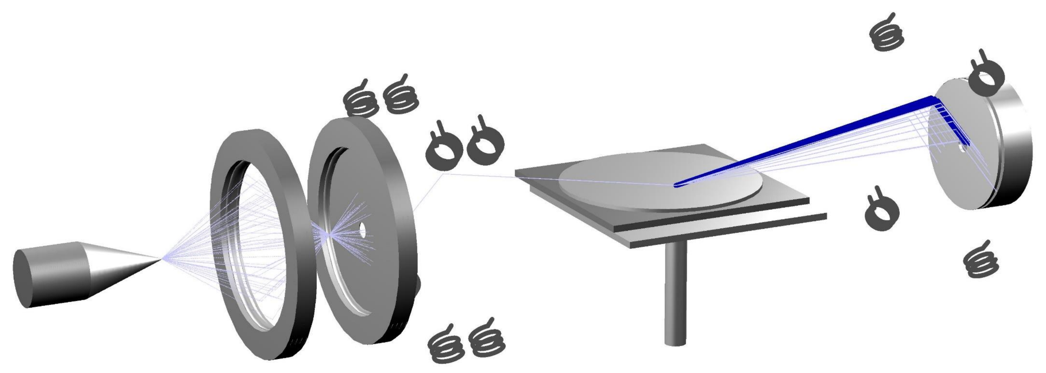
# Electron Reflectometry for Measuring Nanostructures On Opaque Substrates

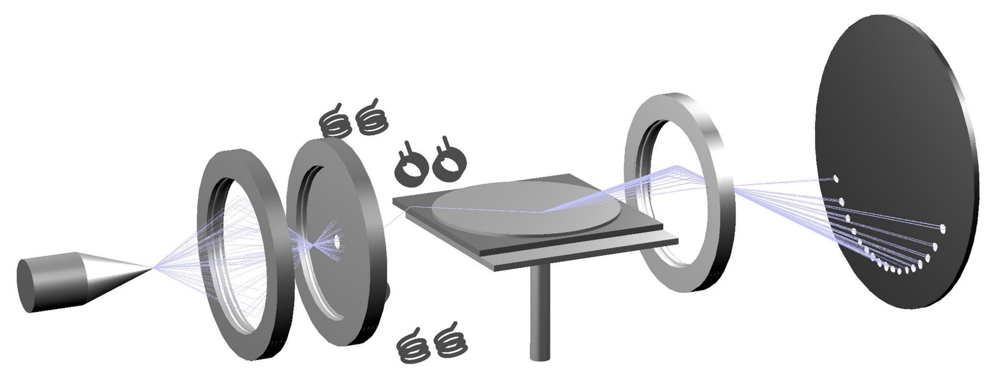
Lawrence H. Friedman[1], Wen-Li Wu[2]

National Institute of Standards and Technology
U.S. Department of Commerce

## Electron Reflectometry



## Reflective Small Angle Electron Scattering



Electrons with energies from 5 keV to 100 keV can be used for dimensional measurement of nanoscale features on an opaque substrate.

Electron Reflectometry (ER) is stream-lined version of Reflective Small-Angle Electron Scattering (RSAES).

RSAES extracts nanoscale dimensions from collected scattering patterns.

**ER is simpler and extracts information from just the specularly reflected beam.**

Both RSAES and ER benefit from:

