Deep levels roles in non-equilibrium conductivity in irradiated Si

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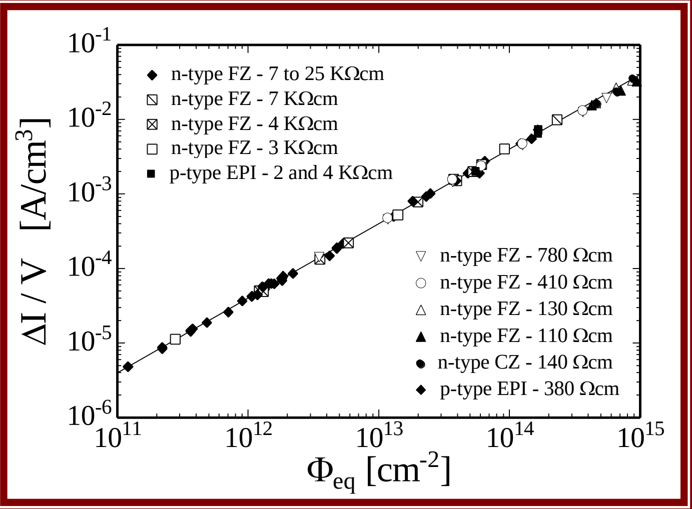
Outline:

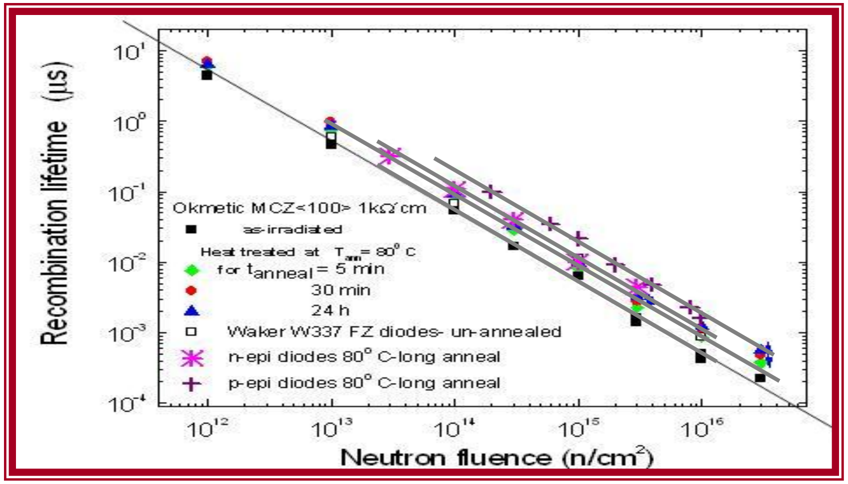
- Introduction: the purpose of the work:
  - This presentation is similar to our talk at RD50 at CERN (different sample type).
- Peculiarities of:
  - Electrical conductivity;
  - Photoconductivity;
  - Thermally stimulated current.
- Conclusion.

Investigation of DLTS, TSC in the diode structures reveals many different traps in irradiated p-Si and n-Si structures, **and they change with the fluence non-monotonous.**

The reverse current [Lindstrom G., Moll M., Fretwurst E. Radiation hardness of silicon detectors - a challenge from high-energy physics. NIMA 426, 1999, 1-13 p.] and free carrier lifetime [E. Gaubas, T. Čeponis, A. Uleckas, J. Vaitkus. Anneal dependent variations of recombination and generation lifetime in neutron irradiated MCZ Si. NIMA 612, 2010, 563-565 p.] linearly depend on the fluence in a wide range of fluence.



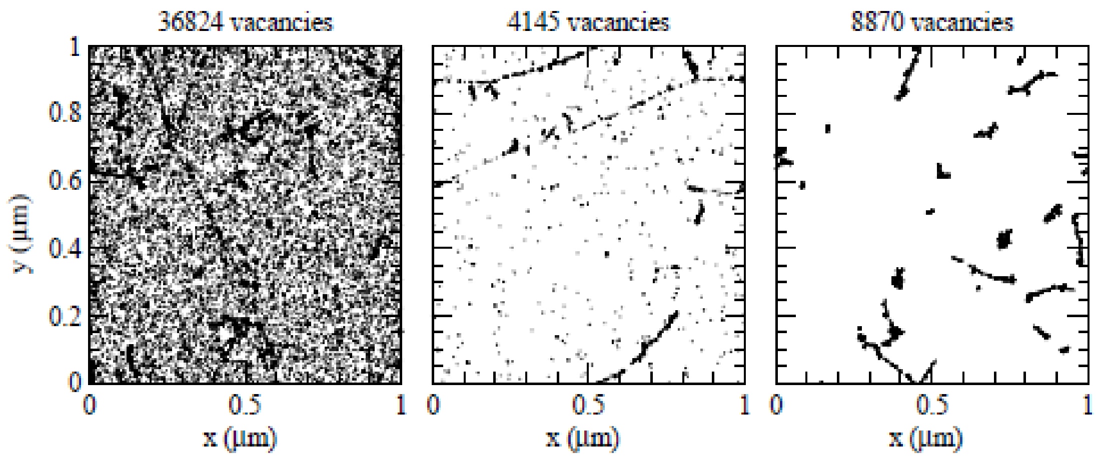
$$\frac{1}{\tau} = \gamma P_R = aF$$



It shows a single factor – a deep centre - is responsible for the lifetime dependence. (Annealing change the details but not a general trend.)

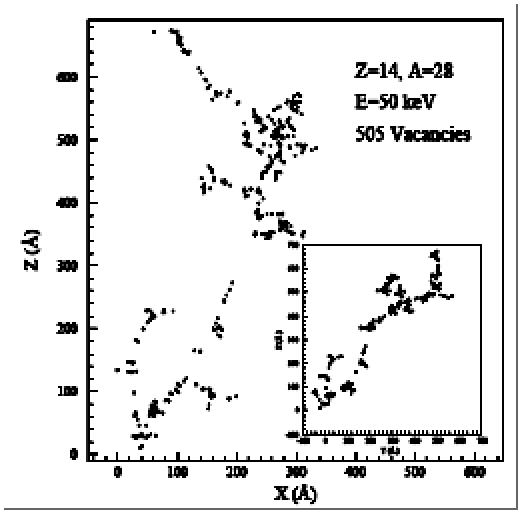
Most easy to relate it to the clusters and **the diffusion-drift time** of the carriers to the cluster. **In what way could it happen?**

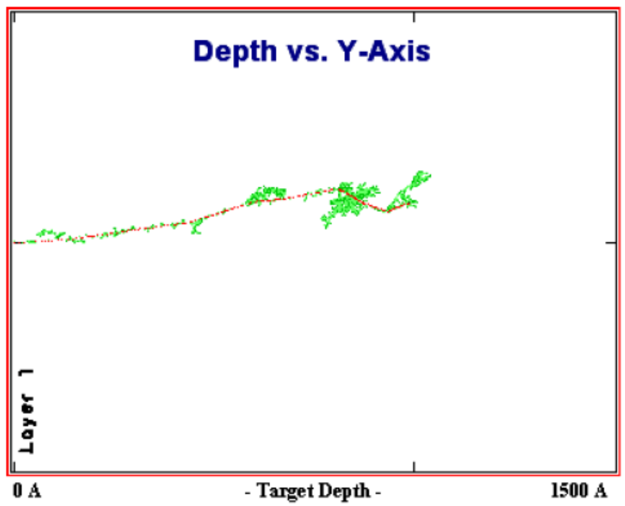
Back to modeling of defect generation



One cluster:

Vacancies generated by 10 MeV protonais, 24 GeV/c protonais (middle) ir 1 MeV neutronais. Fluence: 10^{14} cm^{-2} . [M.Huhtinen. NIMA 491 (2002) 194–215]





- **General points.**

TRIM calculation. A 50 keV ion creates a cluster about 100 nm length in a time of 20 fs. (one vibrational period).

The energy deposited gives a high temperature (up to ~1000 K).

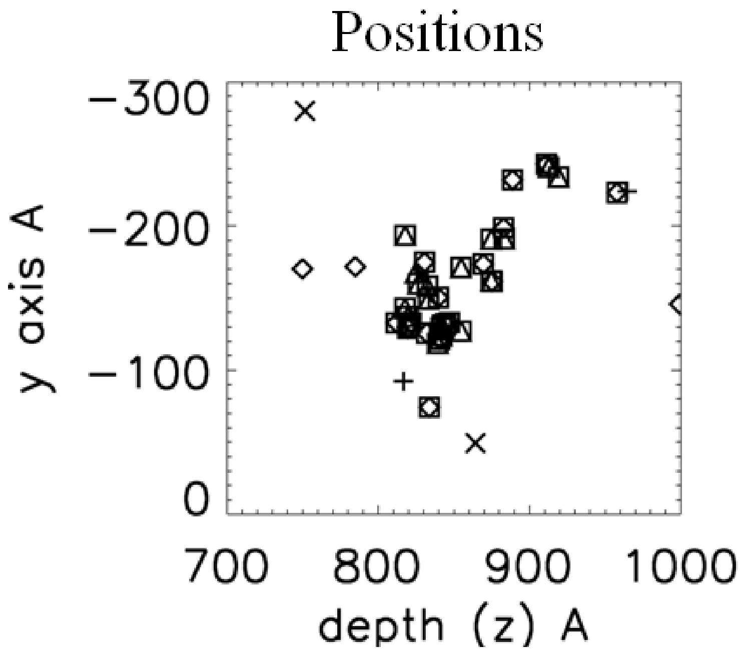
No impurities present: if [O] = 10^{18} cm^{-3}, may have 1 O atom in the cluster.

Following the WODEAN (Bucharest) 1.

