Anneal dependent variations of lifetime and deep levels in neutron irradiated MCZ Si

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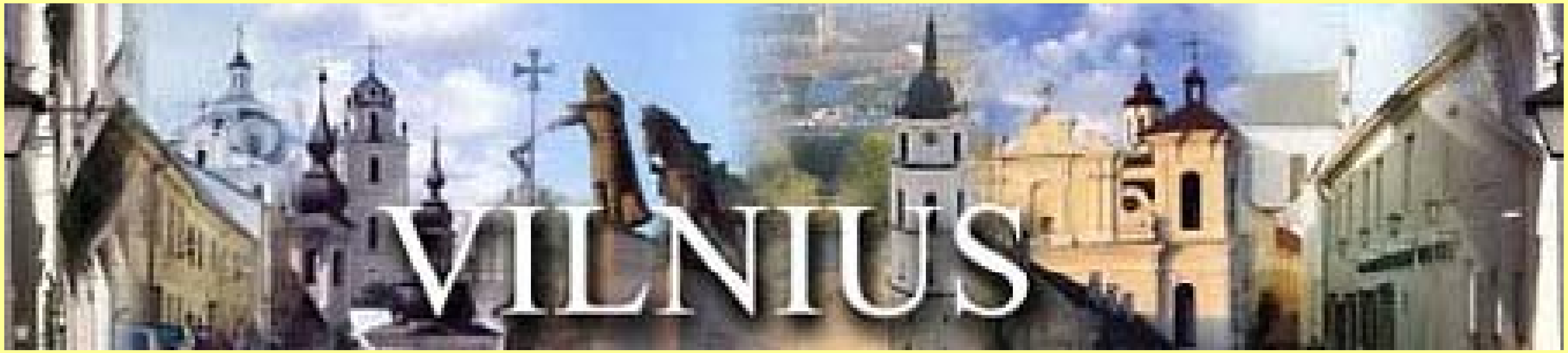
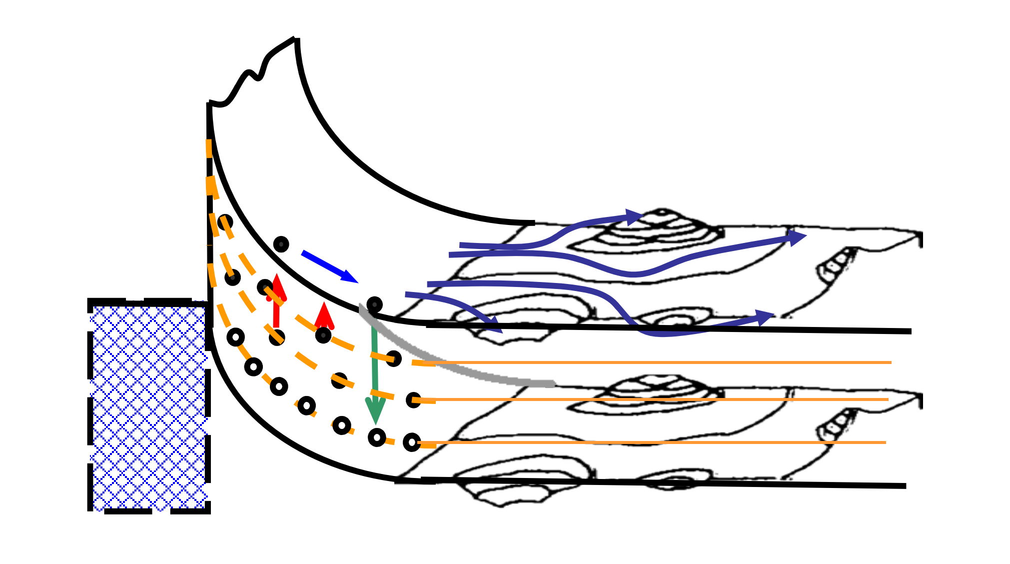


Outline:

- A bit about the methods
- Samples and measurements
- The results of analyze of the deep levels parameters in the differently irradiated samples
- The PC decay analyze in irradiated samples
- Conclusions

“The real” contact and semiconductor



Model of metal-semiconductor junction with defect levels and inhomogeneous potential relief of the conductivity band bottom

This picture tries to illustrate the irradiated by hadrons semiconductor.

It allows to see the differences of electrical and optical methods:

Optical excitation excites all electrons that can be excited:

DC PC registers the non-equilibrium carriers that can to move;

MW register a change of conductivity in the bulk.

Electrical methods controls the properties of channel through that current runs and of an effective space charge region.

General remarks

- Therefore the photoconductivity gives information about all deep levels existing in the sample, but it problematic to recognize their type and role:
  - It needs to apply the additional methods:
    - I(V) measurement (and modeling according the proposed deep level parameters)
    - testing a linearity of dependence of signal on intensity of excitation
    - Measurement of temperature dependences
    - Measurement of photoconductivity decay and analyze its character.
  - And also, it would be nice to have the data of other methods that were planned according the WODEAN scheme.

- But in any case, due to the general properties of deep level photon-cross-section the steps in PC spectrum shows the deep level existence.

Samples and measurements

Irradiated p^+-n-n^+ Si diodes (WODEAN 2nd run)

Doses:

$1x10^{13}$ neutrons/cm^2
$1x10^{14}$ neutrons/cm^2
$1x10^{15}$ neutrons/cm^2
$1x10^{16}$ neutrons/cm^2

Some samples were annealed:
- isothermal 80 C for 1 min -24 h

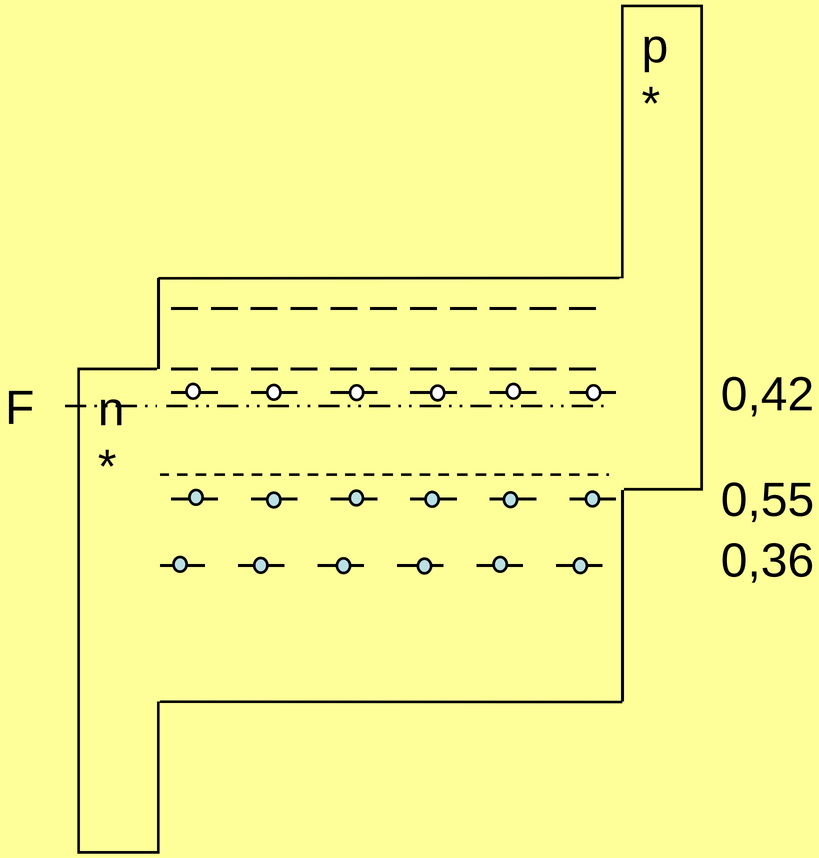
- isochronal for 24 h
at temperatures 80^0C , 120^0C ,160^0C, 240^0C, 320^0C and 420^0C

Measurements:

I(V), TSC, PC (T),
PC – spectrum at 18 K by DC excitation,
PC spectrum at 300 K by excitation of a short light pulses,
PC decay

Annealing
80^oC 4 min
80^oC, 120^oC, 180^oC, 240^oC - 15 h

I(V) modeling



- Modeling of the p*-n-n* detector sample with homogenuously distributed traps was performed with with Synopsys TCAD program.

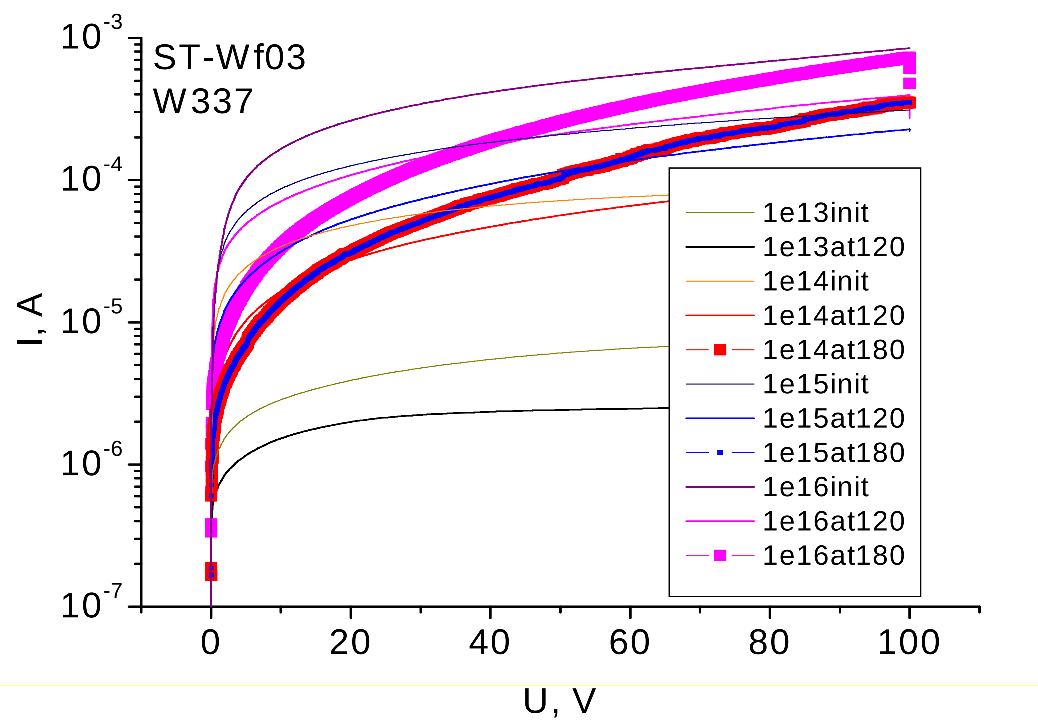
- The trap model consists of two acceptor levels at Ec – 0.42 eV, Ec – 0.55 eV and one donor level at Ev + 0.36 eV

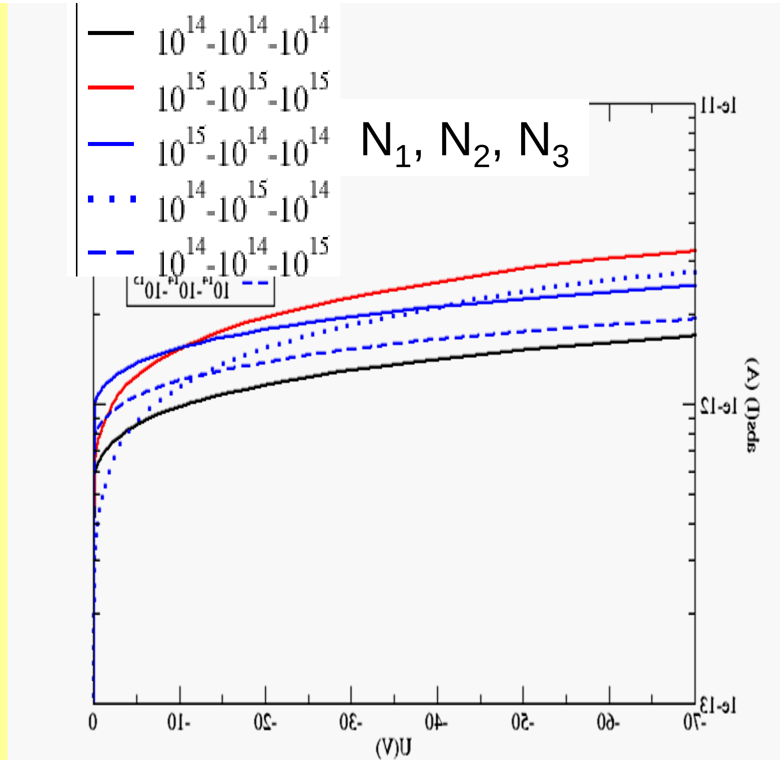
  (according to D. Passeri, P. Ciampolini, G. Bilei, and F. Moscatelli, IEEE Trans. Nucl. Sci., 48, 1688, (2001)).

