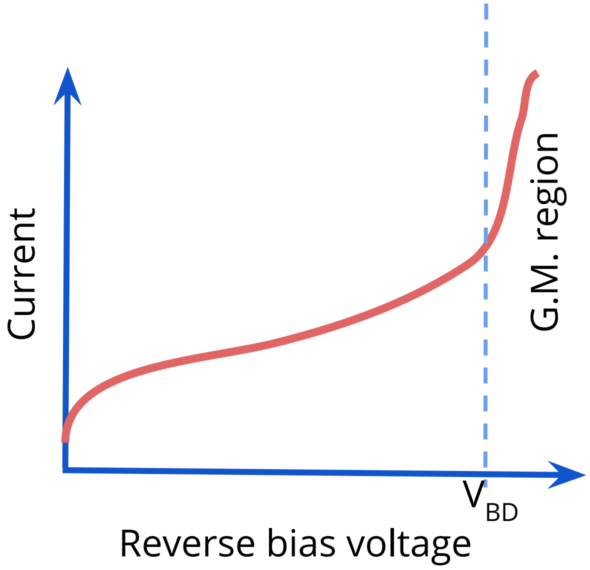
Photo Detection Efficiency of SPAD

HighRR Biweekly Seminar
11-11-2020

Basic Terms

Impact Ionization

- Process of acceleration of free charge carrier with enough kinetic energy - creation of e-h pairs by ionization process.
- Geiger mode operation - multiplication of e-h pairs goes infinite.



Basic Terms

- If electrons or holes collide with equal effective masses - -
    - According to law of conservation of momentum,

Initial Momentum $k_0 = k_1 + k_e + k_h$ Final Momentum

$$\hbar^2 k_0^2/2m^* = E_i = E_g + \hbar^2 k_1^2/2m^* + \hbar^2 k_e^2/2m^* + \hbar^2 k_h^2/2m^*$$

Momentum of secondary charge carriers are equal after collision ; $k_1 = k_e = k_h = ⅓\, k_0$

=> **Threshold energy(E_i) = 1.5 E_g**

- Carrier energy > Threshold energy; **No. of carriers (n) ~ exp($-E_i/k_BT_e$).**

Basic Terms

- From energy balance equation,

$$eFv_d\tau = 3/2\ k_B(T_e - T) \approx k_BT_e$$

- At high fields, drift velocity(v_d) = constant and with constant relaxation time ($\boldsymbol{\tau}$); carrier mean free path, $\boldsymbol{\lambda = v_d\tau}$.
- Ionization rate or coefficient can be determined by $\boldsymbol{\alpha = (1/n)\ dn/dx}$ **;**

$$\boldsymbol{\alpha \propto \exp(-E_i/k_BT_e) = \exp(-E_i/eF\lambda)}$$

=> Average no. of e-h pairs produced by single carrier per unit length.

What is SPAD?

- **SINGLE PHOTON AVALANCHE DIODE**

- Reverse-biased p-n junction
- $V_b > V_{bd}$; Geiger-mode operation
- High electric field (>3×10^5 V/cm)
- Self sustained avalanche
- Quenching with resistor in series.

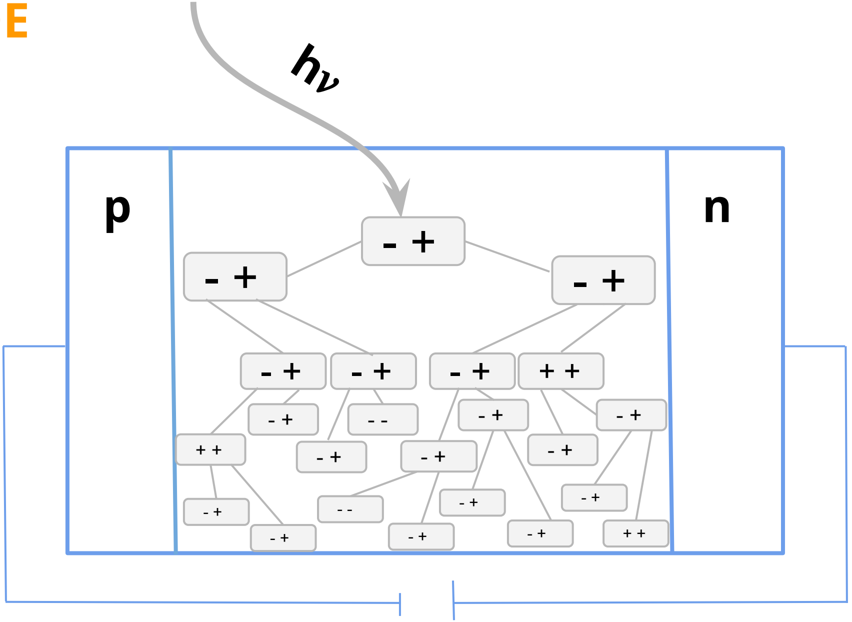


Photo Detection Efficiency

$$\mathrm{PDE}(\lambda) = (1-R(\lambda)) \int_{Z_p}^{Z_n} \alpha(\lambda)\, e^{-\alpha(\lambda) z}\, P_t(z)\, dz + \eta_{e,ph}(\lambda, z_p) P_e(z_p) + \eta_{h,ph}(\lambda, z_n) P_h(z_n)$$

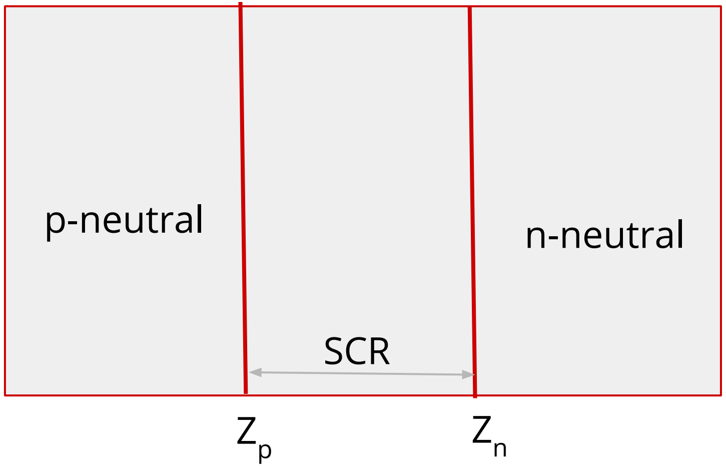
$R(\lambda)$ = Reflectivity ; **$\alpha(\lambda)$** = Absorption Coefficient ;

η = Quantum Efficiency , **z** = Depth;

