Secondary Electron Emission Models for PIC Simulations

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Outline

- **Secondary Electron Emission by electron impact: Physics**
- **Linear/Power Law Model**
- **Vaughan/Modified Vaughan Model**
- **Furman-Pivi Model**
- **Results**
- **Conclusions / Future works**

Secondary Electron Emission by electron impact: Physics

o Possible effects on HT: sheath; wall losses; EVDF; electron transport; anomalous erosion;

o Discharge current and electron temperature starts to depend from the material from a certain level of discharge voltage.

o Discovered in 1902 by Austin and Starke studying the reflection of electrons from metals.

o Cascade process of ionization and excitation, combined with elastic and inelastic scattering of the cascade electrons + their transport and escape from the surface -> their energy and angle distributions.
This study requires a Monte Carlo microscopic approach (similar to TRIM).

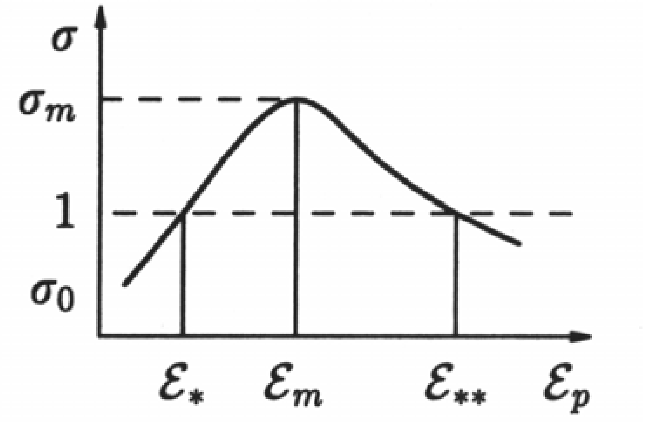
o Another approach is phenomenologic based on 2 main quantities representing SEE:
- secondary-emission yield (SEY) σ;
- emitted energy/angle spectrum $d^2\sigma/dEd\theta$.

Both are mainly function of incident electron energy Ep, angle θp and material temperature Tw.

Secondary electron emission yield SEY

o The general dependance of σ from the incident electron energy (the same for all materials) requires 5 parameters:

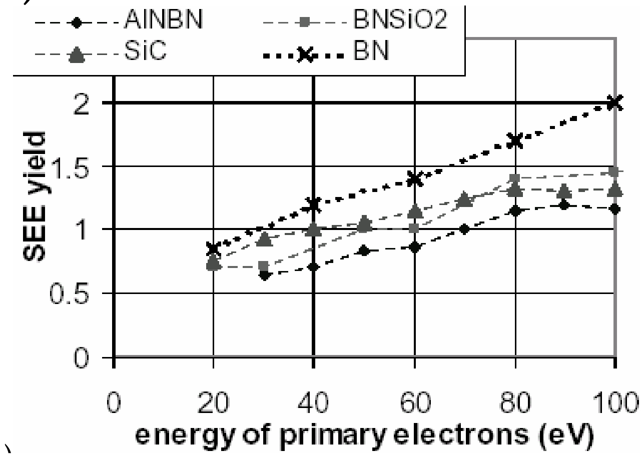
- σ_0 → SEY at E_p=0
- σ_{max} → maximum value
- E_* → first crossover energy
- E_{**} → second crossover energy
- E_{max} → energy corresponding to σ_{max}



o In the HT regime (E_p<1 keV) 2 parameters can be sufficient:

- σ_0 (debate about its value: it cannot be 1 but a value 0.1-0.7)
- E_*

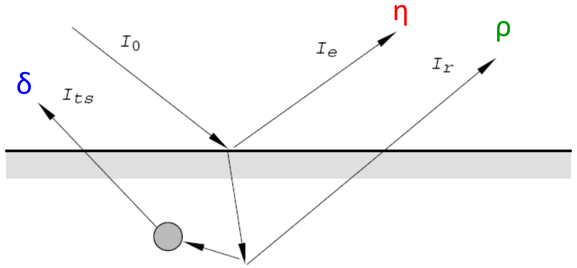
Mat.	σ_0	σ_{max}	E_{max} (eV)	E_1 (eV)
Al_2O_3	0.57	4.7	650	25
BN	0.45	2.9	600	50
SiO_2	0.2	4	400	44

