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Resilient Self-Healing Materials for the Extreme Environment of Space Electric Propulsion and Power

Hsing-Yin Chang (irischang@ucla.edu)

Department of Materials Science & Engineering
University of California, Los Angeles

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Abstract

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Advances in electrode, chamber, and structural materials will enable breakthroughs in future generations of electric propulsion and pulsed power (EP & PP) technologies. Although wide ranges of electric propulsion and pulsed power technologies have witnessed rapid advances during the past few decades, much of the progress was based on empirical development of materials through experimentation and trial-and-error approaches. To enable future technologies and to furnish the foundations for quantum leaps in performance metrics of these systems, a science-based materials development effort is pursued in this project. We aim to develop new plasma-resilient material architectures that will enable future generations of electric propulsion and pulsed power technologies through an integrated research approach that combines multiscale modeling of plasma-material interactions, experimental validation, and material characterization. The range of materials of interest in EP & PP include refractory metals, such as tungsten and its alloys (W-Re) and molybdenum, ceramic insulators, such as BN and Al_2O_3, high-strength copper alloys, and carbon-carbon composites. These classes of materials serve various design functions; primarily in cathode and anode applications, in accelerator grids, and in beam dumps of HPM sources. The research provides an opportunity to design material architectures that may dramatically improve their performance.

What is an Ion Thruster?

- A form of electric propulsion (EP) used for spacecraft propulsion.
- Creates thrust by accelerating ions with electricity.
- Categorized by how they accelerate the ions:

 - **Electrostatic ion thrusters** use the Coulomb force & accelerate ions in the direction of the electric field.
 1. Gridded electrostatic ion thrusters
 2. Hall effect thrusters
 - **Electromagnetic ion thrusters** use the Lorentz force to move the ions.

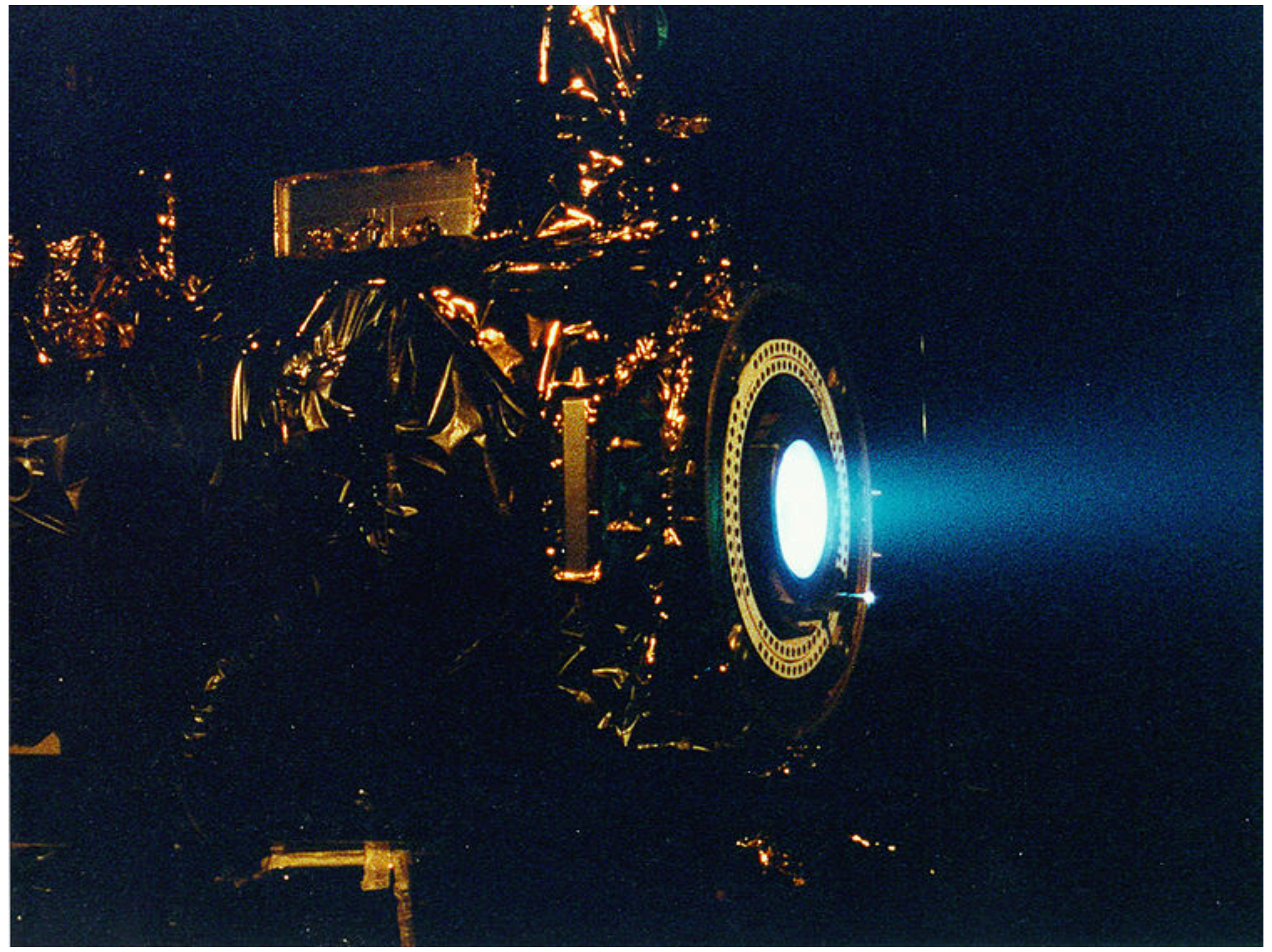

Fig 1. NASA's 2.3 kW NSTAR ion thruster for the Deep Space 1 spacecraft during a hot fire test at JPL.