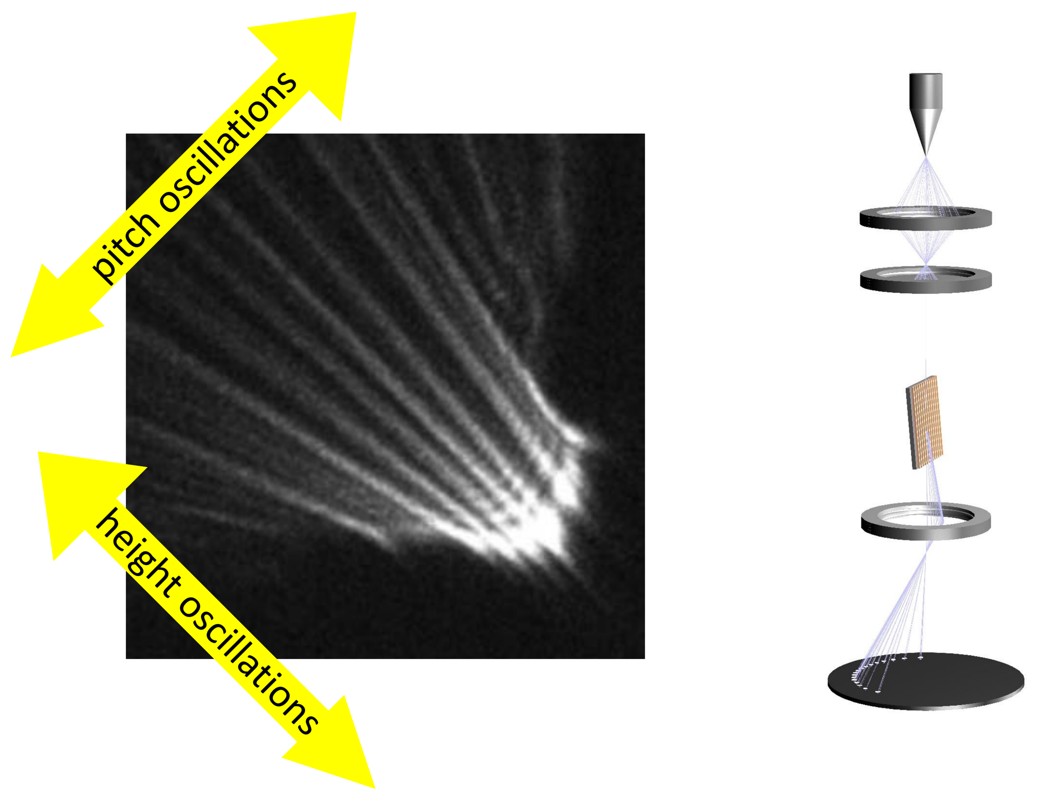
- compact easily available sources
- well-developed technology for beam manipulation: lenses; scanning coils, detectors, energy filters.
- scattering cross sections $10^8$ times as large as X-rays' but similar wave dynamics.

RSAES and ER can complement existing dimensional measurement techniques.

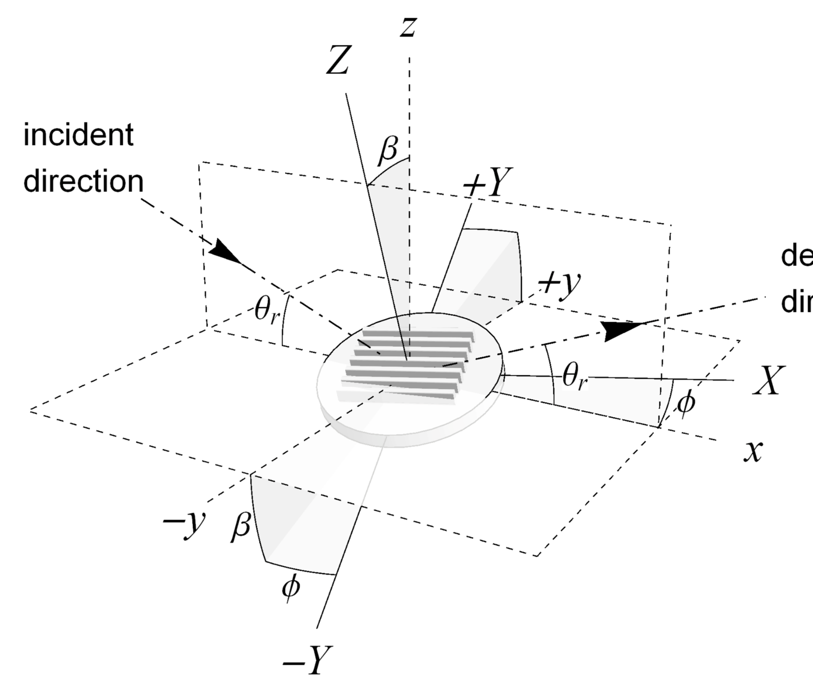
### APPLICATION TO SUB 10-nm FEATURES

| | Electron Reflection | Scanning Probe Microscopy | Scanning Electron Microscopy | Transmission Electron Microscopy | Optical Scatterometry | X-Ray |
|---|---|---|---|---|---|---|
| Advantages | 1. high precision including 3D capability – Y | | | Y | | Y |
| | 2. small footprint but good statistical sampling – Y | | | | Y | |
| | 3. little to no sample preparation – Y | Y | Y | | Y | Y |
| | 4. strong output so that samples can be measured quickly – Y | Y | Y | Y | | |
| Disadvantages | 5. fully developed / commercially available – N | Y | Y | Y | Y | Y |
| | 6. simplicity of interpretation – N | Y | Y | Y | | |
| | 7. measure buried structures – N | | | Y | | Y |
| | 8. sensitive to composition – N | | Y | Y | Y | Y |

