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Enhancing Electron Emission

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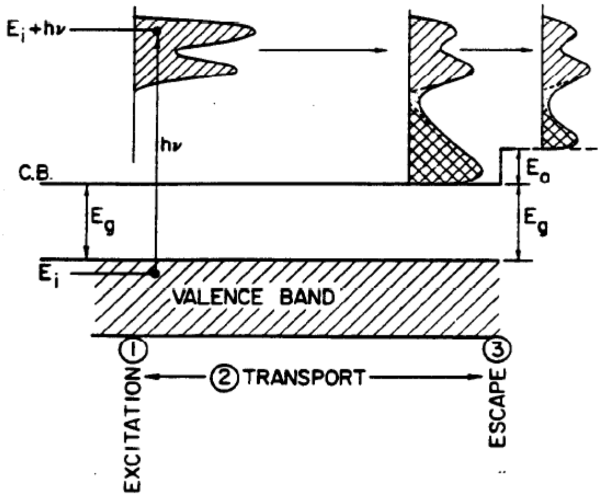
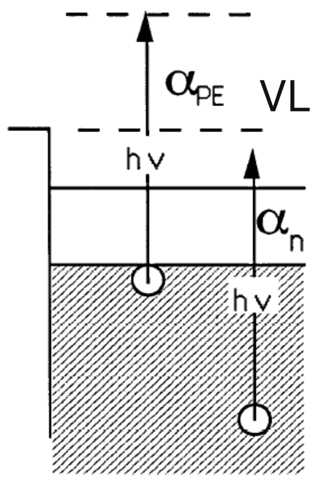
Outline

- Introduction – Spicer's Photoemission model
- Search for new PC materials
  - Band structure of bi- and multi-alkali PC
- Electron emission enhancement
  - Anti-reflecting coatings (Nanorod Arrays, Moth-eye concept)
  - Electric field assisted PE
- MC simulation of pillar photocathode
- MC simulations of MCP test experiment
- PC lifetime, aging, ion feedback
- Summary

Introduction - Spicer's model



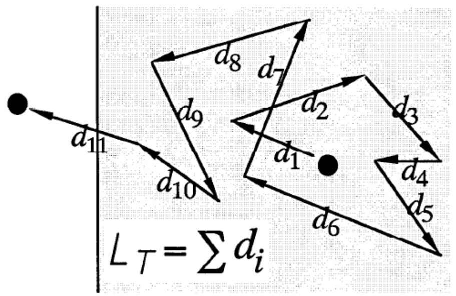
(1)



Excitation

α_{PE} - electrons are excited above the vacuum level (VL) and have possibility to escape, α_n is the absorption that does not produce yield. $\alpha_{PE}/\alpha \approx 1$ for NEA

(2)



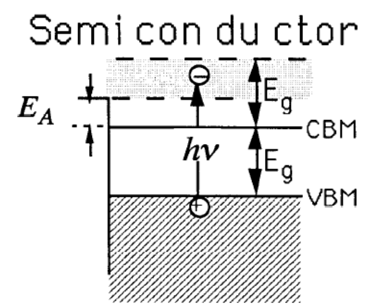
Random walk

with small loss due to collisions (~ 100 colls)
l_a/L is an important parameter

l_a is the absorption length, L is the escape length. If $L \ll l_a$, only a small fraction of the PE contributes to the yield.

L can be obtained from experiment or by MC.

(3)



Escape to vacuum

P_E can be approximated by a step function. Usually P_E does not exceed 0.5.

$$QY = \frac{\alpha_{PE}}{\alpha} \frac{1}{1 + \frac{l_a}{L}} P_E$$

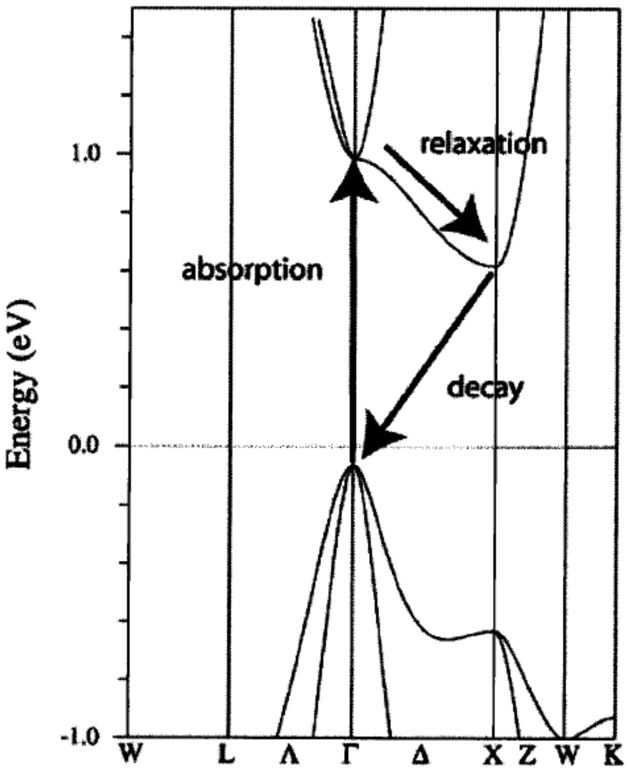
[W. Spicer, Phys. Rev.112 (1958) 114]

Parameters for efficient PC

- The photon absorption $\alpha=1/l_a$, E_a, E_g : Search for new materials
- The diffusion length L:
  - In UV region: $l_a/L \sim 10^4$
  - For semiconductors: $l_a/L \sim 1$
- The escape probability P_E
  - normally it is ~ 0.5
  - For CsI : ~ 1
  - For metals: < 0.1
- Field enhancement, band bending
  - (110)-Cs-O: ΔE=0.23eV (GaAs, [2])
  - (110): ΔE=0.28eV
  - (111A)-Ga: ΔE=0.86eV, w = 155Å, P_E=0.21
  - (111B)-As: ΔE=0.1eV, w = 51Å, P_E=0.49-0.58
- NEA

[1] Spicer, slac-pub 6306 (1993)
[2] James et al, J. Appl. Phys. (1971)

New PC material: Li_2CsSb



- Band structure, absorption coefficient of Li_2CsSb were calculated via full potential linearized plane wave DFT-method [1].
- The direct vertical transitions generate photoelectrons.
- After relaxation to X, and it can only recombine through an indirect annihilation process with a valence band hole in Γ.
  - ΔE_{Γ}=1.05 eV, (red part)
  - ΔE_{X}=0.68 eV
  - No barrier for Γ→X
  - $\alpha = 35\ \mu m^{-1}$ – calculation (l_a=285Å)

$$\tau_{indirect} \sim 1-10\,ms, -\text{from texbook}$$

$$D \sim 2.5\times10^{-7}\, m^2/s\ [2],$$

$$L \approx \sqrt{D\tau_{indirect}} \approx 15\,\mu m\ (Li_2CsSb)$$

[1] Ettema, Appl. Phys. Lett. (2003)
[2] Niigaki, ibid (1999)

Diffusion and drift of carriers

Step2: Diffusion

$$-D_\Gamma \frac{\partial^2 n_\Gamma}{\partial z^2} + \frac{n_\Gamma}{\tau_{\Gamma V}} = \frac{n_X}{\tau_{X\Gamma}} + J(z),$$

$$-D_\Gamma \frac{\partial^2 n_X}{\partial z^2} + \frac{n_X}{\tau_{X\Gamma}} = J(z).$$

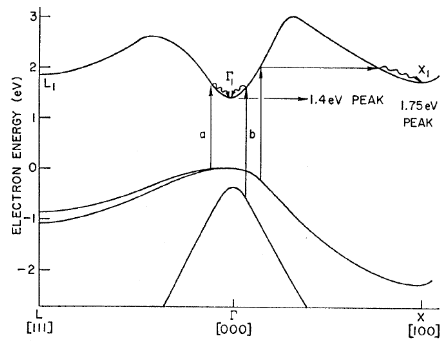
z – the distance to surface,

D - diffusion coefficients,

F_Γ, F_X – band coefficients,

$\tau_{\Gamma V}$ – recombination times,

$\tau_{X\Gamma}$ – relaxation times ,



$$Y_X = \frac{P_X F_X}{1+(1/\alpha L_X)}(1-R),$$

$$Y_\Gamma = (1-R)\frac{P_\Gamma}{1+(1/\alpha L_\Gamma)}\left\{F_\Gamma + \frac{F_X L_\Gamma}{\alpha L_X (L_\Gamma + L_X)\left[1+(1/\alpha L_X)\right]}.\right\}$$

$$L = \sqrt{D\tau} = \sqrt{\mu\tau\left(kT/e\right)}$$ – the diffusion length of electrons,

μ - mobility .

L depends on defects, dislocations, impurities.
GaAs – $L \approx$ 1.2-1.6 μm for N_{Zn}=(1-3)×10^{19} cm-3

Best GaAs PC [doped Ge]: L ~ 5-7 μm [1]

[1] Eden, Mall, Spicer, Phys. Rev. Lett. (1967)
[2] James, Moll, Phys. Rev. 183 (1969)

Drift, impact ionization

$$\vec{J}_e = eD_e \nabla N_e + e\mu_e N_e \vec{E},$$

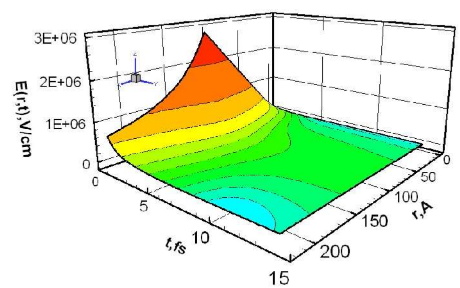
$$\vec{J}_h = -eD_h \nabla N_h + e\mu_h N_h \vec{E},$$

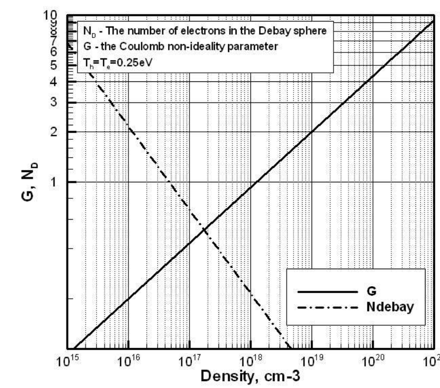
$$\frac{\partial N_e}{\partial t} = \frac{1}{q}\nabla J_e + G_{ii},$$

$$\frac{\partial N_h}{\partial t} = -\frac{1}{q}\nabla J_h + G_{ii},$$

$$G_{ii} = \alpha_n \frac{J_e}{e} + \left(\alpha_h \frac{J_h}{e} + \alpha_{ch}\frac{J_{ch}}{e}\right),$$

$$\nabla^2 \varphi = \frac{e}{\epsilon\epsilon_0}(N_e - N_h - N_{ch}).$$



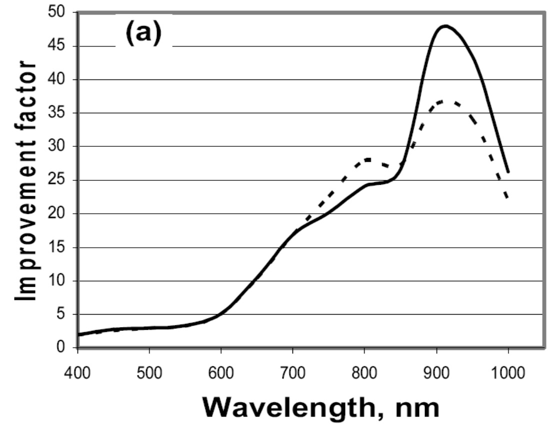


[Insepov et al, Phys. Rev. A (2008)]

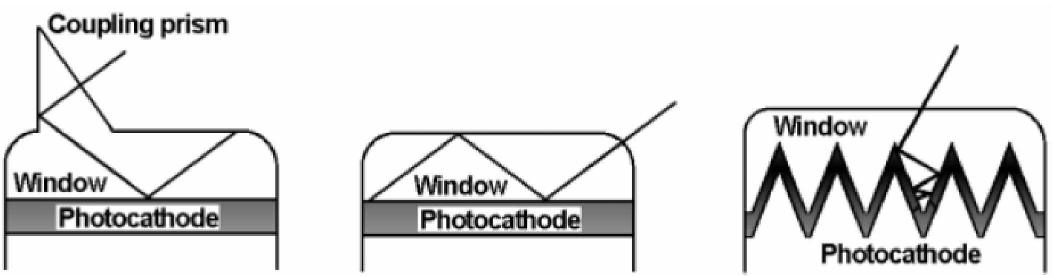
EEE: Anti-reflecting coatings

Tissue has a transparency window λ=700-900 nm that can be used for detection of breast cancer.

