Electron Beam Lithography

Process, principles and capabilities

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Ph.D. Students NTNU

MICRONOVA Centre for Micro and Nanotechnology myfab NorFab DTU Nanolab

NNN Nordic Nanolab Network

Lithography is a method of printing

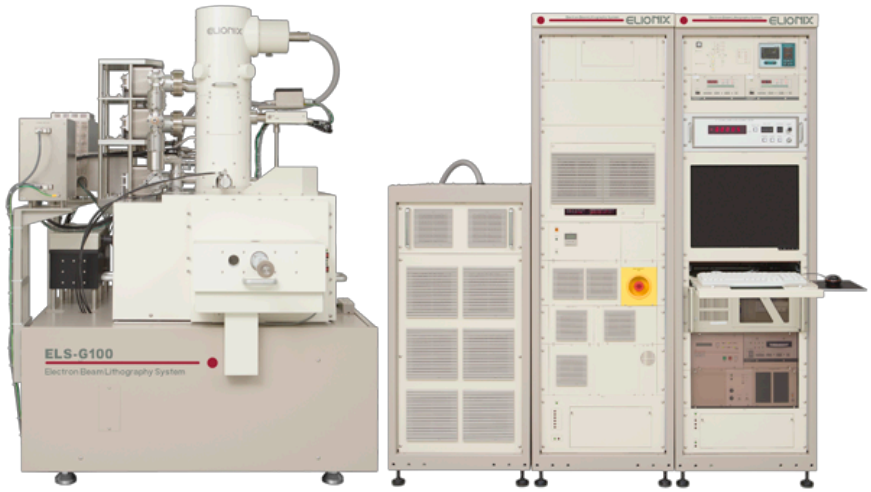
Negative lithography stone

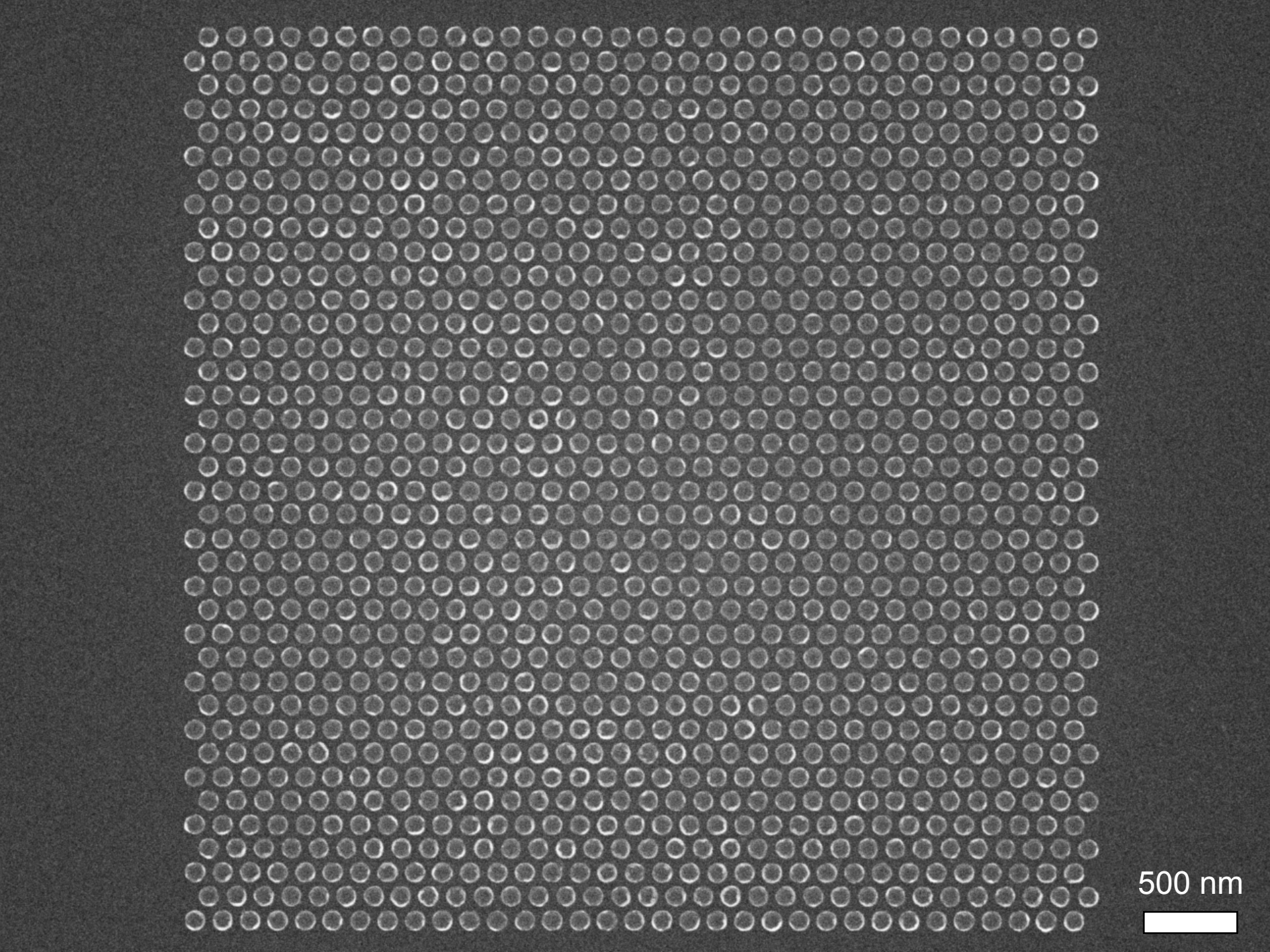
Positive print

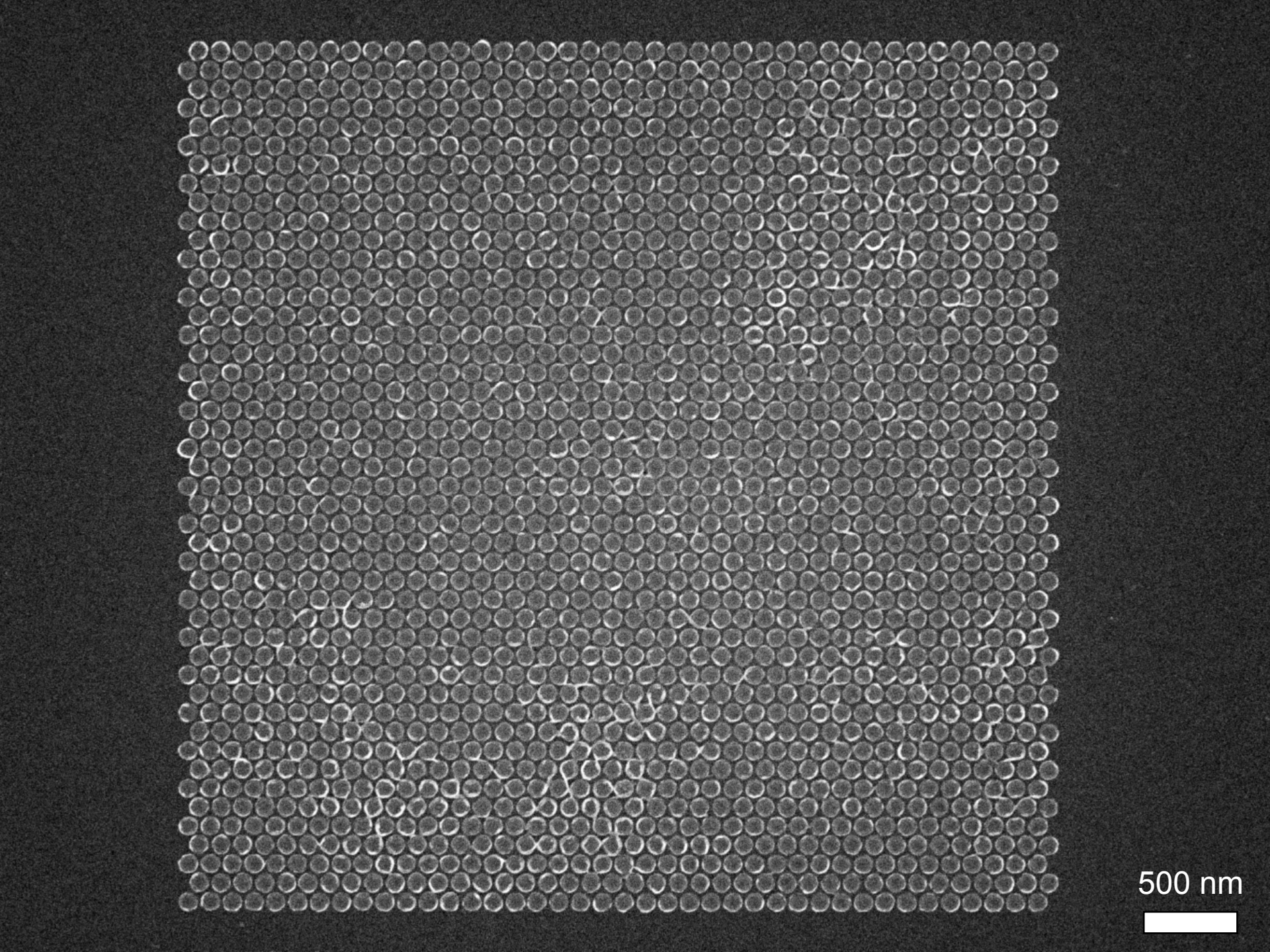
Chris 73 / Wikimedia Commons

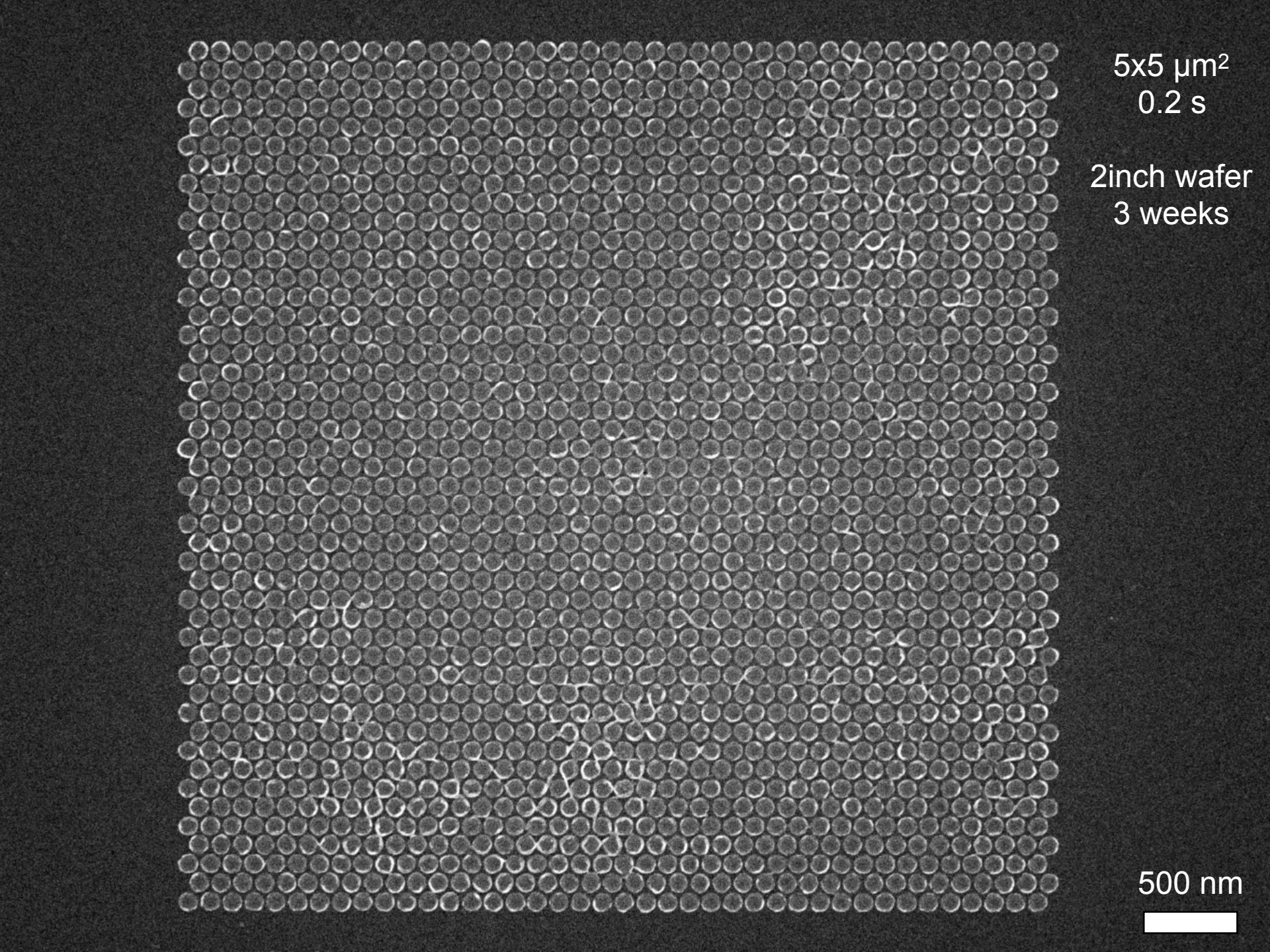
Electron Beam Lithography

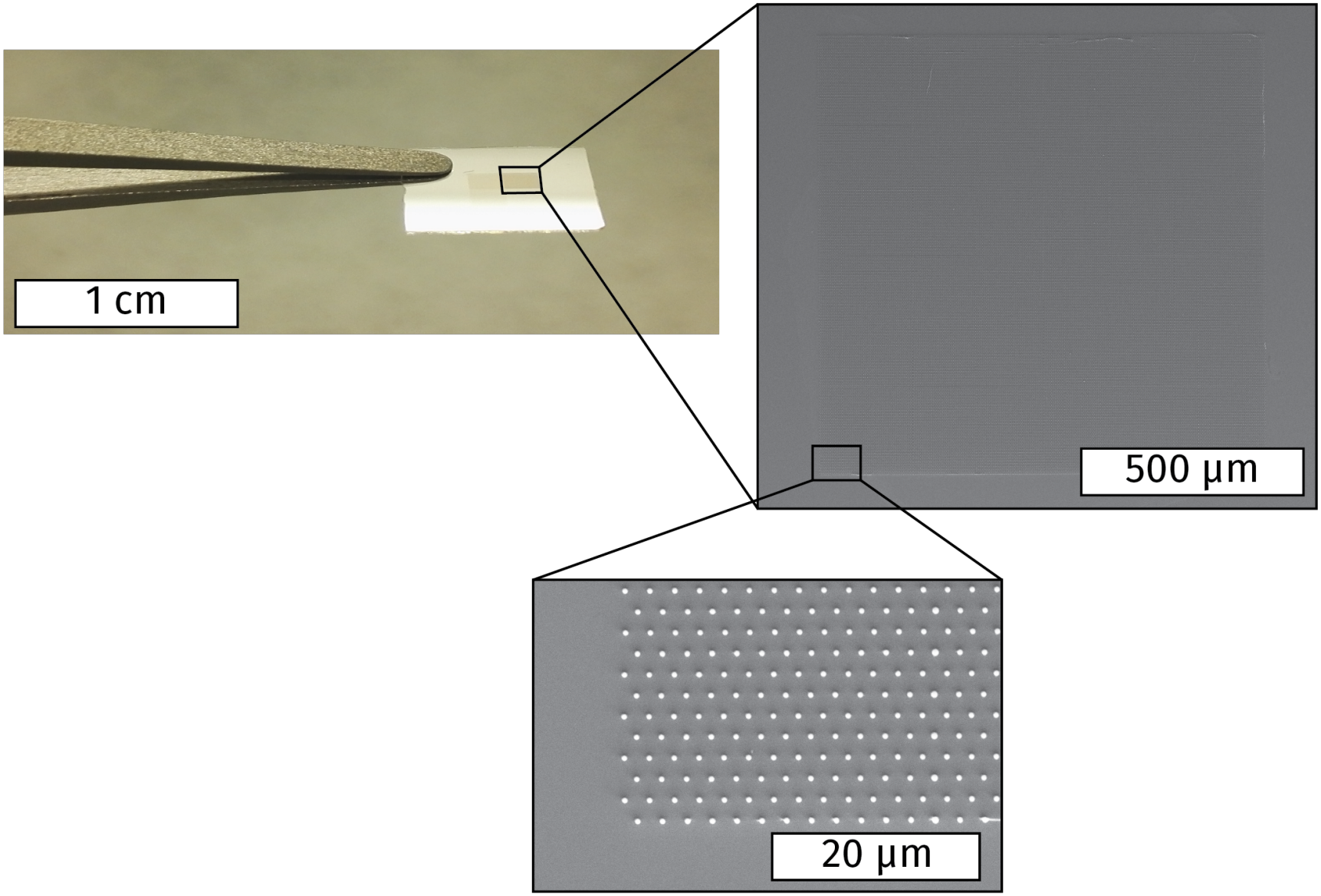
- Direct writing with electron beam
- Down to a few nm resolution
- Design structures on computer
- Ideal for prototyping




500 nm


500 nm

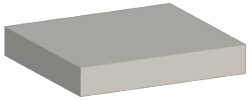

5x5 μm²
0.2 s
2inch wafer
3 weeks
500 nm



SU-8 pillars on glass: 1 * 1 mm in 30 seconds

Steps of EBL

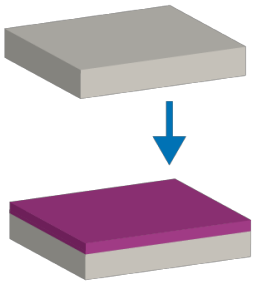
1. Sample pre-treatment



Steps of EBL

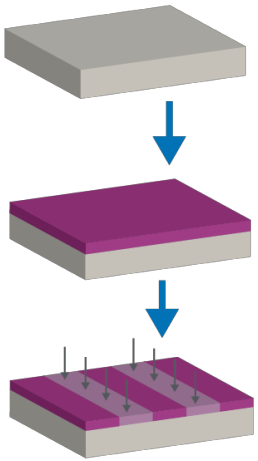
1. Sample pre-treatment

2. Applying resist



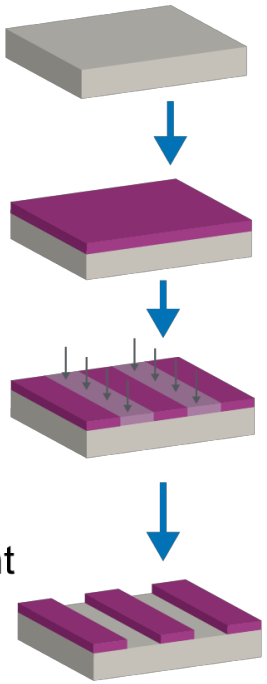
Steps of EBL

1. Sample pre-treatment
2. Applying resist
3. Exposure by electrons

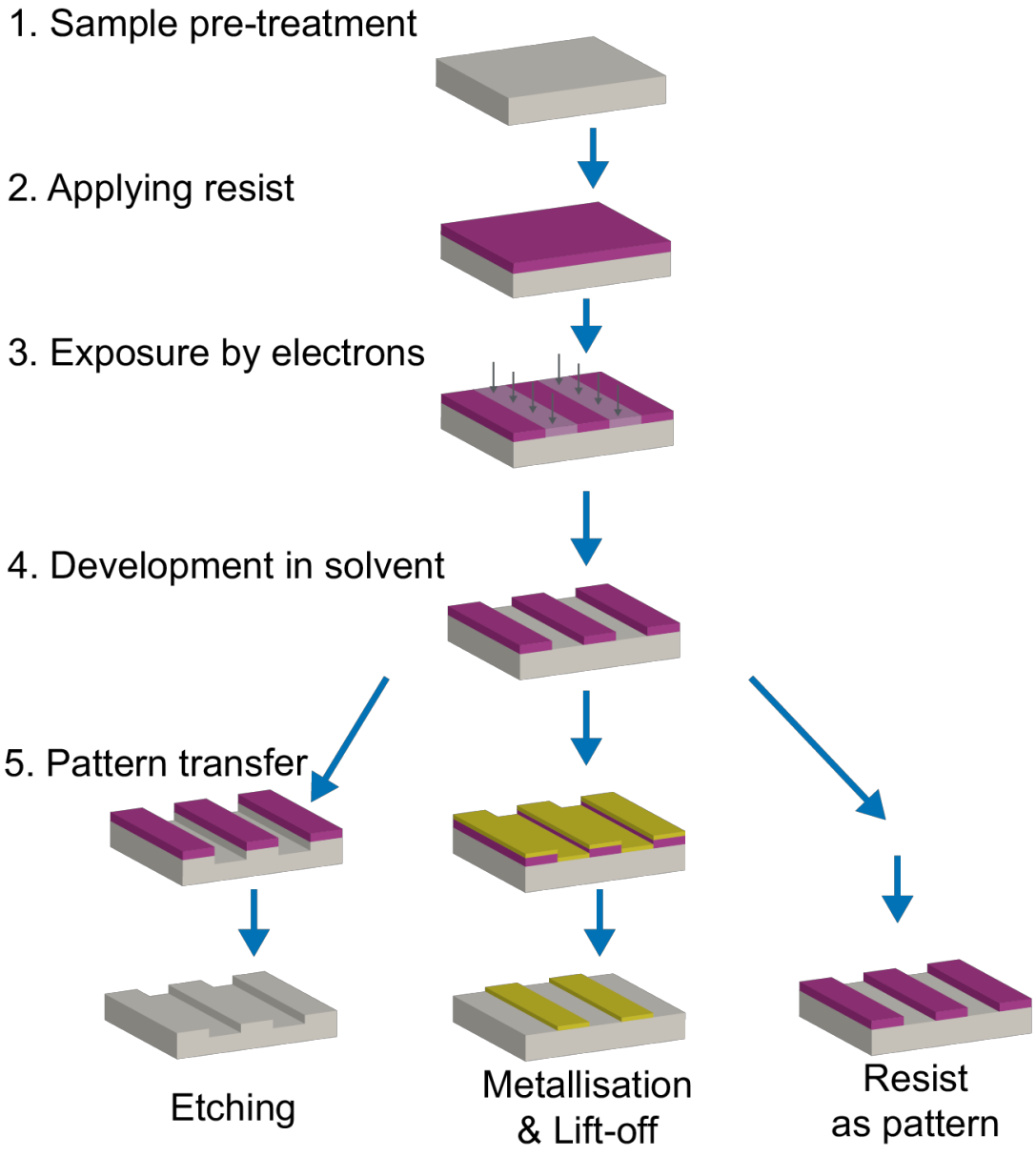


Steps of EBL

1. Sample pre-treatment
2. Applying resist
3. Exposure by electrons
4. Development in solvent

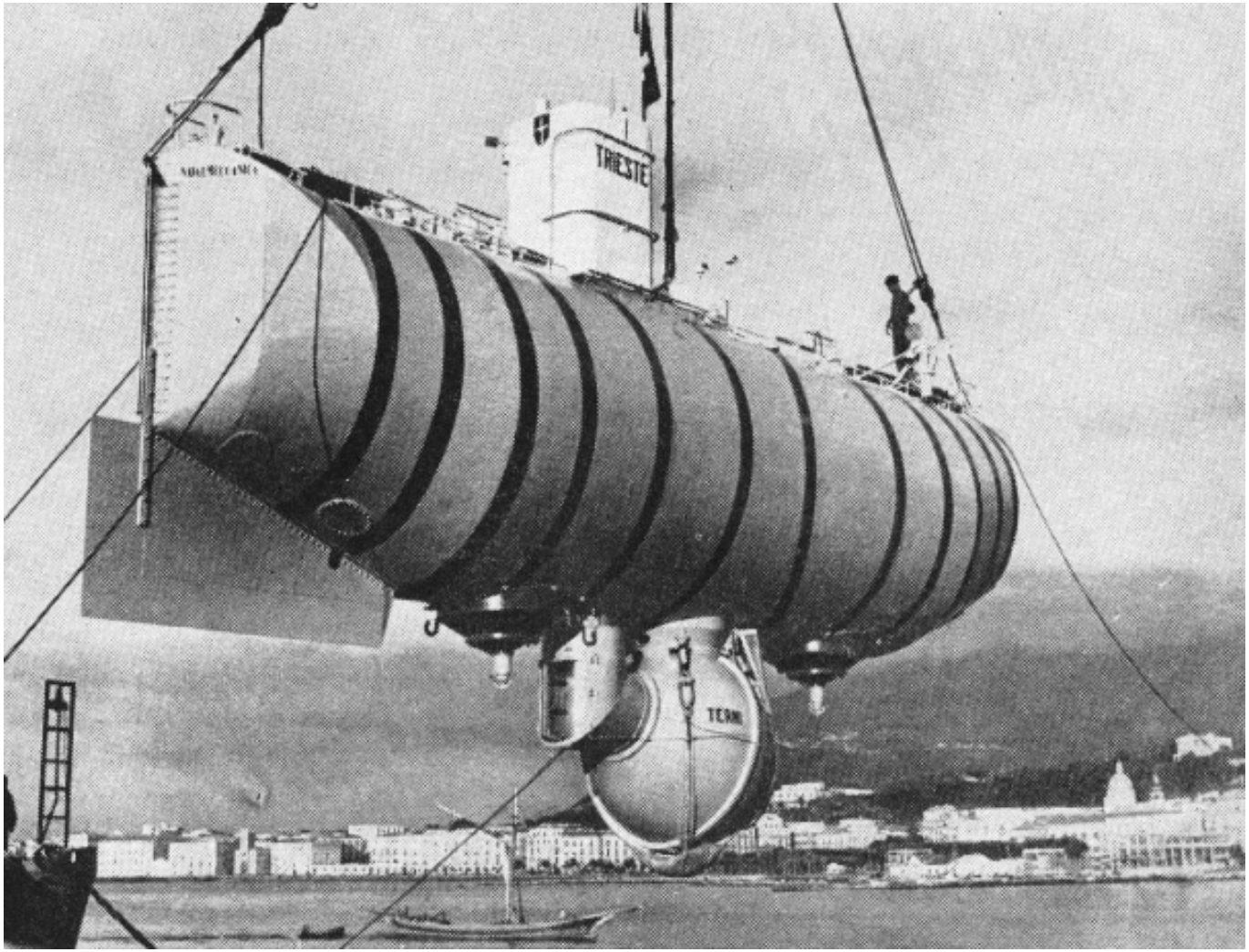


Steps of EBL


1. Sample pre-treatment
2. Applying resist
3. Exposure by electrons
4. Development in solvent
5. Pattern transfer
Etching
Metallisation
& Lift-off
Resist
as pattern

Electron Resist

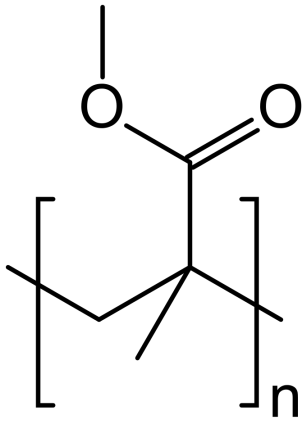
Bathyscaphe Trieste



Bathyscaphe Trieste

Bathyscaphe Trieste

Poly(methyl methacrylate)



What makes EBL work?

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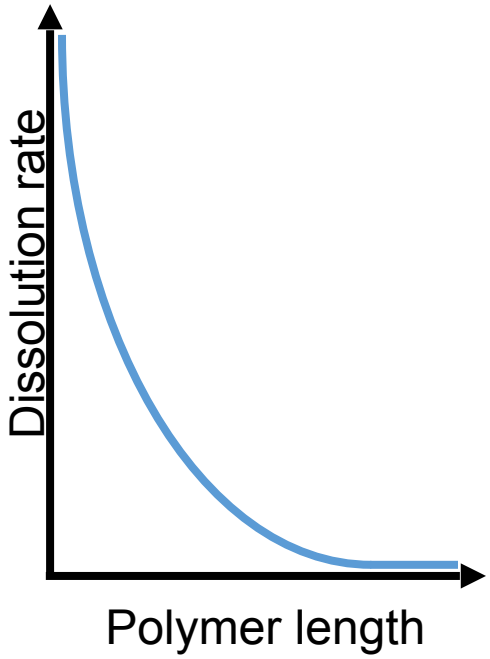

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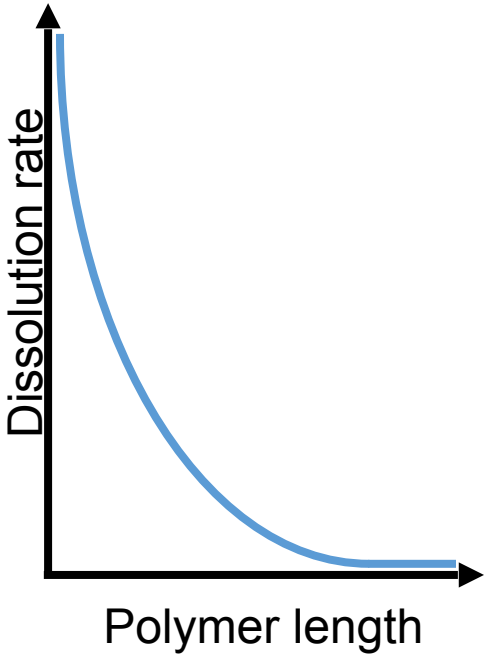

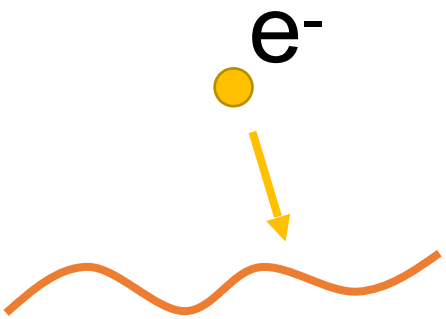

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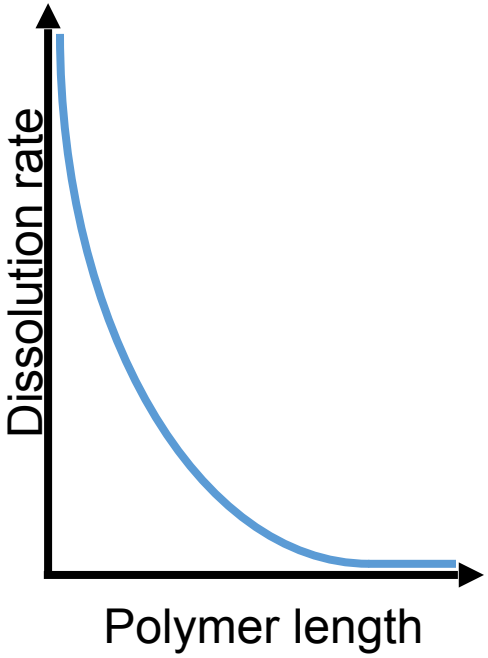