After random walk (Time nano- to milli-seconds)

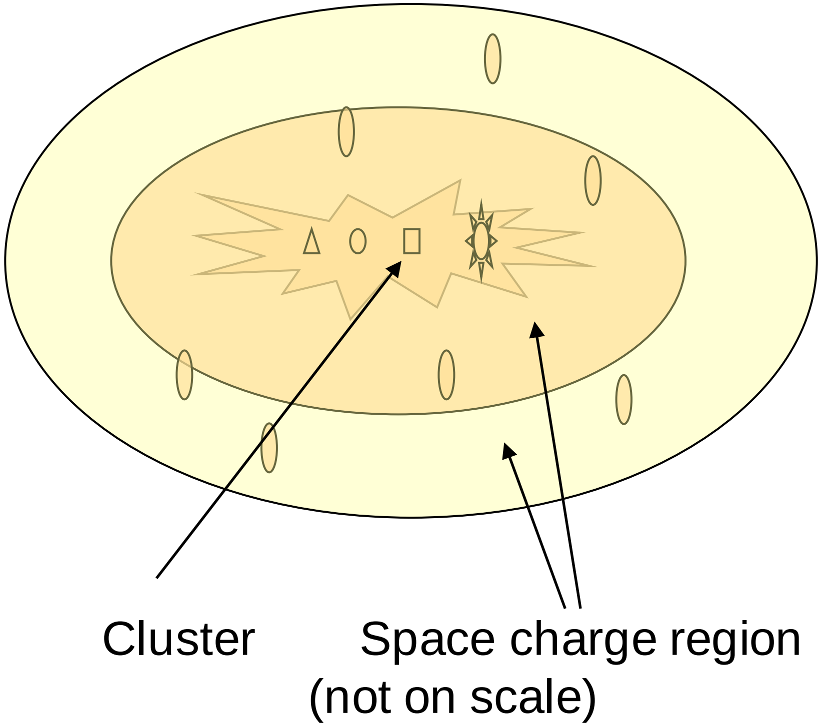
I (X)   V (+) I_2 (♦) V_2 (Δ)

I-clusters (♦) and V-clusters (Δ) in squares



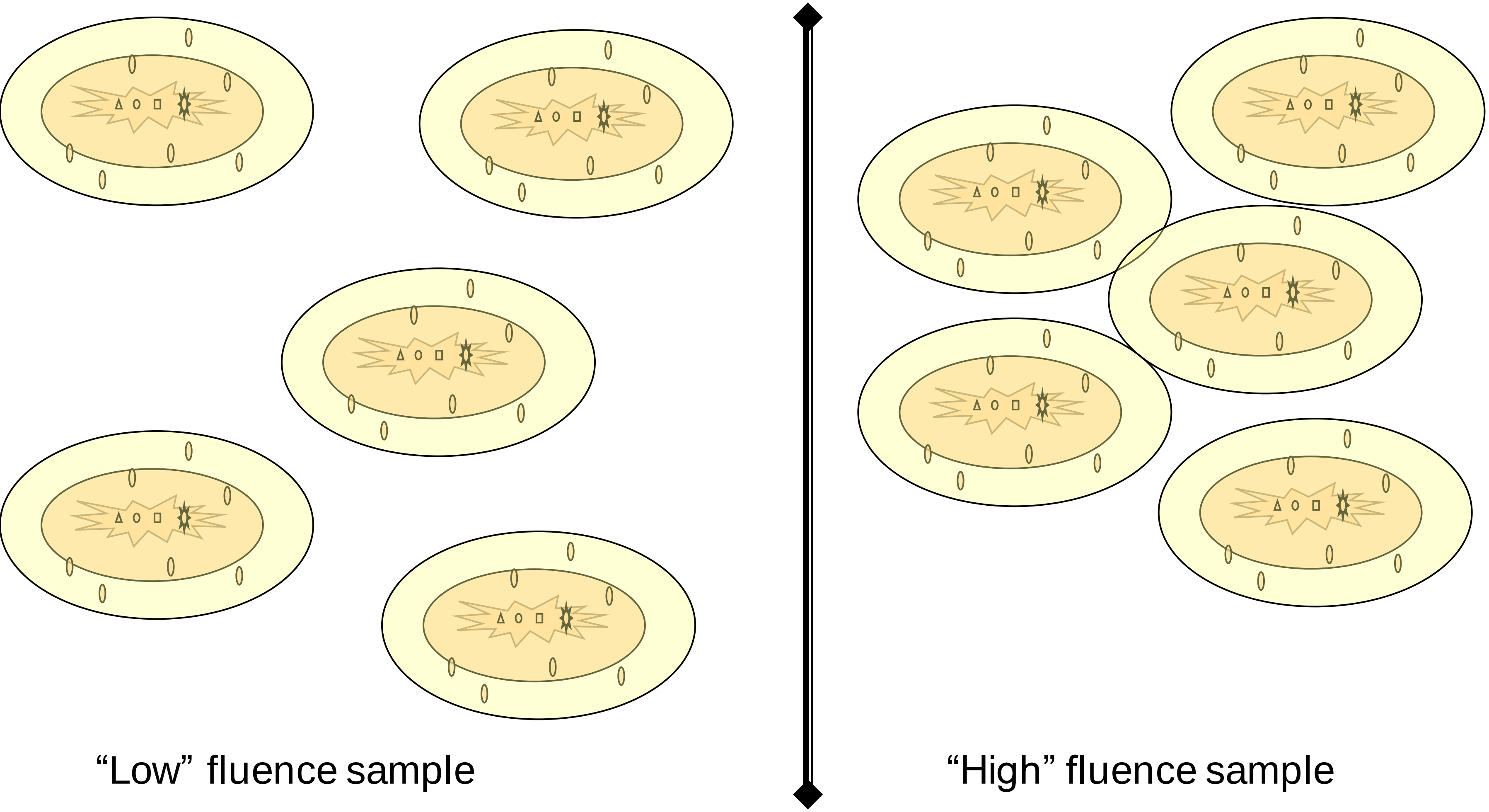
Reconstruction of the cluster in a cube.
G.Davies, RD50 WODEAN conference, Bucharest:

Approximation:



Following the WODEAN (Bucharest) 2.

(neutron irradiation) the sample consists the specific defects

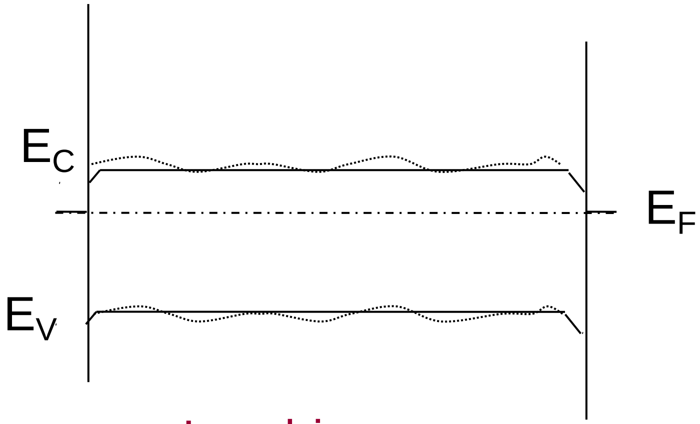


“Low” fluence sample

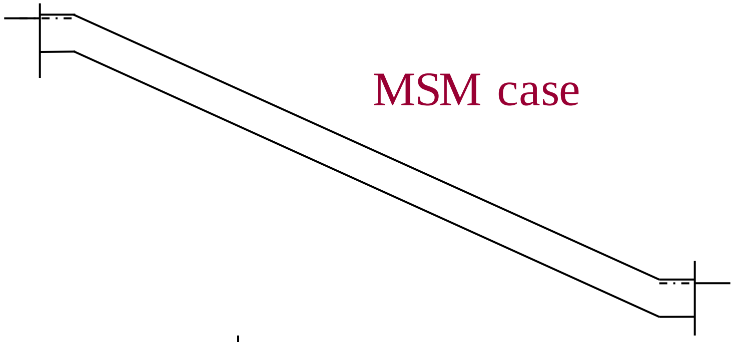
“High” fluence sample

n*-n-n*, p*-i-n* structures

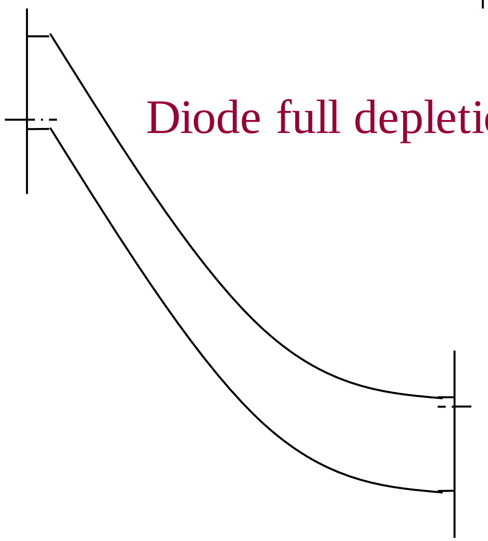
Our choice – homogeneous samples with neutral contacts.
The main aim: to show if this modulation is significant.



Low bias



MSM case



Diode full depletion

- Deep levels as recombination centers
- Shallow levels as trapping centers
- Deep levels as generation current origin
- Barrier and bulk region contributions (diode case)
- Conductivity and valence bands modulation by micro-inhomogeneities

Samples (WODEAN):

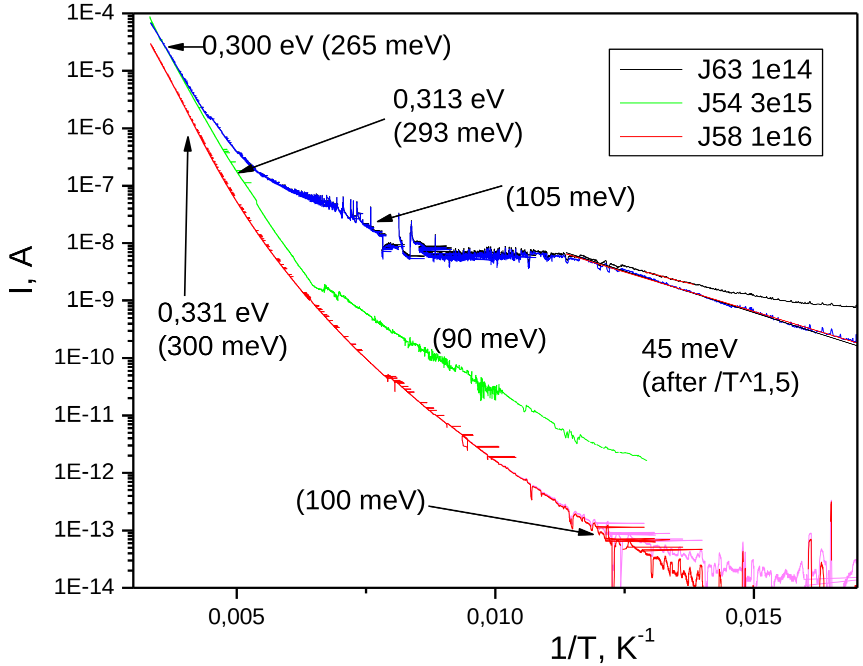
A 1 kΩcm n-MCz <100> silicon wafer was irradiated with reactor neutrons at the research reactor of the Jozef Stefan Institute in Ljubljana. The fluence was normalized to the equivalent fluence of 1 MeV neutrons.