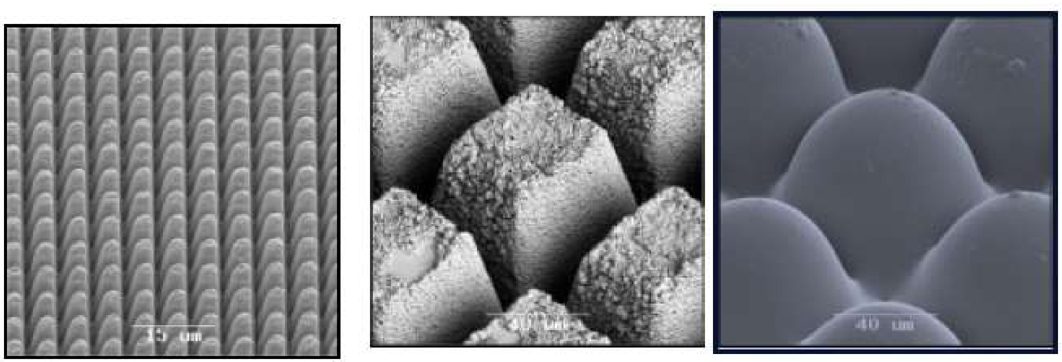
- **Improvements can be done due to strong dependence of the absorbance on the impact angle.**
- **Surface cone design improve absorption**
  - **Half angles between 45 and 9 degrees give increase ~ 2 at 400 nm;**
  - **8 times at 850 nm.**



45 times improvement factors for two S20 photocathode tubes resulting from waveguide coupling.



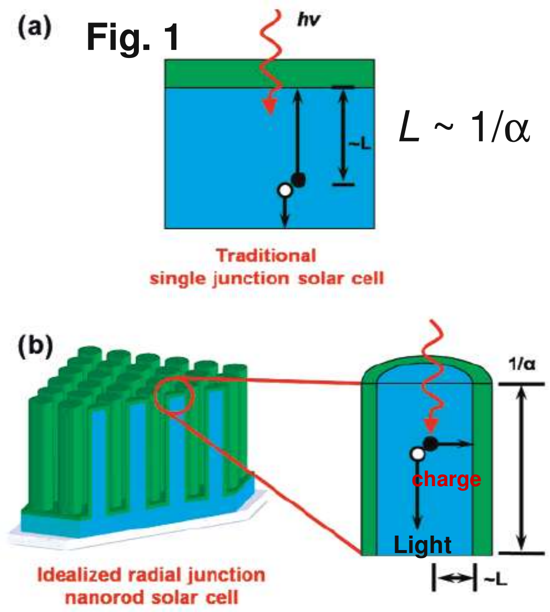
Waveguiding in the PMP window,



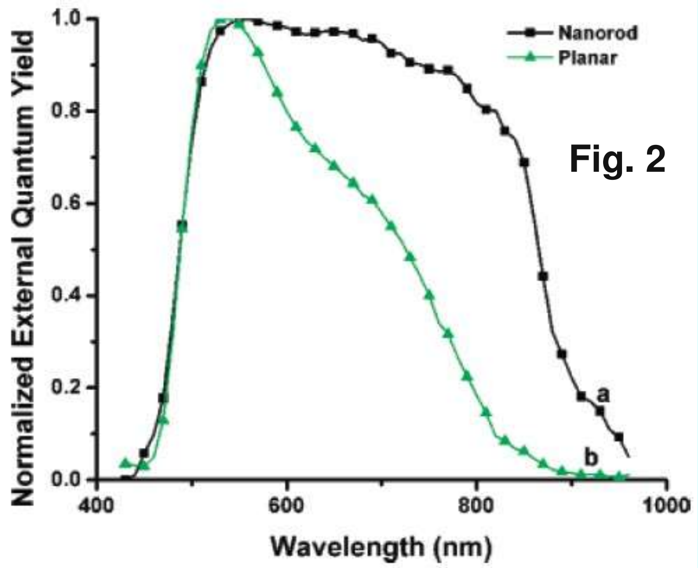
The full widths of the images are 60, 133 and 133 μm respectively.

[Downey et al, Phys. Stat. Sol. (2005)]

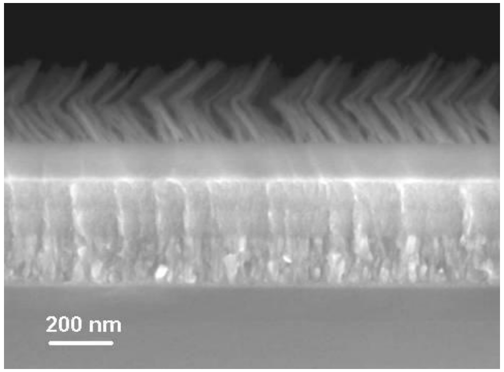
EEE: Nanorod Array layers



- Planar Cd-(Se, Te) PE vs nanorod array :
- Hi-aspect ratio nanorods could provide absorption along its axis, while collecting carriers radially (Fig. 1).
- The spectral response of the nanorod array PE exhibited better QE for collection of near-IR photons. (Fig. 2)

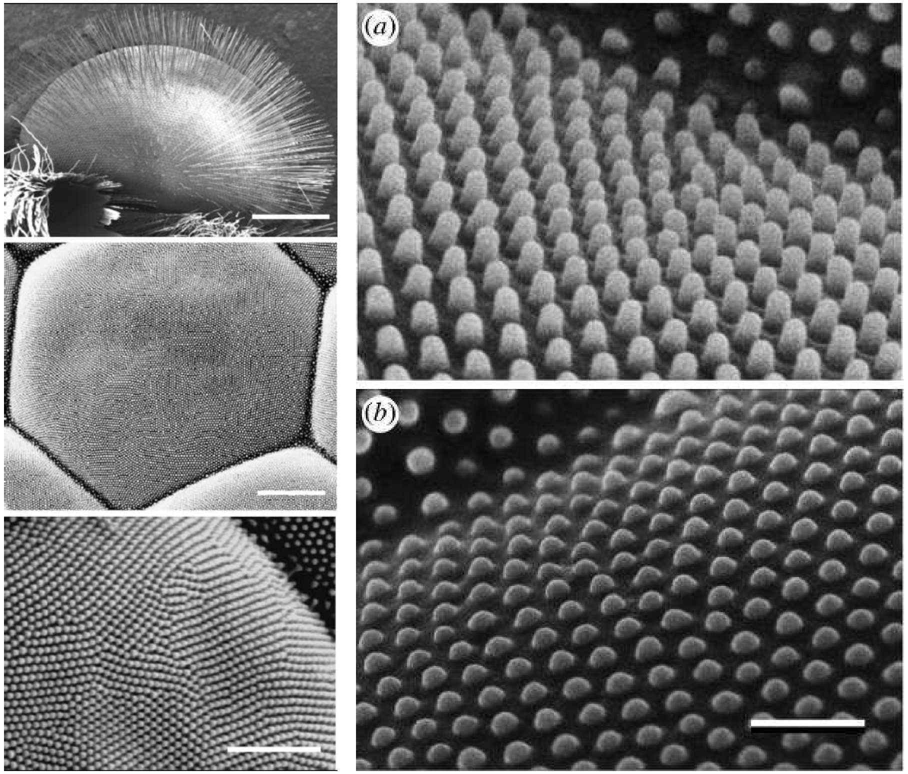


[Spurgeon et al, 2008]



- Solar cell's antireflective and all-angle coating built by seven layers, with a height of 50-100 nm, made up of SiO_2 and TiO_2 nanorods positioned at an oblique angle, absorbs 96.21% of the spectrum from UV to visible light and IR, from all angles. [Rensselaer Polytech Inst]

EEE: Moth-eye concept



- The surface of the moth eyes consists of an array of protuberances, termed corneal nipples.
- The nipples are arranged in domains with hexagonal packing, the distances are from 180 to 240 nm, the nipple heights varied between 0 and 230 nm.
- The nipples create an interface with a gradient refractive index between that of air and the lens material.
- The reflectance progressively diminished with increased nipple height. Nipples with a paraboloid shape and height 250 nm, touching each other at the base, virtually completely reduced the reflectance for normally incident light.

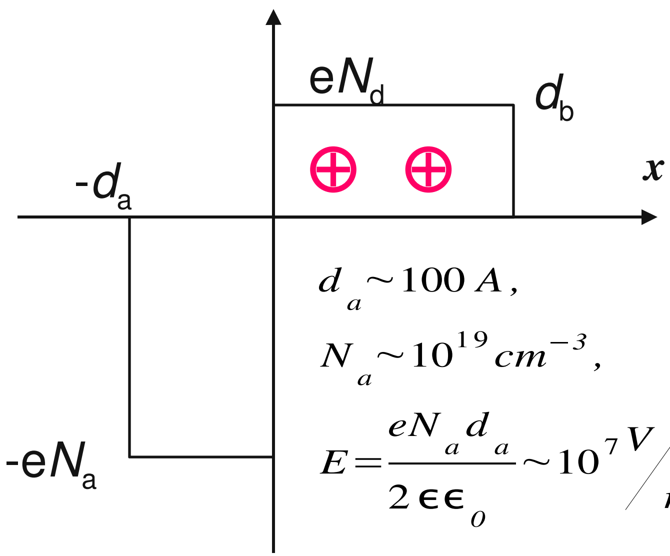
[Stavenga et al, Proc. R. Soc. B (2006)]

EEE: high electric field

- Poisson equation $$\frac{d^2V(x)}{dx^2} = -\frac{\rho(x)}{\epsilon},$$

$V(x)$ the potential, ρ the charge density, and ε the dielectric constant

Internal electric fields:



$$d_a \sim 100\,A,$$

$$N_a \sim 10^{19}\,cm^{-3},$$

$$E = \frac{eN_a d_a}{2\epsilon\epsilon_0} \sim 10^7\,V/m$$

External electric fields:

$E = 7.9\times10^5$ V/m [1]

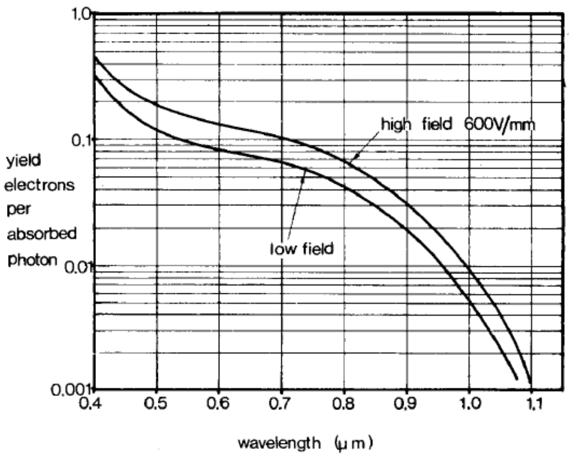
$E = 4\times10^6$ V/m [2]

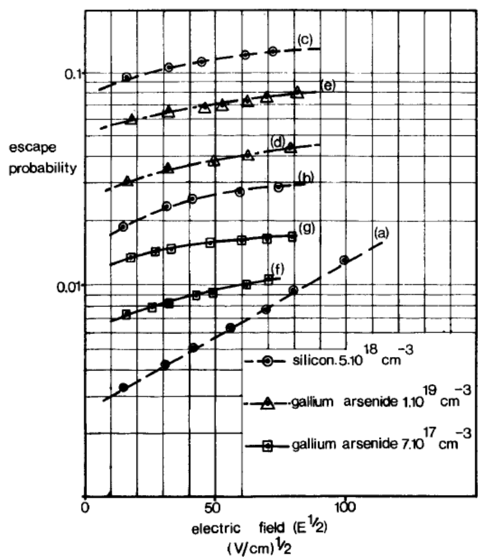
- E-field increases QE in IR
- Negative effect - dark current

[1] Crowe et al, Appl. Phys. Lett. (1967)
[2] Coleman, Appl. Opt. (1978)

Field Enhancement: Si, GaAs

- Electric field enhancement from NEA Si, GaAs was observed.
- *E* increases the *PE* and does not change the spectral response of the NEA surface.
- Surface potential lowering by the Schottky effect.