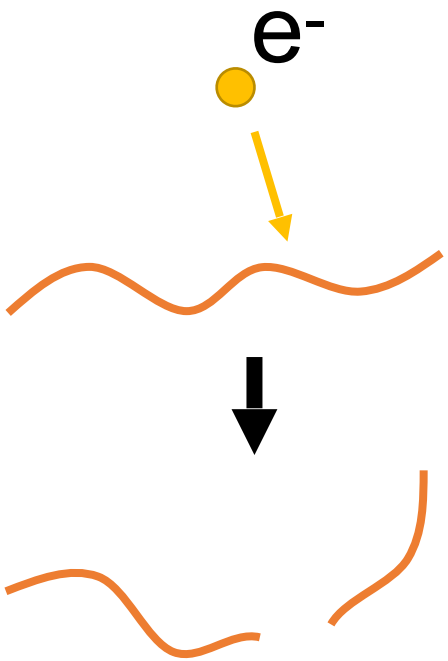

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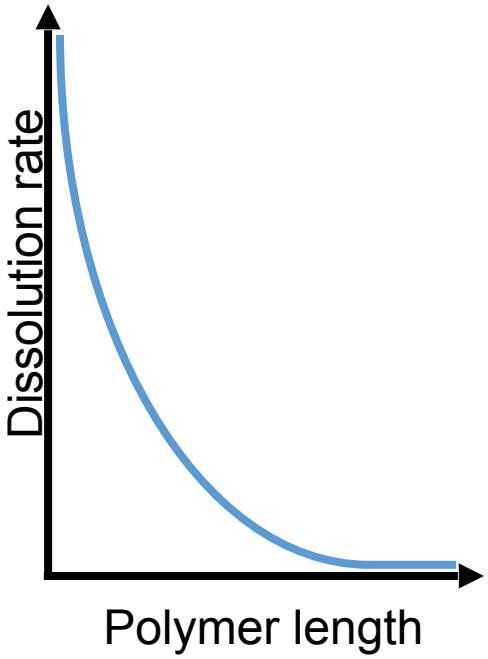
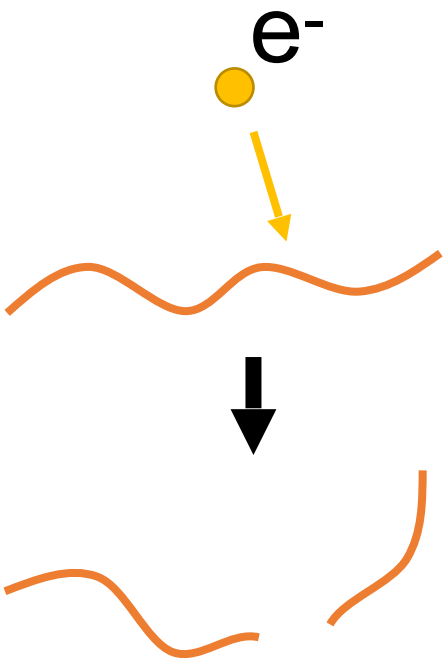
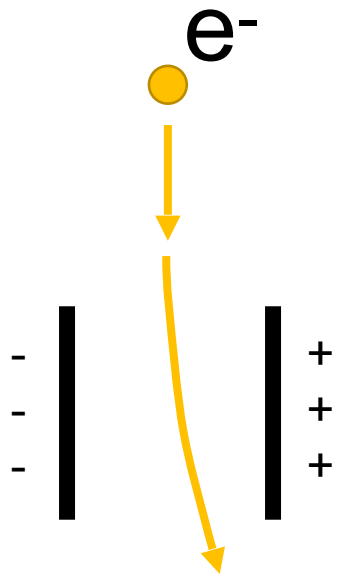
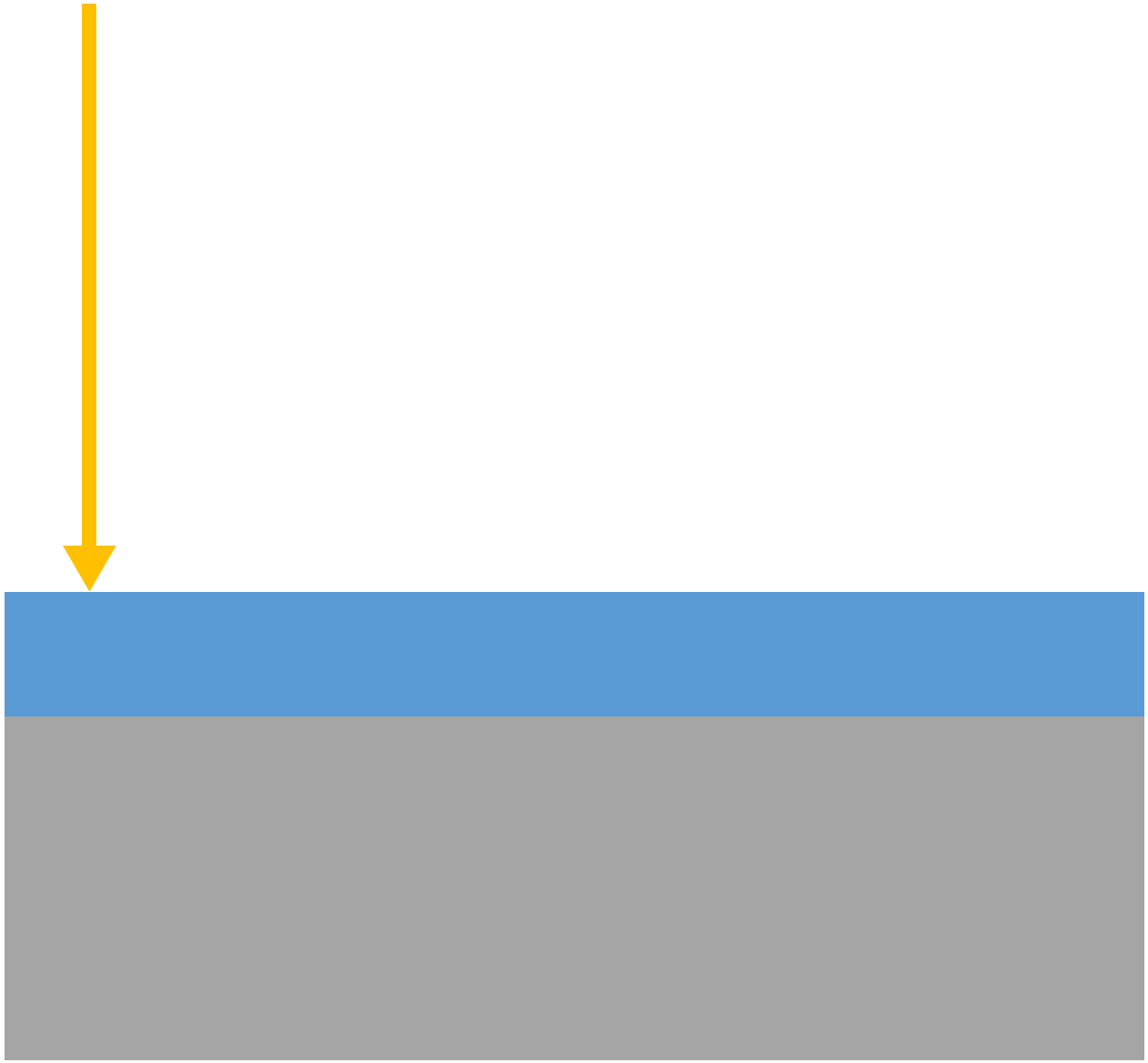
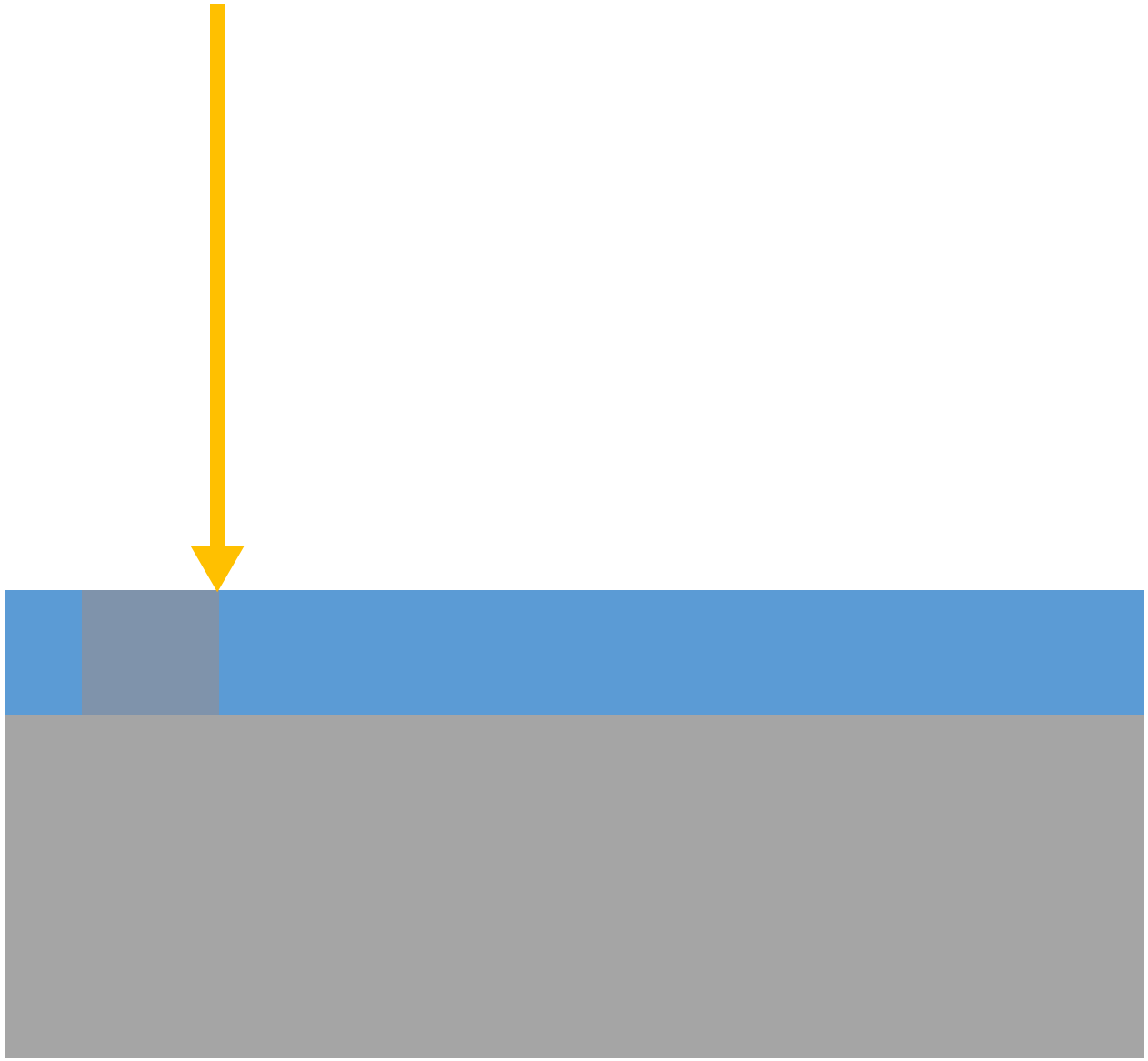
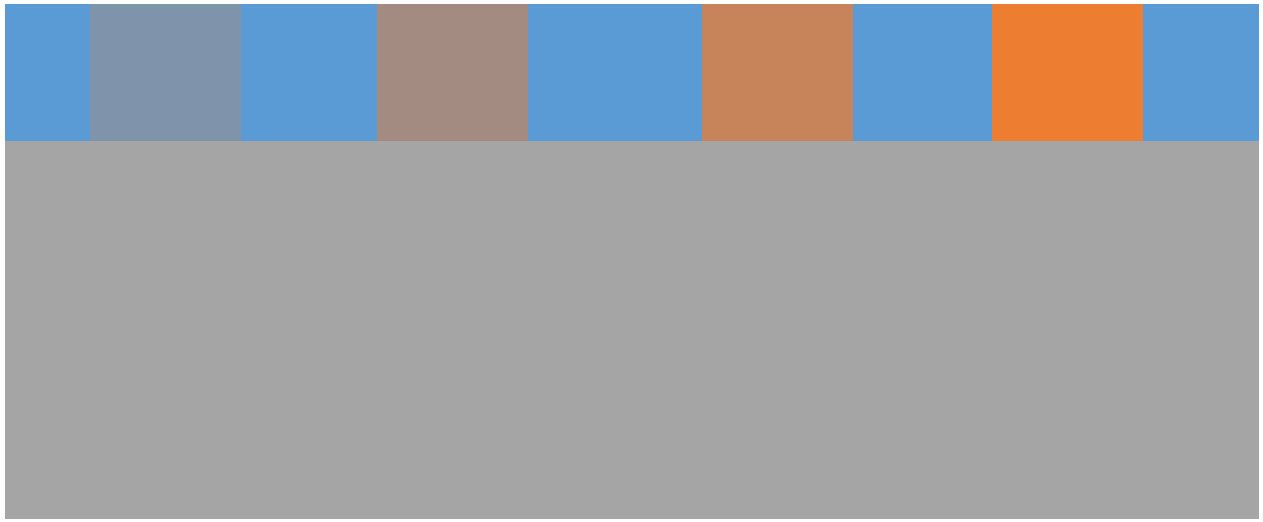






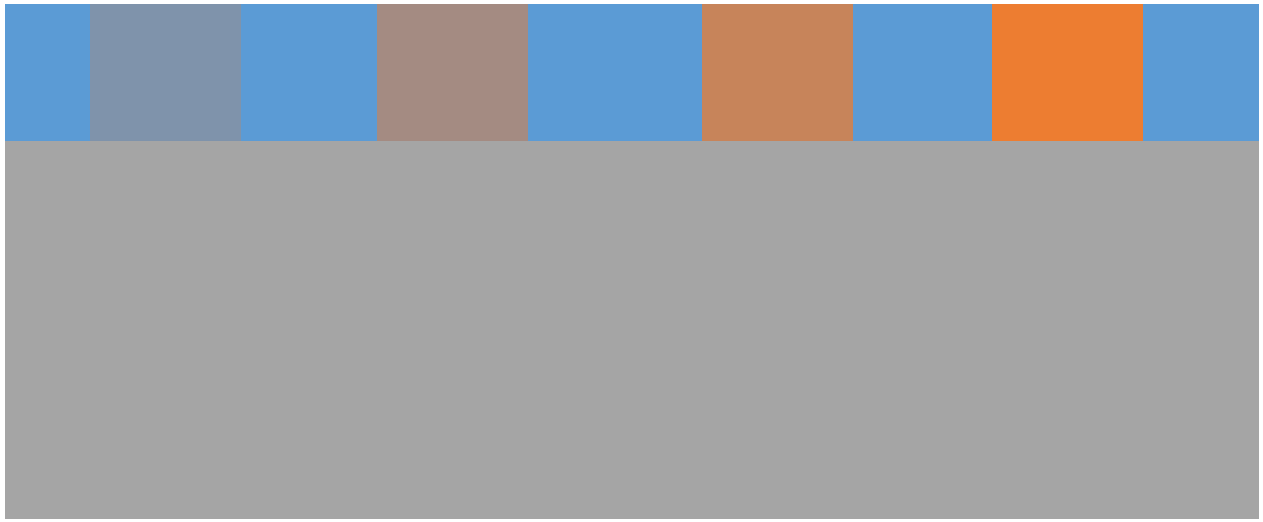


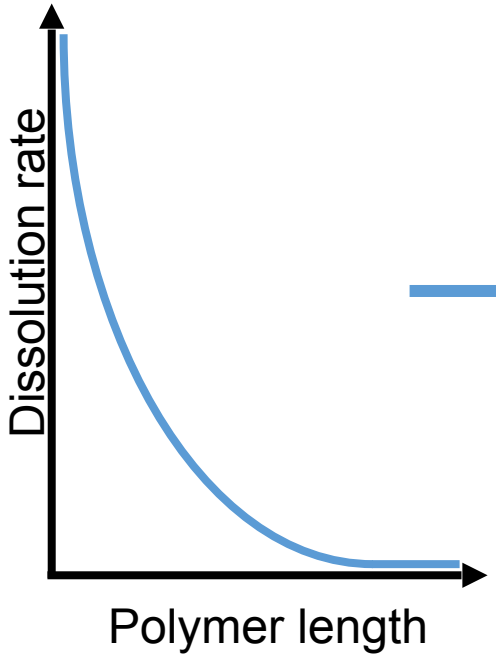




Higher Exposure Dose

Dose =





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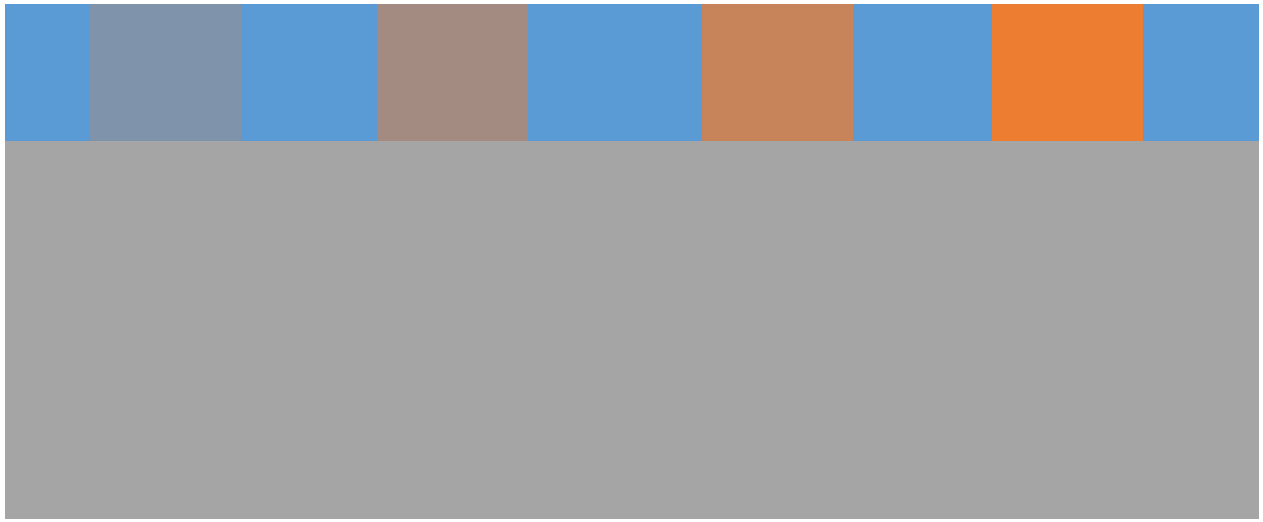
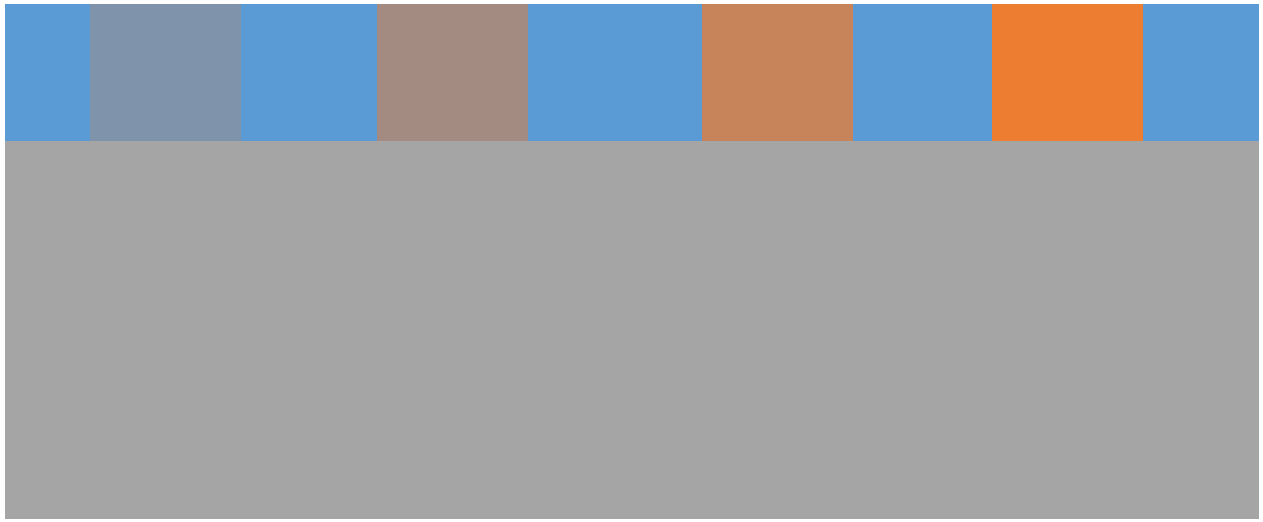
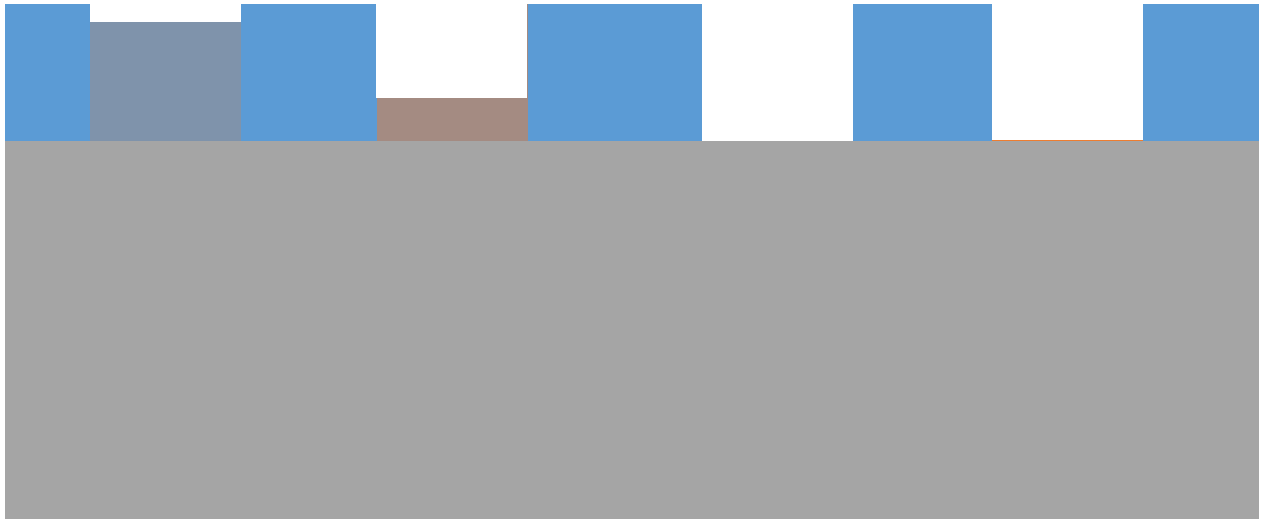
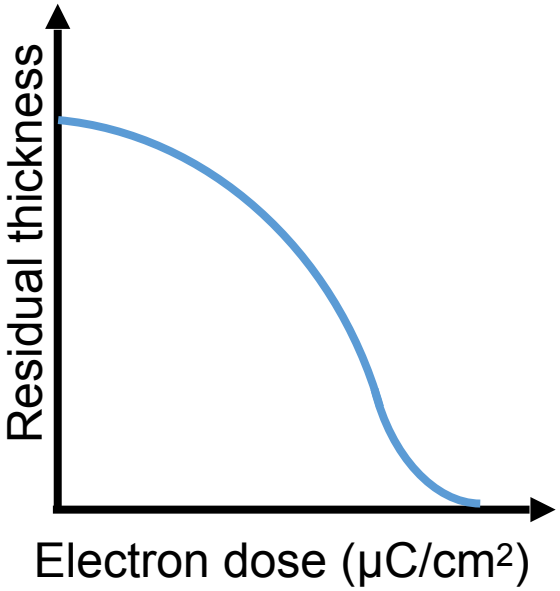
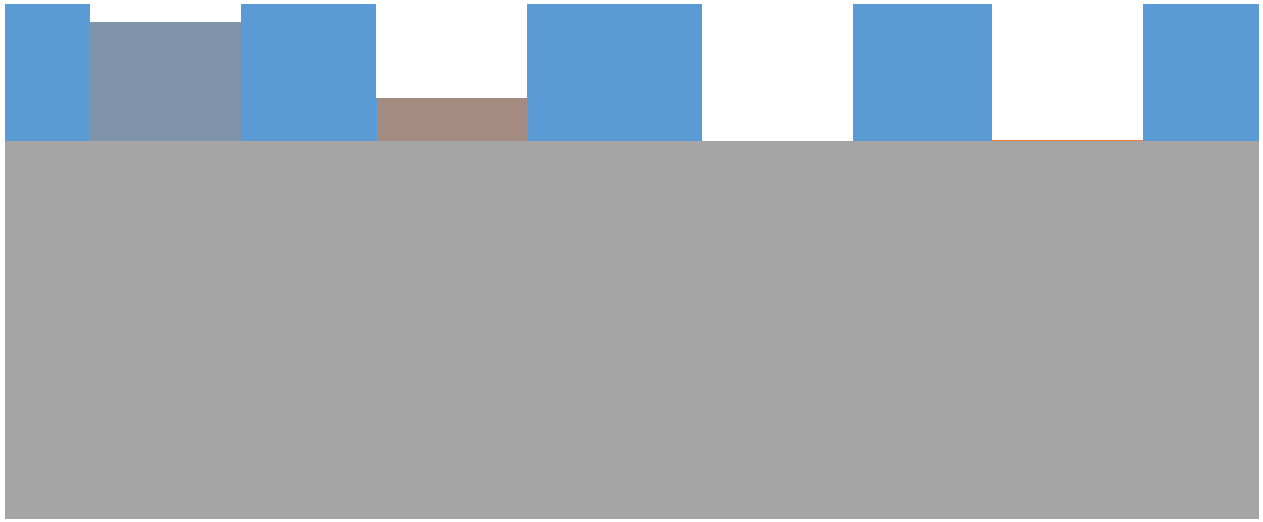
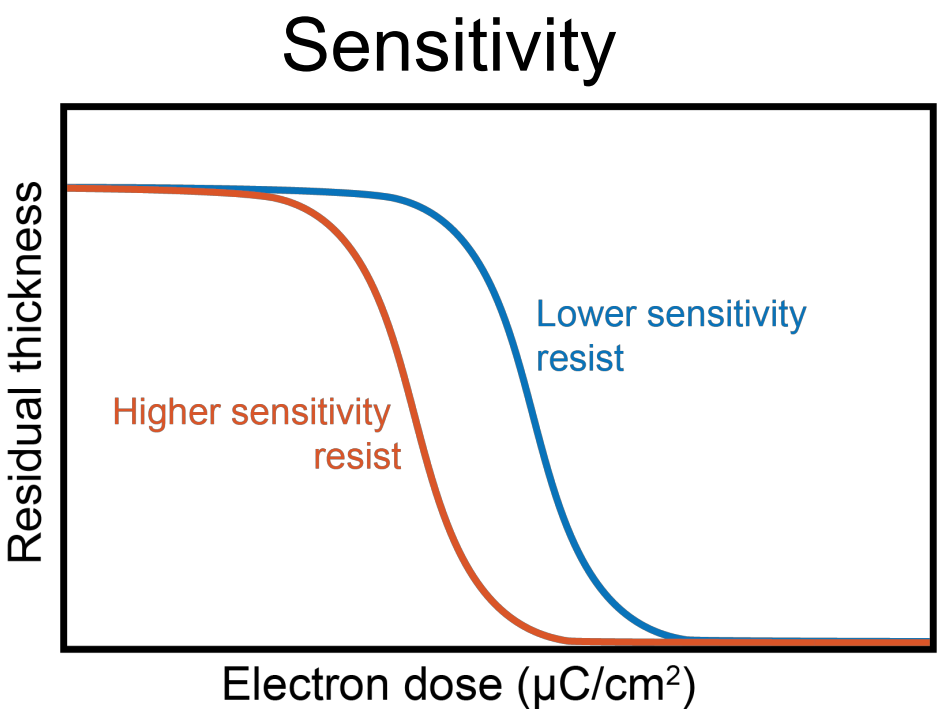


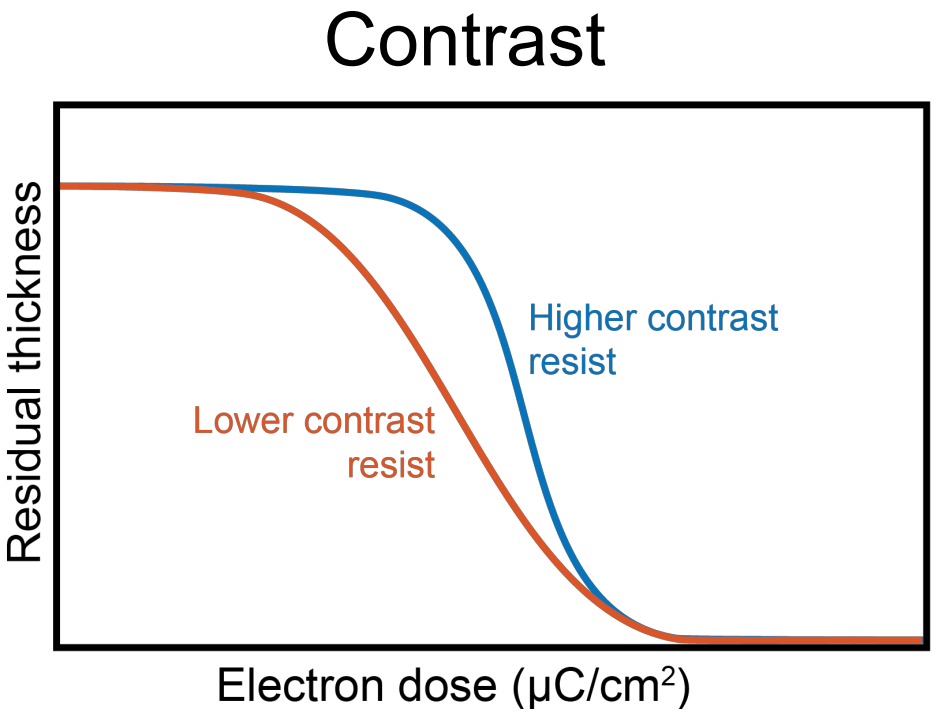




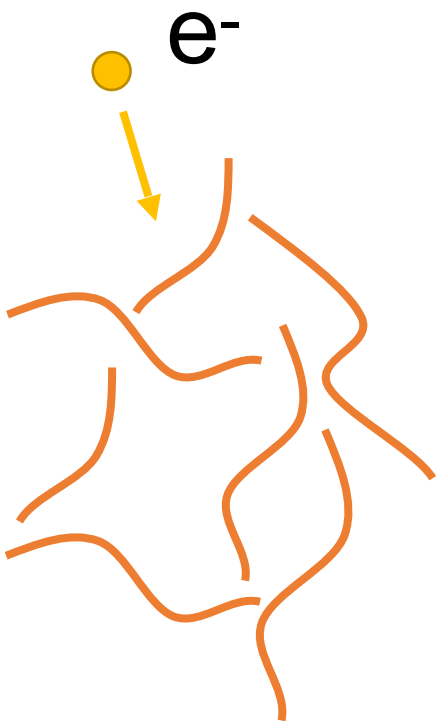

Residual thickness
Electron dose (μC/cm²)




Sensitivity
Residual thickness
Lower sensitivity resist
Higher sensitivity resist
Electron dose (μC/cm²)


Contrast
Residual thickness
Higher contrast resist
Lower contrast resist
Electron dose (μC/cm²)

Negative Resist



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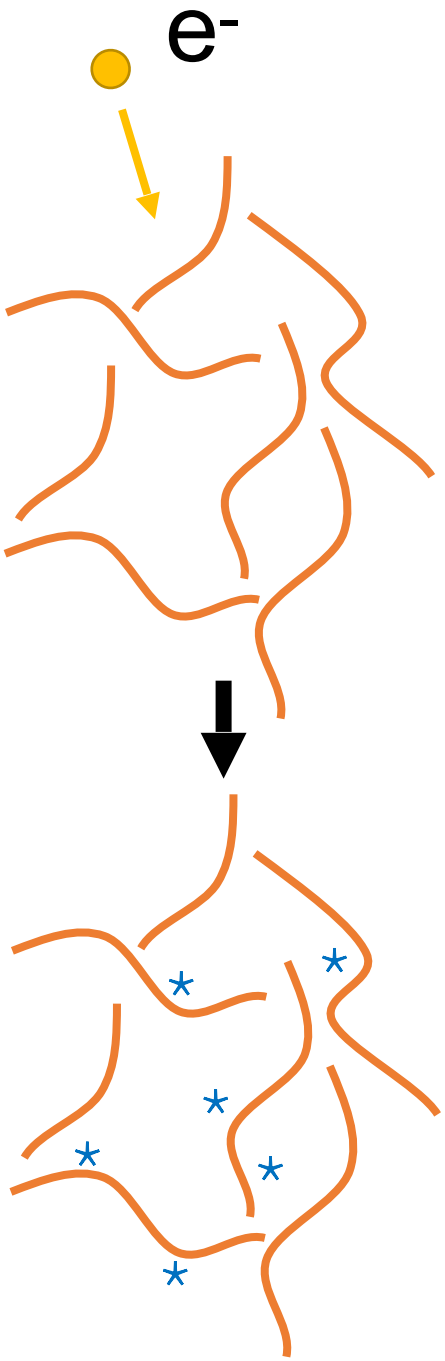

