Charge carrier mobility evaluation in Silicon Microstrips detectors exploiting photoconductivity phenomena

Algirdas Mekys (Vilnius University),
Michael Moll (CERN),
Darius Jurciukonis (Vilnius University),
Paula Baltaseviciute (Vilnius University),
Juozas Vidmantis Vaitkus (Vilnius University)

The 43rd RD50 Workshop (CERN, Zurich 2023-11-28 / 12-01)

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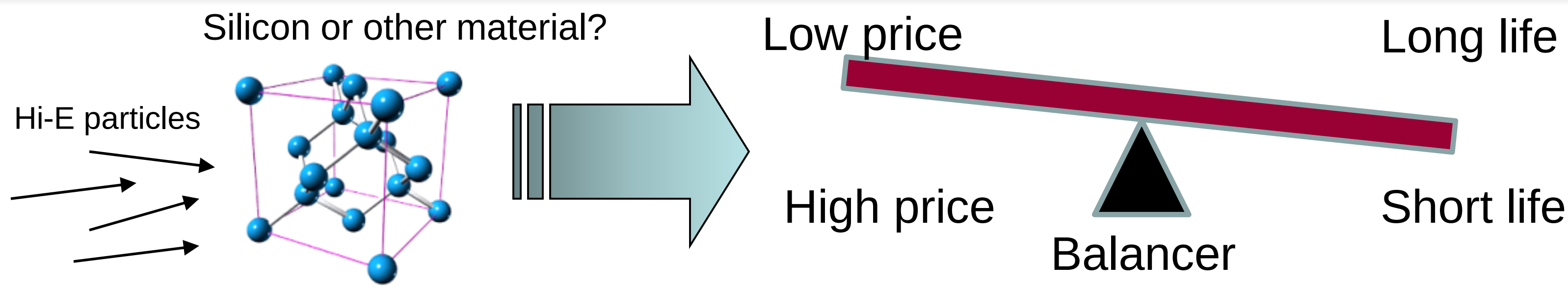
Motivation

- The demand of radiation detectors!
- Which results in available material sorting, analysis and engineering for a better detector fabrication

This work was performed as a part of CERN RD50 collaboration and the Vilnius University contribution was supported by the Lithuanian Academy of Sciences CERN-RD50 grants.



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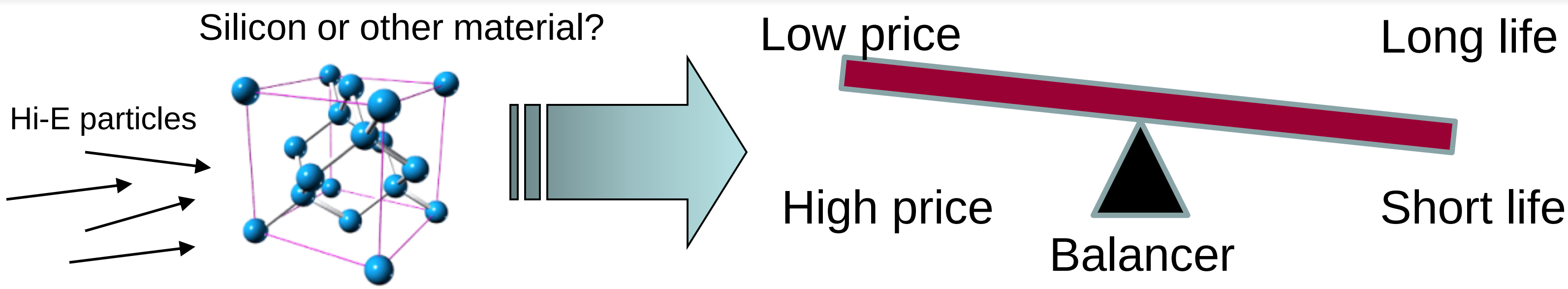

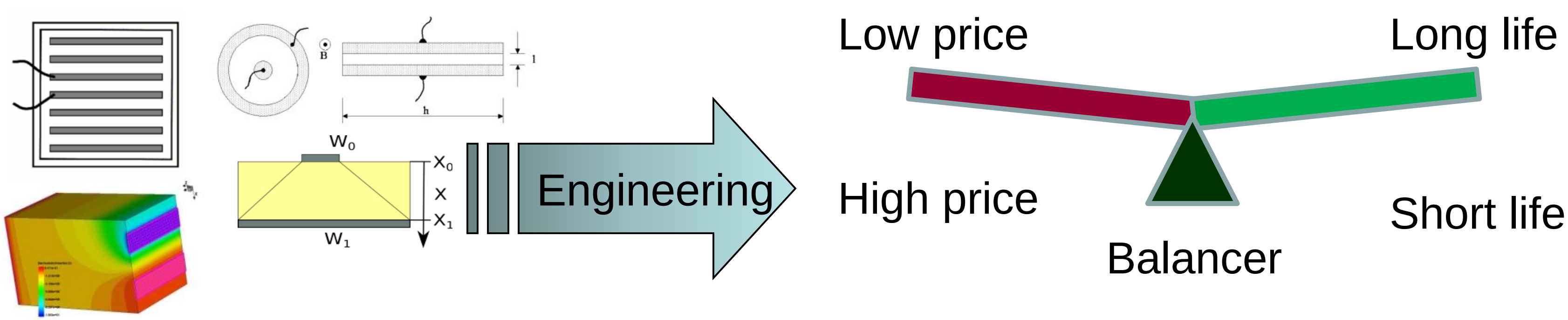

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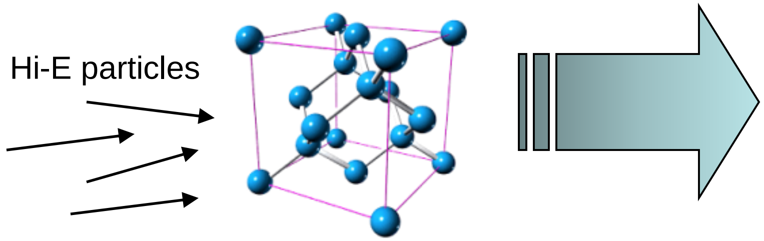
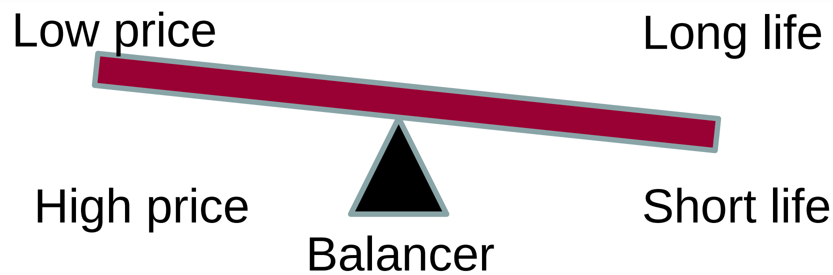
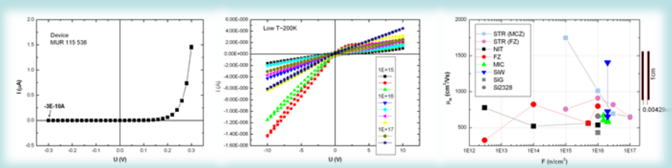
Silicon or other material?





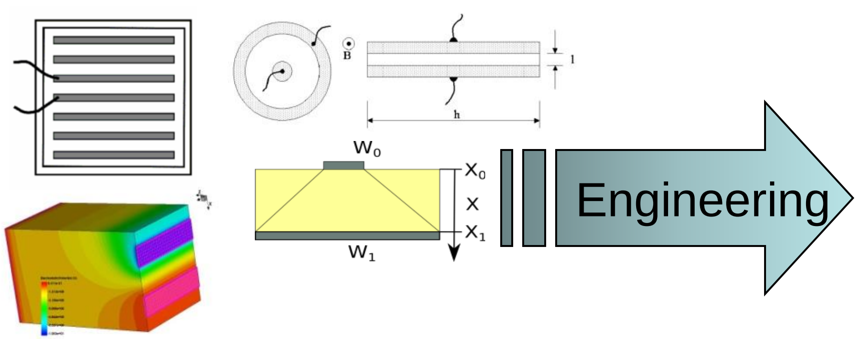
Understanding

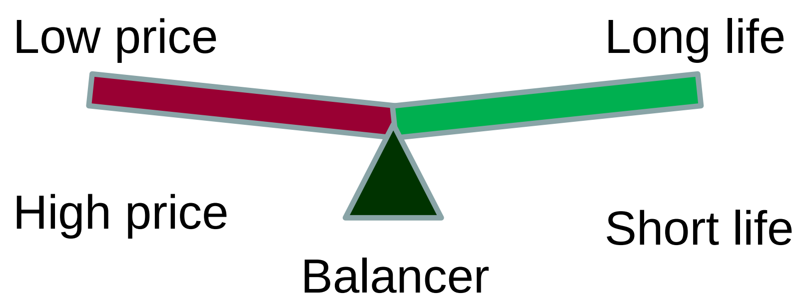


$$\mu \approx \frac{8}{3}\left(\frac{\hbar}{k_B T}\right)\left(\frac{e}{m^*}\right)\left(\frac{a_0}{d_0}\right)^2\left(\frac{N_C}{n_0}\right)$$