Concentrations of traps N_1, N_2, N_3 were variated within the interval 10^{14} – 10^{15} cm^{-3}.

Comparison of I(V) exp and simulation

Acceptors Ec – 0.42 eV, Ec – 0.55 eV (N_1, N_2)
Donor level at Ev + 0.36 eV (N_3)



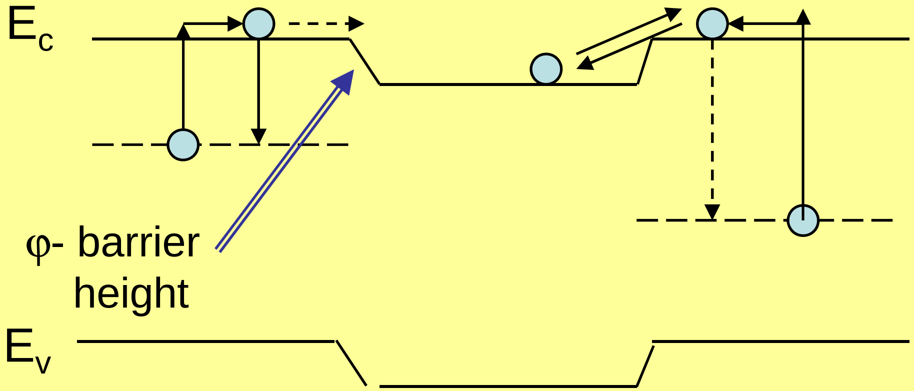


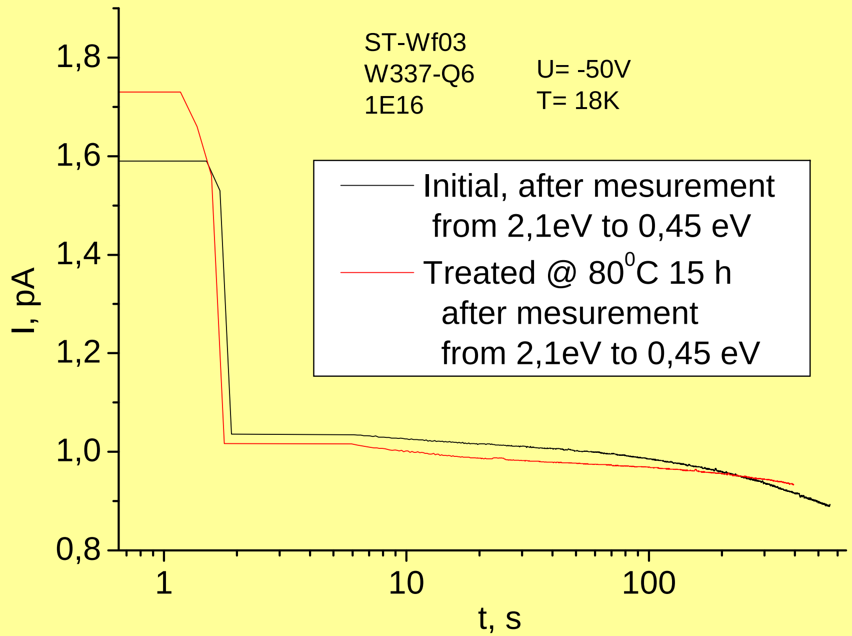
Relative increase of concentration of deep acceptor leads to a change of I(V) shape

Simulation suggests, that the common decrease of traps concentrations from 10^{15} down to 10^{14} cm-3 or decrease just only of the donor trap concentration results into the similar set of I-V curves as shown for the annealing cases up to 120^0C. However the increase of concentration of just only one sort of acceptor traps supposedly the one with the energy Ec – 0.42 eV leads to the I-V curve shape look alike as of the annealed sample at 150^0C.

A peculiarity of irradiated samples

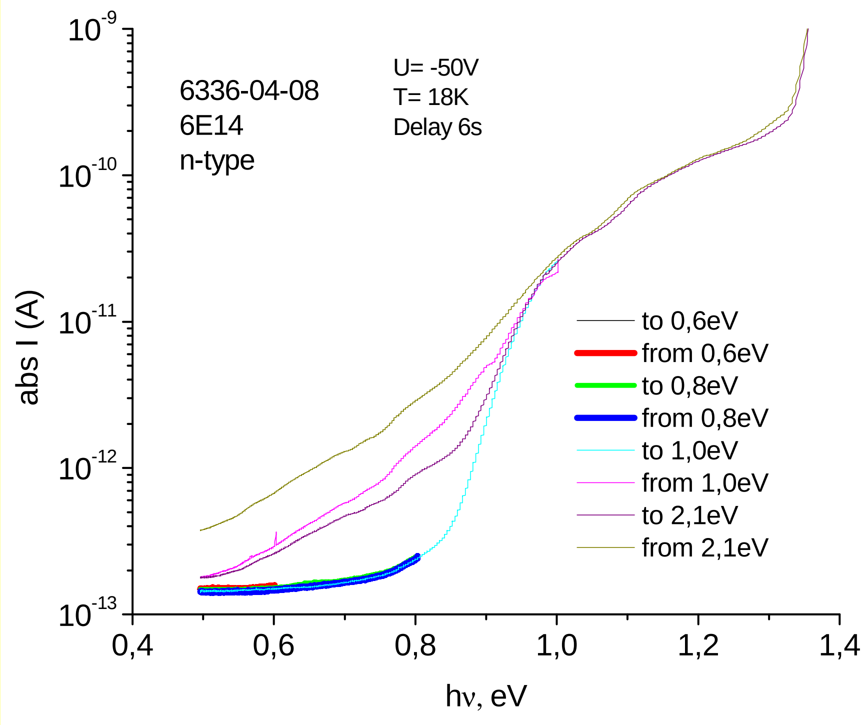
- The I-V at room T qualitative fits to the homogeneous semiconductor model
- But PC at low T demonstrates that the conduction band (or the bandgap) is modulated and it causes the persistent PC.

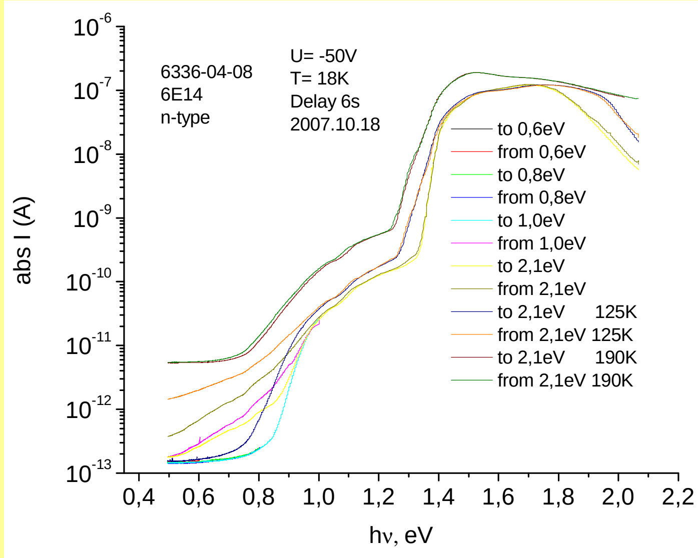


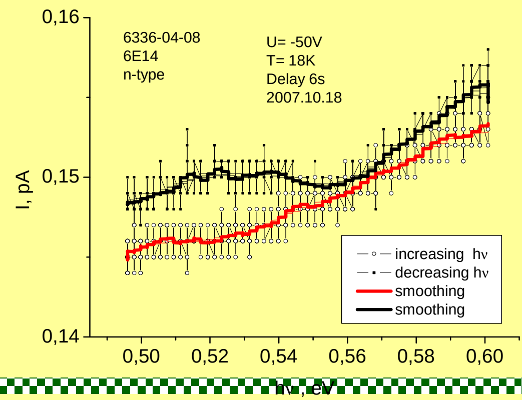


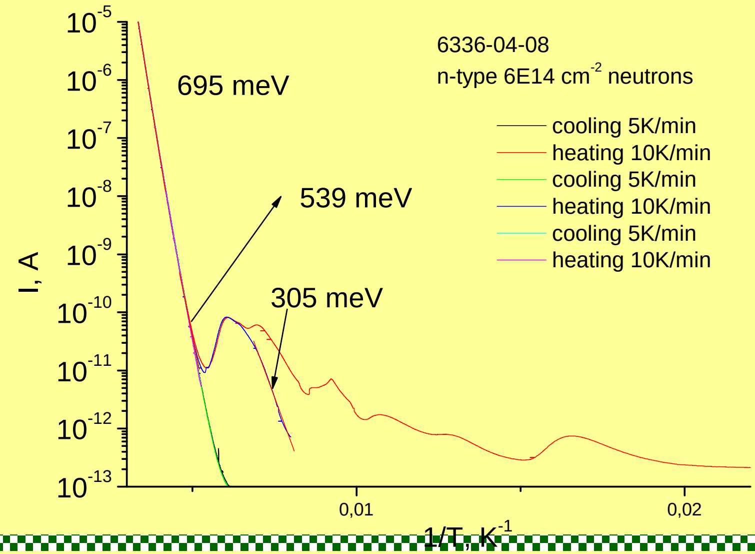
A persistent current decay time is related to the inhomogeneity barrier height

Persistent PC activates @ hν>0.8 eV, i.e., appears due to a deep donor or two step excitation