External field E reduces the work function via Schottky equation:

$$\Delta\varphi = \left(eE/4\pi\epsilon_0\right)^{1/2},$$

$$P = \exp\left[-(B-\Delta\varphi)/kT\right],$$

$$B - \text{the Schottky barrier}$$

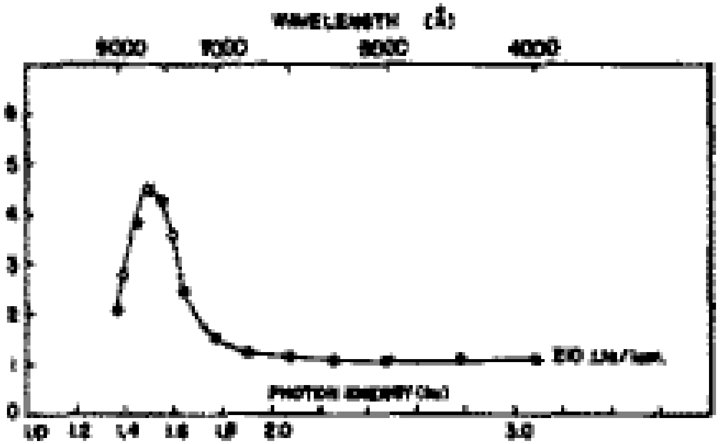
Band bending region:

w=200Å Si : 5×10^{18} cm^{-3}, 0.6 MV/m
w=240Å GaAs : 7×10^{17} cm^{-3}

[Howorth et al, Appl. Phys. Lett. 1973]

Field Enhancement: Alkali PC

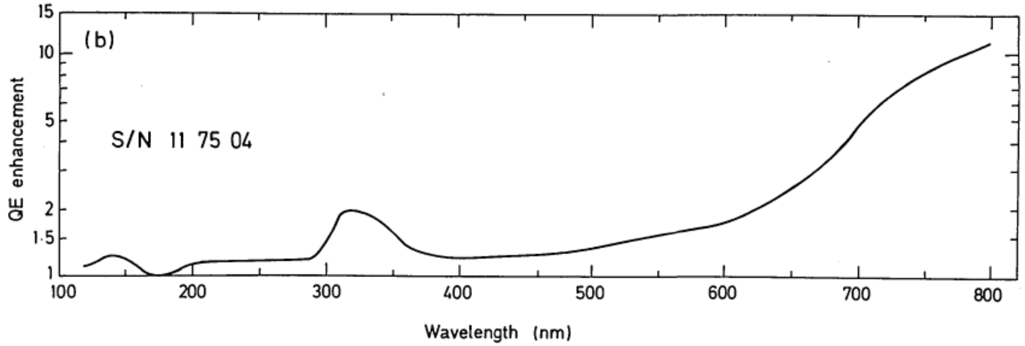
- **Trialkali (Cs)Na_2KSb – the electric field was applied and the magnitude of QE increase from 3 to 6 times was observed with a maximum in λ = 925 nm.**
- **This is due to a lowering of the potential barrier at the vacuum interface.**
- **Experiment [1]:**
  - **1) E = 1.3 ×10⁴ V/m**
  - **2) E = 7.9×10⁵ V/m**



Gain

Photon energy, eV

- Cs_2Te photocathode was studied
- Schottky lowering explained the results for enhancement factor ~ 5.
- E= 4 MV/m [2]



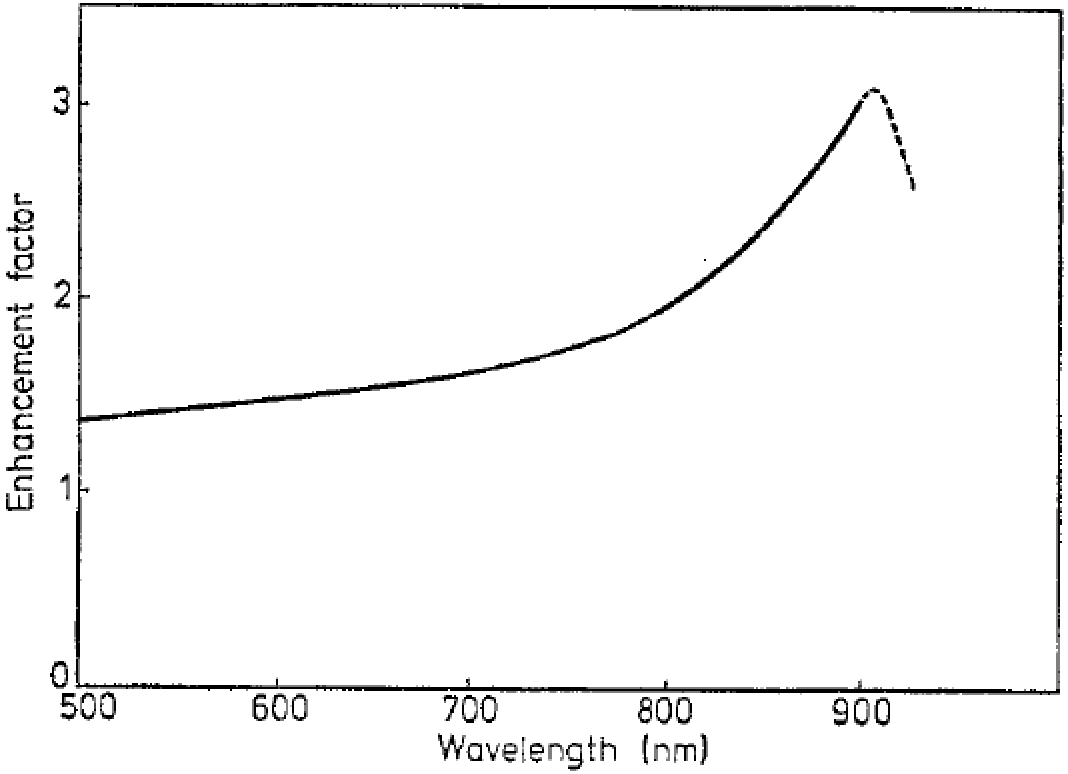
QE enhancement factor (ratio of high-field and low-field QE) as a function of wavelength.

[1] Crowe et al, Appl. Phys. Lett. (1967)

[2] Coleman, Appl. Opt. 1978

Field enhancement: Multi-alkali

- S20 and S25 photocathodes [Na2KSb(Cs)]
- E=3 MV/m



This is consistent with a Schottky explanation and the increase in photo yield with applied field was found to obey the Schottky equation.

[Holtom, J. Phys. D (1979)]

MC study - Motivation

- Nanostructured PC surface study – MC can recreate roughness, poly- or nano-crystalline, pillar, nipple, or other metamaterial types
- Arbitrary doping, impurity and electric field simulation
- Arbitrary barrier shapes and realistic escape probability
- Testing various electron scattering models
- All materials (metals, alkaline, semiconductors)

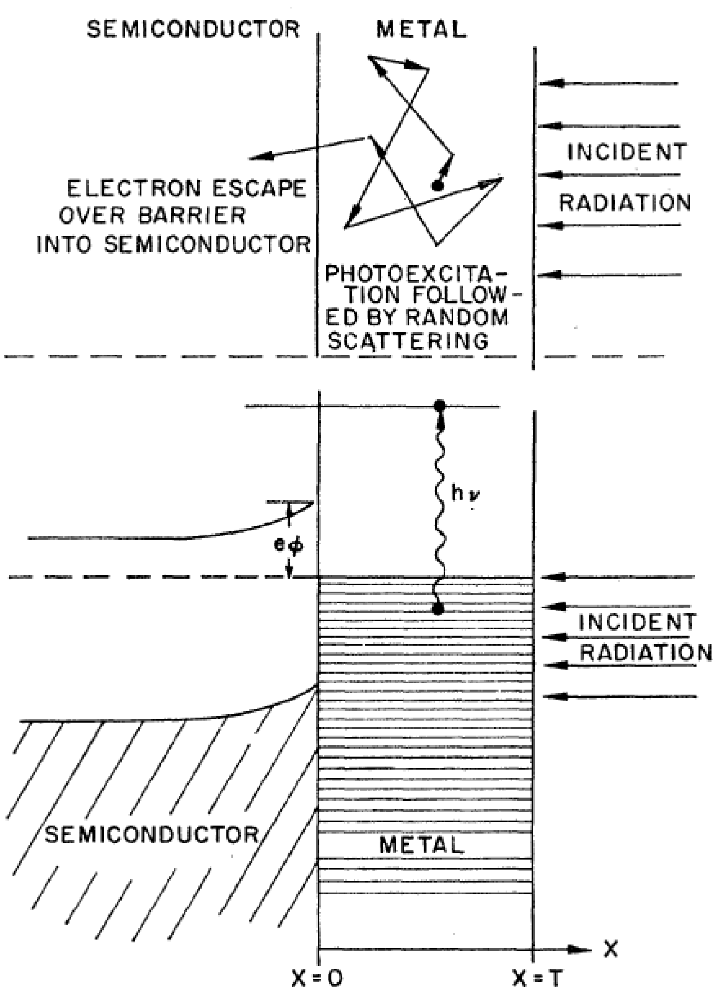
Transport of hot electrons in metals

- Monte Carlo method was applied to the problem of "hot" electron motion in metals;
- e-e scattering length, e-ph length and attenuation length was obtained.
- Specular and diffuse reflectance at the boundaries were simulated.
- Comparison with the theory for Au, Ag, Pd.

Probability of e^- excited at x reach the barrier with E

$$P(x) \sim e^{-x/L}$$

By calculating the number of hot electrons crossing the barrier, for different sample thickness, the attenuation length *L* can be obtained.



[Stuart, Wooten, Spicer, Phys.Rev.1964]

Physical model and parameters

- (1) Photoexcitation of carriers – $I(x)=I_0 \exp(-\alpha x)$
  - exponential law with $\alpha=7.7\times10^5$ cm^{-1} (typical for Au) – can be adjusted for different materials;
  - Electrons are isotropically distributed in all directions
- (2) Scattering of excited carriers;
  - *e*-*e*, *e*-*ph* scattering $E_{ph} \approx k\theta$ (θ - Debye temperature)
  - e-impurity/defect scattering (Brooks-Herring law)
- (3) Escape of carriers over the barrier.
  - *E*lastic scattering interface (no energy change)
  - *L*ambert law in direction

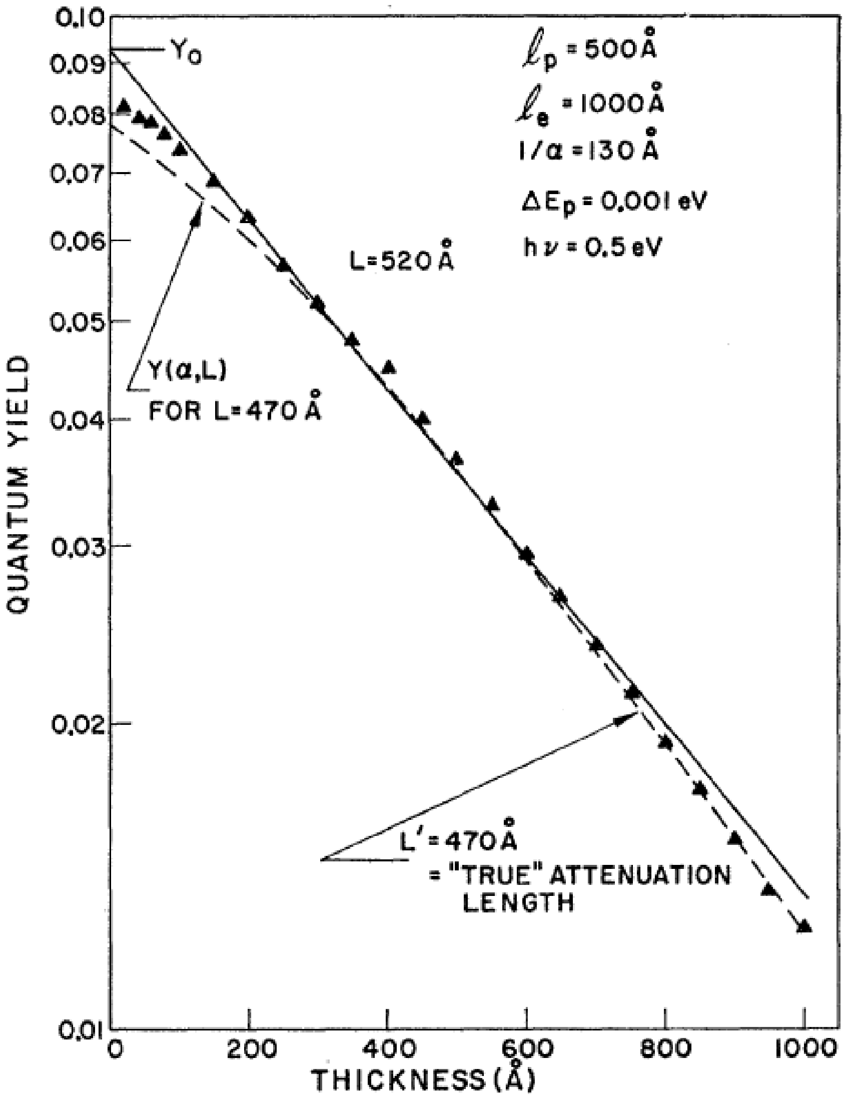
[Stuart, Wooten, Spicer, Phys.Rev.1964]

