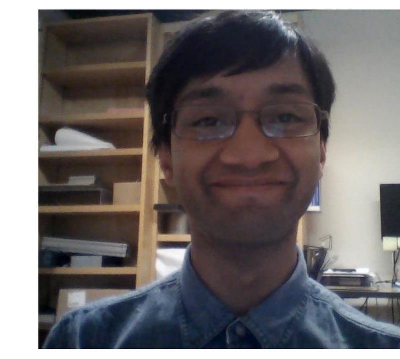
Energy Delivery and Mean Free path of Secondary Electrons in EUV Resists

Suchit Bhattarai[a], Andreas Schmid[c], Gong Chen[c], Andrew R. Neureuther[a], Patrick P. Naulleau[b]
[a]Department of EECS, University of California, Berkeley 94720
[b]Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley 94720
[c]National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley 94720

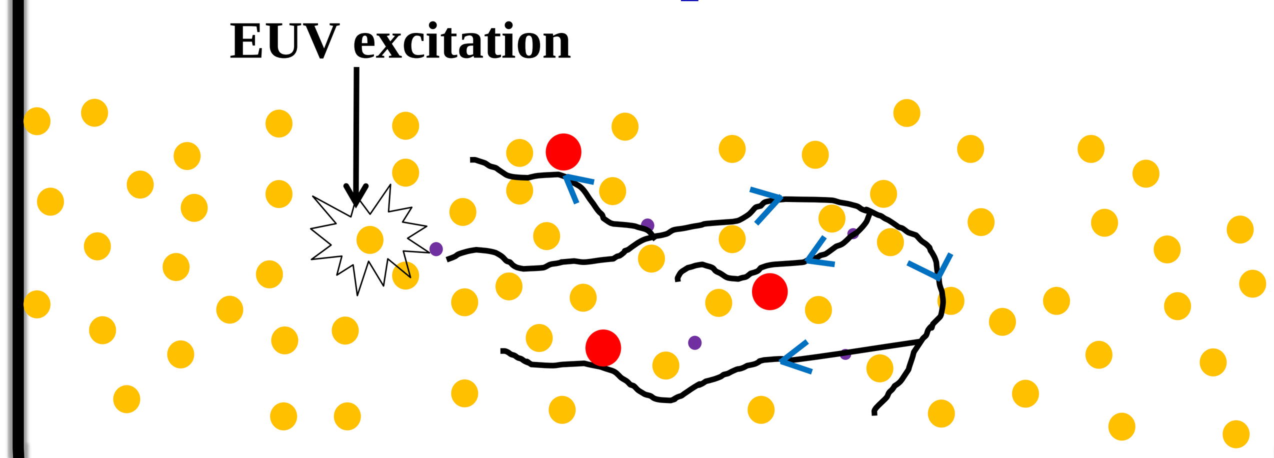


Motivation

Secondary electrons follow a complex trajectory as they deliver energy that leads to acid creation

→ Energy delivery capacity of electrons = ?

→ Electron mean free path = ?



- Resist constituent molecules
- Electrons with <92 eV energy
- Acids created through PAG activation