Samples were fabricated for the Hall effect investigation were fabricated by cutting the wafer into 7 mm x 2 mm x 0.28 mm bars and the colloidial carbon planar contacts were processed.

The contact properties were controlled from the linear current dependence on bias voltage. (Linear I-V and trend to superlinear at higher bias)

The thermally stimulated conductivity, excited by the light, and photoconductivity were investigated in the same Hall samples.

Dark current = F(T) (WODEAN samples)

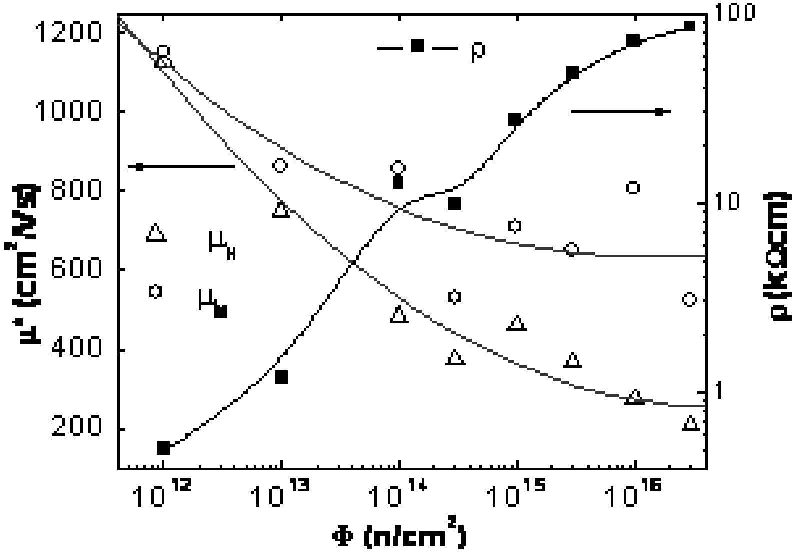


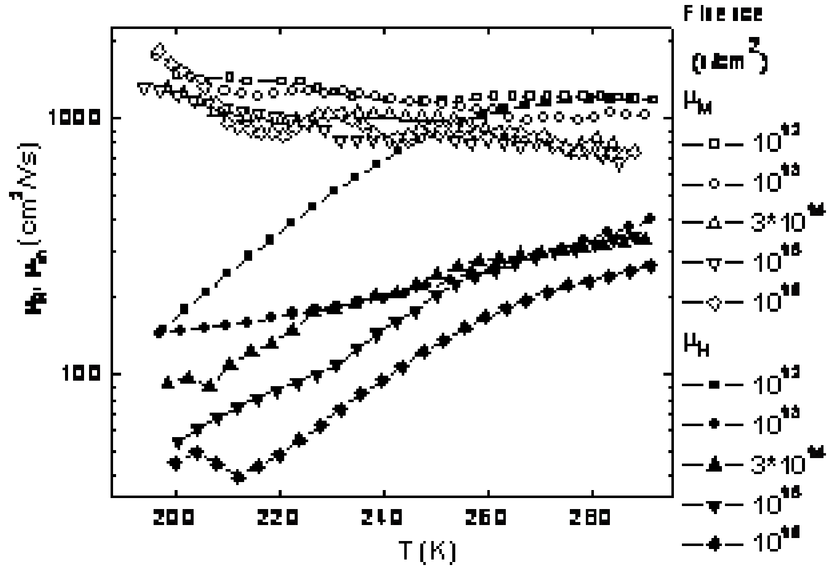
45 meV - P dopant

100 meV - (?)

300 meV - “main” centre, and up to 30-90 meV extra barrier

Peculiarity 1): Hall effect





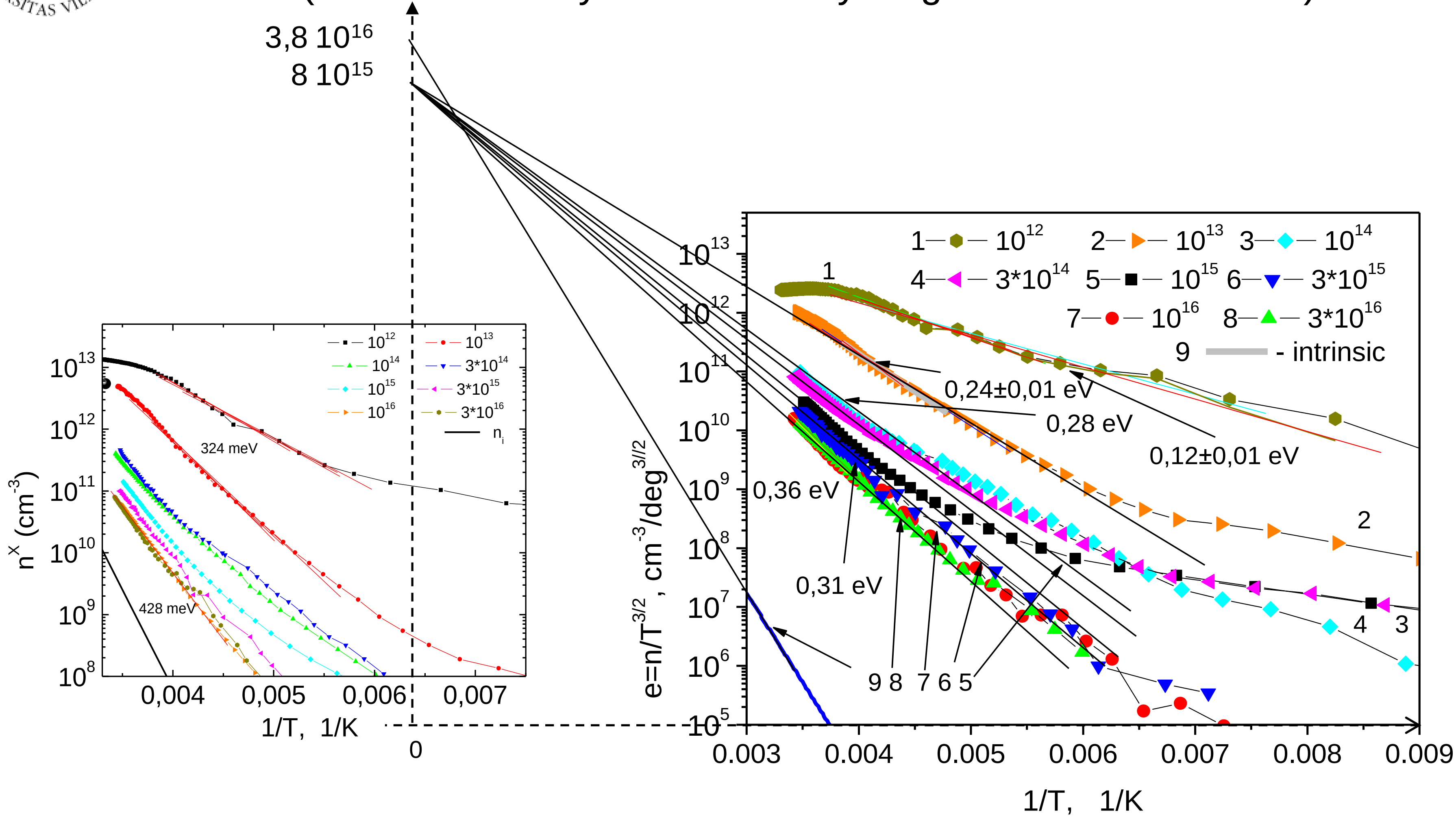
Hall effect temperature dependence shows the existence of inhomogeneity [Siegel W., Schulte S., Reichel C., Kuhnel G. , Monecke J. Anomalous temperature dependence of the Hall mobility in undoped bulk GaAs. J. Appl. Phys. 82, 1997, 3832]:

1) Hall mobility differs from magnetoresistance mobility (that follows the cluster scattering mechanism dependence ~T$^{-\sim 1}$);

2) Hall mobility decrease with temperature, probably due to the increase of resistance of the inhomogeneous regions.

Dark conductivity analyze

(electron mobility determined by magnetoresistance effect)



Electron concentration (a) and thermal excitation rate (b) dependence on temperature.

The thermal excitation asymptotes crossing at 1/T=0 is one of property of barrier surrounding the defect. (D.Lang, A.Strunk)

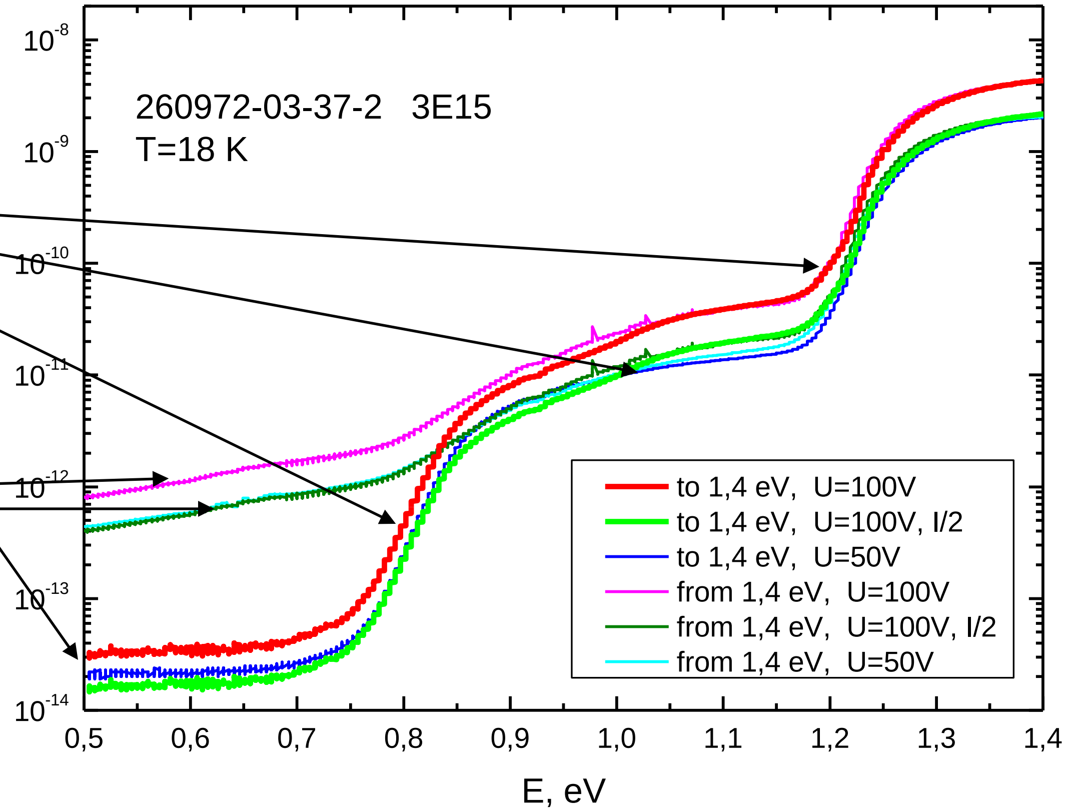
What could be expected in photoconductivity (PC)?

