Index

- Presentation at Spring Meeting of Deutsche Physikalische Gesellschaft –“Annealing studies on 23GeV proton irradiated epitaxial diodes “(Mar 2010)
- Group presentation – “Deep level transient spectroscopy for determination of charge carrier traps parameters in irradiated sensors” (Mar 2010)
- Presentation at Workshop on Defect Analysis in Silicon Detectors in Bucharest (May 2010)

Annealing studies on 23 GeV proton irradiated epitaxial silicon diodes

C.Pirvutoiu[1,2],E.Fretwurst, A.Junkes[1], V.Khomenkov[1], R.Klanner[1]
[1]Hamburg University
[1,2]Marie Curie Initial Training Network

Epitaxial (Epi) silicon is considered to be an option for sensors in high energy physics experiments at the super Large Hadron Collider due to its high radiation hardness. In order to understand the properties of such sensors and the radiation induced damage, we investigated standard epitaxial (Epi-St) and oxygen enriched epitaxial (Epi-Do) material with 100 and 150 µm thickness by Deep Level Transient Spectroscopy (DLTS). The irradiations were carried out at the PS at CERN with 23 GeV protons with fluences of 6.4 10^{11} cm^{-2}. We performed macroscopic measurements like capacitance-voltage (CV) and current-voltage characteristics (IV) to obtain the sensor properties (depletion voltage, leakage current, effective doping concentration) and DLTS measurements in order to obtain the defect properties (defect concentration, cross section, activation energy). Isothermal annealing was performed at 80 ^{o}C up to annealing times of 30 minutes followed by isochronal annealing up to 300 ^{o}C. It was found a correlation between two defect levels and the leakage current.

Annealing studies on 23 GeV proton irradiated epitaxial silicon diodes

C.Pirvutoiu[1,2], E.Fretwurst1, A.Junkes[1], V.Khomenkov[1], R.Klanner[1]

[1] Institute for experimental Physics, Hamburg University

[1,2] Marie Curie Initial Training Network (MC-PAD)

Outline

- Motivation
- Overview of radiation induced defects
- Deep level transient spectroscopy
- Analyzed samples
- Annealing studies of clusters
- Correlation between leakage current and defect concentration
- Conclusions