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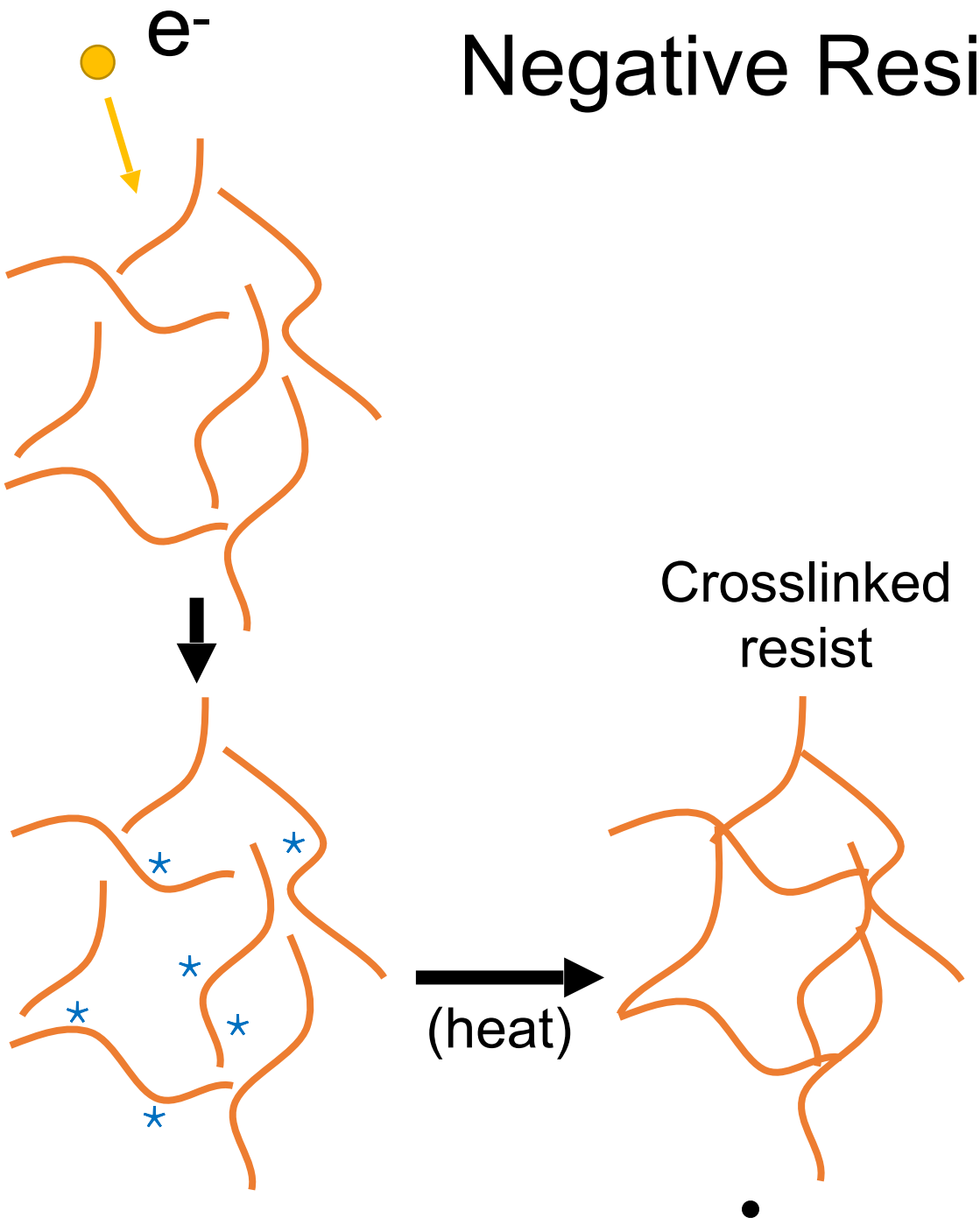
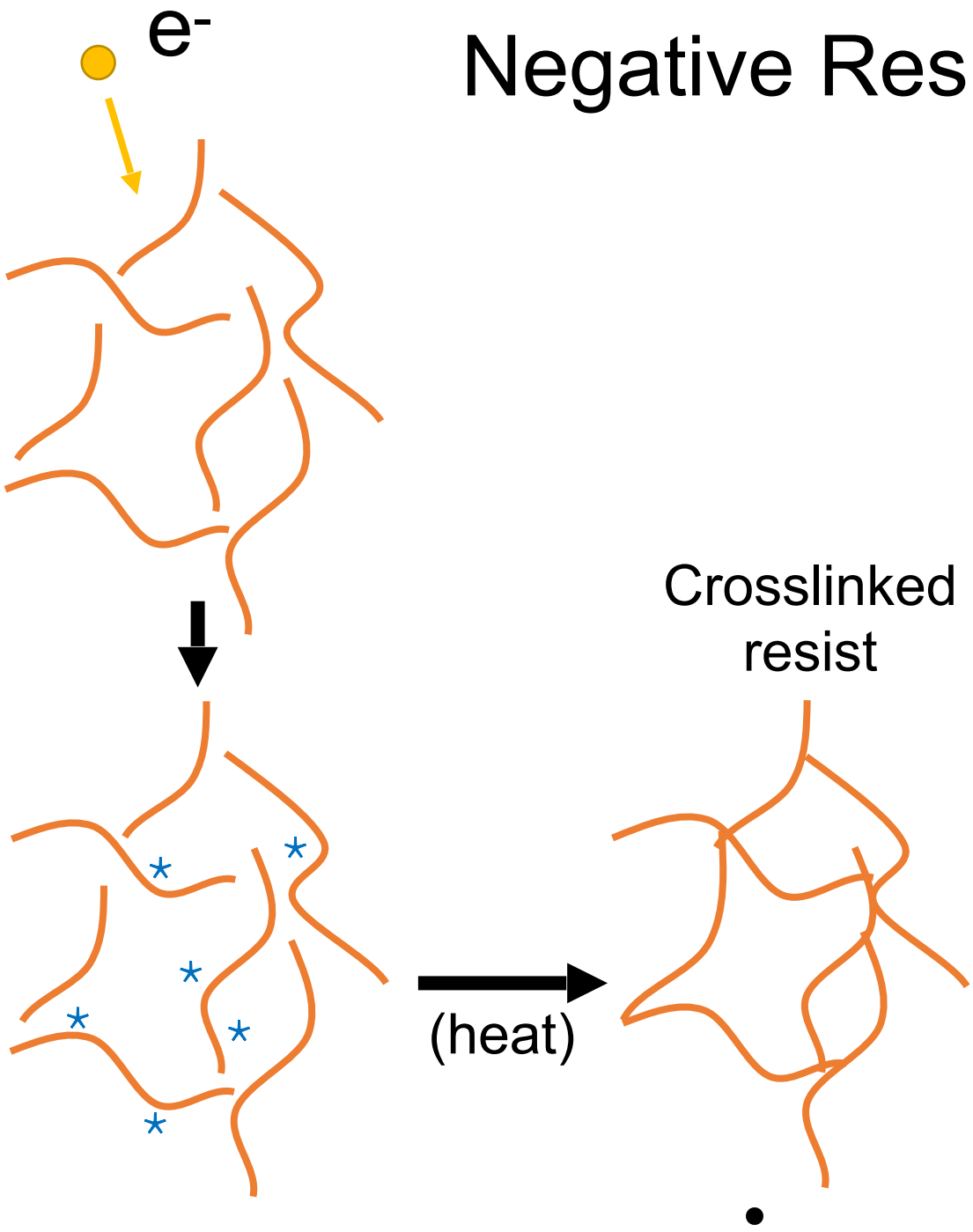
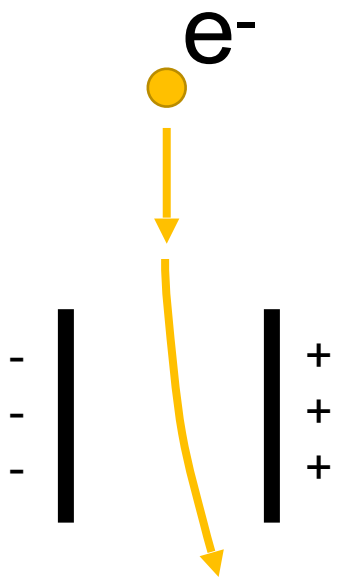
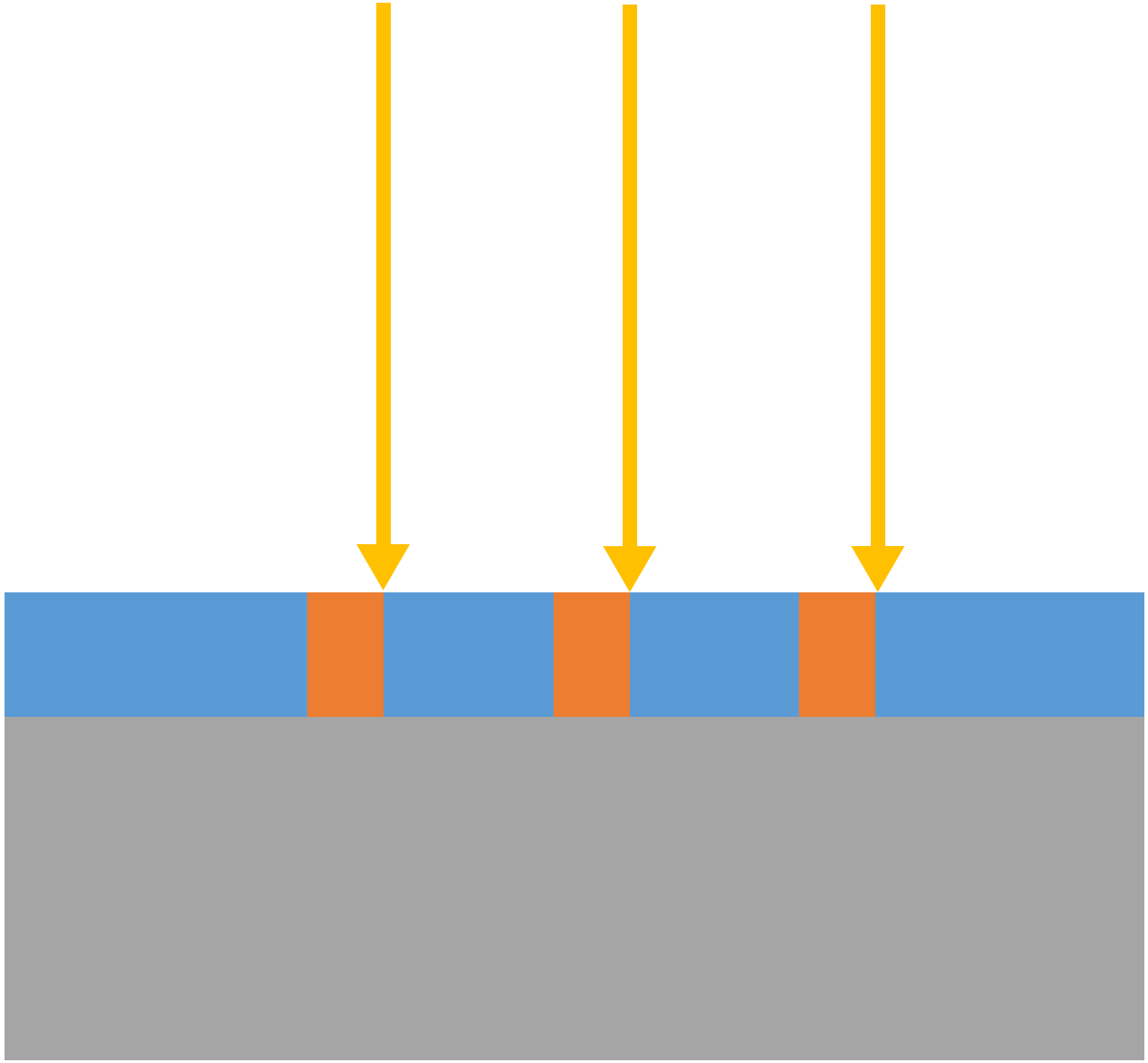
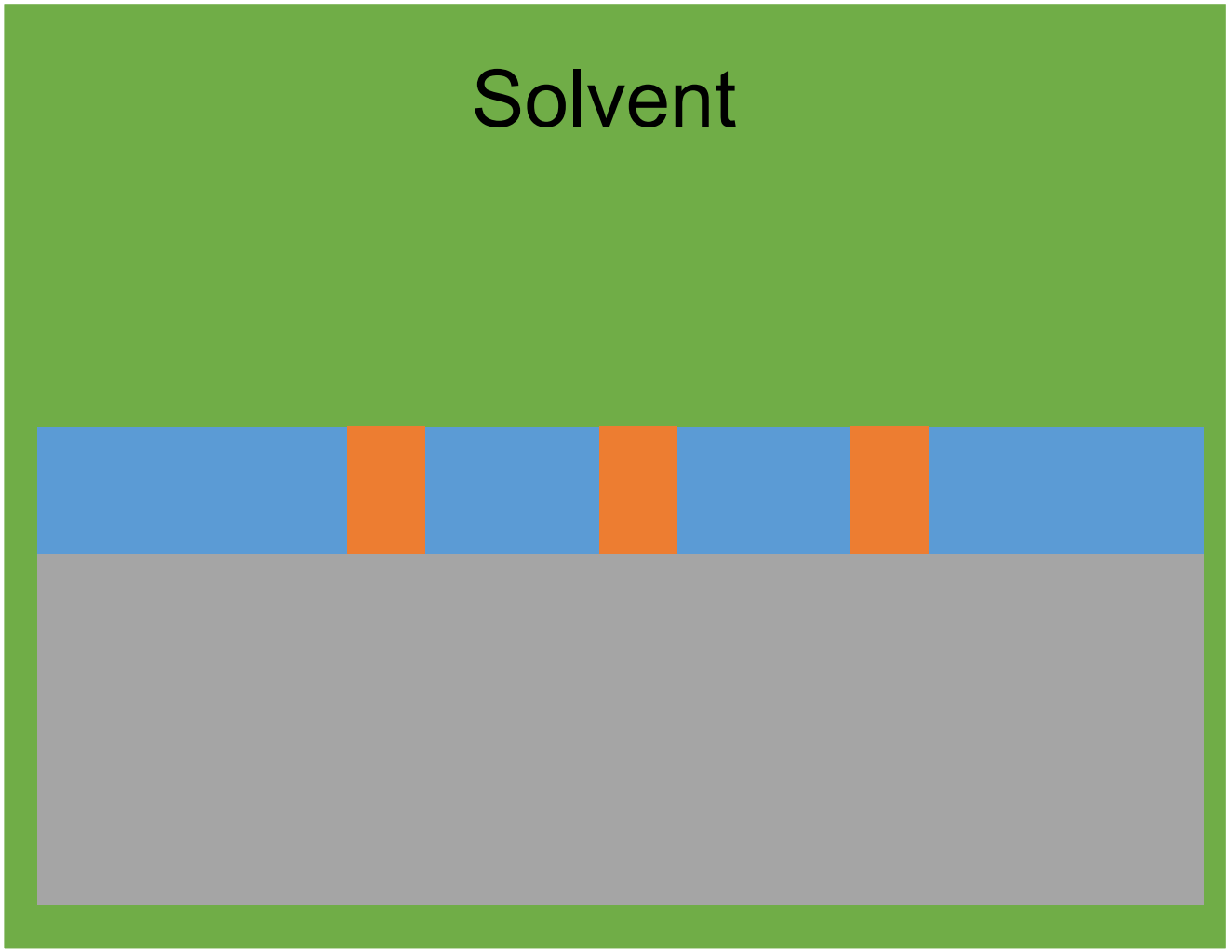


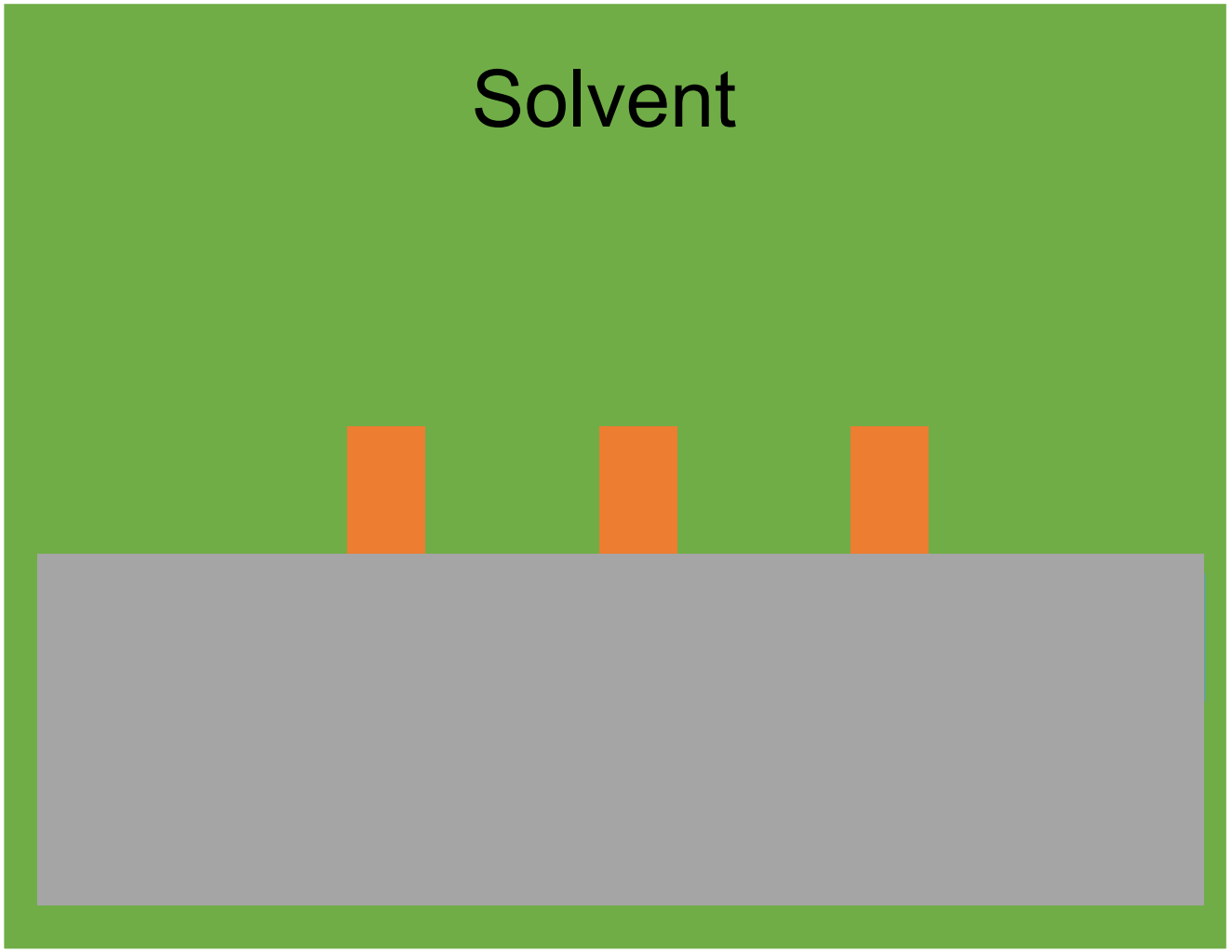
Negative Resist



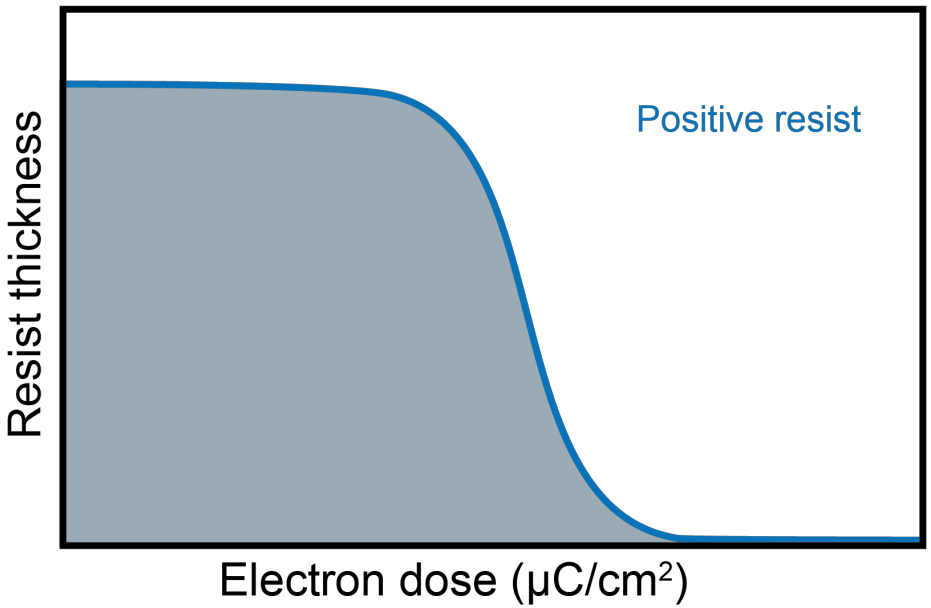


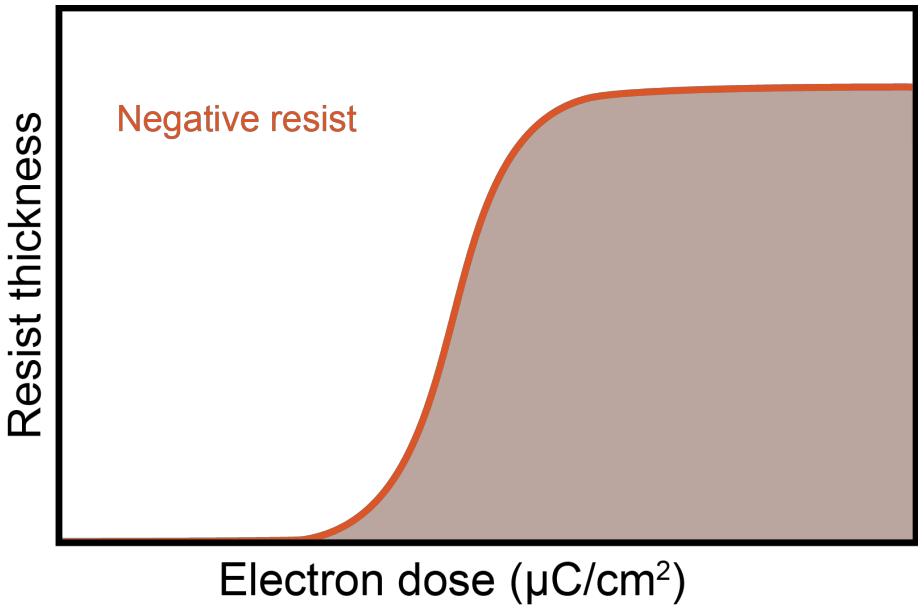



Solvent

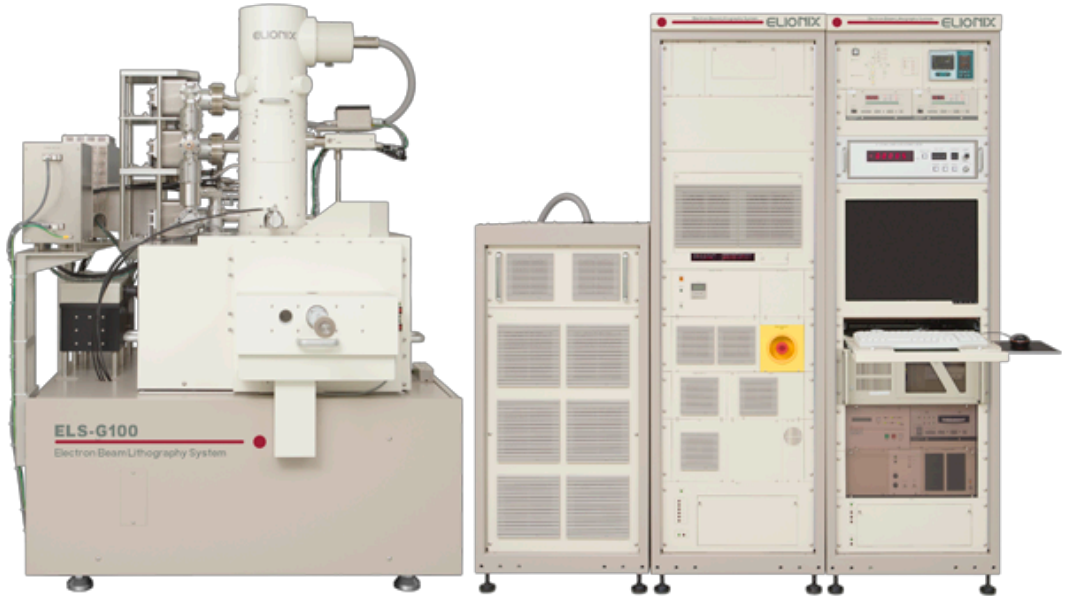

Solvent

Electron resists





Energy density and electron dose

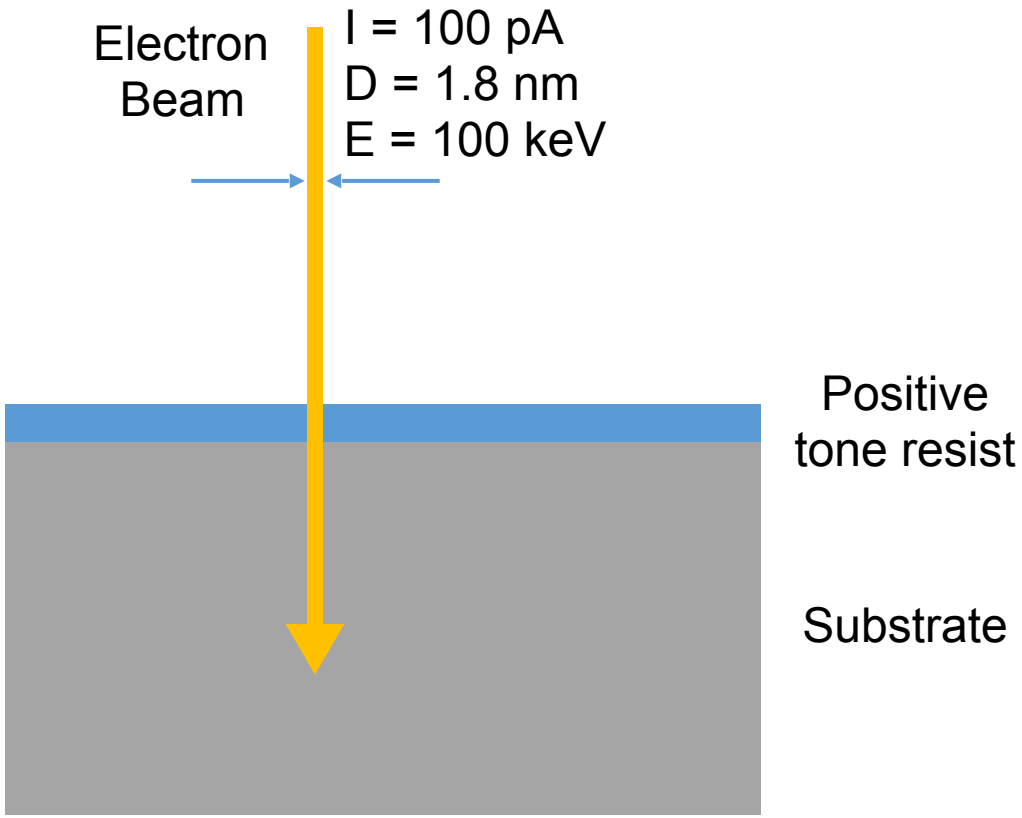


Elionix ELS-G100: EBL installed at NTNU NanoLab
Minimum beam spot size: 1.8 nm

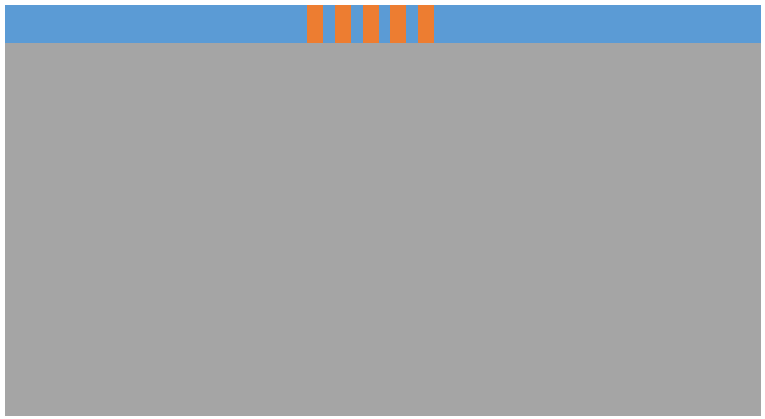
Resolution: 7 nm

What is limiting the achieveable resolution in EBL?

Electron Beam Lithography in the «ideal» world



Electron Beam Lithography in the «ideal» world

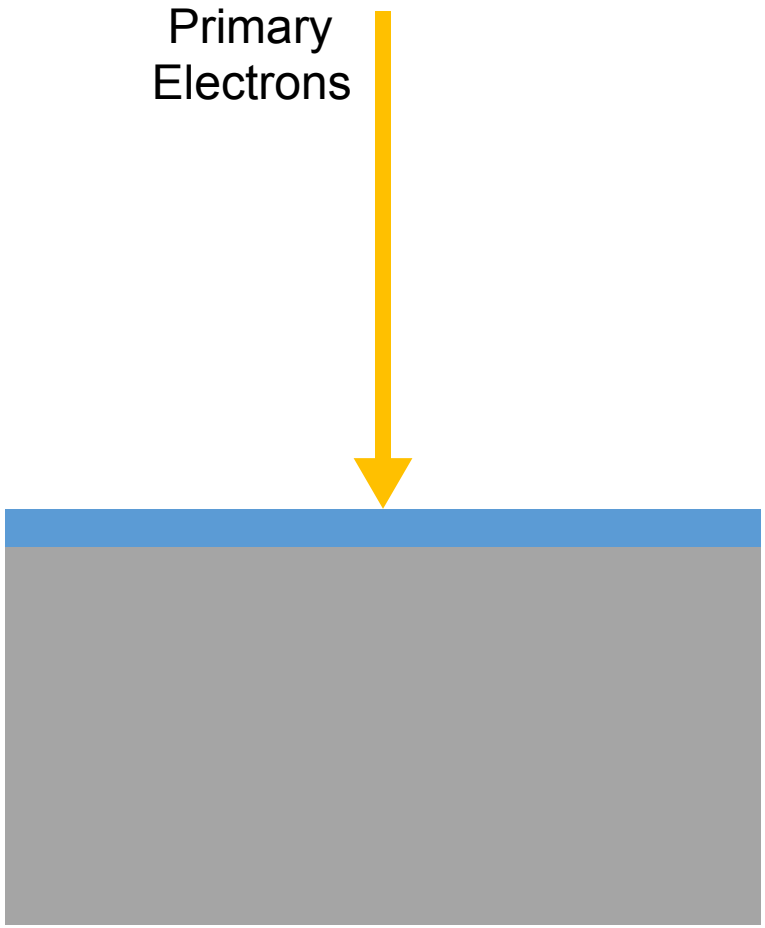


Positive tone resist

Substrate

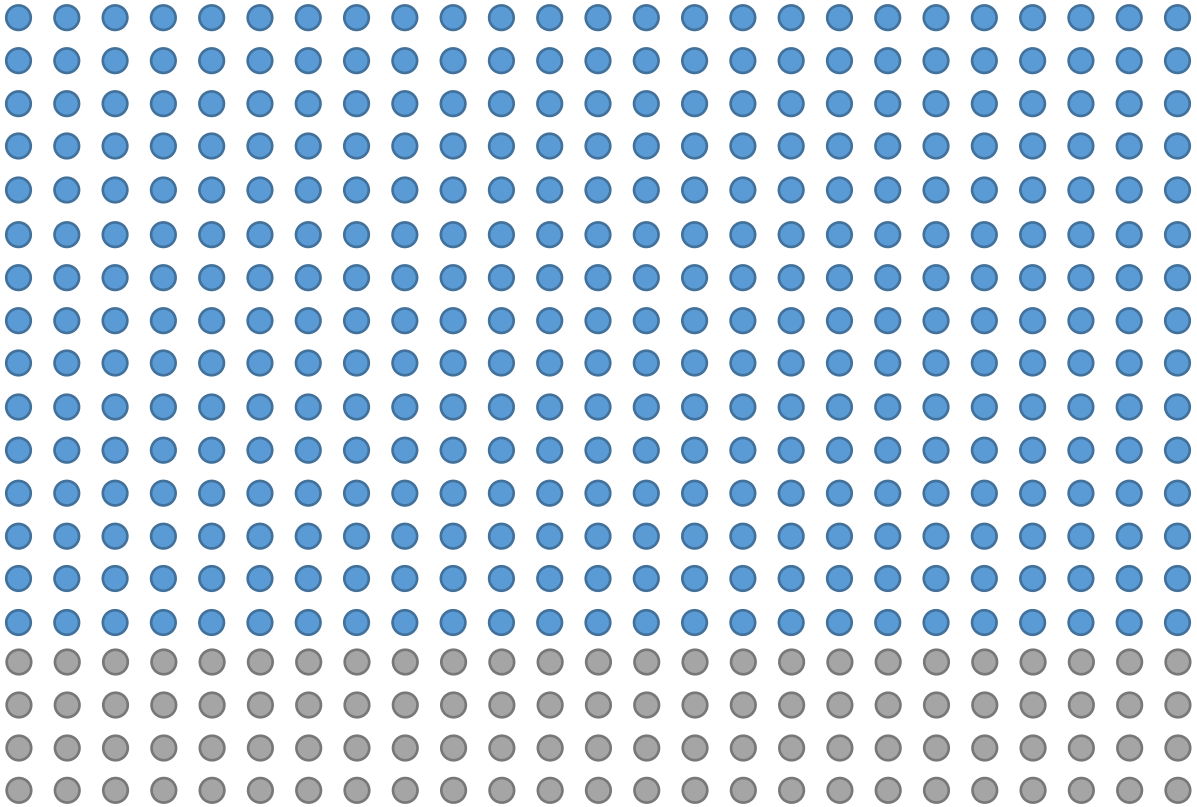
Electron Beam Lithography in the real ~~«ideal»~~ world