Algorithm of MC program

- Initial source of electrons $S(X,E)$ is created
  - $E = E_F + h\nu-(h\nu-e\phi)c_1$, $0\leq c_1\leq 1$
  - Exp attenuation: $X=T+(1/\alpha)\ln\{1-c_2[1-\exp(-\alpha T)\}$,
    - *T – sample thickness,* $0\leq c_2\leq 1$
  - Collision simulation: $l_T=l_e l_p/(l_e+l_p)$ – the mean free path
  - Exp law: $l=l_T\,|\ln c_3|$, $0\leq c_3\leq 1$
  - Angle to normal: $\cos\theta = 2c_4 - 1$, $0\leq c_4\leq 1$ (all $d\Omega$ are eq. probable)
  - c5 < l_T/l_e, $0\leq c_5\leq 1$ – choice for kind of collision
- New electron, new trajectory, similar to previous
  - The process continued until the electron $E < E_0$
- 10,000 trajectories computed for each sample; (statistics)
- 200, 400, 600, 800 , and 1000Å samples were simulated
- Specular reflection from the vacuum boundary

[Stuart, Wooten, Spicer, Phys.Rev.1964]

MC simulation results



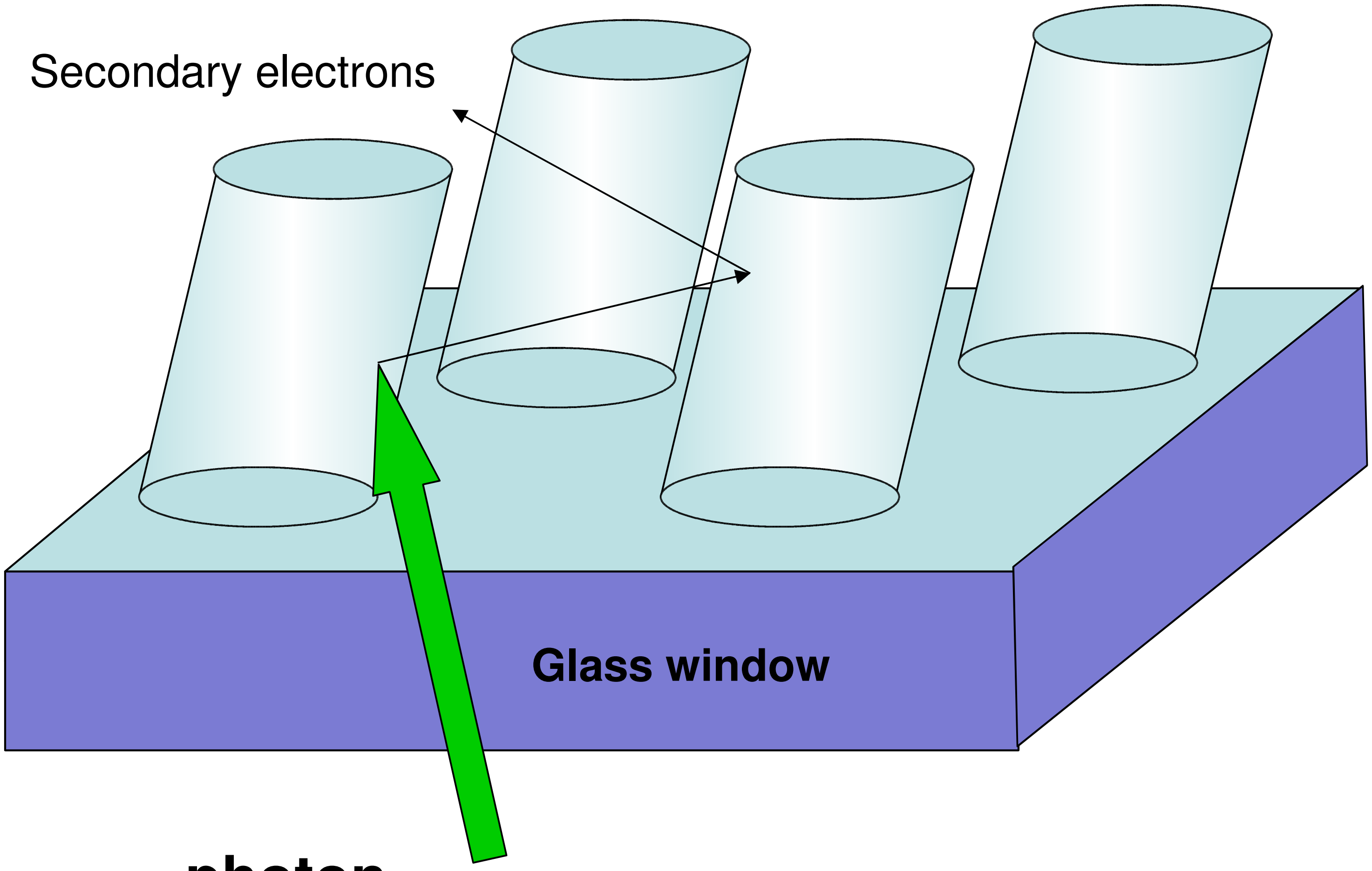
- Quantum Yield vs thickness
- Comparison of MC *e-e* mean free path l_e with experimental [1,2] and theory-I [2] and theory –II [2] with d-electrons.

[1] Spitzer et al, Phys. Rev. (1962)
[2] Quinn, Phys. Rev. (1962)

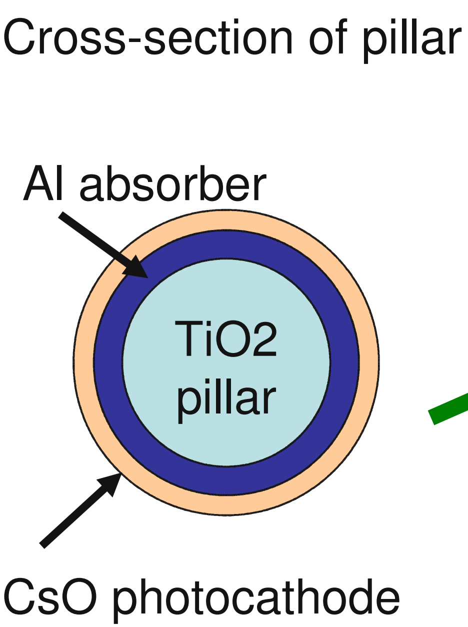
Quantum yield vs thickness for specular reflectance. Each data point – 10^5 trajectories.

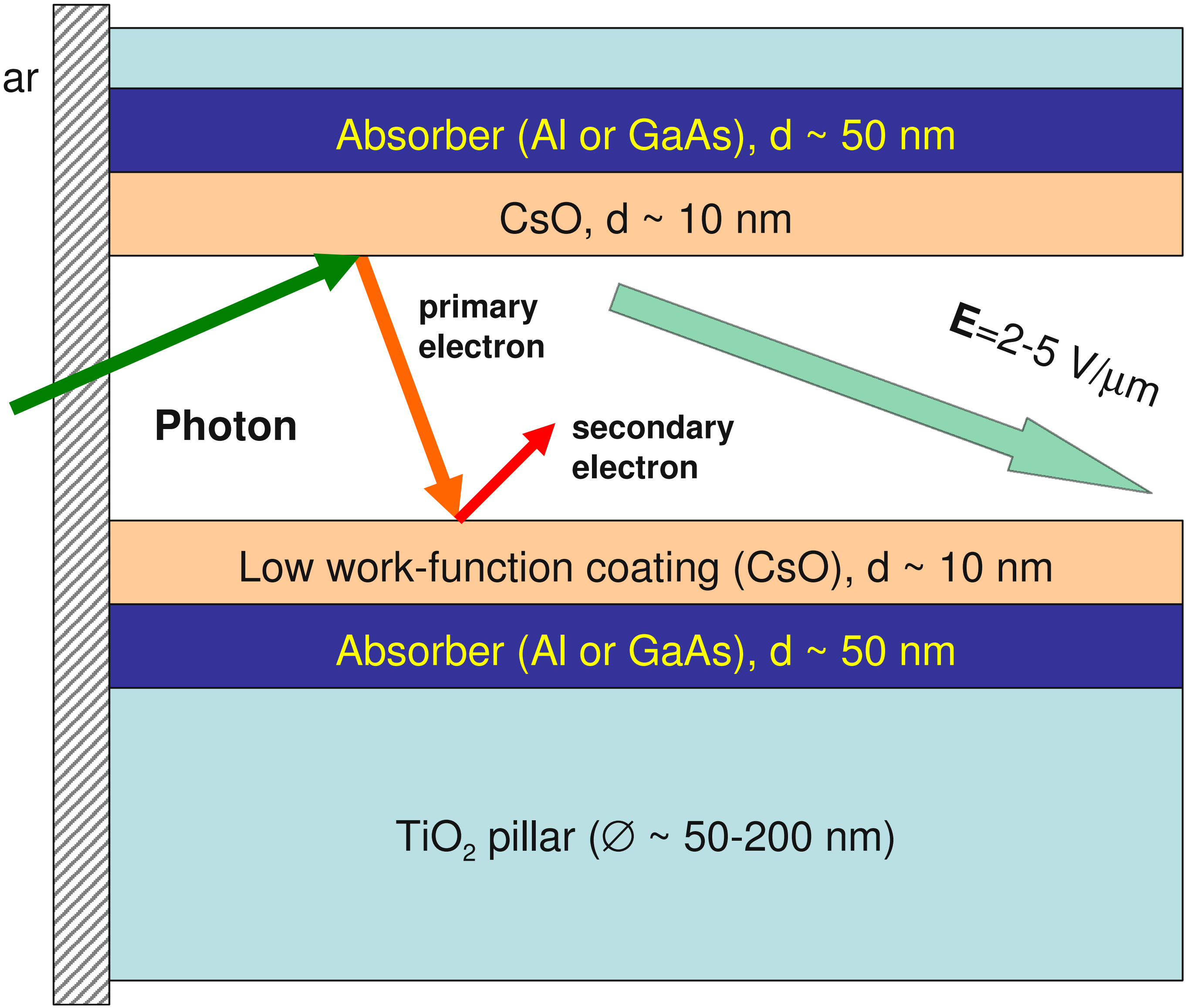
[Stuart, Wooten, Spicer, Phys.Rev.1964]