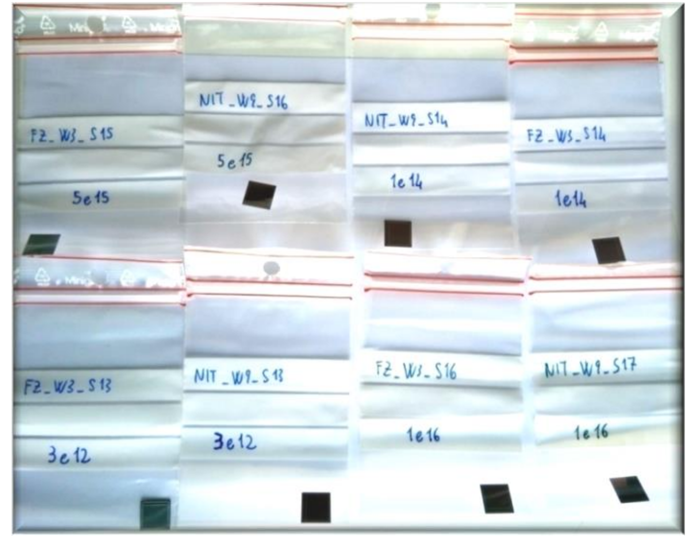
$$\mu = \frac{1}{B}\sqrt{\frac{R_B}{R} - 1} \qquad \mu_{ph} = aT^{-3/2}$$

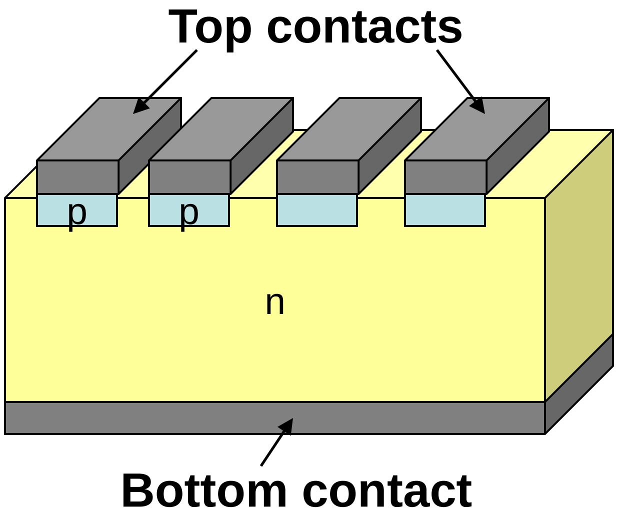
$$\mu_{ion} = b\left(T, N, n\right)T^{+3/2}$$





The samples

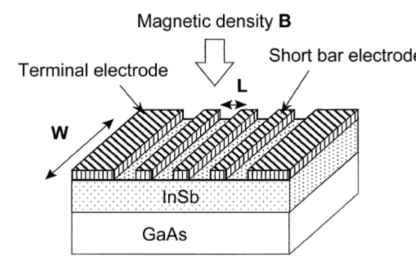




n in p
or
p in n

Irradiated with 1MeV neutrons
Most recent batch:
Fluence from 10^{15} to 10^{17} n/cm^2

Similar to
B sensor



Ichiro Shibasaki and Naohiro Kuze, Molecular Beam Epitaxy. 2013

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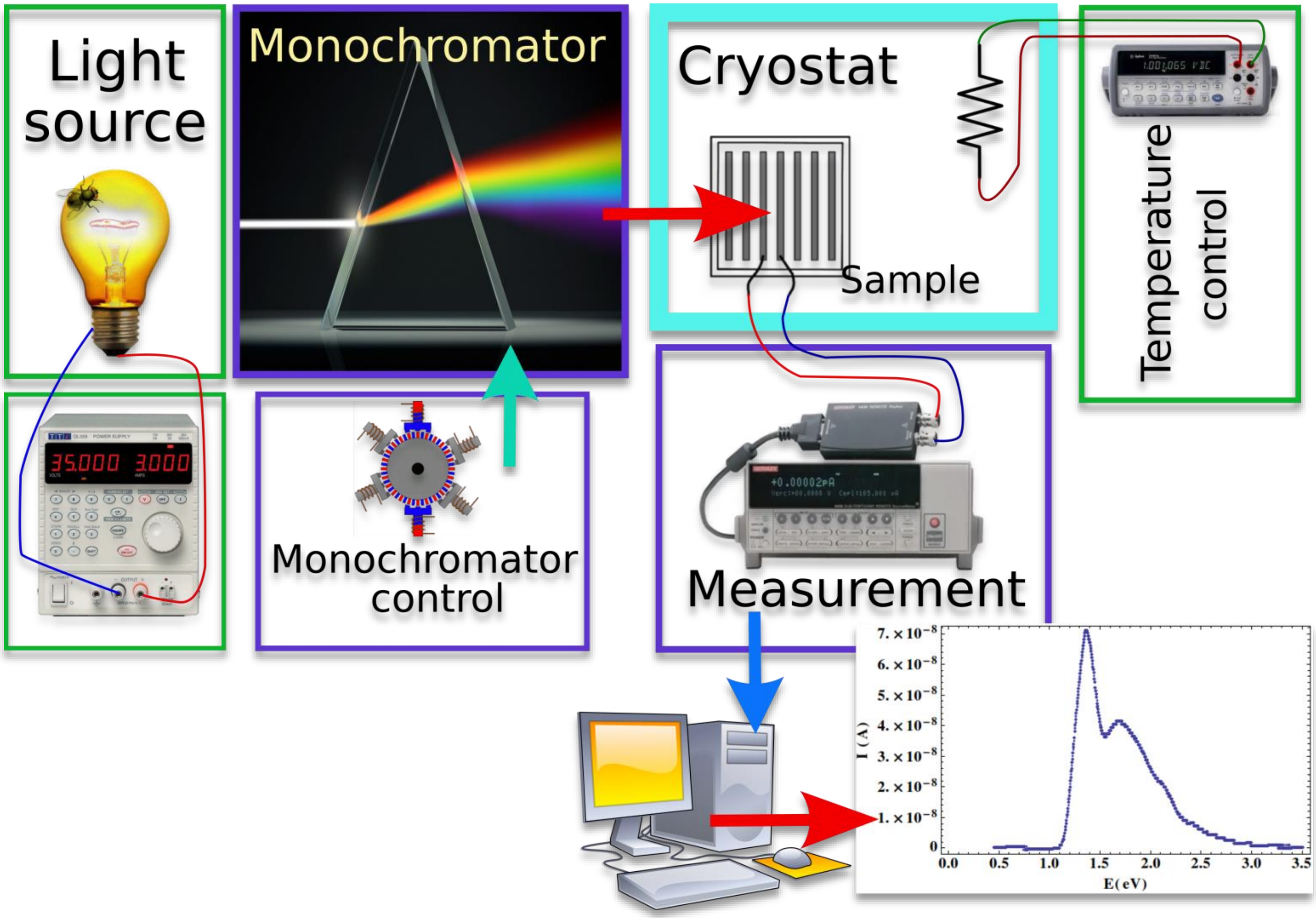
Experimental setup