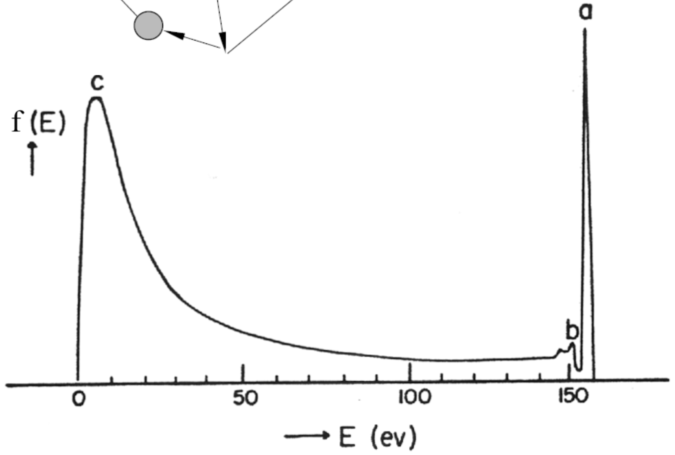


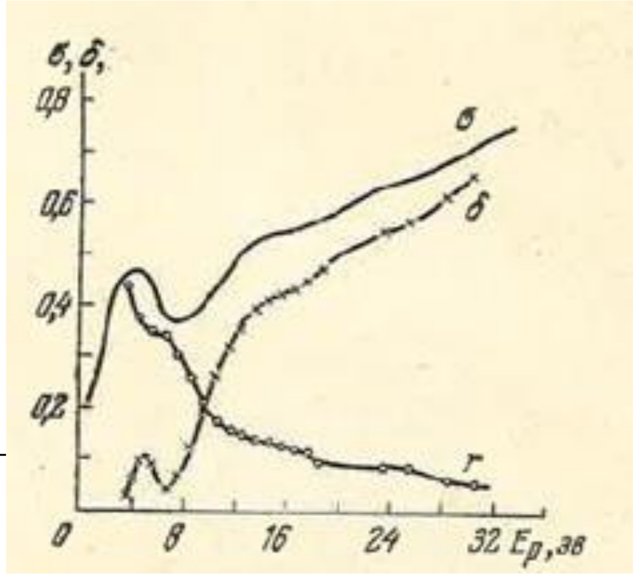
F. Taccogna, Plasma-wall interaction in Hall thrusters, PhD Thesis, Bari University (2003)

Emitted Energy Spectrum

- o The total yield σ_{tot} is the sum of 3 contributions:
  - peak (a) corresponds to electrons scattered elastically from the surfaces with energy slightly below the incident energy;
  - peak (b) due to electrons that suffer inelastic scattering;
  - peak (c) corresponds to true (from material) secondary electrons with low energy (<50 eV).
- o The repartition is a strong function of incident electron energy:
- o The backscattering coefficient ($r=\eta+\rho$) is growing with the decrease of E_p, while the yield of true secondary electrons δ decreases and reaches zero at an energy of about the width of the potential gap between vacuum and the upper level of the valence band.
- o Therefore, the superposition could have a distinguishable maximum and minimum in the low enrgy region, which can not be reproducible by the common used linear or power fit of SEY.