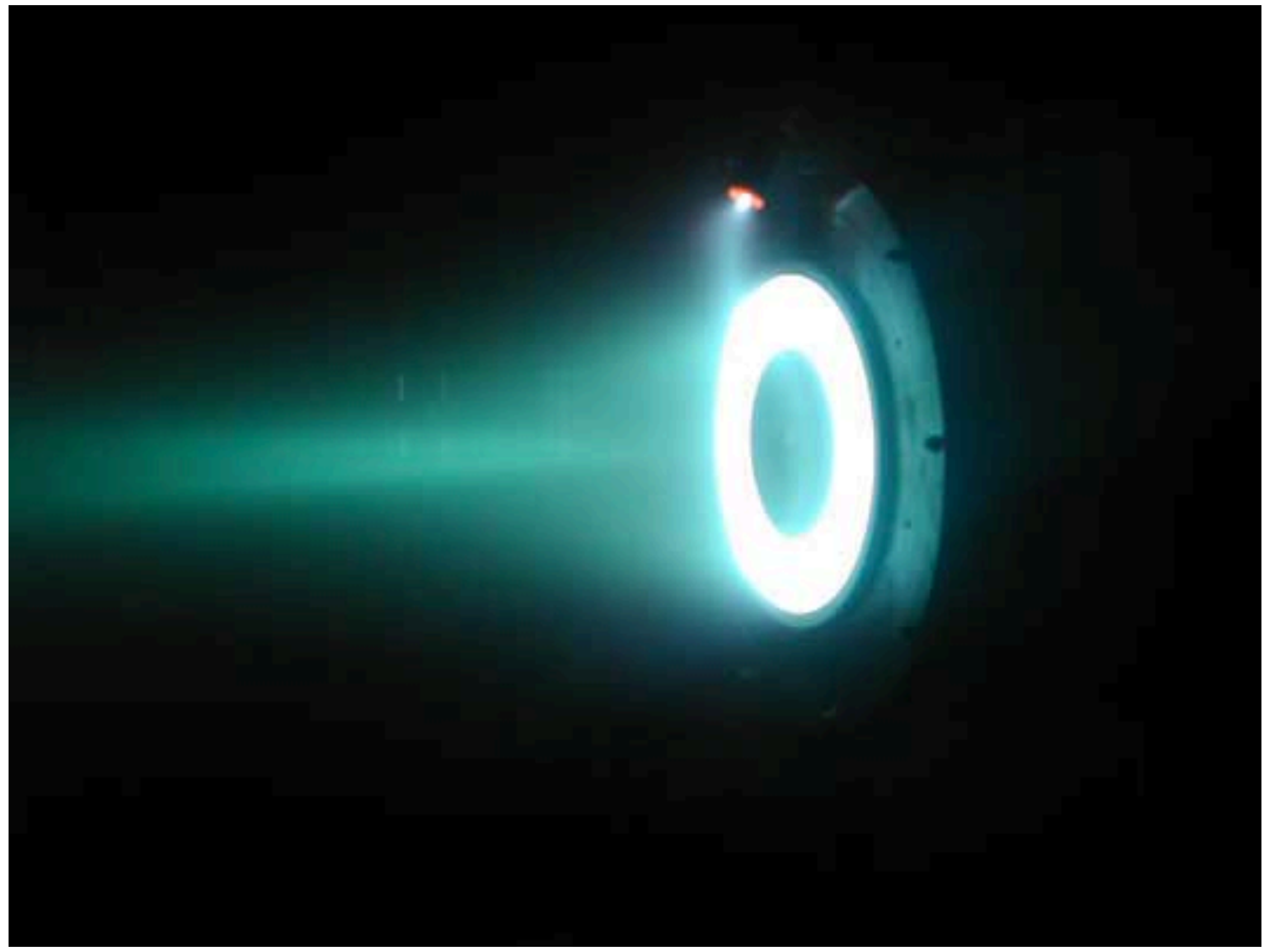

Fig 2. 2 kW Hall thruster in operation as part of the Hall Thruster Experiment at PPPL.

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Secondary Electron Emission (SEE)

- Electron bombardment of materials leads to SEE, depends on primary electron energy & material properties.
- Plasma with $T_e > 20$ eV for dielectric walls, and $T_e > 100$ eV for metal walls is subject to strong SEE effects.
  - Can change plasma properties
  - Can increase electron heat flus form plasma to the wall
    (1) Wall evaporation
    (2) Plasma cooling

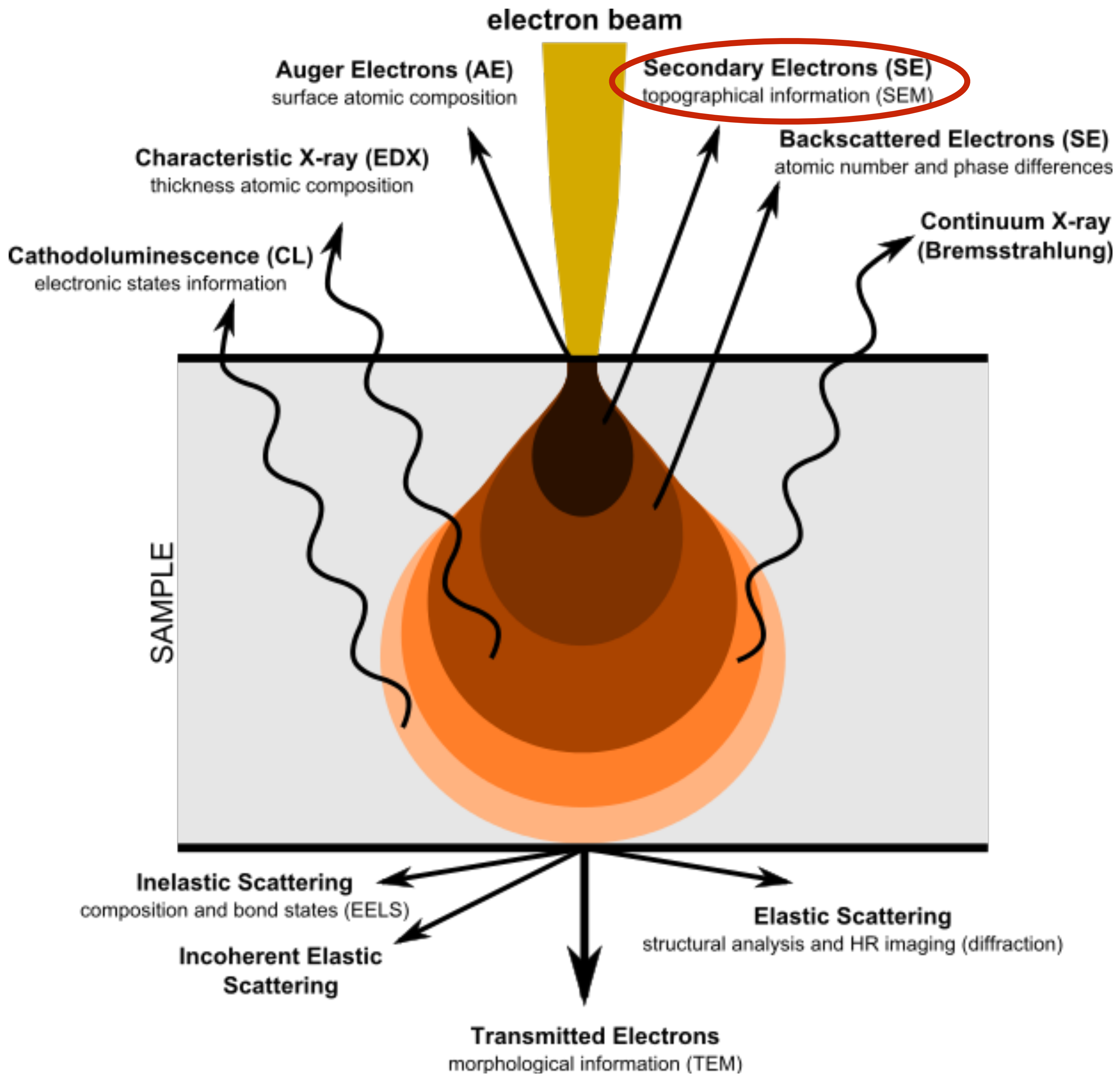
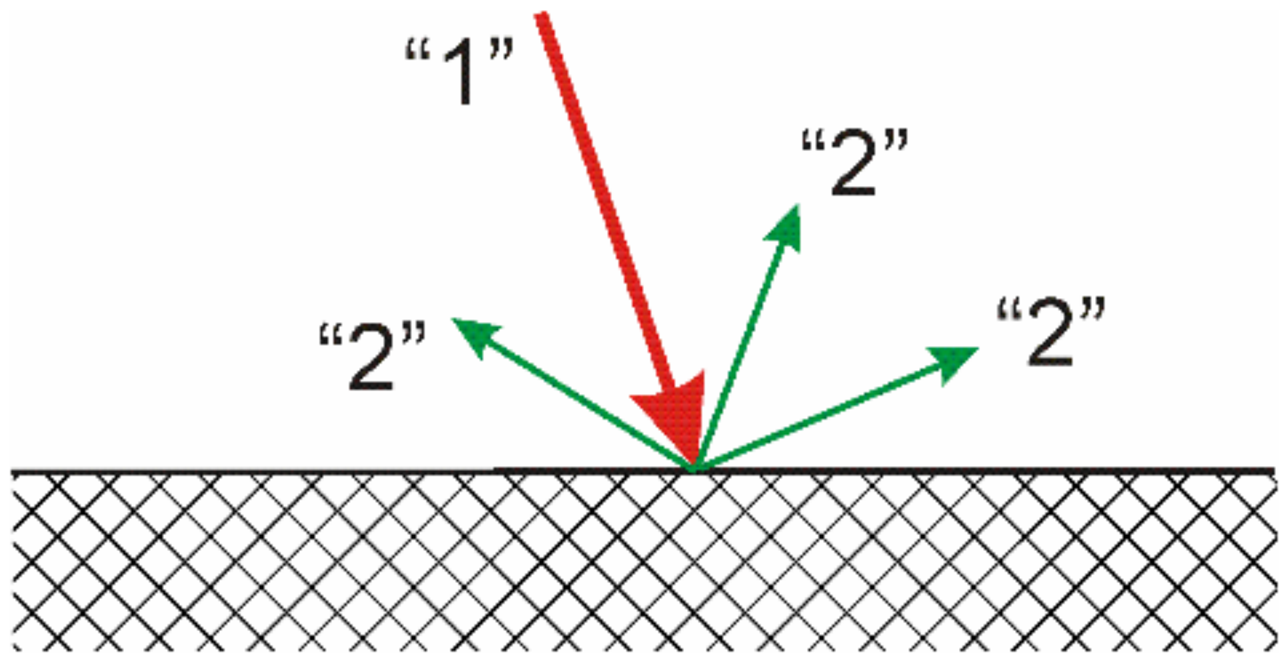


