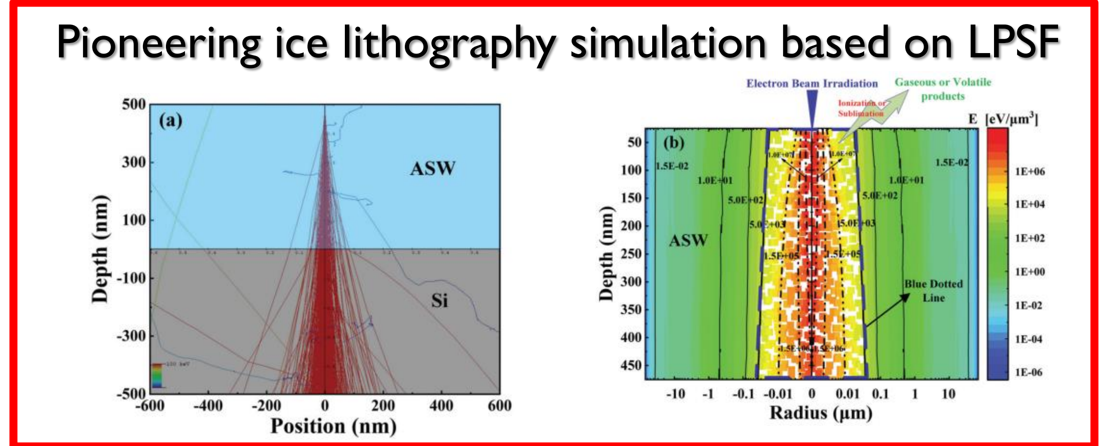



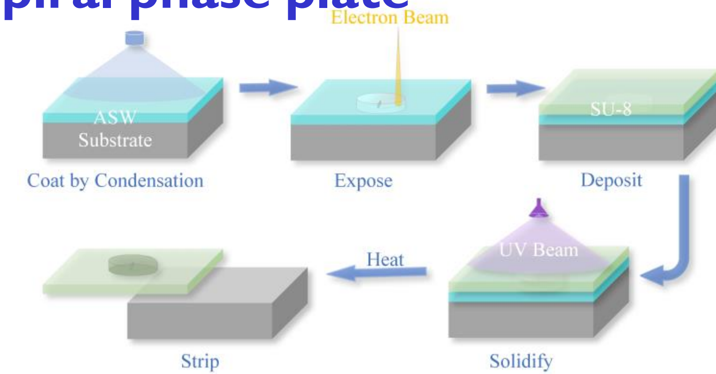



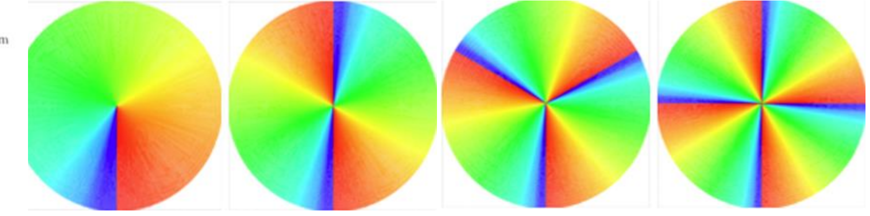

## Pioneering ice lithography simulation based on LPSF

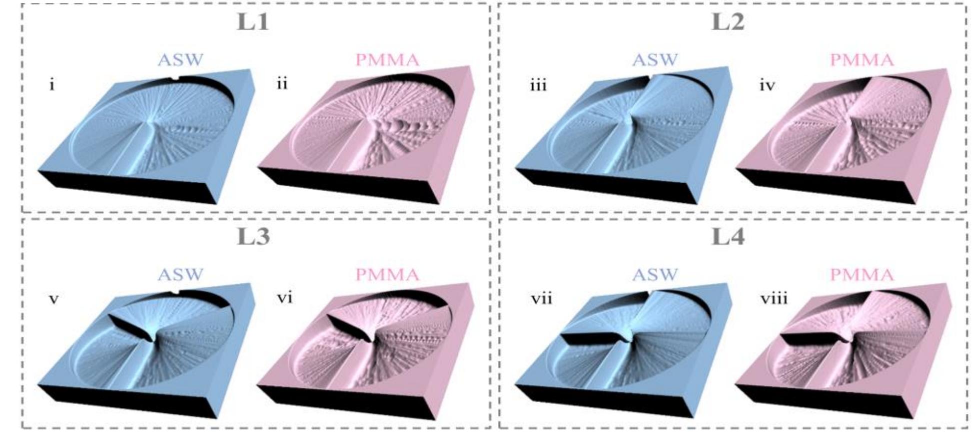



## Spiral phase plate




dose by color




**Roughness**

ASW < PMMA

Tao Liu, Nanoscale, 2022
Jinyu Guo, Microelectronic engineering, 2024

# Acknowledgement




- Huge thanks to GenIsys for providing the powerful BEAMER/TRACER/LAB
- Thanks to all group members for their contributions

# Thanks for your attention!