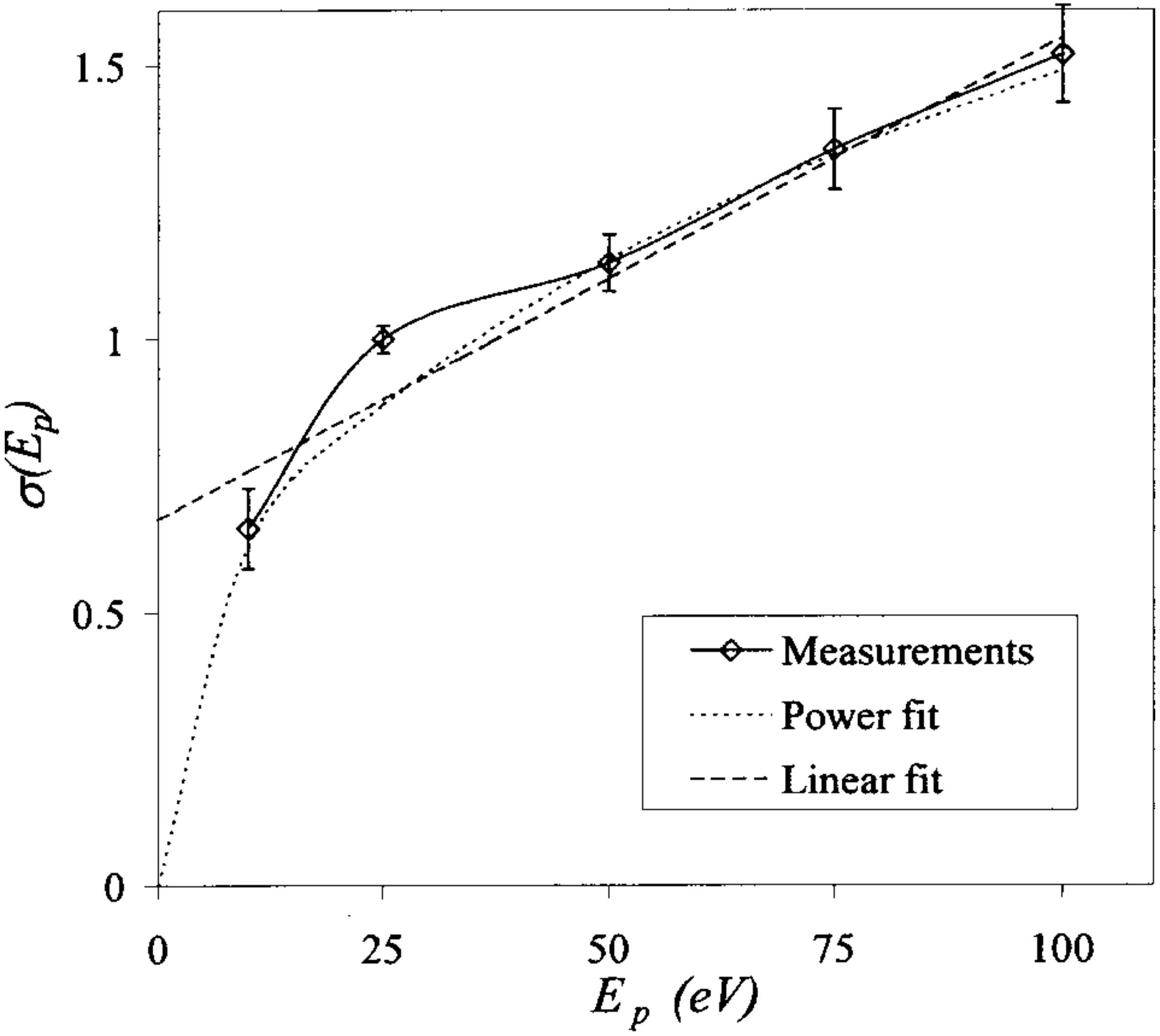






I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat (1969)

Linear / Power Law Model: 2 parameters



$$\sigma(E) = \sigma_0 + \frac{E}{E_*}(1 - \sigma_0)$$

$$\sigma(E) = \left(\frac{E}{E_*}\right)^{\alpha}$$

	Power fit		Linear fit	
Material	$\mathbf{E}_1$	α	$\mathbf{E}_1$	σ_0
Boron nitride (our measurements)	35	0.5	40	0.54
Boron nitride (Bugeat and Koppel)	30	0.57	30	0.59
Macor (our measurements)	35	0.38	38	0.67
Quartz (our measurements)	30	0.26	35	0.8
Quartz (Dionne)	45	0.32	45	0.73