Fig 3. Electron beam-material interactions.



$$\gamma = \frac{SEE}{primaries}$$

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Status Quo

Plasma with a strong secondary electron emission (SEE) is relevant to plasma thrusters, high power MW devices, etc. Strong SEE can significantly alter plasma-wall interaction affecting thruster performance and lifetime. The observed SEE effects in thrusters requires multiscale modeling of plasma-wall interaction.

Solution?

⇒ Use micro-architectured materials to trap SEE between surface features.

Goals of the Study

- Develop fundamental understanding on plasma-material interactions.
- Build multi-scale models to simulate plasma-induced sputtering and SEE from micro-architectures surfaces.
  - Design new plasma-resilient material architectures that will enable future generations of electric propulsion and pulsed power (EP & PP) technologies.

Experiments for Sputtering/SEE Effects of Micro-architectured Surfaces

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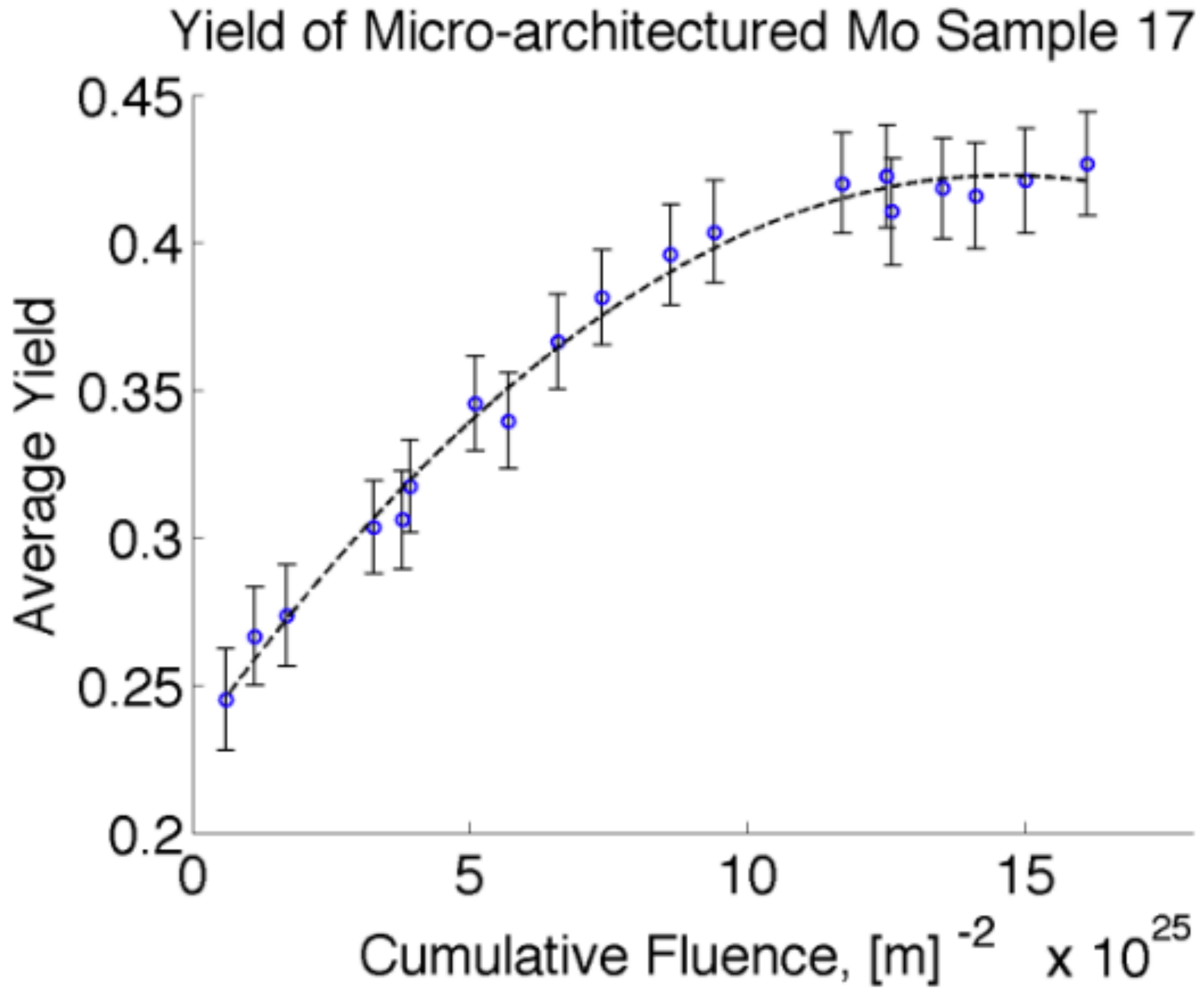
Significant Reduction in Surface Erosion