Pillar structure



Pillar simulation





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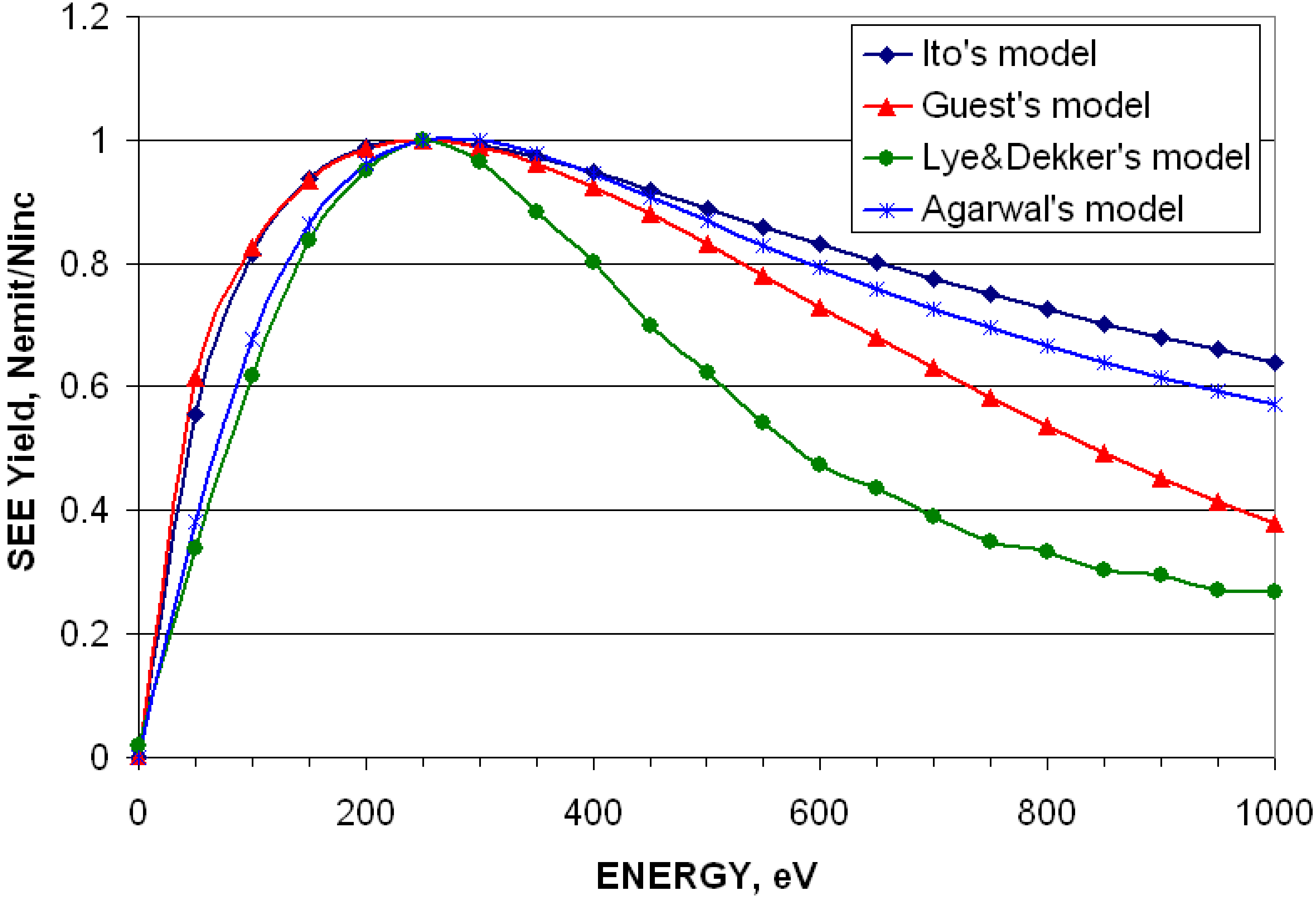
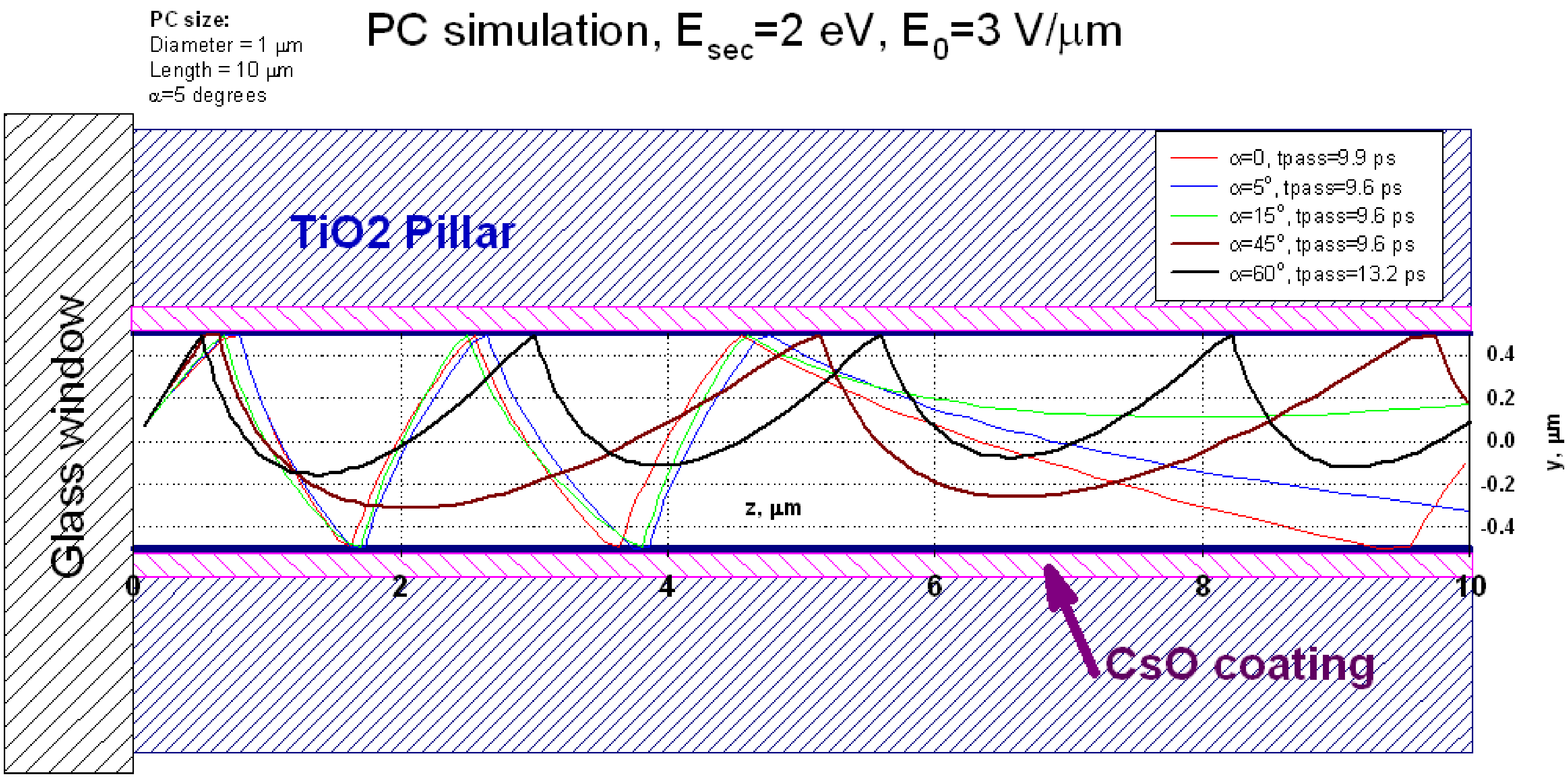
Comparison of SEE- models

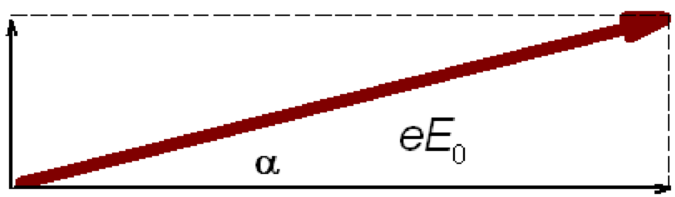


PC simulation parameters

- Photon energy : 1.5-6.2 eV (800nm-200nm) **1.4eV**
- Kinetic energy of SEE: **0.5-5 eV**
- Electric field ~ 2-5 V/µm accelerates *PE* to **2.5-10 eV**
- Electric field geometry is being determined by the resistivity of PC: **100 MΩ (Comsol)**

Pillar Simulation Geometry





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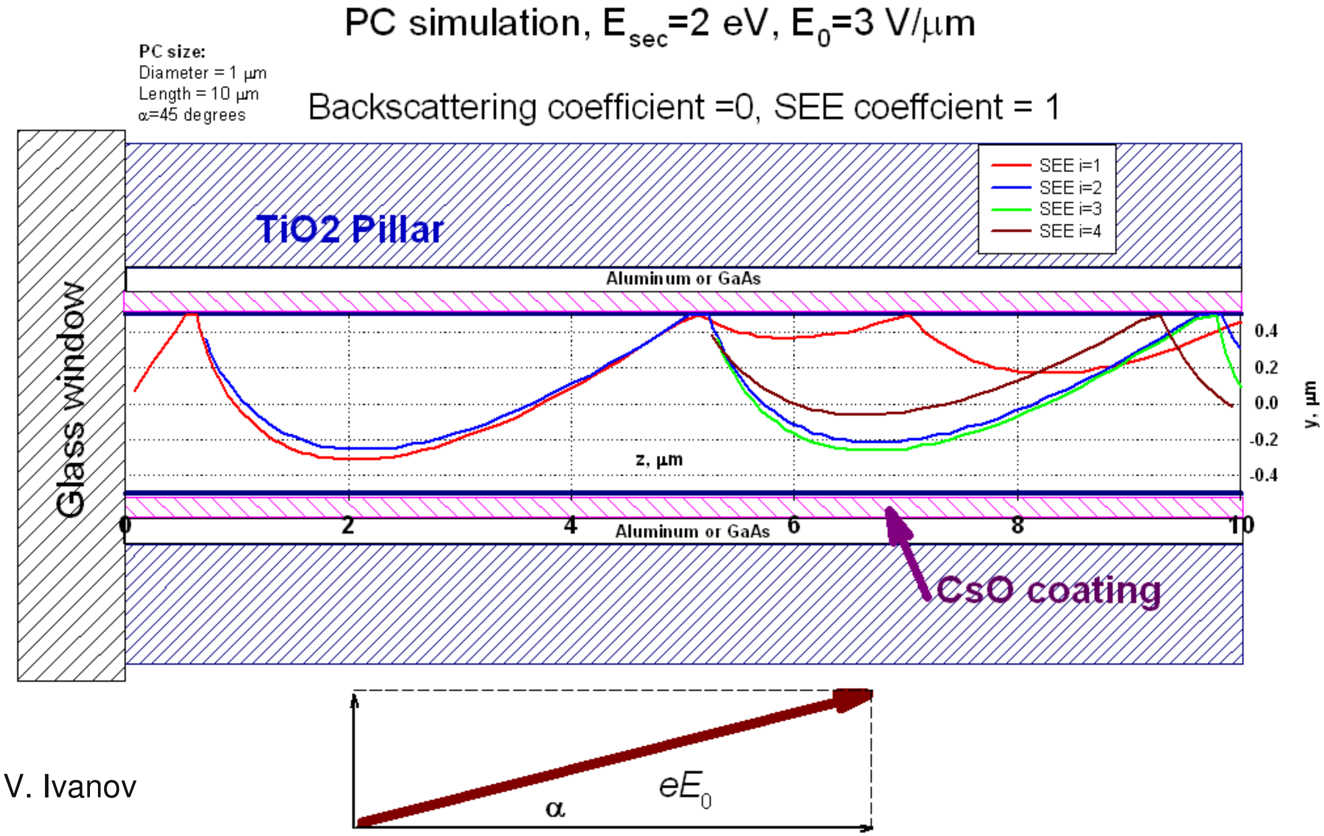
Angular dependence of Gain, TTS

- At 45°, the electron trajectories are switching from "crossing" to "hopping" mode. This reduces the TTS value.
- At large angles, the number of collisions becomes higher and that reduces the Gain: SEE ≤ 1 at small energies.