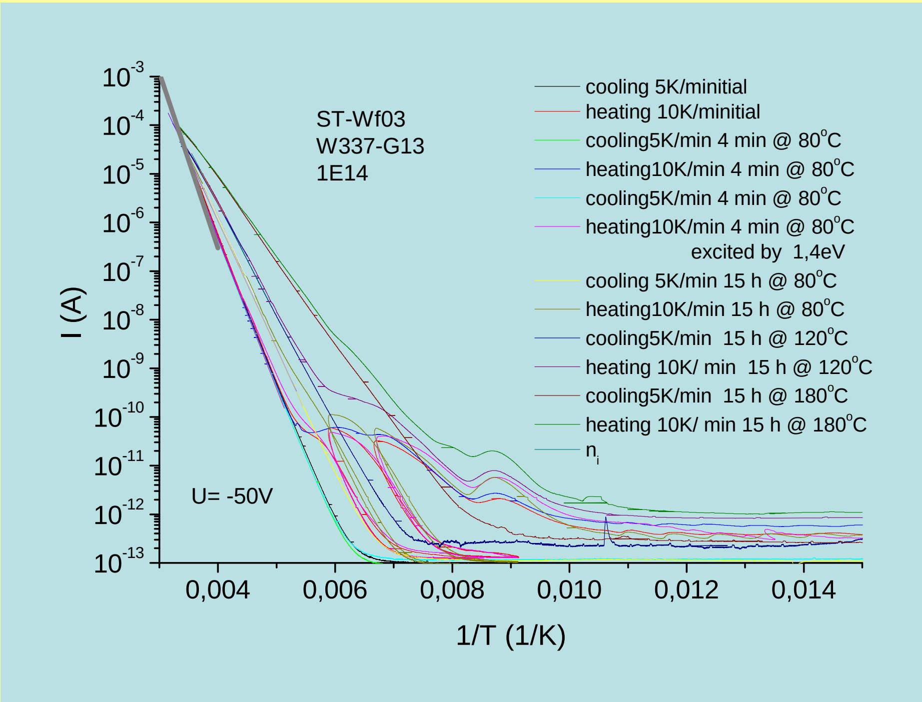


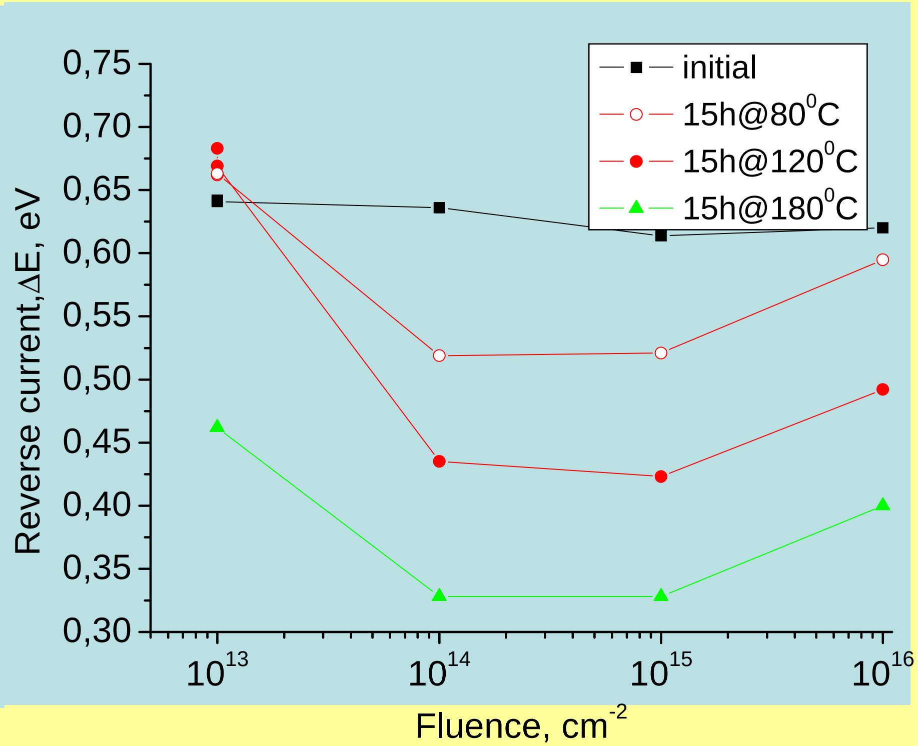




Dark current=f(T) and TSC

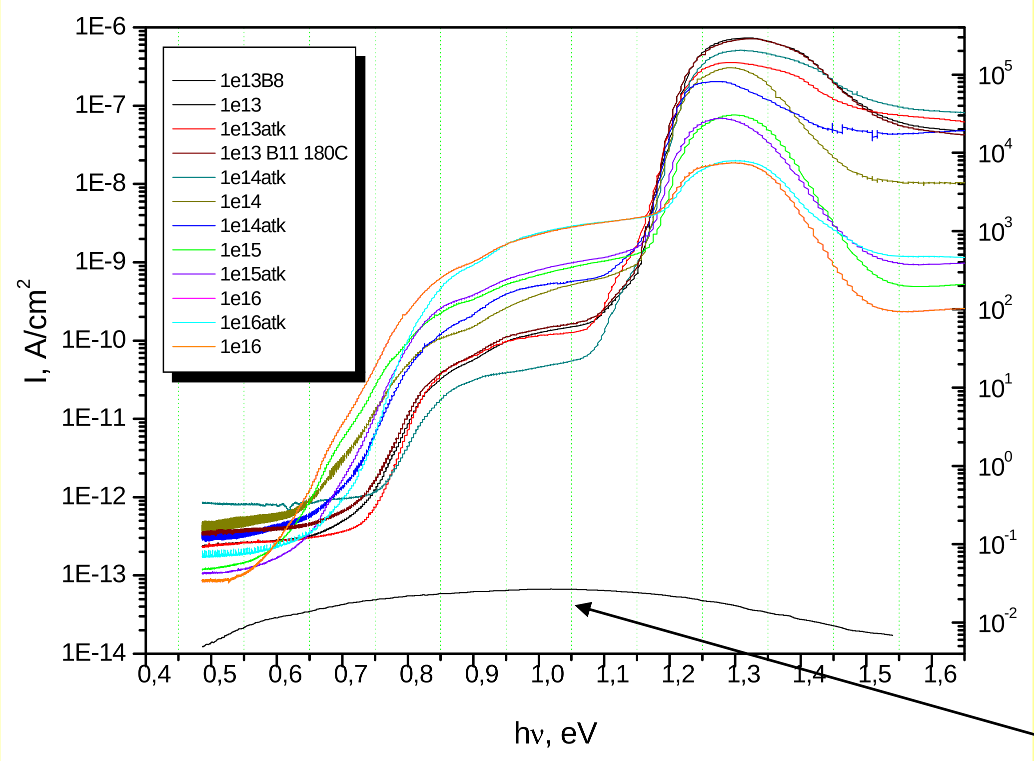
I_{dark} and TSC in the high temperature region (near to room T) was slightly dependent on the irradiation in the non-treated samples and differently depended on the izochronal thermal treatment





The activation energy if to account a dependence of density of state on temperature is very similar to the intrinsic generation lifetime activation energy lifetime and shows the thermal activation energy of compensated deep center or the bandgap

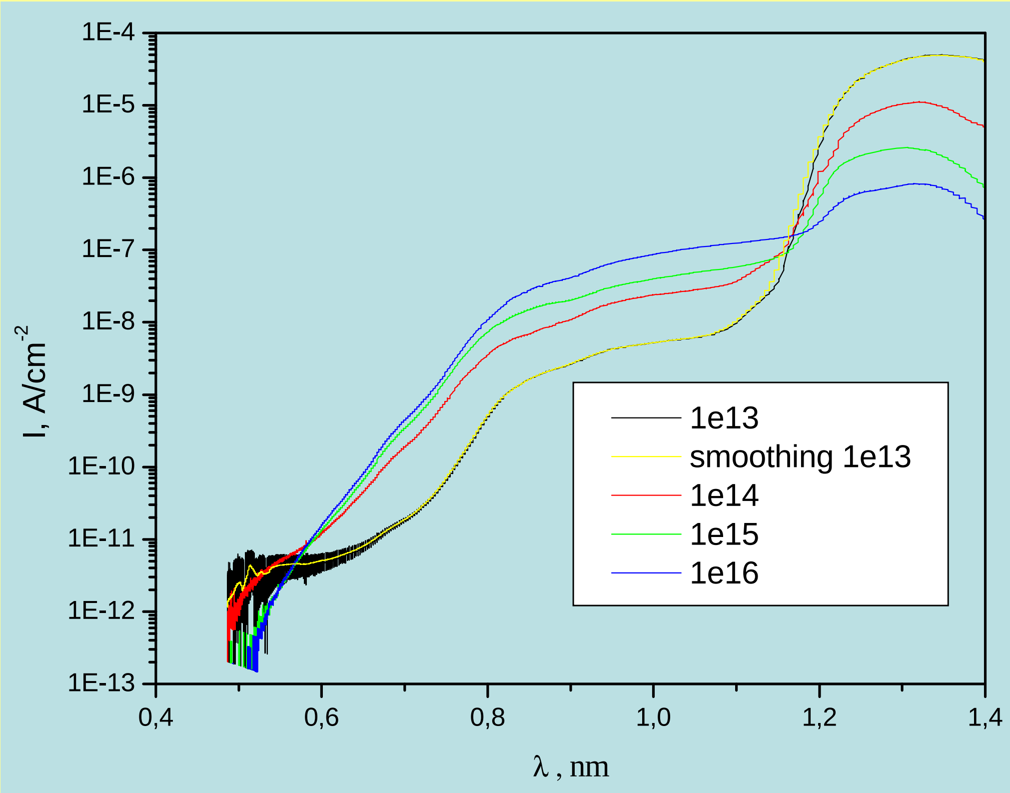
PC spectra in irradiated Si



The spectra were measured at constan bias of light source therefore the spectra was necessary to normalize to the equal number of incident photons.

For this the dark or persistent current was substracted and the lamp intensity distribution was used.

