Reflective Small Angle Electron Scattering to Characterize Nanostructures on Opaque Substrate

Wen-Li Wu[1] , Lawrence H. Friedman[2]

Wei-En Fu[3] and Yunsan Chien[3]

[1]*Materials Science and Engineering Division, Materials Measurement Laboratory*
National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

[2]*Materials Measurement Science Division, Materials Measurement Laboratory*
National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

[3]*Center of Measurement Science*
Industrial Technology Research Institute, Hsinchu, Taiwan

OUTLINE

- Purposes and experiment results – *Wen-Li Wu*
- Simulations – *Lawrence H. Freidman*

WHY SMALL ANGLE ELECTRON SCATTERING (SAES)

To circumvent the difficulties encountered by GISAXS; i.e.

- Large footprint
- Lack of laboratory based and compact X-ray sources with sufficient brilliance

US Patent 9390888: Apparatus and method of applying small-angle electron scattering to characterize nanostructures on opaque substrate

Inventors: Wu; Wen-Li (Hsinchu, TW), Chien; Yun-San (Kaohsiung, TW), Fu; Wei-En (Taoyuan, TW), Chen; Yen-Song (Taipei, TW), Ho; Hsin-Chia (Hsinchu County, TW)

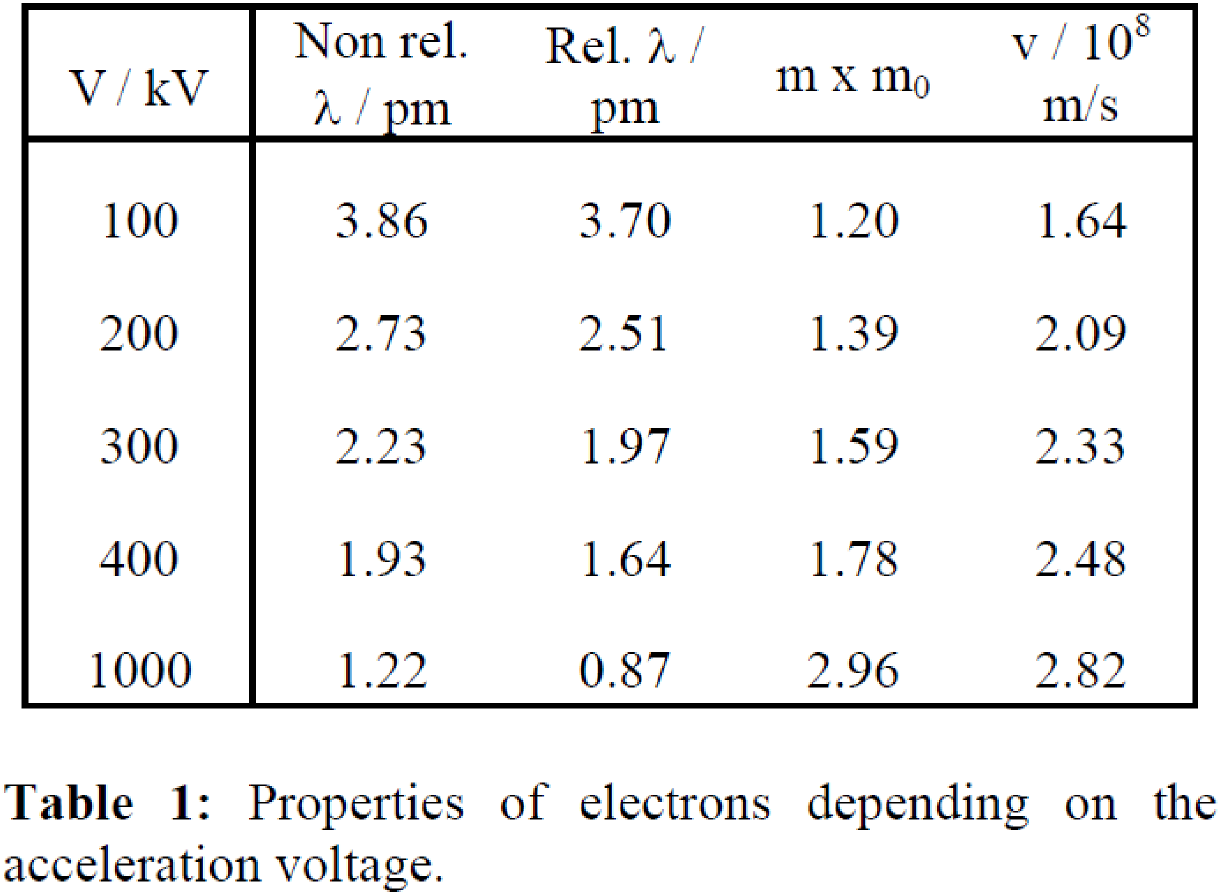
Applicant: Industrial Technology Research Institute, Hsinchu, Taiwan

Small Angle e-beam Scattering (SAES)

- e-beam has the following **advantages** for scattering applications in comparison to X-ray;
    - EM lens and other optical components have been well developed
    - High intensity focus beam available with a focal spot size of **a few nanometers** – footprint can be much smaller than X-ray (a major problem for GISAXS)
    - Scattering cross section is ~10^4 greater than that of X-ray for all materials – incident beam intensity is no longer a show stop for SAES
- E-beam has also the following disadvantages;
    - Complicate interactions with matters including elastic, inelastic scattering, secondary electron and multiple scattering – data interpretation can be challenging
    - **Low** penetration power – SAES has to be operated in a **reflective** mode or back scattering mode; **a complementary** but **NOT a replacement for X-ray based metrologies for buried or HAR structures**
    - Extreme short wavelength, often in picometers. This results in very small scattering angles

$$\lambda = h \Big/ \sqrt{2m_0eV\,(1 + eV / 2m_0c^2)}$$

Short wavelength of e-beam → a great spatial resolution



V / kV	Non rel. λ / pm	Rel. λ / pm	m x m_0	v / 10^8 m/s
100	3.86	3.70	1.20	1.64
200	2.73	2.51	1.39	2.09
300	2.23	1.97	1.59	2.33
400	1.93	1.64	1.78	2.48
1000	1.22	0.87	2.96	2.82

Table 1: Properties of electrons depending on the acceleration voltage.

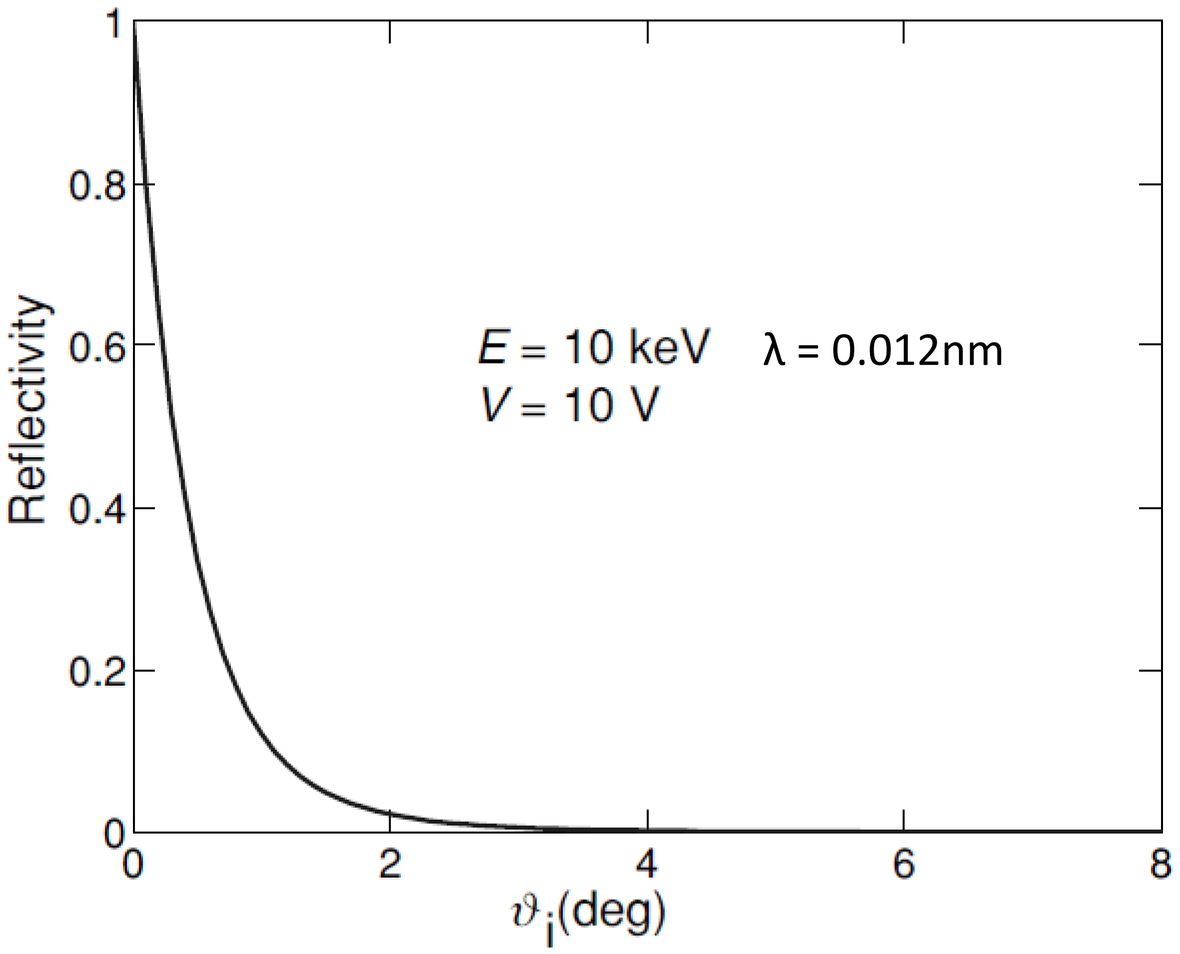


Figure 4.4 Reflectivity vs external incident angle from the Fresnel equation.