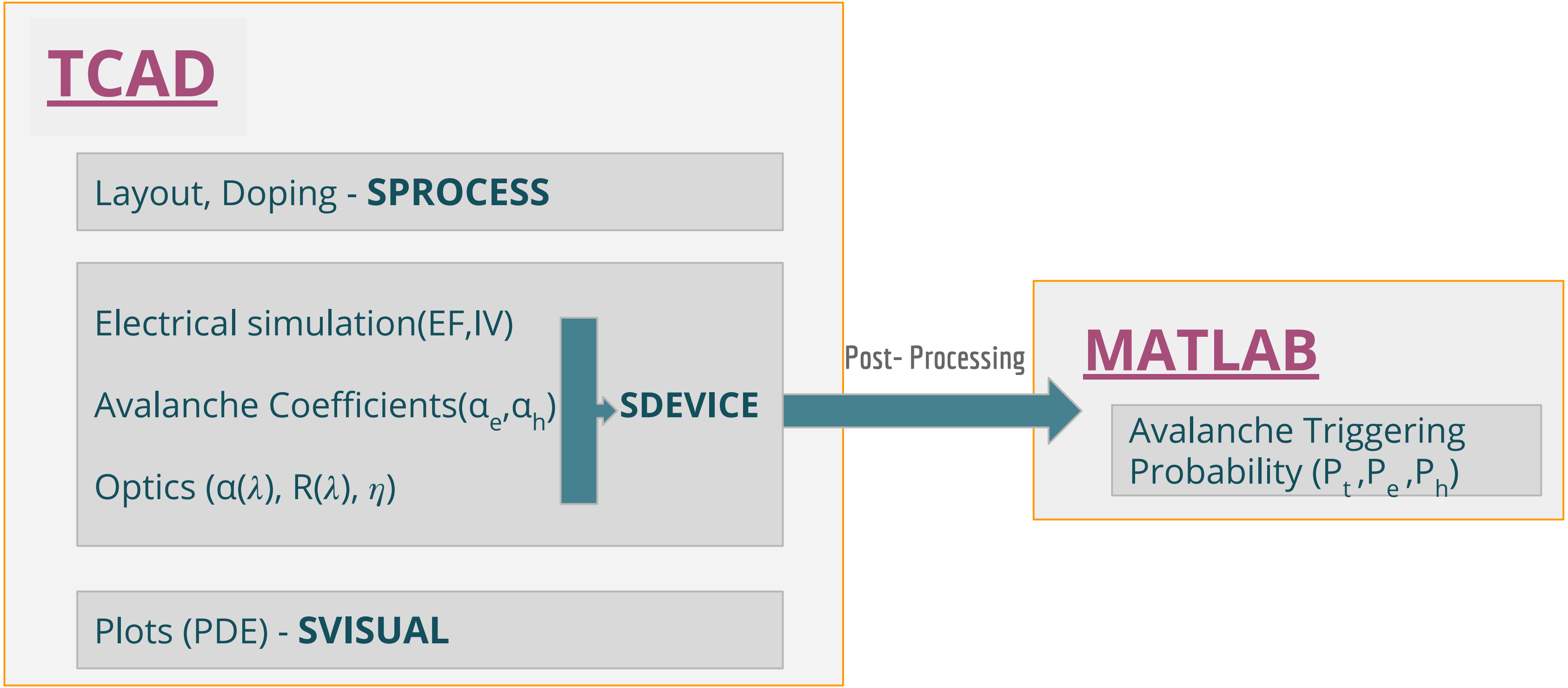
P_t = Total Triggering Probability;

P_e = Electron Triggering Probability;

P_h = Hole Triggering Probability



PDE Modelling



TCAD

Layout, Doping - **SPROCESS**

Electrical simulation(EF,IV)

Avalanche Coefficients(α_e,α_h)

Optics ($\alpha(\lambda)$, $R(\lambda)$, η)

SDEVICE

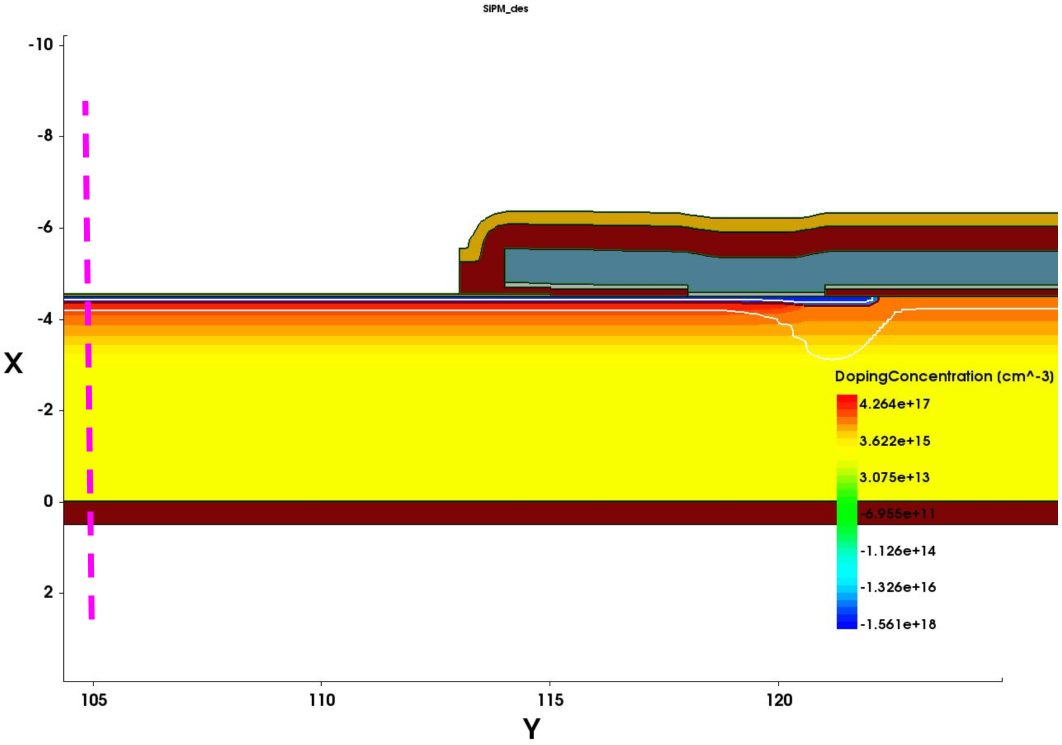
Plots (PDE) - **SVISUAL**

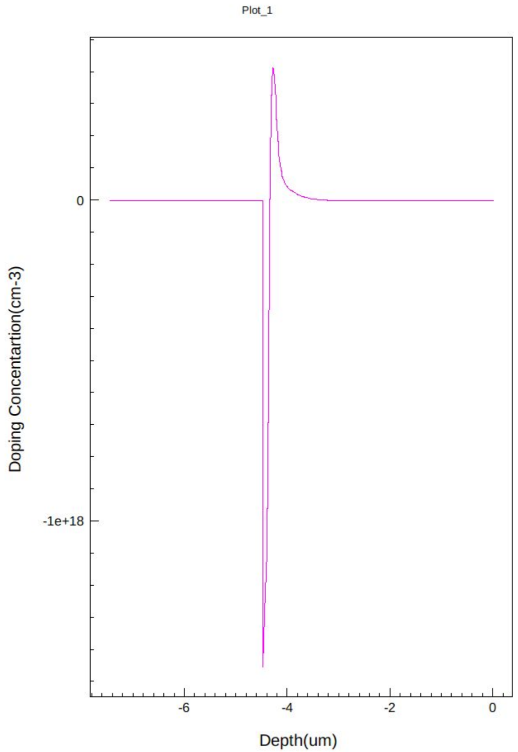
Post- Processing

MATLAB

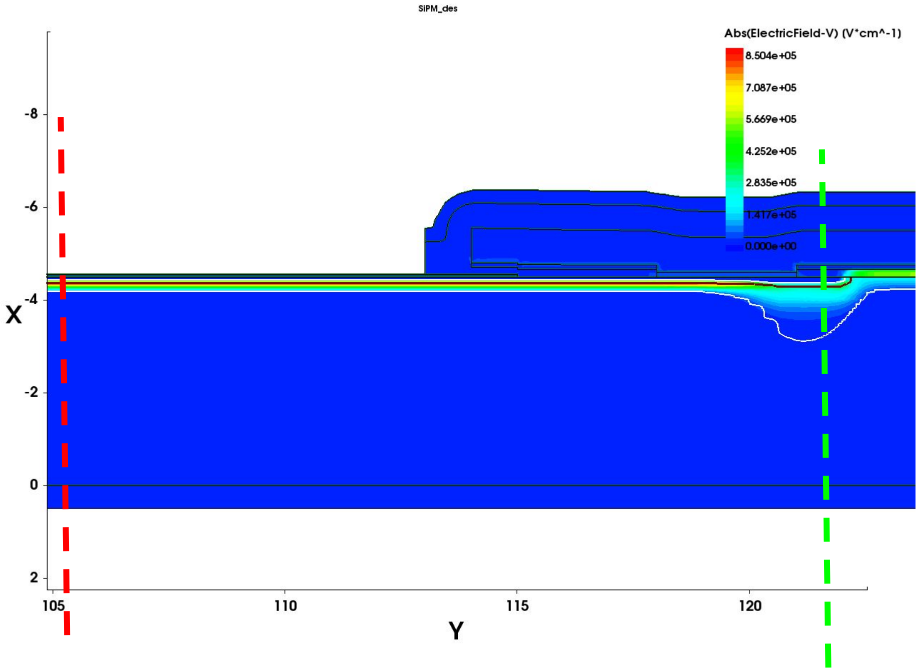
Avalanche Triggering Probability (P_t ,P_e ,P_h)