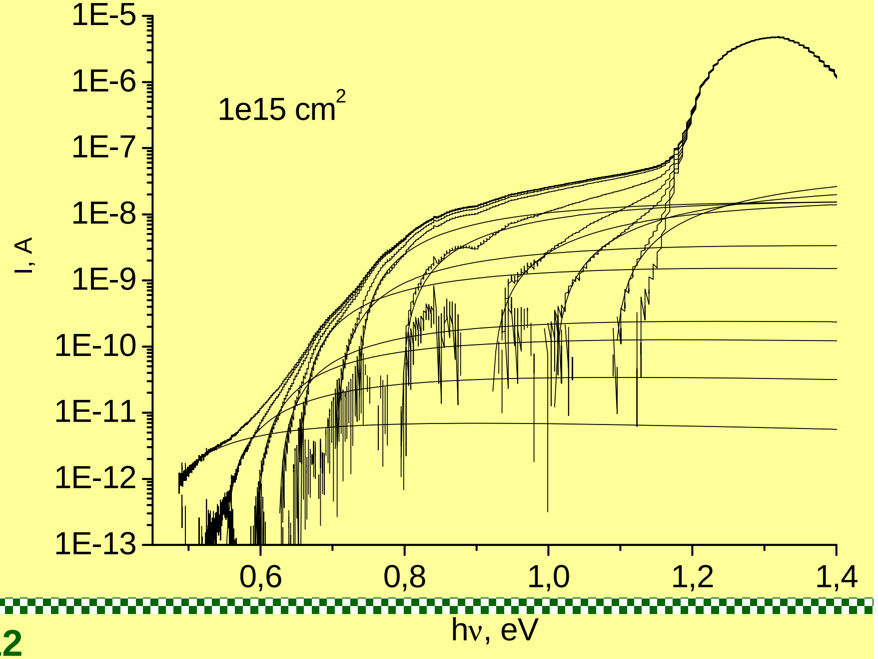
The corrected PC spectra and example of analyze in irradiated Si



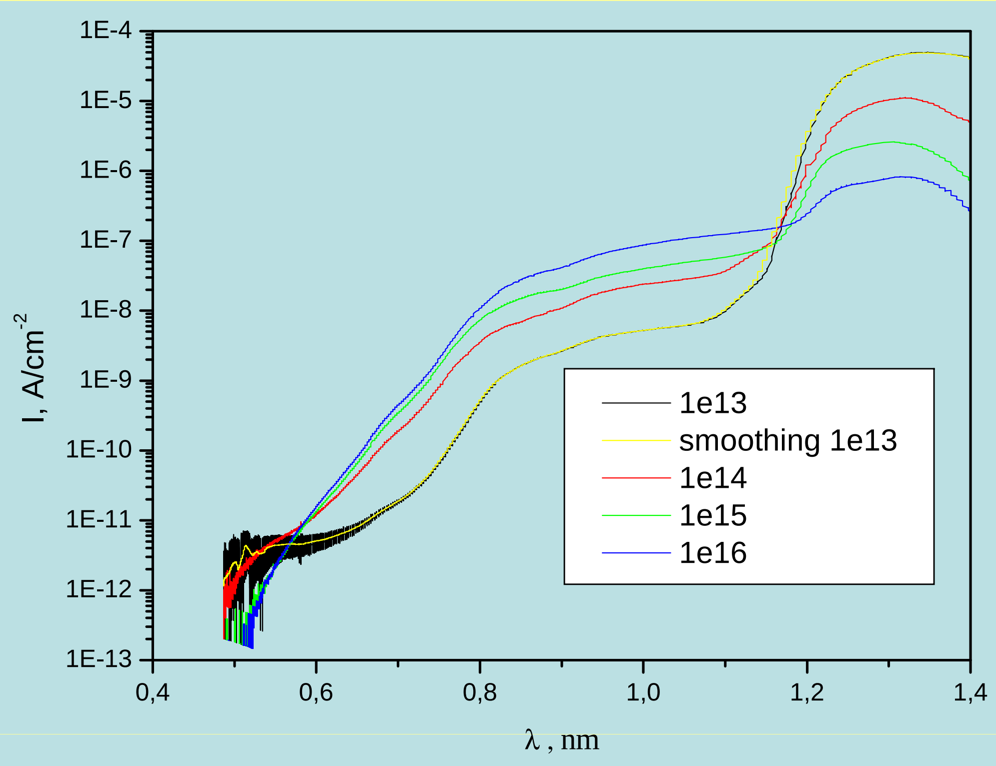
The shape of spectral dependence of photo-ionization depends on electron-phonon coupling, but at low T this effect can be neglected, i.e. Luckovsky model can be used.

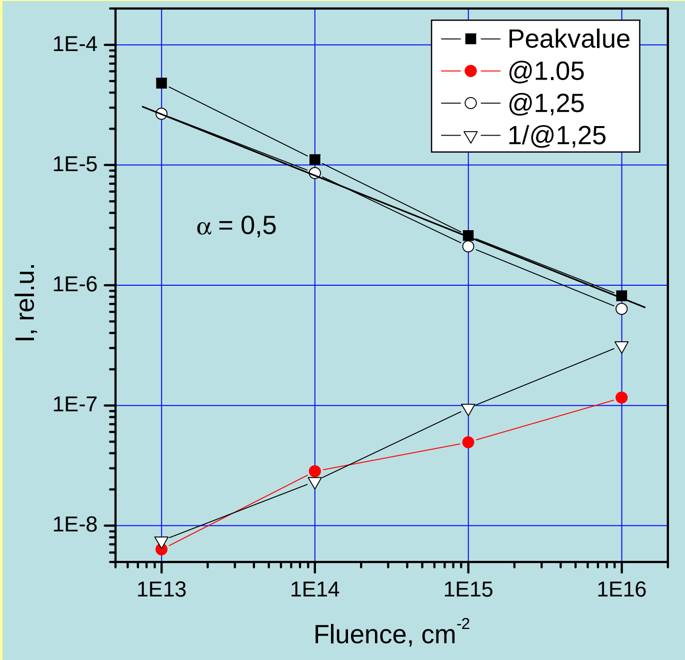
Lukovsky (δ-potential) model:

$I \sim m \times \Delta E_M{}^{0,5}(h\nu - \Delta E_M)1,5/(h\nu)^3)$



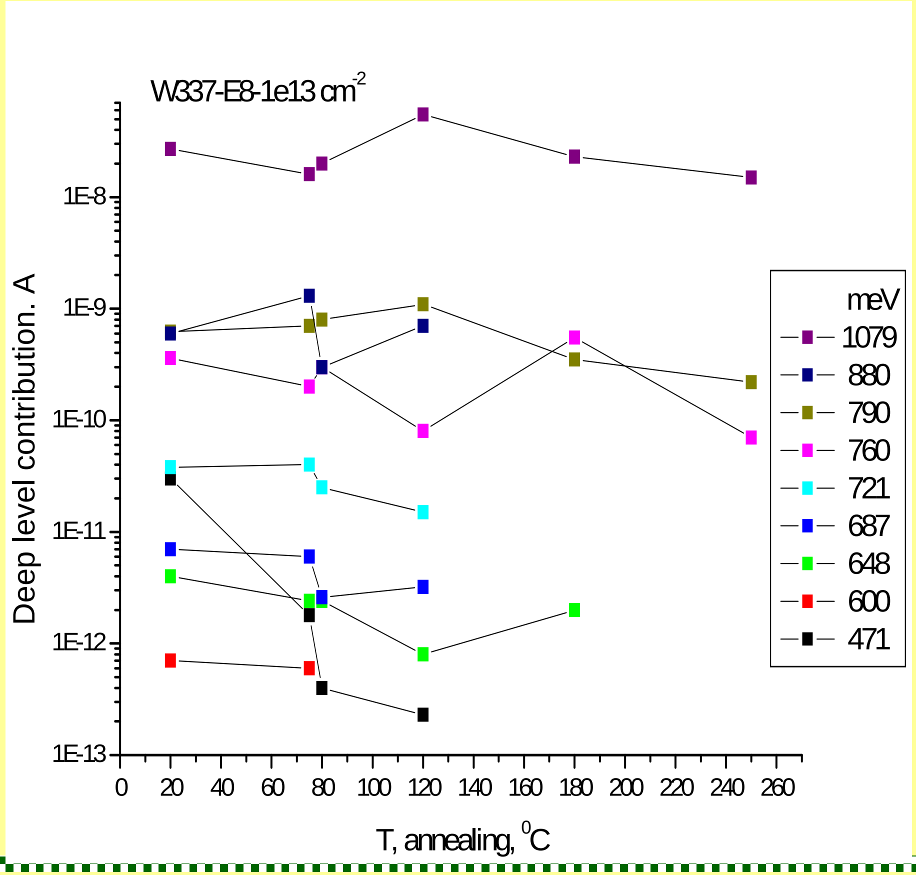
The photoconductivity spectrum changes in the differently irradiated samples:
@ 1.05 eV signal is related to the local level concentration
@ 1,25 eV signal is determined by the free carrier lifetime
Peak value shows the competition of lifetime and recombination in the fron contact layer

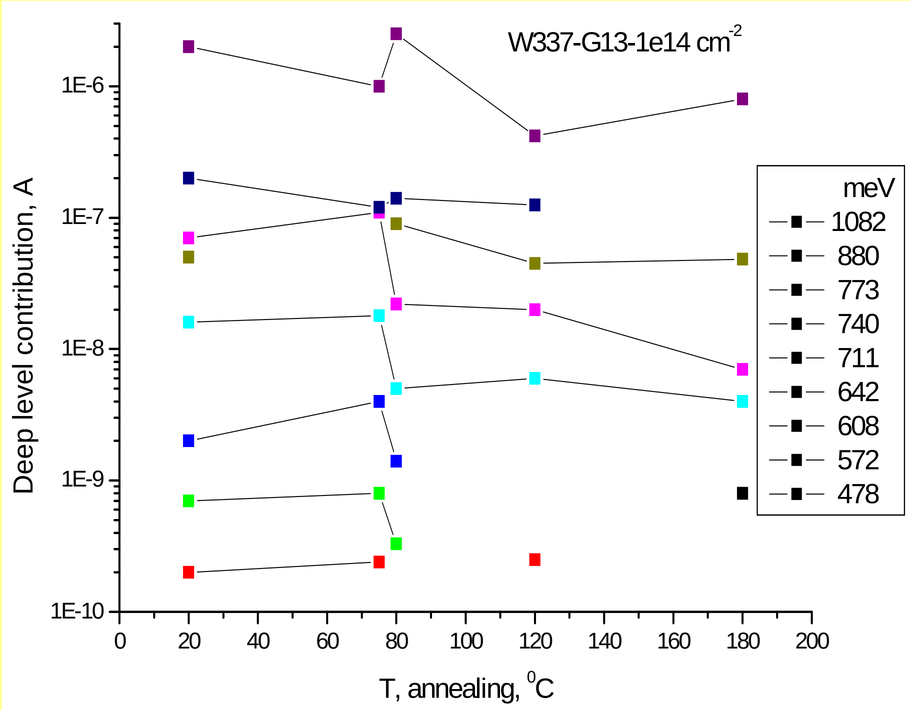




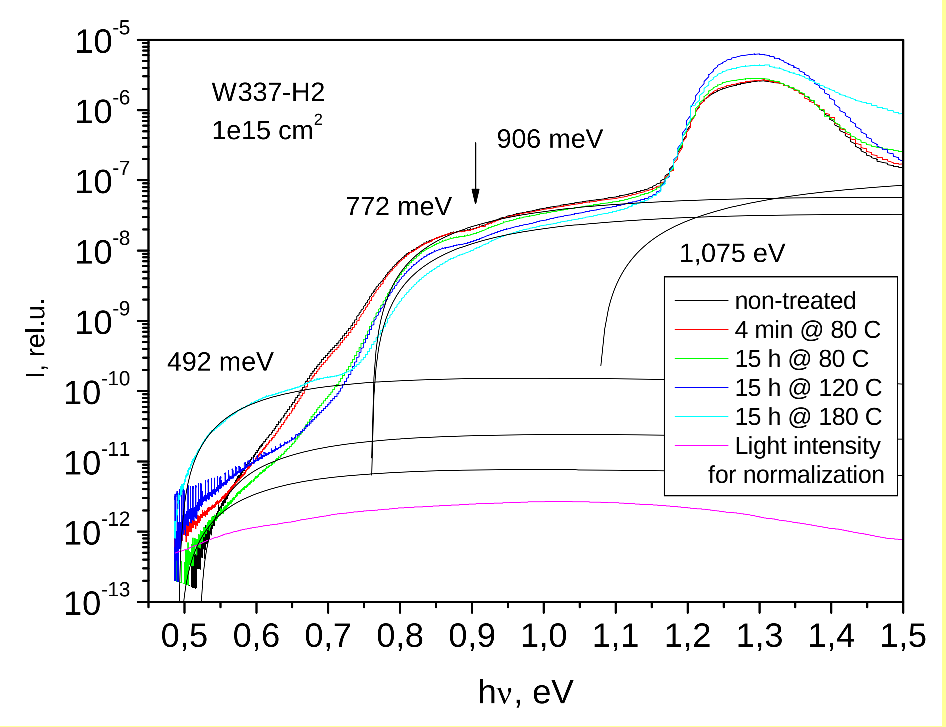
The similar dependence of inverse lifetime on the local level concentration shows their role in the recombination. The deviation from the coincidence can be caused by two step excitation of e-h pairs and PC quenching