Fresnel Coefficient of reflection for electron

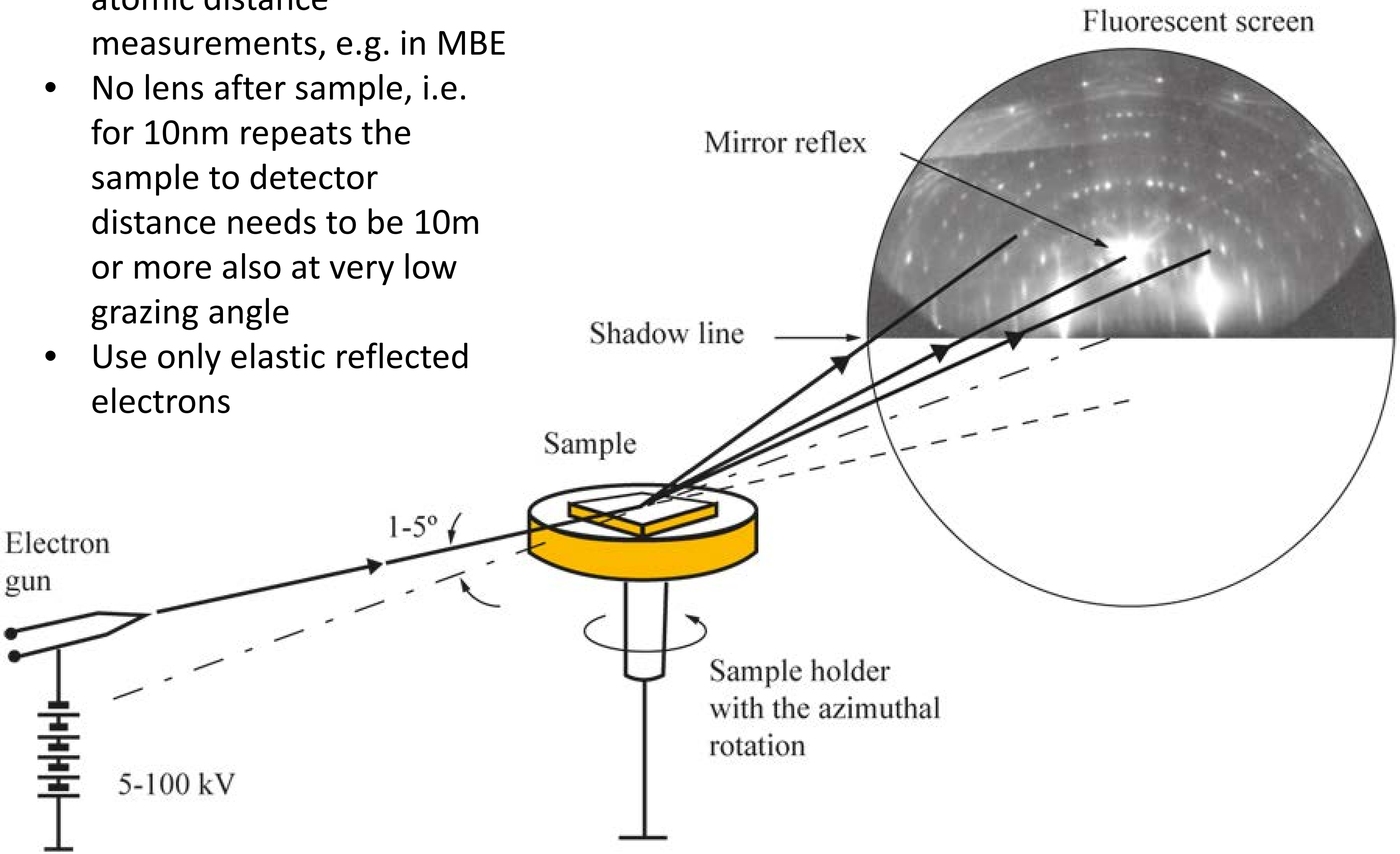
$$\text{reflectivity} = \left| \frac{\Gamma - \sqrt{\Gamma^2 + U}}{\Gamma + \sqrt{\Gamma^2 + U}} \right|^2 .$$

Then using $\Gamma = k \sin \vartheta_{\mathrm{i}}$, $k = 0.512\sqrt{E}$ and $U = V_{\mathrm{I}}/3.81$ with $E = 10\,\mathrm{keV}$ and $V_{\mathrm{I}} = 10\,\mathrm{V}$,

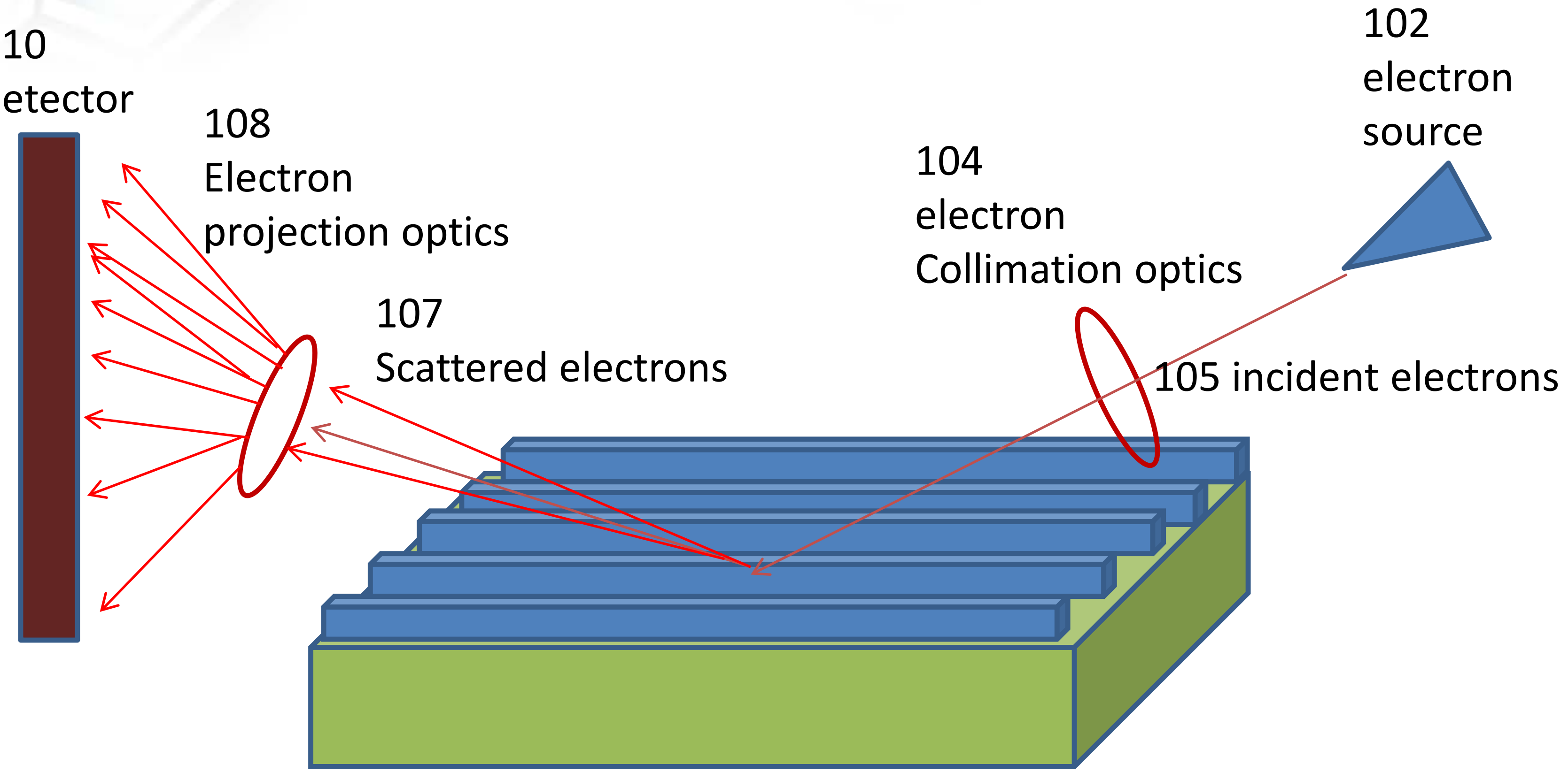
For crystalline Silicon $V_1 = 12.1 \pm 1.3$ V
Y.C. Wang *et al* , Appl. Phys. Lett., 70(10), 1296 (1997)

Existing Art: Reflective High Energy Electron Diffraction (RHEED)

- For surface lattice or atomic distance measurements, e.g. in MBE
- No lens after sample, i.e. for 10nm repeats the sample to detector distance needs to be 10m or more also at very low grazing angle
- Use only elastic reflected electrons