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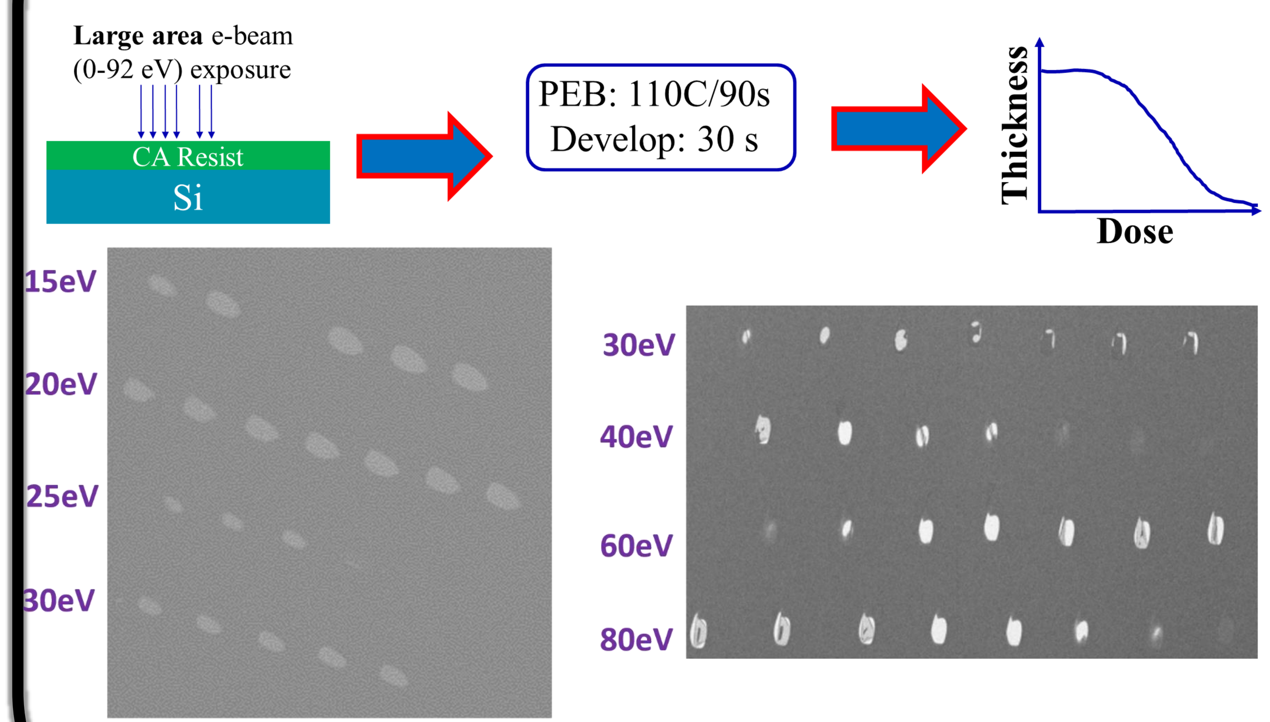
Investigating Energy Delivery with Low Energy Electron Microscopy (LEEM)



SEM Images of Patterns ($15\mu m X 20\mu m$) formed on a leading chemically amplified EUV resist

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Overview of the LEEM Technique

Usefulness

→ Direct assessment of relative importance of 0-92 eV electrons possible [contrast curve measurements]

Limitations

→ Sample charging sets a lower limit on the e⁻ energies that can penetrate the sample and trigger chemistry

→ Outgassing of acids, escape of electrons, contamination

→ Verifying secondary electron range is challenging because acid diffusion lengths are larger than the secondary electron range

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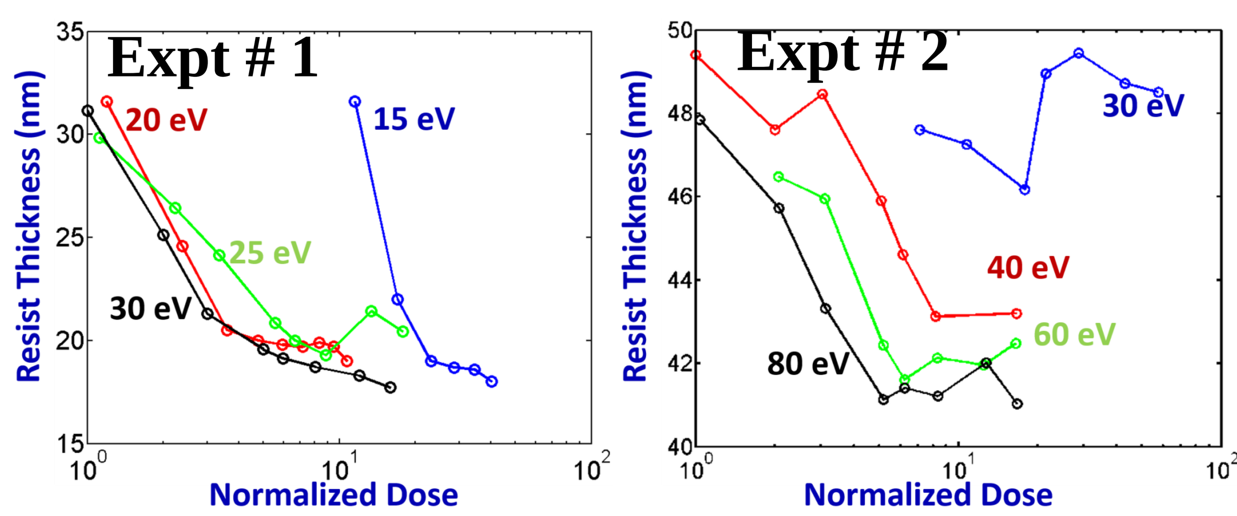
Positive Tone CA Resist Dissolution Rate Contrast Curve Data in 15-80 eV Regime