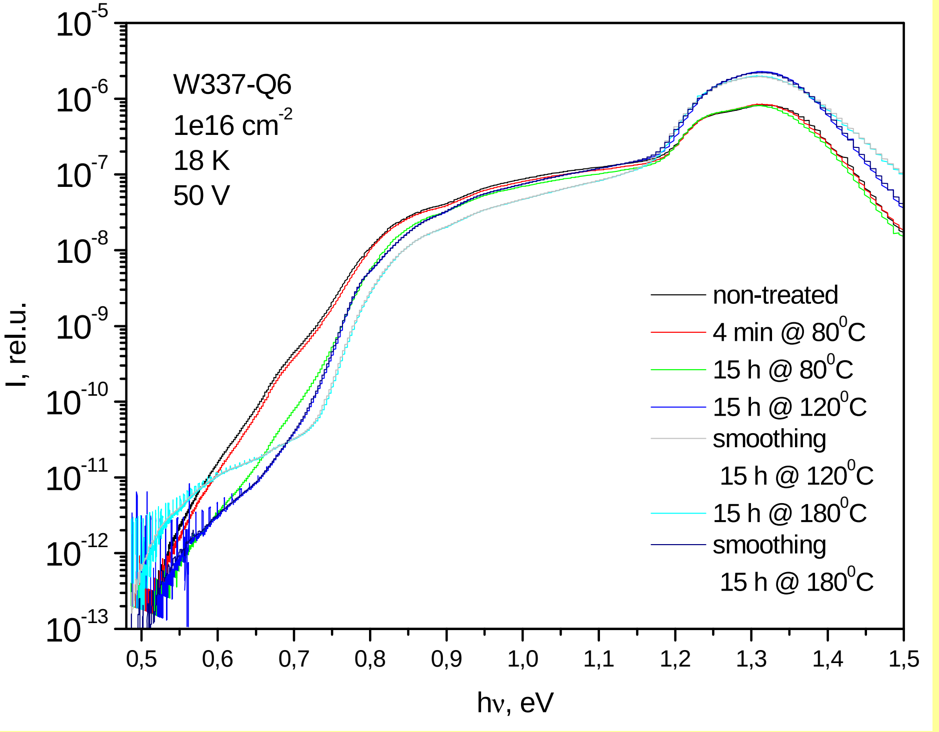
Deep level contribution dependence on annealing



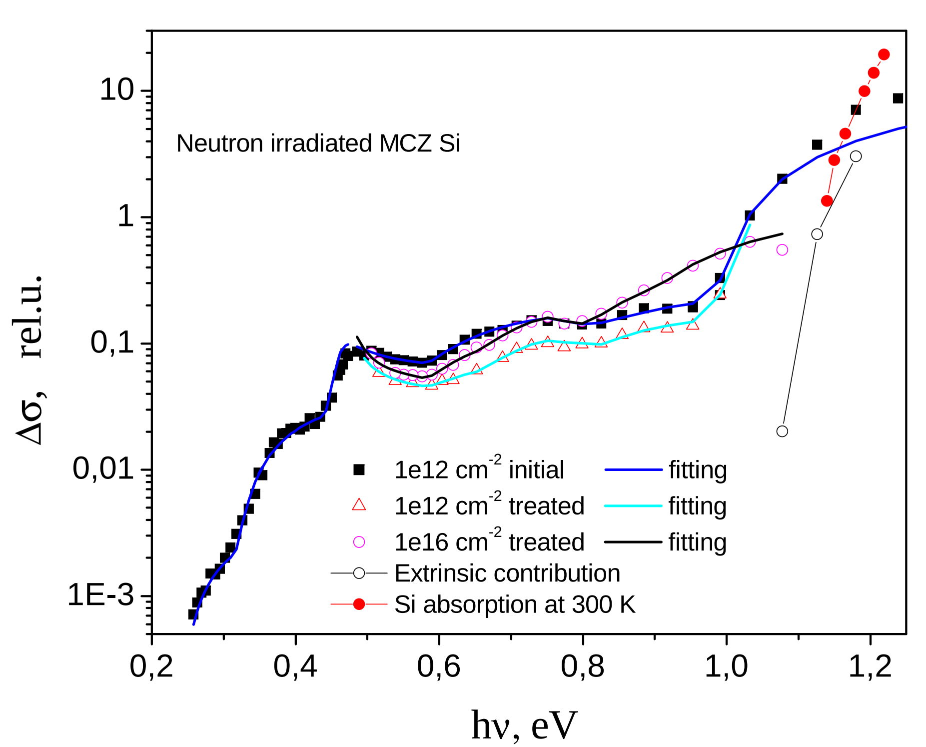


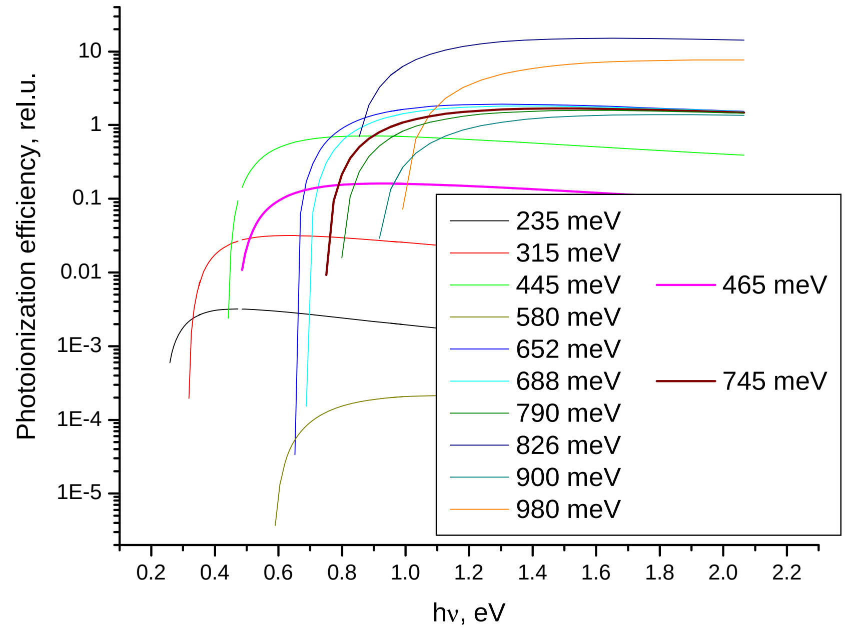
Annealing effects in the samples irradiated to fluence 10^{15} and 10^{16} cm^{-2}





PC spectra @ T=300 K:
dots – experimental, lines - approximation





- quenching 465 meV and 745 meV
- col(**235**)+col(**315**)+col(**445**) +col(**580**) + col(**652**)+ col(**790**) +col(**826**)+col(**900**)+col(**980**)