A. Dunaevsky, Y. Raitses, N. J. Fisch, Secondary electron emission from dielectric materials of a Hall thruster with segmented electrodes, Phys. Plasmas 10(6), 2574 (2003)

Vaughan and Modified Vaughan (Sidorenko) Model: 9 parameters

$$\boxed{\sigma_{Vaug}(E,\theta) = \sigma_{max}(\theta)\left[v(E,\theta)e^{1-v(E,\theta)}\right]^k}$$

$$v(E,\theta) = \frac{E - E_0}{E_{max}(\theta) - E_0}$$

$$E_{max}(\theta) = E_{max,0}\left(1 + \frac{k}{\pi}\theta^2\right)$$

$$\sigma_{max}(\theta) = \sigma_{max,0}\left(1 + \frac{k}{\pi}\theta^2\right)$$

$$k = \begin{cases} 0.62 & E < E_{max} \\ 0.25 & E > E_{max} \end{cases}$$

$$\boxed{\sigma_e(E,\theta) = r_e\sigma_{Vaug}(E,\theta) + \sigma_{e,max}\begin{cases} v_1(E)e^{1-v_1(E)} & E_{e,0} < E < E_{e,max} \\ [1+v_2(E)]e^{-v_2(E)} & E > E_{e,max} \end{cases}}$$

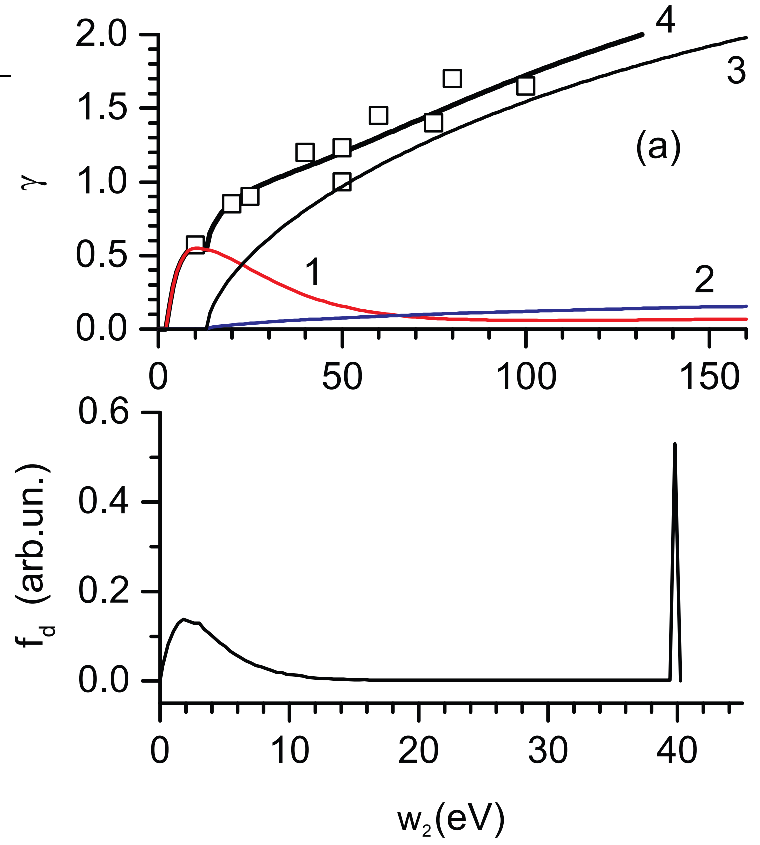
$$\boxed{\sigma_r(E,\theta) = r_r\sigma_{Vaug}(E,\theta)}$$

$$\boxed{\sigma_{ts}(E,\theta) = (1 - r_e - r_r)\sigma_{Vaug}(E,\theta)}$$

$$v_1(E) = \frac{E - E_{e,0}}{E_{e,max} - E_{e,0}}$$

$$v_2(E) = \frac{E - E_{e,max}}{\Delta}$$

w_0 [eV]	k_s	$\gamma_{max,0}$	$w_{max,0}$ [eV]	r_e	$w_{e,0}$	$\gamma_{e,max}$	$w_{e,max}$ [eV]	r_i
13	1	3	500	0.03	2	0.55	10	0.07