Multiple lenses are needed after sample for SAES measurements



110
detector

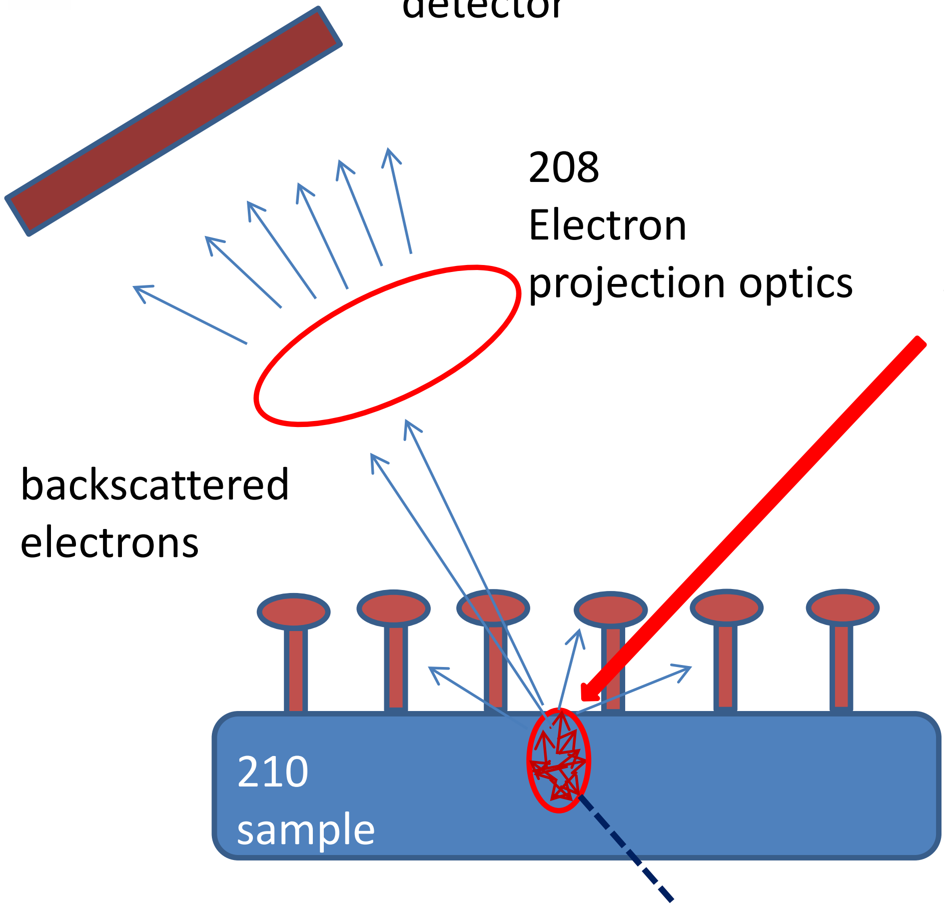
108
Electron
projection optics

107
Scattered electrons

104
electron
Collimation optics

102
electron
source

105 incident electrons



210
detector

208
Electron
projection optics

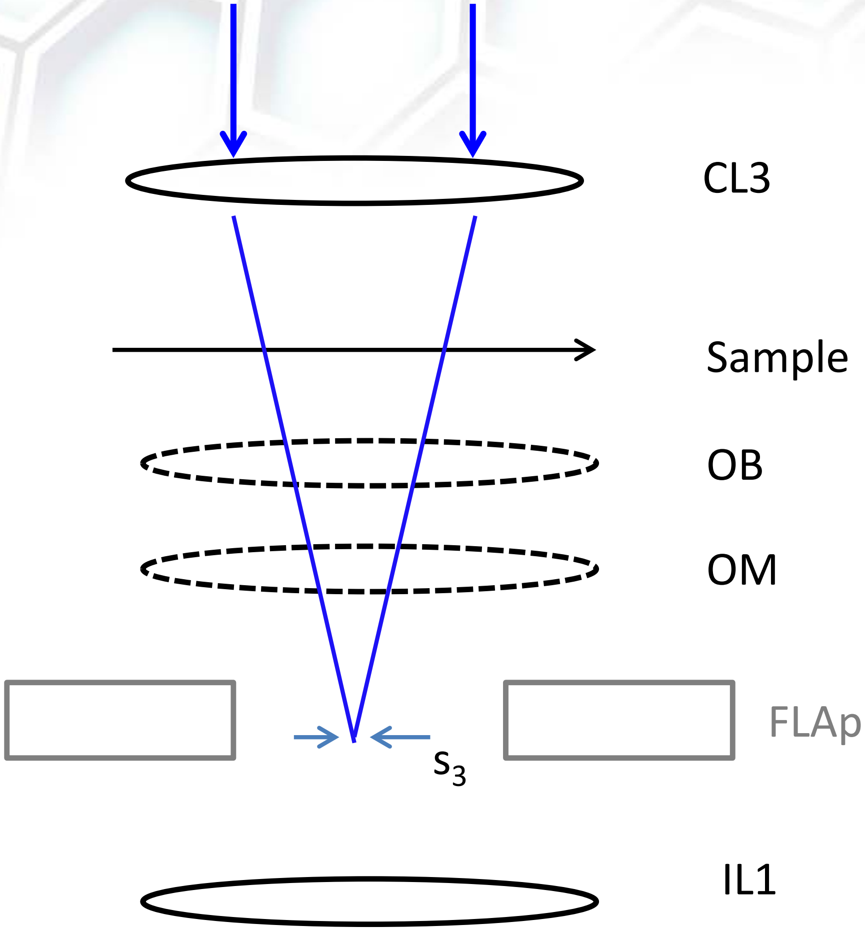
205
incident
e-beam

backscattered
electrons

206 sample: a
nanostructure
target on top of
a substrate

210
sample

excited volume



CL3

Sample

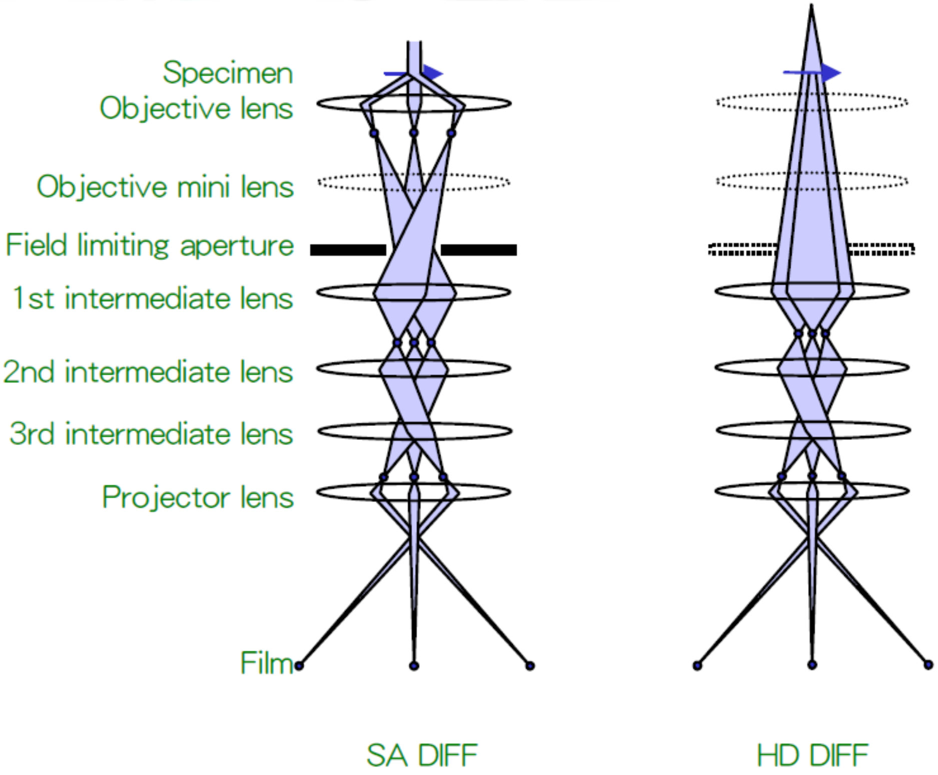
OB

OM

FLAp

s_3

IL1



Specimen

Objective lens

Objective mini lens