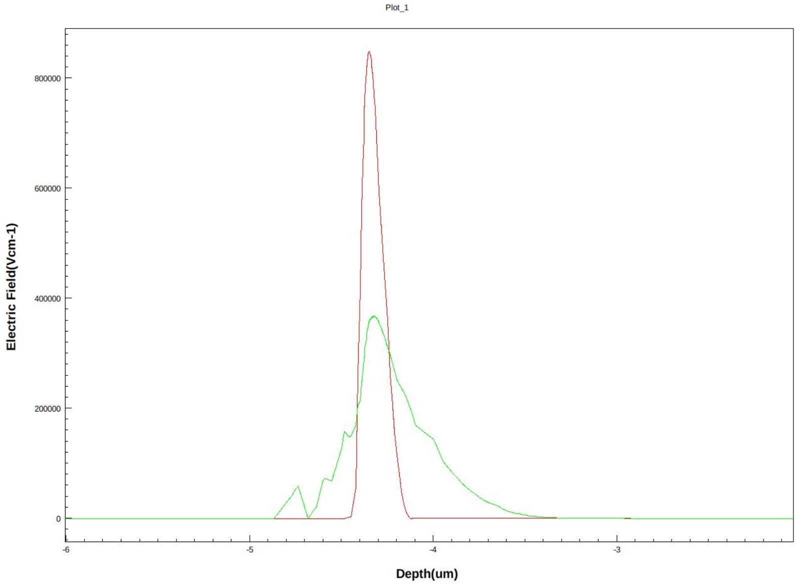
Doping Profile



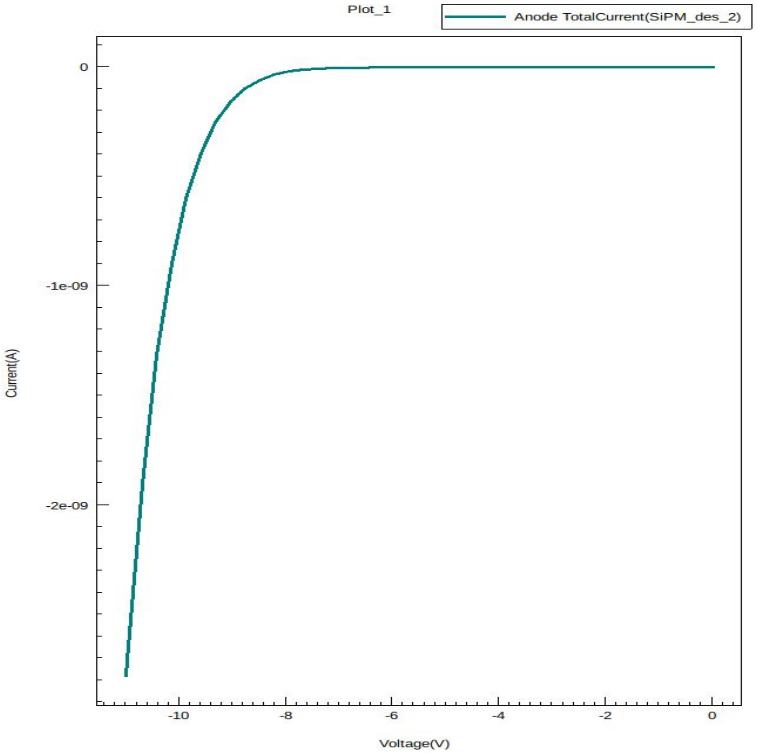


Electric Field Distribution



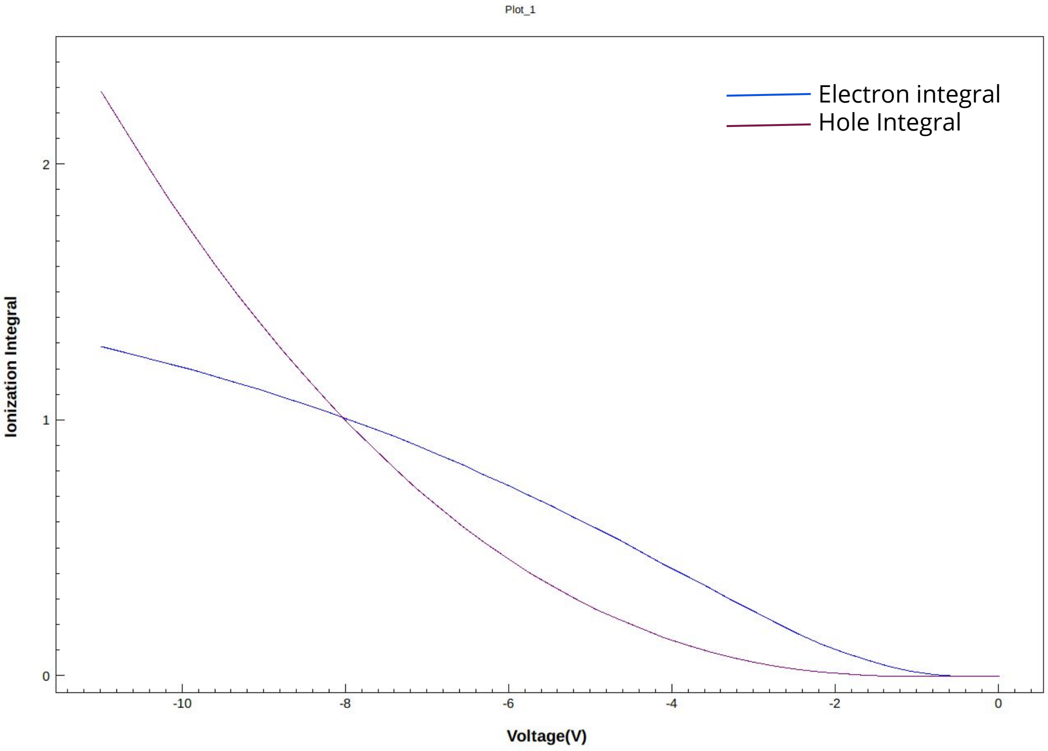


IV Characteristics



- TCAD Breakdown Model : Ionization integral with carrier analysis
- **Breakdown Voltage = 8V**

Ionization Integral



$$1-1/M_h = \int \alpha_h \exp\left(-\int (\alpha_h - \alpha_n) dz\right) dz = \phi_h$$