The experimental results

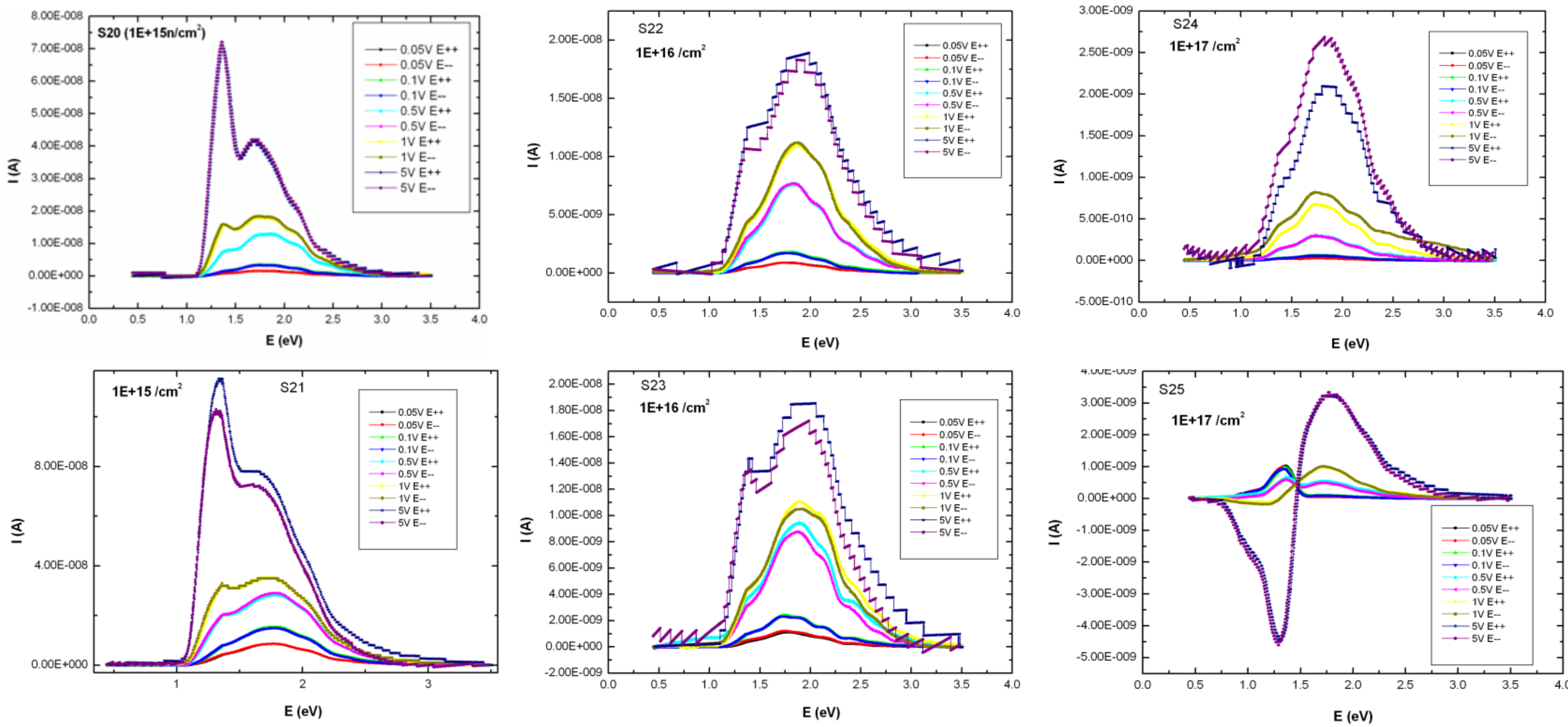


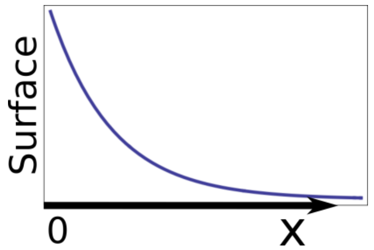
Photo current spectral dependencies with different applied electric potential.

Spectral shape is sensitive to the external electric field and near band-to-band transition, when the absorption is weak at the surface.

The method

Light absorption:

$$I_{photo} = I\,(1-R)\,e^{-\alpha x}$$



Charge carrier generation:

$p = n$

$$D\frac{d^2p}{dx^2} - \frac{p}{\tau} = -G$$

$$p = \frac{C\tau_p e^{-\alpha x}}{\alpha^2 L^2 - 1} + c_1 e^{x/L} + c_2 e^{-x/L}$$

Introduced variables:

$$D = 2\frac{D_n D_p}{D_n + D_p} \qquad D = \frac{\mu k T}{e}$$

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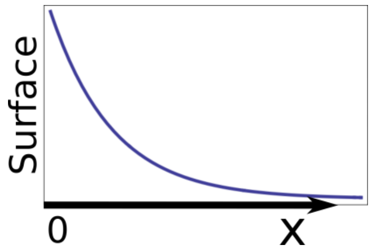

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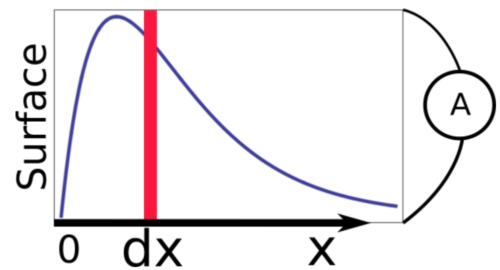

Boundary conditions:

$$D\frac{dp\left(0\right)}{dx} = sp\left(0\right) \qquad c_1 = 0$$

Surface recombination rate

$$p = \frac{\eta\alpha I\tau\left(1-R\right)}{\alpha^2L^2-1}\left(\frac{\alpha L^2+s\tau}{s\tau+L}e^{-x/L} - e^{-\alpha x}\right)$$

[Smith. Seminconductors]

The detected signal: $i = e\mathcal{E}\left(\mu_p+\mu_n\right)w\int_0^\infty p\,dx$

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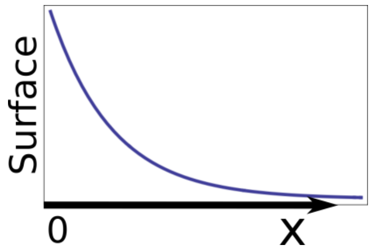

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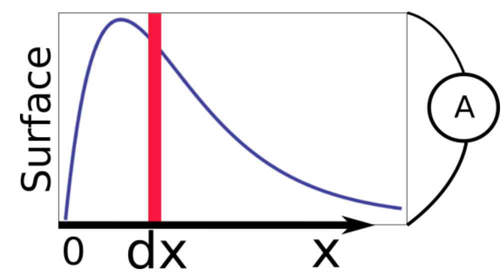

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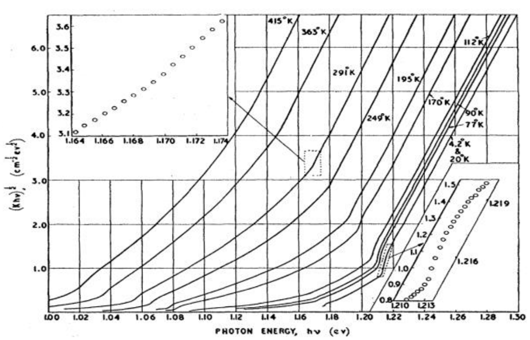
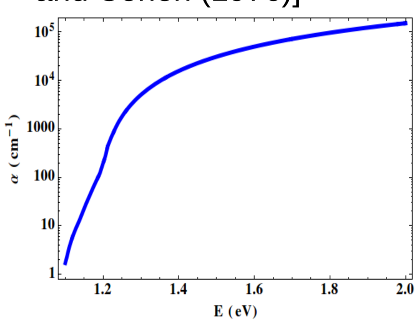
α from [Macfarlane et al. (1959)]



R ~ 0.3 from [Chelikowsky and Cohen (1976)]



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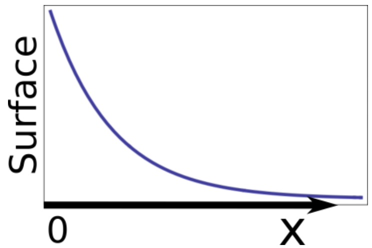

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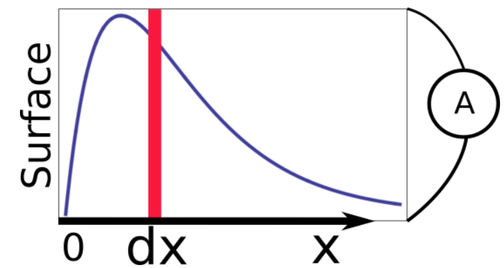

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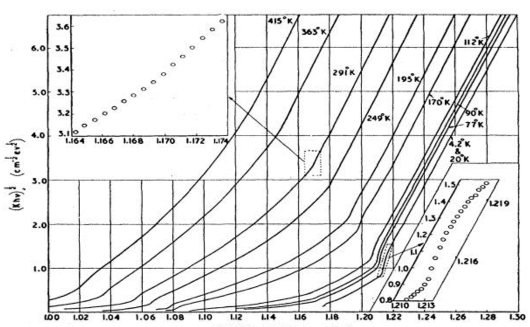