- An intrinsic edge of PC at ~ 0.35-0.4 eV
    - (F-C shift is ~ 50-70 meV in Si)
- The “stepped” PC at the deep level optical activation energy
- PC value has to be determined by the corresponding to an excited level lifetime, level filling and to be independent on the excitation pre-history.

What is observed?:
Peculiarity 2): Photoexcitation memory.

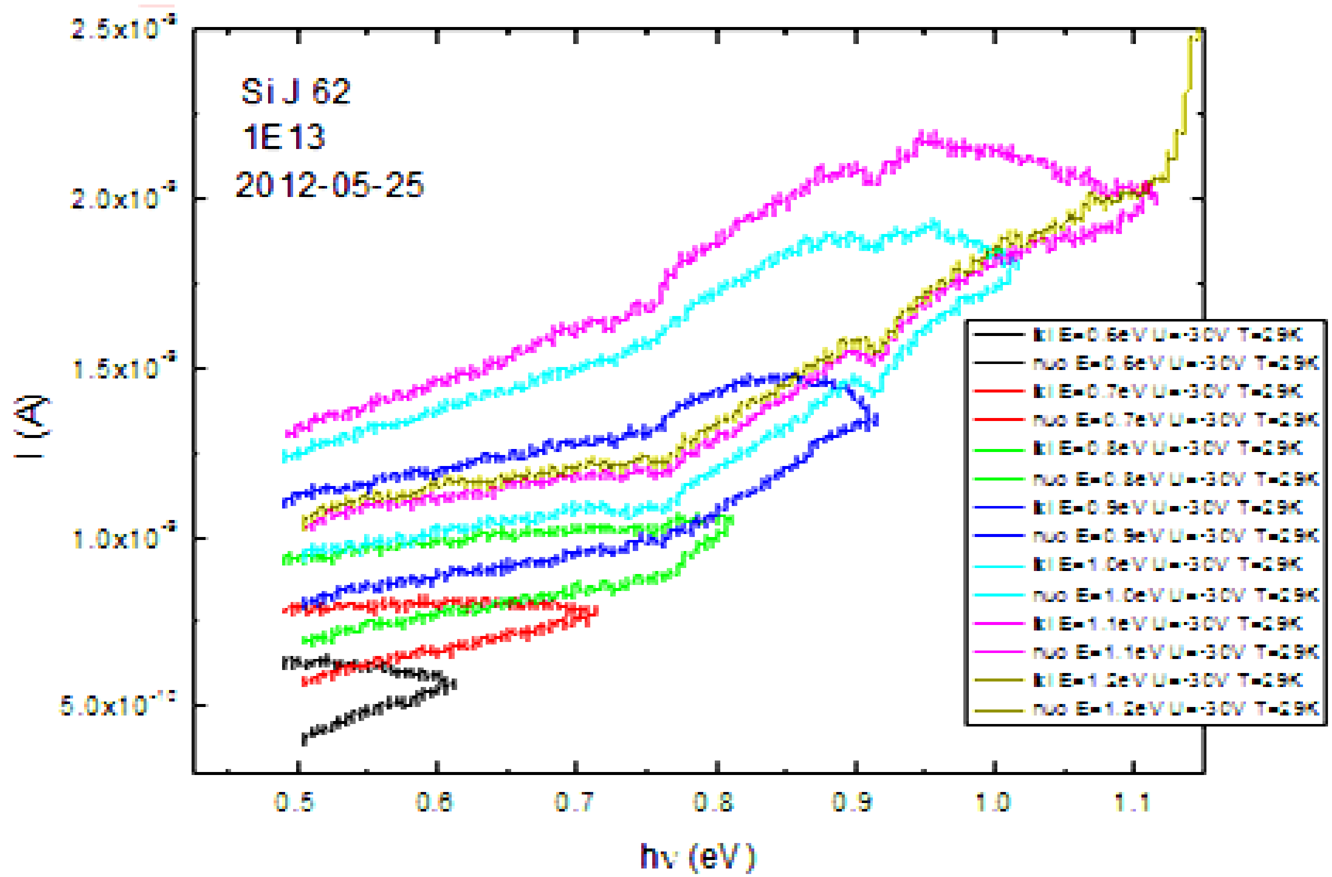
As it is near to that was predicted:

BUT:



- The photoresponse depends on a change of excitation wavelength direction during measurement in the extrinsic range if the light quantum energy is above 0.8 eV.
- I.e., there are the levels that influence on the micro-inhomogeneities barriers.

The details of spectra measurement

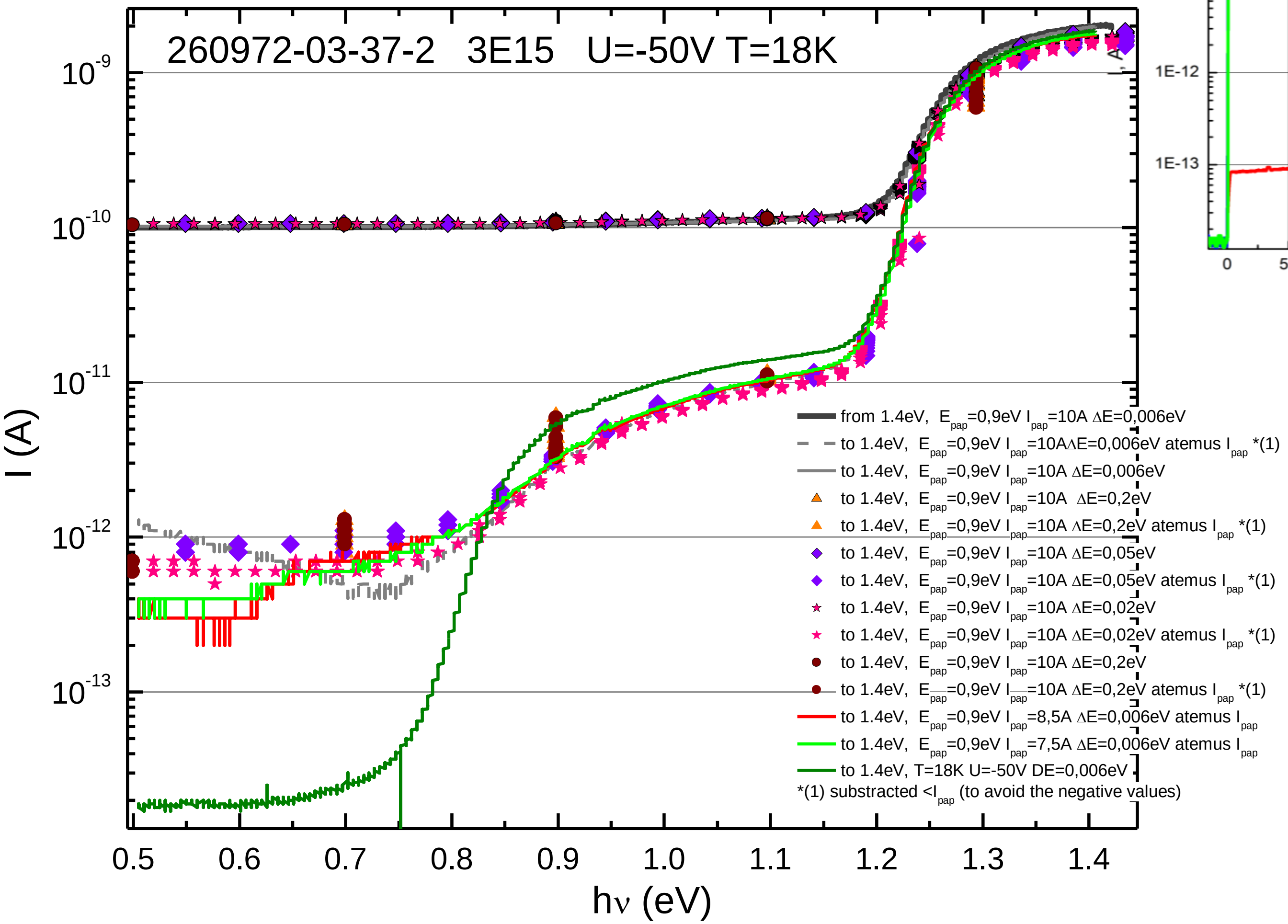


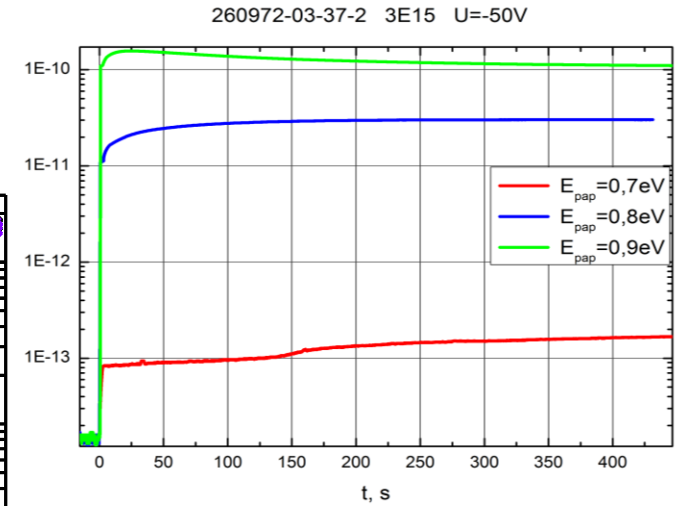
PC spectraq measured as a sequence of measurements without heating to the room T

Additional detail:

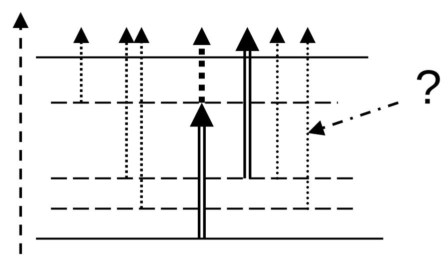
the reverse direction measurement in diodes showed near to coincidence if E<0,8 eV

Photoconductivity dependence in extrinsic excitation and the influence of additional extrinsic excitation on PC spectrum.