Field limiting aperture

1st intermediate lens

2nd intermediate lens

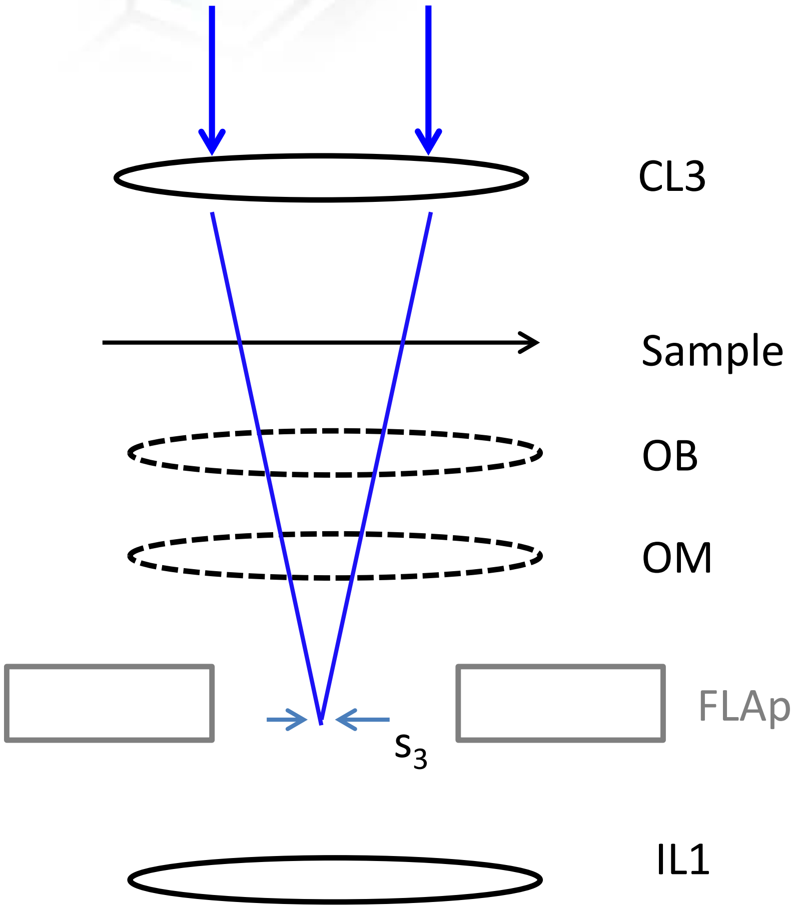
3rd intermediate lens

Projector lens

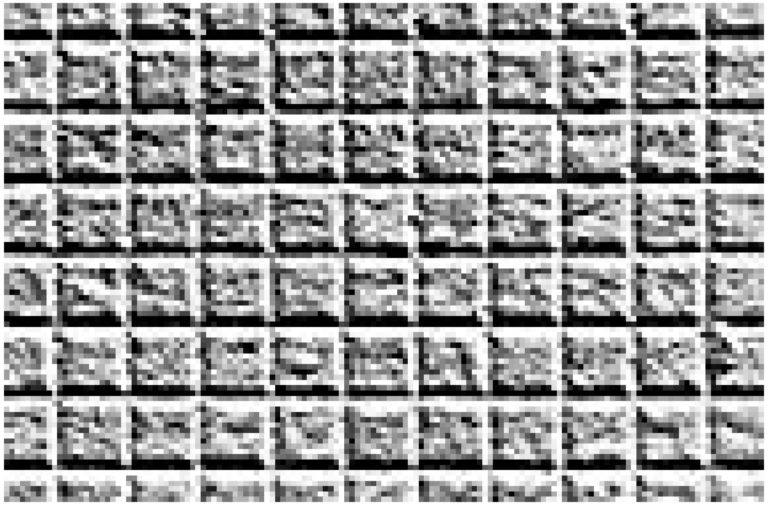
Film

SA DIFF

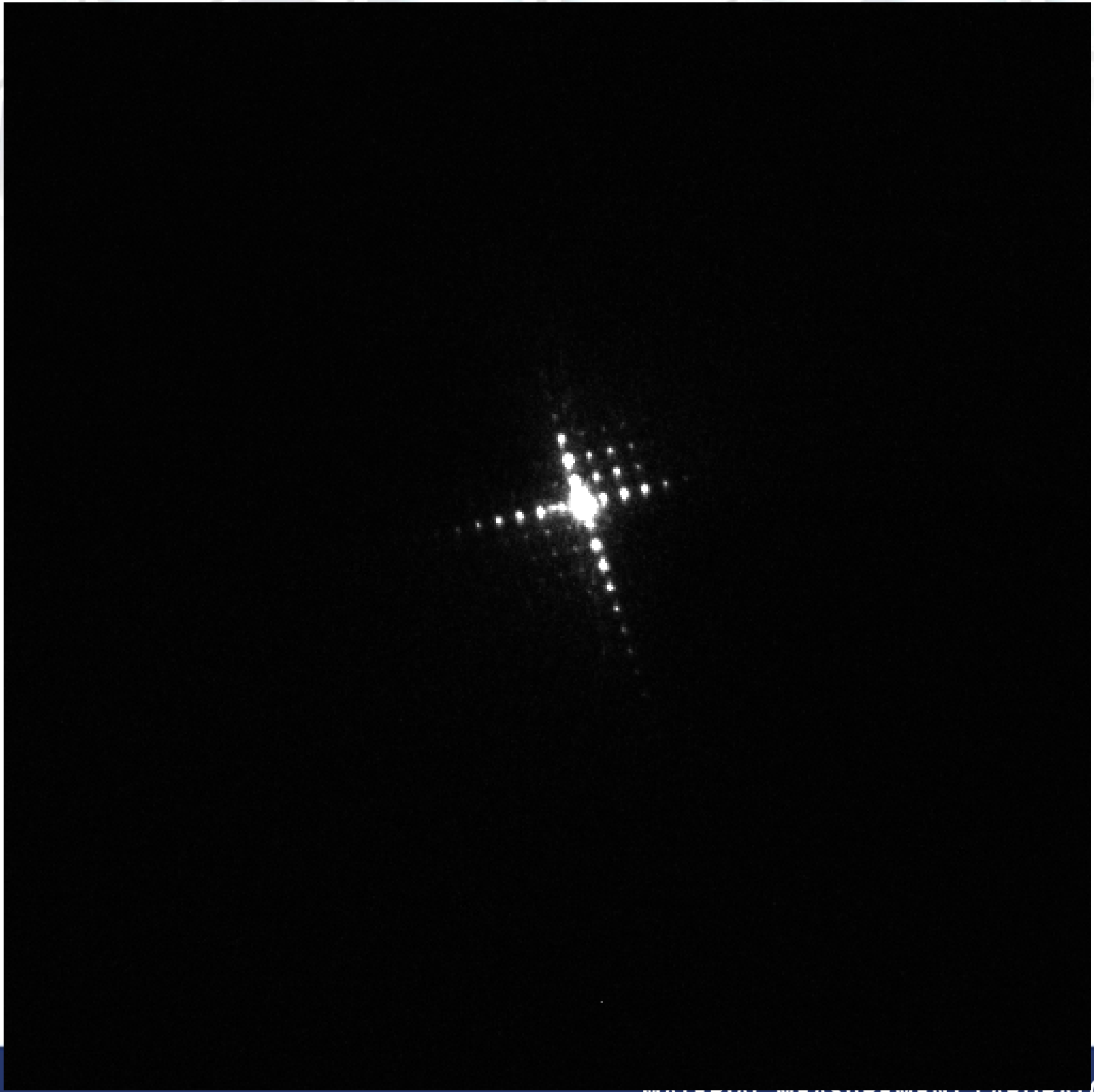
HD DIFF



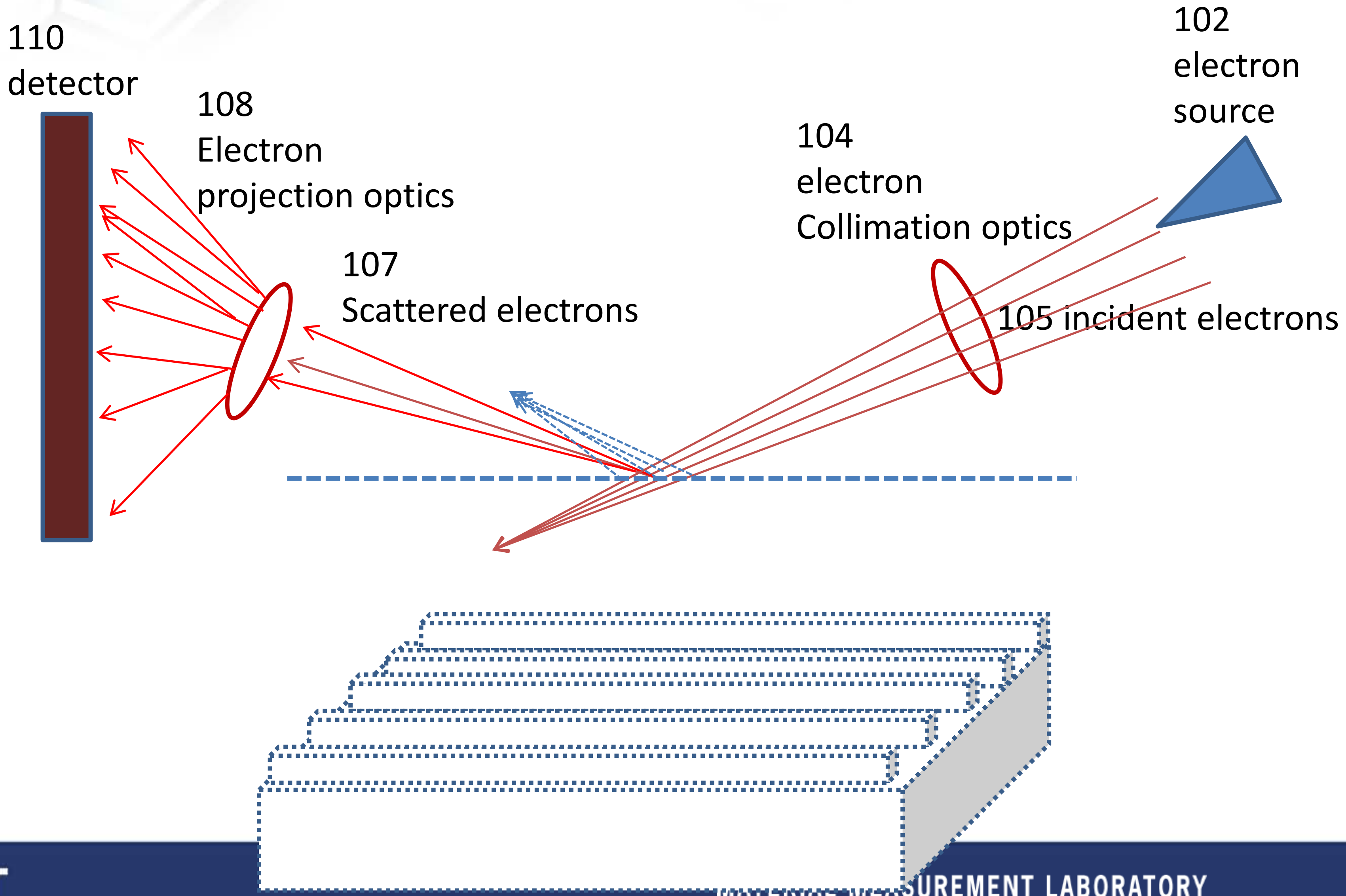
	HD: 40m	3LS
CL1	1.92	1.93
CL2	X	X
CL3	2.39	1.43
CAp	●	●
CM	0	0
OB	0	0
OBA	X	X
OBM	0	0
FLAp	X	X
IL1	1.04	0.91
IL2	2.29	3.04
IL3	1.18	1.15
PL	3.36	3.36

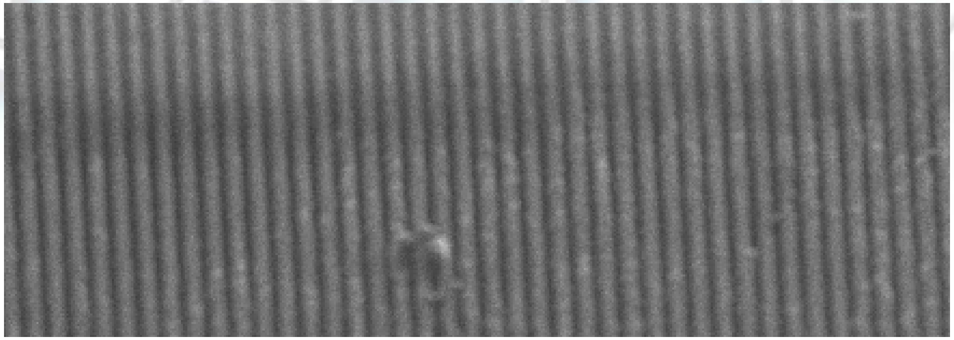


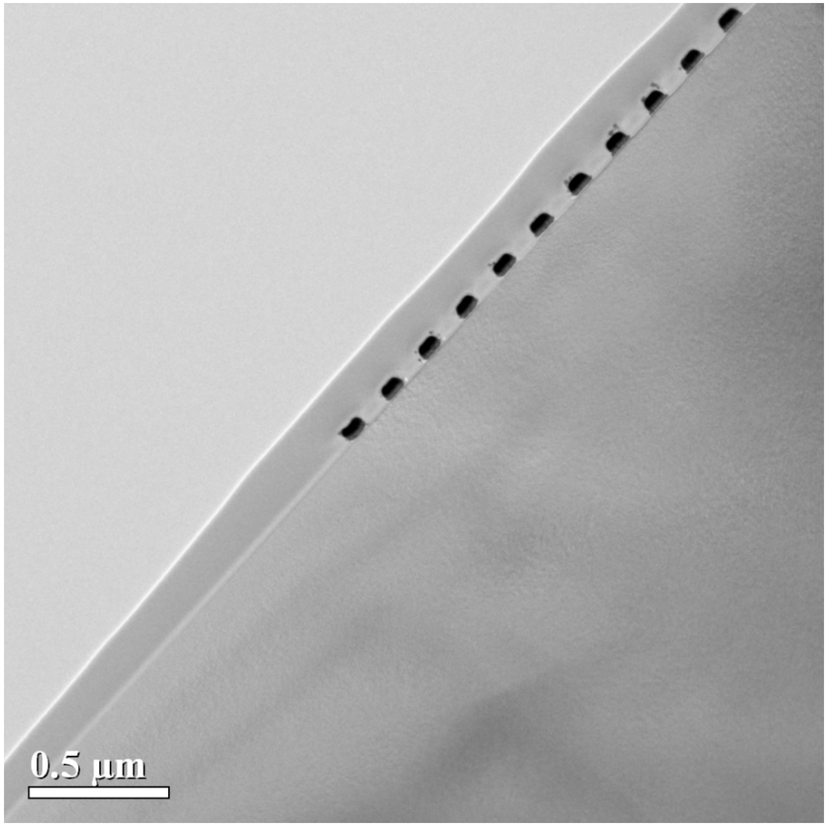
Carbon film with 2160 lines /mm or 463 nm repeat