→ No measurable thickness loss for < 15 eV (3, 6, and 9 eV tried), likely due to charging

→ Increase in thickness at large doses for 30 eV data in expt. # 2 is likely due to cross-linking effects

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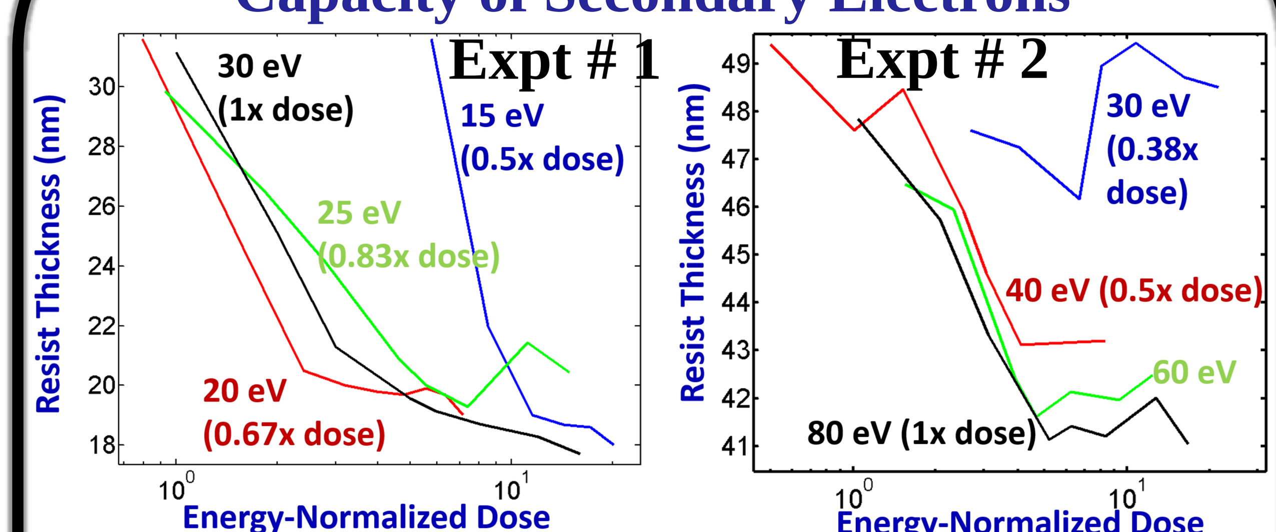
Estimation of Relative Energy Delivery Capacity of Secondary Electrons



→ Dose values scaled by ratio of energies

→ 40-80 eV data shows that energy delivery scales roughly proportionally with electron energy

→ This simple energy scaling does not explain very well the thickness loss in the 15-30 eV regime