Electron – Resist Interaction



Solids at the microscopic level

Solids at the microscopic level

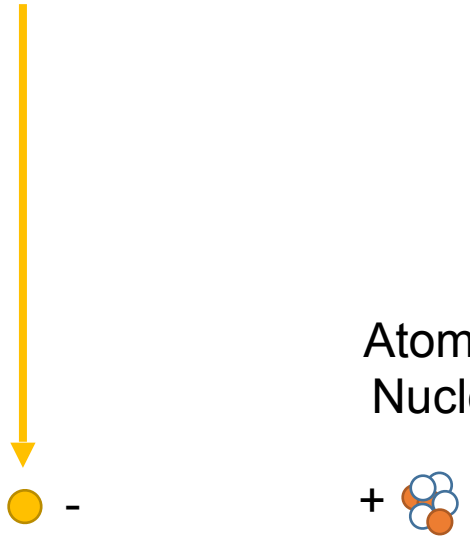


Elastic Scattering

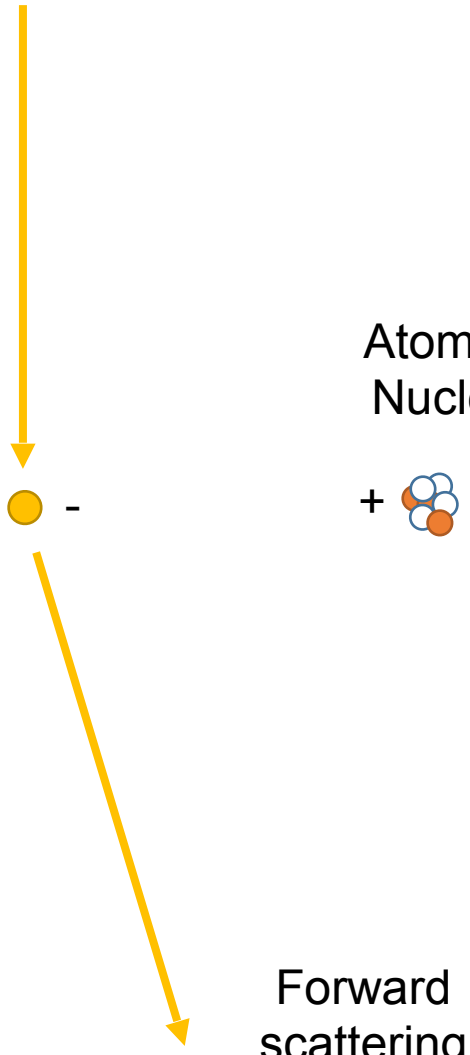
Atomic
Nuclei

+ 

Elastic Scattering



Elastic Scattering



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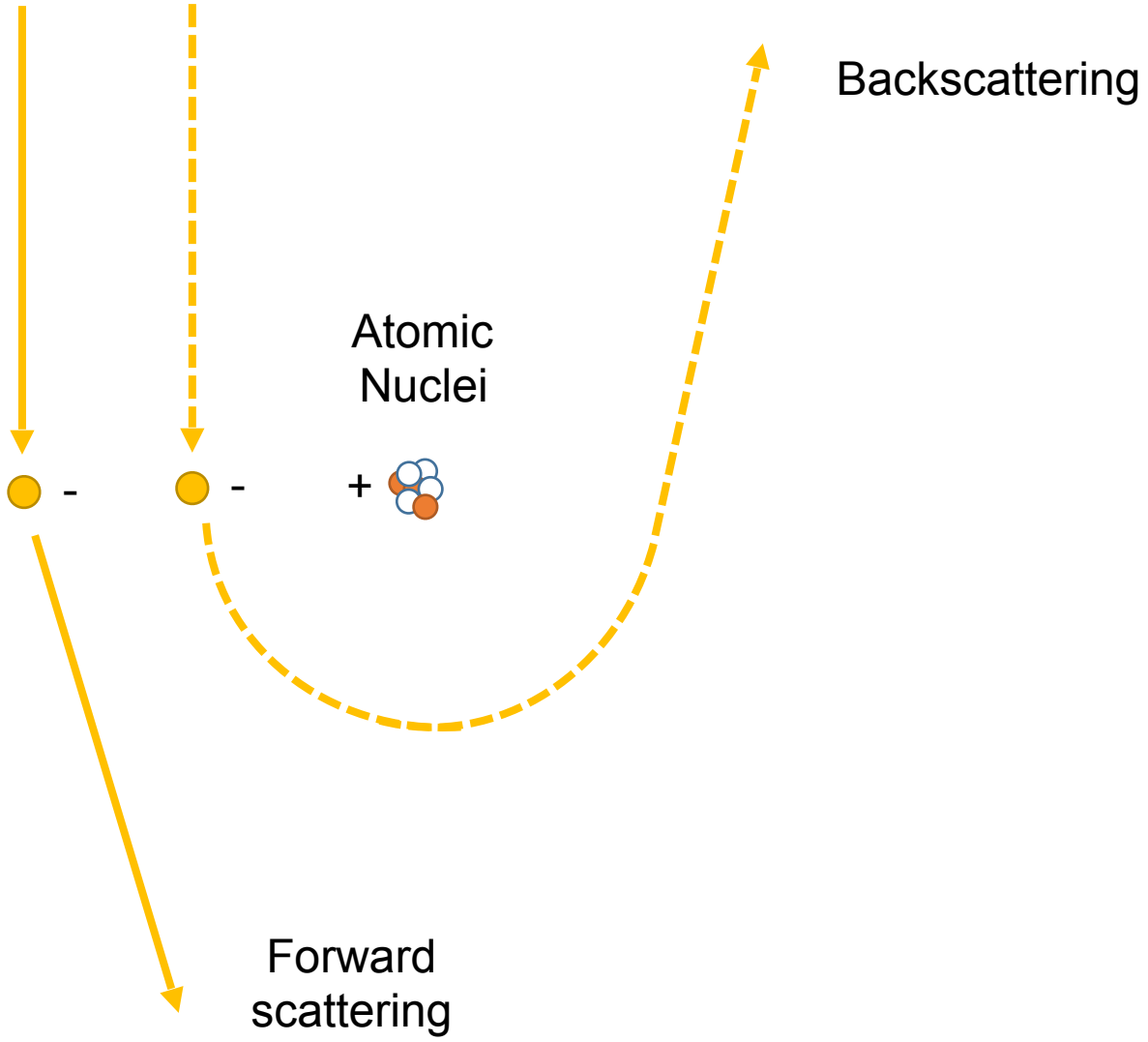

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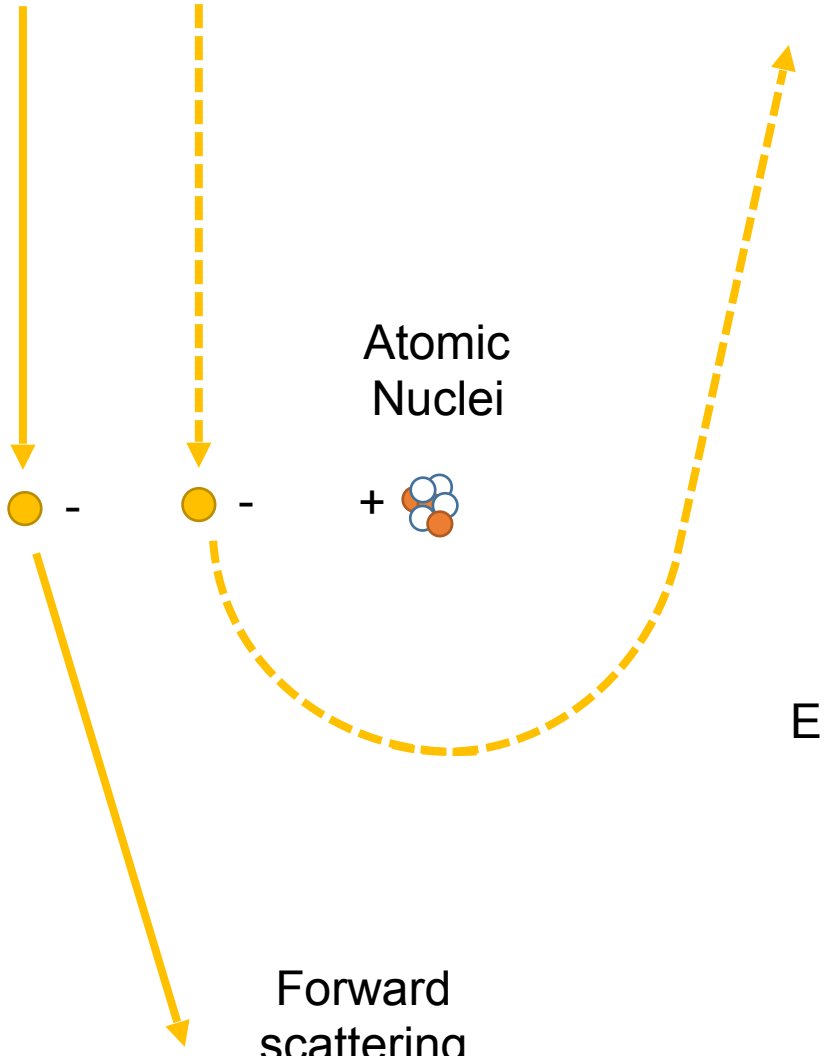
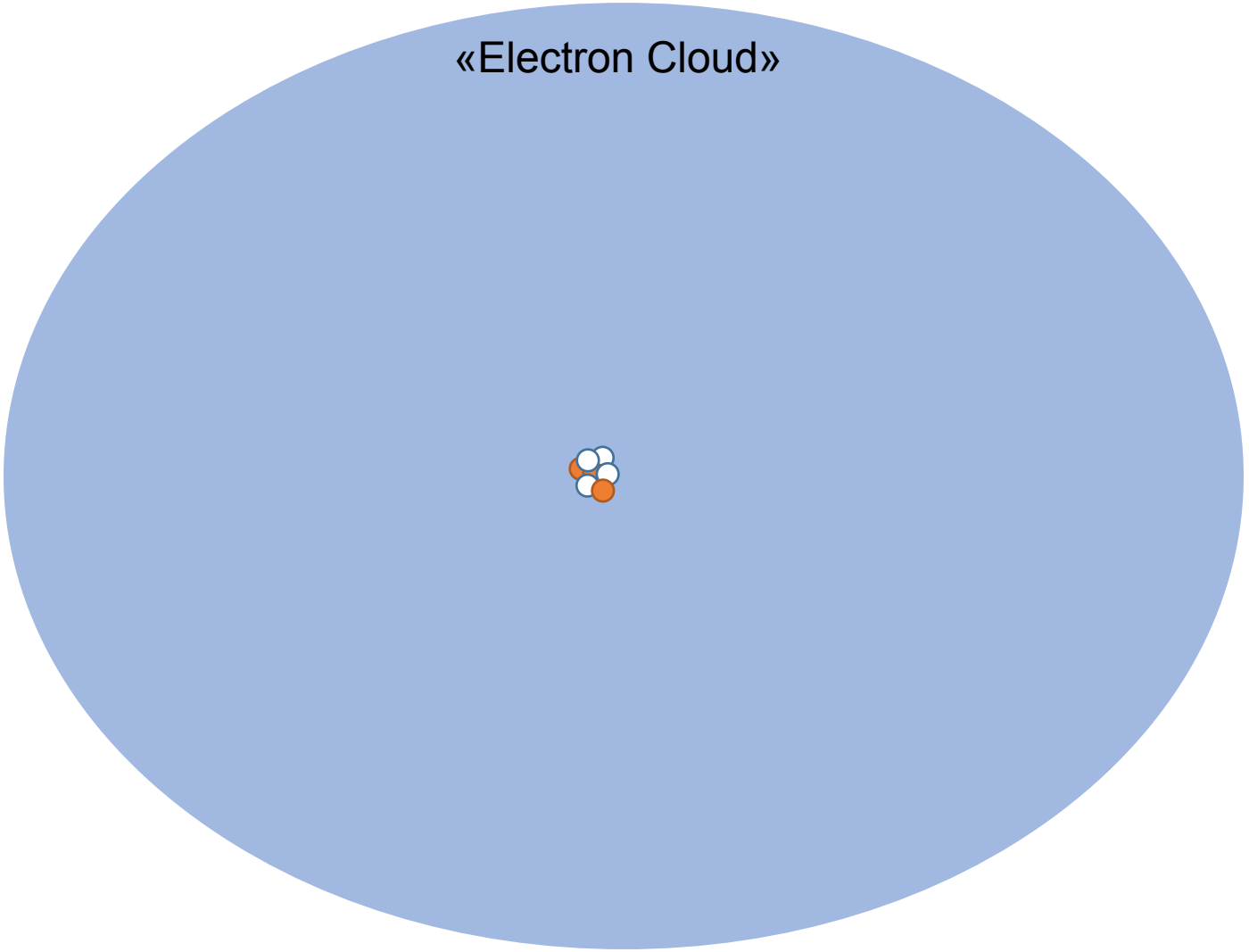
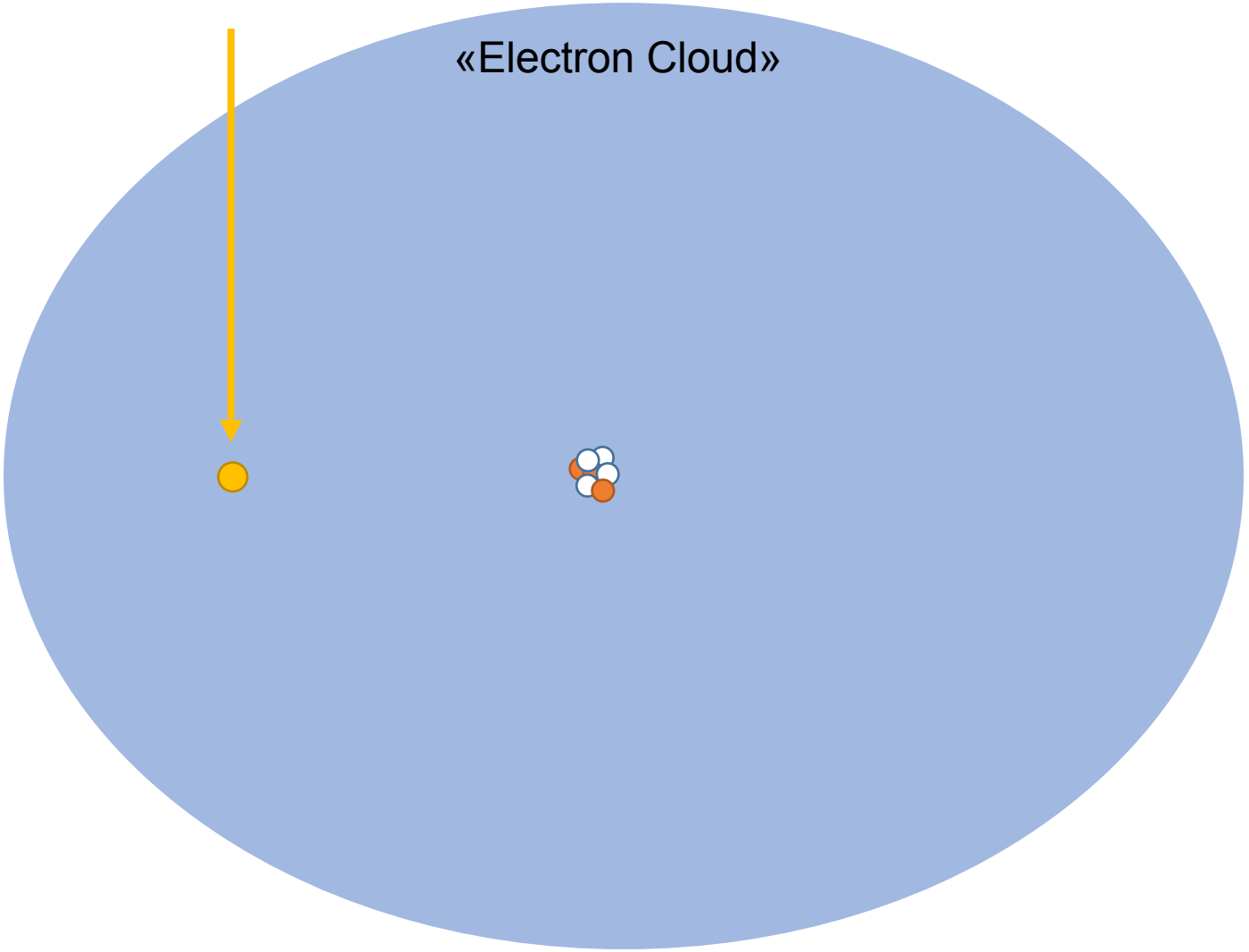


Elastic = No energy loss

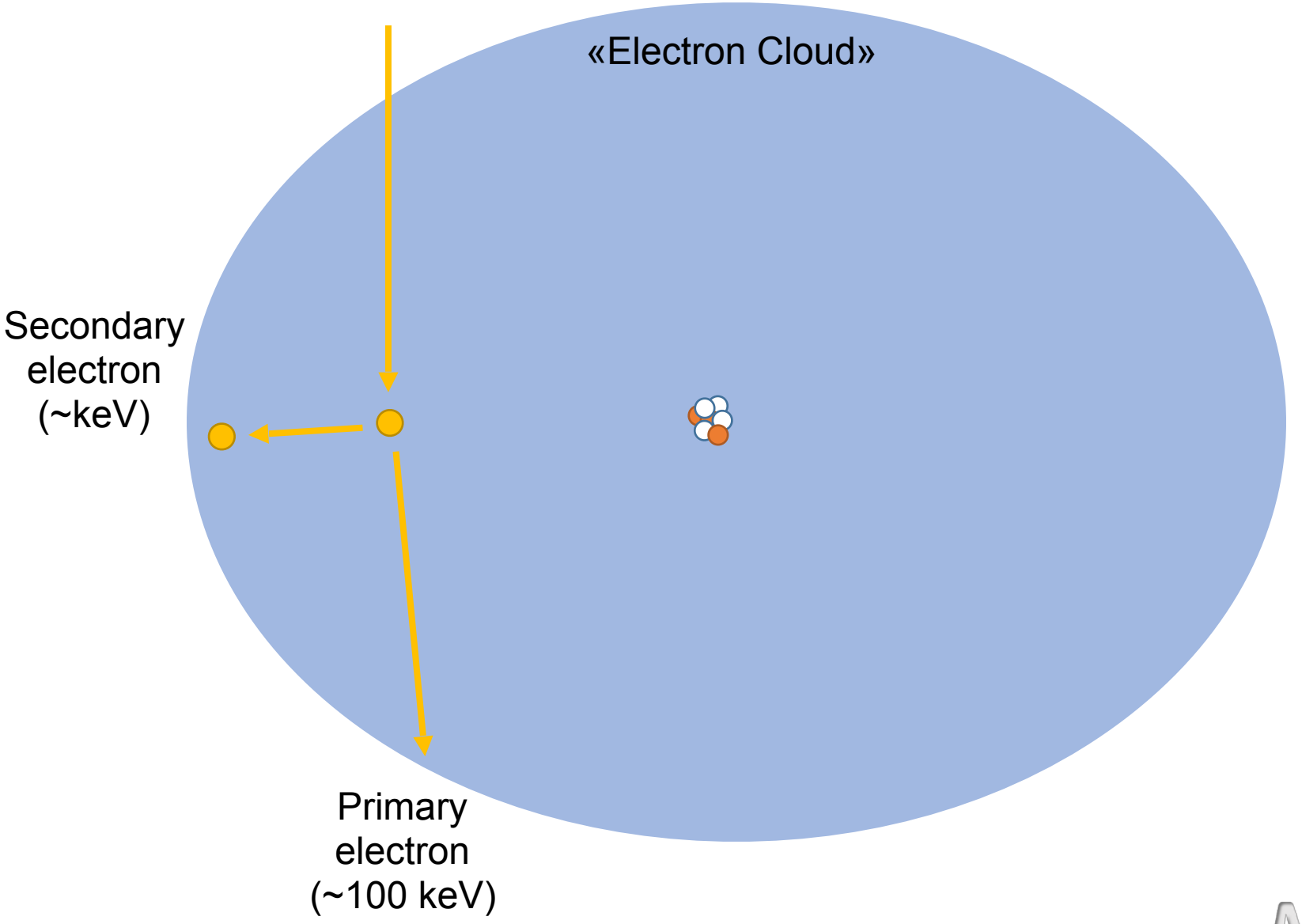
Inelastic Scattering



Inelastic Scattering

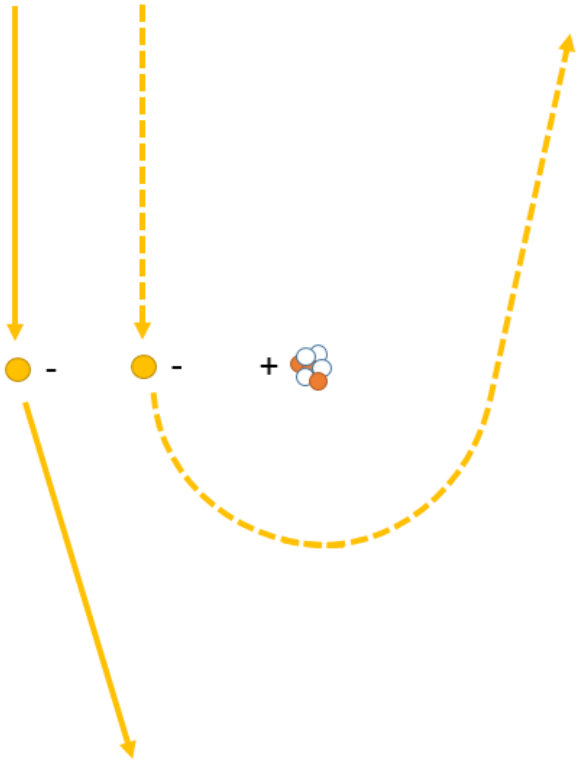


Inelastic Scattering



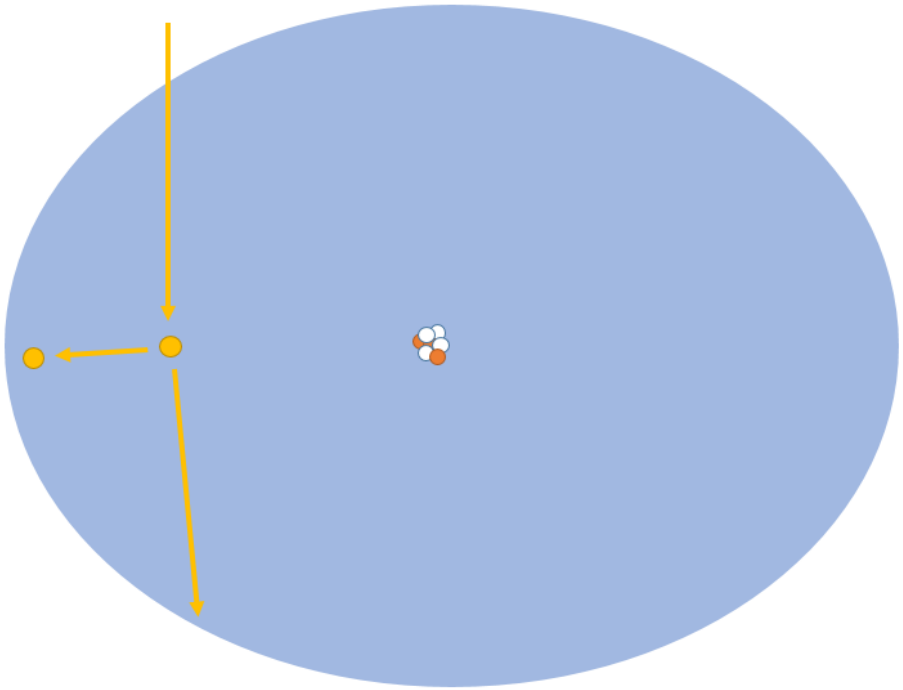
Elastic Scattering

No energy loss
Direction change

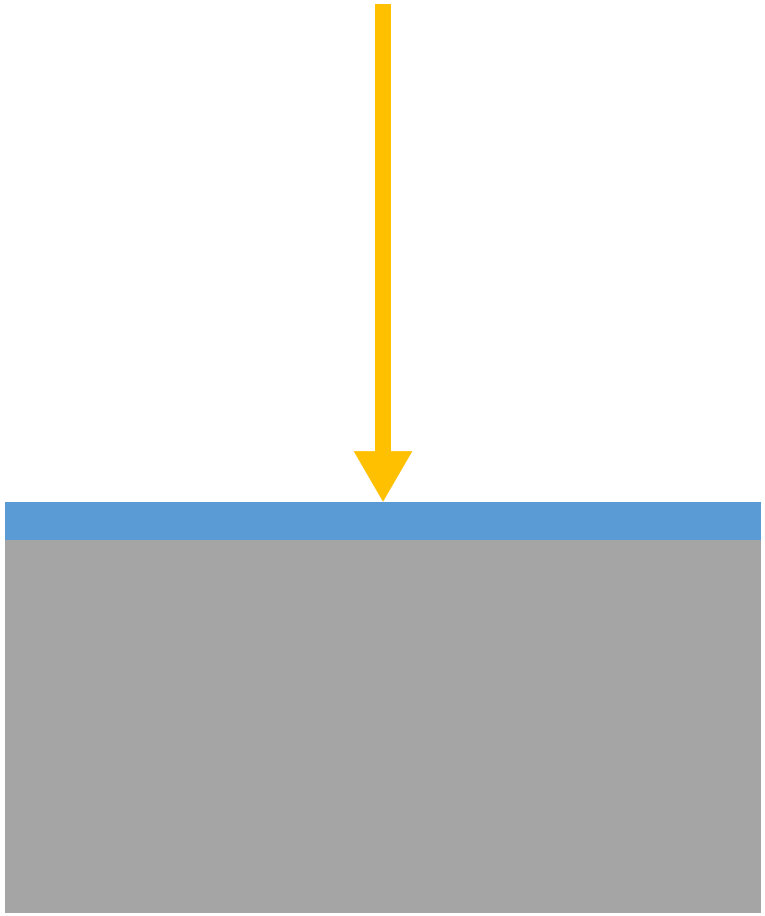


Inelastic Scattering

Small energy loss
No direction change
Generates secondary electrons



Trajectory of Primary Electrons



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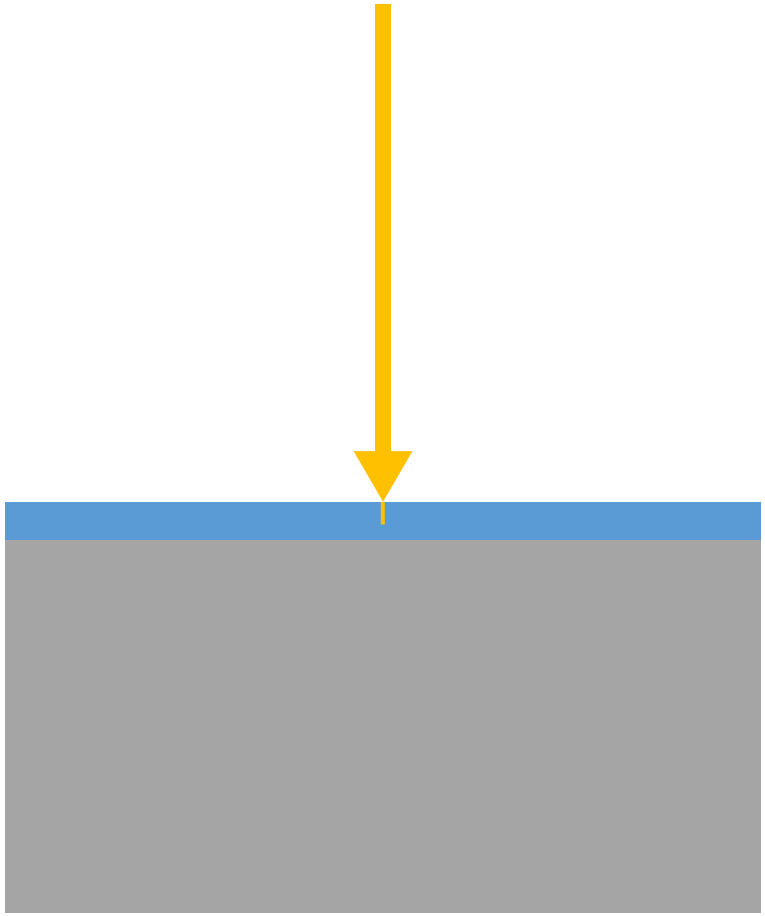
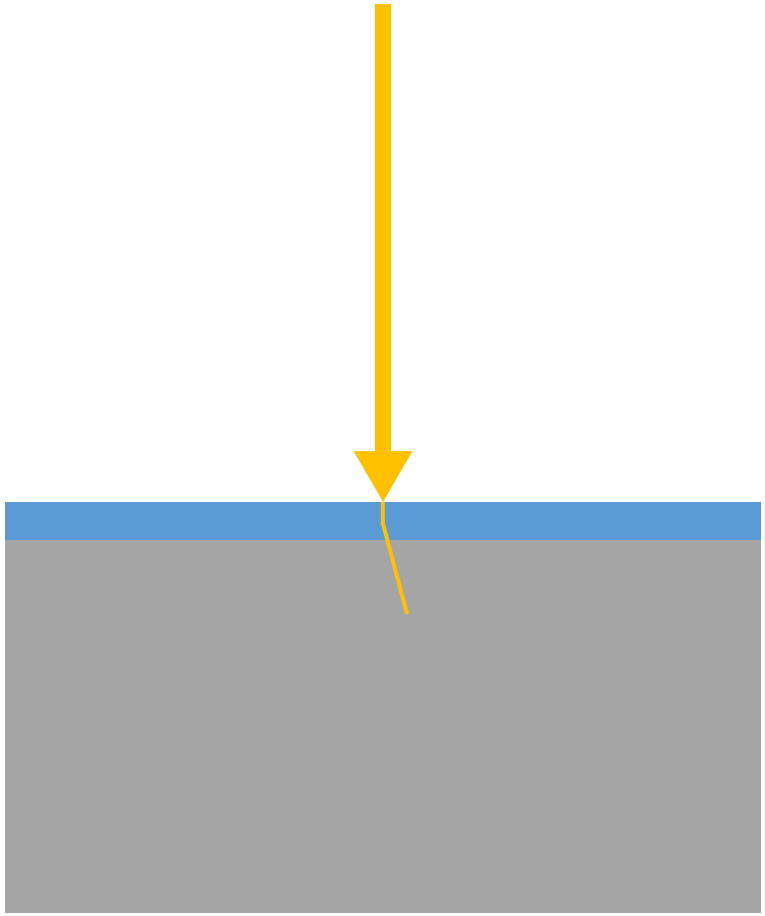
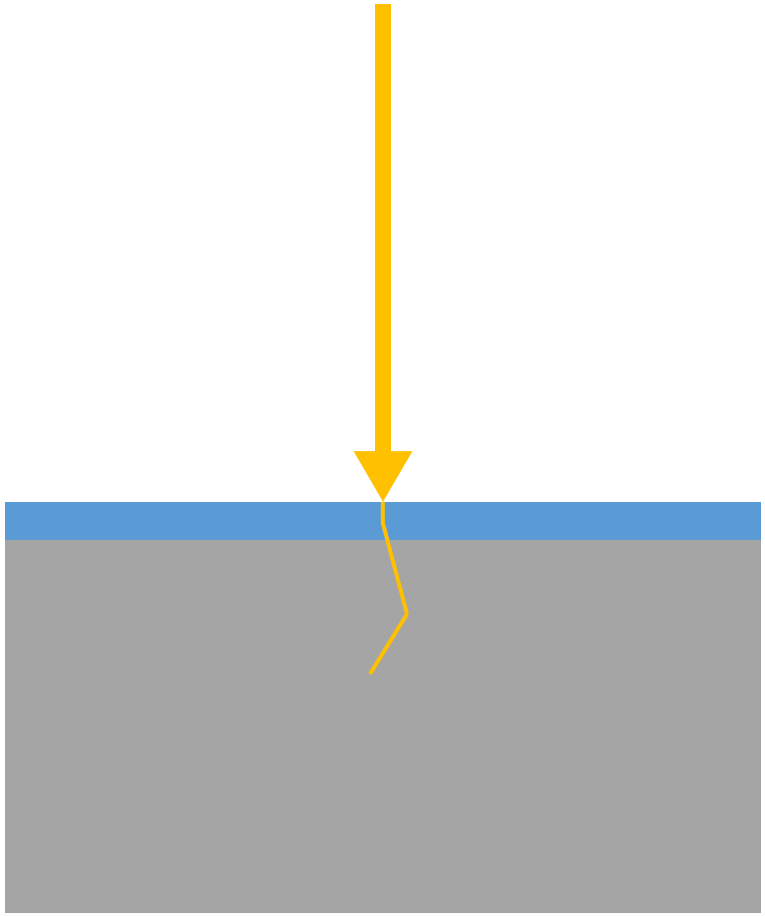