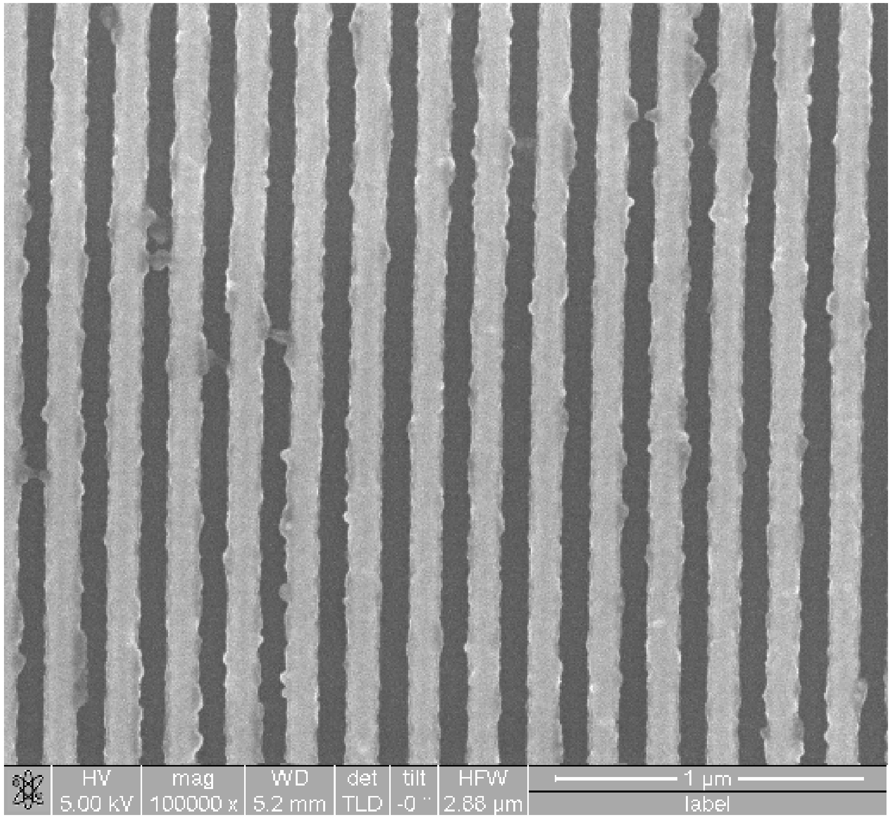


Multiple lenses are needed after sample for SAES measurements

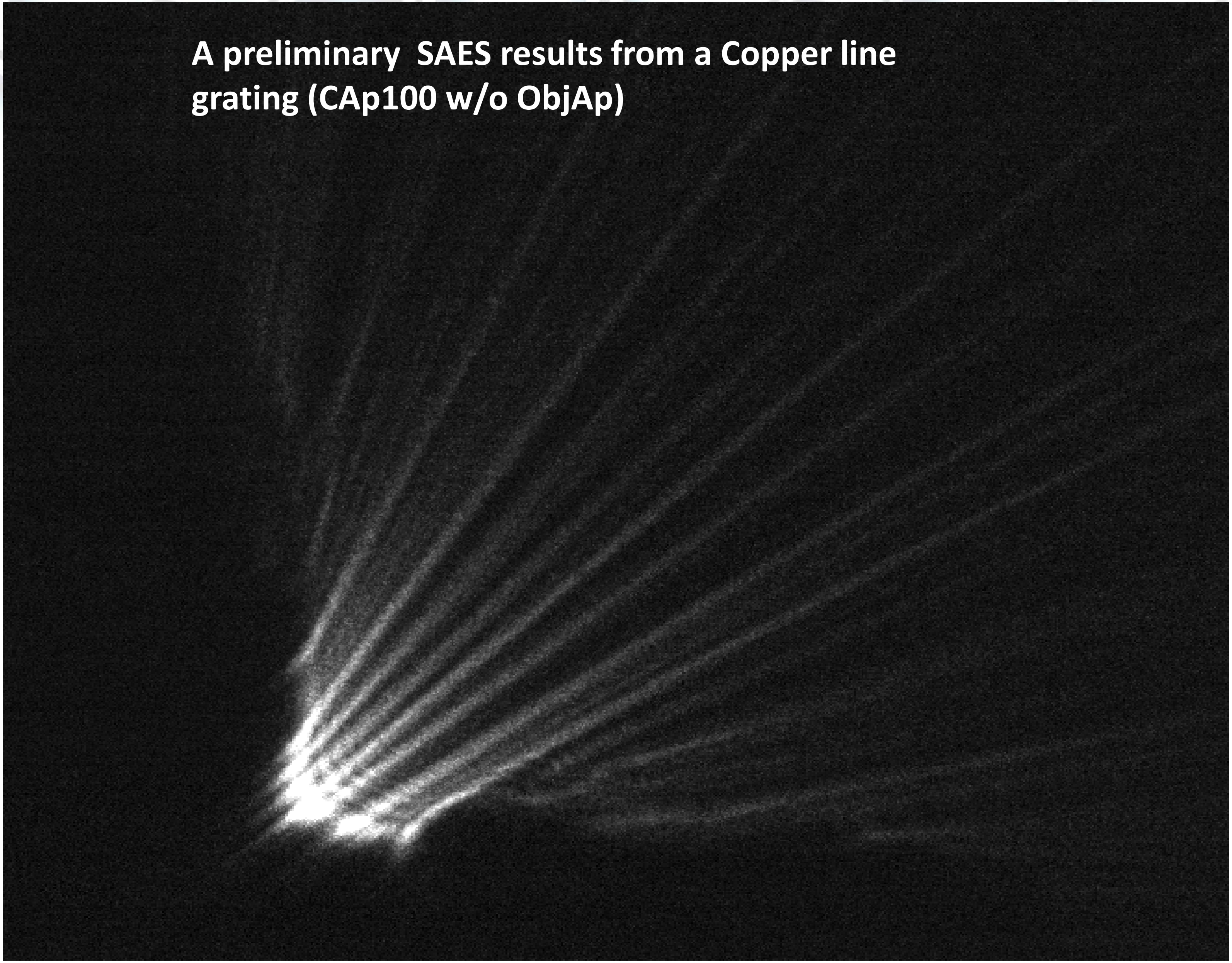


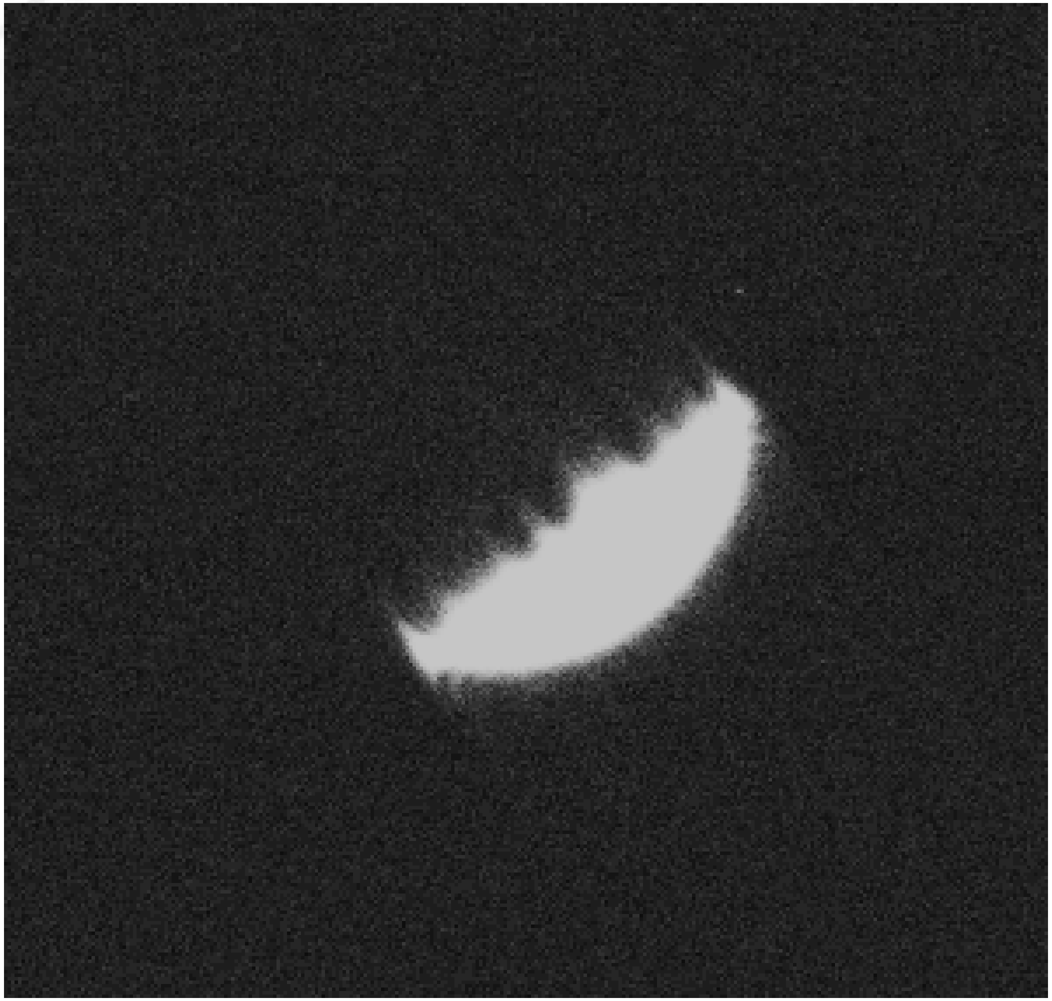


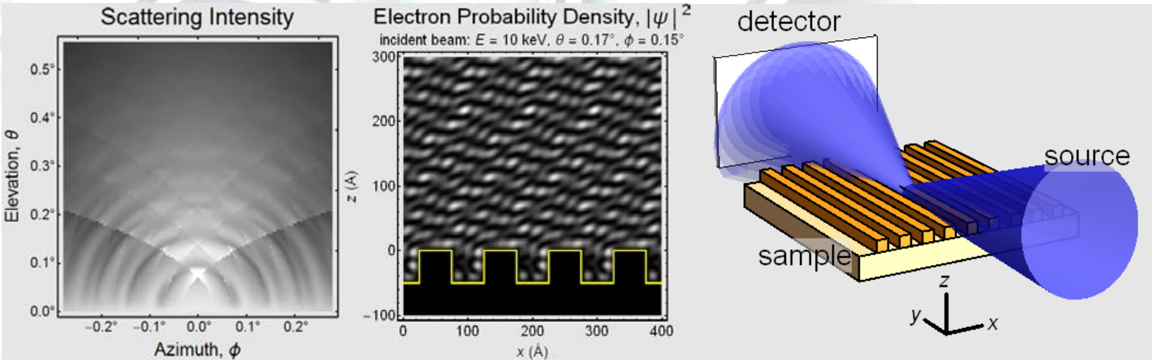

0.5 µm


HV
5.00 kV
mag
100000 x
WD
5.2 mm
det
TLD
tilt
-0 °
HFW
2.88 µm
1 µm
label

A preliminary SAES results from a Copper line grating (CAp100 w/o ObjAp)