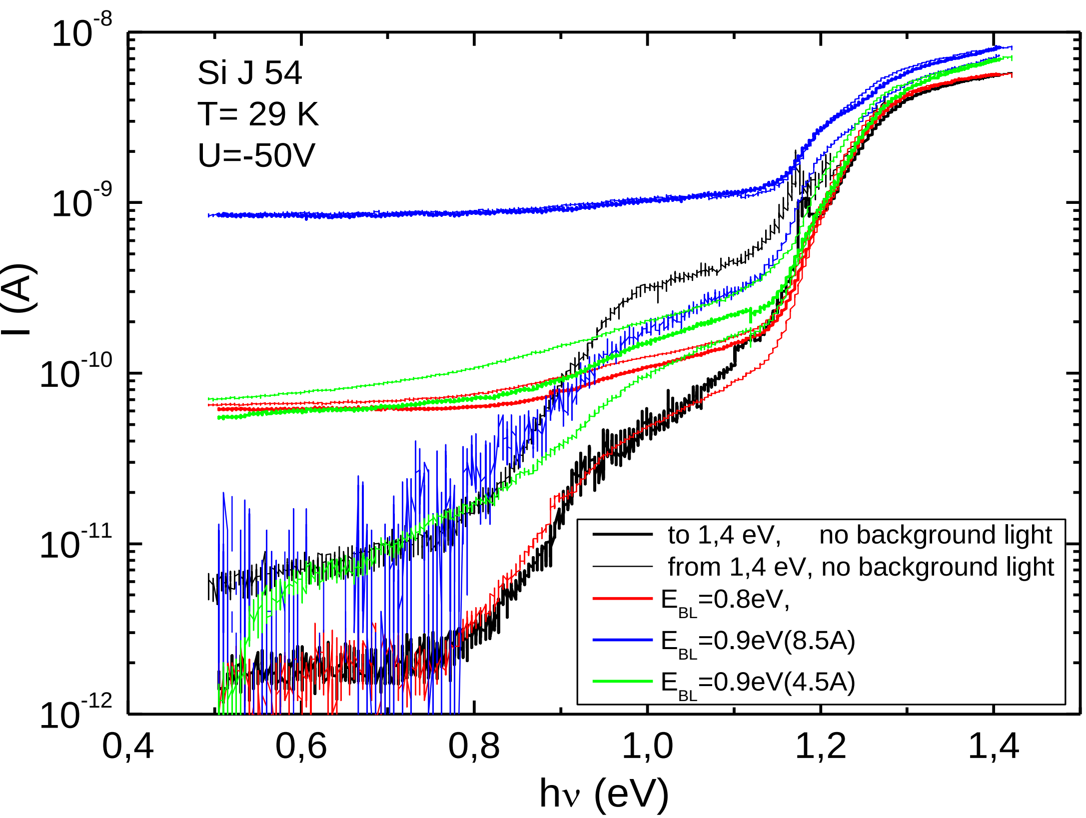


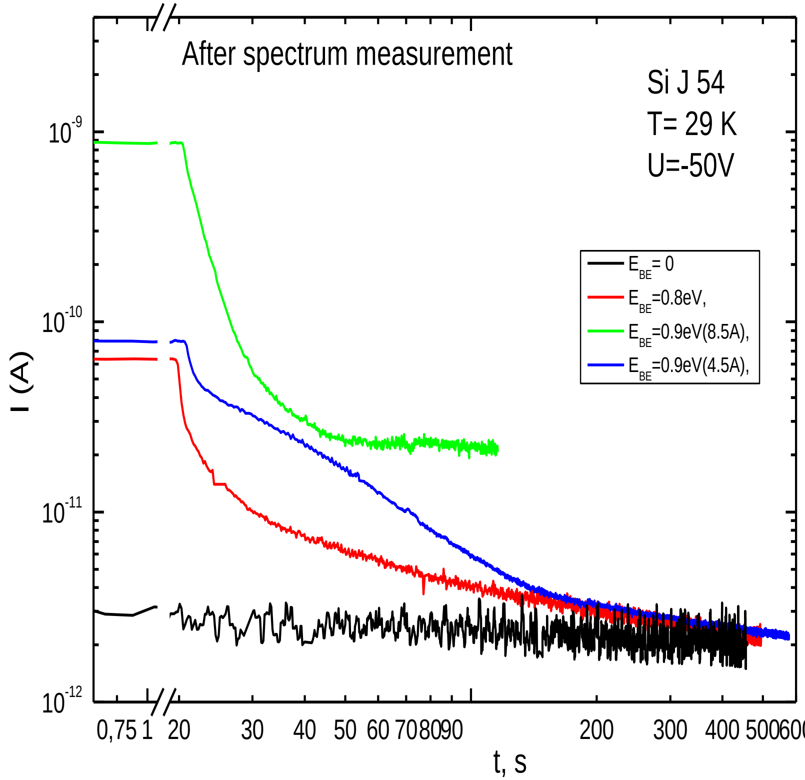


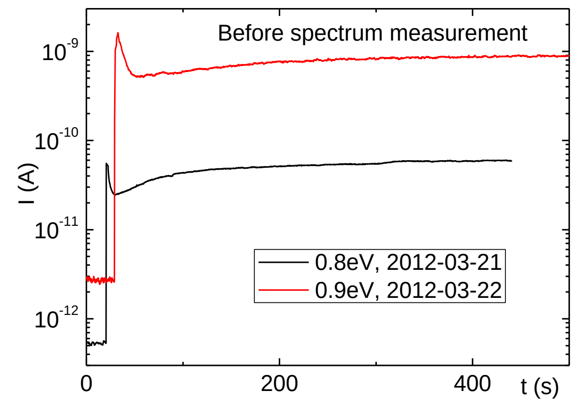
Extrinsic excitation by 0.9 eV light enhance PC at lower energies and quench PC at higher energy.



3e15 cm^{-5} sample







The effects similar, but the PC decay time dependencies show existing of two effects.

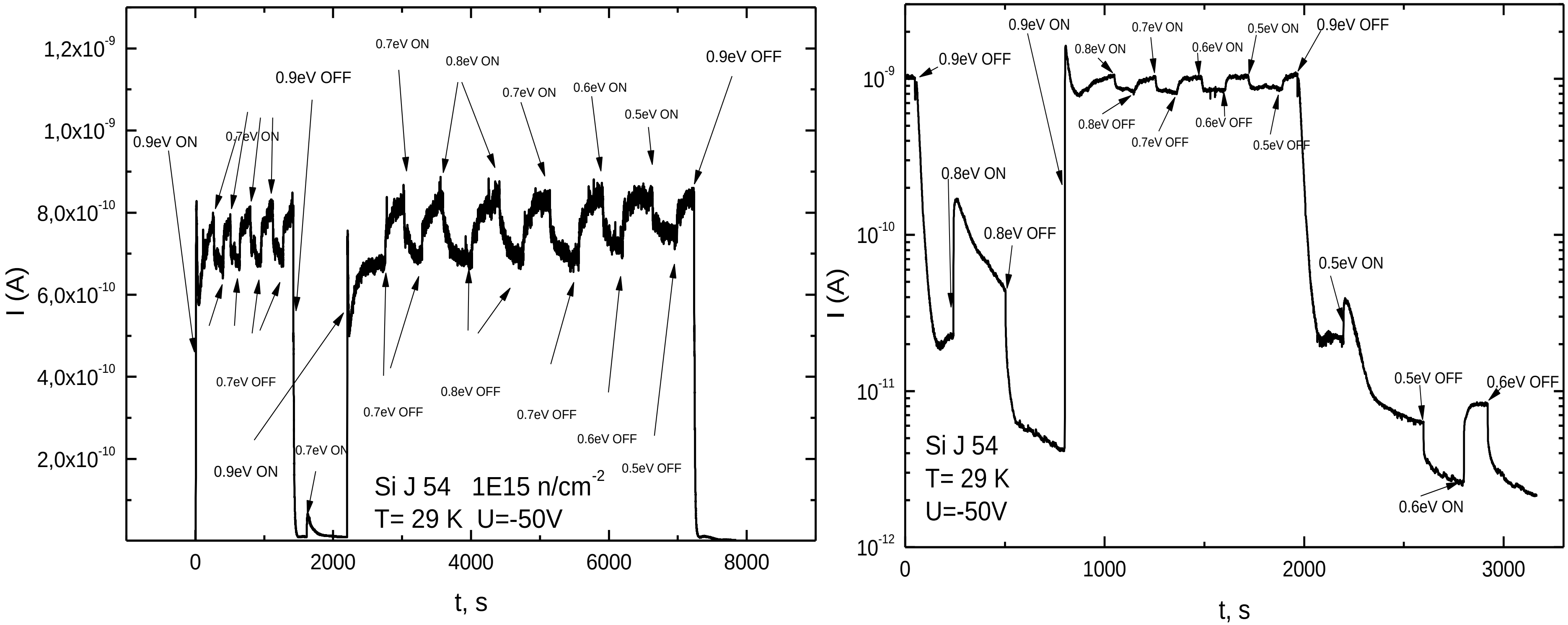
Also absence of PC in the region of 0.3-0.4 eV

What does follows?

- The "memory" effect confirms the separation of captured electrons and holes: they cannot recombine if any is excited.
- The double effect (stimulation and quenching) can be explained only (our view) by a change of deep level charge by its filling and the influence of this charge on the percolation: i.e.,
  - There is level below the E_C at ~0.5 eV which is neutral, if empty, and negative charged, if it is occupied.
  - There is levels above E_V which is neutral if filled and positive charged if excited.