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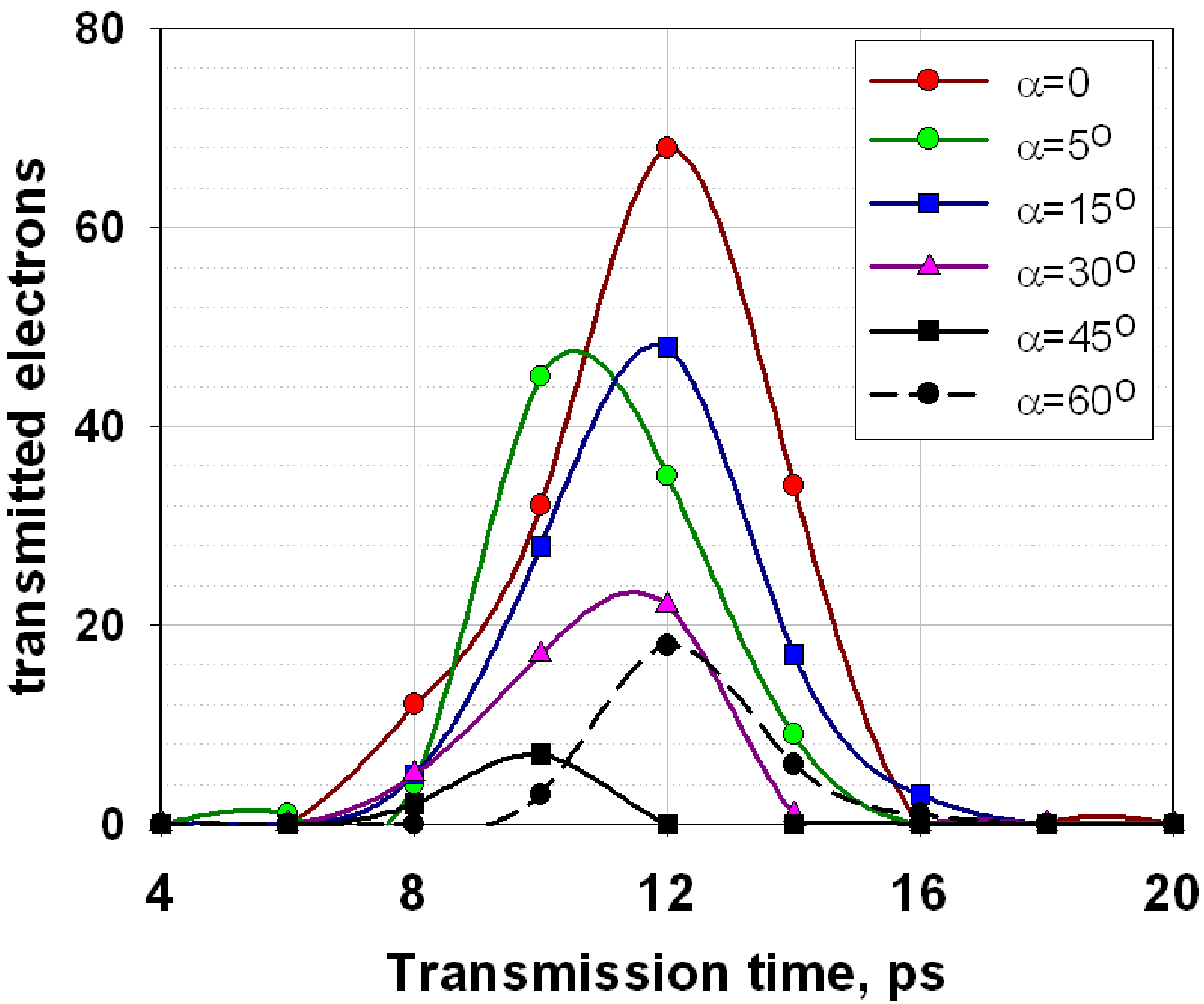
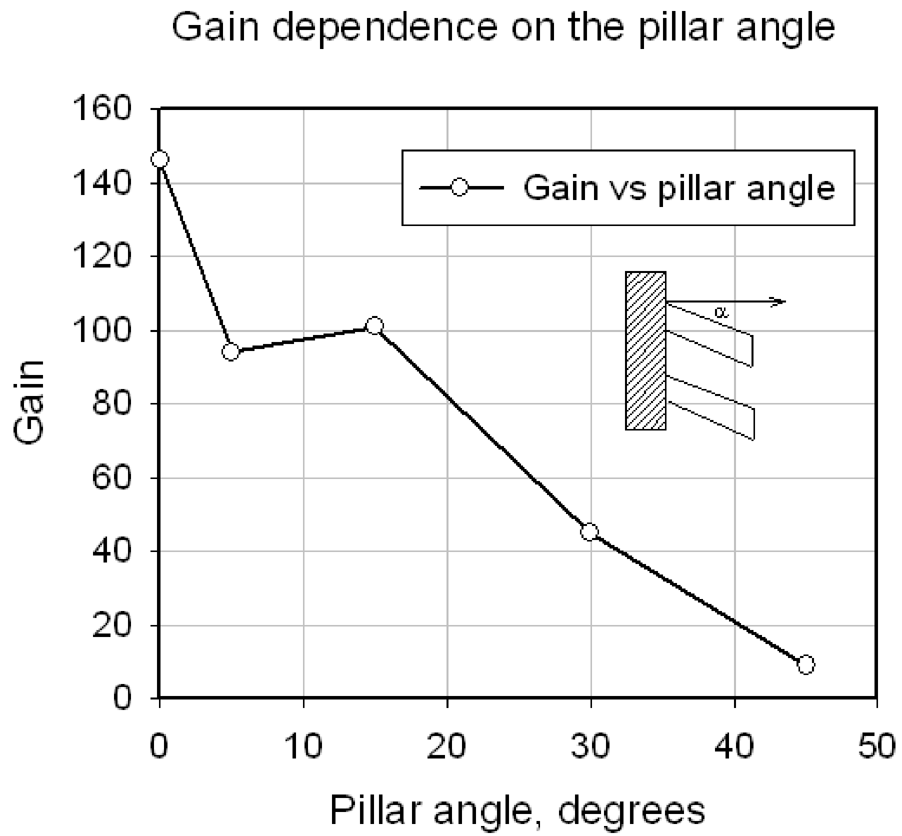
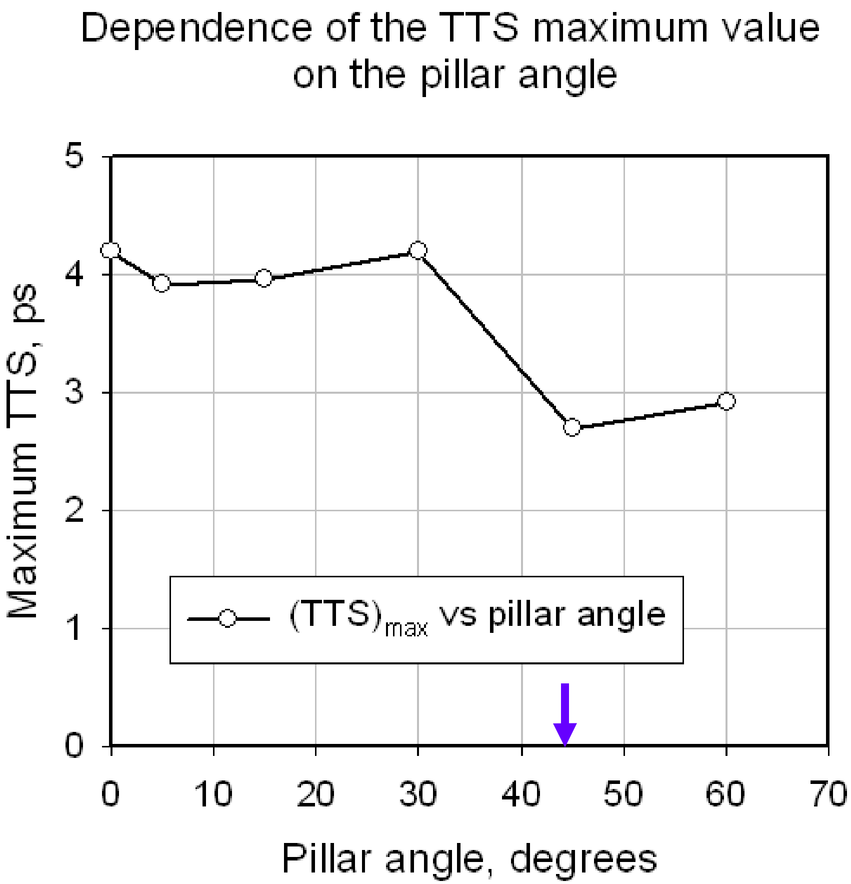
TTS for normal and inclined pillars



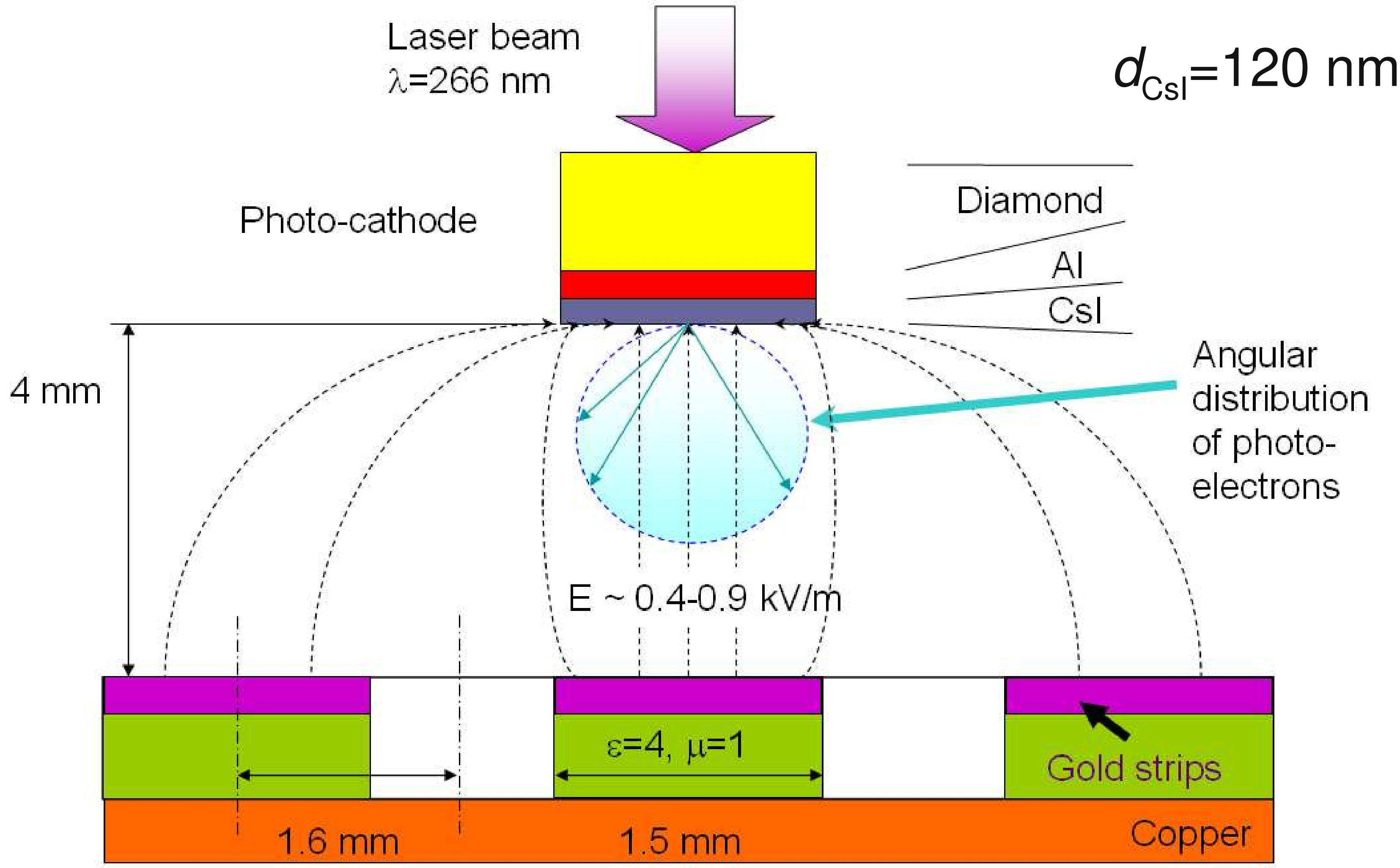
Gain and TTS vs pillar angle





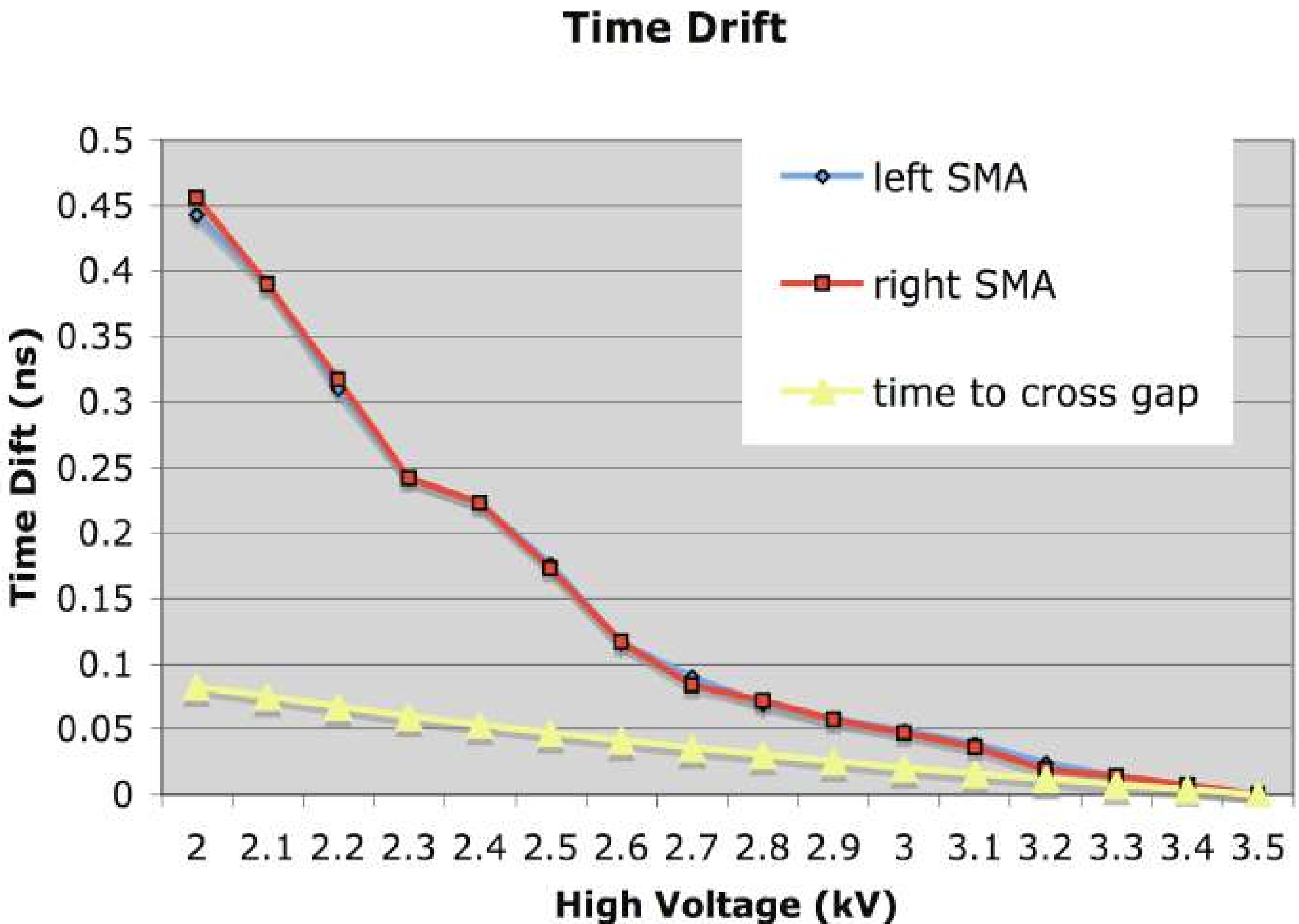
Switching to hopping mode

Time drift simulation for APS setup



[Experiment: M. Wetstein (ANL)]