Reflective Small Angle Electron Scattering: *Simulations*

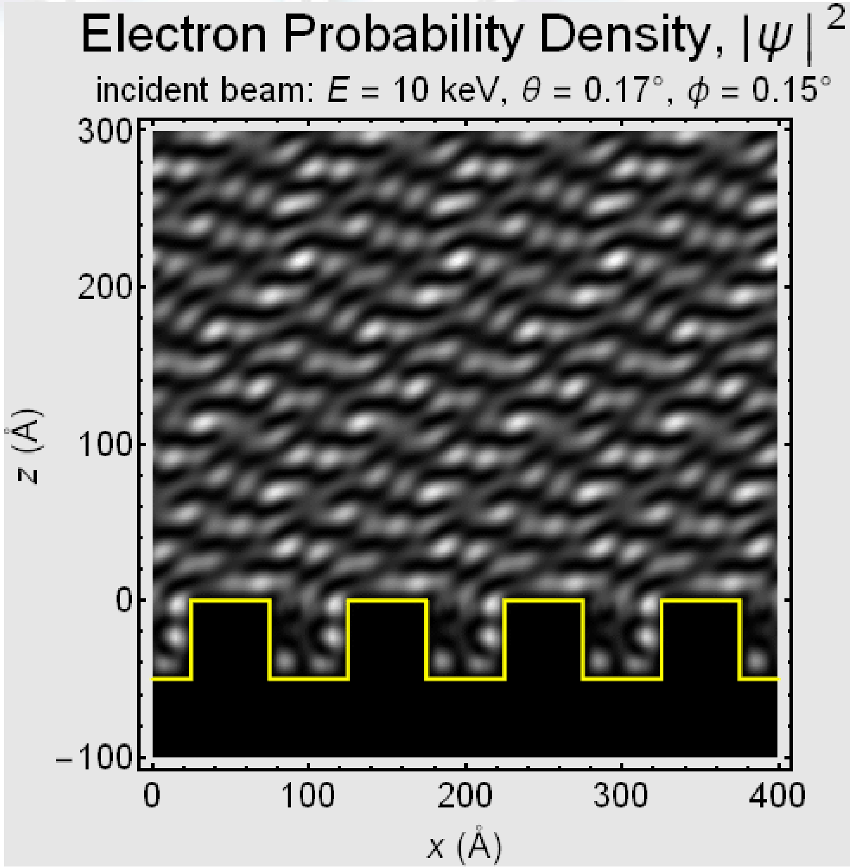
Lawrence H. Friedman
Wen-Li Wu

National Institute of Standards and Technology
USA

Wei-En Fu
Yunsan Chien

Center of Measurement Science
Industrial Technology Research Institute, Taiwan

RSAES Simulations

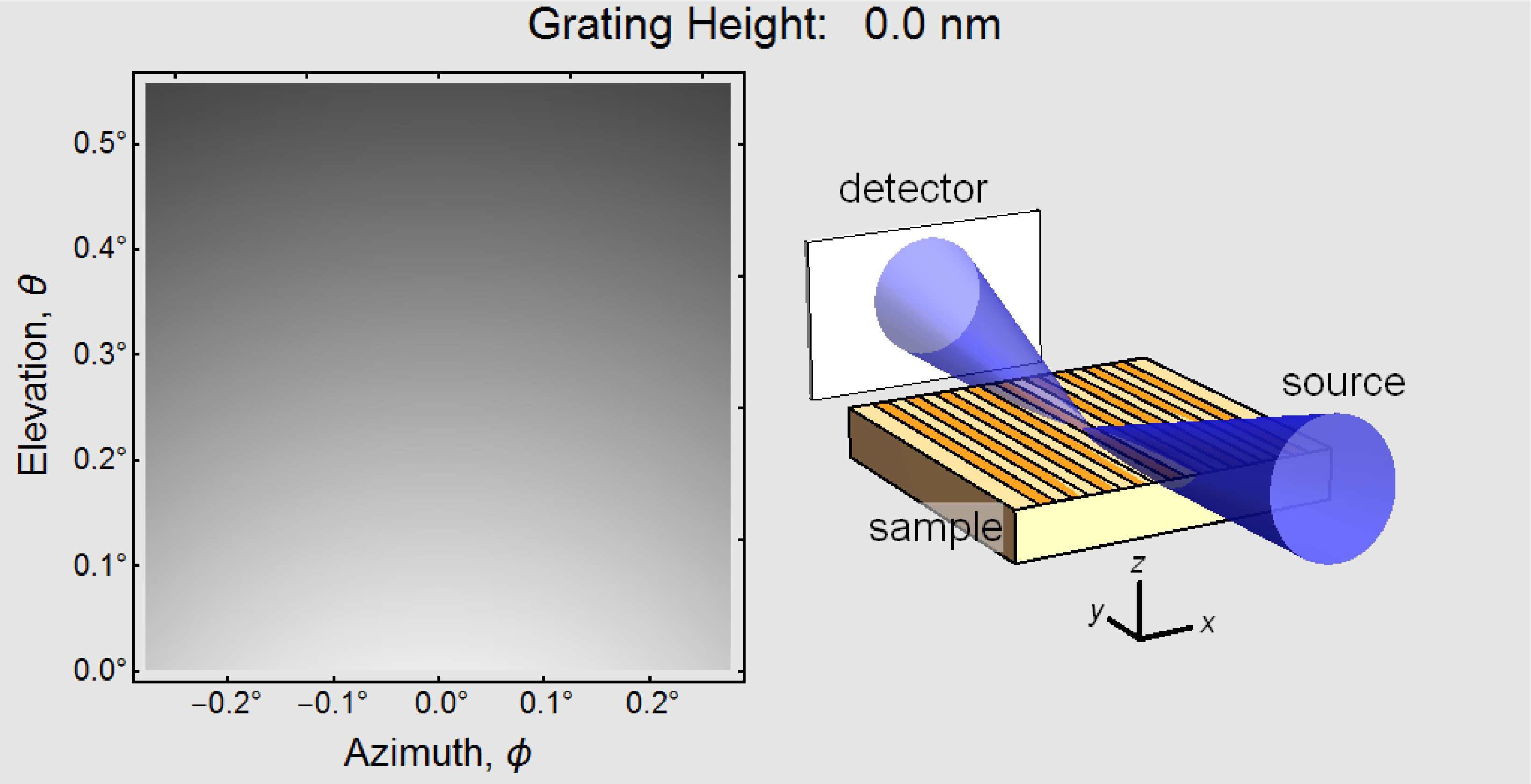


Two key questions

- Is $\theta, \phi < 1°$ interesting?
- Is the signal strong?

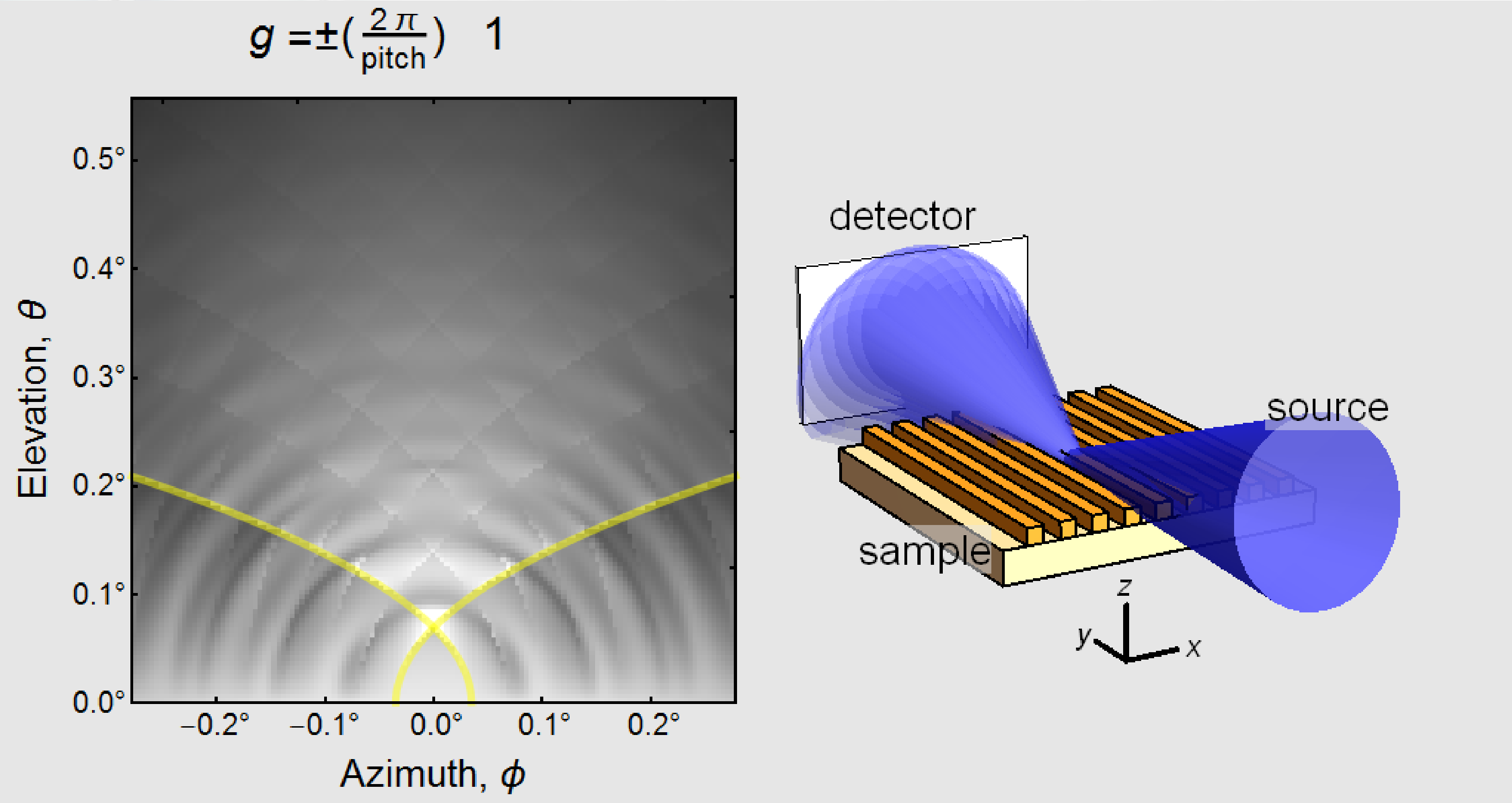
Method

- $(\nabla^2 + k^2 - U(\vec{x}))\, \psi(\vec{x}) = 0$
- $U(\vec{x}) = (\text{mean internal potential}) - i\, (\text{quantum decoherence})$
- Radiative boundary conditions