Initial 1re12 cm-2

- **0,006 + 0,08 + 2,5 + 9 + 30 + 0 + 20 + 0 + 2400**

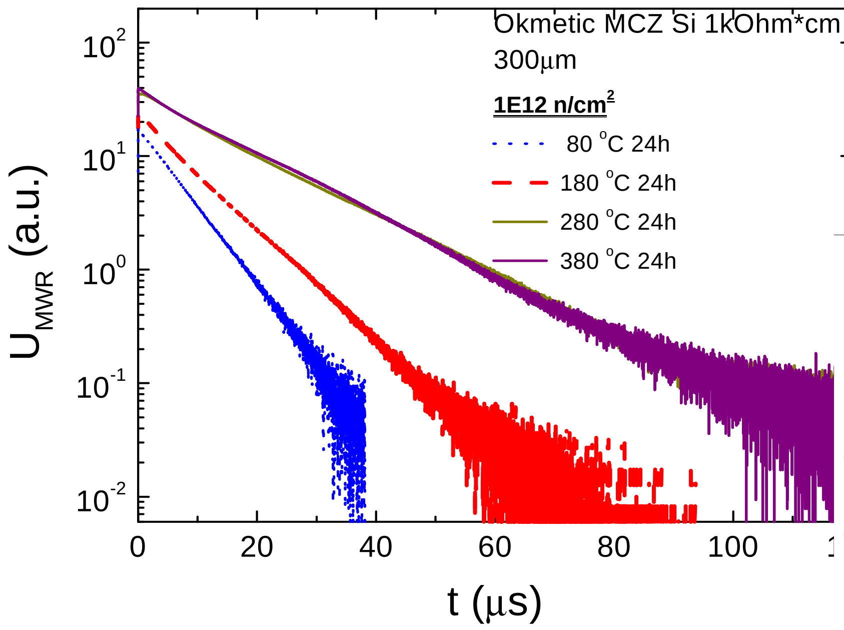
Treated 1e12 cm-2

- **0,006 + 0,08 + 2,5 + 6 + 5 + 0 + 1 + 5 + 900**

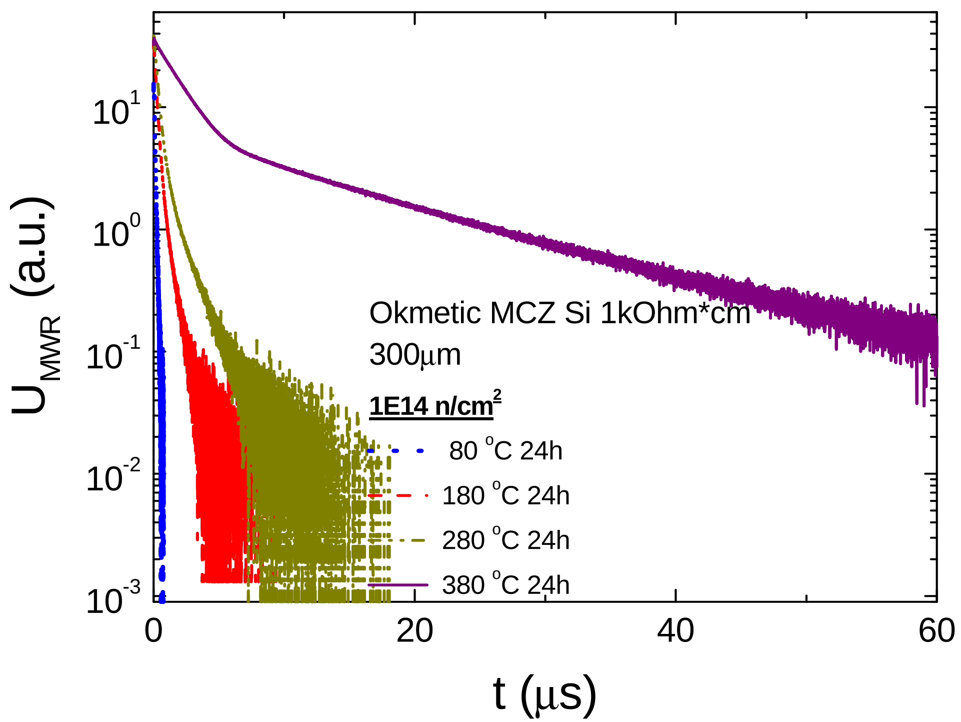
Treated 1e16 cm-2

- **0,006 + 0,08 + 22,5 + 80 + 100 + 1100 + 600 + 3000 + 120**

PC decay



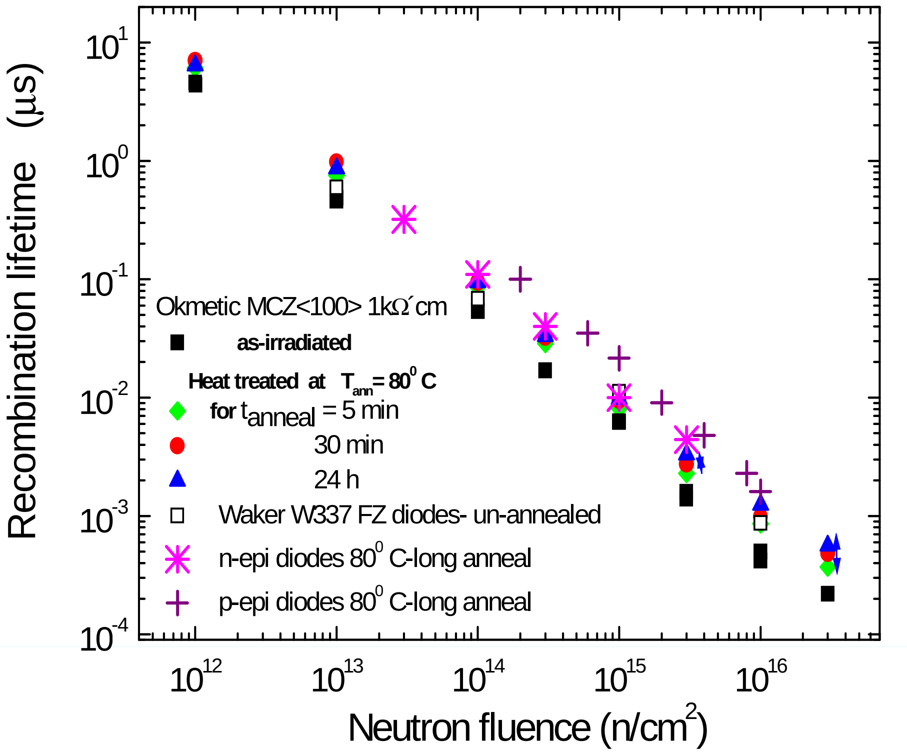
Transients when recombination dominates

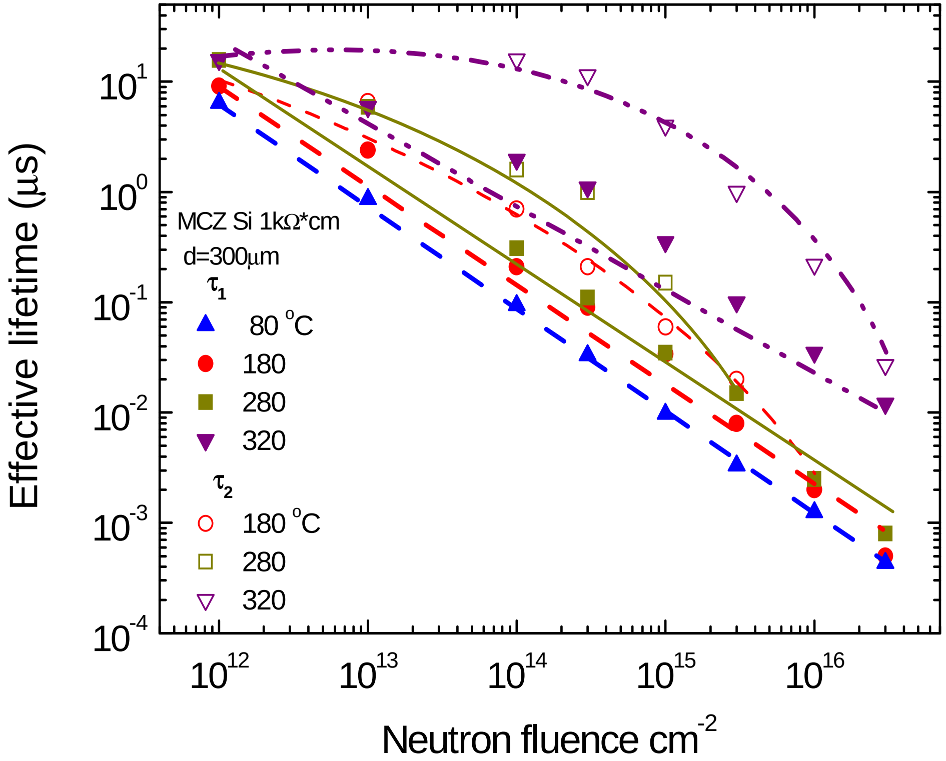


Transients when recombination and trapping compete

Fluence and anneal dependent recombination and trapping

Measurements performed at 1062 nm 500 ps excitation

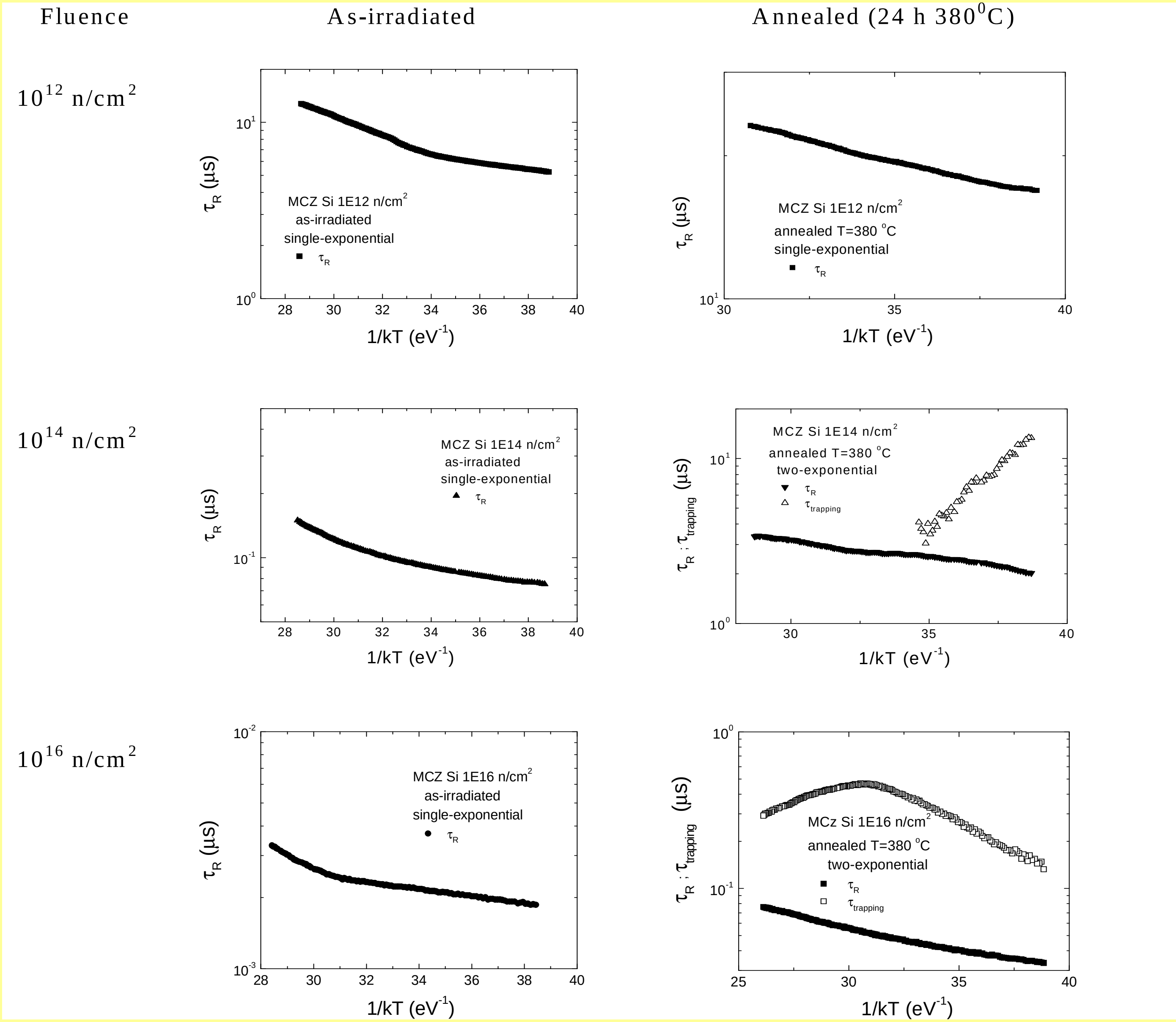




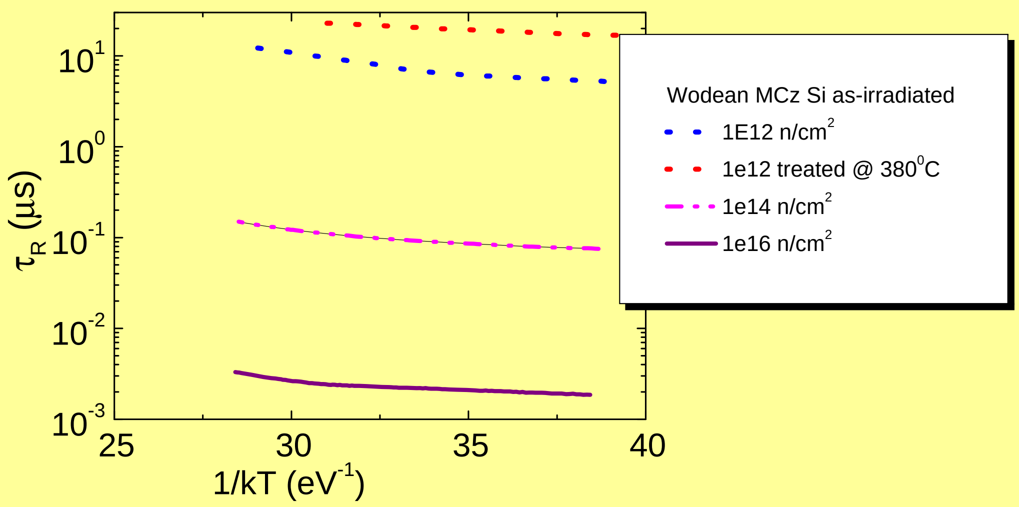
Comparison of the fluence dependent recombination lifetimes in the as-irradiated and isothermally at 80 ⁰ C annealed for 5, 30 and 1440 min Si structures

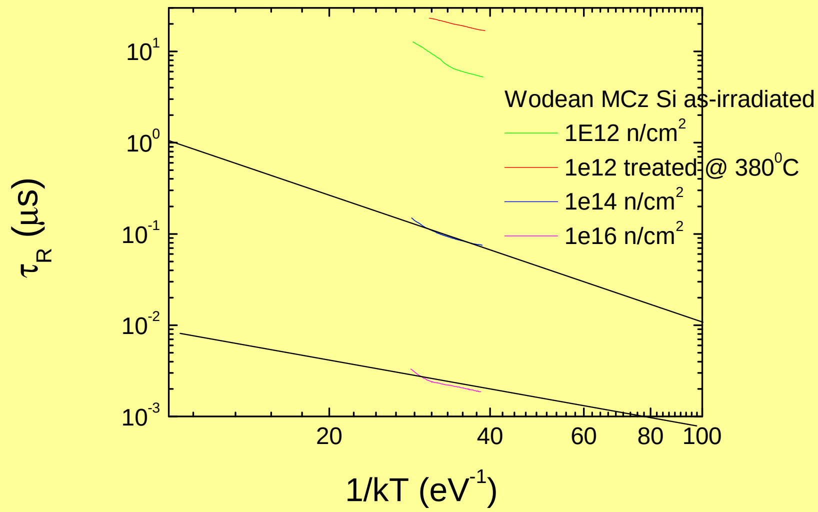
Fluence dependent recombination (τ_1) and trapping (τ_2) effective lifetimes in the isochronally annealed for 24 hours Si wafers varying temperature in the range from 80 to 320 ⁰ C.