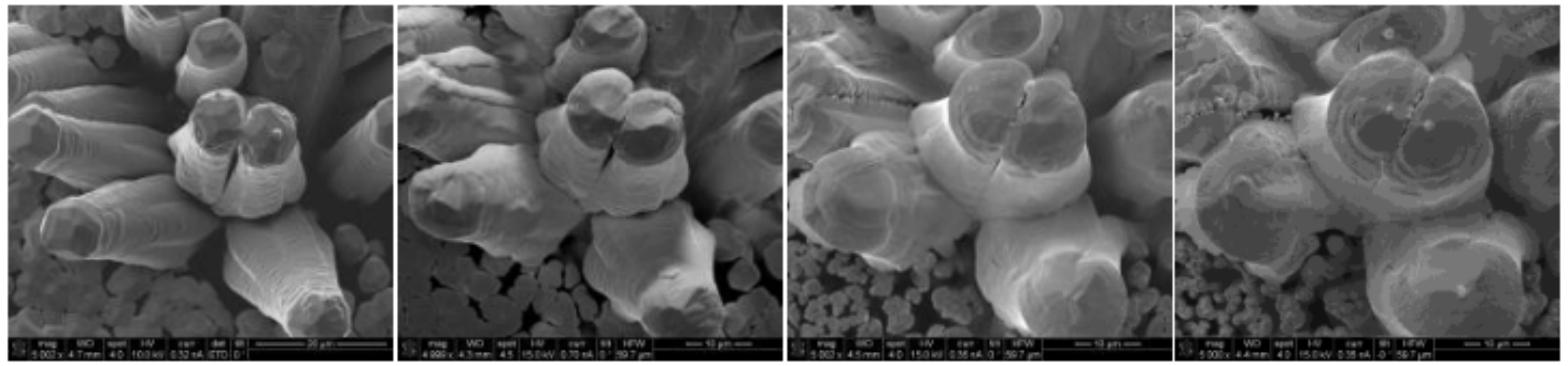


Fig 4. Mo sample feature development at increasing levels of fluence.

Reduction & Control of Secondary Electrons

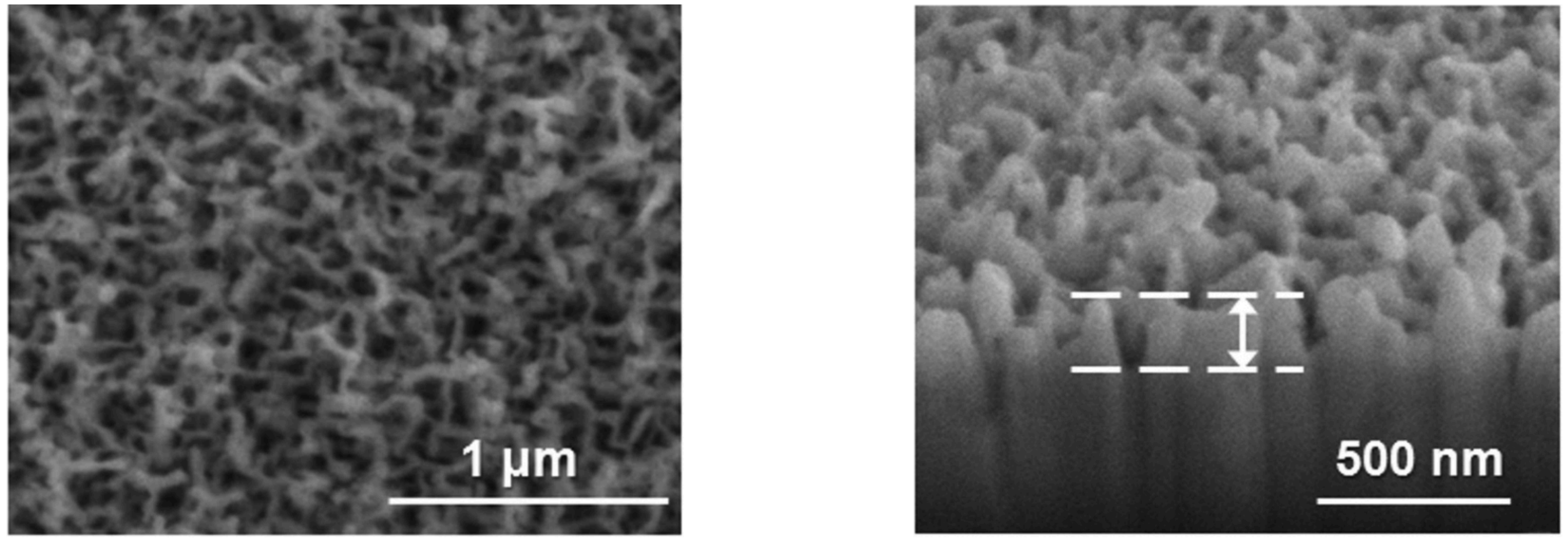
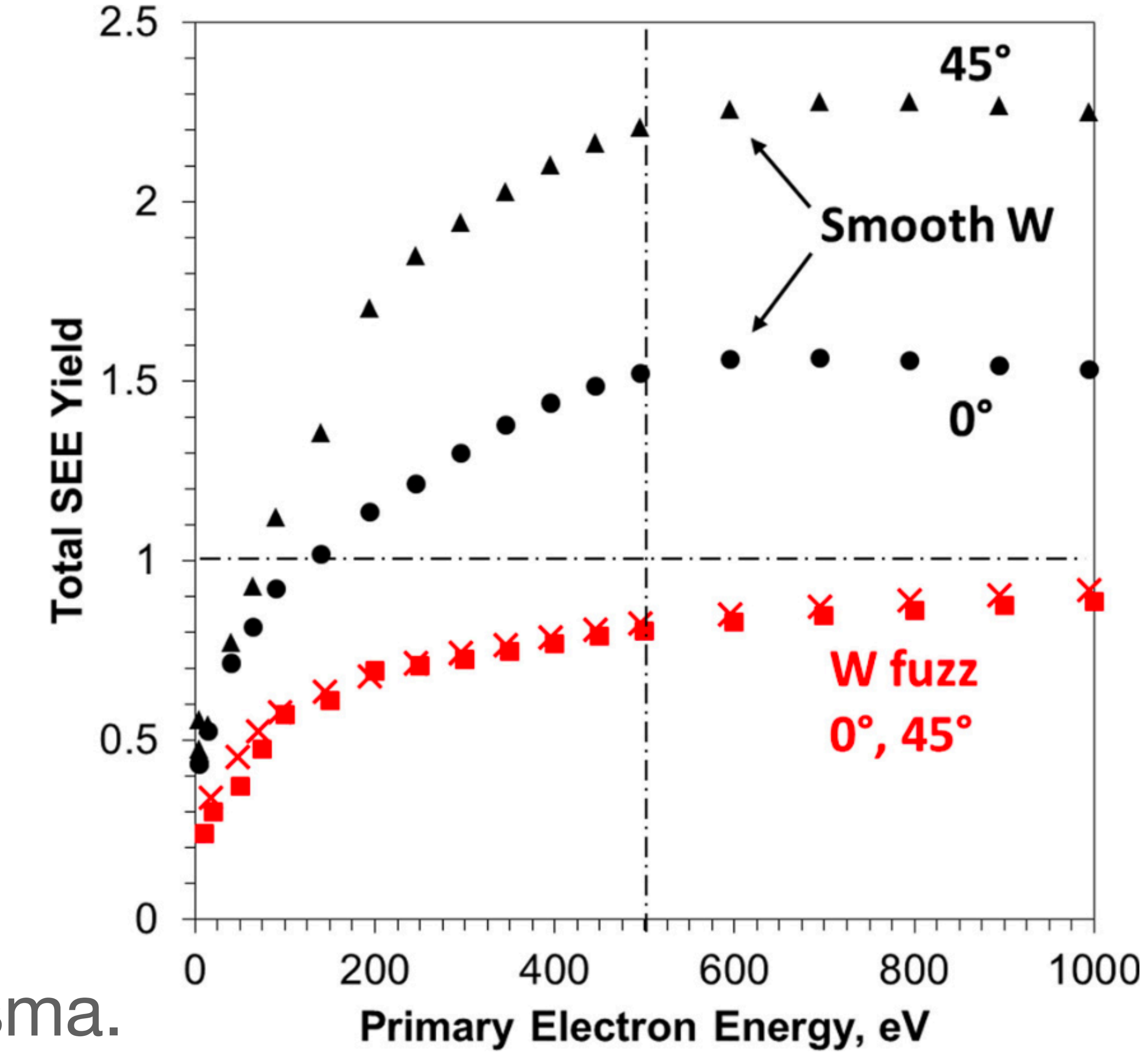