Reflected Intensity = 0.3…1

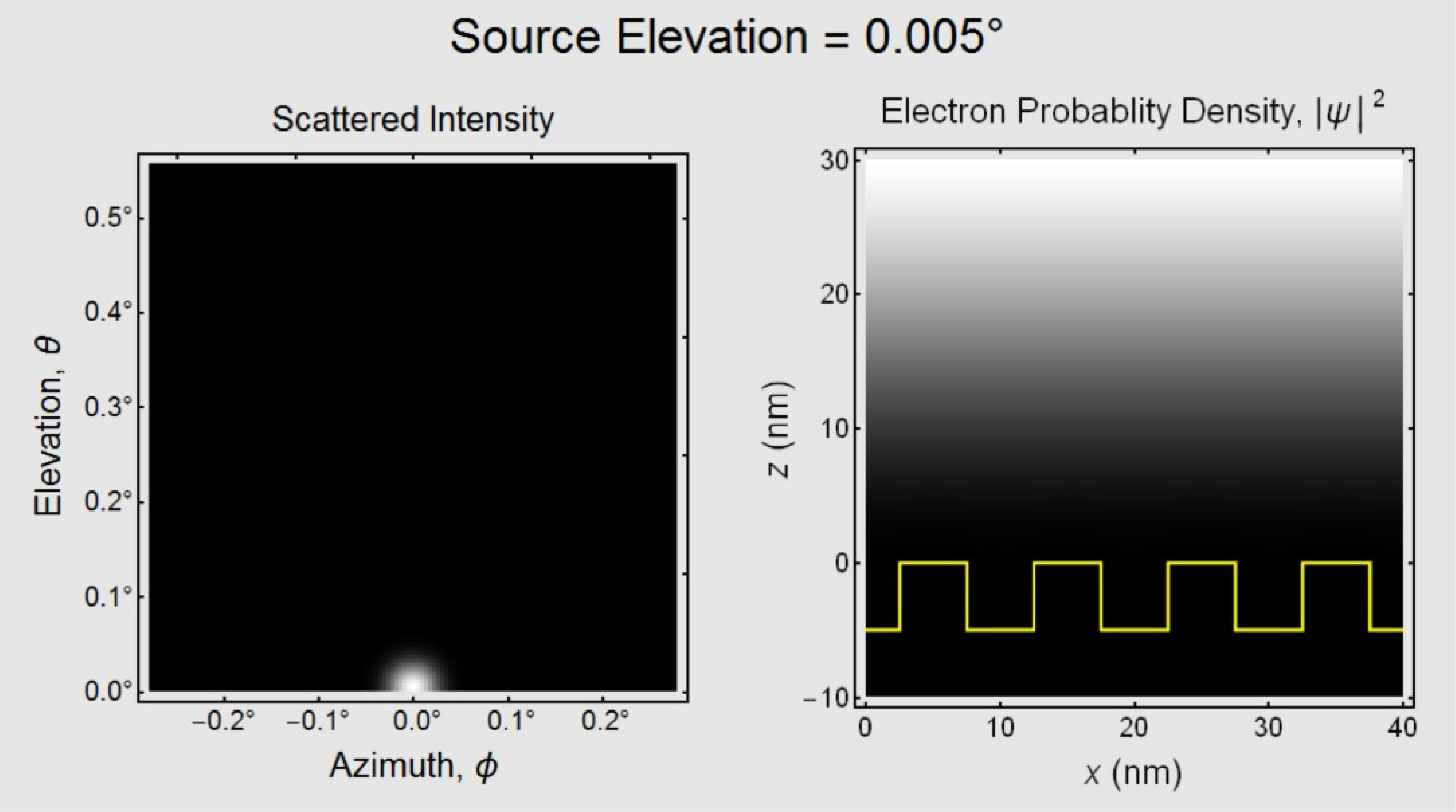
Line height = 0-13 nm
Pitch = 10 nm
Line width = 5 nm



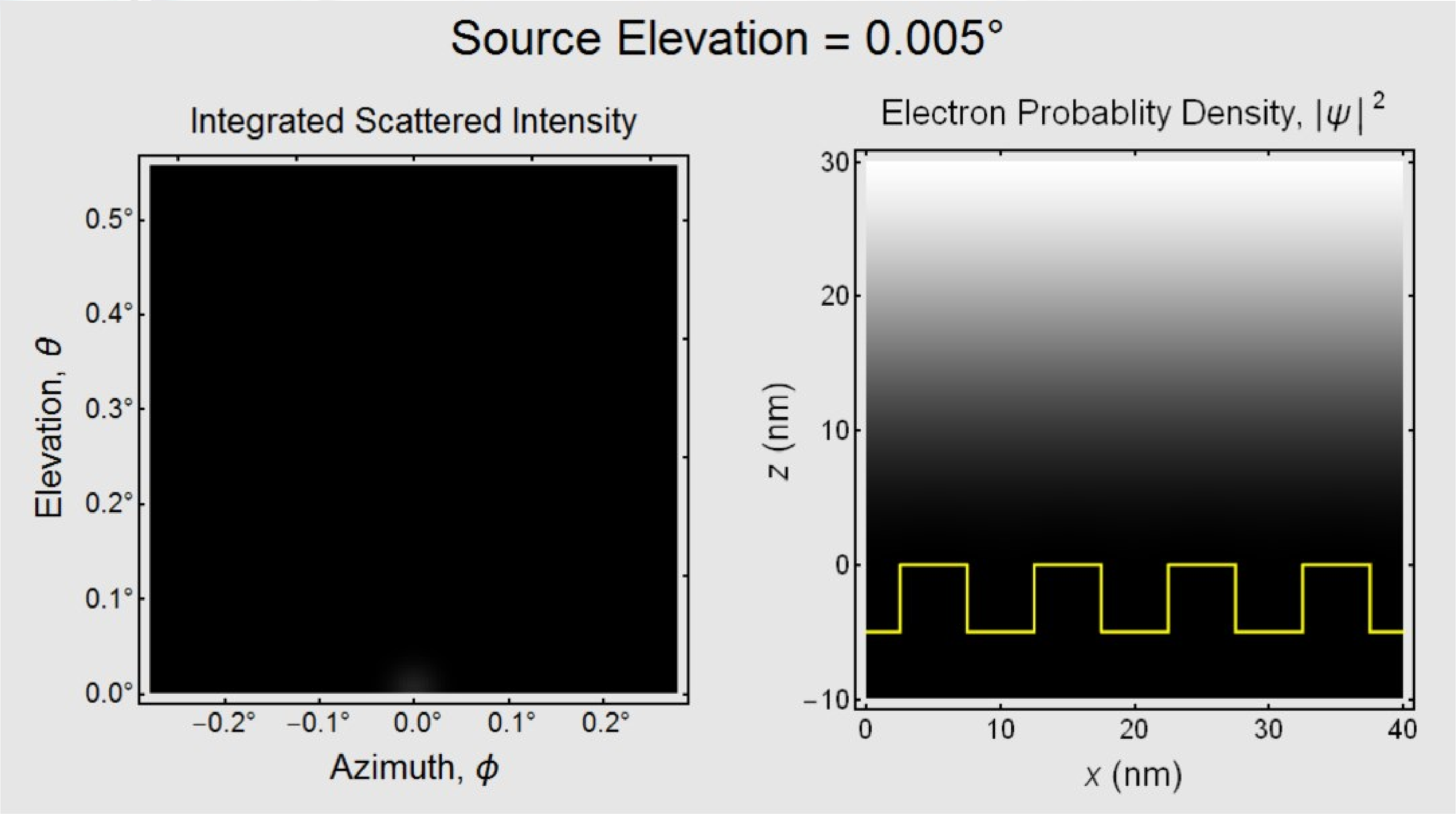
$$q_z = \sqrt{g^2 + (2g)\, q_x}$$

Pitch = 10 nm
Line width = 5 nm
Line height = 5 nm

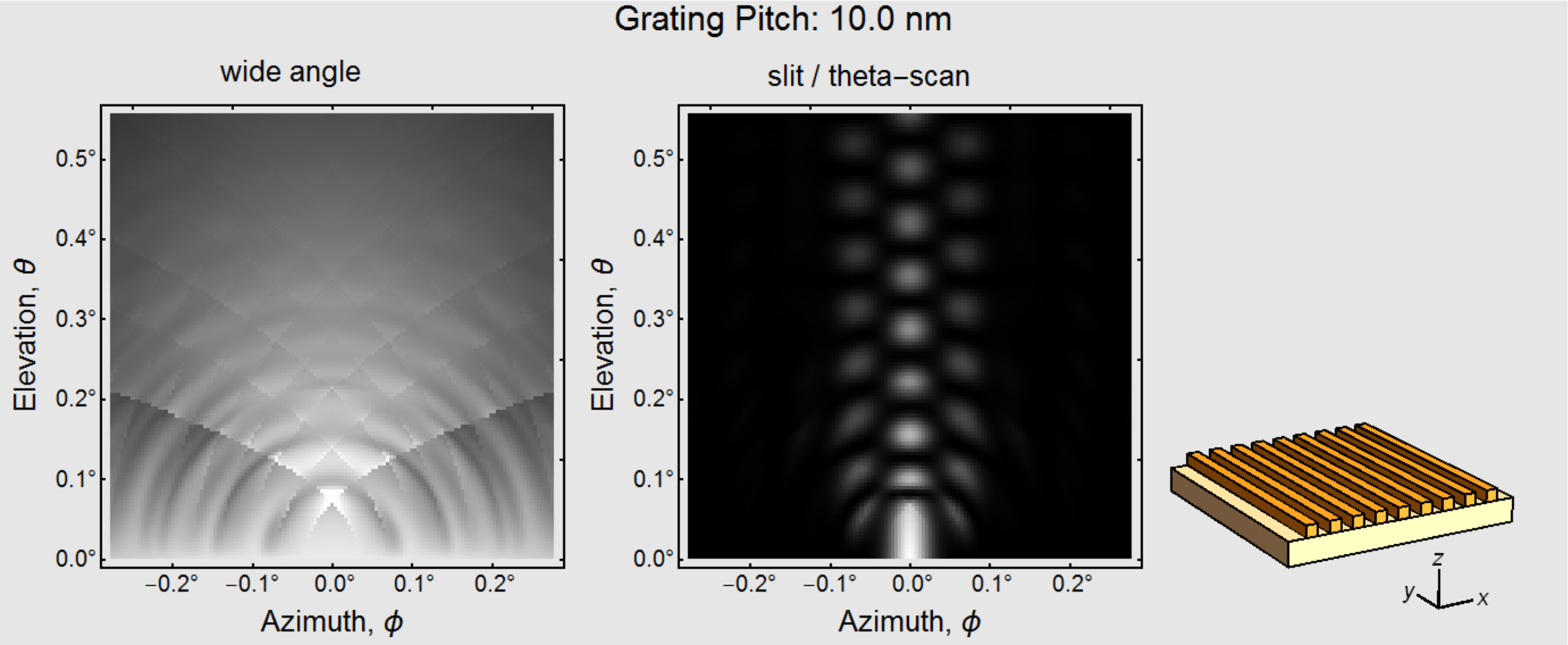
scanning


Source Elevation = 0.005°
Scattered Intensity
Elevation, θ
0.5°
0.4°
0.3°
0.2°
0.1°
0.0°
−0.2°
−0.1°
0.0°
0.1°
0.2°
Azimuth, ϕ
Electron Probablity Density, |ψ|²
z (nm)
30
20
10
0
−10
0
10
20
30
40
x (nm)