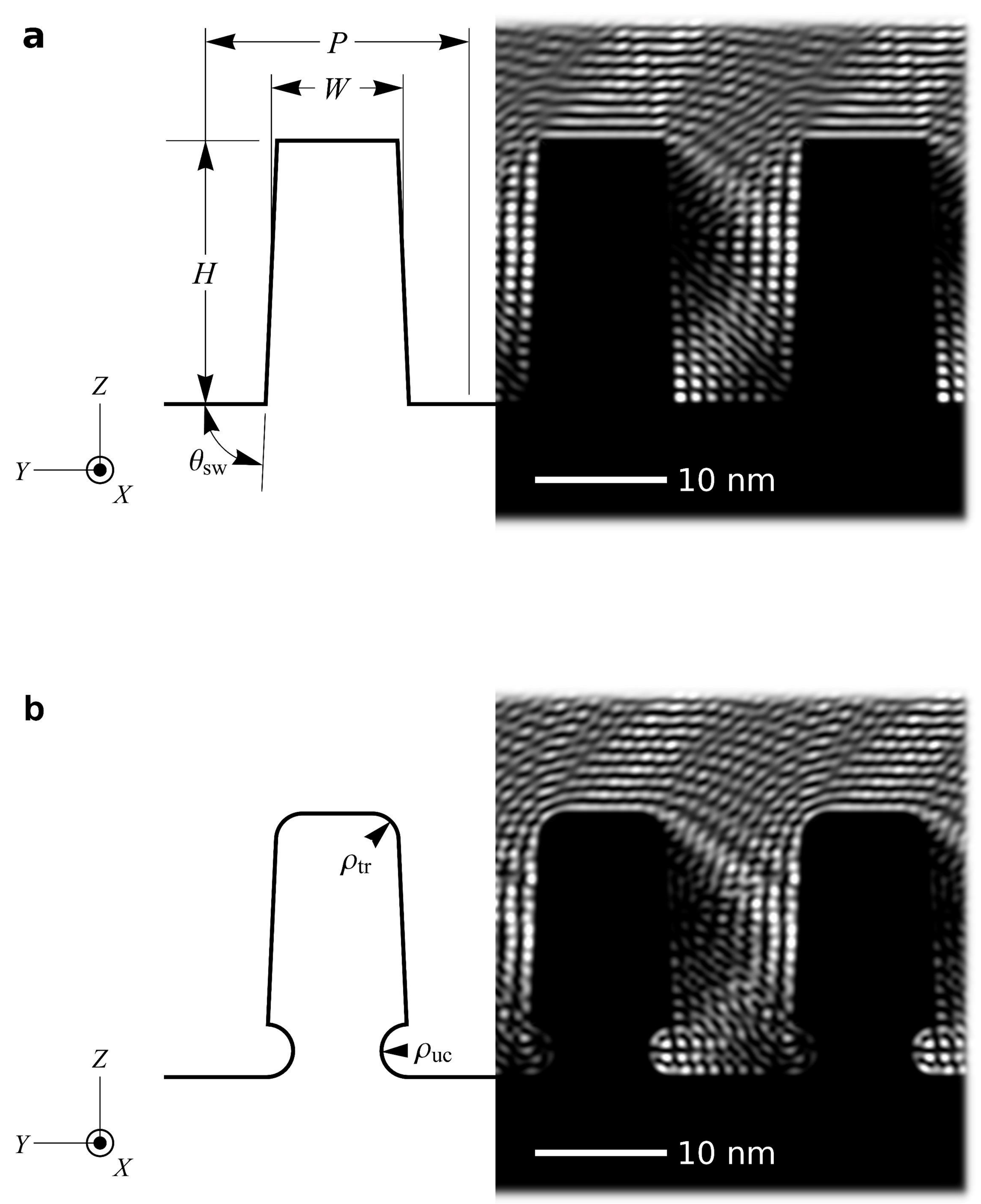
## Proof of Concept from TEM of Cu grating