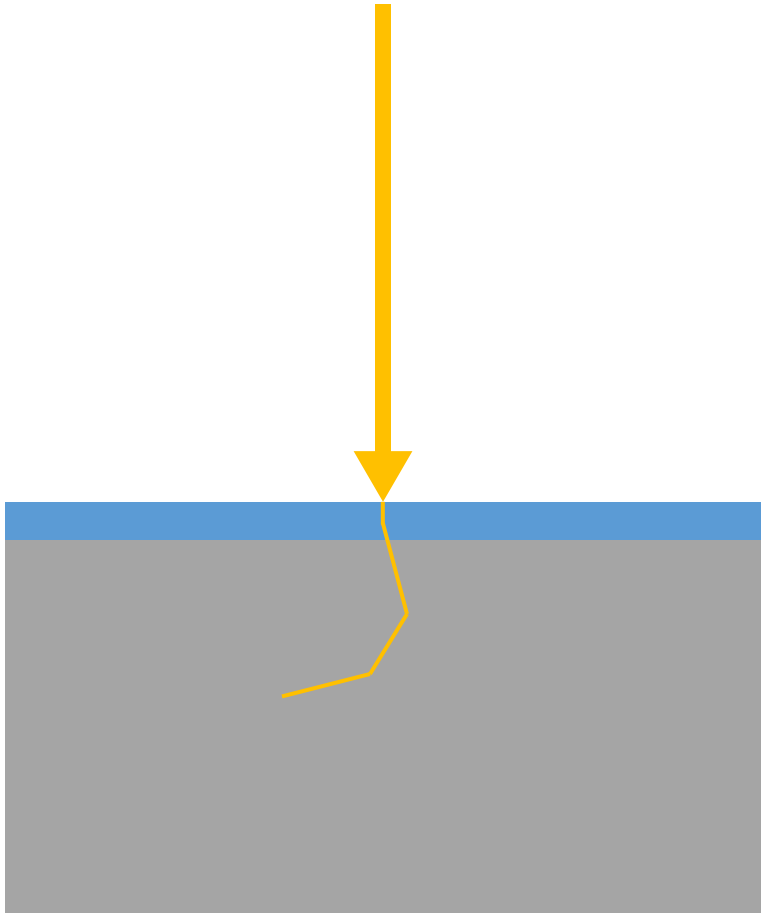
Trajectory of Primary Electrons



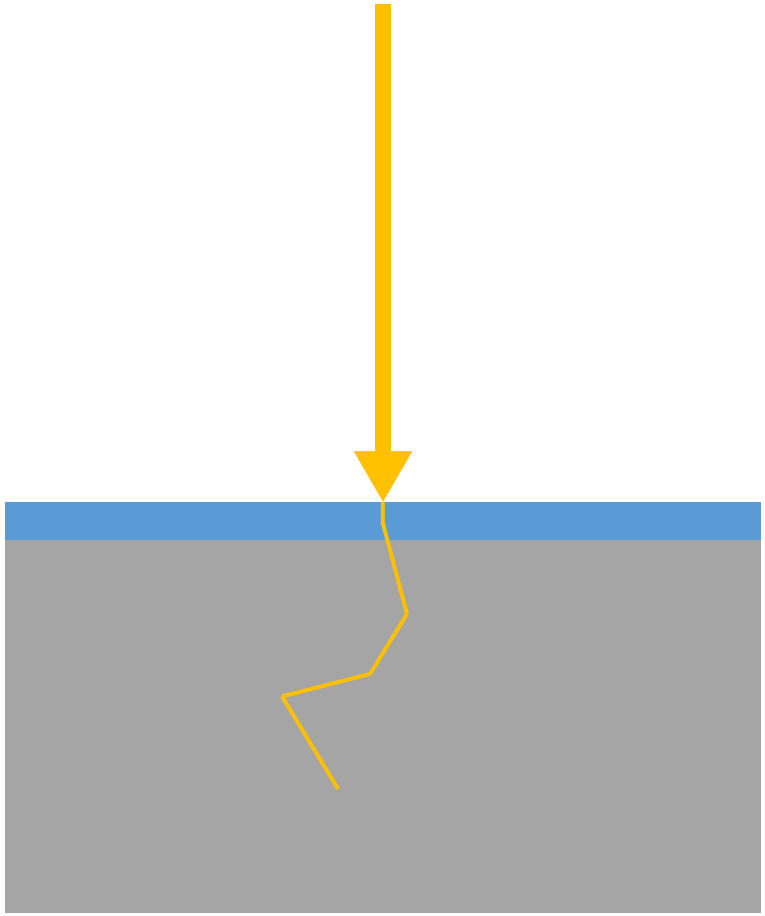
Trajectory of Primary Electrons



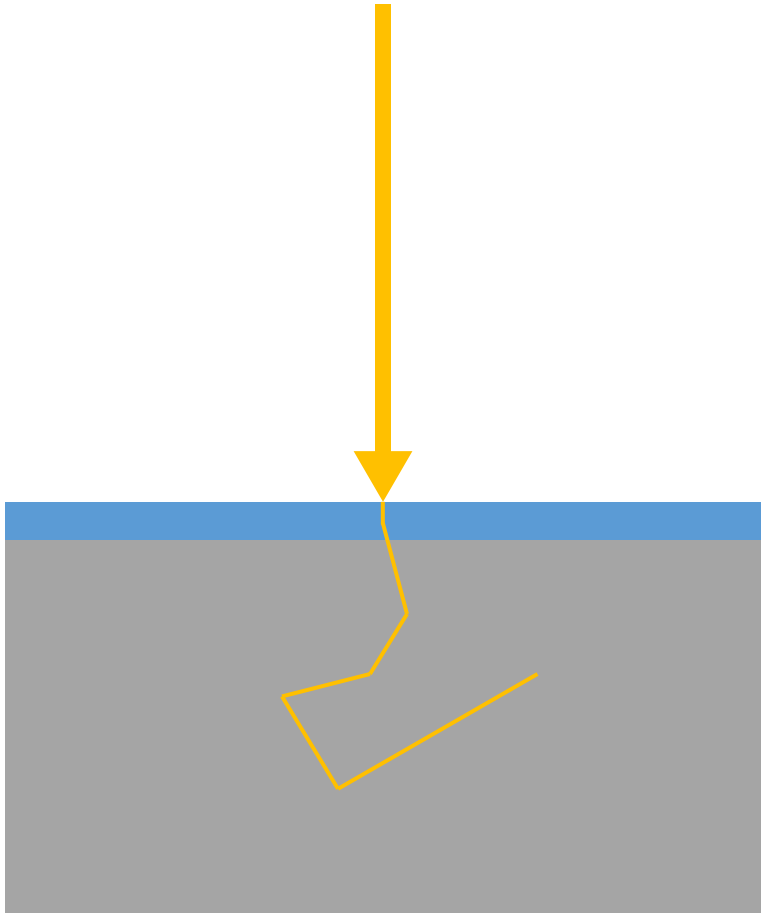
Trajectory of Primary Electrons



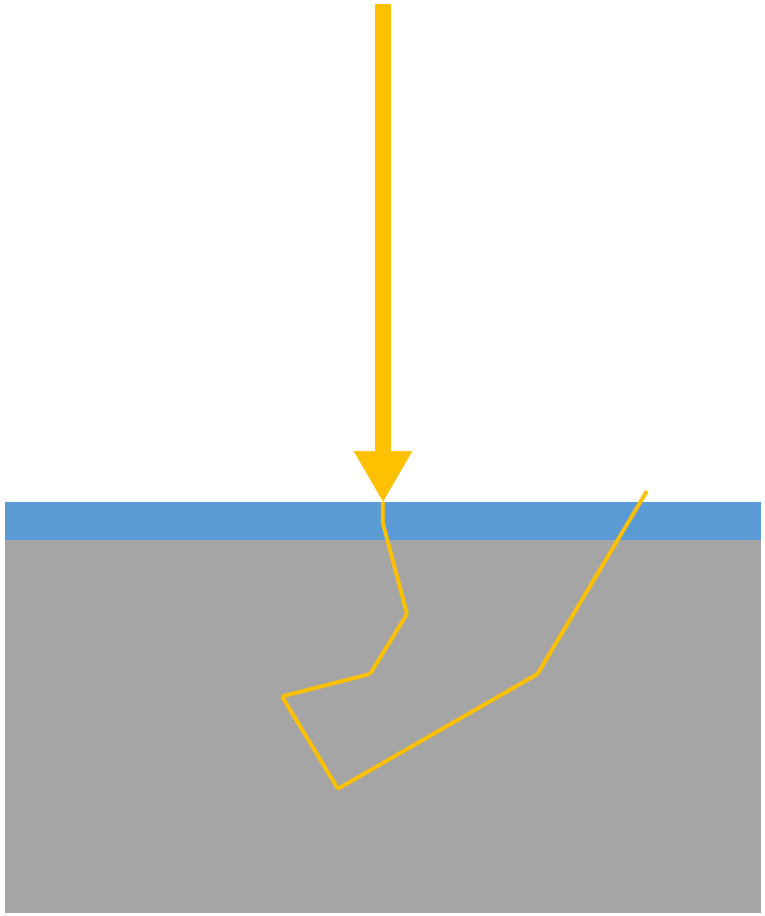
Trajectory of Primary Electrons



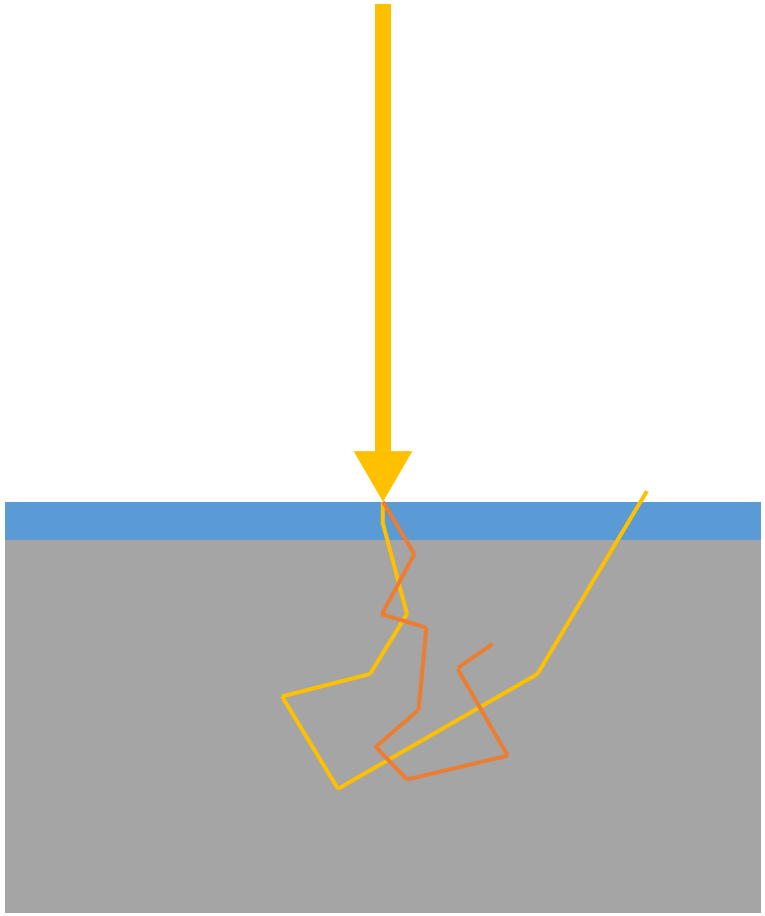
Trajectory of Primary Electrons



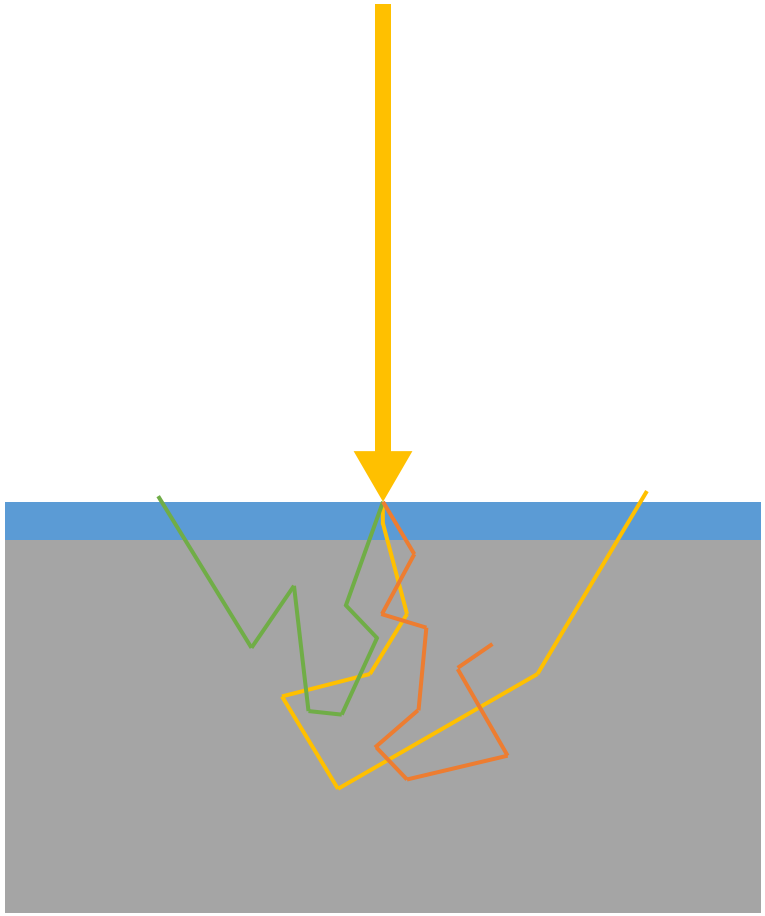
Trajectory of Primary Electrons



Trajectory of Primary Electrons



Trajectory of Primary Electrons



Proximity Effect

Positive tone resist

Proximity Effect

Positive tone resist

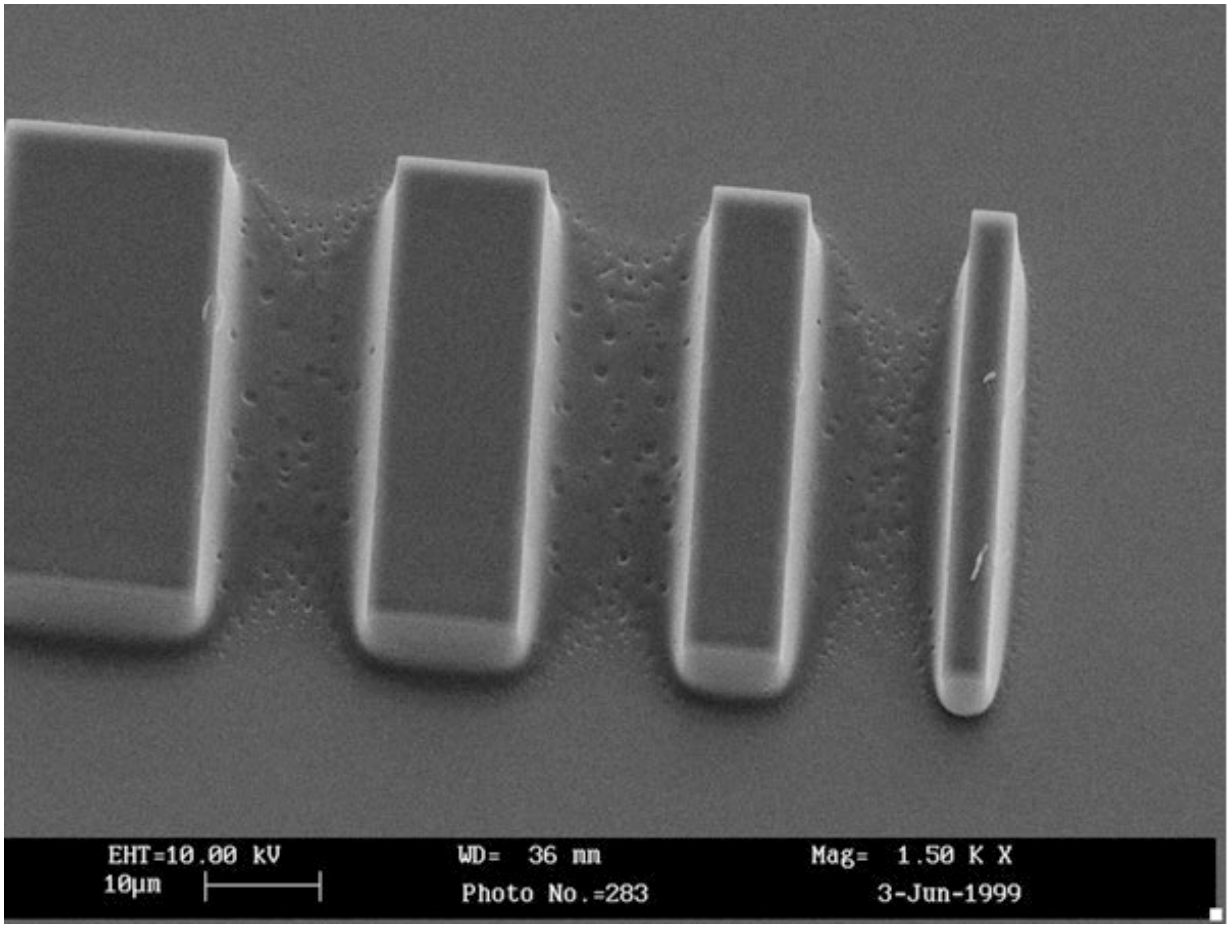
Proximity Effect

Positive tone resist

Proximity Effect

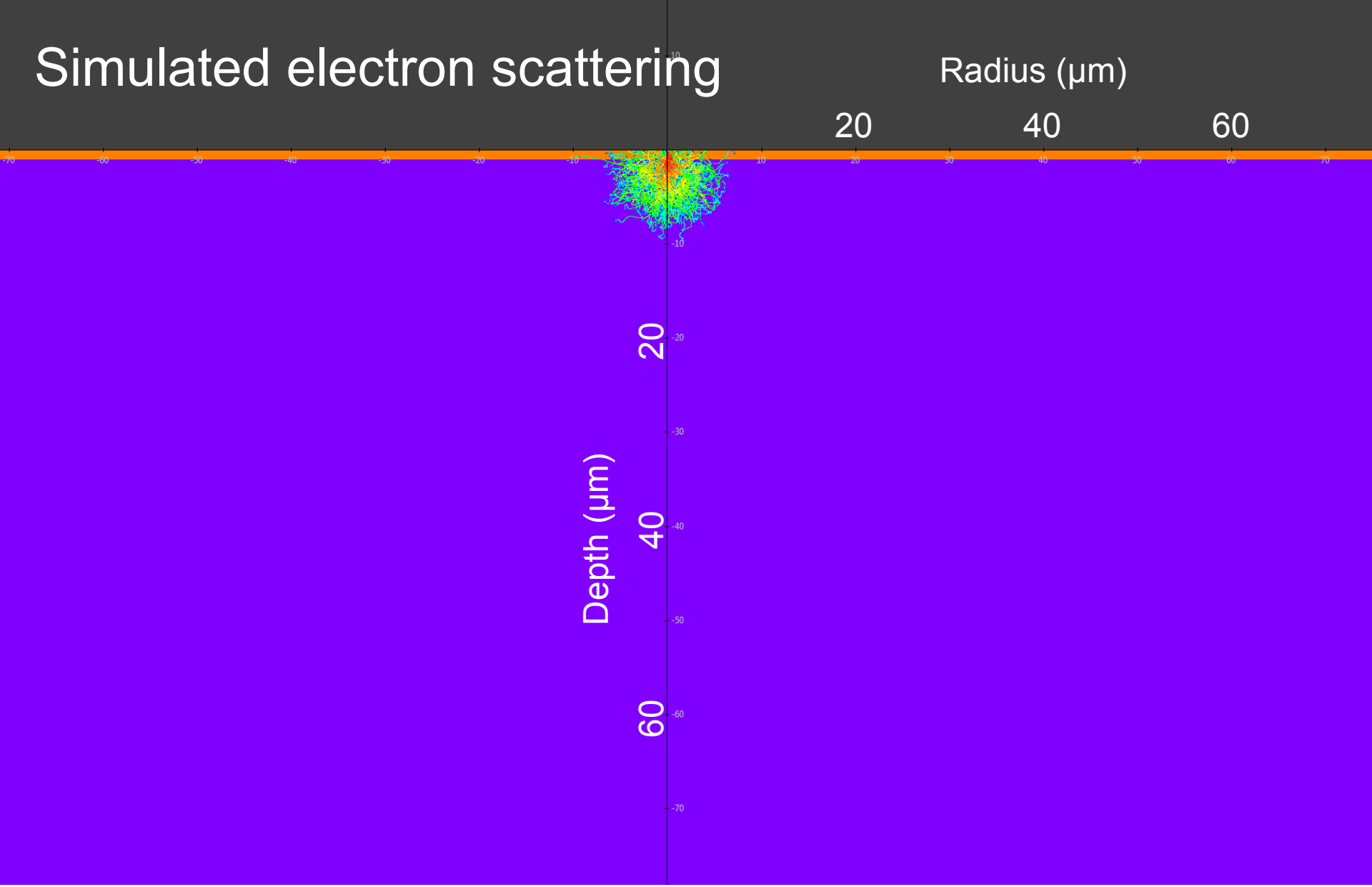
Positive tone resist

Proximity Effect in a Negative Resist



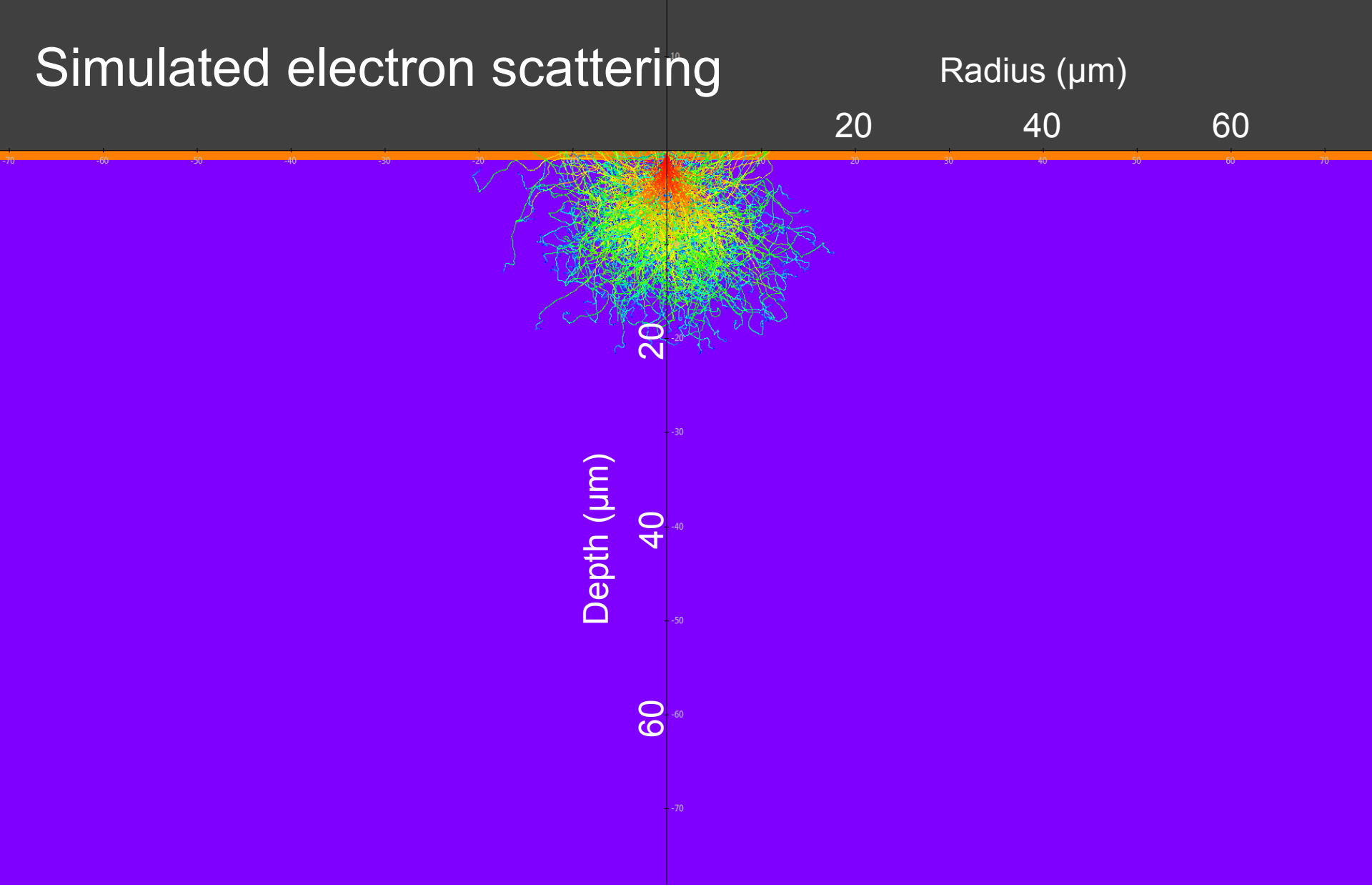
Z. Cui, Nanofabrication, Springer, p.132 (2017)