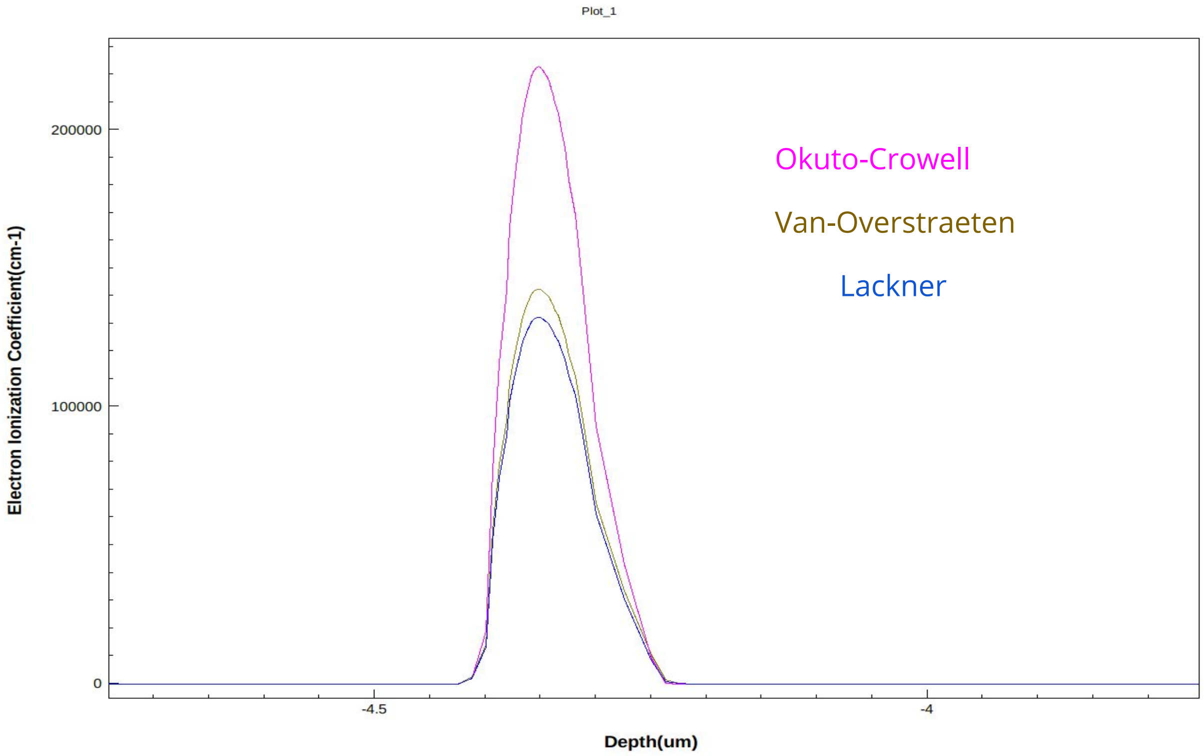
- $M_h = \infty$, when avalanche occurs => $\phi_h = 1$
- Breakdown occurs when one of the ionization integrals reach one.

TCAD Avalanche Models

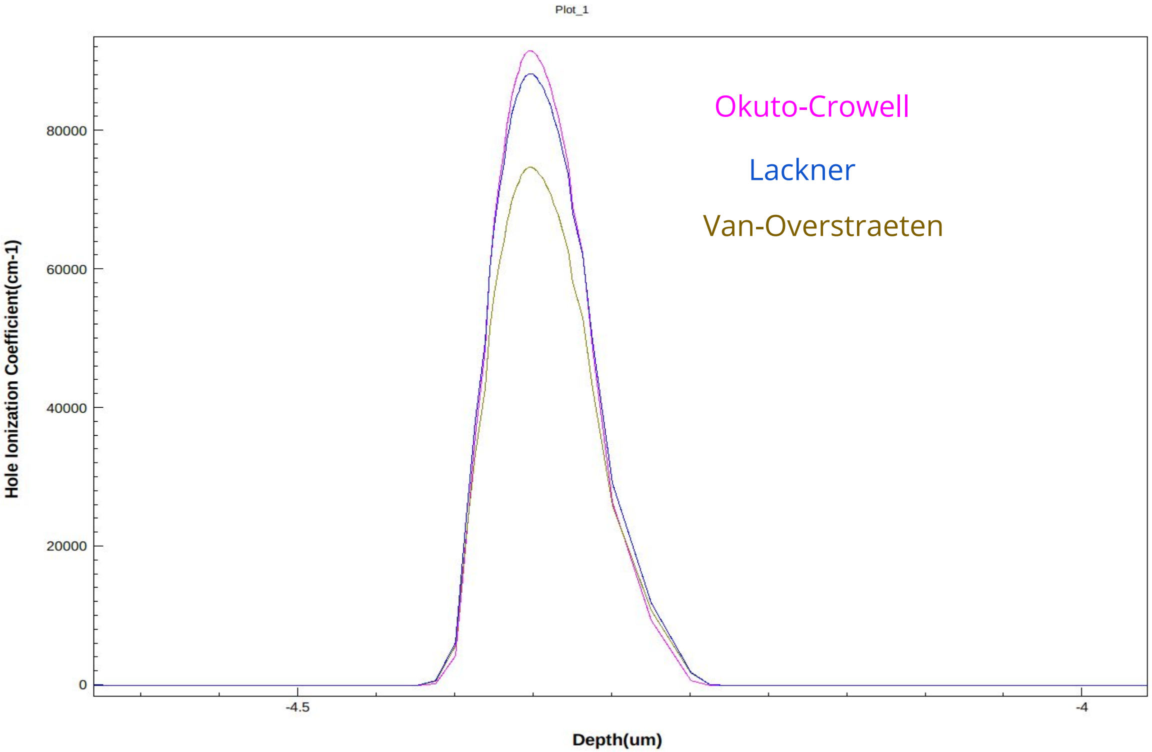
Models	Temperature	Electric Field (Vcm^{-1})
Van Overstraeten	300K	1.75×10^5-6×10^5
Okuto-Crowell	300K	10^5-10^6
Lackner	300K	2×10^5 - 6×10^5
UniBo	300 - 675K	4×10^4 - 5×10^5
UniBo2	300 - 773K	4×10^4 - 5×10^5

EMPIRICAL MODEL(USED)

Comparison of Avalanche Models



Comparison of Avalanche Models



Avalanche Triggering Probability

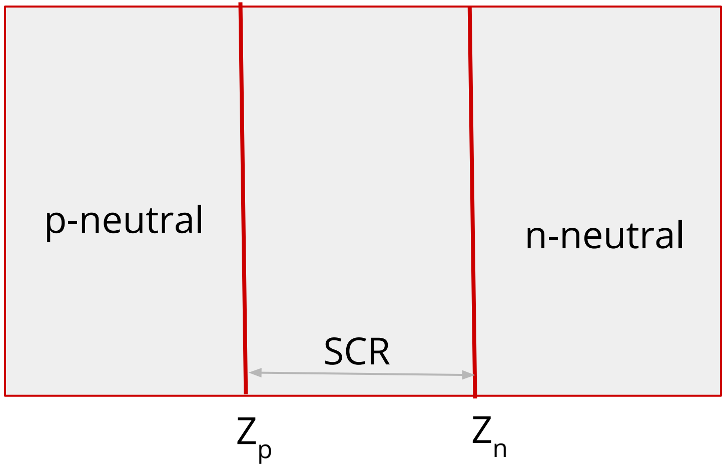
$$dP_e/dz = (1 - P_e)\ \alpha_e[P_e + P_h - P_eP_h]$$