Fig 5. The SEM image of the top view and cross-sectional view of the W fuzz sample.



- Micro-architectured structure can suppress sputtering/SEE effects on thruster plasma.

Patino, M., Y. Raitses, and R. Wirz. "Secondary electron emission from plasma-generated nanostructured tungsten fuzz." Applied Physics Letters 109.20 (2016)
Matthes, Christopher S.r., Nasr M. Ghoniem, Gary Z. Li, Taylor S. Matlock, Dan M. Goebel, Chris A. Dodson, and Richard E. Wirz. "Fluence-dependent sputtering yield of micro-architectured materials." Applied Surface Science 407 (2017)

Monte Carlo Simulation of SEE Yield

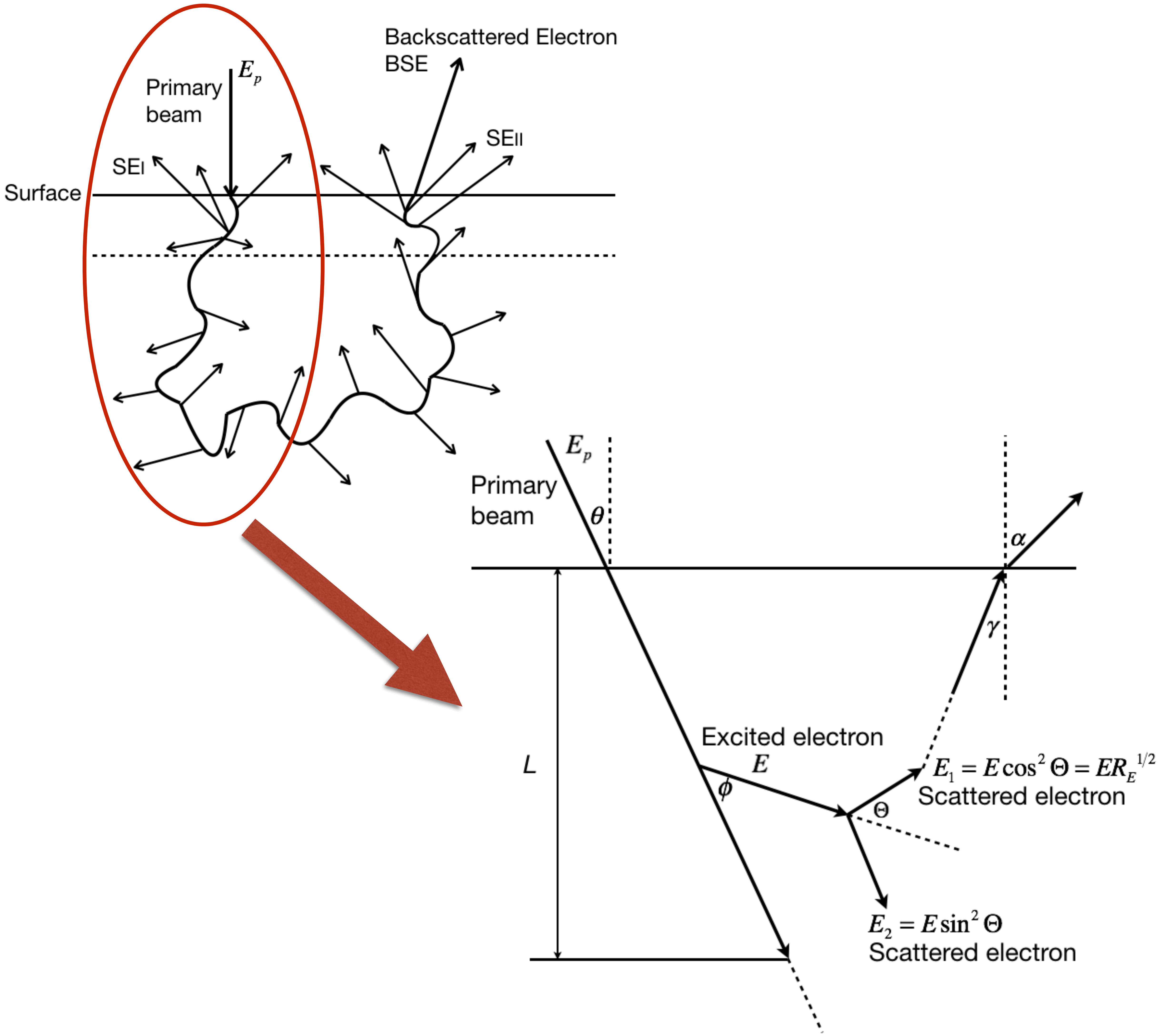


Fig 6. Illustration of electron trajectory of cascade process in Monte Carlo simulation.