Simulated electron scattering



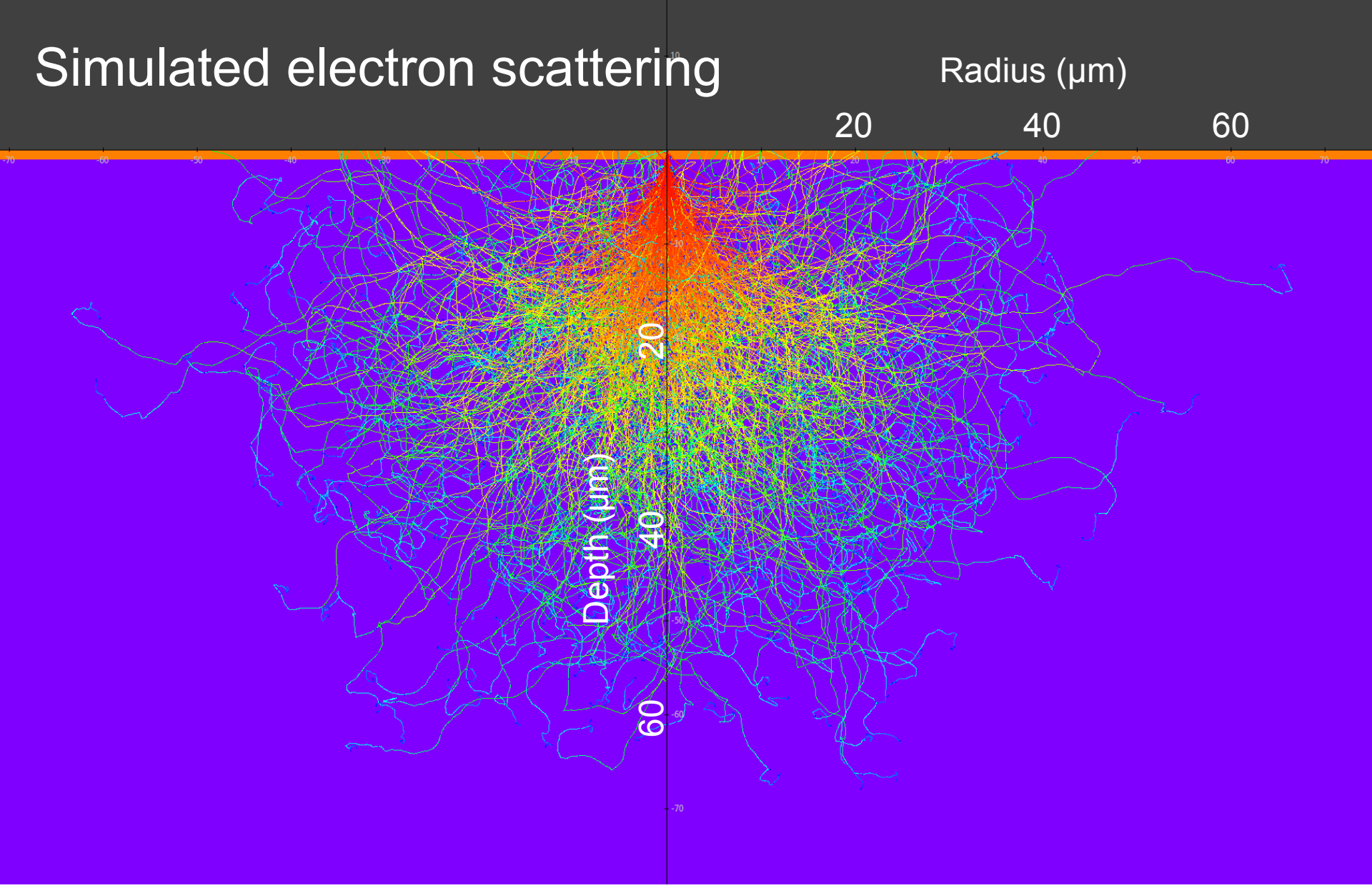
Electron Energy 30 keV

Simulated electron scattering



Electron Energy 50 keV

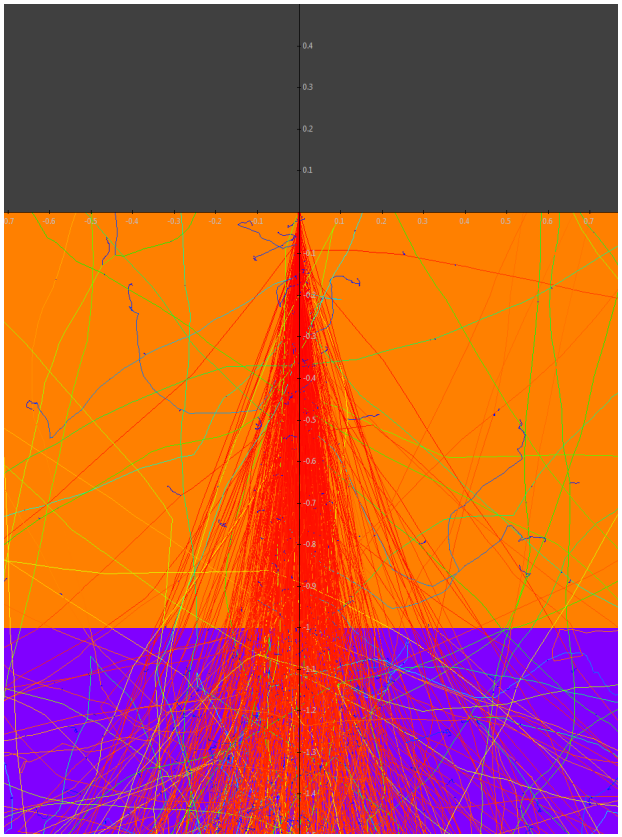
Simulated electron scattering



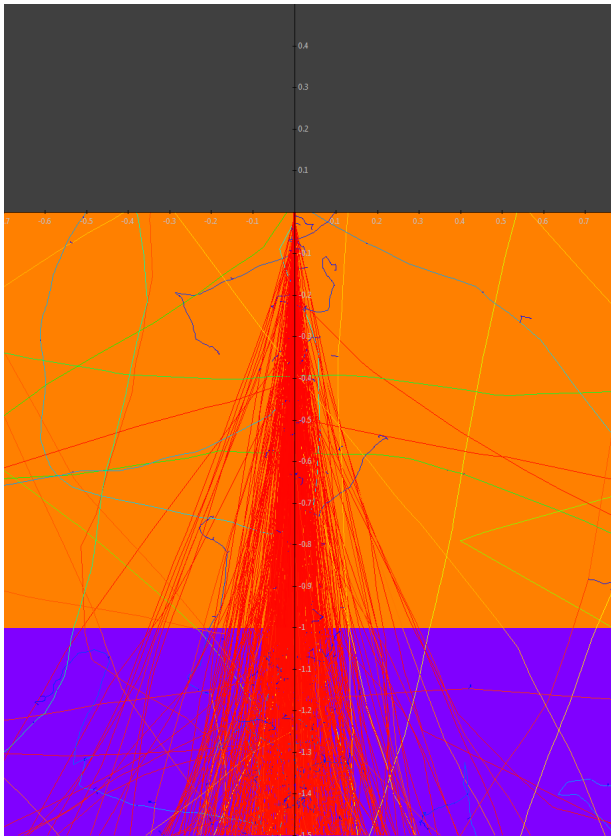
Electron Energy 100 keV

Simulated electron scattering in resist

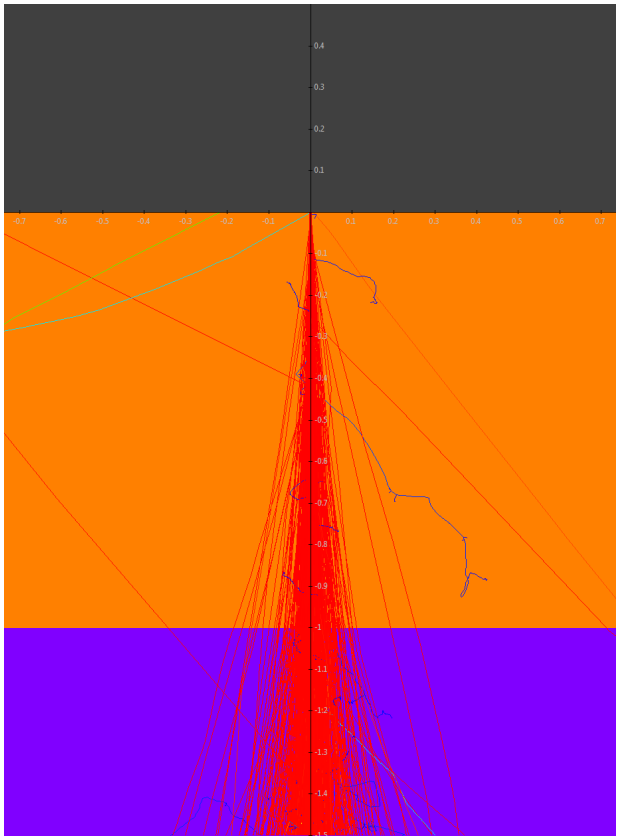
30 keV



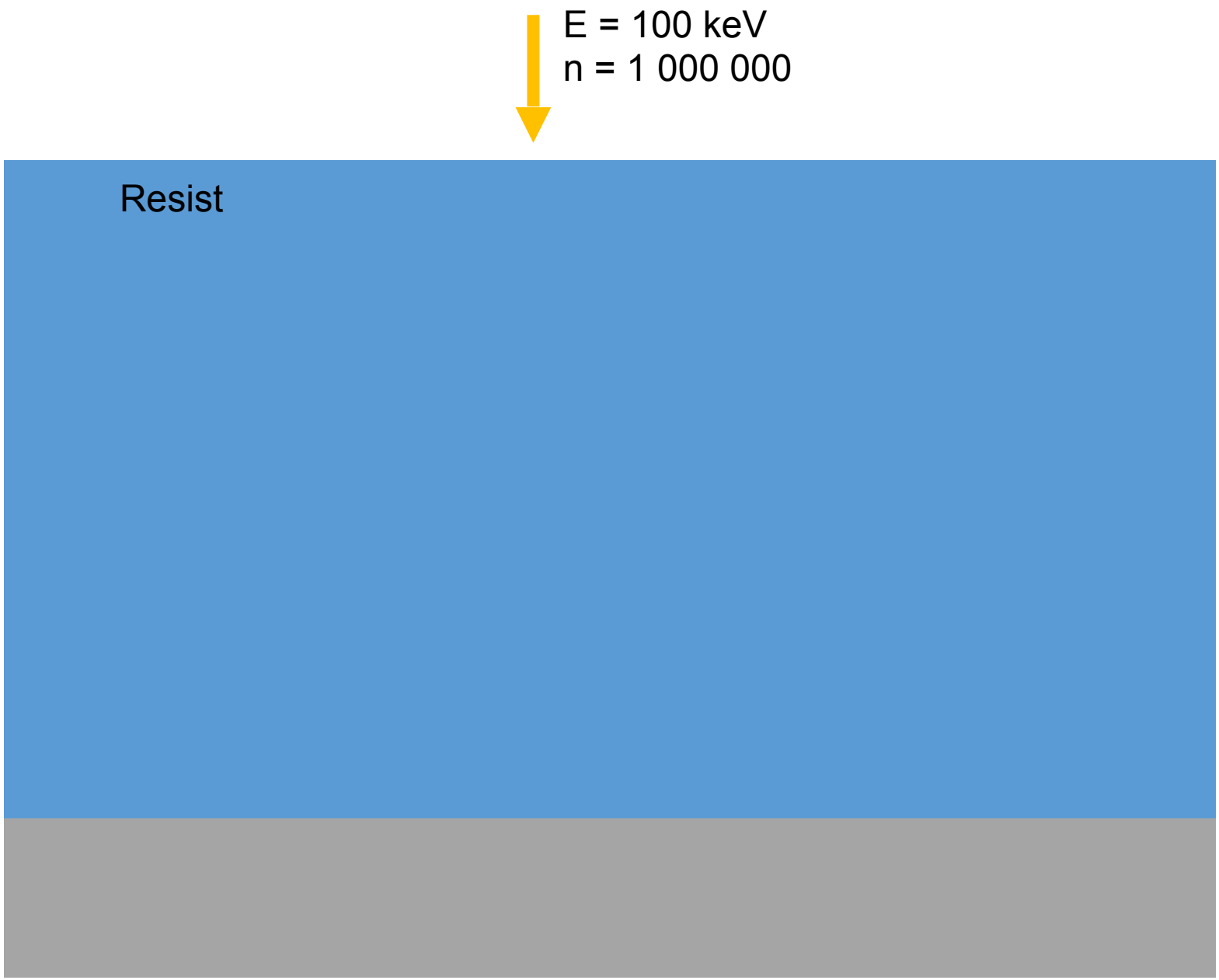
50 keV

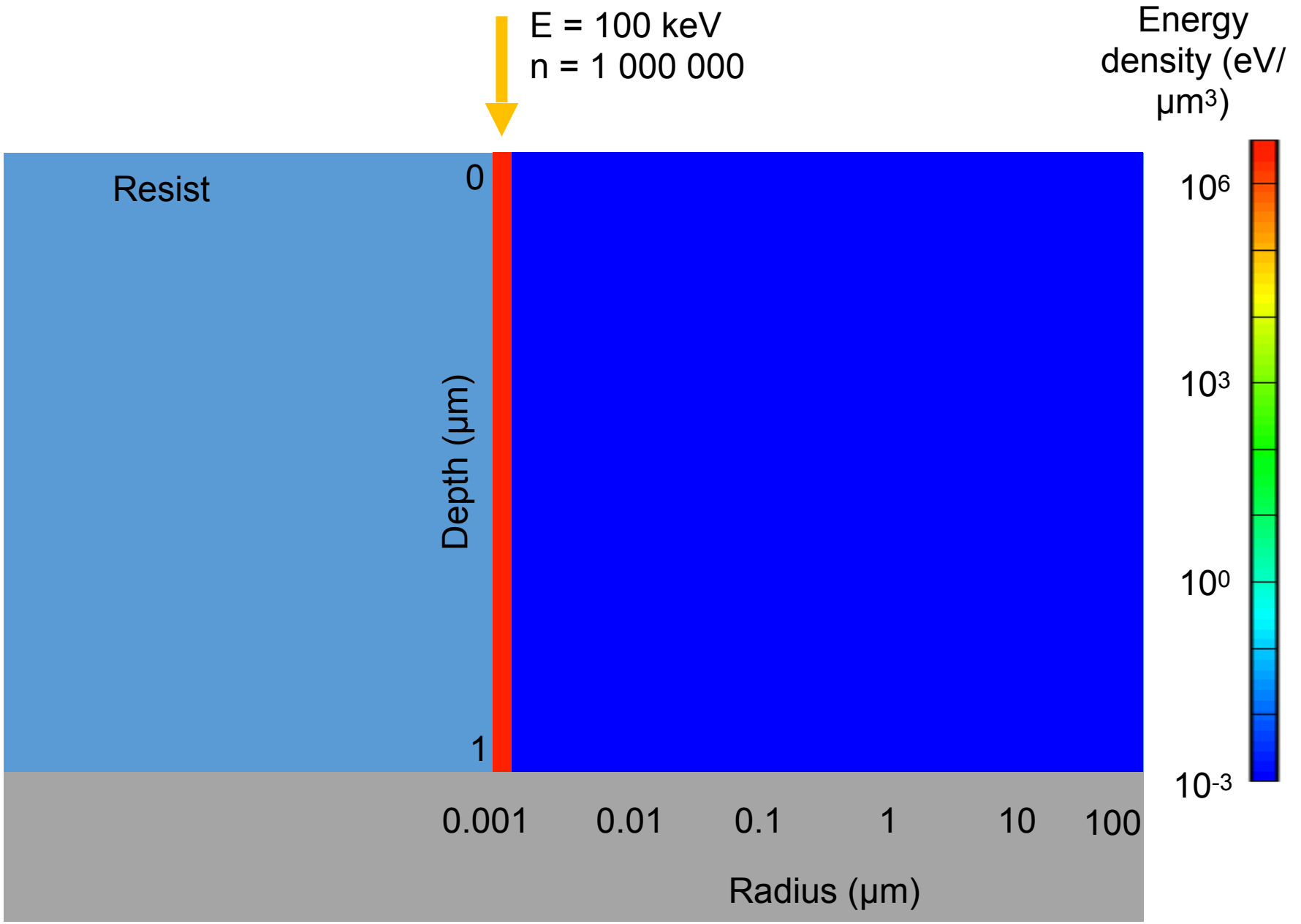


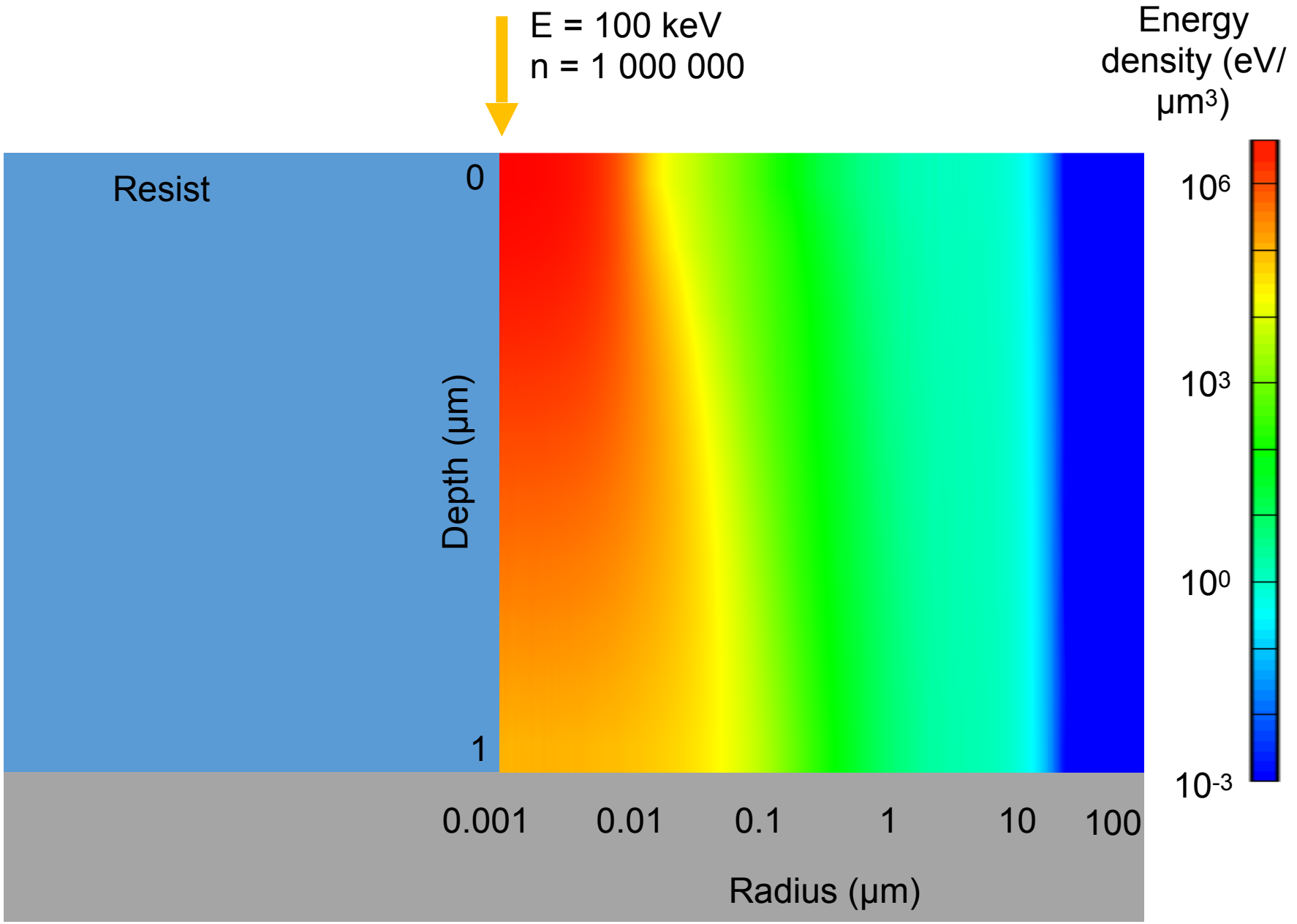
100 keV

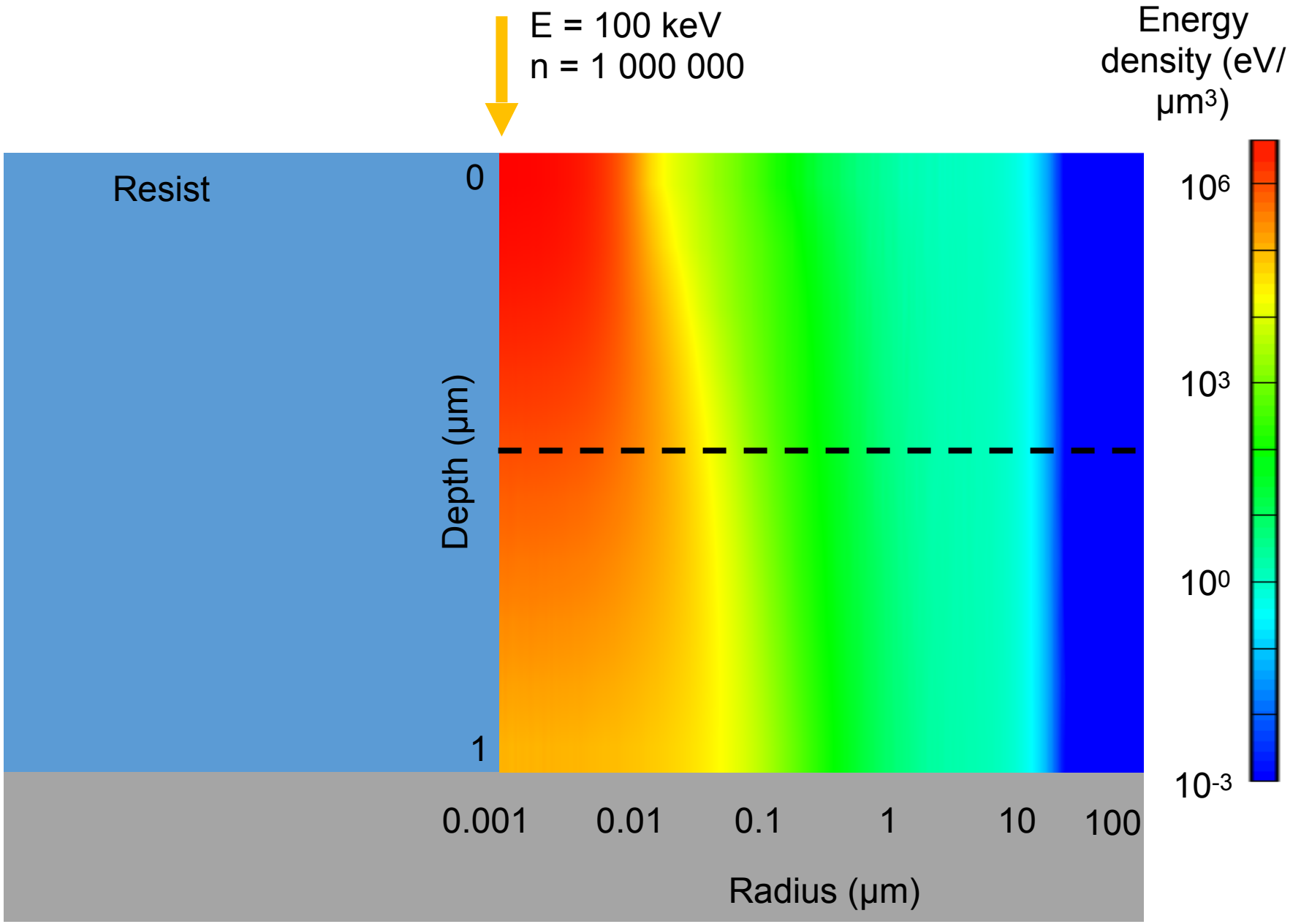


Electron Dose and Energy Density

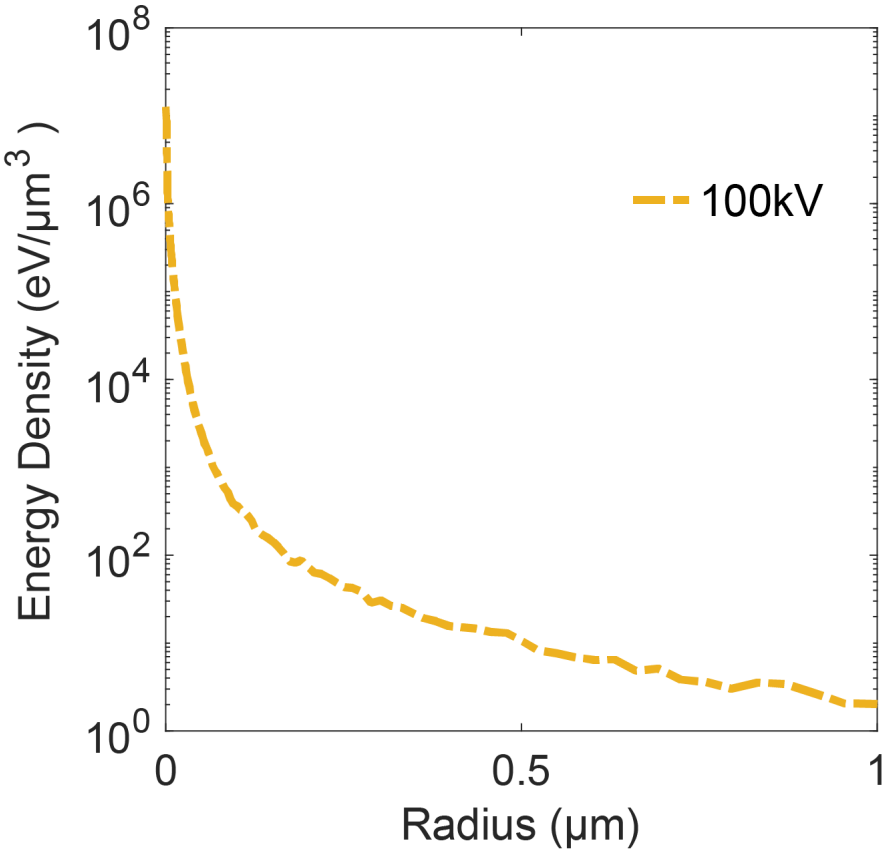

E = 100 keV
n = 1 000 000
Resist


E = 100 keV
n = 1 000 000
Energy density (eV/ µm³)
Resist
0
1
Depth (µm)
10⁶
10³
10⁰
10⁻³
0.001
0.01
0.1
1
10
100
Radius (µm)

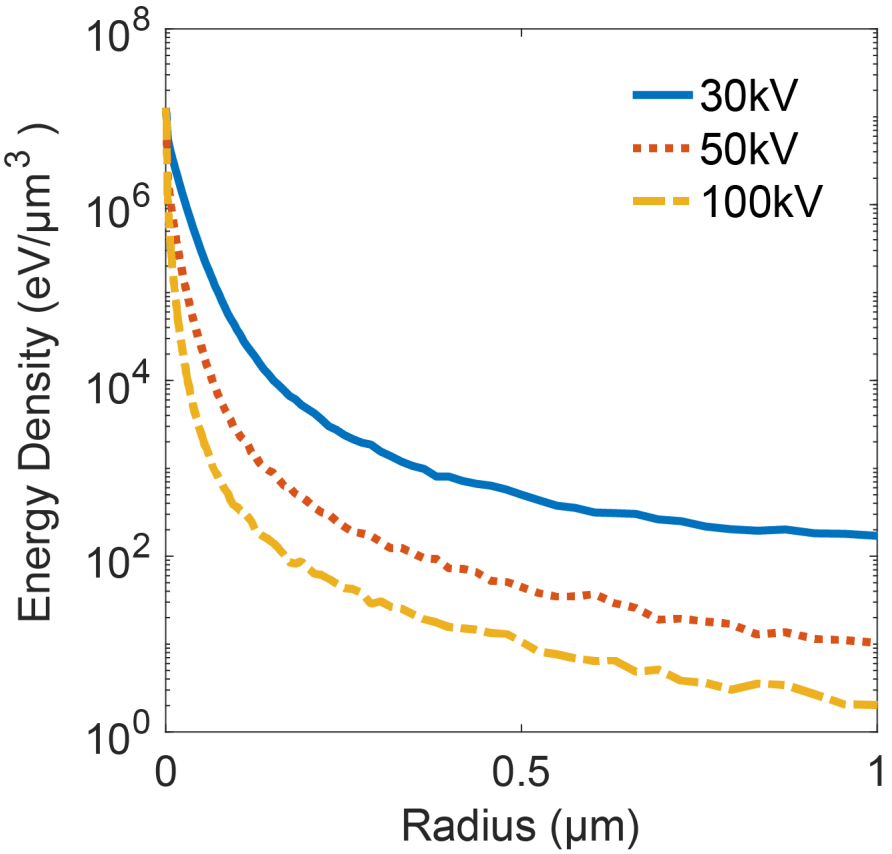

E = 100 keV
n = 1 000 000
Energy density (eV/ µm³)
Resist
0
1
Depth (µm)
10⁶
10³
10⁰
10⁻³
0.001
0.01
0.1
1
10
100
Radius (µm)


E = 100 keV
n = 1 000 000
Energy density (eV/ µm³)
Resist
0
1
Depth (µm)
10⁶
10³
10⁰
10⁻³
0.001
0.01
0.1
1
10
100
Radius (µm)

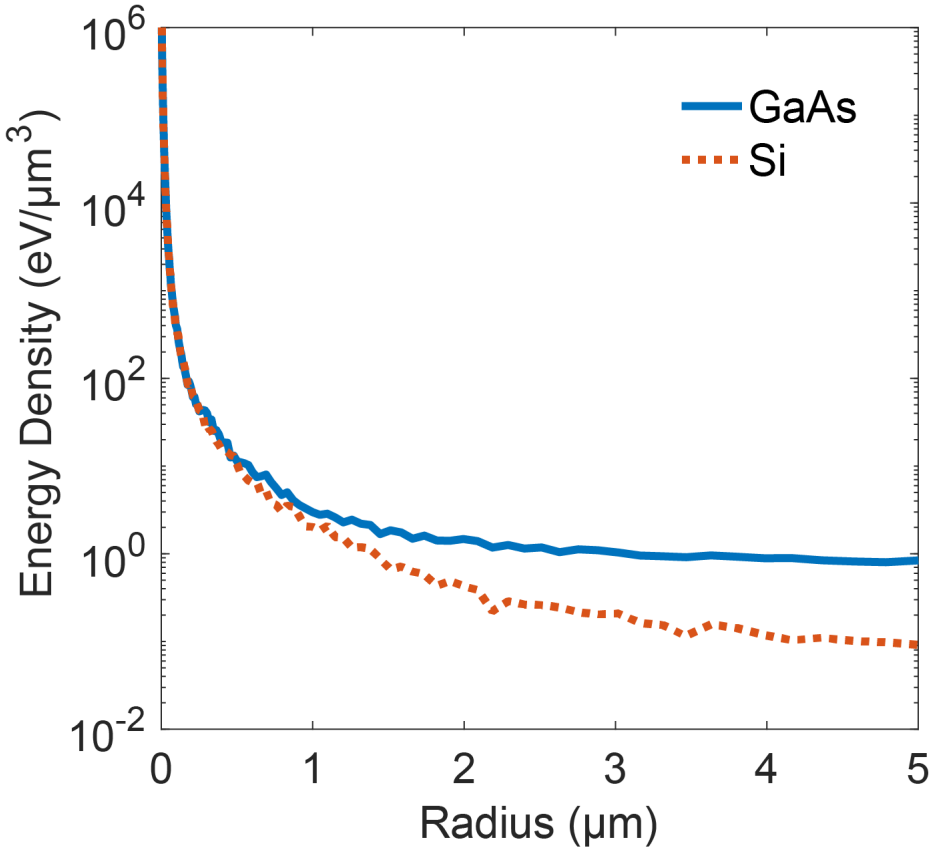
Point Spread Function



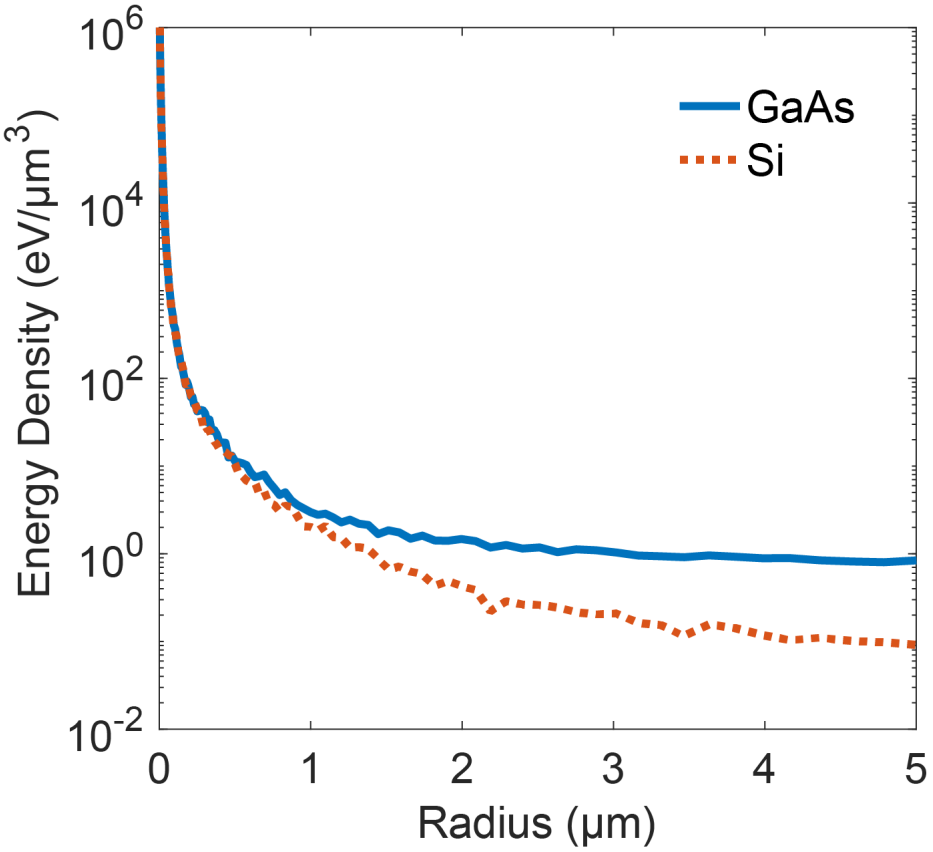
Acceleration Voltage

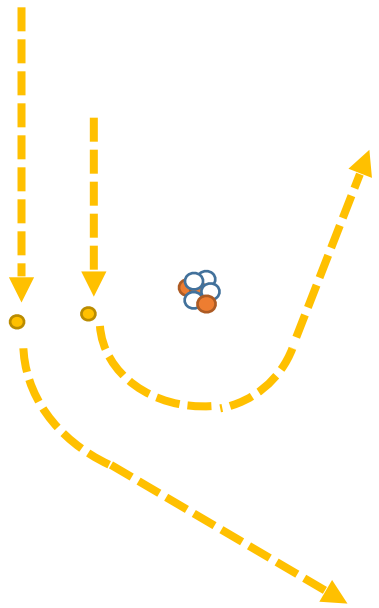


Substrate

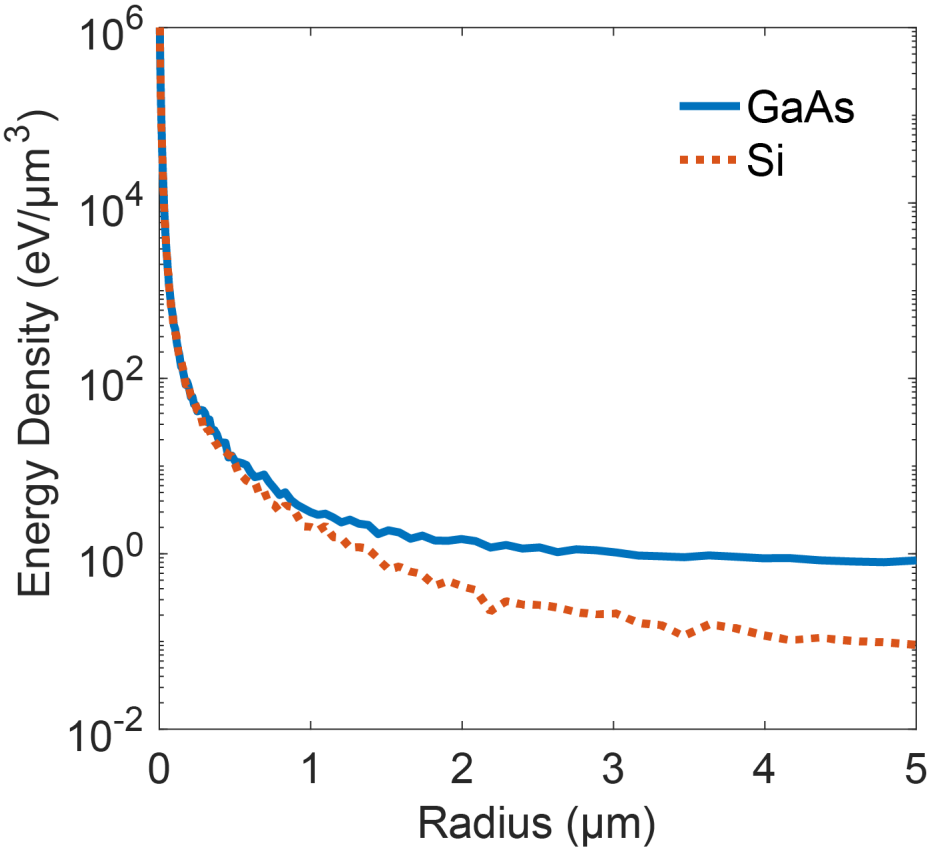

GaAs
Si
Energy Density (eV/μm^3)
10^6
10^4
10^2
10^0
10^{-2}
0
1
2
3
4
5
Radius (μm)

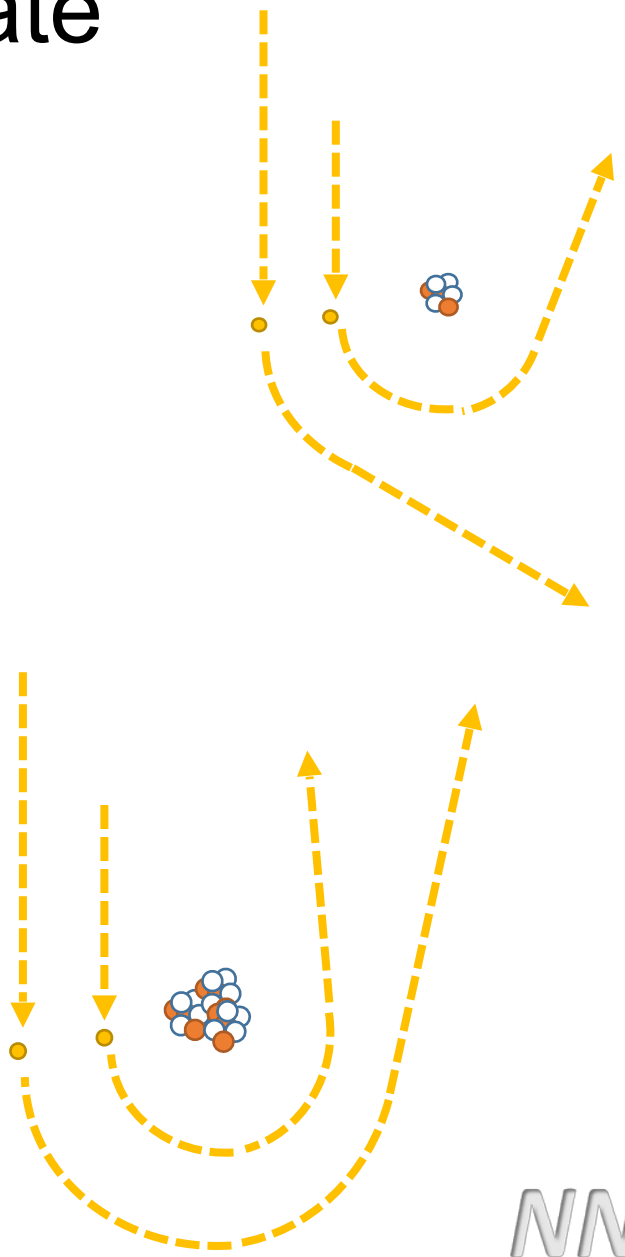
Substrate


GaAs
Si
Energy Density (eV/μm^3)
10^6
10^4
10^2
10^0
10^{-2}
0
1
2
3
4
5
Radius (μm)