$$dP_h/dz = -\ (1 - P_h)\ \alpha_h[P_e + P_h - P_eP_h]$$

$$P_t = P_e + P_h - P_eP_h$$

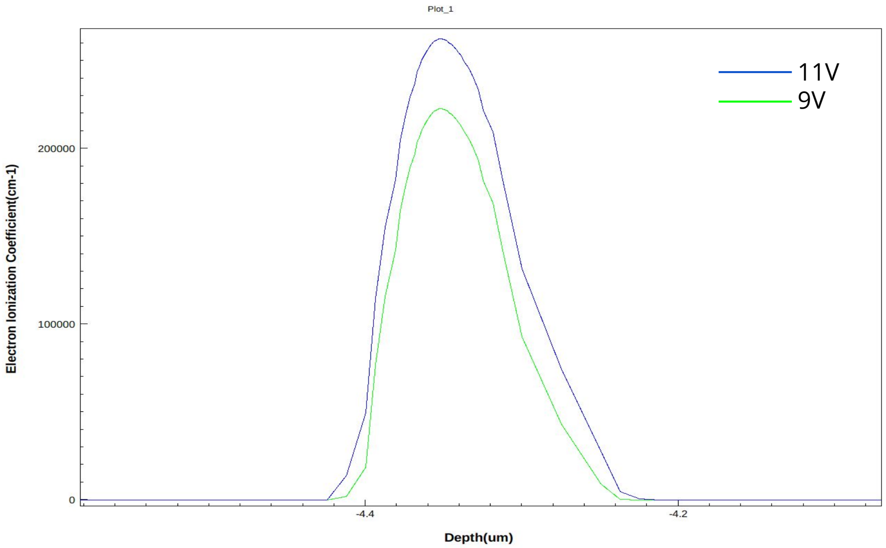
Boundary Conditions : $P_e(Z_n) = 0$

$P_h(Z_p) = 0$

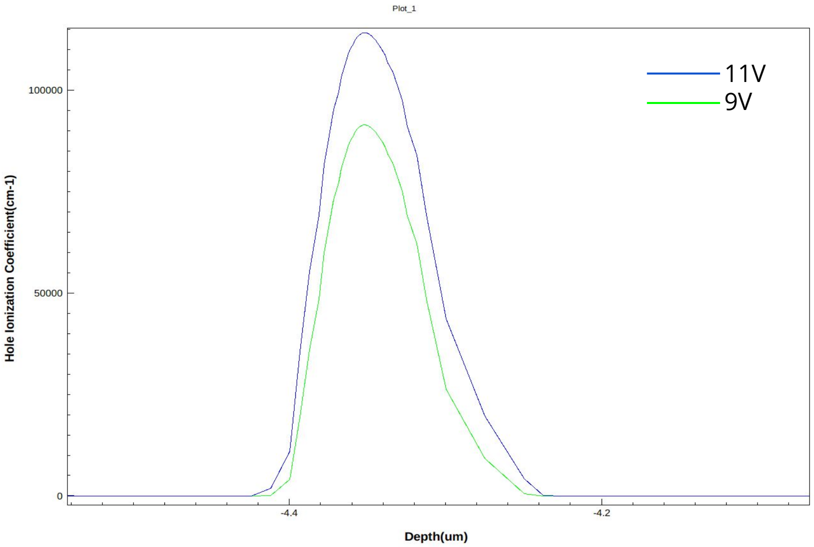


Ionization Coefficient

α_e

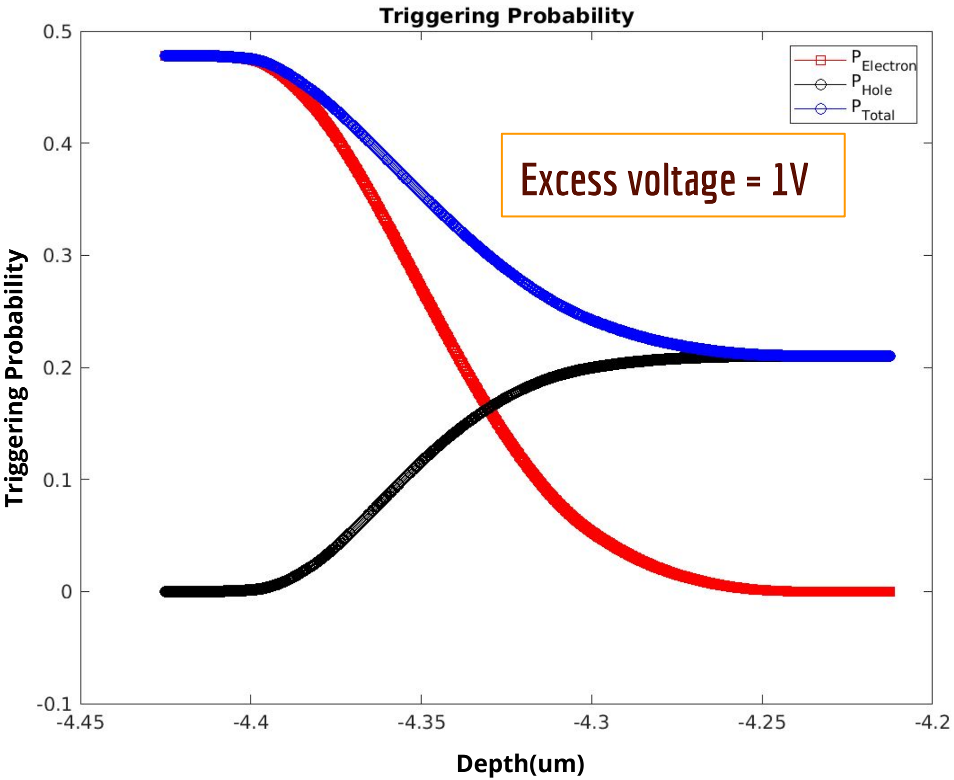


α_h

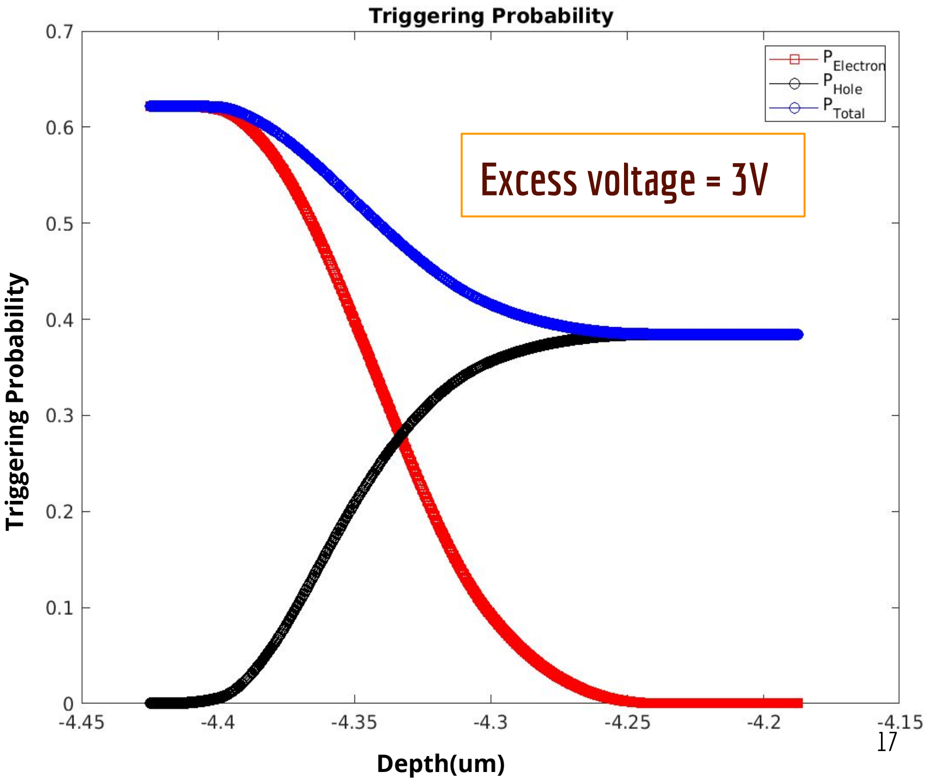


α_e is larger than α_h .

Avalanche Triggering Probability


Triggering Probability

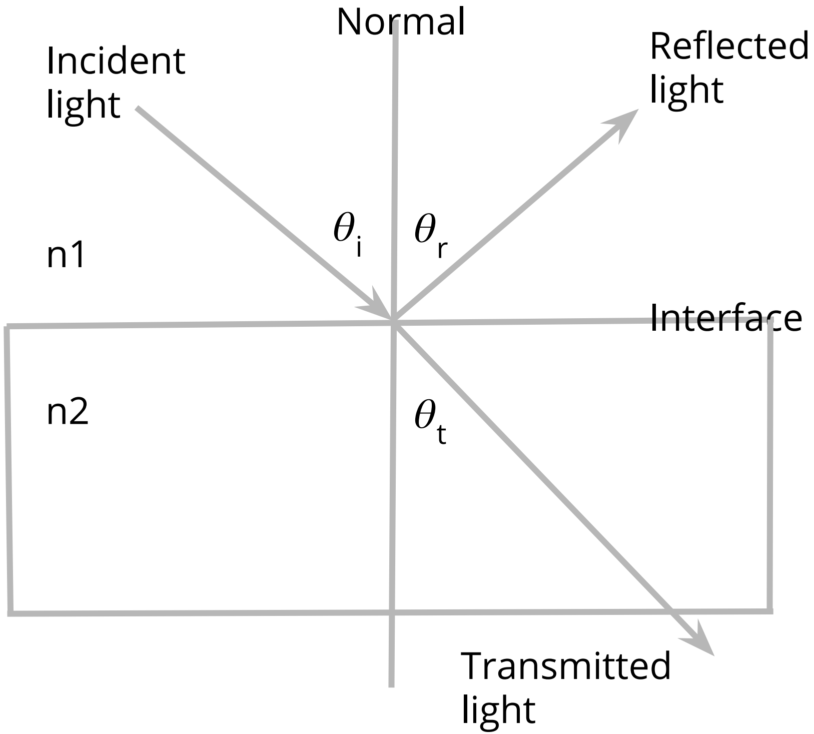
Excess voltage = 1V


Triggering Probability

Excess voltage = 3V

Optics

Fresnel Reflection Coefficient



At normal incidence,
r = (n1-n2) / (n1+n2)