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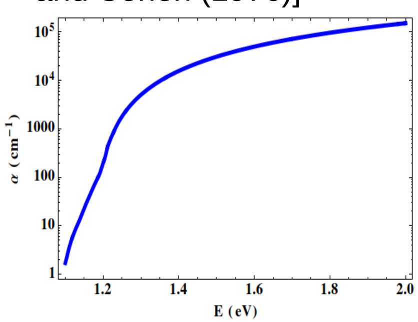
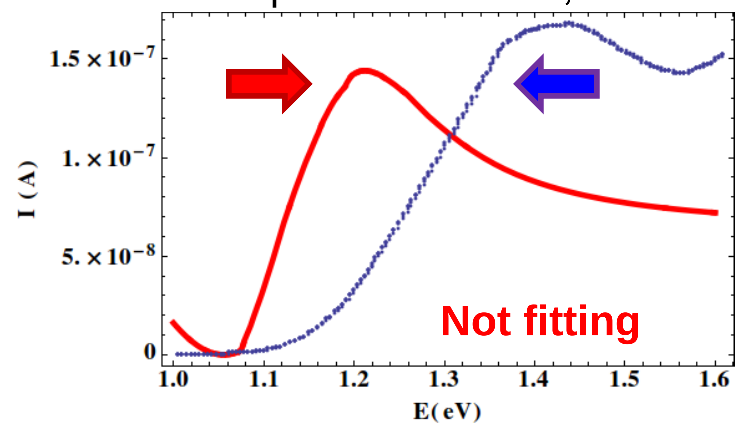


The profile is similar, but…



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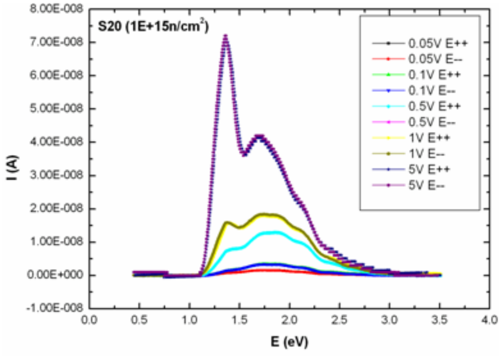
The idea

1. The Si/SiO2 interface may be the cause of the surface mobility degradation.



2. At the surface generated carriers are less mobile, which causes the decrease of the recombination rate.

3. The applied voltage causes the carriers to drift to the clusters in the bulk and recombine faster.

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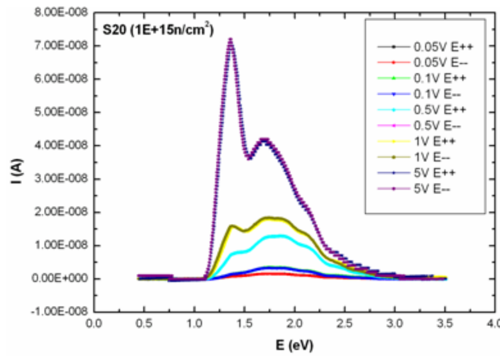
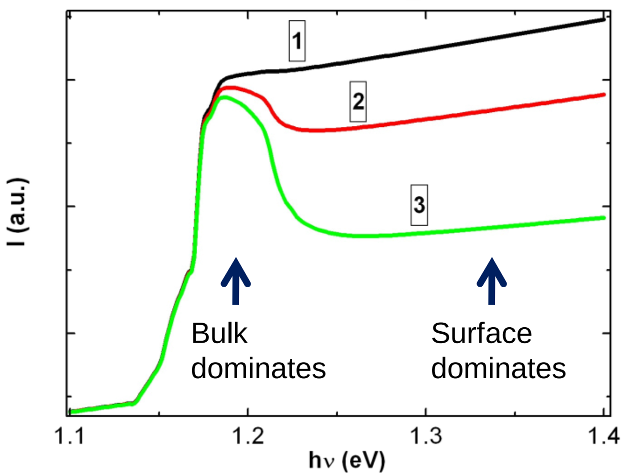


Double layer model: the surface and the bulk



[J.V.Vaitkus et al, LJP, 2023]

The variation of mobility is enough to have the desired tuning of the spectral shape.

1 – homogeneous sample.
2 – surface mob. 2 x smaller.
3 – surface mob. 100 x smaller.

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The double layer model

Light absorption:

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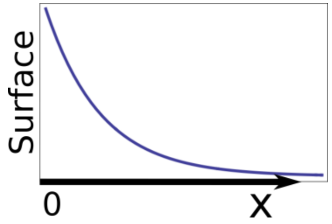

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Introduced variables:

$$\mu_p \tau = M_p \qquad \mu_n \tau = M_n$$

$$M_{n1} + M_{p1} = K_1 \qquad \tau_1 s = S_1$$

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$$S_1/S_2 = S_{12}$$

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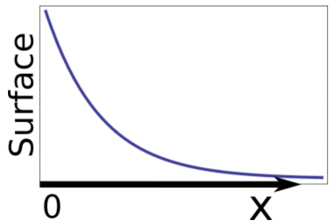

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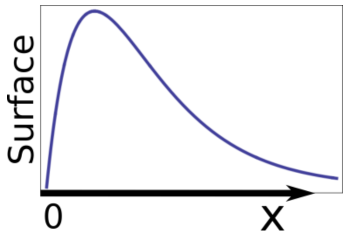

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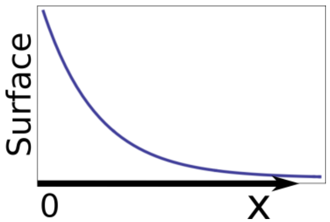

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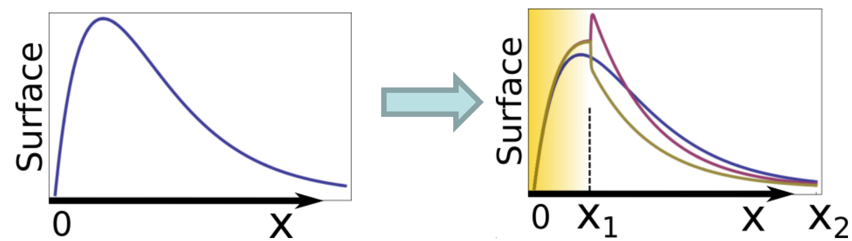

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$$+K_2\eta_2\frac{e^{-\alpha x_2} - e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1}$$ …not complete, much bigger

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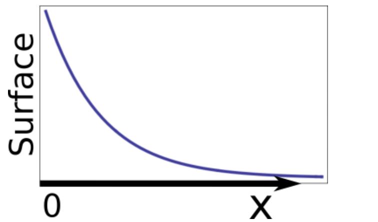

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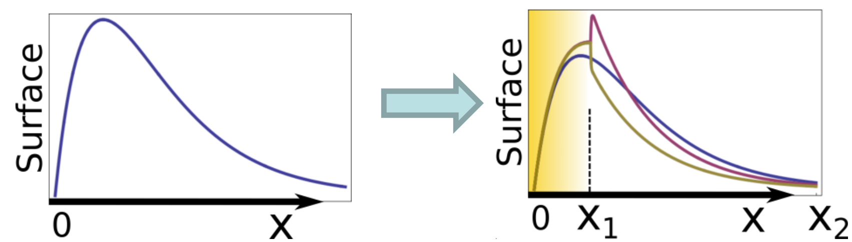

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$$+K_2\eta_2\frac{e^{-\alpha x_2} - e^{-\alpha x_1}}{\alpha^2 L_2^2 - 1}$$

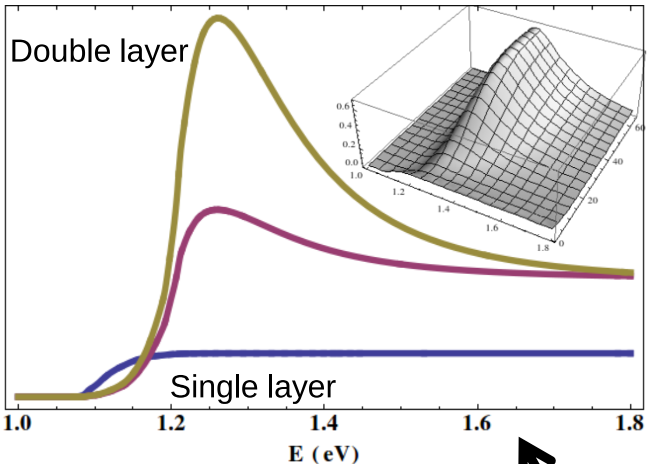
…not complete, much bigger

Deeper analysis:

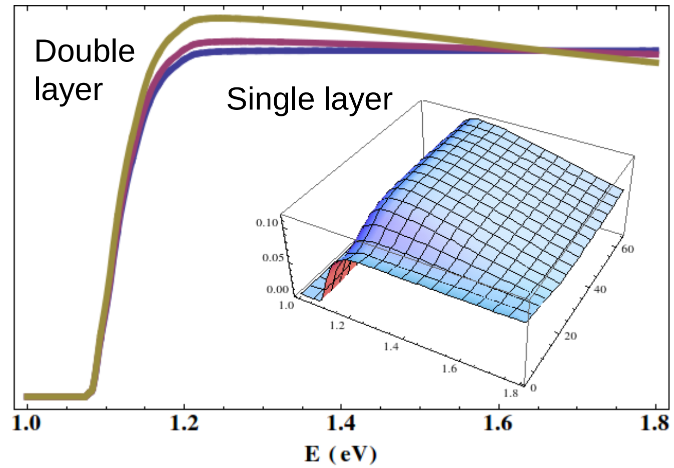
Mobility and lifetime here always comes as a product ($\mu\tau$). The increase of τ because of decrease of μ have an opposite effect on the surface.