D. Sydorenko, Particle-in-Cell Simulations of Electron Dynamics in Low Pressure Discharges with Magnetic Fields, PhD Th. Univ. Saskatchewan (2006)

Furman-Pivi Model: 22 parameters

$$\sigma_e(E_p,0) = P_{1,e}(\infty) + \left[\hat{P}_{1,e} - P_{1,e}(\infty)\right] e^{-\left(\left|E_p - \hat{E}_e\right|/W\right)^b/b}$$

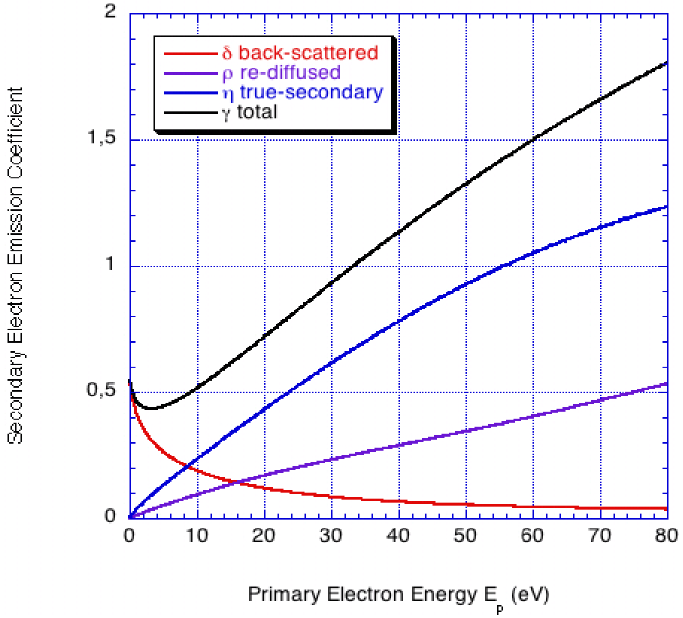
$$f_{1,e}(E) = \theta(E)\theta(E_p - E)\{P_{1,e}(\infty) + \left[\gamma_0 - P_{1,e}(\infty)\right] e^{-(E_p/W)^b/b}\} \frac{2e^{-(E-E_p)^2/2\delta_e^2}}{\sqrt{2\pi}\delta_e erf(E_p/\sqrt{2}\delta_e)}$$

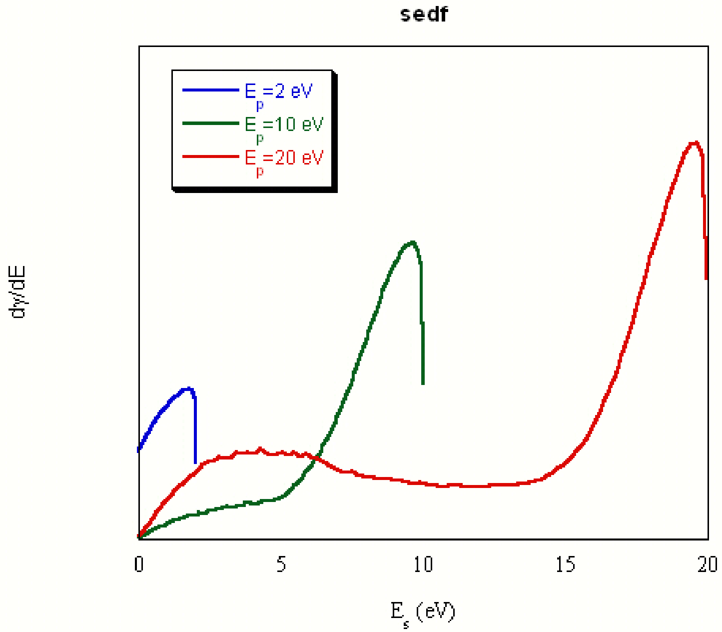
$$\sigma_r(E_p,0) = P_{1,r}(\infty)\left[1 - e^{-(E_p/E_r)^r}\right]$$