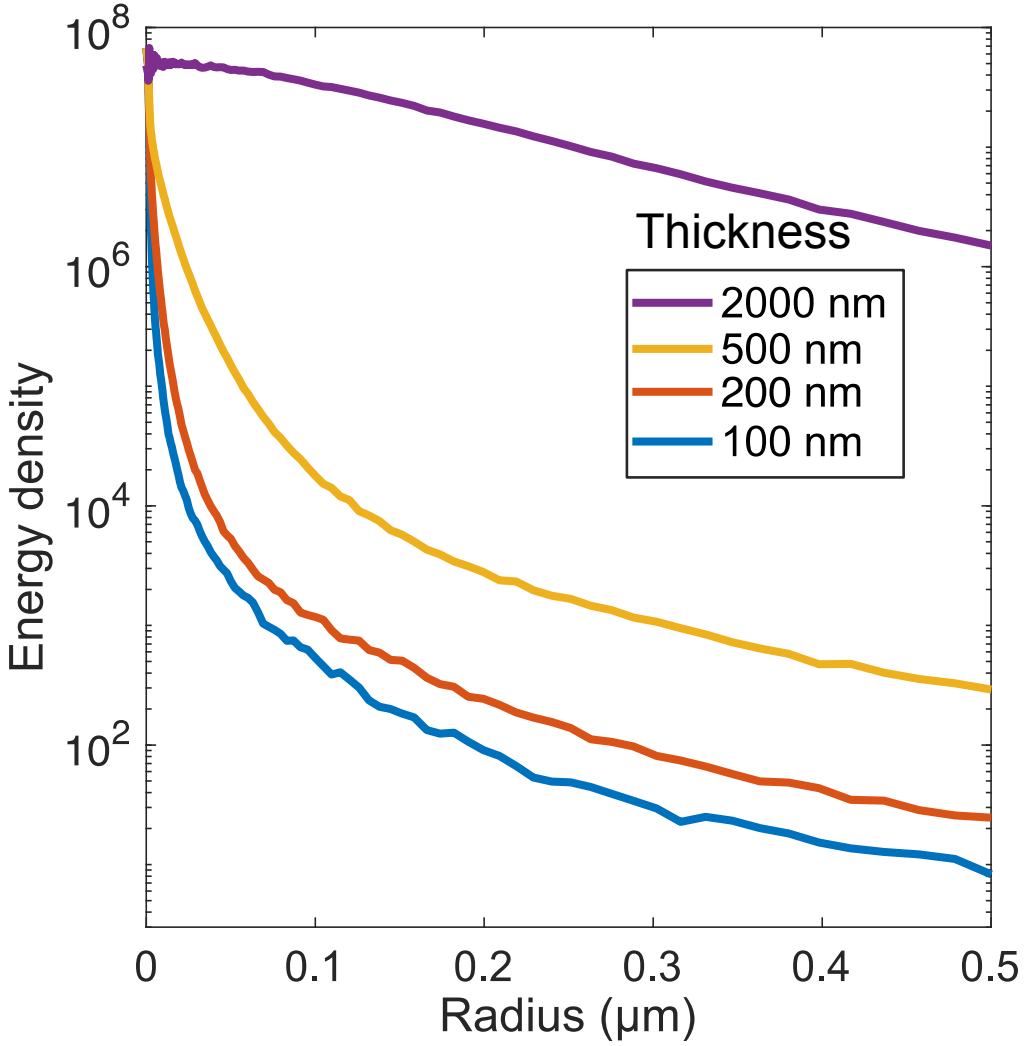


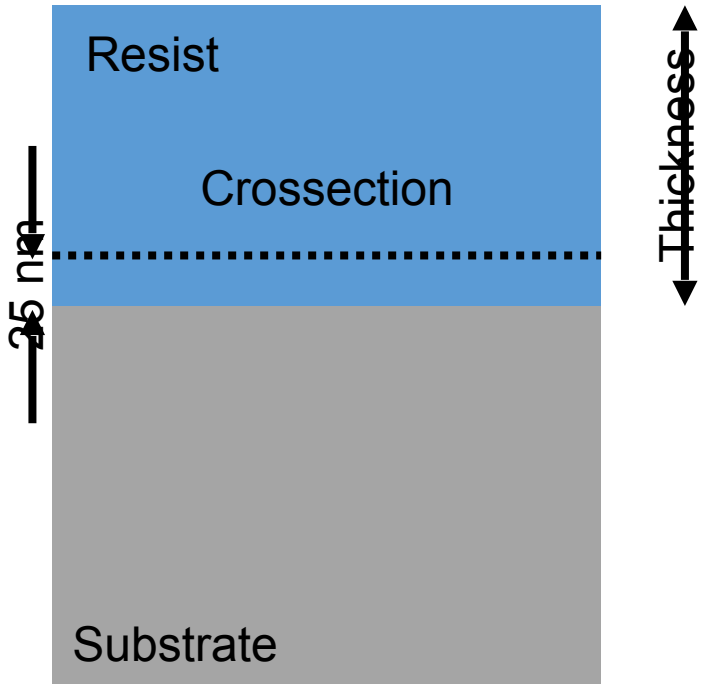
Substrate

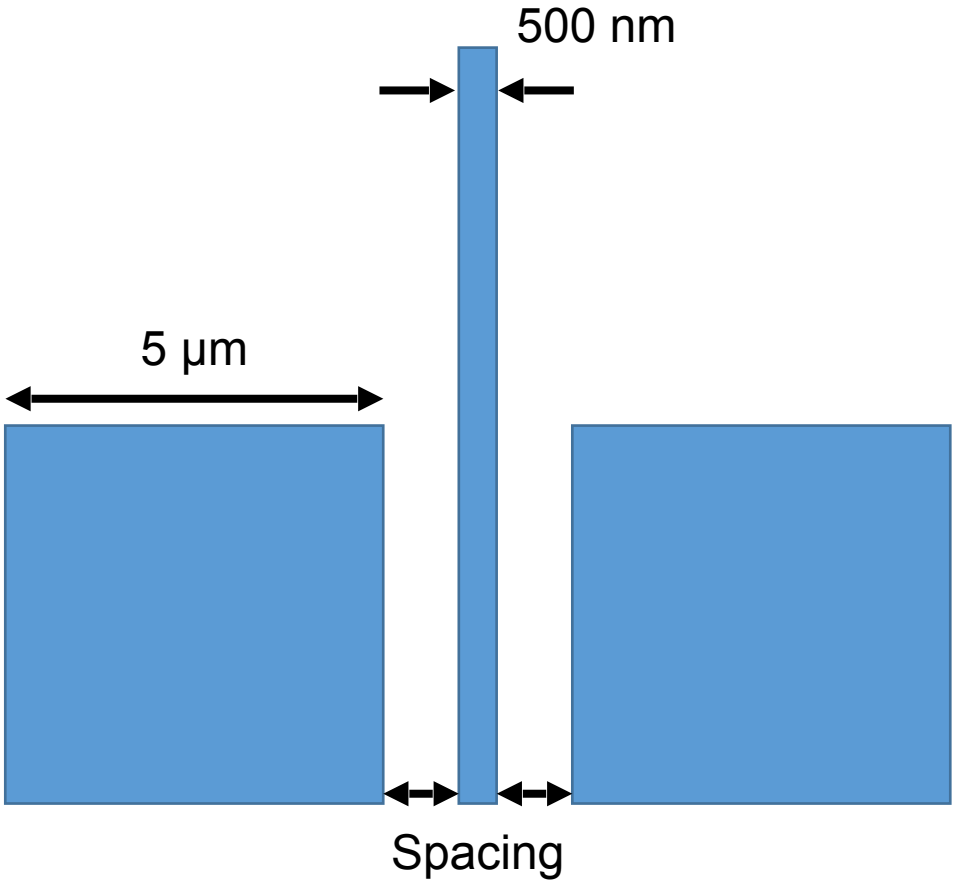

GaAs
Si
Energy Density (eV/μm^3)
10^6
10^4
10^2
10^0
10^{-2}
0
1
2
3
4
5
Radius (μm)

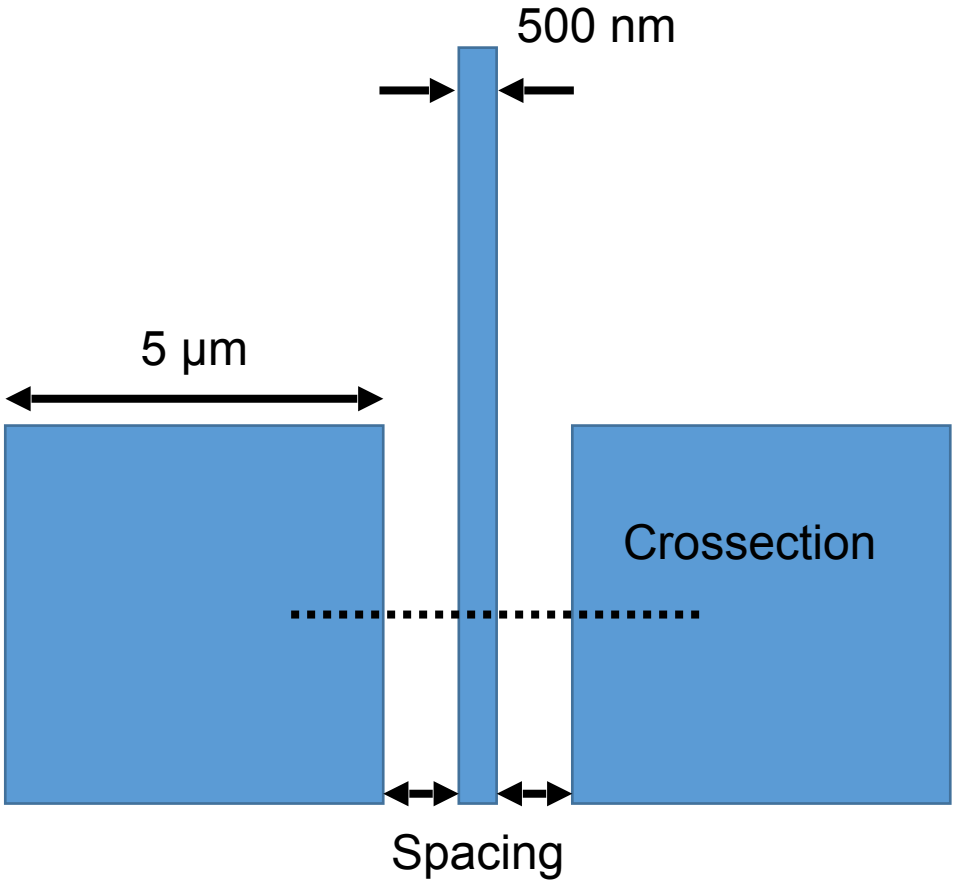


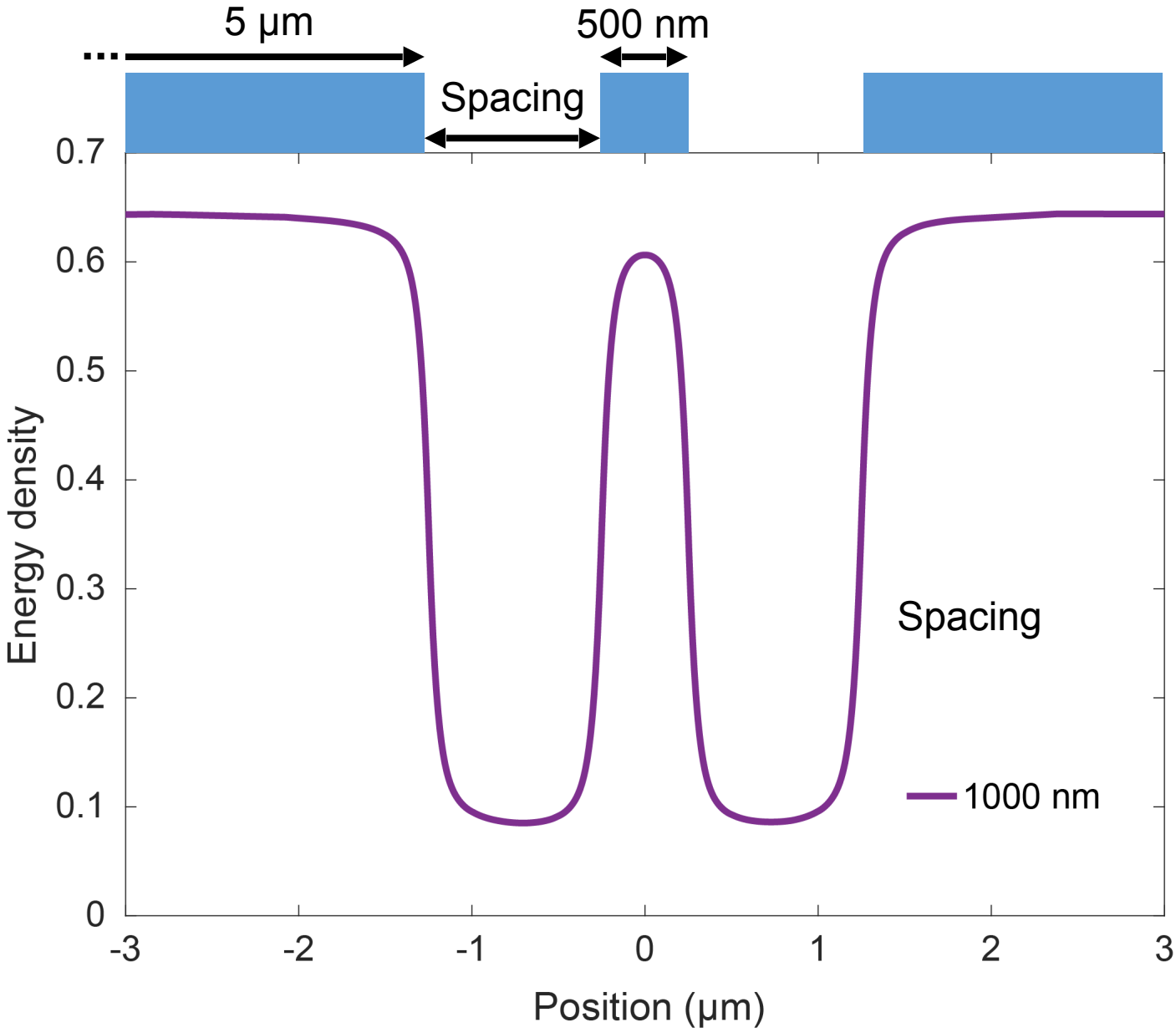
Resist Thickness

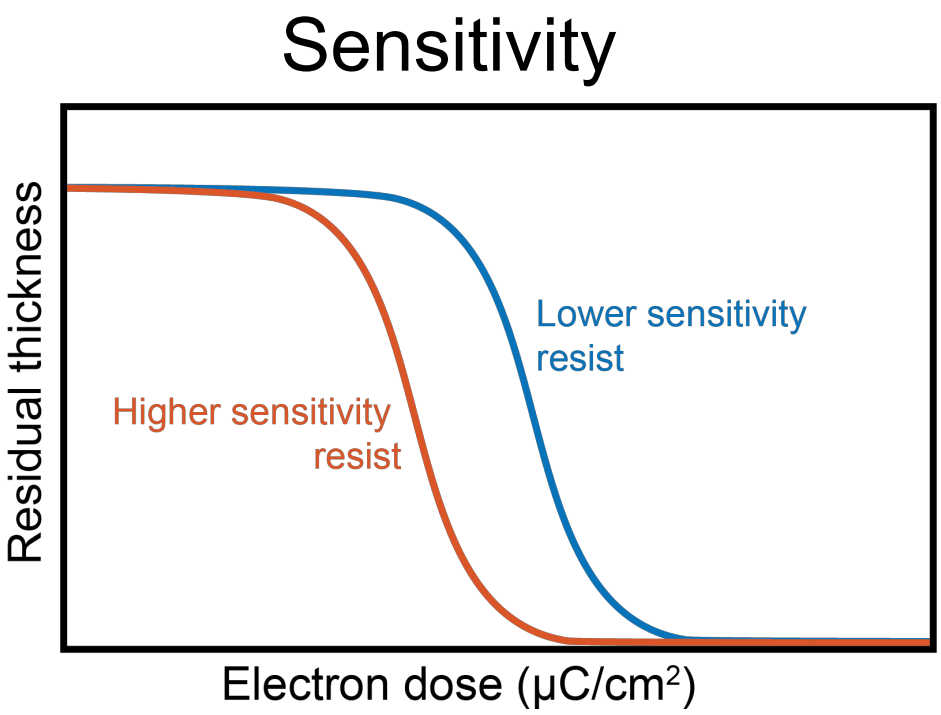


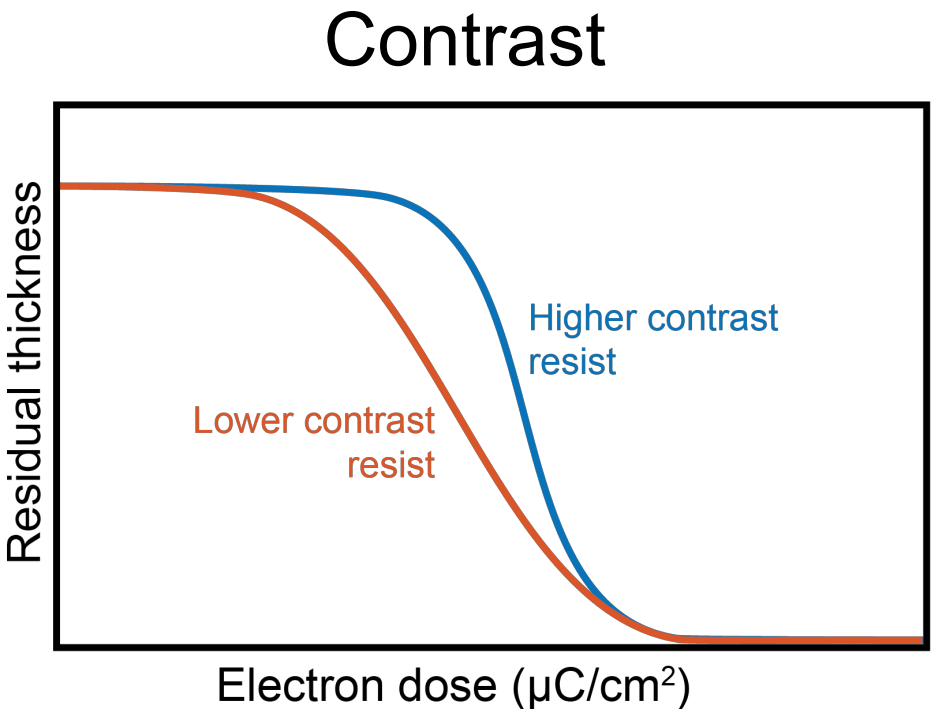


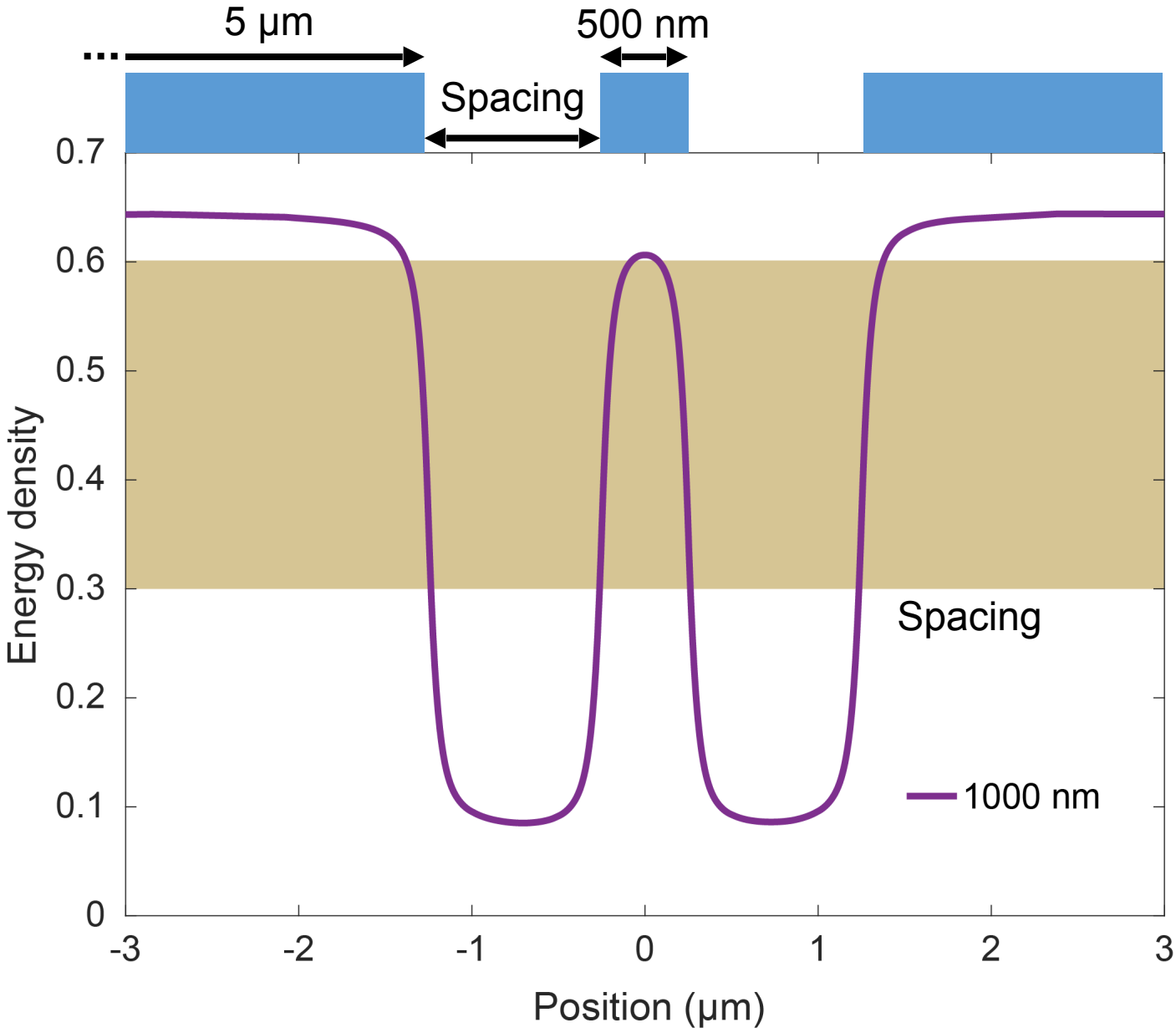

500 nm
5 µm
Spacing

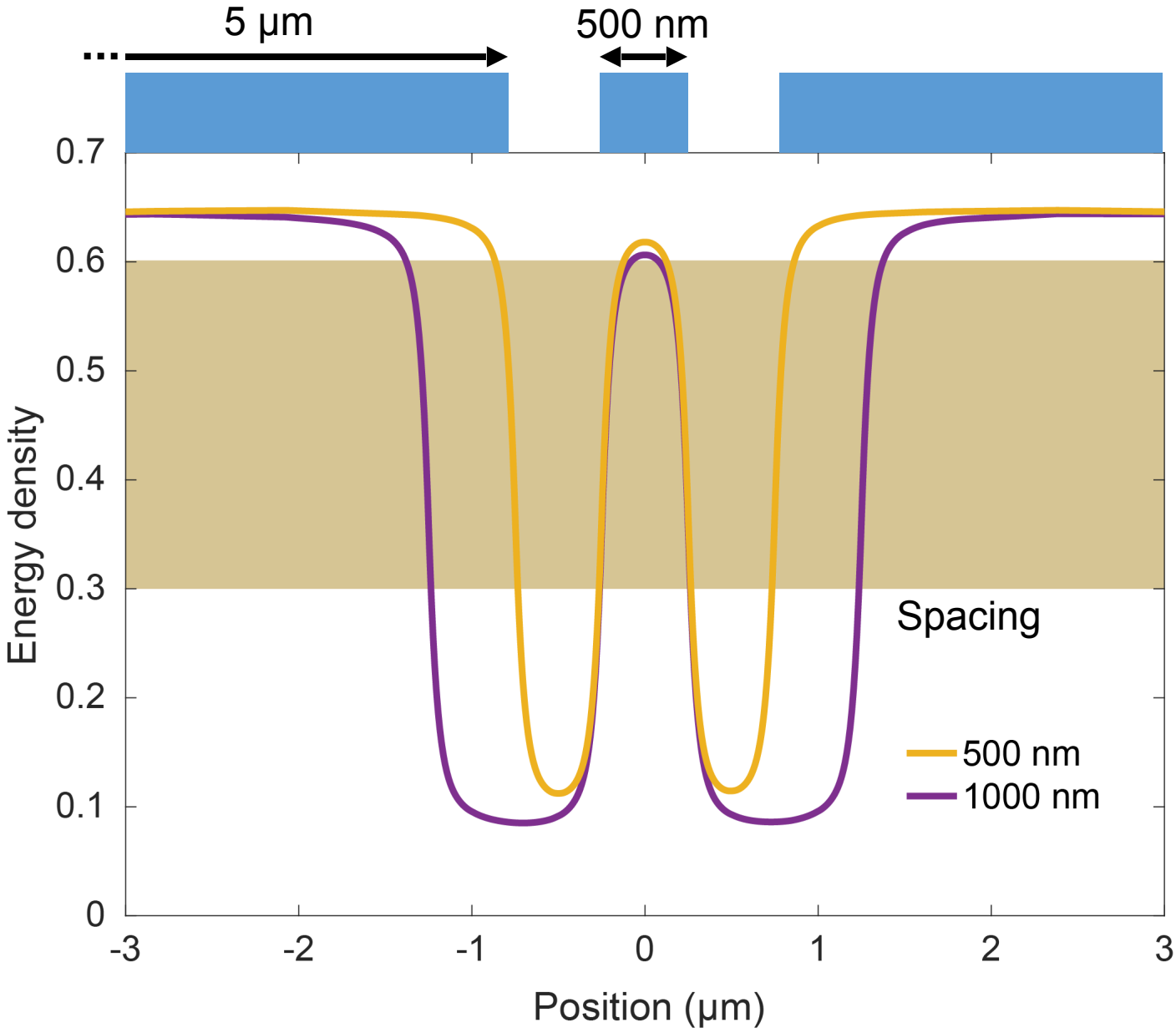

500 nm
5 µm
Crossection
Spacing

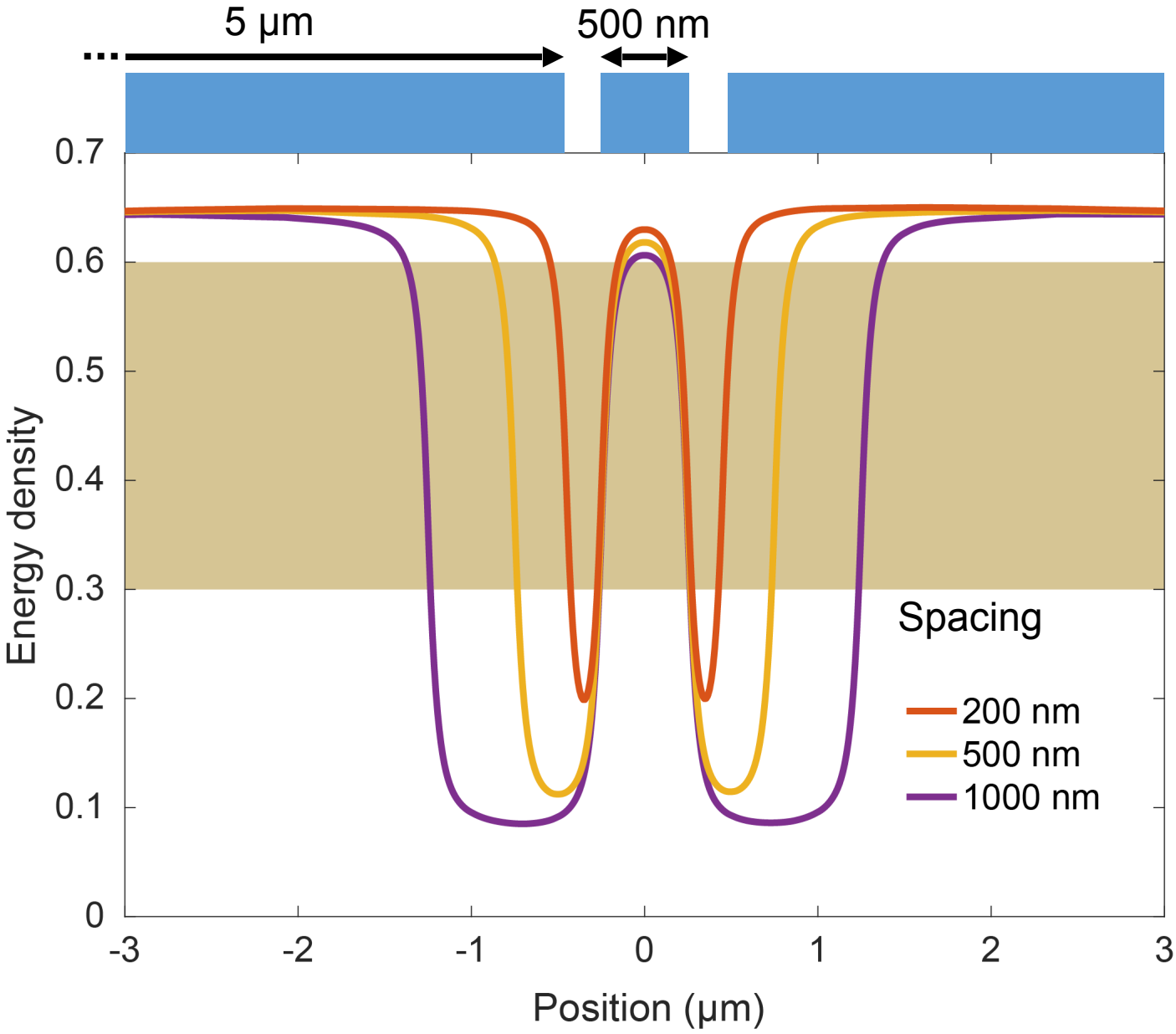

5 µm
500 nm
Spacing
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy density
-3
-2
-1
0
1
2
3
Position (µm)
Spacing
1000 nm

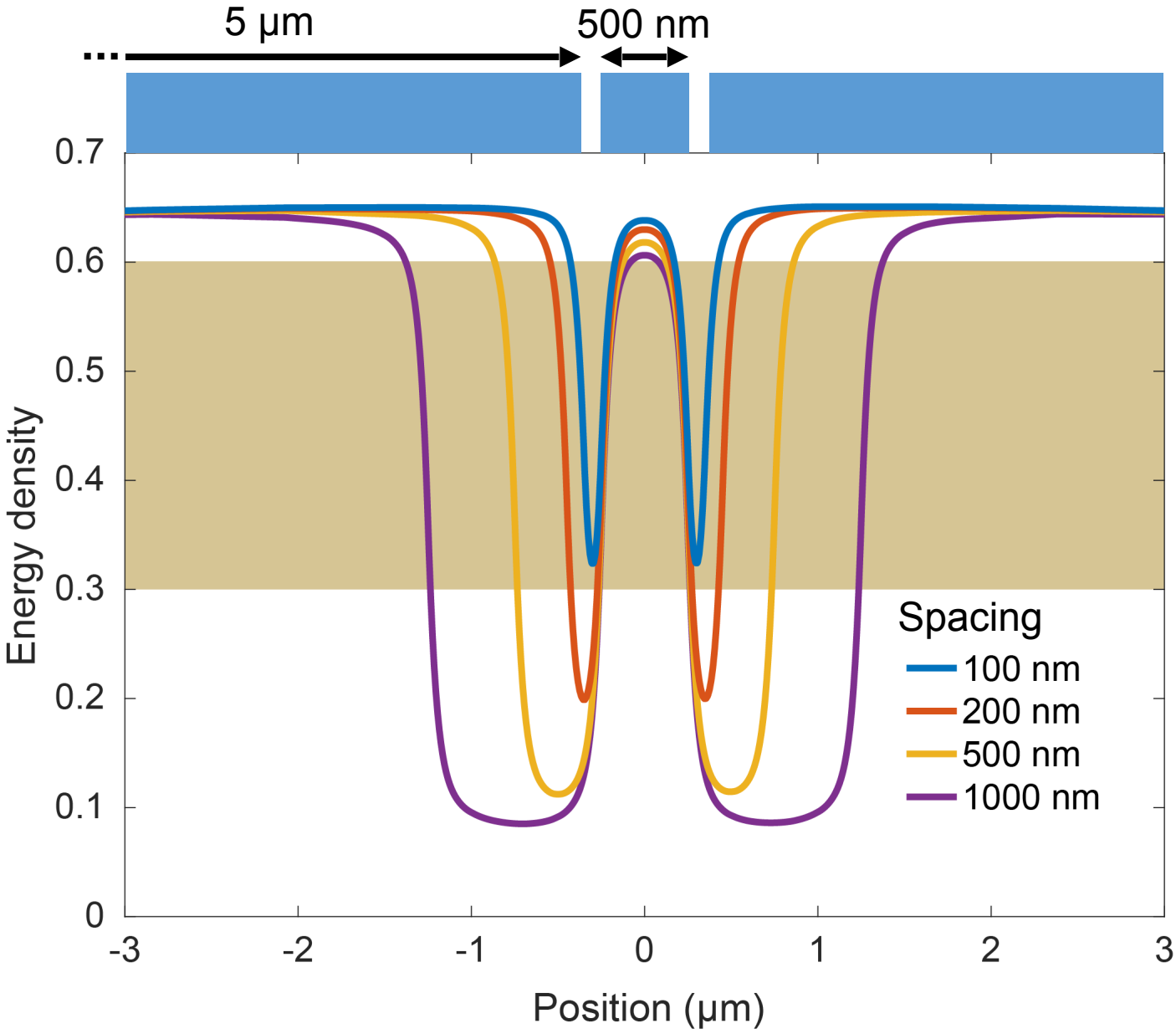

Sensitivity
Residual thickness
Lower sensitivity resist
Higher sensitivity resist
Electron dose (μC/cm²)