Recombination and trapping lifetimes vs. T in carrier decay temperature scans



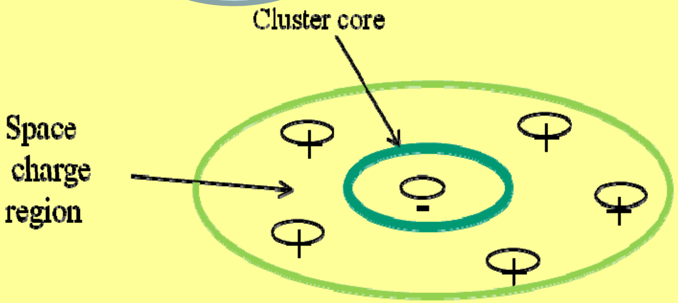
Analysis of recombination lifetime dependence on T

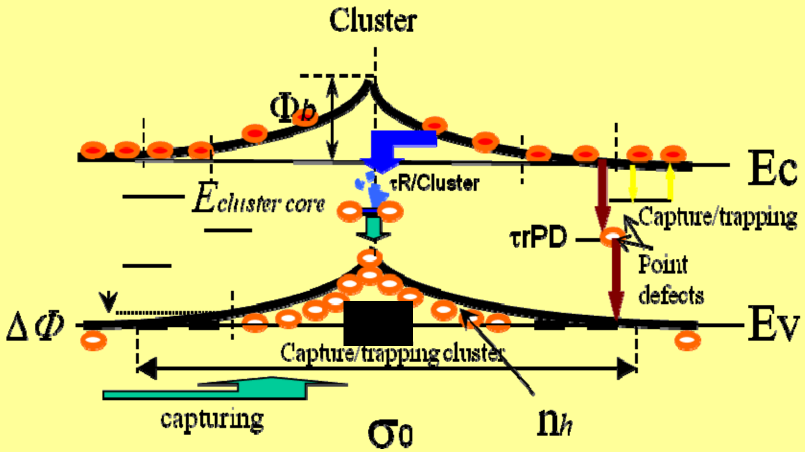


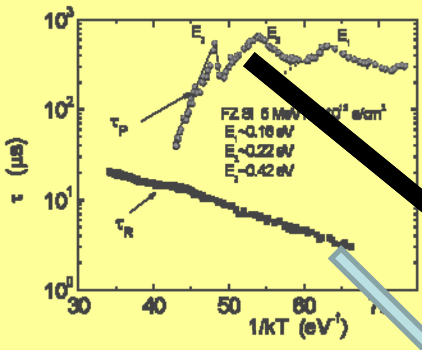


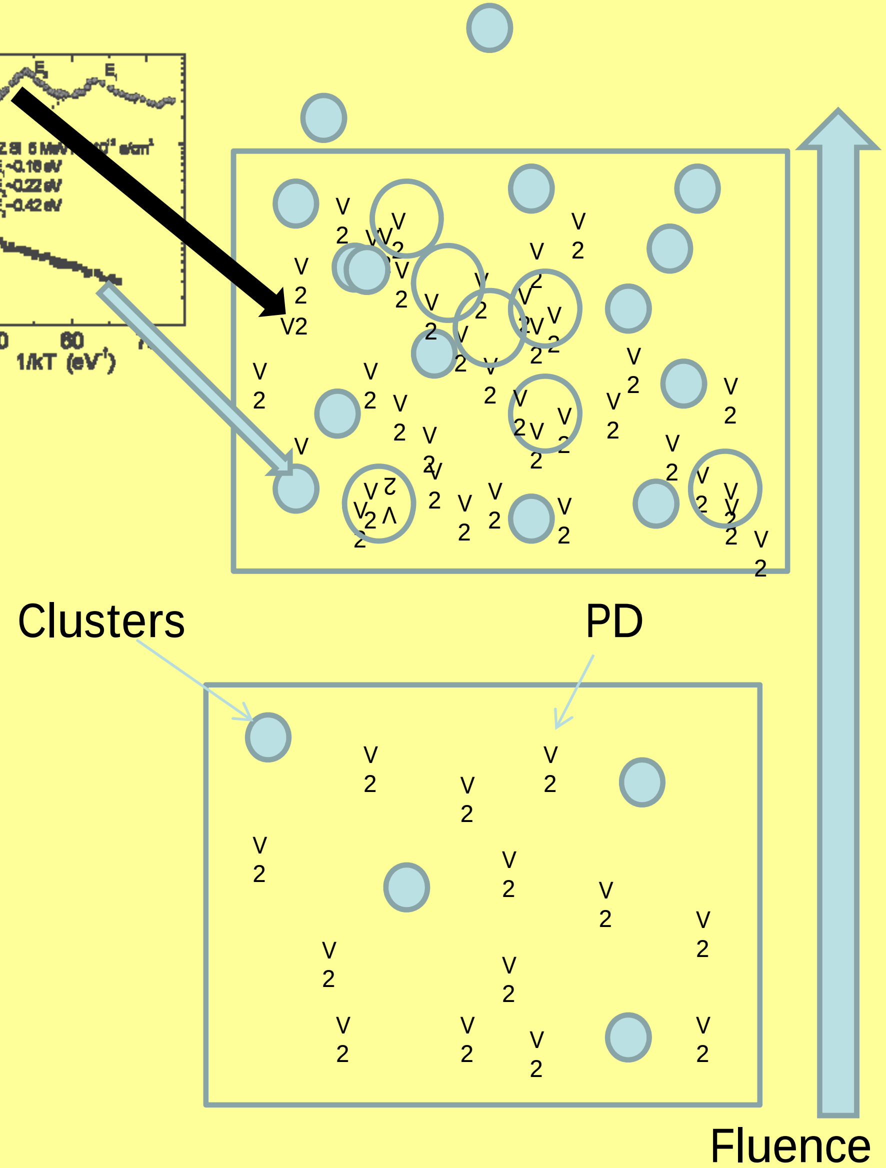
Simulations of neutron interaction with the silicon crystal indicate crystal damages of 0.1 µm dimension which is less than the Debye length. Hereby, this region acts as an extended cluster-like recombination centre. The cluster can be assumed as a volume with inner defective surface which causes carrier diffusion from crystal and subsequent recombination at cluster boundary. The effective lifetime τ_{Reff} for infinite velocity of surface recombination is determined by the minority carrier limited diffusion time $\tau_D = \pi^2 D_m/d^2$, as $1/\tau_{Reff} = 1/\tau_{Rcryst} + 1/\tau_D$. Here, D_m is a diffusion coefficient of holes (minority carriers), d – is an averaged distance between the clusters, and τ_{Rcryst} is bulk recombination lifetime in crystal. According to literature data [8-10], the distance d changes from 200 µm to 20 nm, when fluence increases from 10^{12} cm$_{-2}$ to 10^{16} cm^{-2}, respectively. Analysis of τ_R dependence on temperature, in assumption that $\tau_R \approx \tau_{Reff}$, and τ_{Reff} variations with temperature is mainly determined by a function $D_m=f(T)$, gives an exponential function $\tau_R \approx \tau_{Reff} = T^{-n}$, with 1<n<2. This corresponds to the proposed $D_m(T)$ and explains a rather small activation factor, in contradiction to assumption of pure recombination on cluster with deep levels ascribed.

Qualitative understanding of trapping

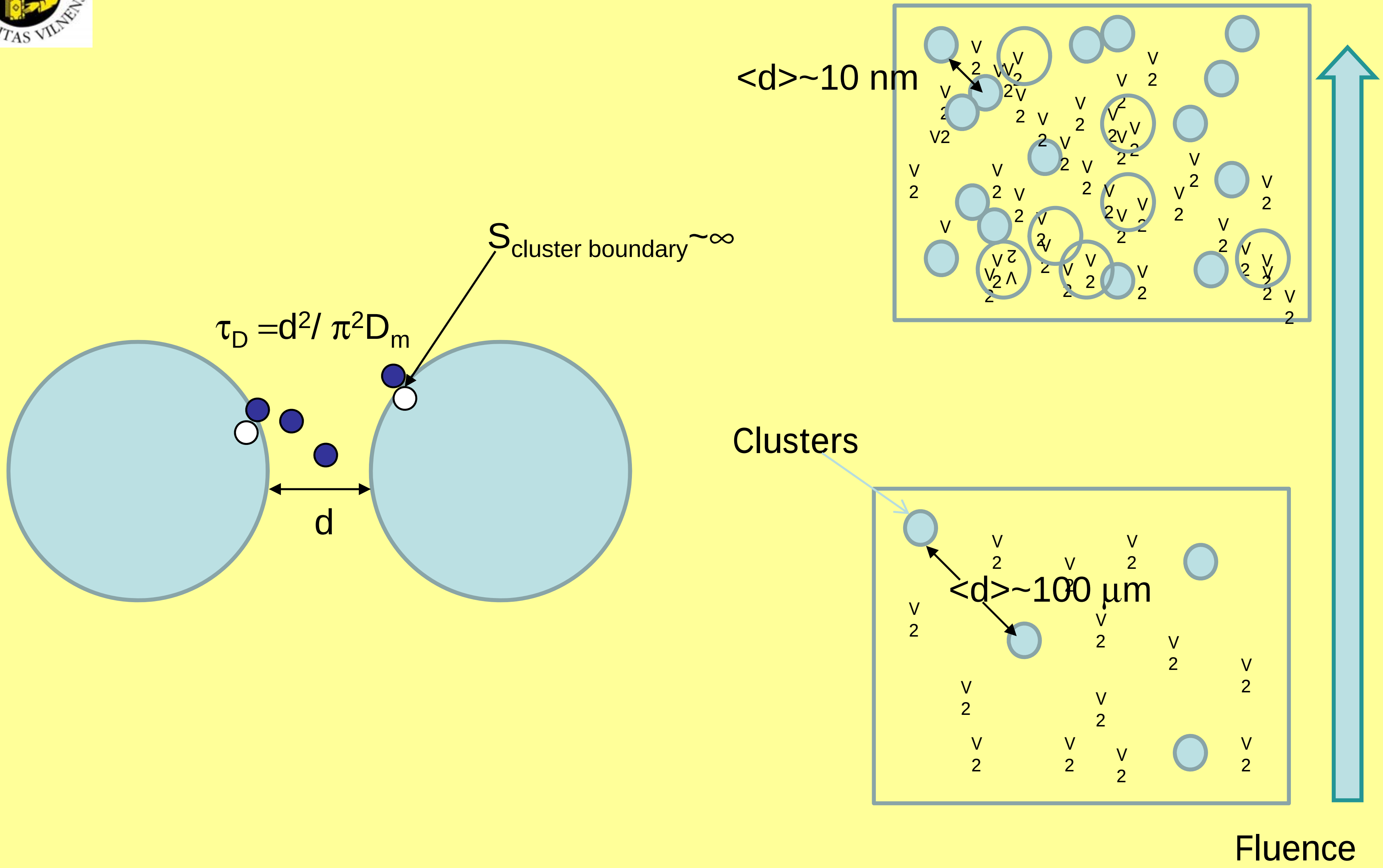








Qualitative understanding of recombination due to clusters



Conclusions:

- Photoconductivity spectral dependence allows to control the general changes of the local levels system in the irradiated and annealed Si.
- PC persistent behavior and linear dependence of recombination lifetime on irradiation demonstrates the microinhomogeneity of irradiated material.