- If n1<n2, r = -ve
  - Phase change π or 180°
  - External reflection
  - Destructive interference

- If n1>n2, r = +ve
  - Phase change 0°
  - Internal reflection
  - Constructive interference

Reflectance, $R = r^2 = [(n1-n2) / (n1+n2)]^2$

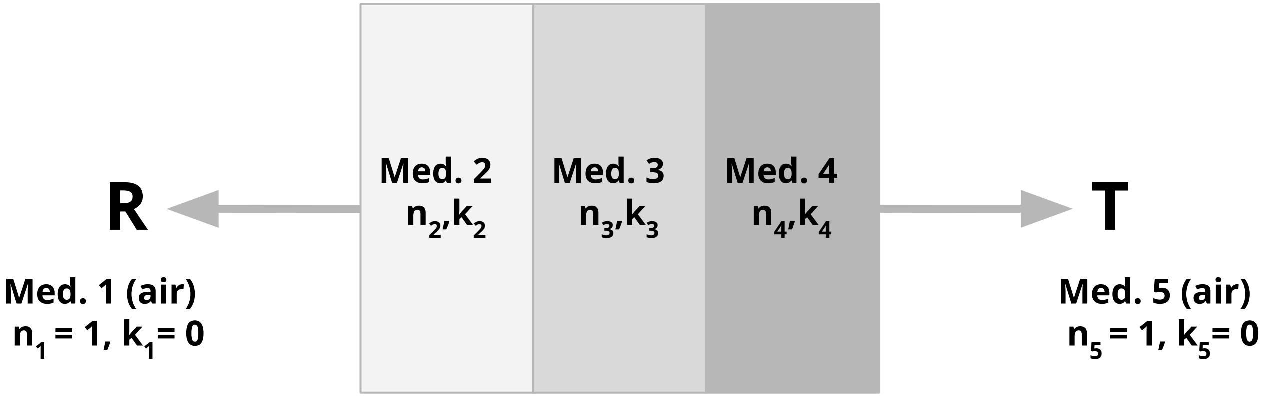
Transfer Matrix Method

Refractive index(n), extinction coefficient(k), thickness of material

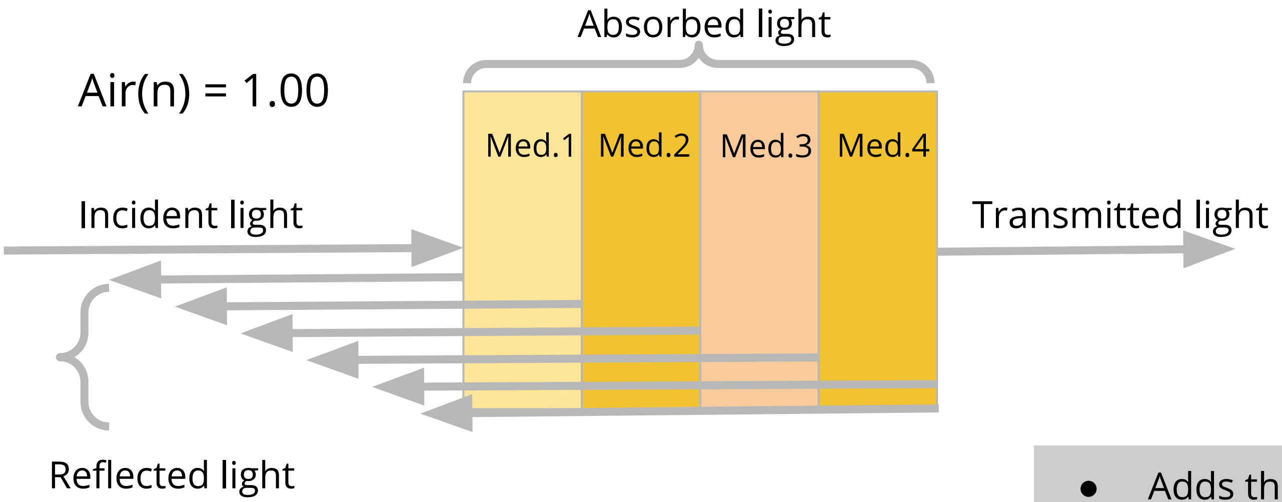
TMM

Multi-layer structure

Reflection coefficient,
Absorption coefficient,
Transmission coefficient



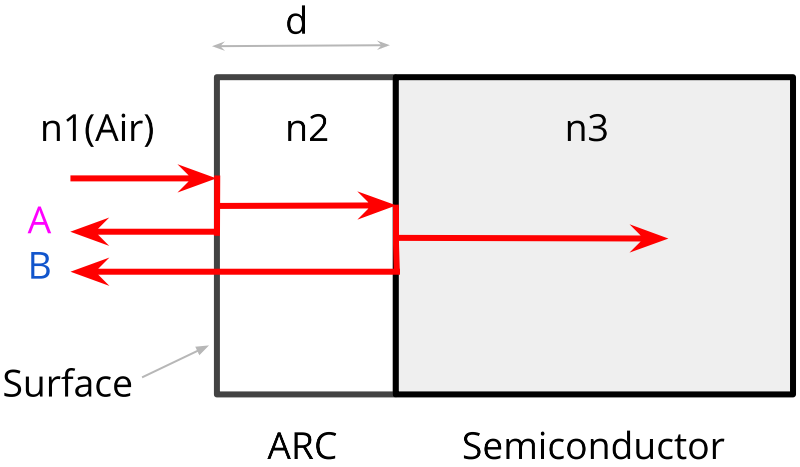
Transfer Matrix Method



- Adds the reflections from every interface in matrix form.

Reflectance+Absorption+Transmission = 100%

Anti-Reflection Coating



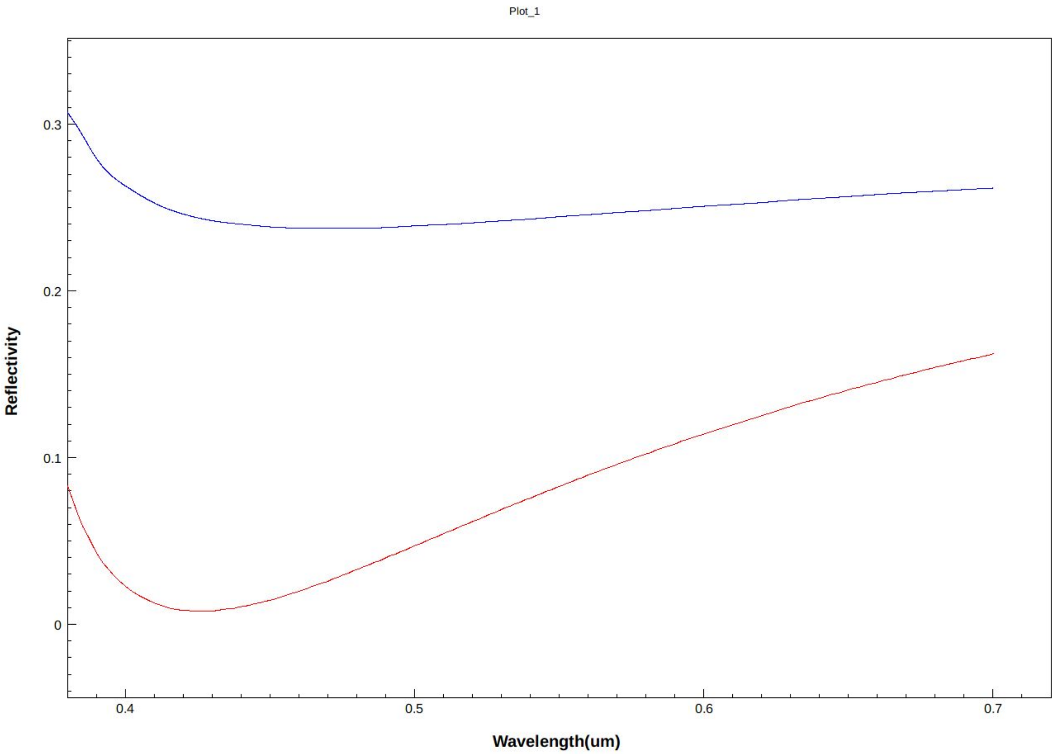
ARC reduces the reflected light intensity