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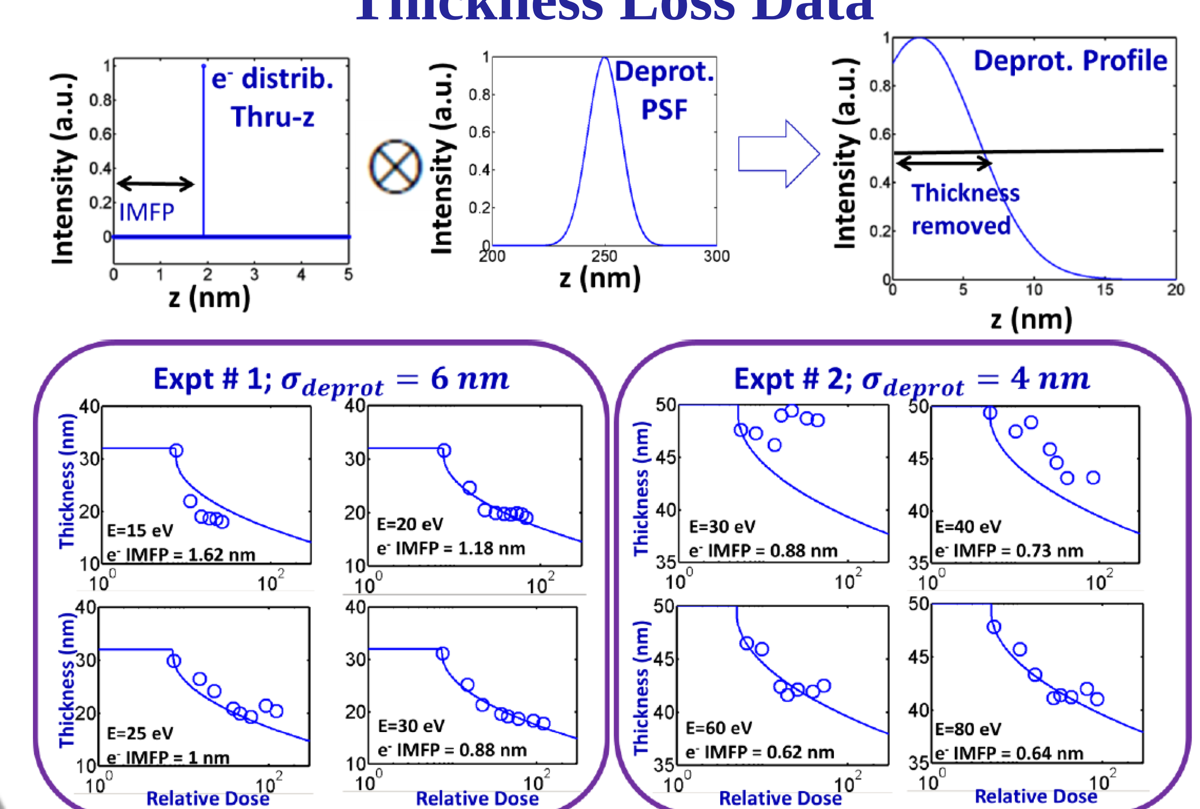
Extracting Resist Deprotection Blur using Thickness Loss Data



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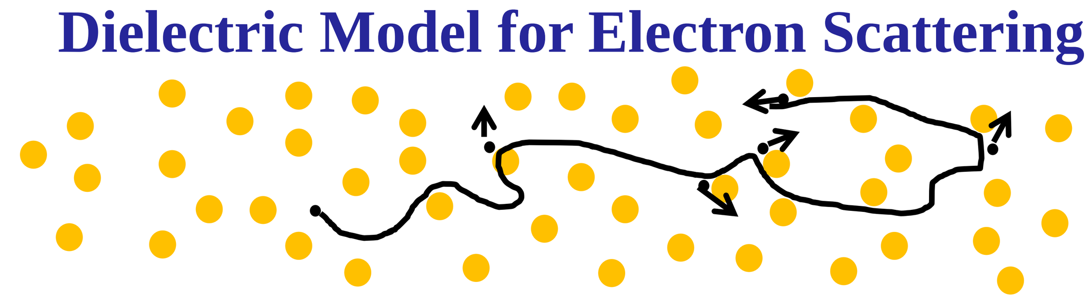
Mean Free Path Mechanism 1: Dielectric Model for Electron Scattering



$$\frac{\partial\lambda^{-1}(E)}{\partial(\hbar\omega)} = \frac{1}{\pi a_o E}\int_{k_-}^{k_+}\frac{1}{k}\, Im\left[-\frac{1}{\epsilon(k,\hbar\omega)}\right] dk$$

$[\hbar\omega, \hbar k] \equiv$ **[Energy, Momentum] transferred**

$v \equiv$ **Secondary electron velocity**

$\lambda \equiv$ **Mean Free Path**

$$Im\left[-\frac{1}{\epsilon(k,\hbar\omega)}\right] \equiv \text{Energy Loss Function}$$

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Energy Loss Function (ELF) as a Linear Combination of Mermin Oscillators

$$Im\left[-\frac{1}{\epsilon(k,\hbar\omega)}\right] = \sum_i A_i Im\left[-\frac{1}{\epsilon_M(k,\hbar\omega,E_i,\gamma_i)}\right]$$

$\epsilon_M(k,\omega) \equiv$ **Mermin dielectric function with well-known momentum (k) dependence**