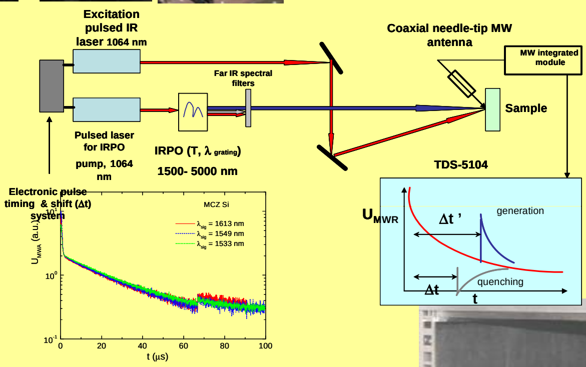
Spectroscopy techniques and instruments

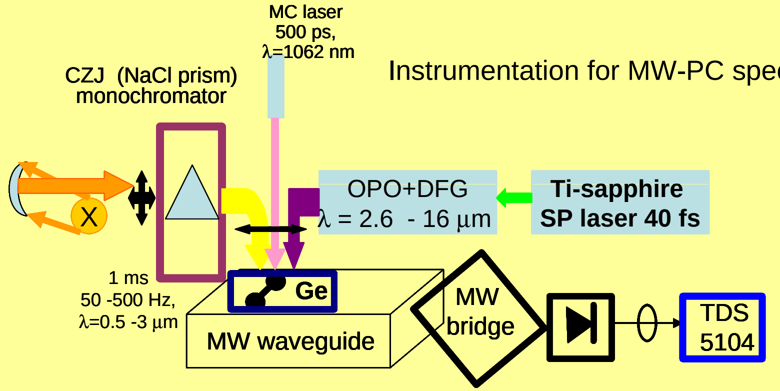
Microwave probed Photoconductivity (MW-PC) Transient Technique:

- **lateral and cross-sectional scans;**
- **temperature scans;**
- **pulsed MW-PC spectroscopy (MW-PCS)**

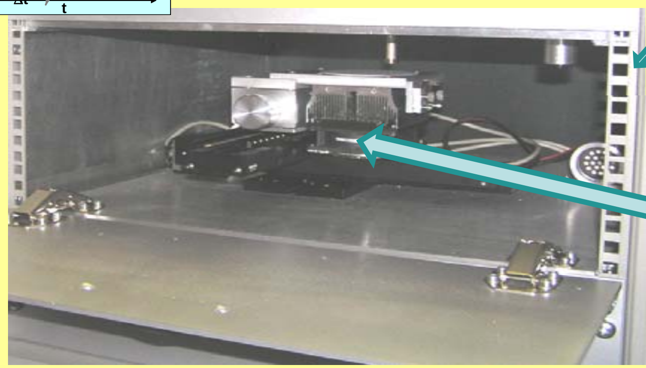
E.Gaubas. Lith. J. Phys. **43** (2003) 145

Instrumentation for MW-PC spectroscopy



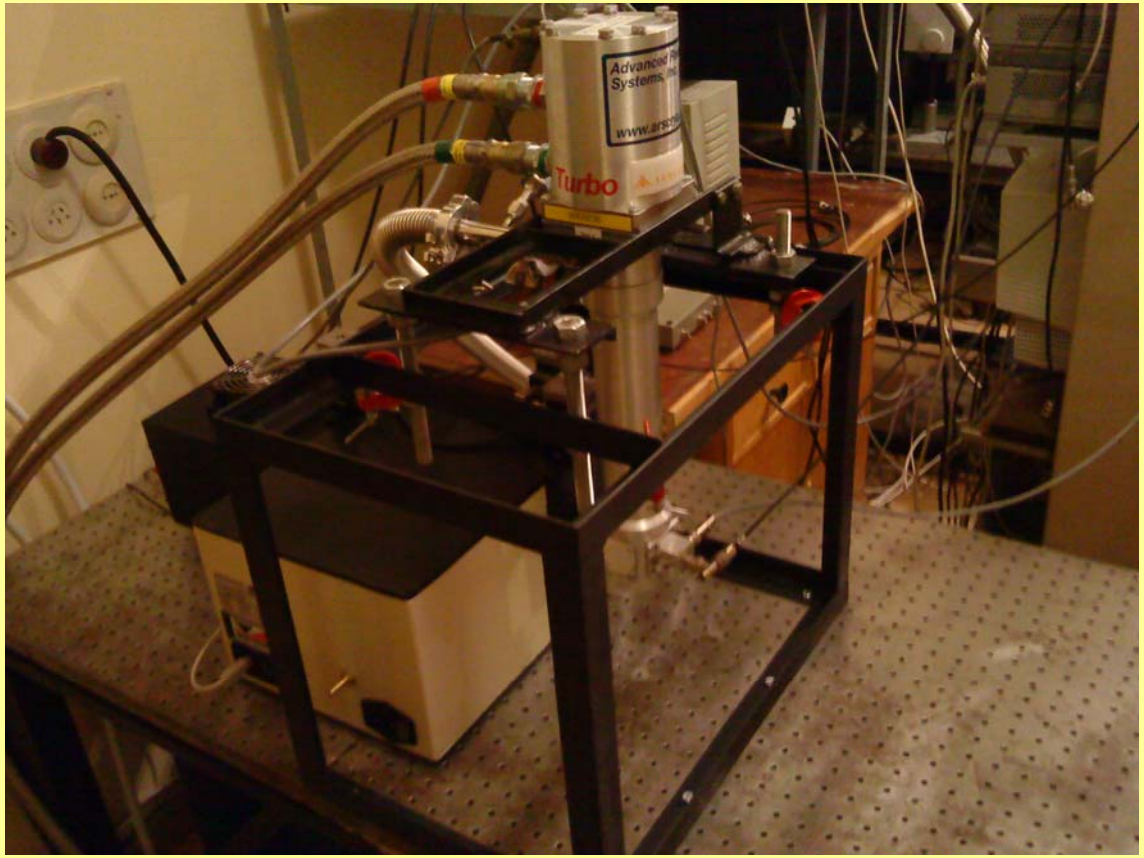


Instrumentation for MW-PC spectroscopy

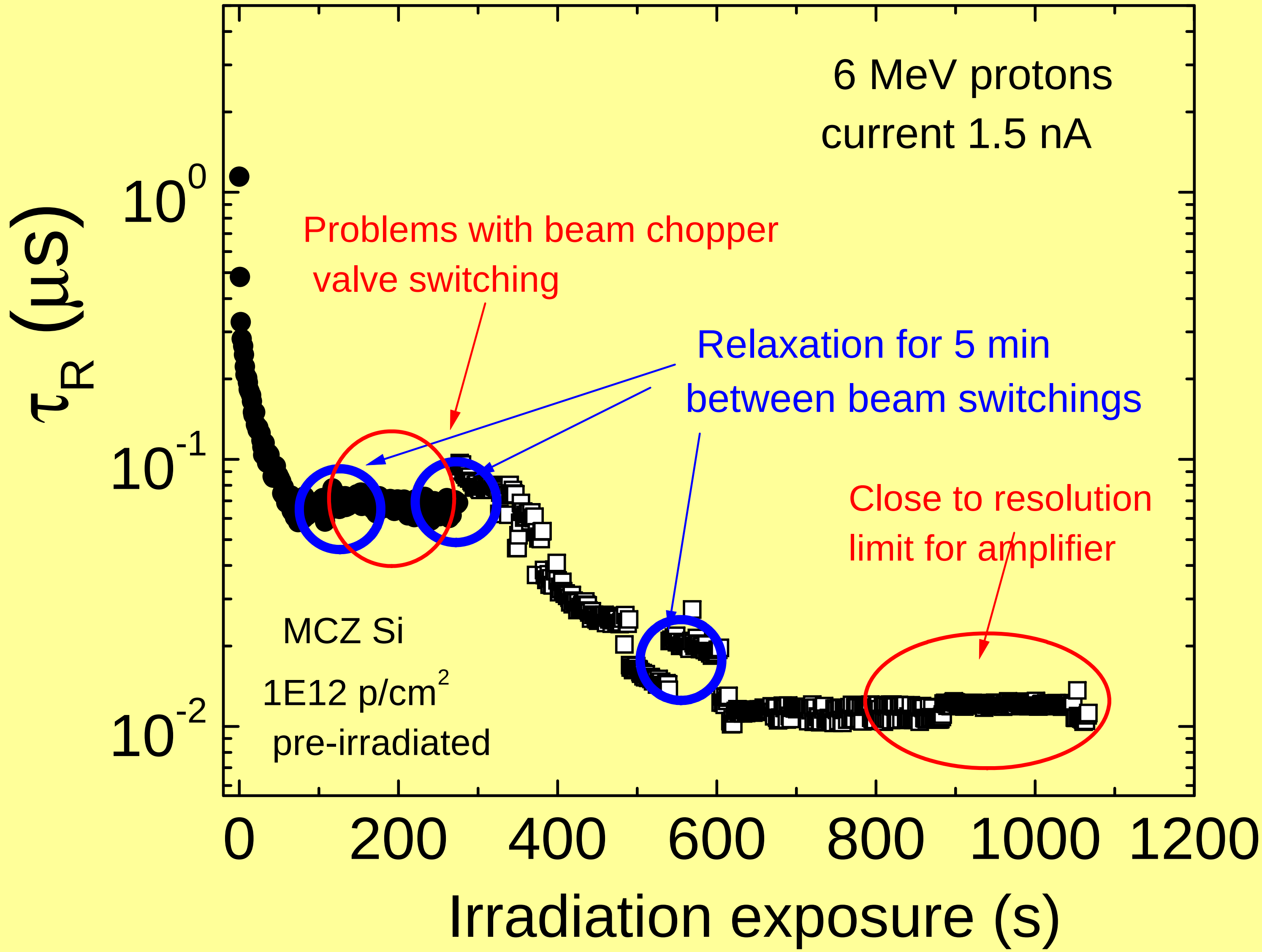


Temperature scans

PC spectra measurement facility



Preliminary results of measurement in situ during the proton irradiation the lifetime measurements



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