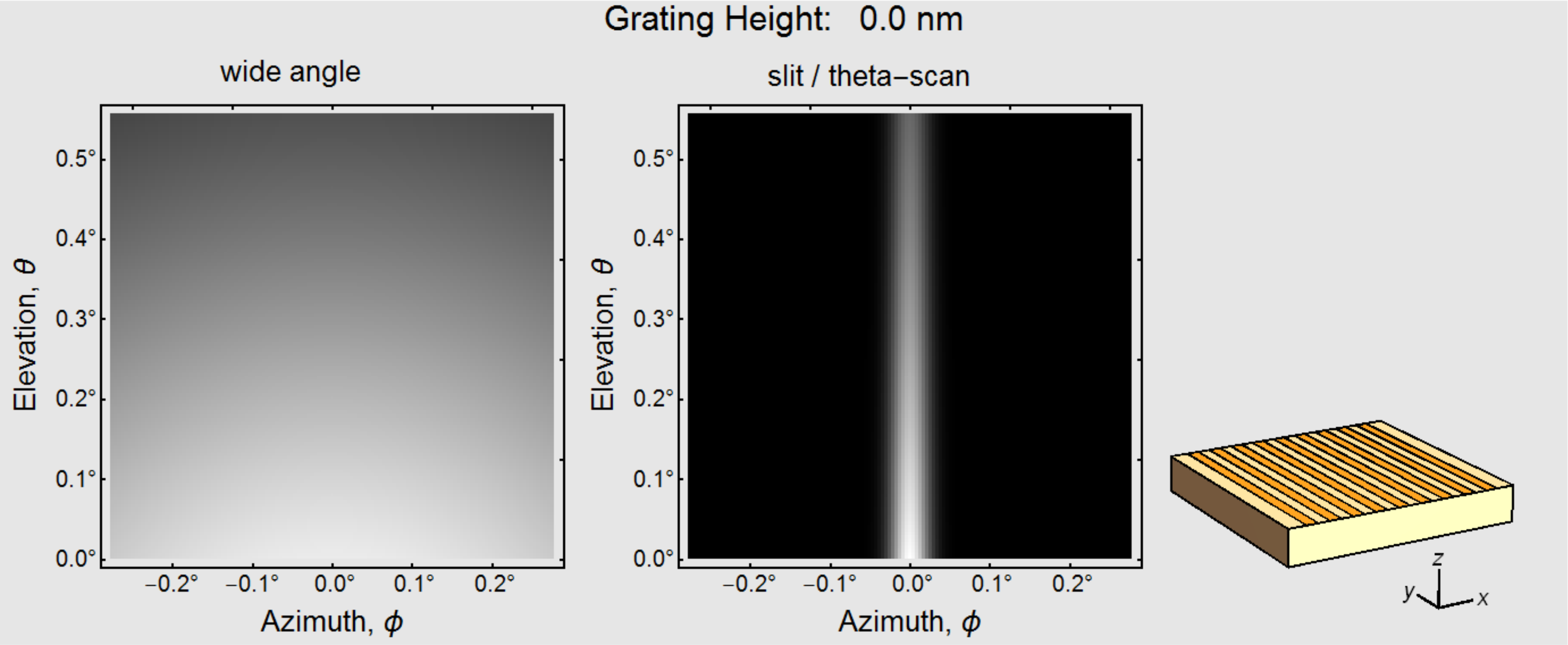
integrating



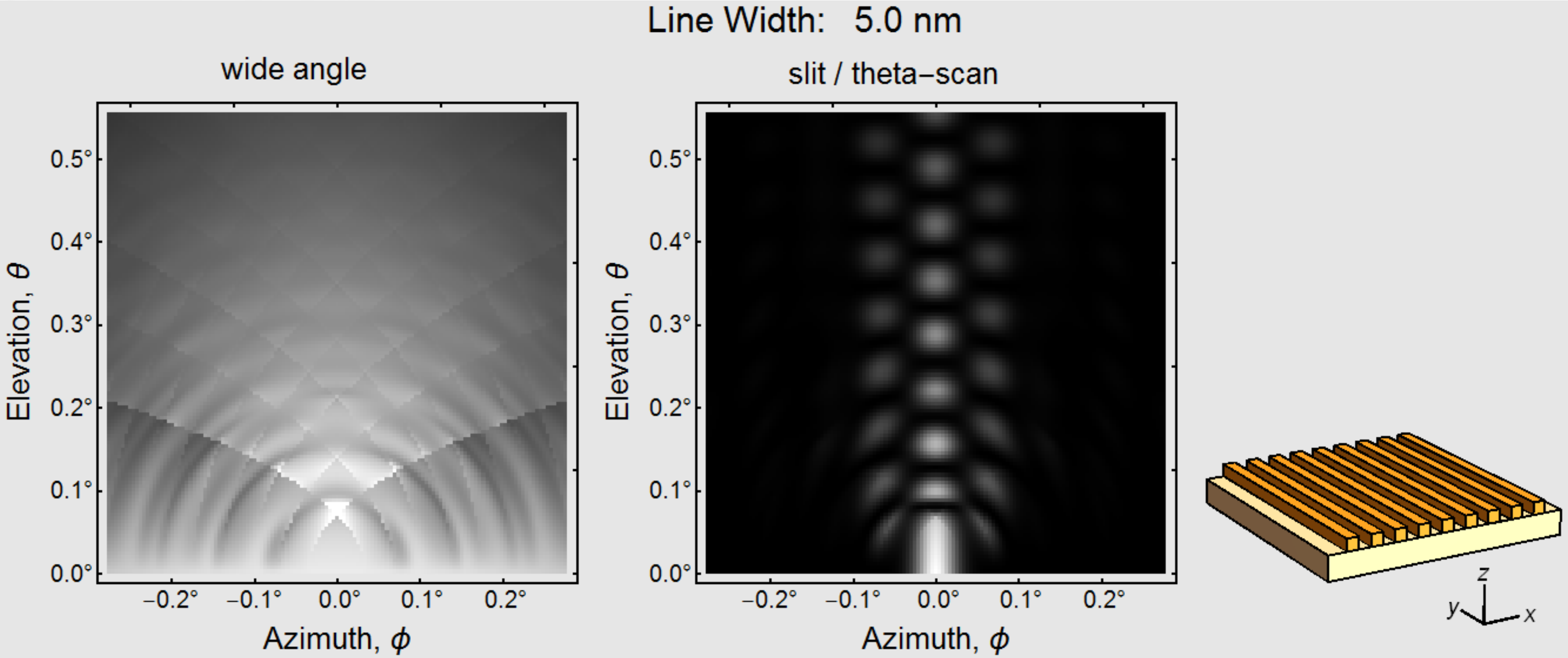
Pitch Sensitivity



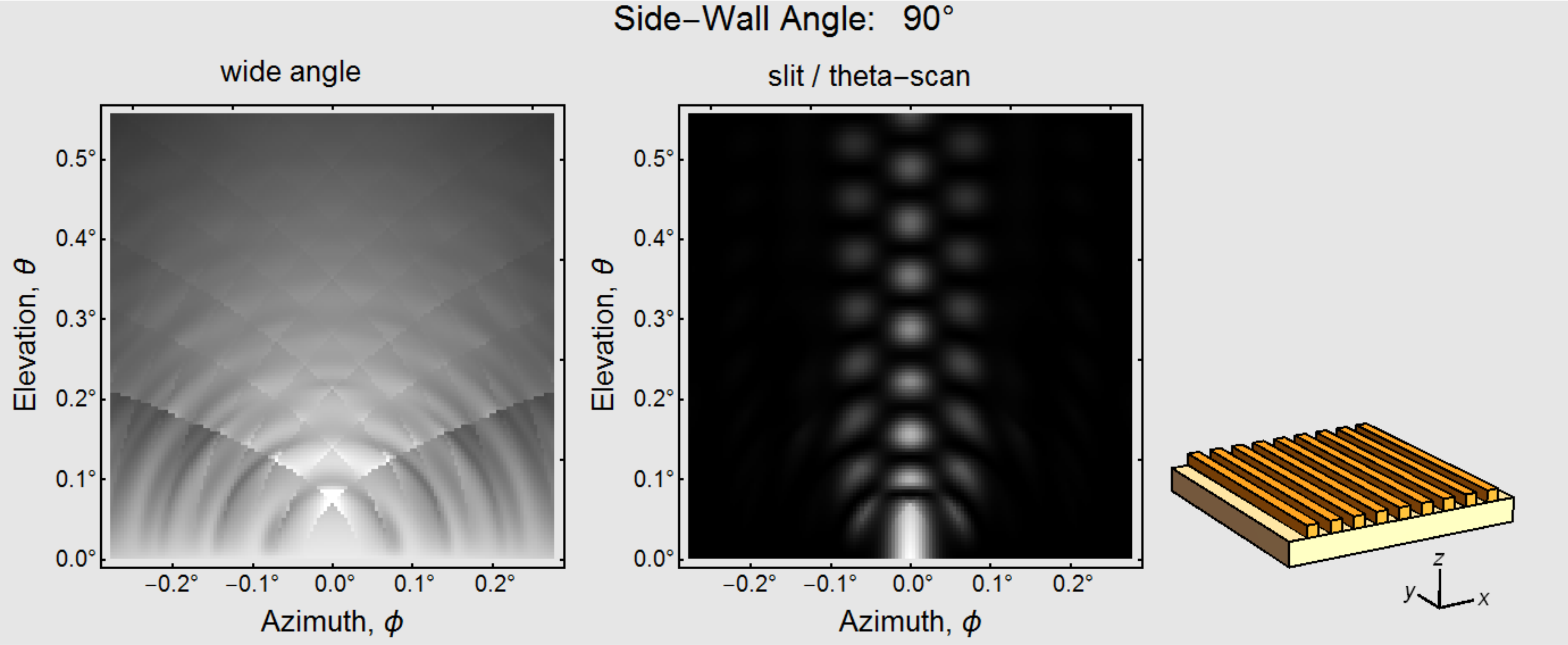
Height Sensitivity



Line Width Sensitivity



Shape Sensitivity



Final Notes

- **full dynamic simulation of Reflective Small Angle Electron Scattering.**
- **efficiency in the 0.3 to 1.0 range for structures smaller than 10 nm**
- **useful geometric information**
- **different aperture/scanning modes**
- **extension possible to:**

rough *pseudo-periodic* *bi-periodic*