$$f_{1,r}(E) = \theta(E)\theta(E_p - E)\{P_{1,r}(\infty)\left[1 - e^{-(E_p/E_r)^r}\right]\} \frac{(q+1)E^q}{E_p^{q+1}}$$

$$\sigma_{ts}(E_p,\theta_p) = \hat{\sigma}(\theta_p)\frac{sE_p/\hat{E}(\theta_p)}{s-1+\left[E_p/\hat{E}(\theta_p)\right]^s}$$

$$f_{n,ts}(E) = \theta(E)\frac{\binom{M}{n}\left(\frac{\gamma_{ts}}{M}\right)^n\left(1-\frac{\gamma_{ts}}{M}\right)^{M-n}}{\left[\varepsilon_n^{d_n}\Gamma(d_n)\right]^n G(nd_n, E_p/\varepsilon_n)} E^{d_n-1}e^{-E/\varepsilon_n}$$



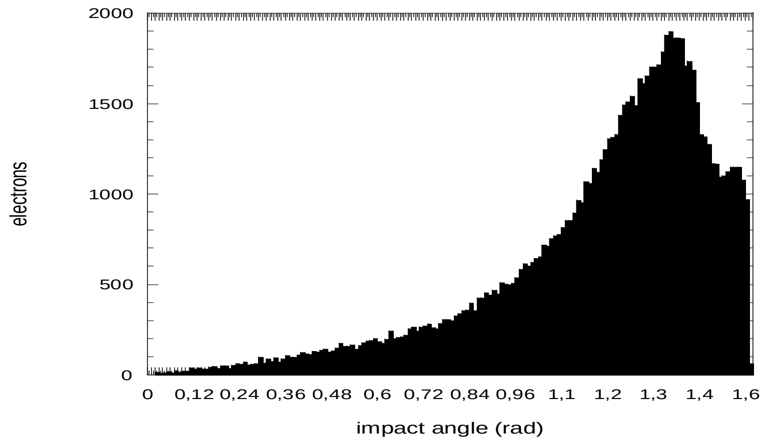


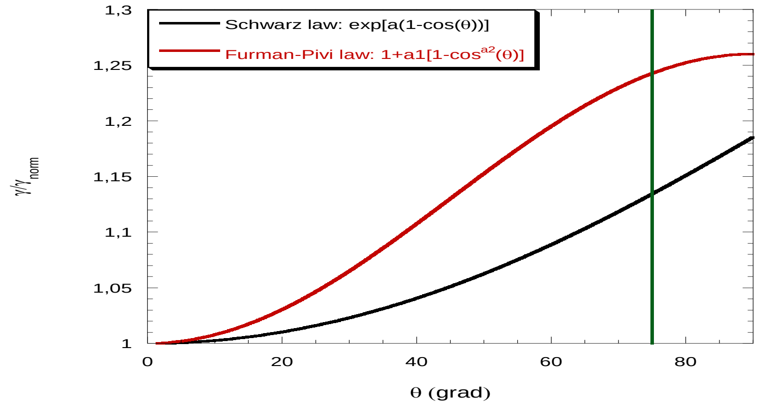
Using this model in 1D(r) PIC code under typical SPT100 condition, only 40% of emitted electrons are true secondary.