Contrast
Residual thickness
Higher contrast resist
Lower contrast resist
Electron dose (μC/cm²)

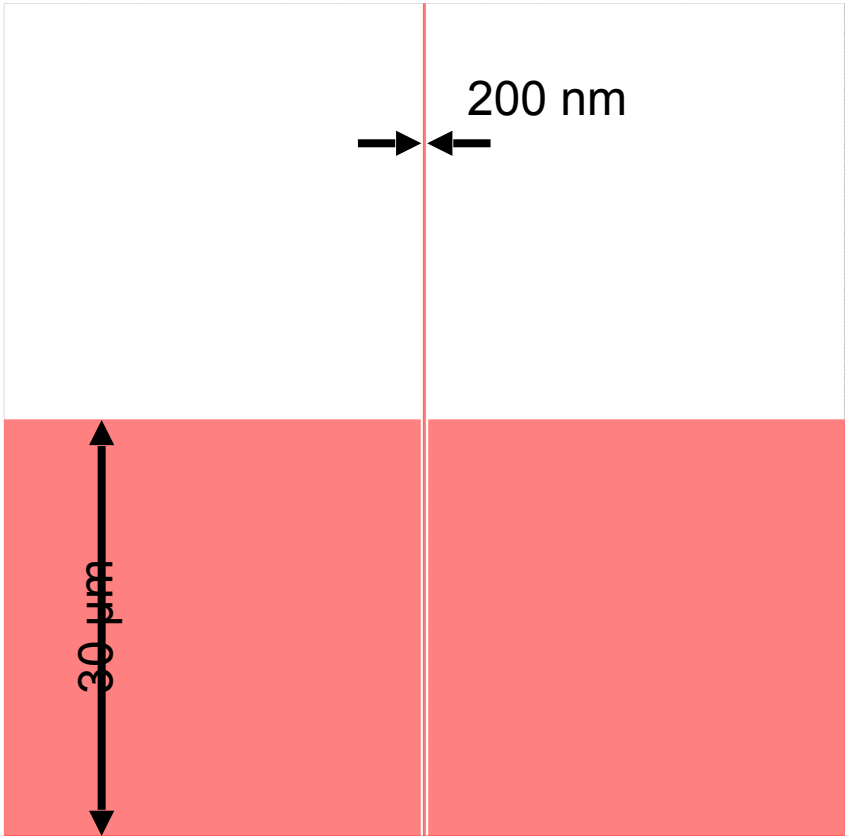

5 μm
500 nm
Spacing
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy density
Spacing
1000 nm
-3
-2
-1
0
1
2
3
Position (μm)


5 µm
500 nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy density
-3
-2
-1
0
1
2
3
Position (µm)
Spacing
500 nm
1000 nm

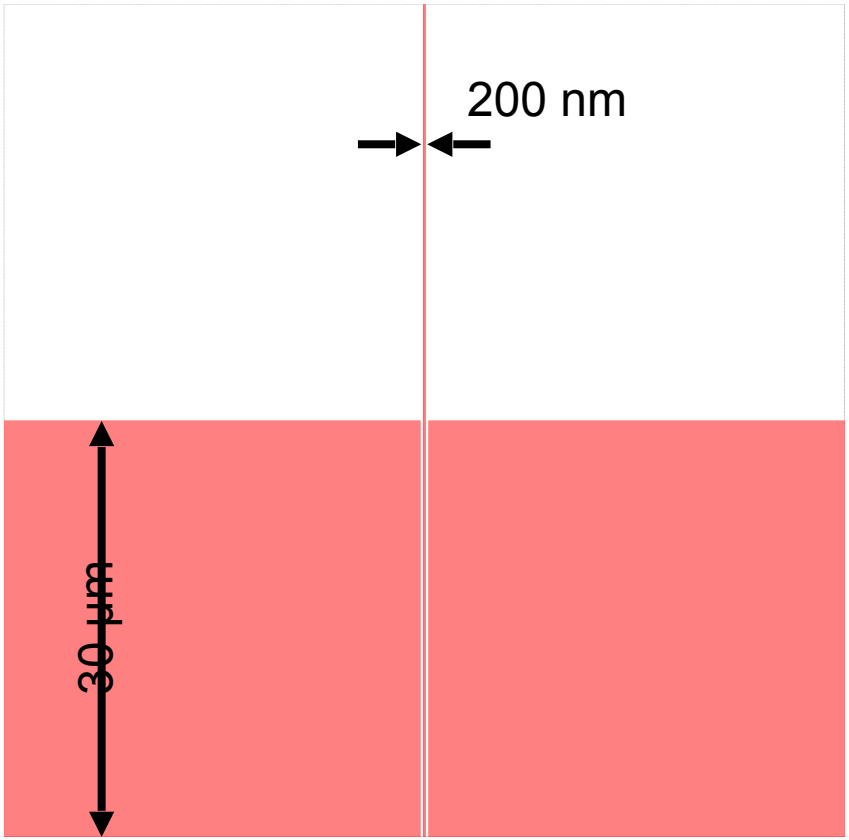

5 µm
500 nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy density
-3
-2
-1
0
1
2
3
Position (µm)
Spacing
200 nm
500 nm
1000 nm


5 µm
500 nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy density
-3
-2
-1
0
1
2
3
Position (µm)
Spacing
100 nm
200 nm
500 nm
1000 nm

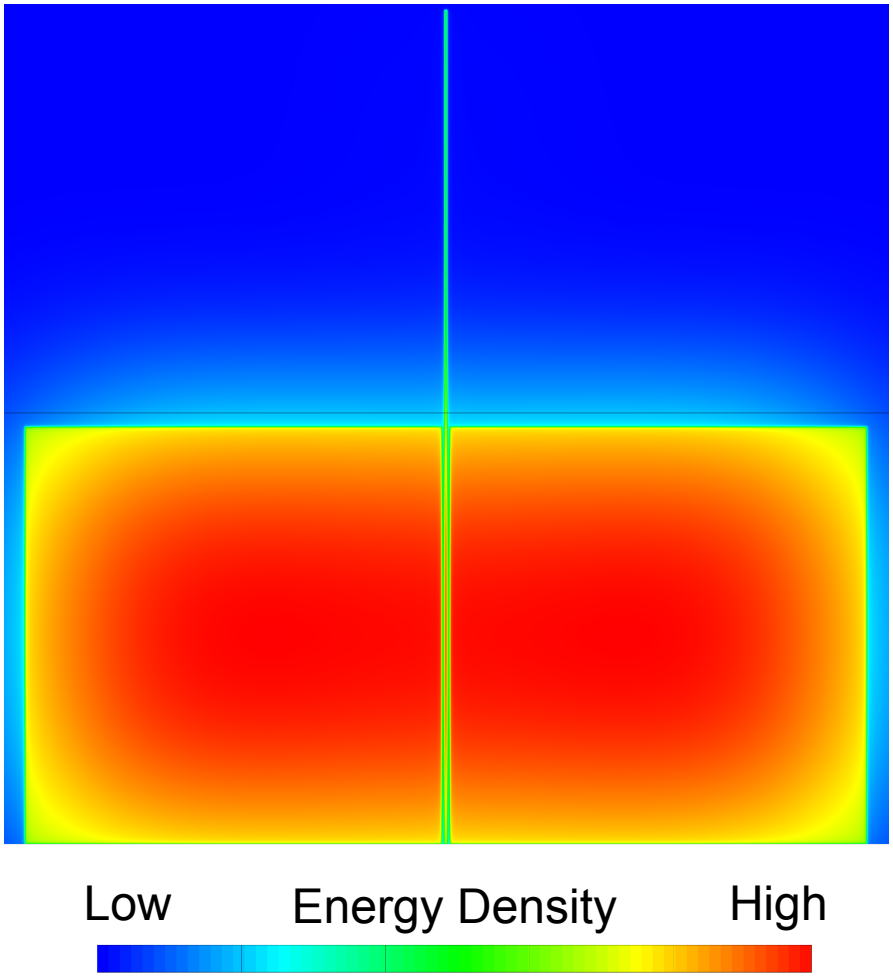
Homogenous Dose



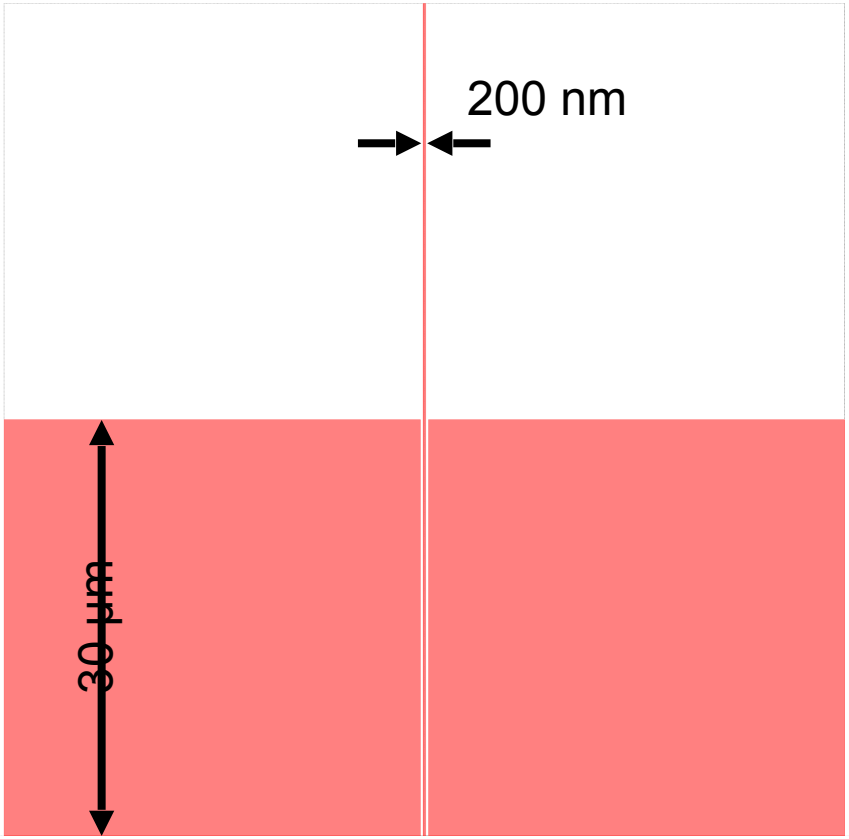
Homogenous Dose



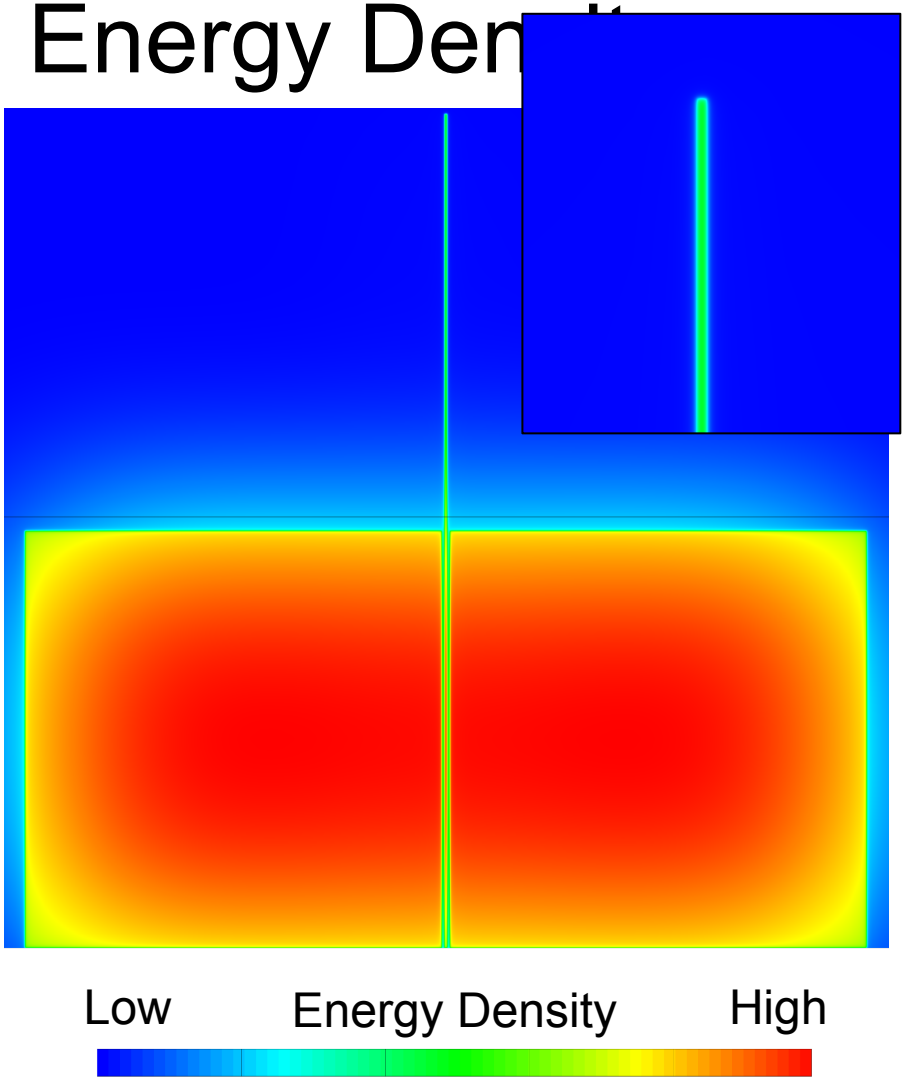
Homogenous Energy Density



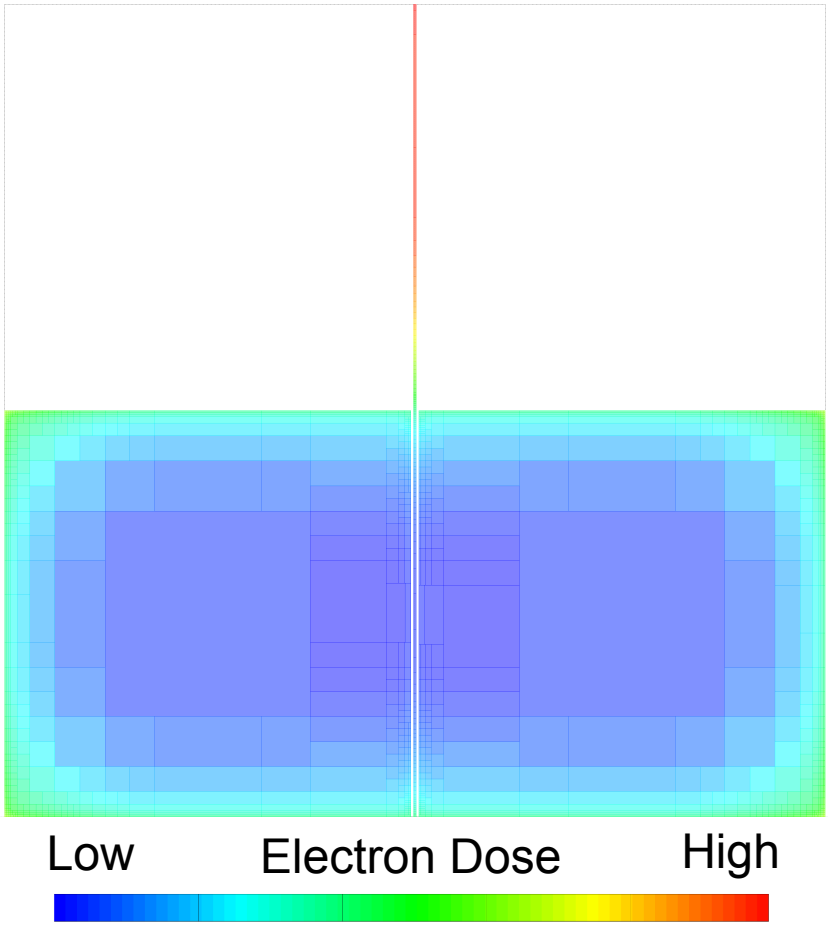
Homogenous Dose



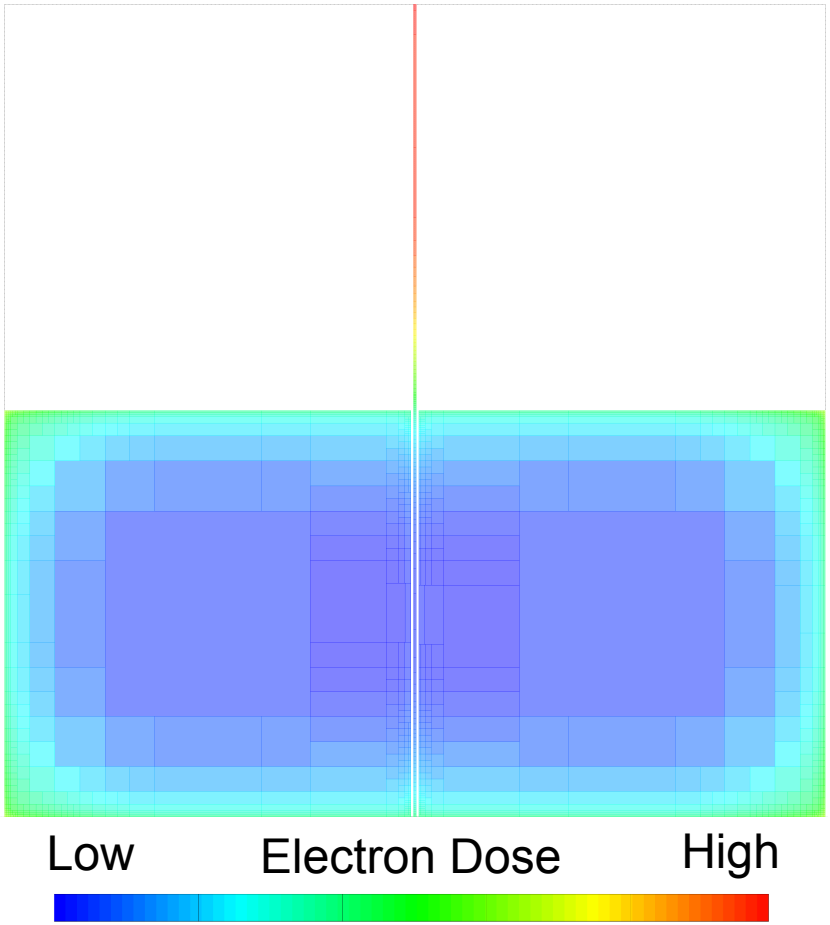
Homogenous Energy Den

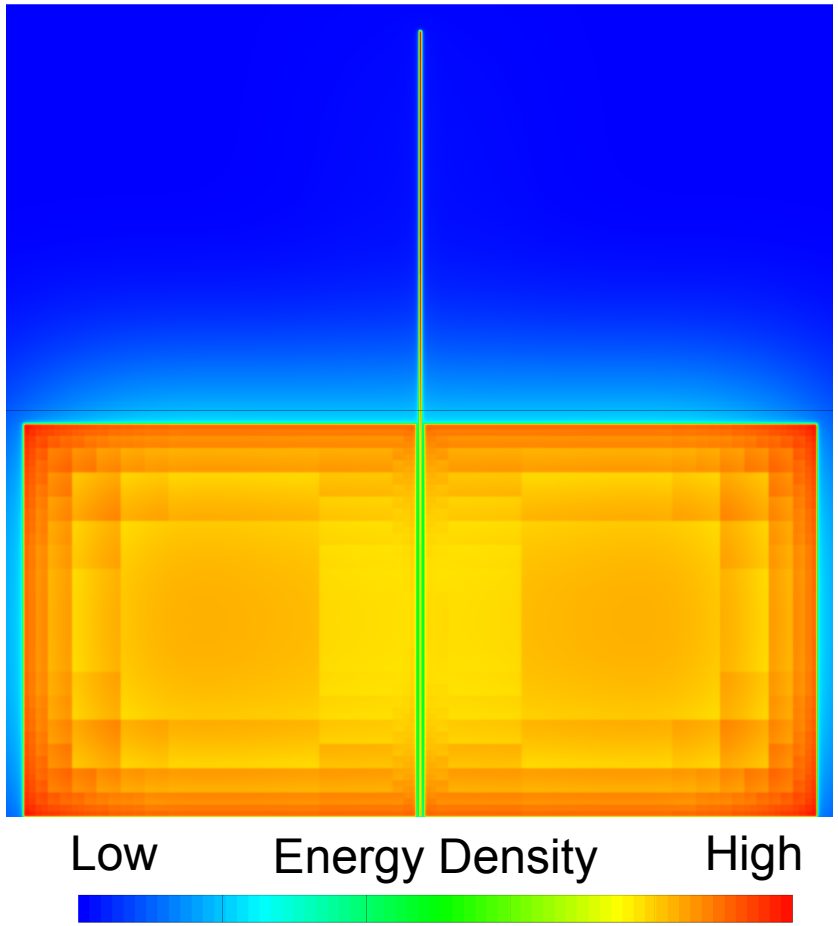


Proximity Effect Correction (PEC)

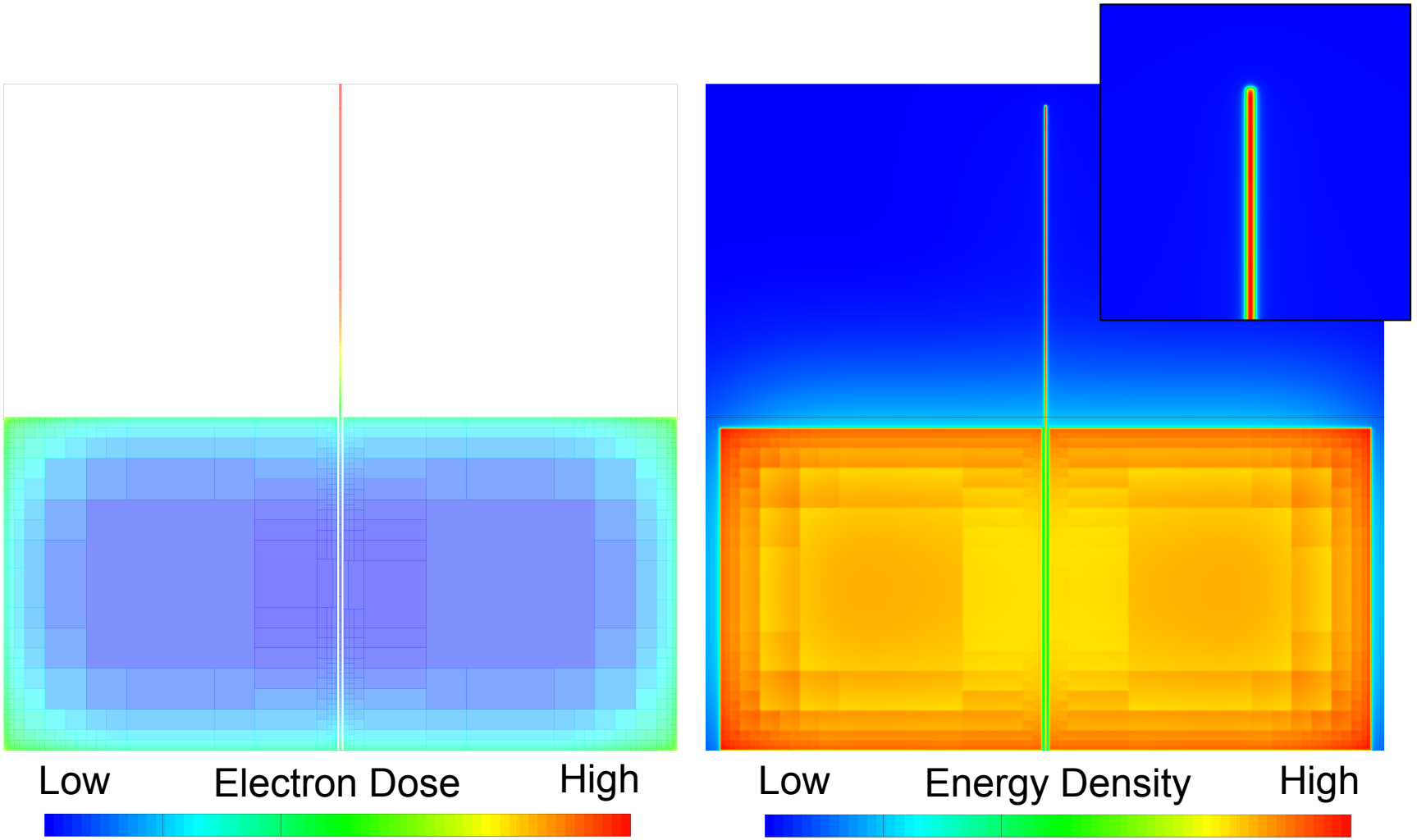


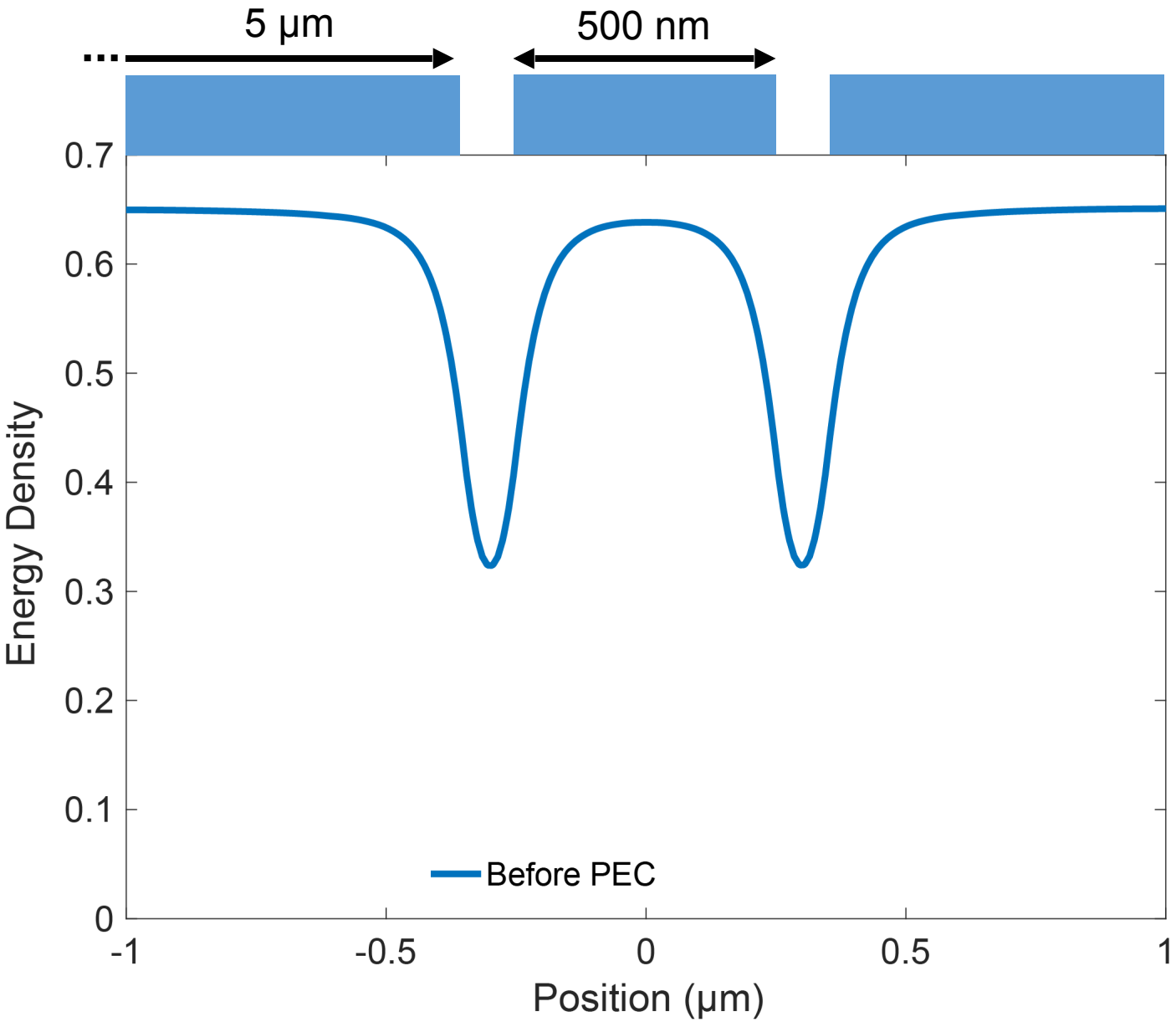
Proximity Effect Correction (PEC)

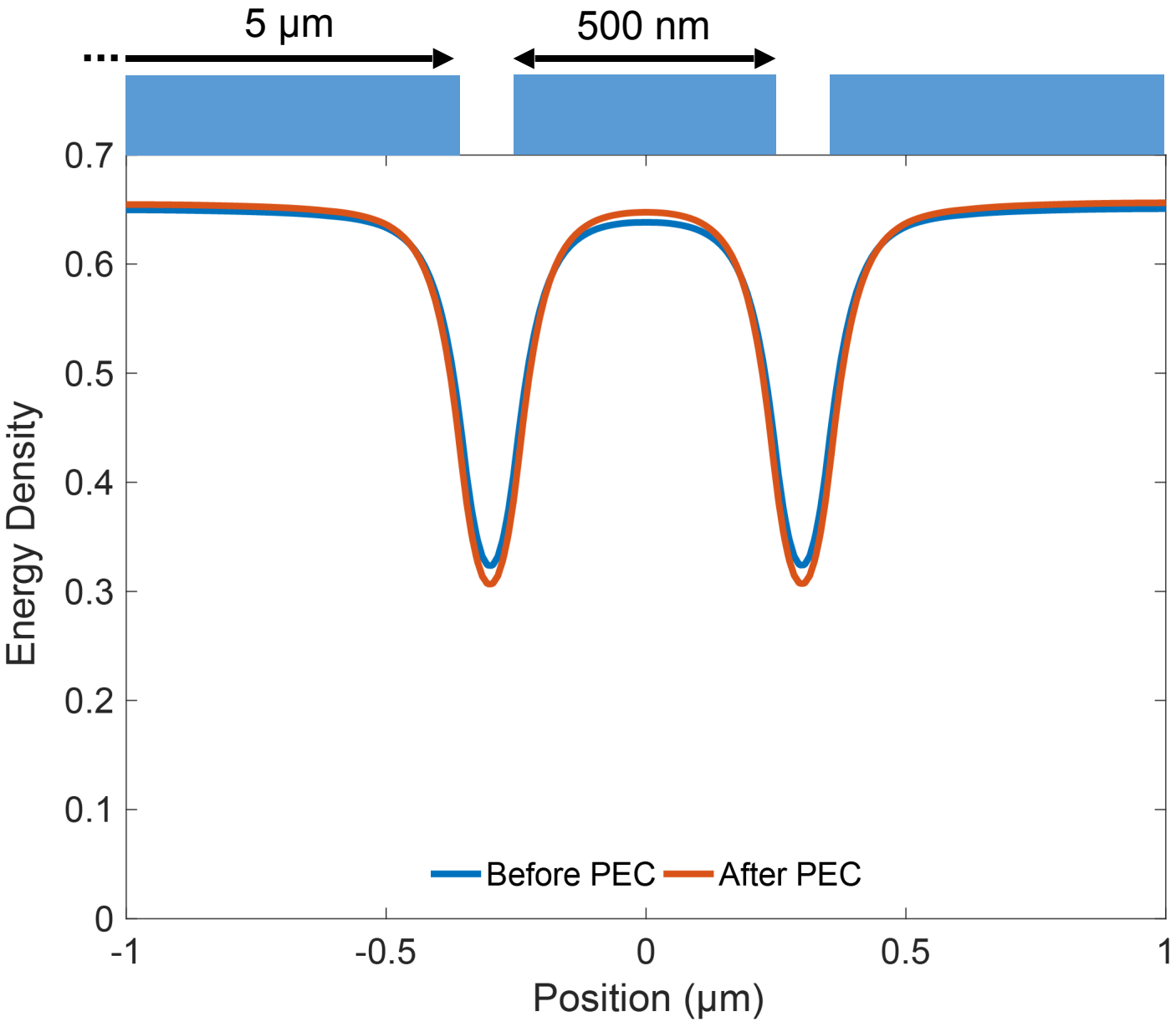




Proximity Effect Correction (PEC)




5 μm
500 nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy Density
Before PEC
-1
-0.5
0
0.5
1
Position (μm)


5 μm
500 nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Energy Density
Before PEC
After PEC
-1
-0.5
0
0.5
1
Position (μm)

How to ensure best possible EBL results?

1. High electron energy
2. Small aperture
3. Low beam current
4. Small scanning field
5. Low sensitivity resist
6. Thin resist layer
7. Optimize resist processes
8. Avoid high density patterns
9. Avoid high density or poor conducting substrates
10. Stable environment for the EBL

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