1. Excitation of secondary electrons (SE)

Streitwolf equation $S(E) = e^4 k_F^3 / 3\pi E_p (E - E_F)^2$

Random number distributed according to $S(E)$

$$R_s = \int_{E_F+\phi}^{E} S(E)dE \Big/ \int_{E_F+\phi}^{E_p} S(E)dE$$

$\Rightarrow$ SE energy distribution

$$E(R_s) = \left[R_s E_F - A(E_F + \phi)\right] / \left[R_s - A\right]$$

$$A = E_p - E_F / E_p - E_F - \phi$$

2. Transport of the internal SE towards the surface

Mean free path deduced from experiments (Palmberg 1973)

$$\begin{cases} \lambda = 10^{(-2.6\log E + 4.3)}\,\mathring{A} & (E \le 25eV) \\ \lambda = 5\,\mathring{A} & (25eV < E \le 100eV) \end{cases}$$

Actual step length follows Poisson's distribution

$$\Rightarrow \lambda_r = -\lambda \ln R_r$$

3. Escape of SE at the surface

Slow electrons are refracted at the surface when having velocities greater than the surface potential barrier $V = E_F + \phi$

Refraction index $n = \dfrac{\sin\alpha}{\sin\gamma} = \left(\dfrac{E + V_0}{E}\right)^{1/2}$

Results & Discussion

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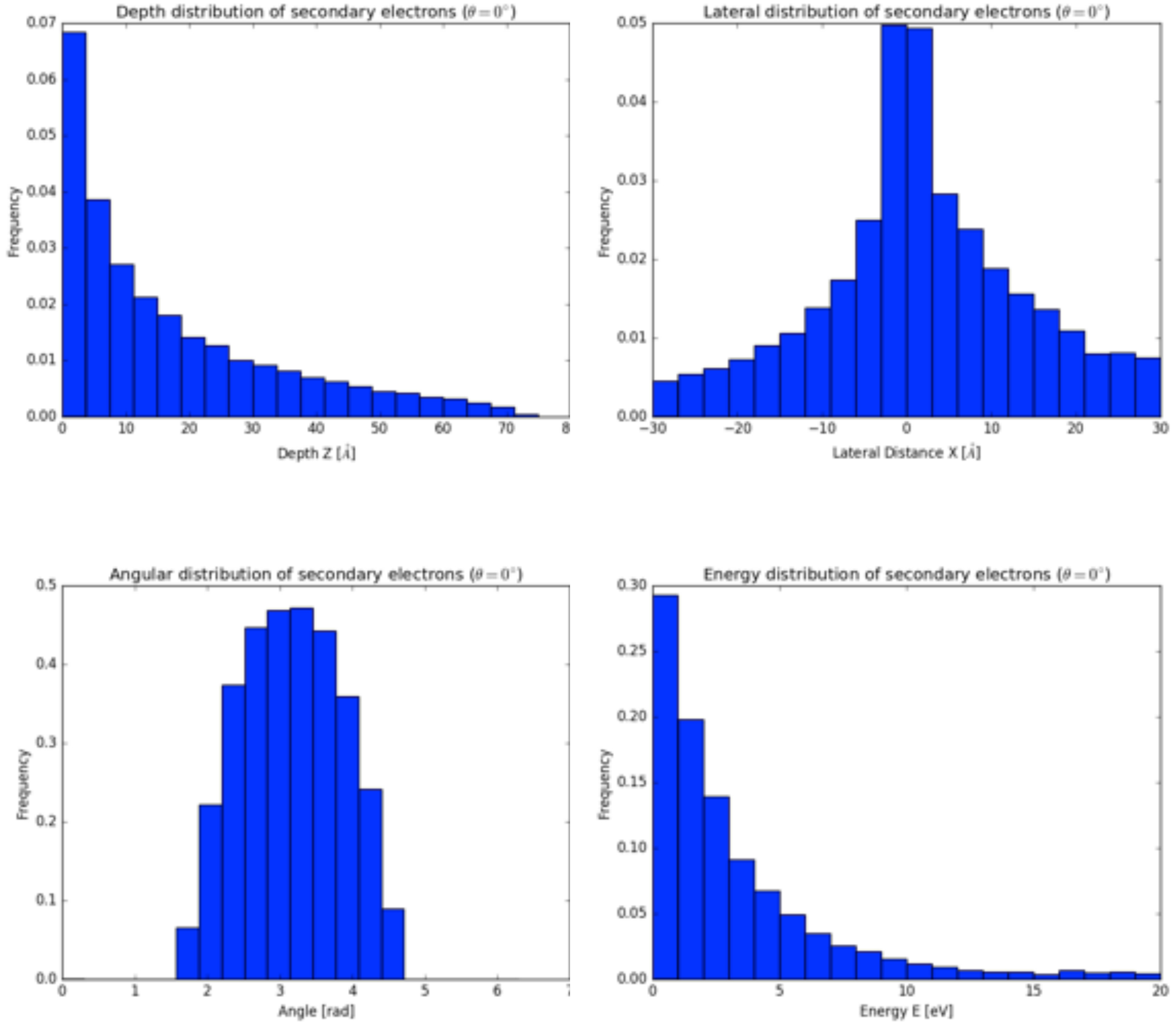
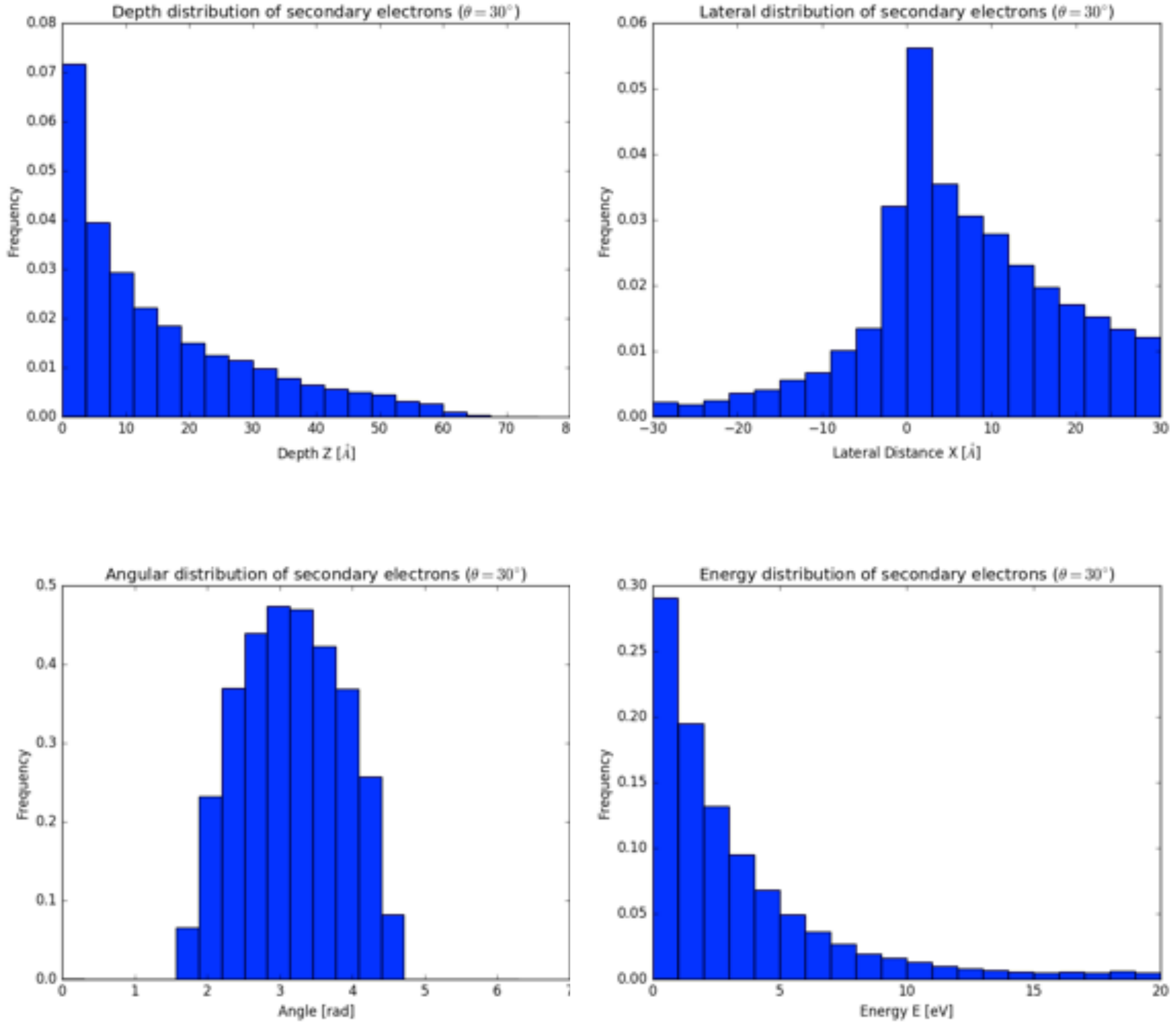
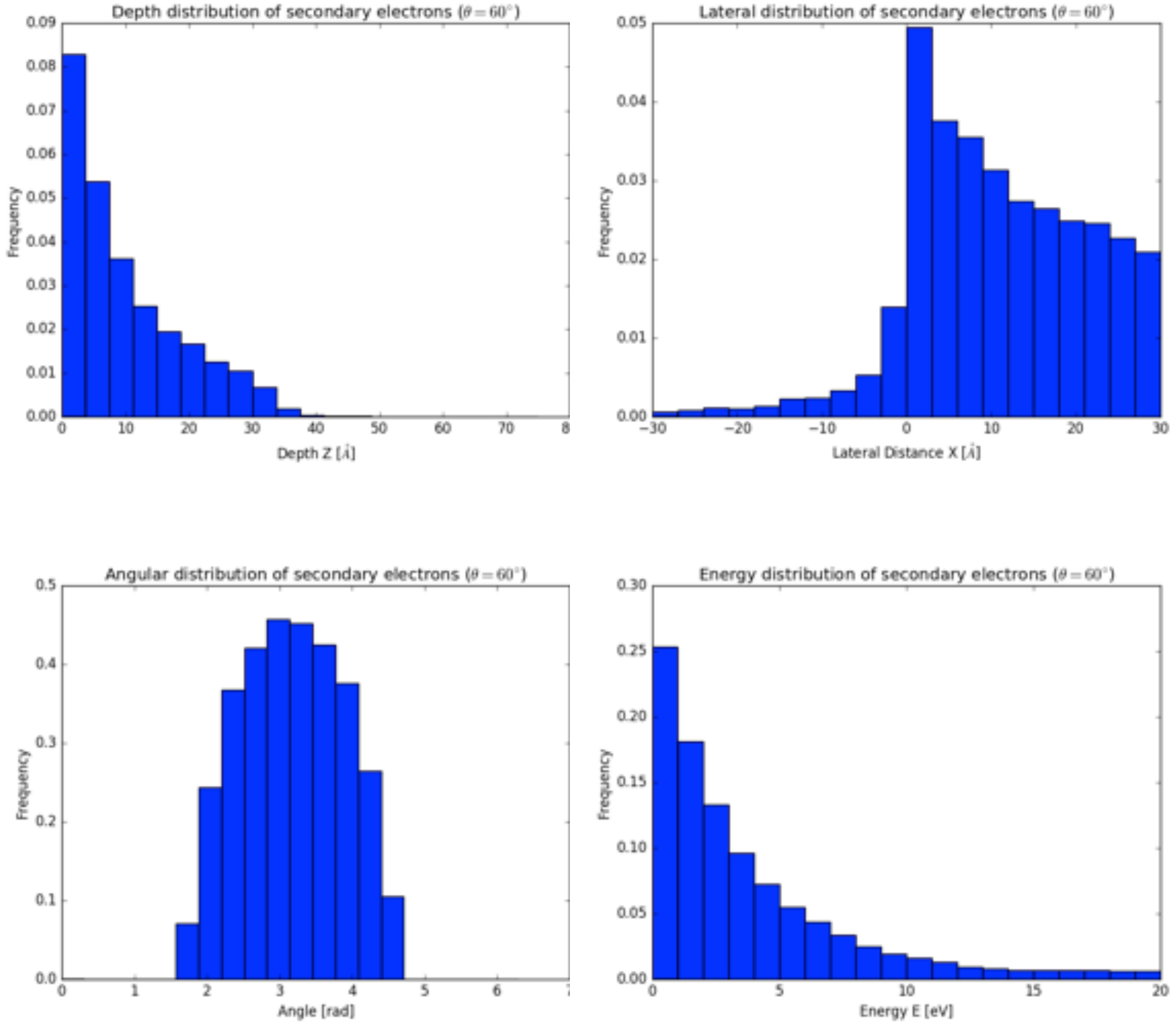
1. Normal incidence $\theta = 0$