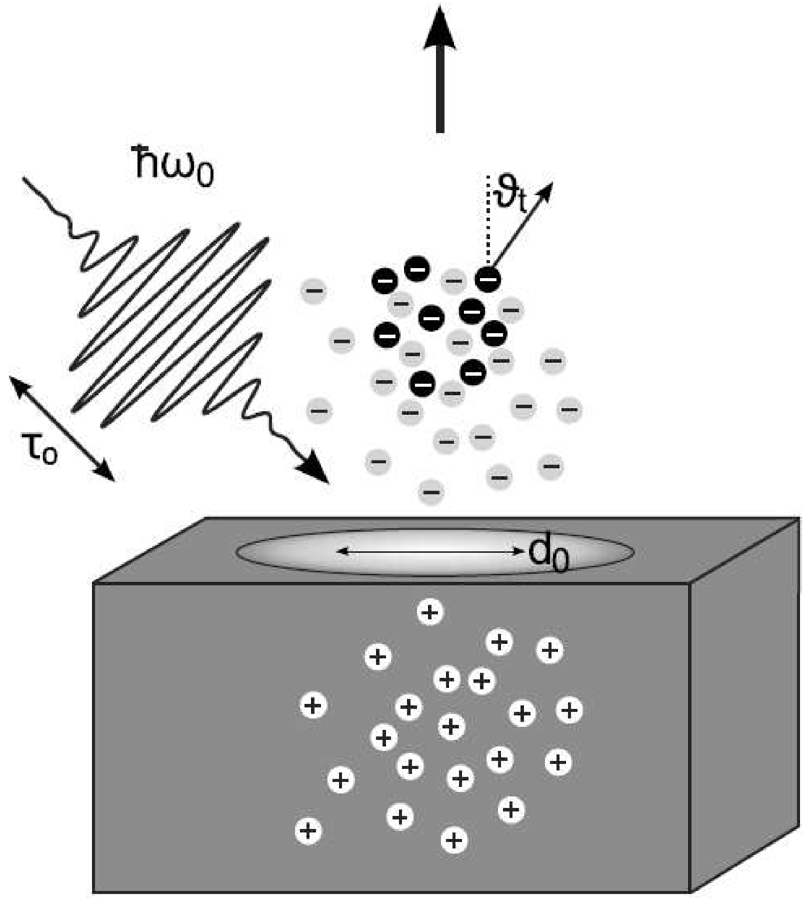
APS experiments



[Experiment: M. Wetstein (ANL)]

Space-Charge Effect in PC

- The higher the number of cloud electrons per pulse N_c, the stronger is the space-charge effect.
- Non-negligible space-charge effects occur already at rather low values of N_c of about 1000*e* per pulse [1].
- APS experiments have estimated N_c per pulse >> 1000e [2].



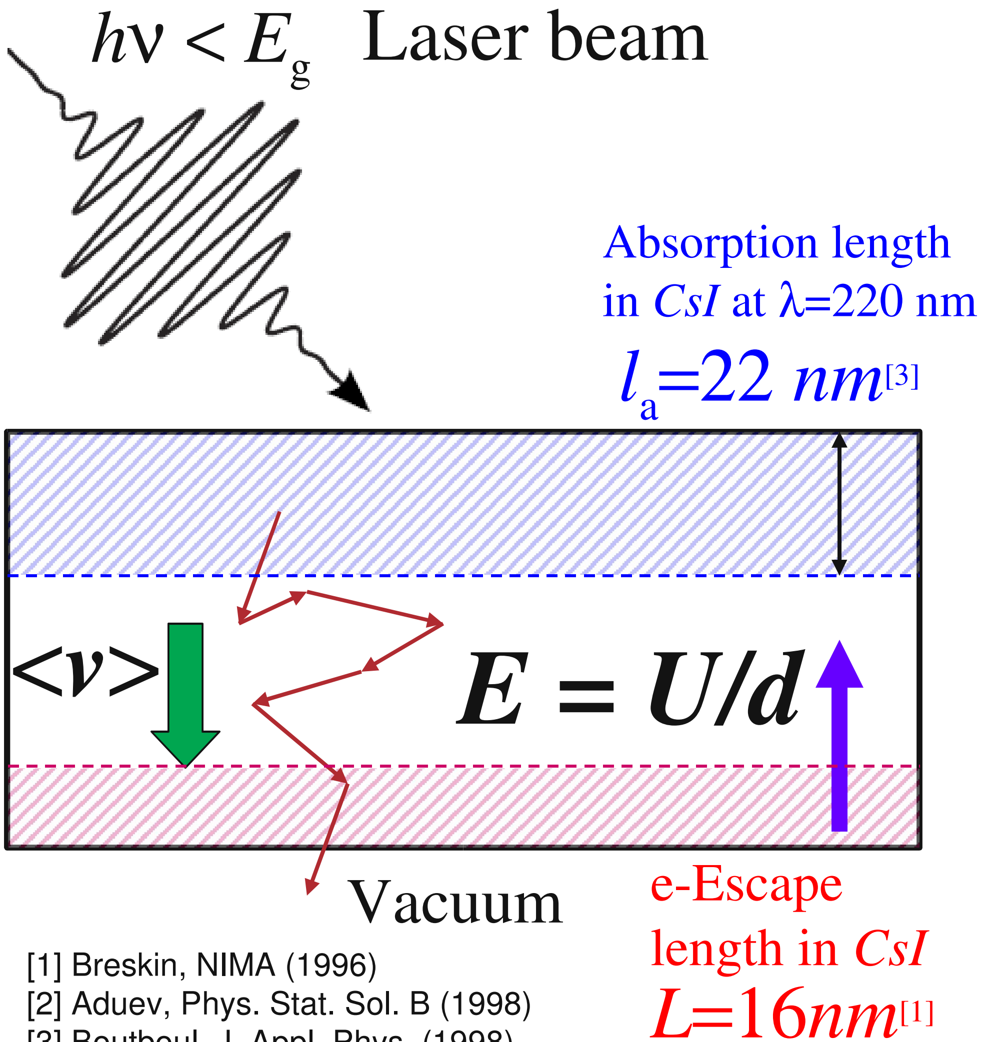
APS experimental data

$Q = I_{max} * \tau_0 = 140\mu A * 80 \text{ ps} = 1.12 \times 10^{-14}$ C

$N_c = 7 \times 10^4$ electrons per pulse [2]

[1] J. Zhou et al, J. El. Spec. Rel. Phen. 2005.
[2] Matt Wetstein, ANL

Drift-diffusion model of electrons



Drift+Diffusion model

Langevin equation

$$\dot{\vec{v}}_i(t) = -\nabla U(\vec{r}_i)/m_e - \gamma \cdot \vec{v}_i(t) + \vec{R}_i/m_e,$$

$\vec{E} = -\nabla U(\vec{r}_i)$ − electric field,

γ − friction coefficient,

$\vec{R}_i$ − random force,

$$\langle \vec{R}(t) \rangle = 0,$$

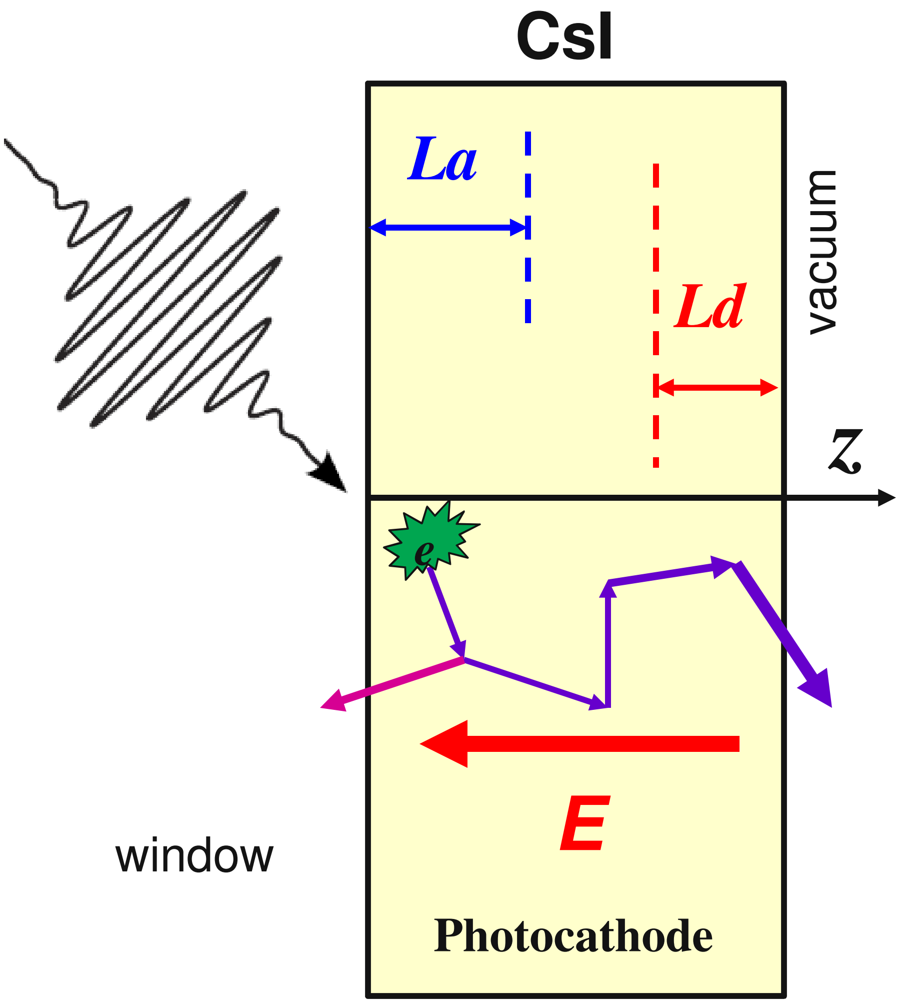
$$\langle \vec{R}(t)\vec{R}(t') \rangle = 2\frac{\gamma k_B T}{m_e}\delta(t-t'),$$

$\gamma = e / \mu_e m_e$, μ_e − mobility

$$\mu_e = 8 \times 10^{-4}\, m^2/V \cdot s\,[2]$$

[1] Breskin, NIMA (1996)
[2] Aduev, Phys. Stat. Sol. B (1998)
[3] Boutboul, J. Appl. Phys. (1998)