Meanwhile, the irradiation decreases μ and τ both. And at some fluence its product in the bulk may become smaller than on the surface? Is surface affected by irradiation in a similar way?

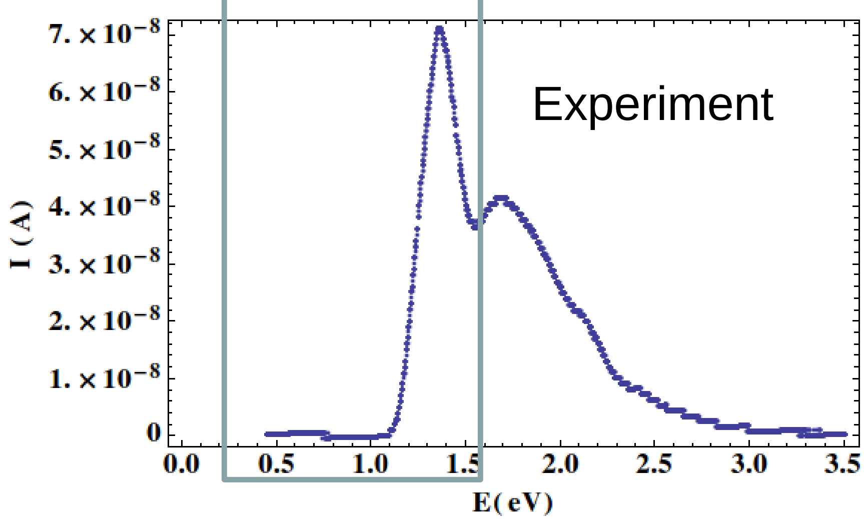
The double layer model



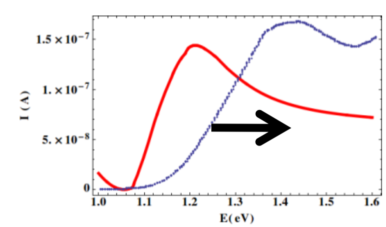
(μτ) is bigger at the top



(μτ) is bigger at the bottom



Which one fits better?



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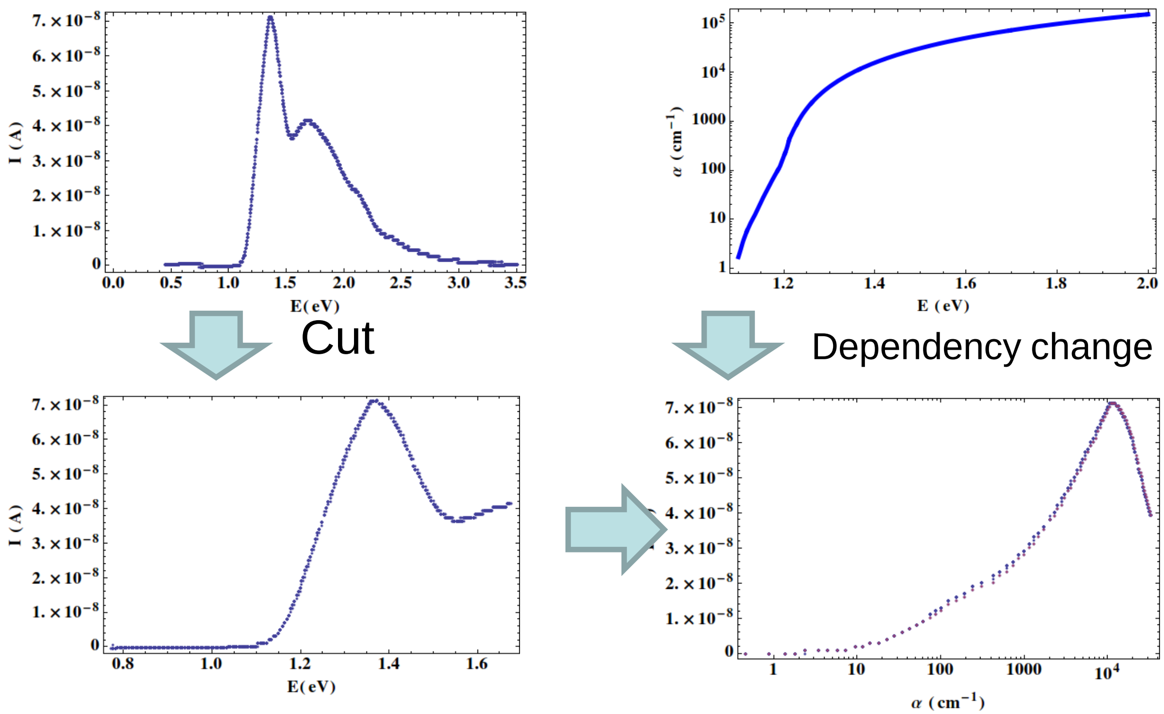
The fitting steps



The fitted curve is very sensitive to the initial values!

The algorithm uses variable error evaluation to maintain the required curve shape.

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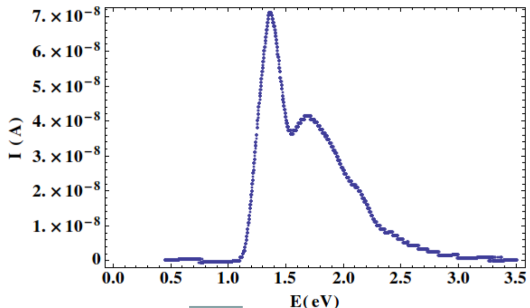
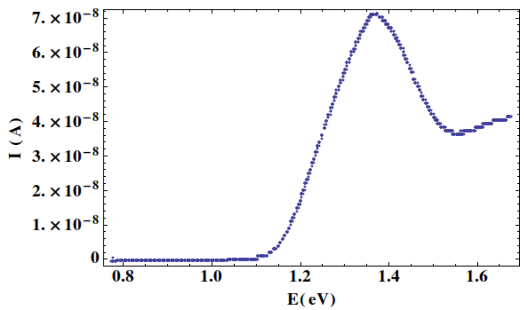
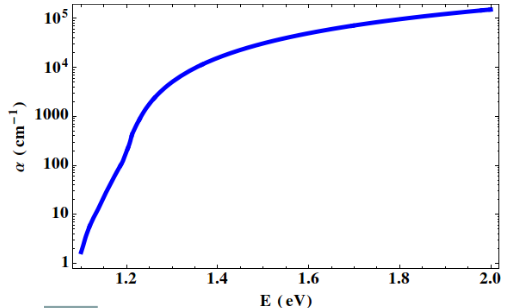
The fitting steps

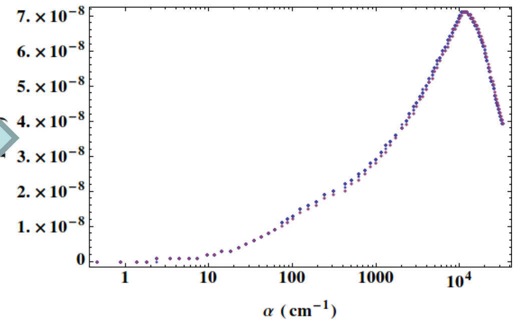


Cut

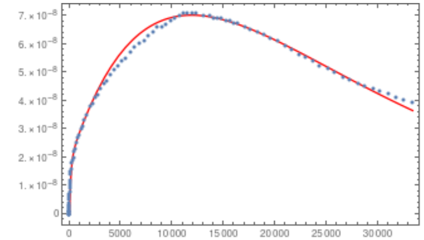


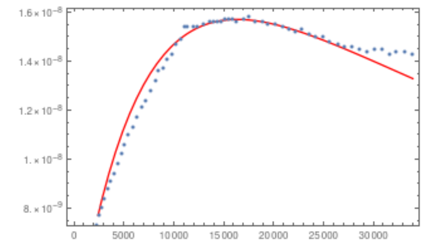


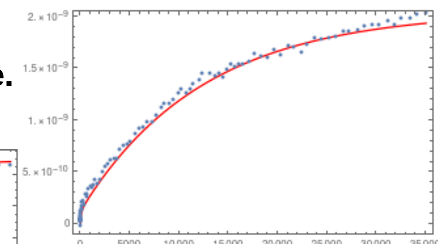
Dependency change



Some fits:







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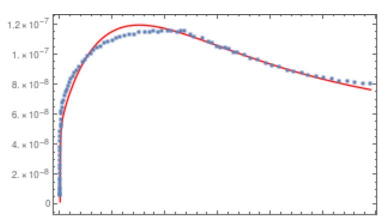
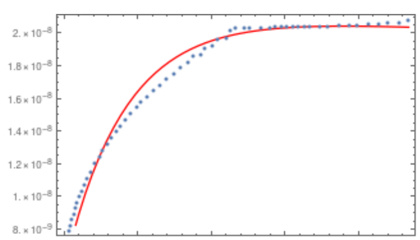
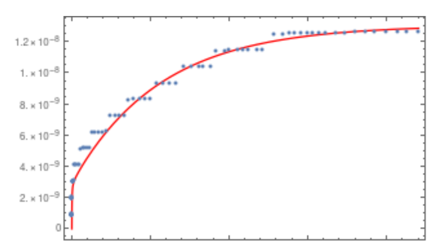






Could be better

The fitting results

$$\mu_p \tau = M_p \quad \mu_n \tau = M_n$$

$$M_{n1} + M_{p1} = K_1$$

$$M_{n2} + M_{p2} = K_2$$

$$L = \sqrt{D\tau}$$

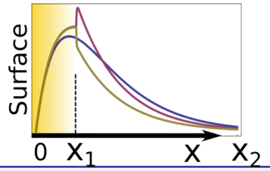
The fitting confirms the order of the layers:

Top layer is “better” than bottom ($\mu\tau$ is bigger).

$K_1 >> K_2$ (x100 and more for 1E+15/cm^2)

$L_1 >> L_2$

$x_1 << x_2$



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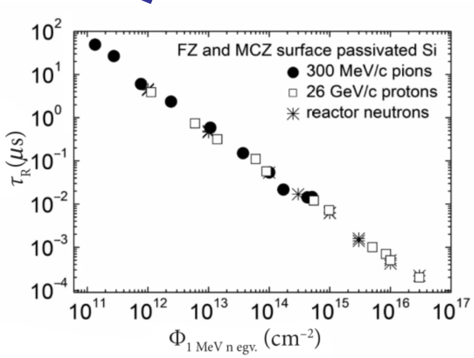
$$M_{n1} + M_{p1} = K_1$$

$$M_{n2} + M_{p2} = K_2$$

$$L = \sqrt{D\tau}$$

Universal law:



[L. Deveikis et al]

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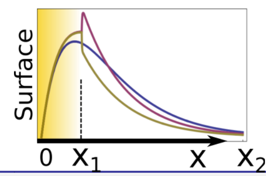

Next steps:

1. Obtain τ or μ from other experiments at required T.
2. Reduce the fitting parameter distribution by simultaneous fitting of the several dependencies.
3. Complete more photoconductivity experiments.

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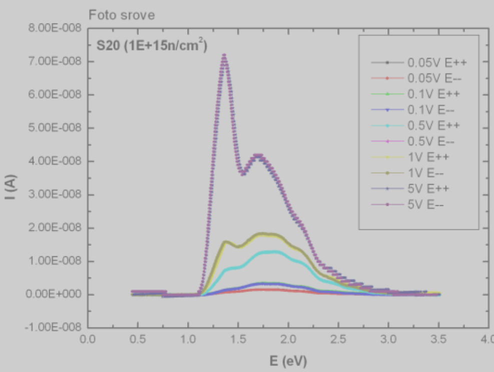
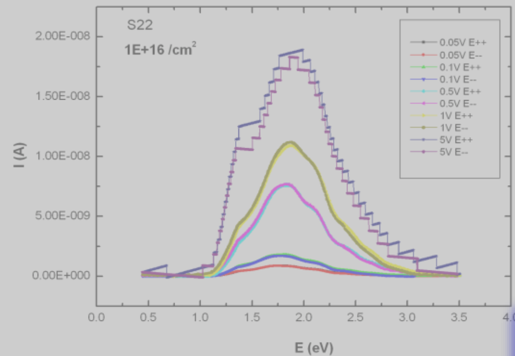
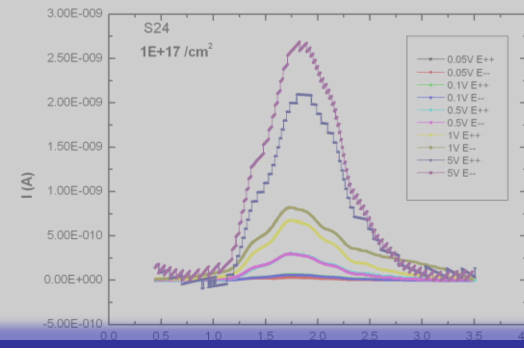
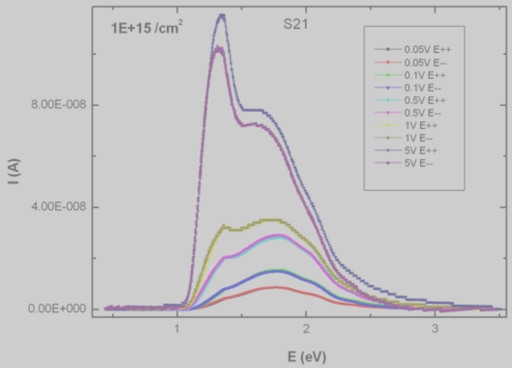
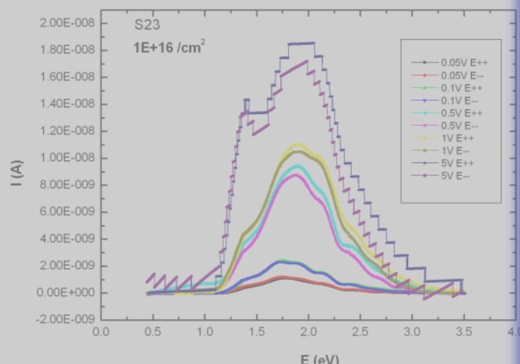
The experimental results