M. A. Furman, M. T. F. Pivi, Probabilistic model for the simulation of secondary electron emission, Phys. Rev. Special Topics – Accel. and Beams 5(12), 124404 (2002)

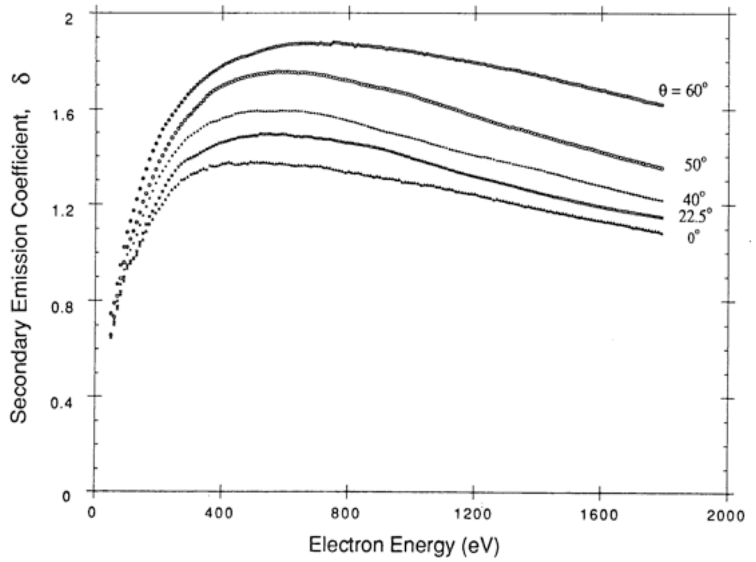
Importance of the angle of impact

- For a given primary energy, SEY increases with increasing angle of incidence θ. For rough surfaces, the dependence of SEY on θ virtually disappears.
- The combined effect of the radial sheath and azimuthal ExB drift makes the electrons having a grazing impact => $v_\theta >> v_r$



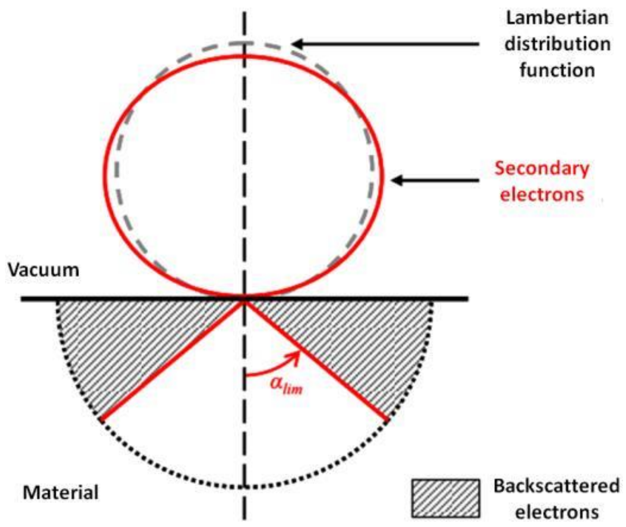


The angular dependence is a function of the impact energy

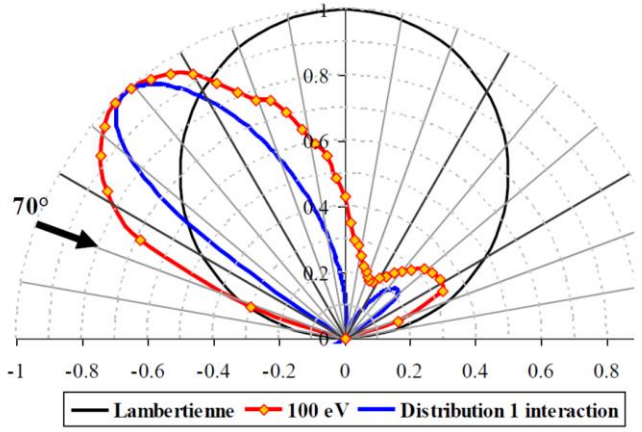


Emitted Angle Distribution

- True secondaries have a cosine angular (Lambertian) distribution independent of the incident energy and angle.