MC model of random walk



Ld – e-e + e-ph + e-defects

$L_a = 22\ nm$, absorption length [1],

$\alpha = 1/L \approx 0.03\ nm^{-1}$,

$L_D = \sqrt{D\tau_e}$, electron diffusivity,

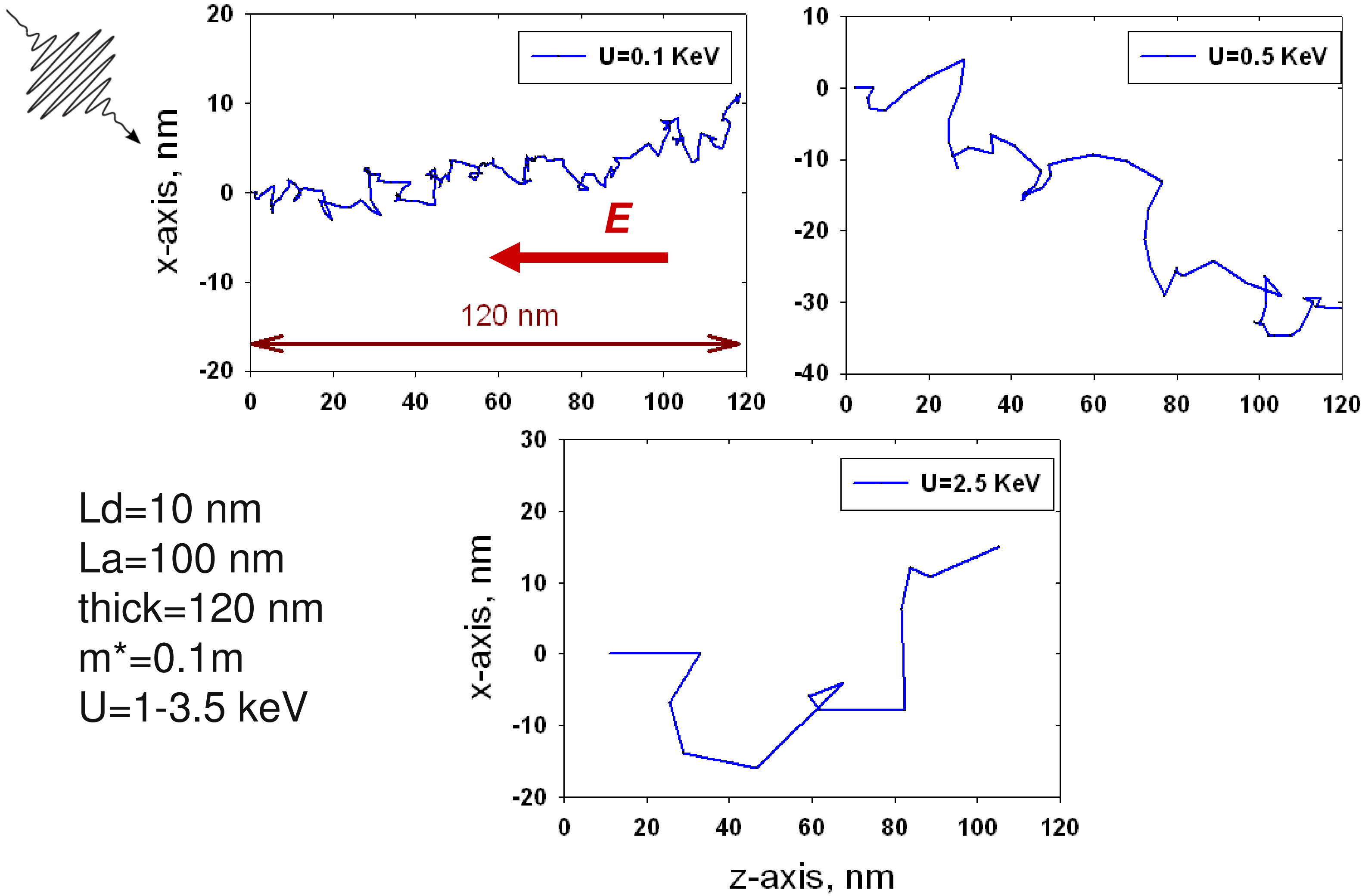
$L_D \sim 16\ nm$ [2],

$U = 1 - 3.5\ keV$

$Y \approx (1\text{-}R) \times QE$,

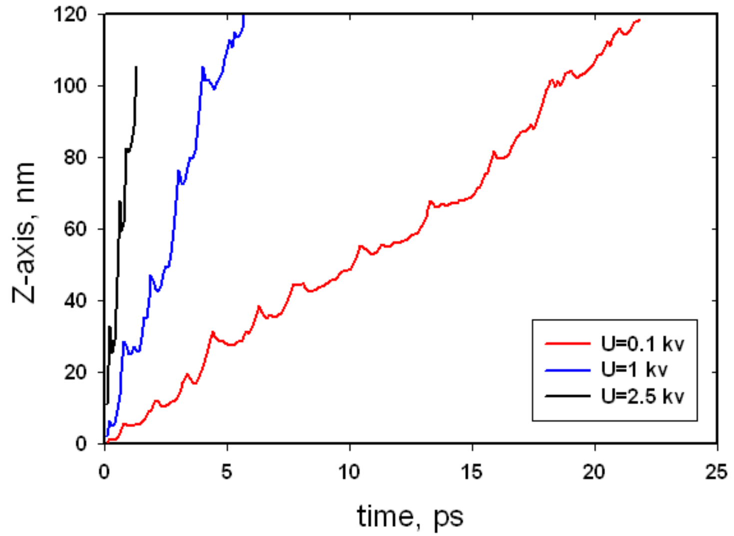
[1] Boutboul, J. Appl. Phys. (1998)
[2] Breskin, NIMA (1996)

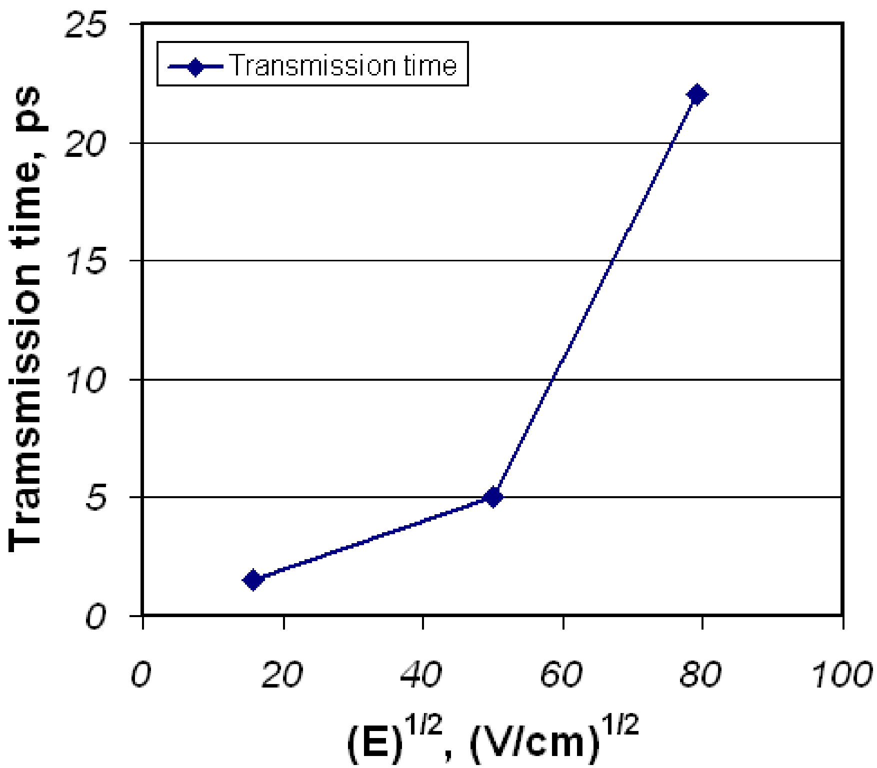
Random walk + drift

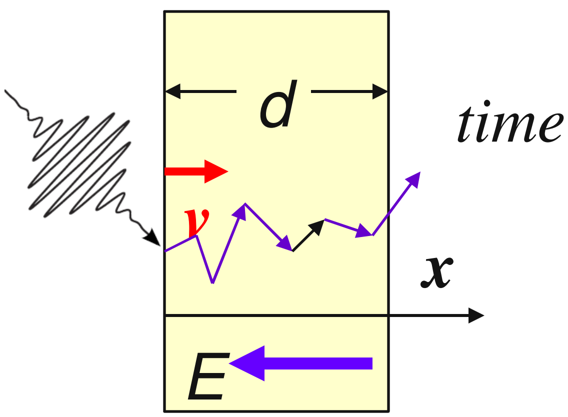


Ld=10 nm
La=100 nm
thick=120 nm
m*=0.1m
U=1-3.5 keV

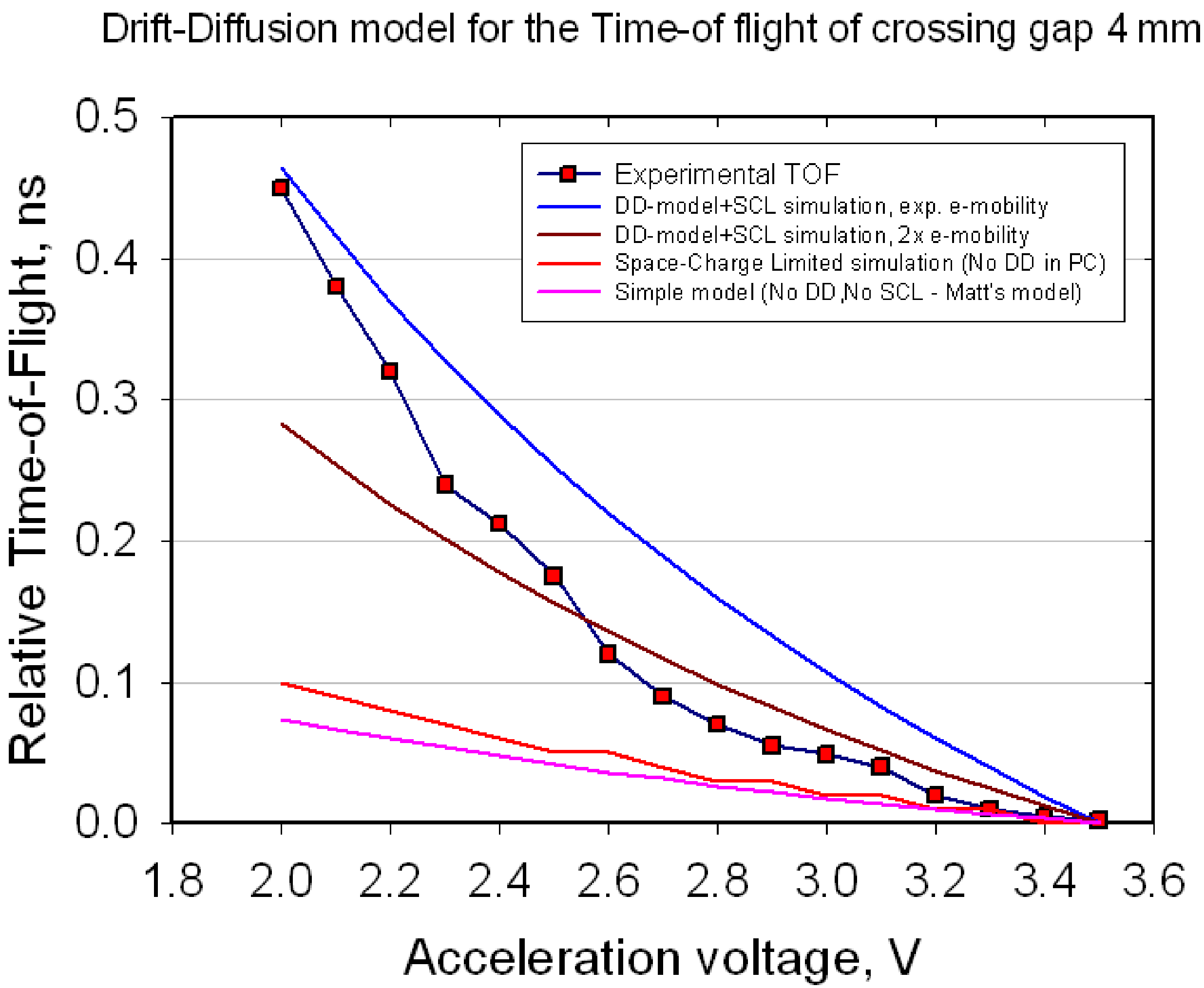
Field dependence of TT







Time to Drift in vacuum



Summary

- Electron emission can be enhanced by various methods: nanostructured interfaces, doping and applying electric fields, multilayer coatings, NEA
- Theory and simulation methods are not yet capable of treating complex PC tasks, such as surface roughness, nano-structured, real material properties, hot carriers and plasma effects, high electric fields in PC, **aging**
- Nano-pillar PC structure was simulated and optimized
- MC method is being developed to evaluate surface roughness, plasma and hot electrons effects, complex materials, high electric fields and photon fluxes.

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