- $n1<n2<n3$; Phase change = π
- B travels twice of A
- Phase diff. between A & B : $n_2k(2d)$

How to adjust the thickness of ARC?

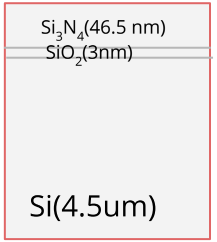
- ARC thickness, d should be $\boldsymbol{\lambda/4n_2}$

Effect of ARC




SiO_2(49.5nm)

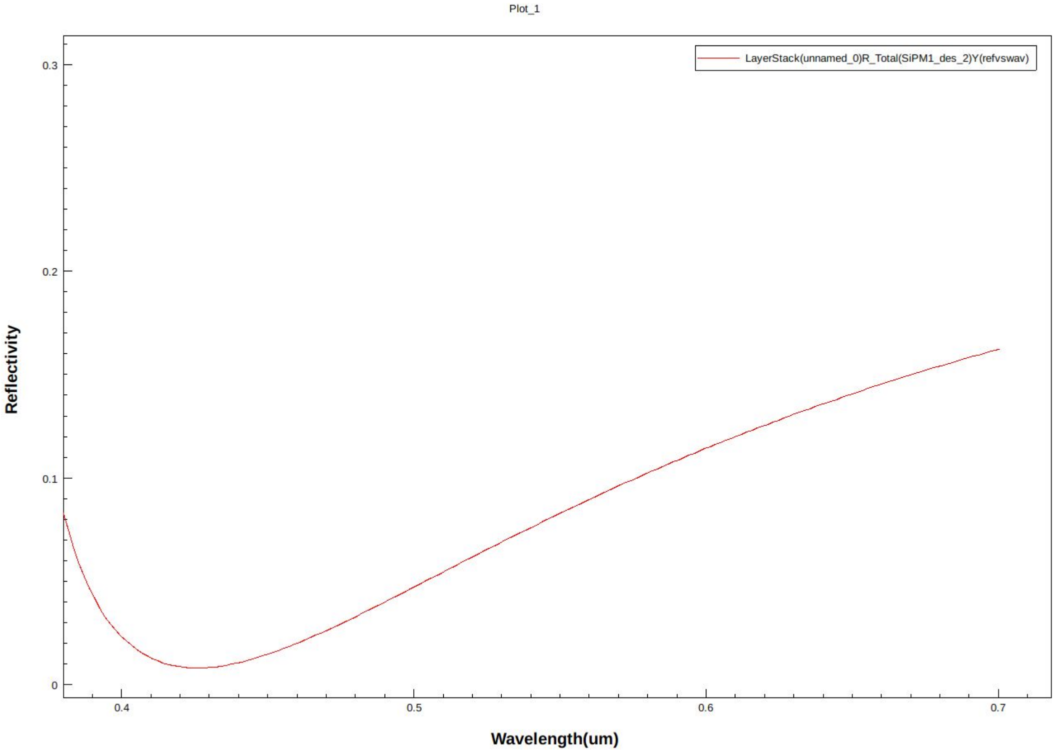
Si(4.5um)

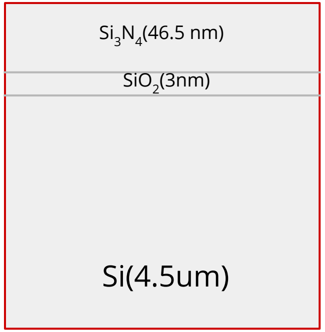

Si_3N_4(46.5 nm)

SiO_2(3nm)

Si(4.5um)

Tuned ARC at 420 nm





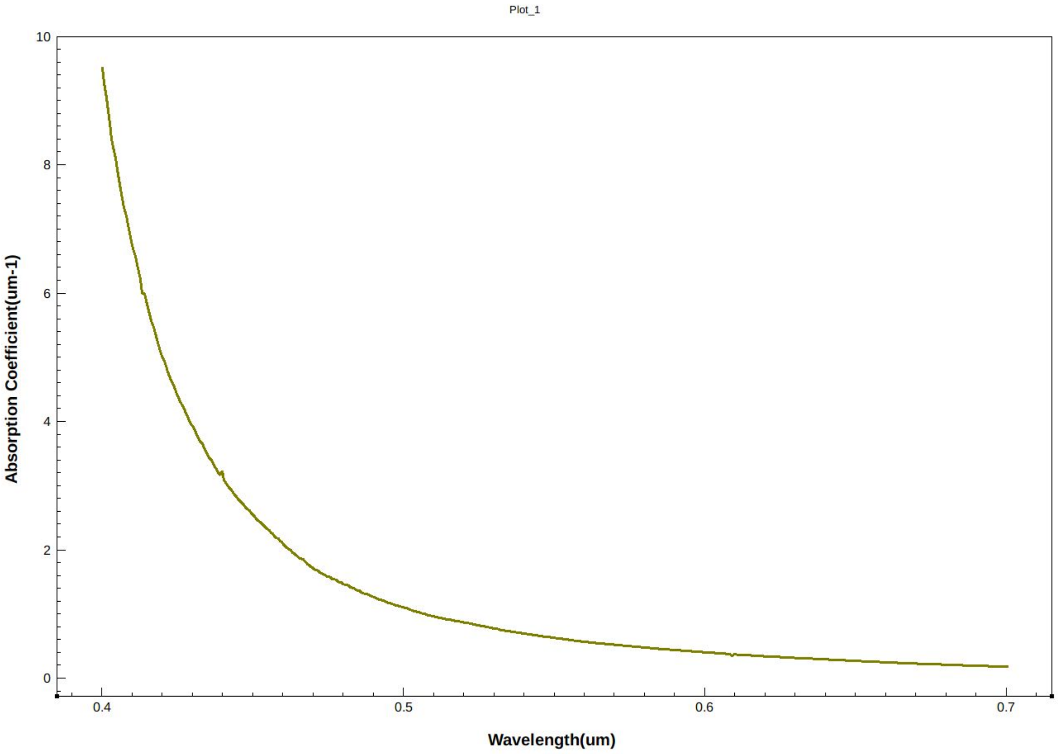
Si_3N_4(46.5 nm)

SiO_2(3nm)

Si(4.5um)