$[A_i, E_i, \gamma_i] \equiv$ *Mermin* oscillator parameters that best fit the measured Optical Data

J. D. Bourke et. al., J. Phys. Chem. A 2012, 116, 3202-3205

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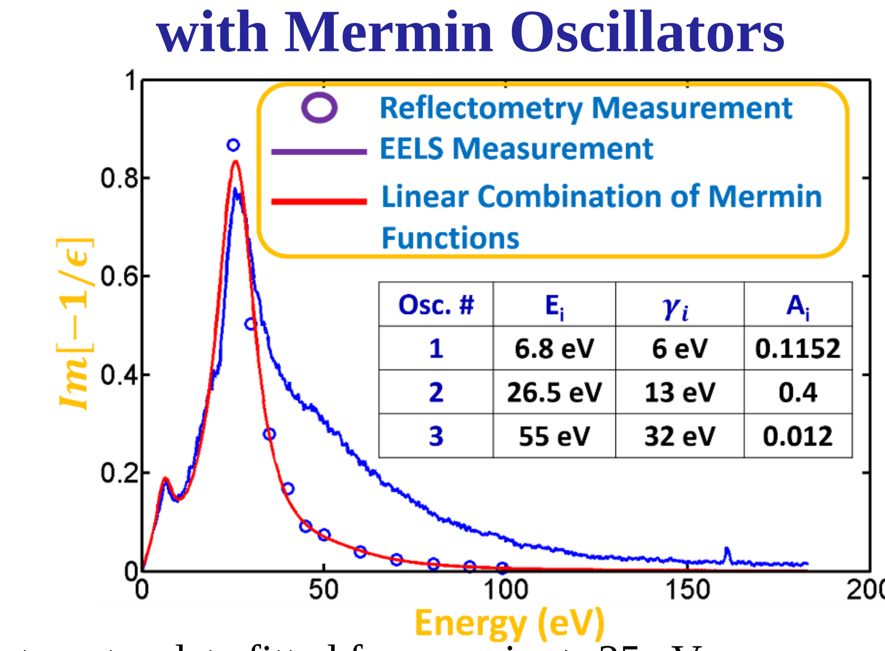
Fitting Optical Energy Loss Function with Mermin Oscillators



Osc. #	E_i	γ_i	A_i
1	6.8 eV	6 eV	0.1152
2	26.5 eV	13 eV	0.4
3	55 eV	32 eV	0.012

→ Reflectometry data fitted for energies > 25 eV

→ EELS data fitted for energies < 25 eV

→ We verified experimentally that EELS data is much larger than reflectometry at >30 eV due to sample damage induced by the e-beam during measurement

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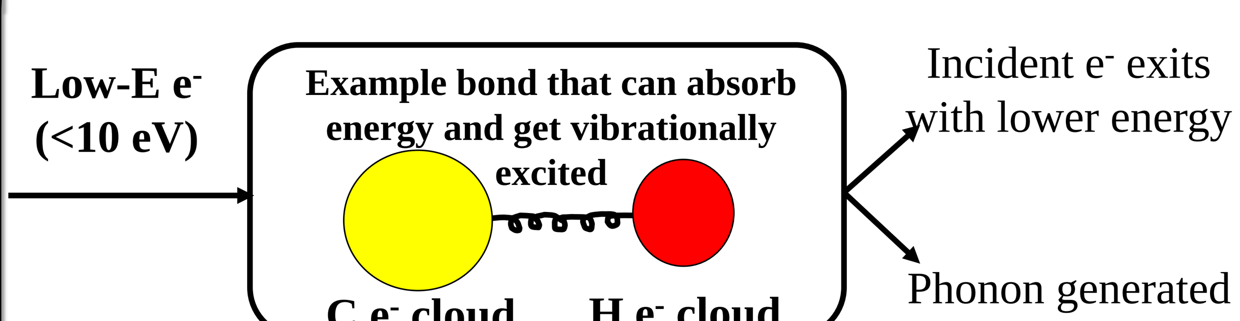
Mean Free Path Mechanism 2: Phonon Creation



$$\lambda^{-1} = \frac{1}{a_0}\frac{n(T)+1}{2}\left(\frac{1}{\epsilon_\infty}-\frac{1}{\epsilon_0}\right)\frac{\hbar\omega}{E}\, ln\left[\frac{1+\sqrt{1-\hbar\omega/E}}{1-\sqrt{1-\hbar\omega/E}}\right]$$