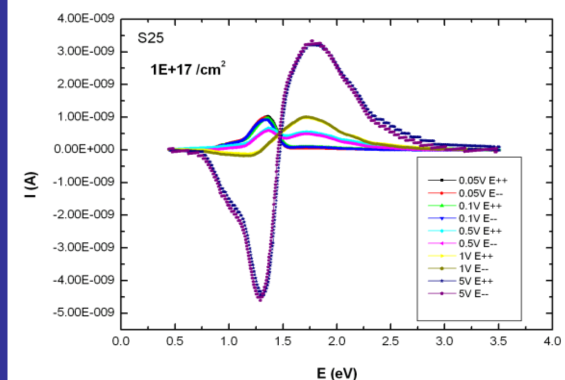








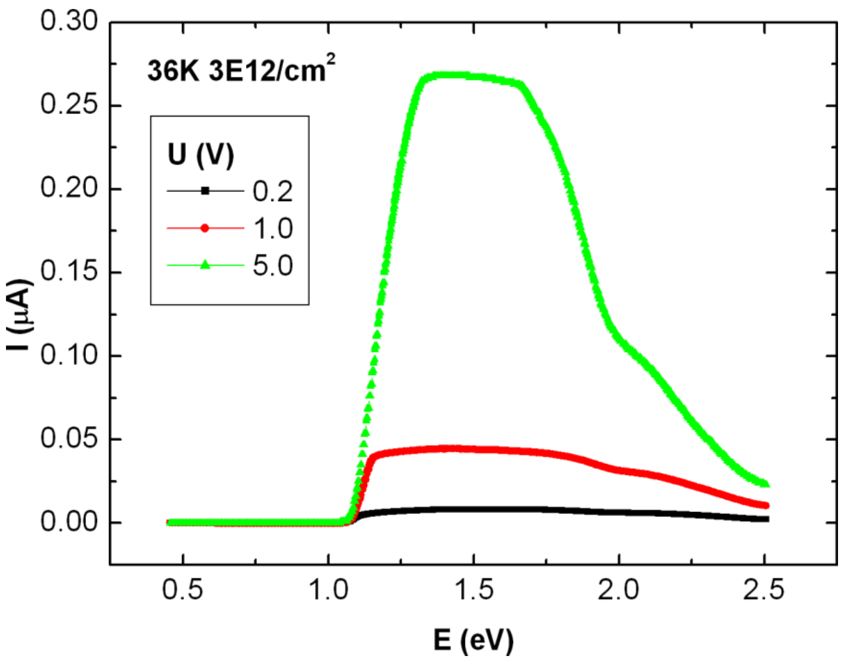


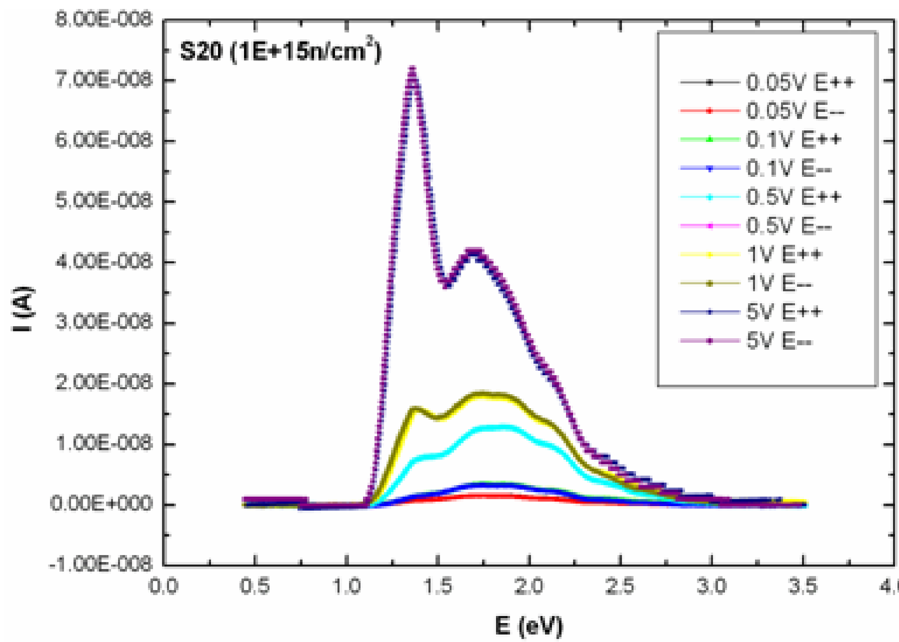


Exceptional case for sample S25: **negative** photo current. The photo carrier density is positive, so the current has to be. The mobility may decrease because of the band structure (excitation to the valley of higher effective mass?) But the slower carriers still contribute as addition to the total photo current. The effect is related to the **deeper layer** (less photo absorption) and is sensitive to the external electric field. The explanation is that the presence of internal electric field or the current blockade work like in FET. Perhaps, this is related to the defect charge separation of dipole type or Photo-Volt effect?

The previous results

At low fluence the double layer is not observed. If the surface quality is defined by the surface oxide, then at a certain fluence the product of ($\mu\tau$) may become the same in the whole sample. Then the second layer would not show up too. Meanwhile the experiments show the opposite: the double layer appears at higher fluence.





Difficult to compare the surface of the samples, because the low fluence was applied for the other batch.

For this reason older batch was included for the analysis (next slide).

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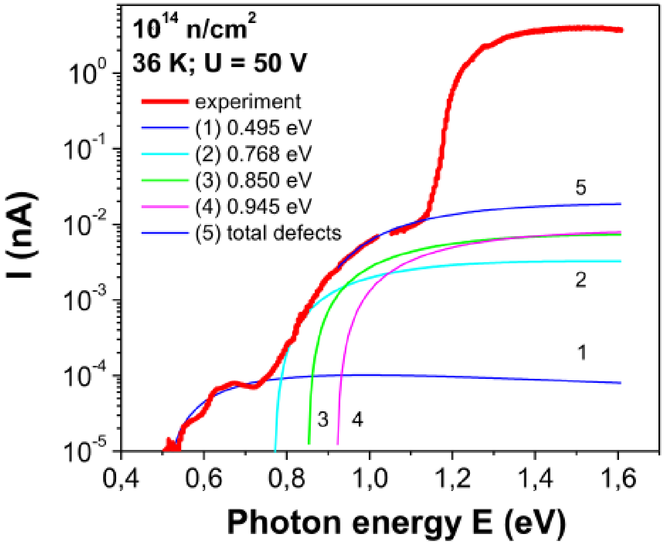
The previous results



[J. V. Vaitkus et al, J. Phys. D: Appl. Phys. 55 (2022) 395104]

The previous analysis was mostly concentrated at the bandgap. The later effect is best expressed above the bandgap.

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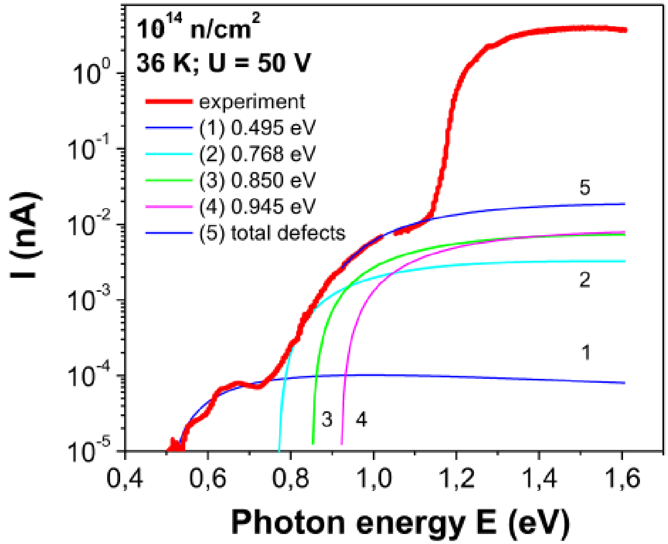
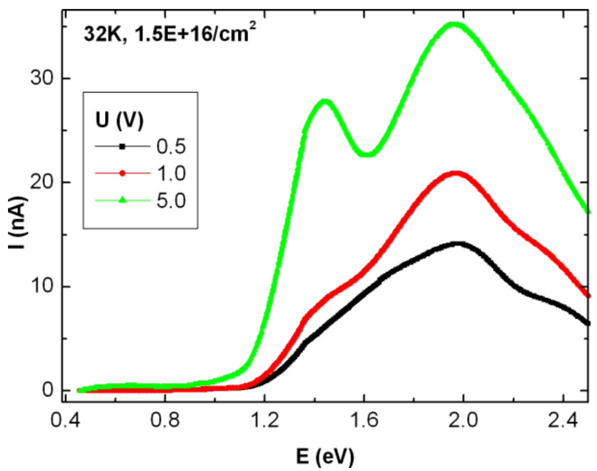
The previous results



[J. V. Vaitkus et al, J. Phys. D: Appl. Phys. 55 (2022) 395104]



The previous analysis was mostly concentrated at the bandgap. The later effect is best expressed above the bandgap.

The effect of double layer is observed at higher electric potential.

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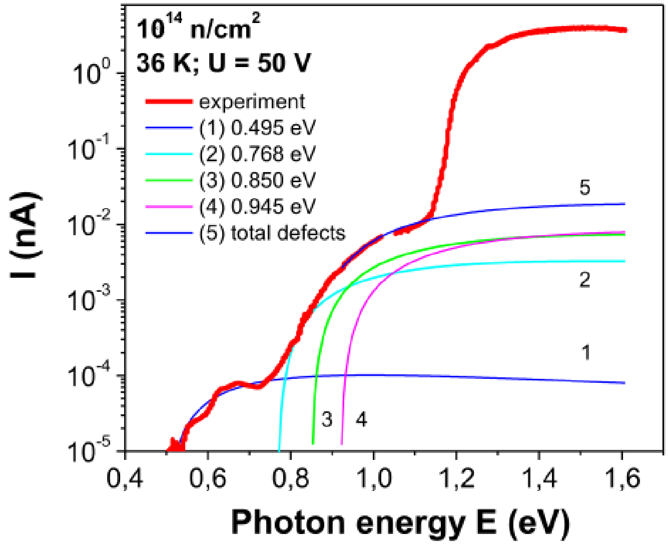
The previous results