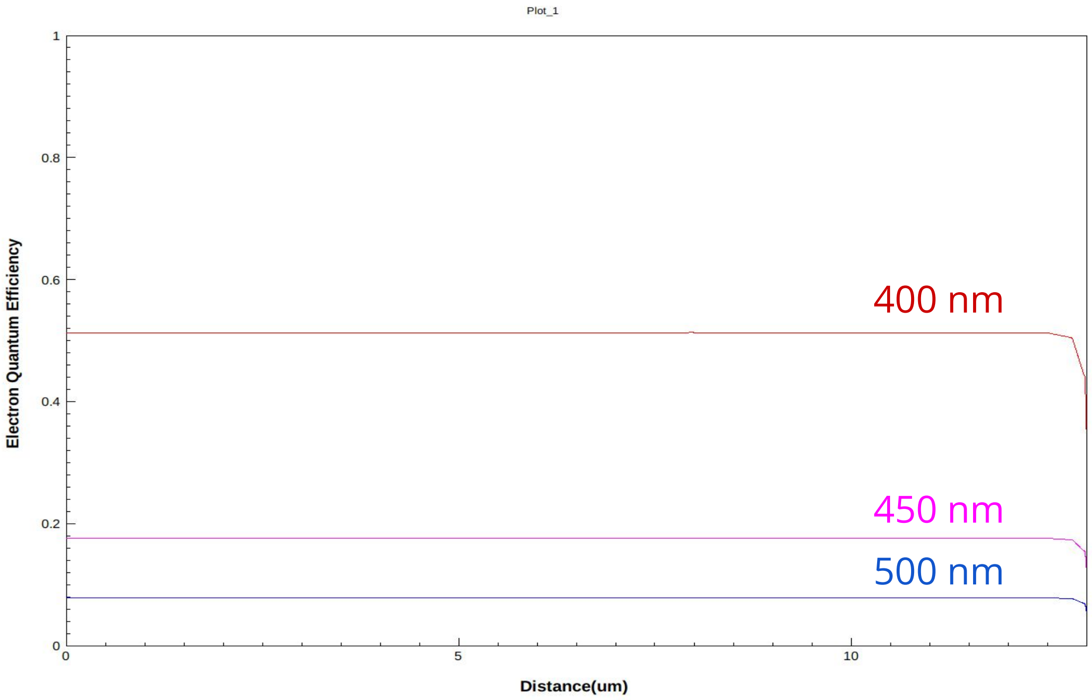
- ~1% reflection

Absorption Coefficient ($\alpha(\lambda)$) of Si



- Strongly depends on wavelength.
- $\alpha(\lambda) = 4\pi k/\lambda$

Quantum Efficiency

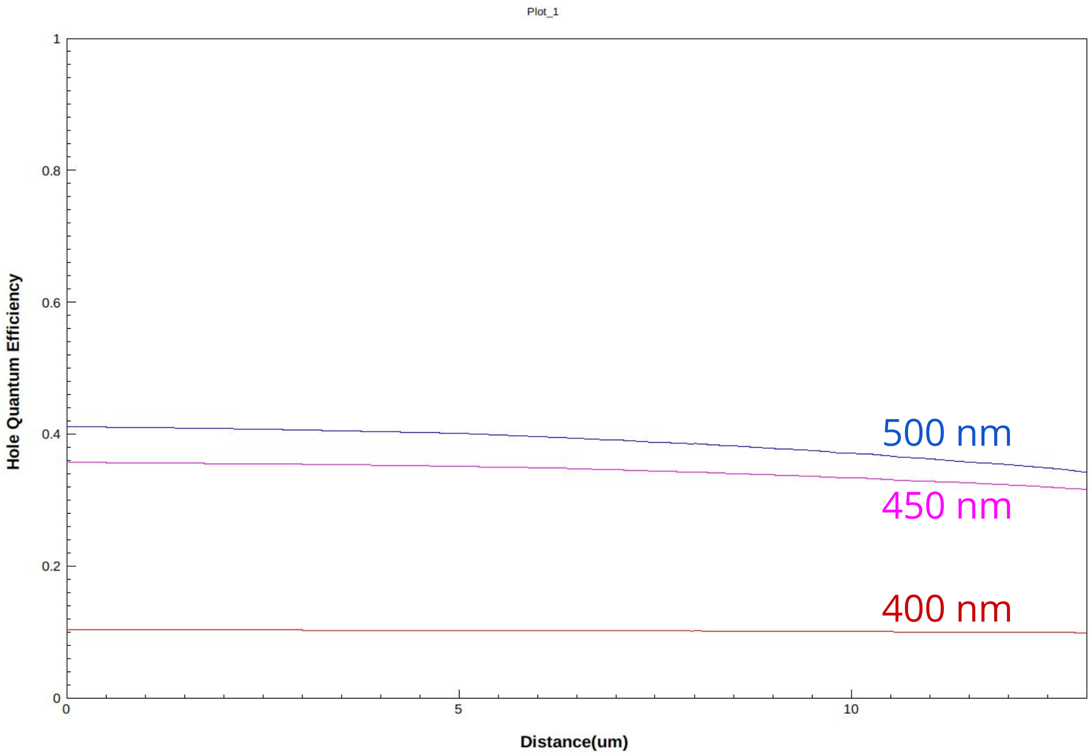


Drops at depletion edge

$$\eta = (hc/q\lambda)*J/P$$

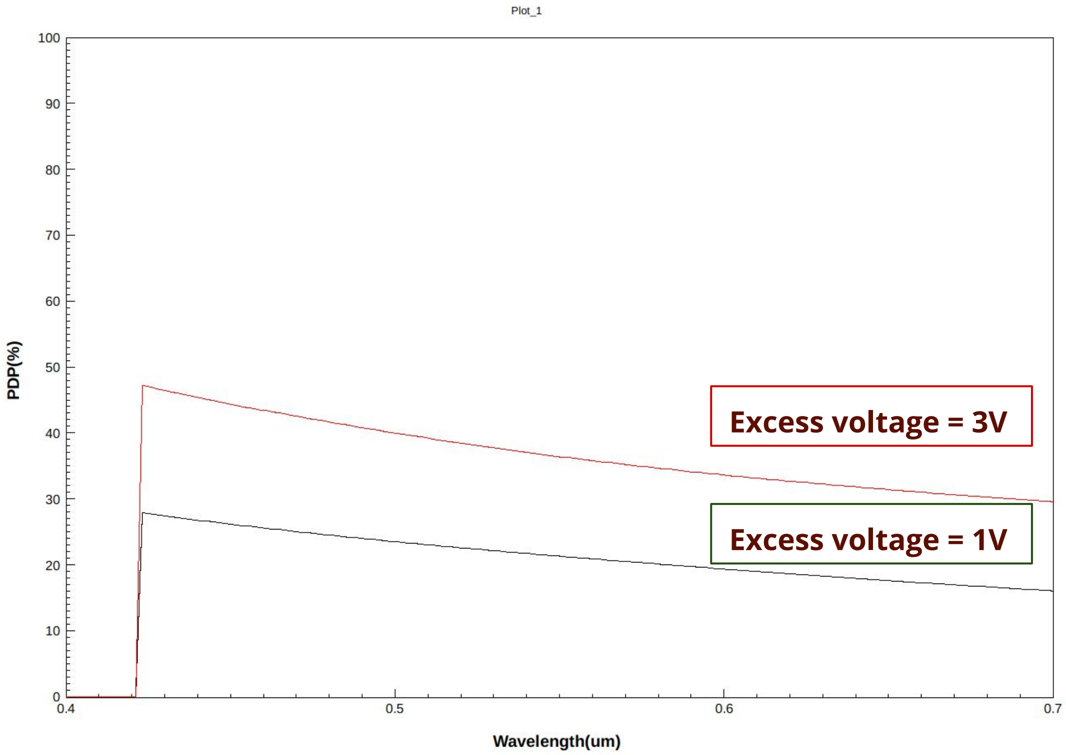
$P = 0.05W/cm^2$

Quantum Efficiency



Drops at depletion edge

Photo Detection Probability



Excess voltage = 3V

Excess voltage = 1V

- **28% for V_{ex} = 1V**
- **48% for V_{ex} = 3V**

Conclusions

- Anti-reflection coating can be adjusted by $\boldsymbol{\lambda/4n_2}$.
- Reflectivity ~ 1% at 420 nm of wavelength.
- PDP = 28% for 1V_{ex}; 48% for 3V_{ex} at 420 nm.
- PDP increases with the increase of excess voltage.