(An existence of these levels types follows from DLTS measurements in Hamburg. Here we see more deep level below E_C and cannot neglect the both levels charge influence on the PC)

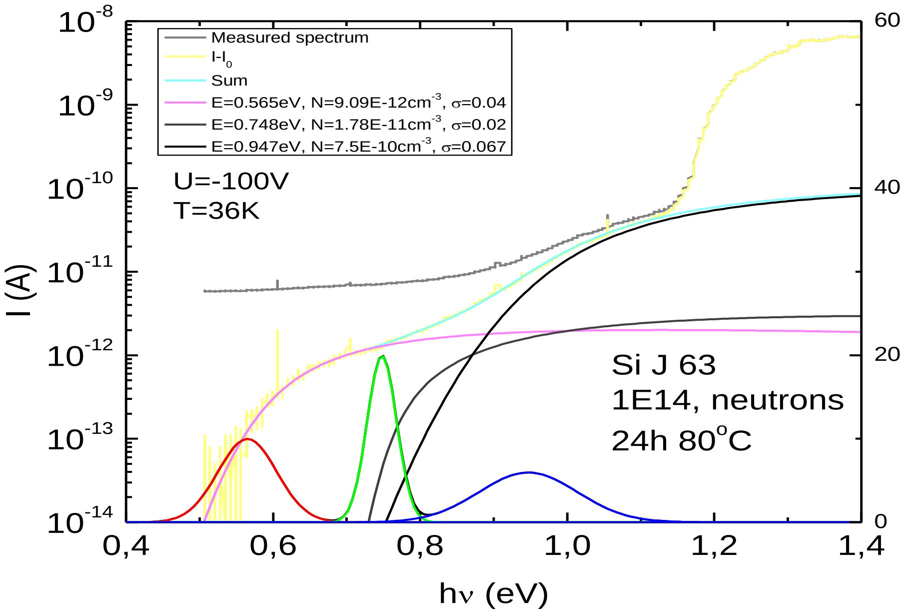
PC response on the additional extrinsic excitation

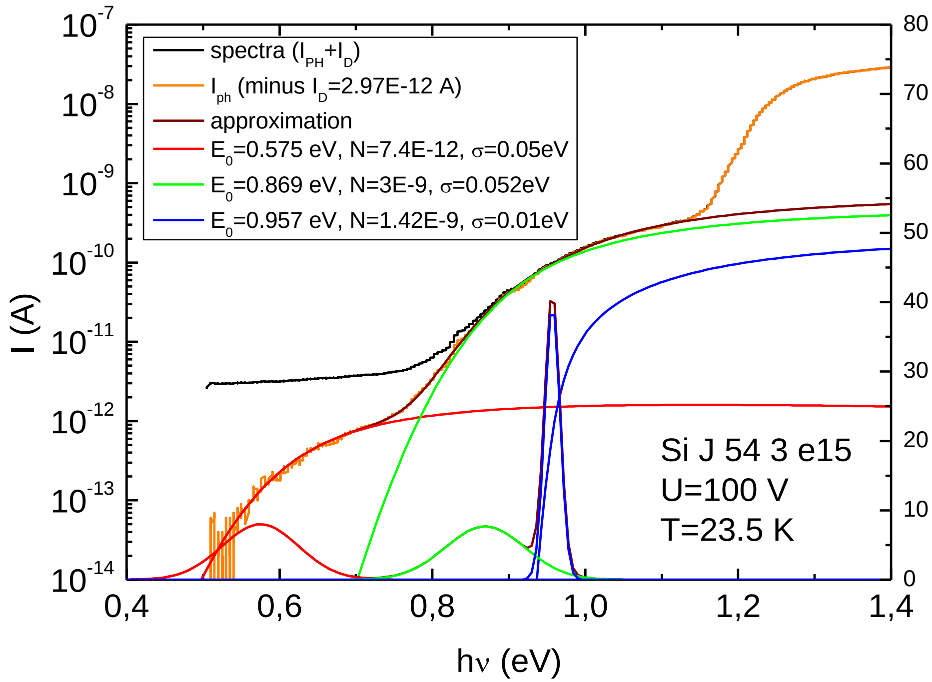


An evidence of a double role: excitation of PC and quenching of photoresponse.
Si excited by 0.9 eV light, additional extrinsic excitation.

There are the deep levels, and their excitation by extrinsic light gives the increase of PC. If Si is excited by 0.9 eV light then the same light reduces photoresponse. It can be related to the excitation of electrons from the VB to the level at ~E_C-0.3 eV and it increases the barrier surrounding the centers and modulates the percolation.

Some details of deep level spectrum:

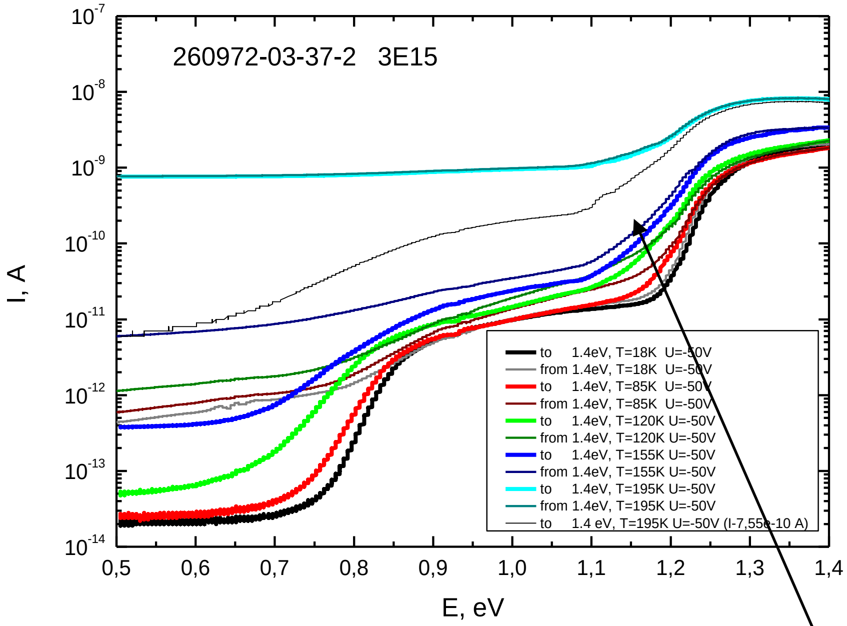


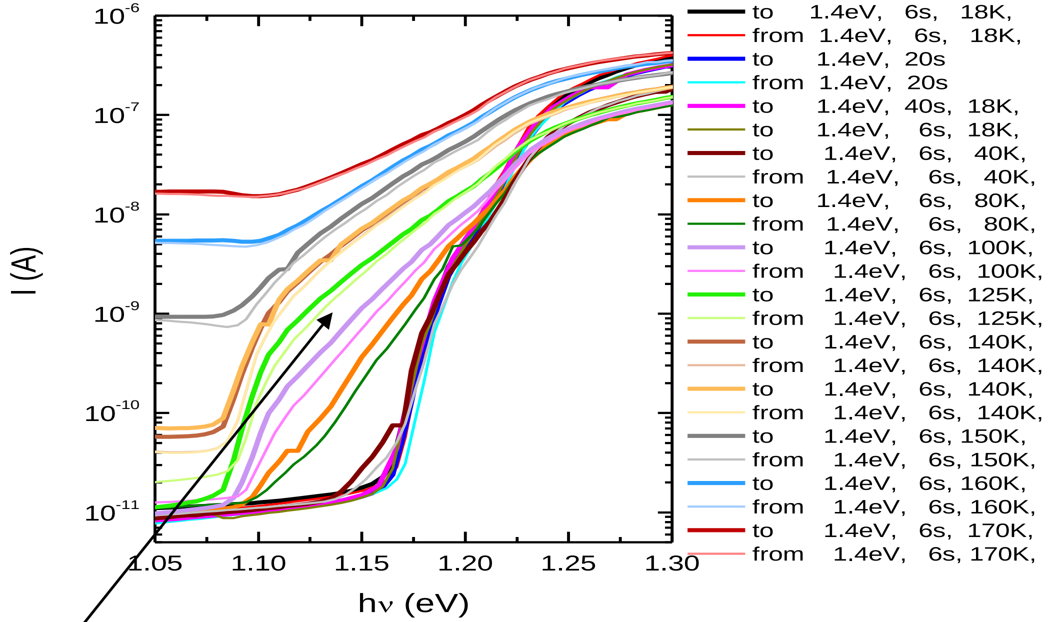


The PC with a background excitation allows to reveal the centers near to the midgap that probably are most important for the generation current.

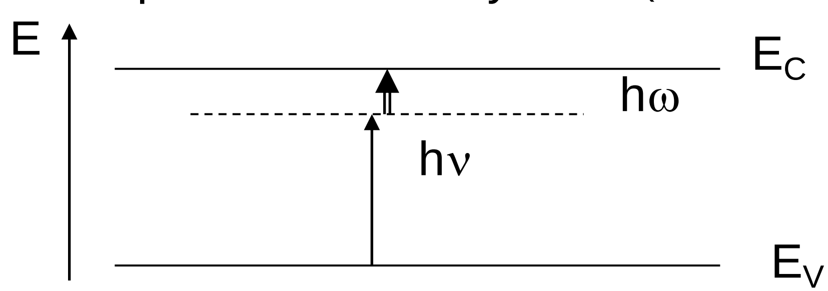
The extrinsic PC kinetics can be used for their parameters measurement. (If it is important, it can be done, **if the interesting samples would be available**)

PC response as a f(T): it was earlier demonstrated at last RD50 workshop the role of center E_C-0.1 eV