## Scanning Geometry

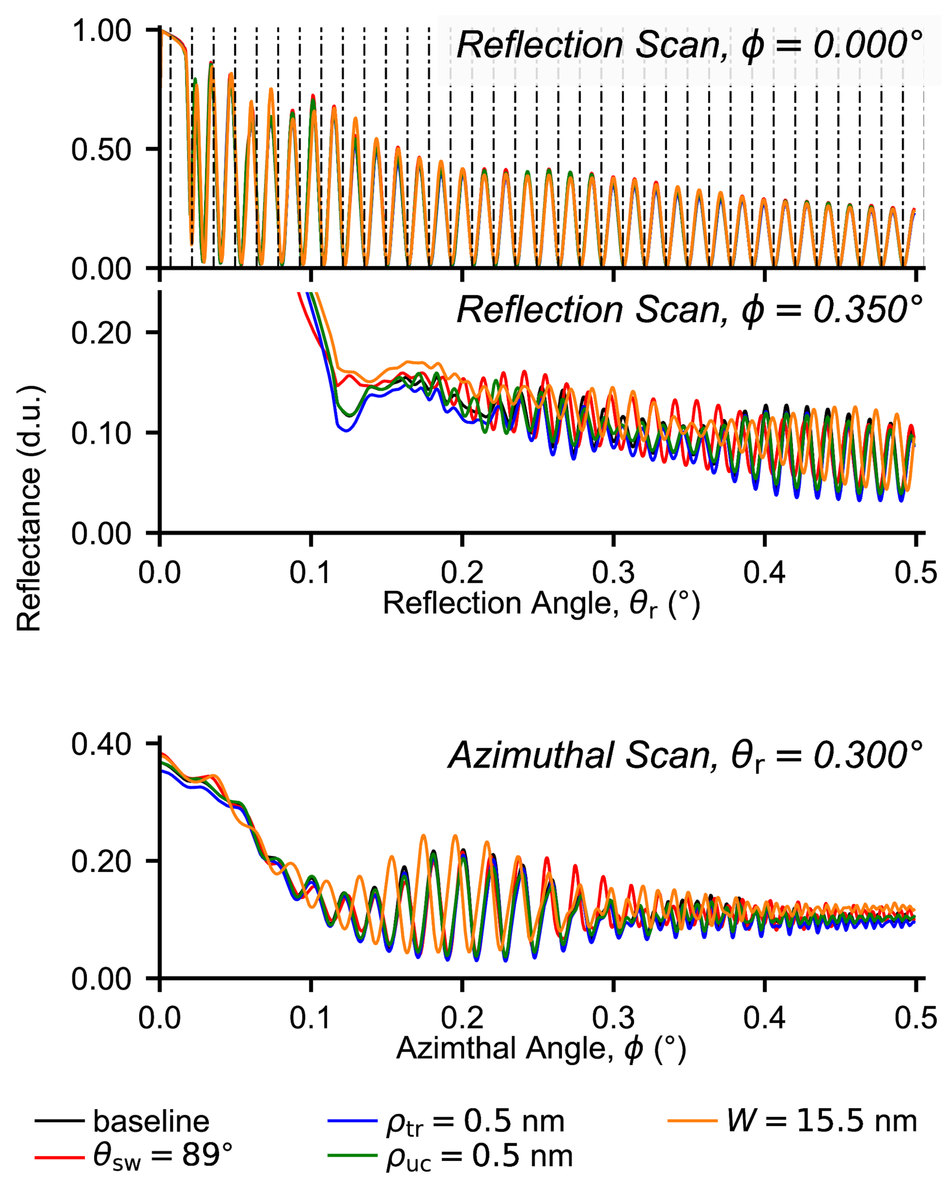



## Dynamically Simulated Wave Functions (etched Si grating)

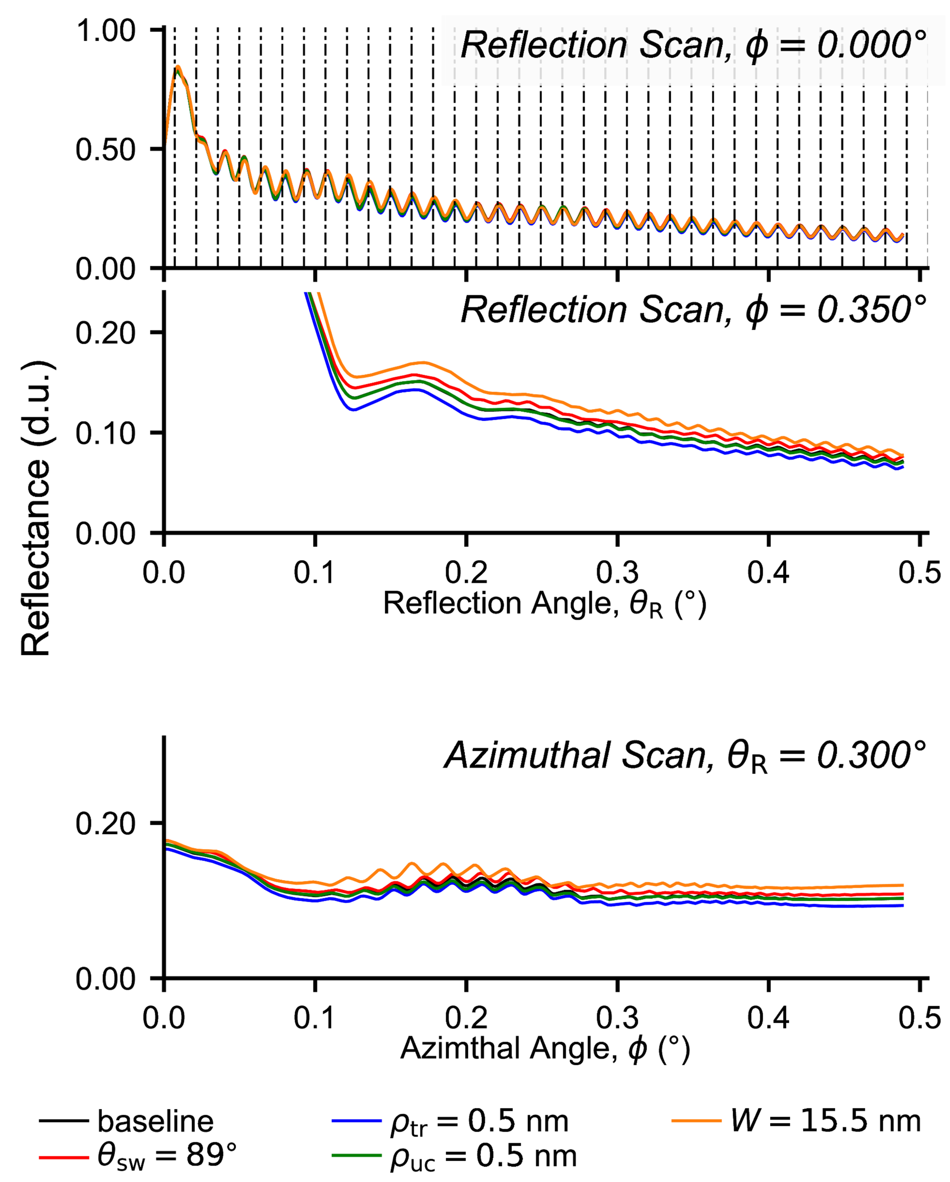



**Incident beam has wavelength (9.94 pm), elevation angle ($\theta_r$ = 0.3°) and azimuthal angle ($\phi$ = 0.2°). In b, $\rho_{tr}$ = 2.0 nm, and $\rho_{uc}$ = 2.0 nm. Associated multimedia available on request.**

## Simulated Small-Aperture Scan




## Simulated Large-Aperture Scan




**Baseline parameters: pitch $(P) = 30$ nm; width $(W) = 14.5$ nm; height $(H) = 20$ nm; sidewall angle $(\theta_{sw}) = 88°$; undercut $(\rho_{uc}) = 0$ nm; top-rounding $(\rho_{tr}) = 0$ nm; electron wavelength $(\lambda_e) = 9.94$ pm.**

ER results in electron wave functions and reflectances that are sensitive to 3D geometry and small variations in sidewall angle ($\theta_{sw}$), width ($W$), top-rounding ($\rho_{tr}$), and undercut ($\rho_{uc}$).

## References

LH Friedman, W-L Wu, U.S. Patent Application: Pub. No. 2019/0057834 (2019)
W-L Wu, Y-S Chien, W-E Fu, Y-S Chen, H-C Ho, US Patent: 9390888 (2016)
LH Friedman, W-L Wu, W-E Fu, Y Chien, *Appl. Phys. Lett.* 111, 123106 (2017).
*International Technology Roadmap for Semiconductors 2.0. Metrology* (2015).
B Bunday, *Proc. of SPIE*, 97780E (2016).
B Bunday, AF Bello, E Solecky, and A Vaid *Proc. of SPIE*, 105850I (2018).

[1,2]National Institute of Standards and Technology, Gaithersburg, MD ; [1]lawrence.friedman@nist.gov (L.H.F.); [2]wen-li.wu@nist.gov