2. $\theta = 30^\circ$



3. $\theta = 60^\circ$



- Monte Carlo calculations for depth, lateral, angular and energy distribution show good agree with experimental results.

Next Steps

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- Use Monte Carlo particle transport codes (e.g. MCNP, Penelope) or develop codes to track particle trajectory.
  - The SEE yield function will be used as a sampling source term to emit electrons out of the micro-architectured surface structure.

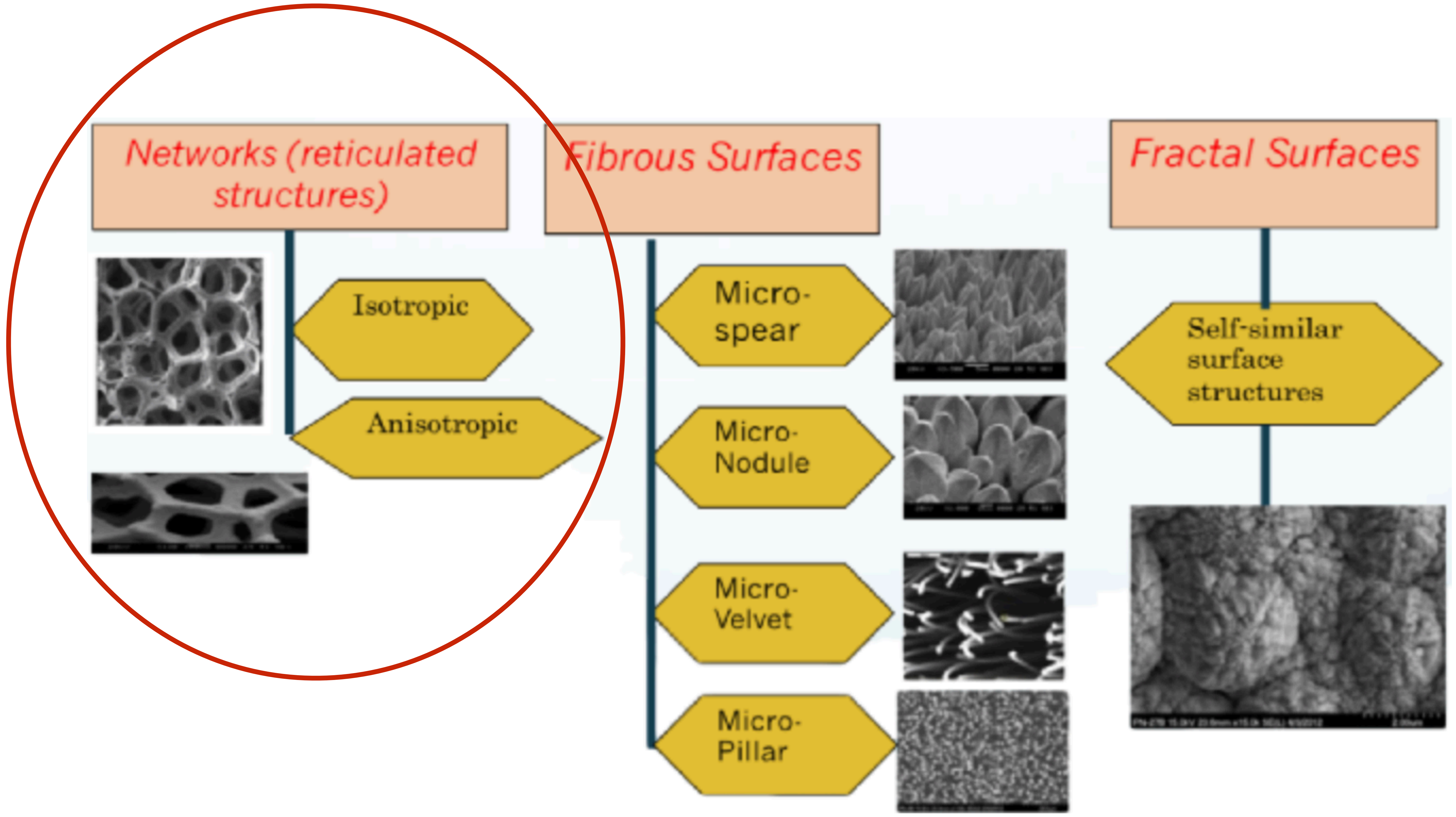

Fig 7. Classes of Micro-architectures Materials. Various categories of each class are pictured to show the diverse types of engineering materials surfaces.

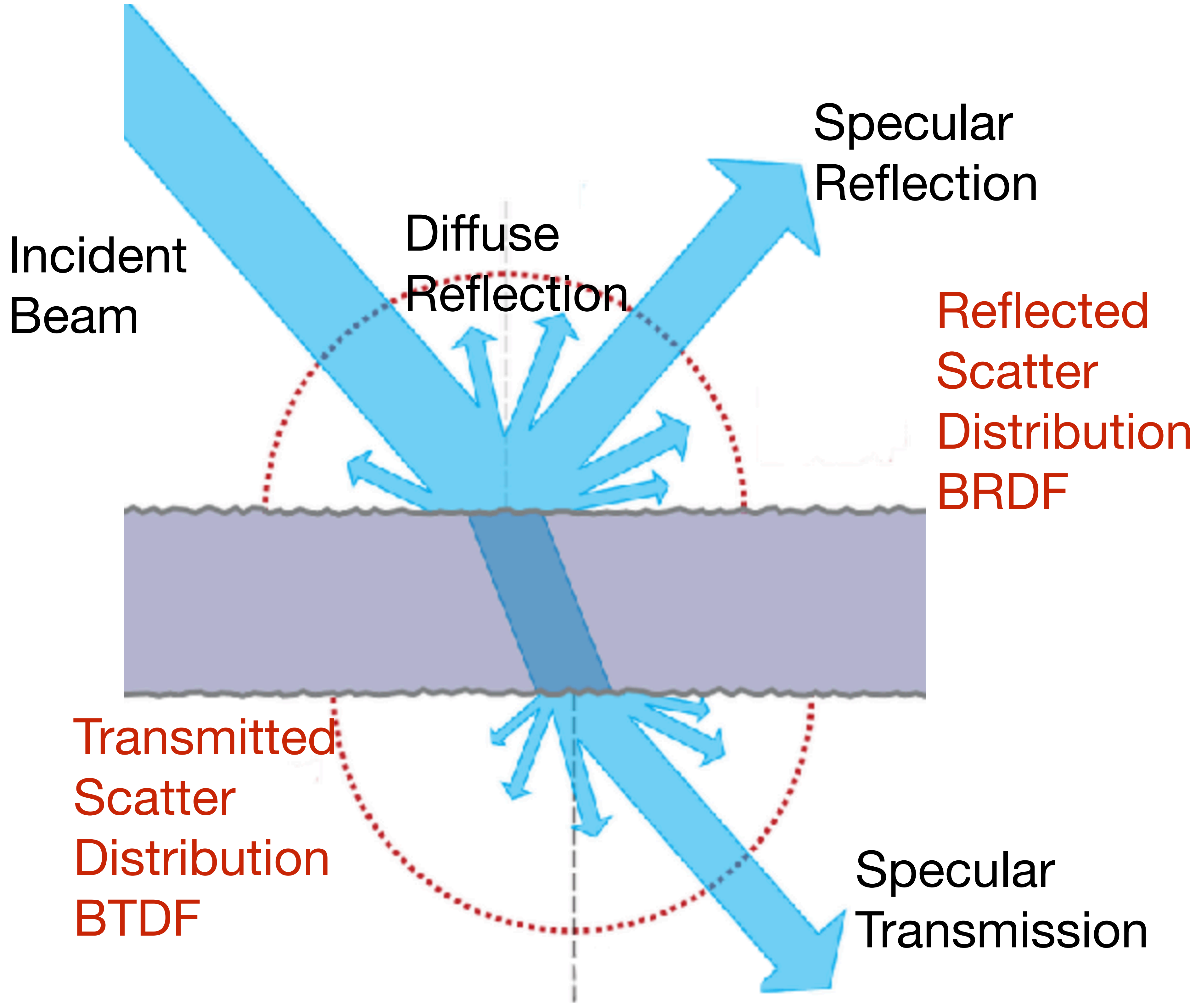

Fig 8. Illustration of Monte Carlo Ray Tracing.