$\hbar\omega \cong 0.1\ eV$ **for DUV resists**

(Raman Scattering Data, Potma 2004)

Dapor (2012)

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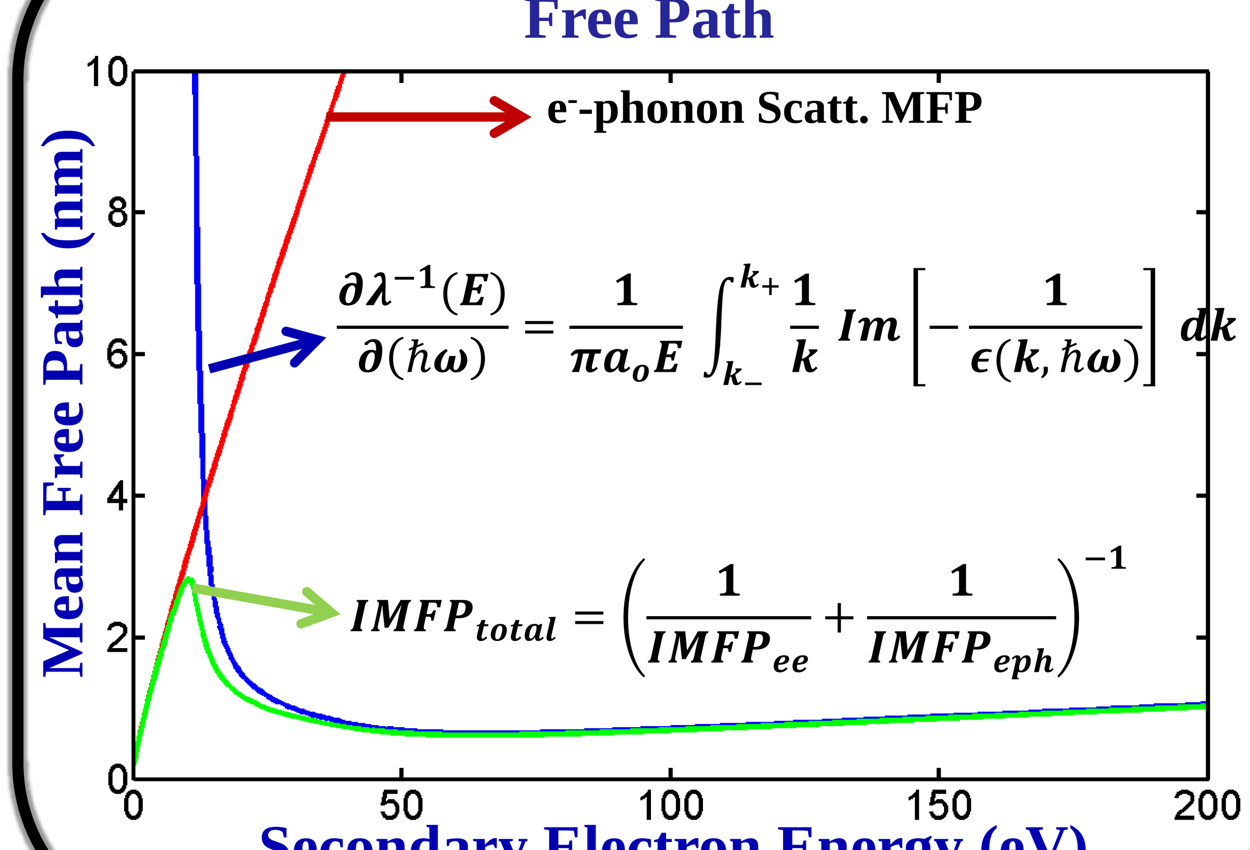
Estimate of Secondary Electron Mean Free Path



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Summary

- LEEM results show that in the 40-80 eV regime, energy delivery scales roughly proportionally with e⁻ energy
- In 15-30 eV regime, this simple energy scaling model for energy delivery is found to not work very well
- Dielectric model for scattering and electron-phonon scattering theory were used to estimate mean free path of electrons in an EUV resist
- Mean free path values range between 2.8 nm and 0.6 nm in the 10-80 eV regime
- Lithographic importance of phonons needs to be further examined

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