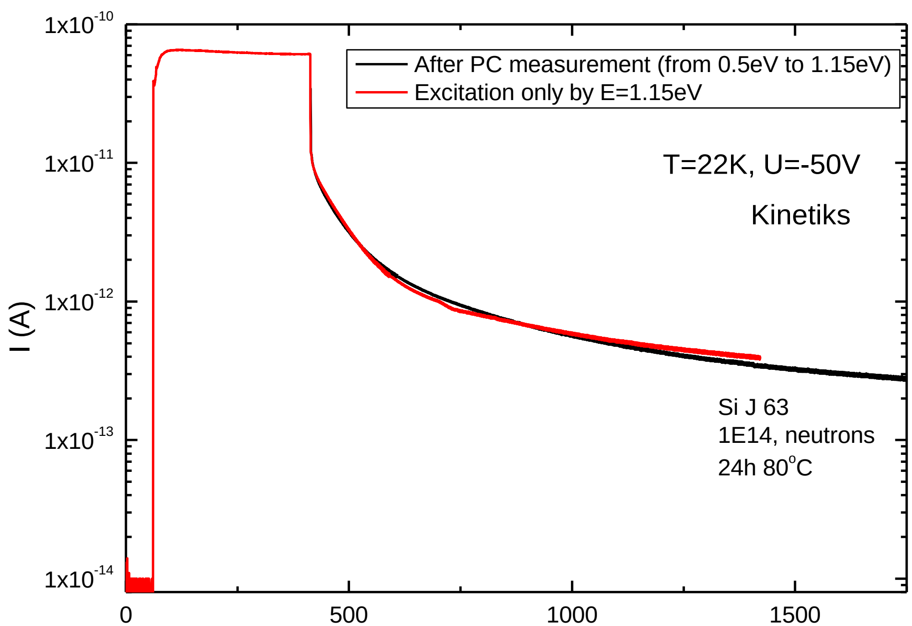


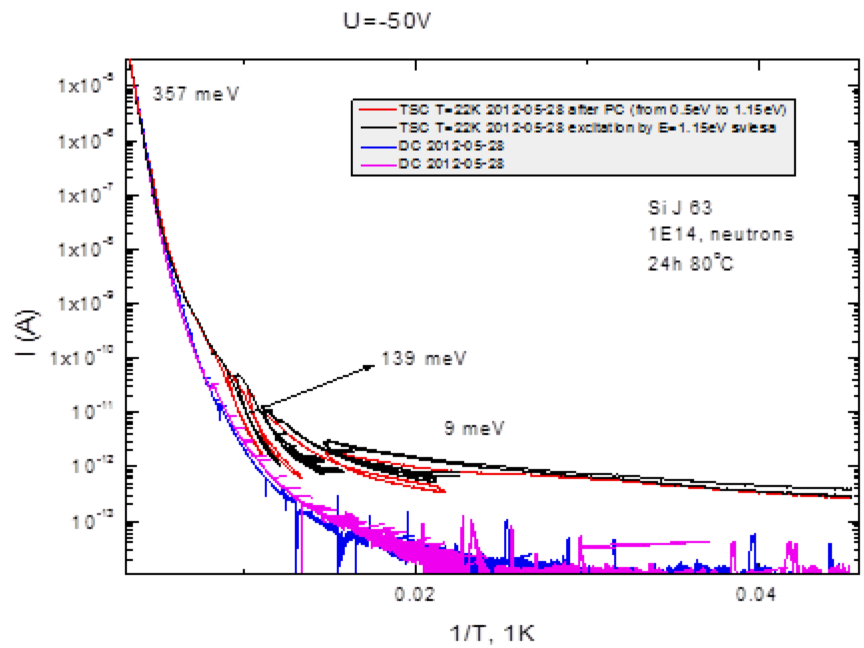
Thermally activated photoconductivity band (left – measurements in p-i-n structure)



Peculiarity 3) – TSC:

thermally stimulated current behaves as percolation current.





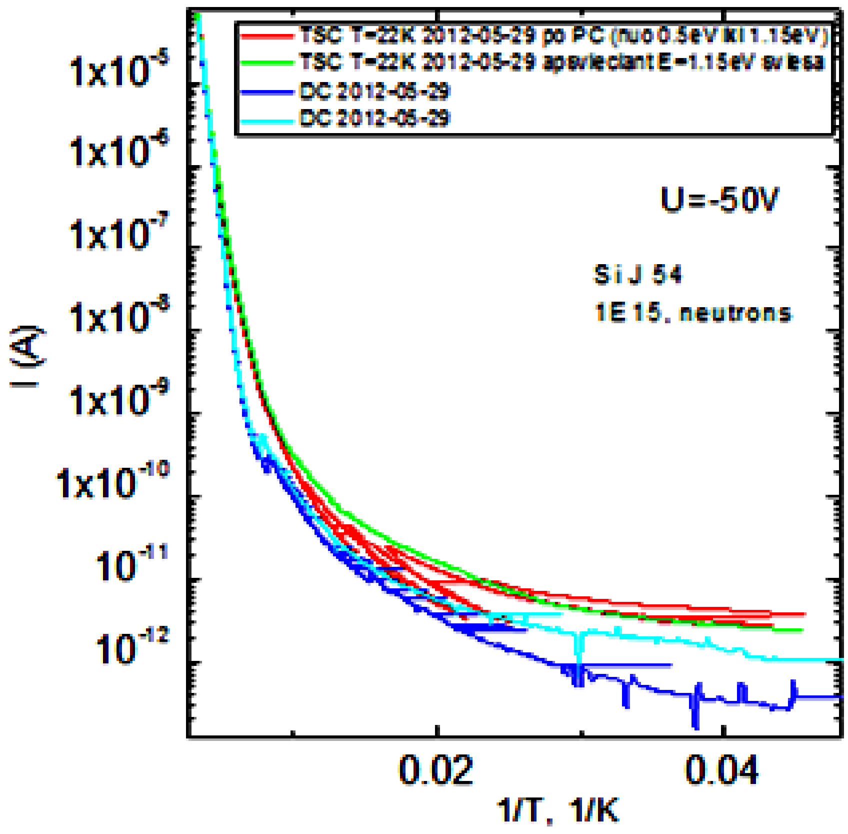
The photocurrent dependence on time. Efcitation 1.15 eV "ON" and "OF".

The photocurrent dependence on time. Efcitation 1.15 eV "ON" and "OF".
dark current and TSC dependence on temperature at different bias. Left – the same, a wide T range. The sample number, irradiation fluence neutrons/cm^{-2}, bias voltage and activation energy are given in the inse

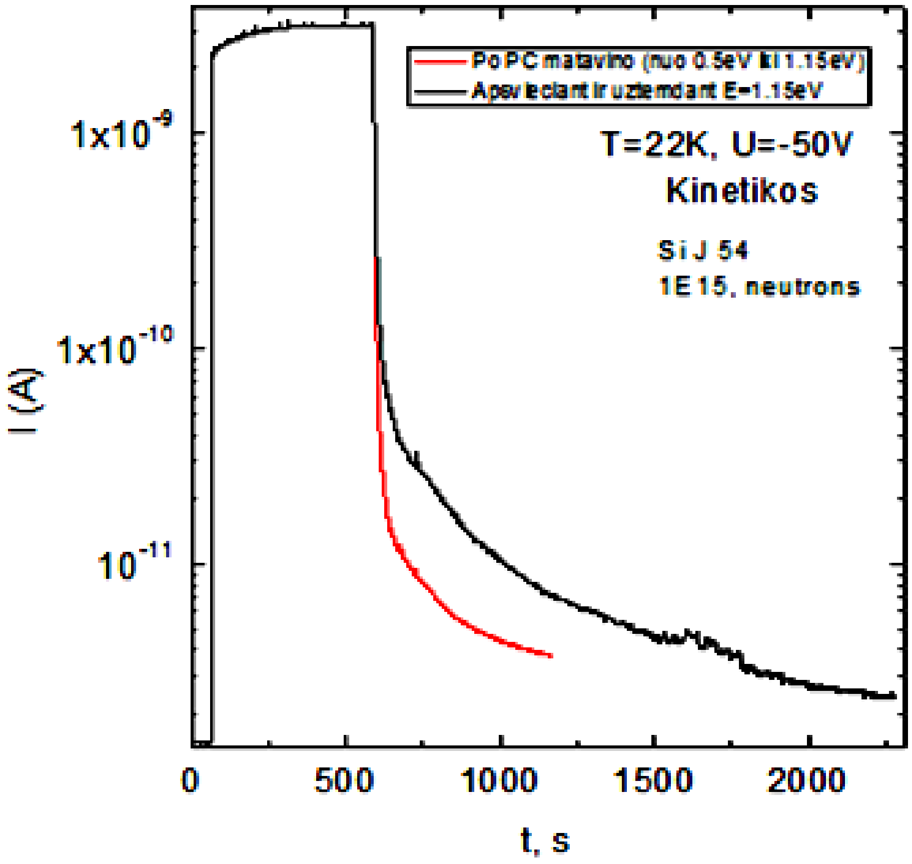
1) TSPC does not decrease in the dark at low temperature: i.e., it exists the separation of "e" and "h";

TSC, 1e15

-



TSC T=22K 2012-05-29 po PC (nuo 0.5eV iki 1.15eV)
TSC T=22K 2012-05-29 apsviecant E=1.15eV sviesa
DC 2012-05-29
DC 2012-05-29
U=-50V
Si J 54
1E15, neutrons
1x10^-5
1x10^-6
1x10^-7
1x10^-8
1x10^-9
1x10^-10
10^-11
10^-12
I (A)
0.02
0.04
1/T, 1/K

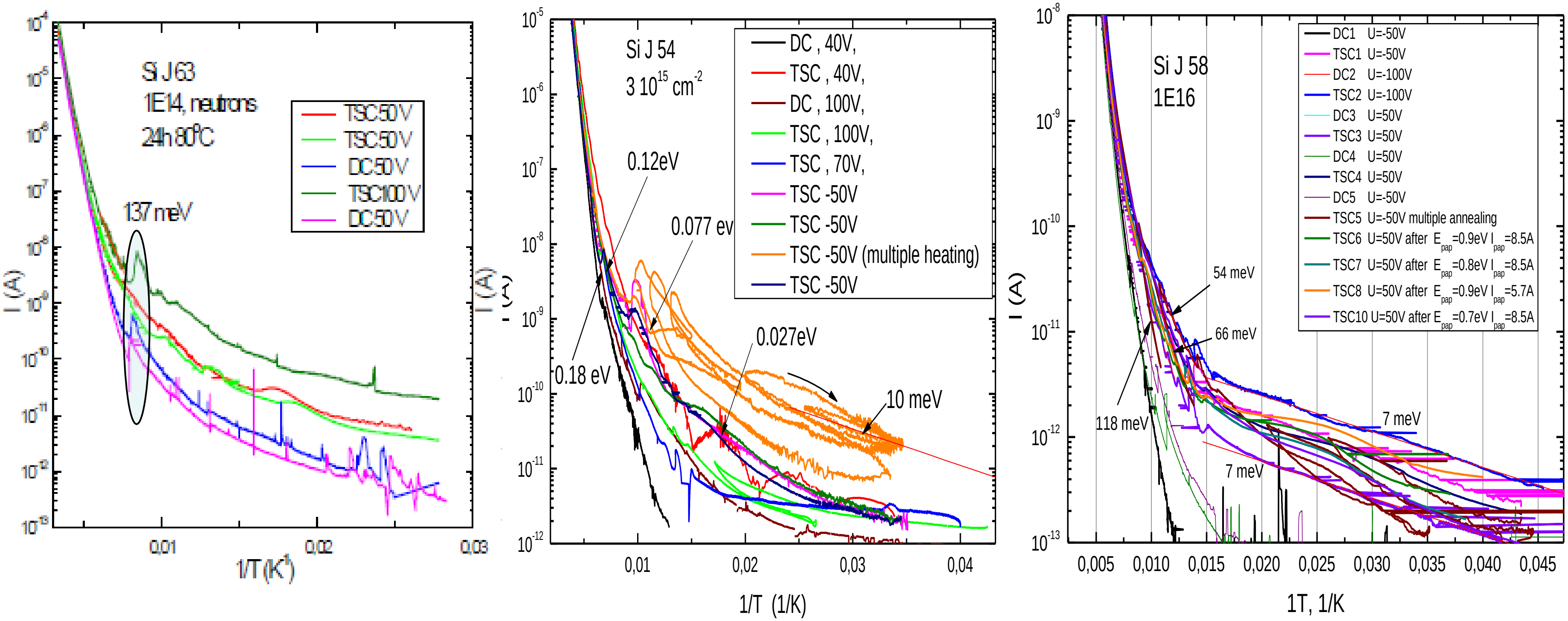


Po PC matavimo (nuo 0.5eV iki 1.15eV)
Apsviecant ir uztemdant E=1.15eV
T=22K, U=-50V
Kinetikos
Si J 54
1E15, neutrons
1x10^-9
1x10^-10
10^-11
I (A)
0
500
1000
1500
2000
t, s

- a

Peculiarity 3) – TSC:

thermally stimulated current behaves as percolation current.