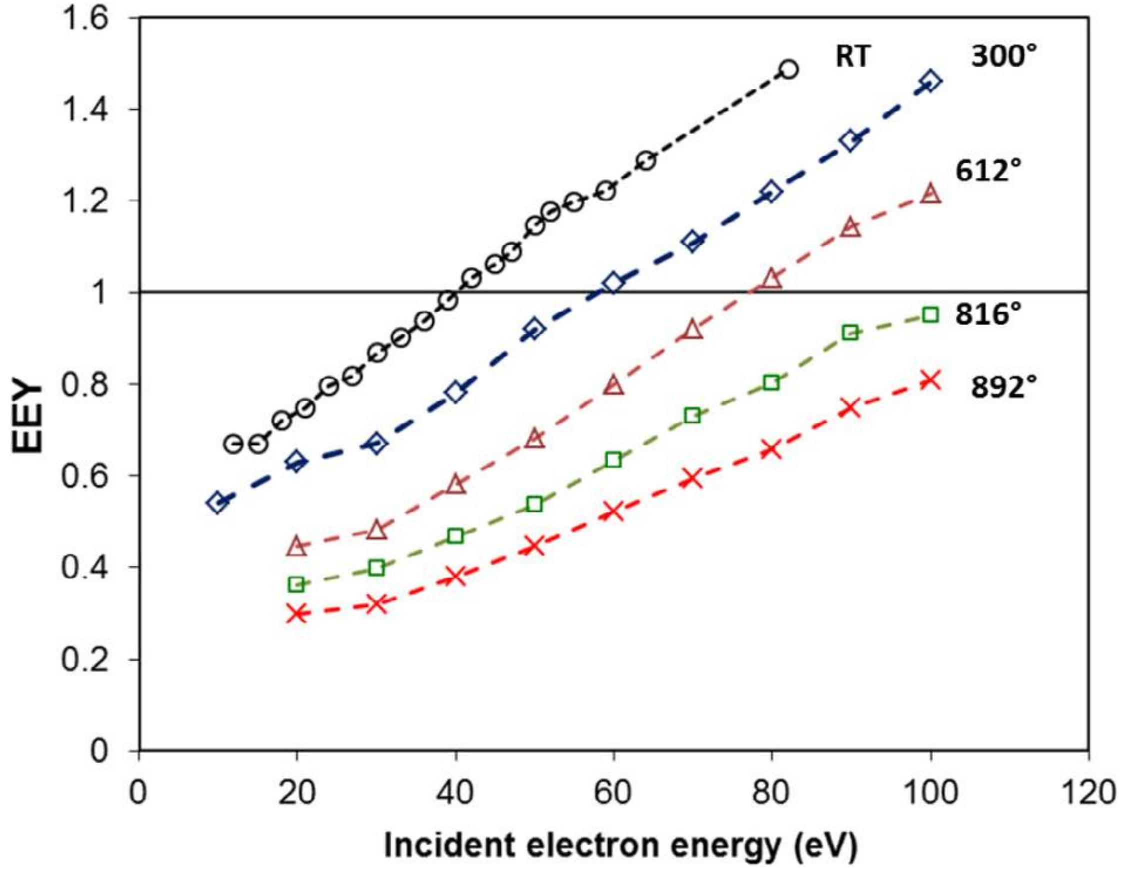


- Elastically reflected and rediffused electrons have more complicated angular distribution.



Wall temperature Dependance

– σ_0 decreases while E_* increases with wall temperature, making the SEE process more negligible.



M. Belhaj, K. Guerch, P. Sarrailh, N. Arcis, Nucl. Instrum. Meth. Phys. Res. B 362, 163 (2015)

Conclusions

- Three different SEE Models
- The most important variables: energy/angle of impact and wall temperature
- Simple Linear/Power low model well suited for parametric investigation
- Higher sophisticated model necessary to distinguish the 3 different secondary electron populations: emission energy and angle distribution
- Study to determine the most important parameters for the HT physics