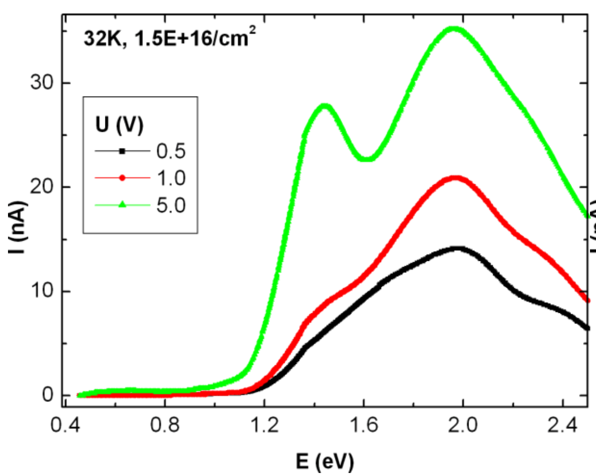


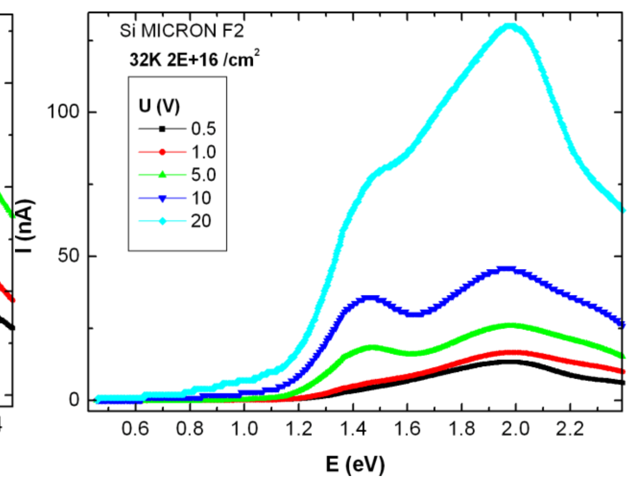
[J. V. Vaitkus et al, J. Phys. D: Appl. Phys. 55 (2022) 395104]

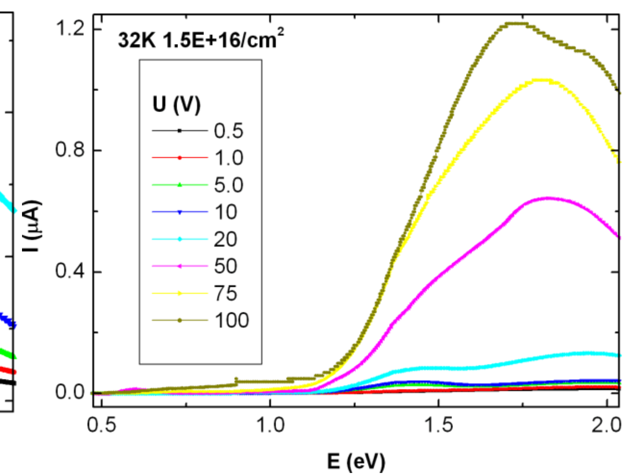
The previous analysis was mostly concentrated at the bandgap. The later effect is best expressed above the bandgap.

The effect of double layer is observed at higher electric potential.

Too high potential hides the effect again!







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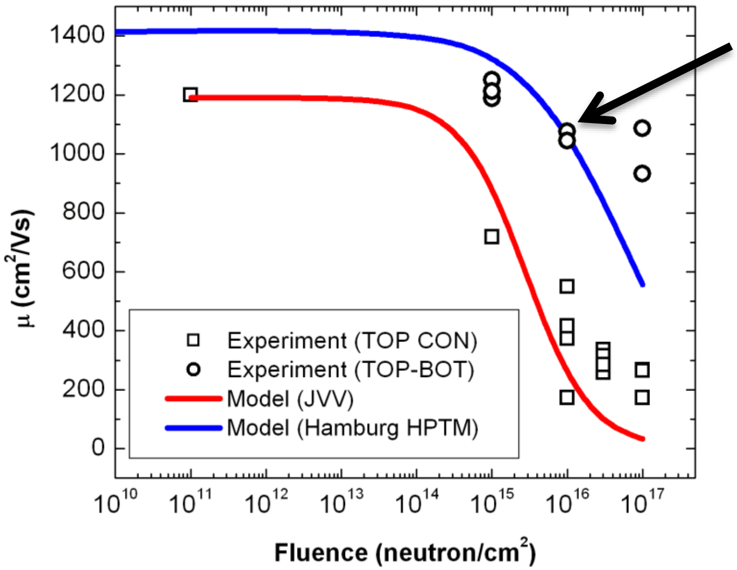
Relation to the magnetoresistance (MR)

From 41st RD50:



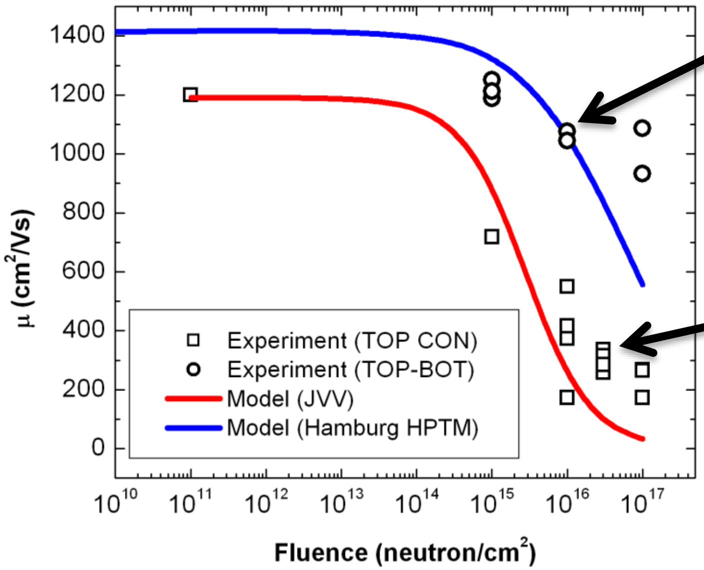
[JVV] J. V. Vaitkus, etc., https://doi.org/10.3952/physics.v61i2.4438

MR top to bottom shows a good quality material

MR measurement is separated from τ, so "good quality" means bigger μ, but not μτ.

Relation to the magnetoresistance (MR)

From 41st RD50:



[JVV] J. V. Vaitkus, etc., https://doi.org/10.3952/physics.v61i2.4438

MR top to bottom shows a good quality material

MR measurement is separated from τ, so "good quality" means bigger μ, but not μτ.

MR top to top shows an **irradiated** material (or like degraded at the Si/SiO2 interface?)

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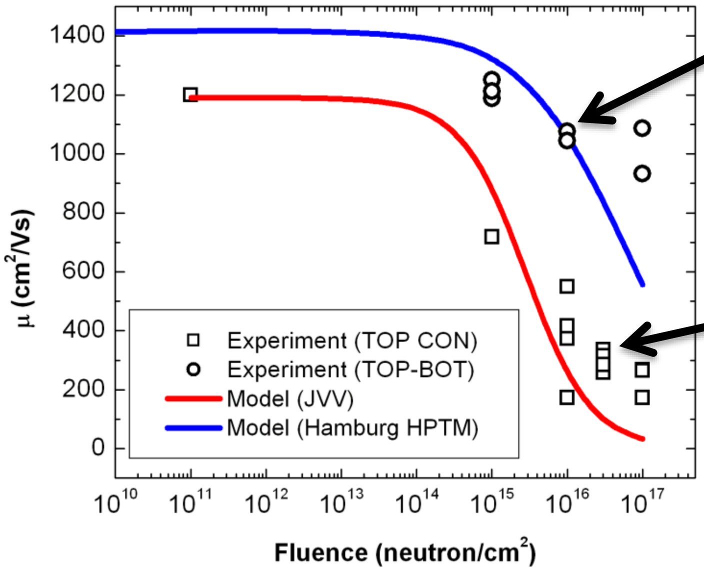
Relation to the magnetoresistance (MR)

From 41st RD50:



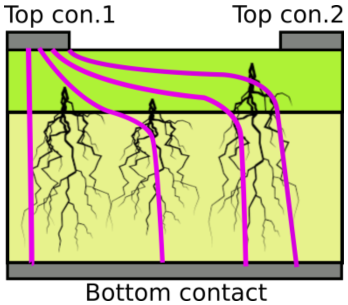
[JVV] J. V. Vaitkus, etc., https://doi.org/10.3952/physics.v61i2.4438

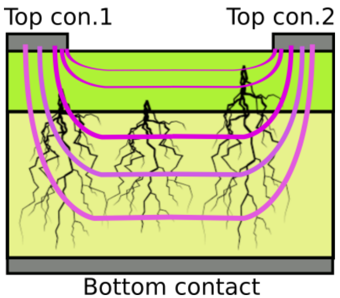
MR top to bottom shows a good quality material

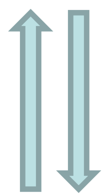
MR measurement is separated from τ, so "good quality" means bigger μ, but not $\mu\tau$.

MR top to top shows an **irradiated** material (or like degraded at the Si/SiO2 interface?)

Current flow







B direction

Only perpendicular to B electric current experiences MR.

What if the irradiated device still has another layer of better quality material?

Irradiation with neutrons increases R in the bulk, so what remains more conductive? Surface?

Summary

Silicon STRIP detectors were investigated by photo conductivity effect in range 0.45 eV to 3.5 eV with constant photon number.

The model of good crystal quality on sample top and irradiated material below was proposed and parameter extraction procedure estimated.

Negative photo response in sample irradiated to 1E+17/cm^2 was observed and its origin was discussed.

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Thank you