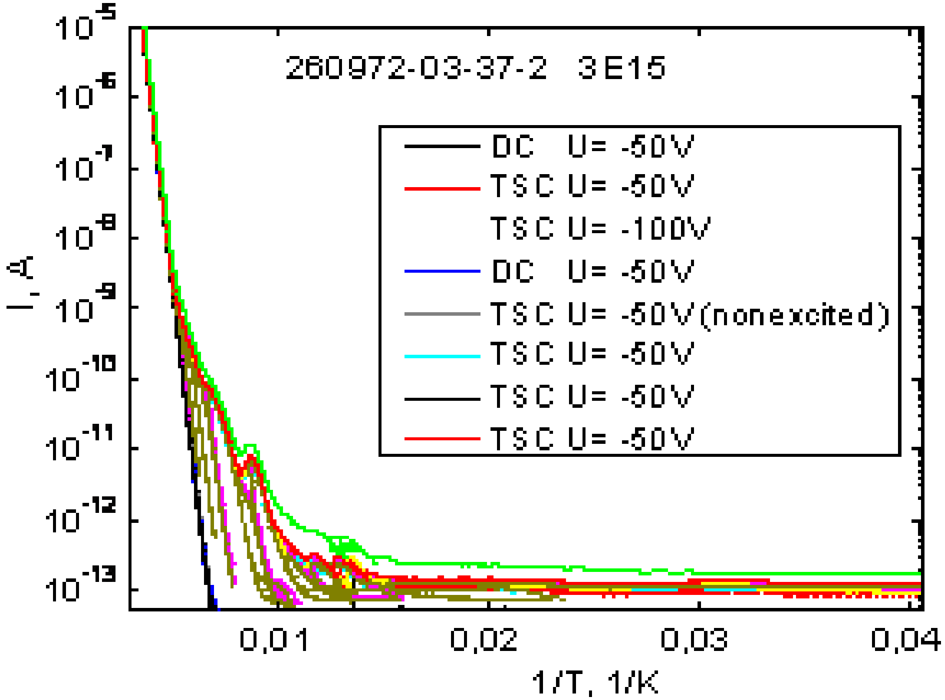


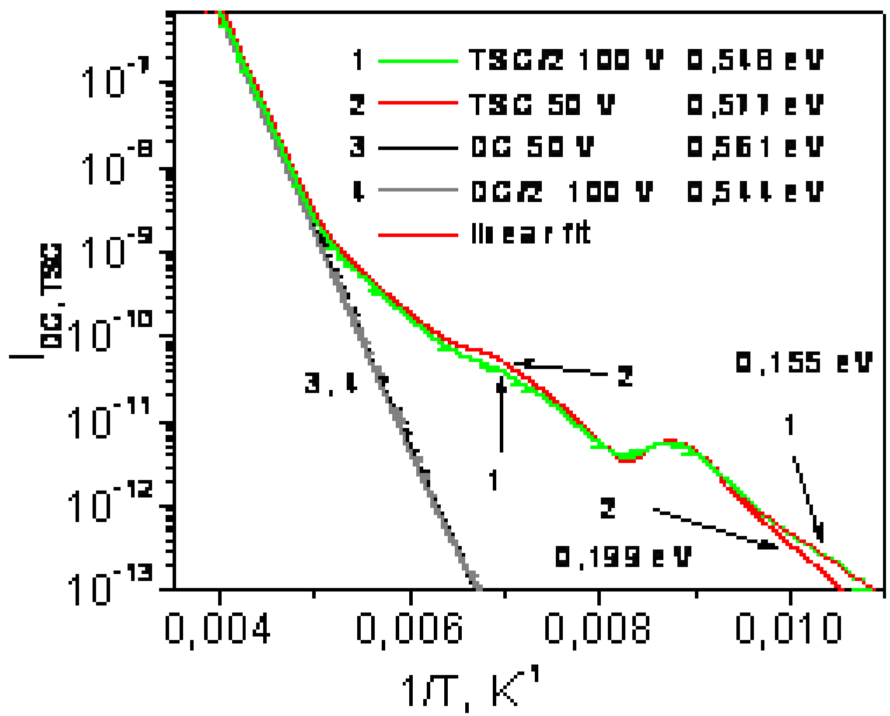
The dark current and TSC dependence on temperature at different bias in the irradiated by neutrons Si samples.

The sample number, irradiation fluence neutrons/cm^{-2}, bias voltage and activation energy are given in the inset.

1) TSPC does not decrease in the dark at low temperature: i.e., it exists the separation of “e” and “h”;
2) Activation energy depends on bias: macro-inhomogeneity’s barrier

Peculiarity 2) –The same TSC is observed in in diodes





The dark current and TSC dependence on temperature at different bias. Left – the same, a wide T range. The sample number, irradiation fluence neutrons/cm^{-2}, bias voltage and activation energy are given in the inset.

1) TSC does not decrease in the dark at low temperature: i.e., it exists the separation of “e” and “h”;
2) Activation energy depends on bias: macro-inhomogeneity’s barrier

Conclusions:

- Irradiated by hadrons Si is the semiconductor consisting microinhomogeneities separating by potential barrier ~10-100 meV.
- At high fluence the conductivity via impurity band appears.
- Optical-thermal excitation cascade was observed.
- Extrinsic excitation can cause the photo-response quenching and it could be a tool for **the deep level responsible for generation current** and **the inhomogeneities barriers** investigation.

Thanks to Lithuanian Science Council for a grant MIP-068

THANK YOU FOR YOUR ATTENTION!

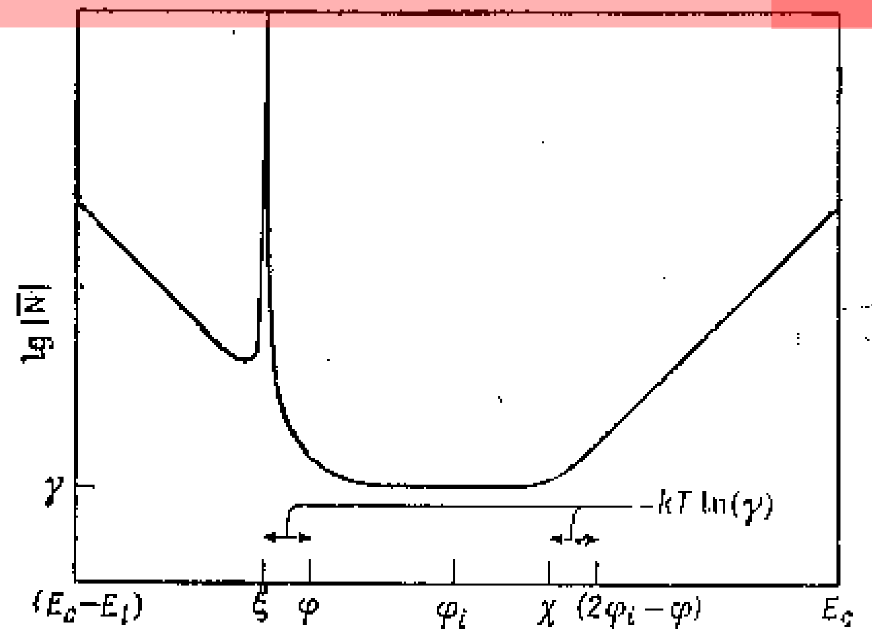
but I like to make one remark
and express one wish ..

Many times I have heard “Schokley-Read-Hall recombination” term.

This term can be used ONLY if the concentration of all levels is low:
(this condition works well in Si for the classical microelectronics)

J.S.Blakemore. Semiconductor Statistics. Pergamon Press. N.Y. 1962

S-R-H valid if $N_{RC} \ll p_0|\bar{N}|$ or $\ll n_0|\bar{N}|$



Dependence of critical concentration of recombination centers on the recombination center energy (cross sections are fixed and defined in γ)

$$\gamma = \tau_{n0}/\tau_{p0} = \sigma_{pRC} \langle v_{pT} \rangle / \sigma_{nRC} \langle v_{nT} \rangle$$

WODEAN batch sample list

150 samples n-MCz <100>1 kΩcm (OKMETIC, CiS): 84 diodes, 48 nude standard, 16 nude thick

90 samples n-FZ <111>, 2 kΩcm (Wacker, STM): 67 diodes, 24 nude thick samples;

Φ, n (1MeV)	C-DLTS	I-DLTS	TSC	PITS	PL	τ_{recomb}	FTIR	PC	EPR
6e11-3E16	HH,Oslo	Florence	HH, NIMP	TME	KC, ITME	Vilnius Vilnius	Oslo	Vilnius Vilnius	NIMP ITME

- **It was planned that the samples, at least some of them will be "mobile"**
- **Are any of these samples** (after irradiation and annealing) **available?**
- Especially are interesting the nude thick samples to measure the optical absorption edge (that was obeyed to measure but not fulfilled).
  - These data are very important for the PC interpretation
    - (100 meV level and percolation problem)