Motivation

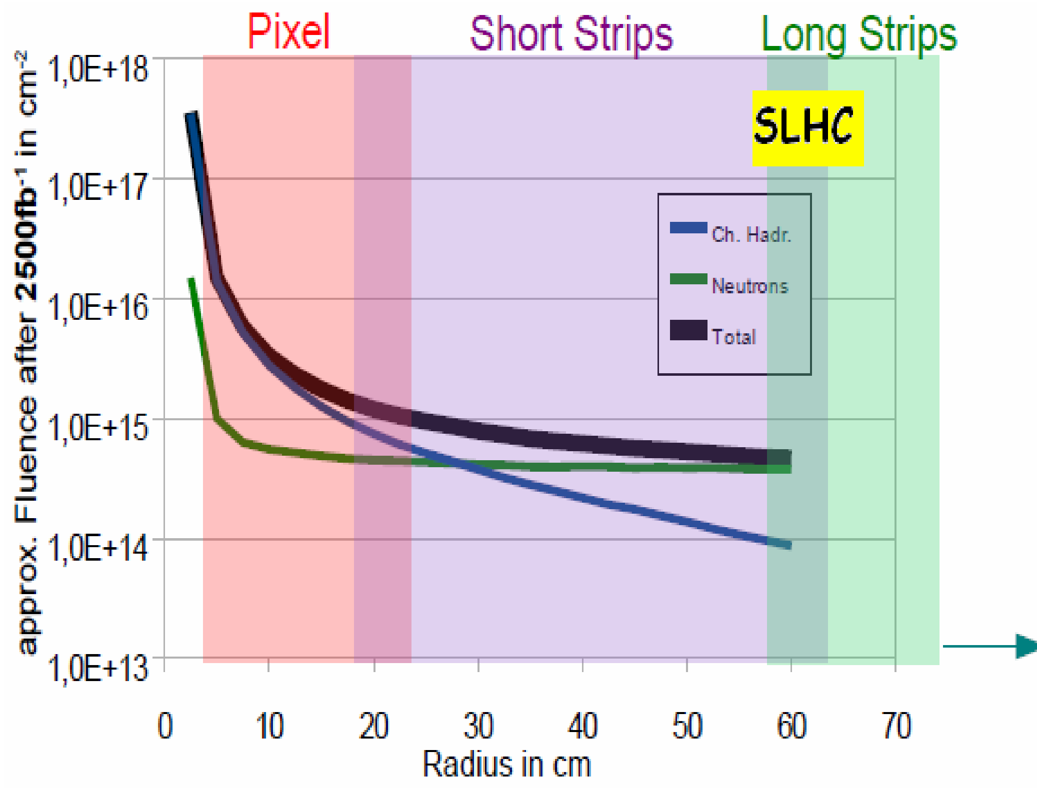
LHC (2009), $L=10^{34}\,cm^{-2}s^{-1}$

(14 TeV pp collider, 25 ns bunch spacing)

10 years → $\Phi(r=4cm) \sim 3\times10^{-15}cm^{-2}$
500fb-1

sLHC (2020?), $L=10^{35}\,cm^{-2}s^{-1}$

5 years → $\Phi(r=4cm) \sim 1.6\times10^{-16}cm^{-2}$
$2500fb^{-1}$

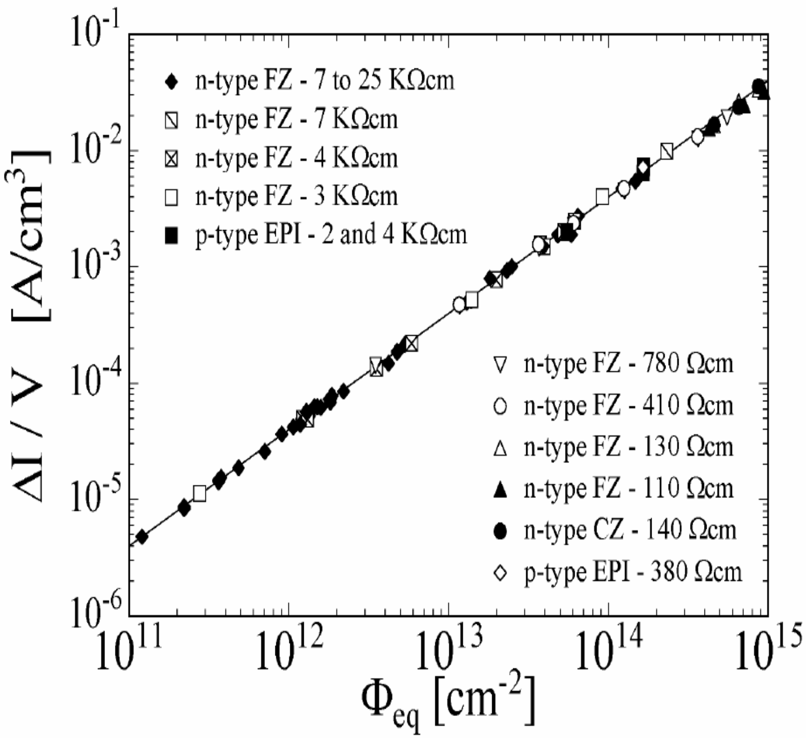


(Simulation by M. Huntinen for CMS)

Radiation Damage effects in Si

Bulk (crystal) damage due to Non Ionizing Energy Loss (displacement damage: point defects, clusters)

- **Change of effective doping concentration Neff (full depletion voltage)**
- **Increase of leakage current (increase of shot noise, thermal runaway)**
- **Increase of charge carrier trapping (reduced charge collection efficiency (CCE))**

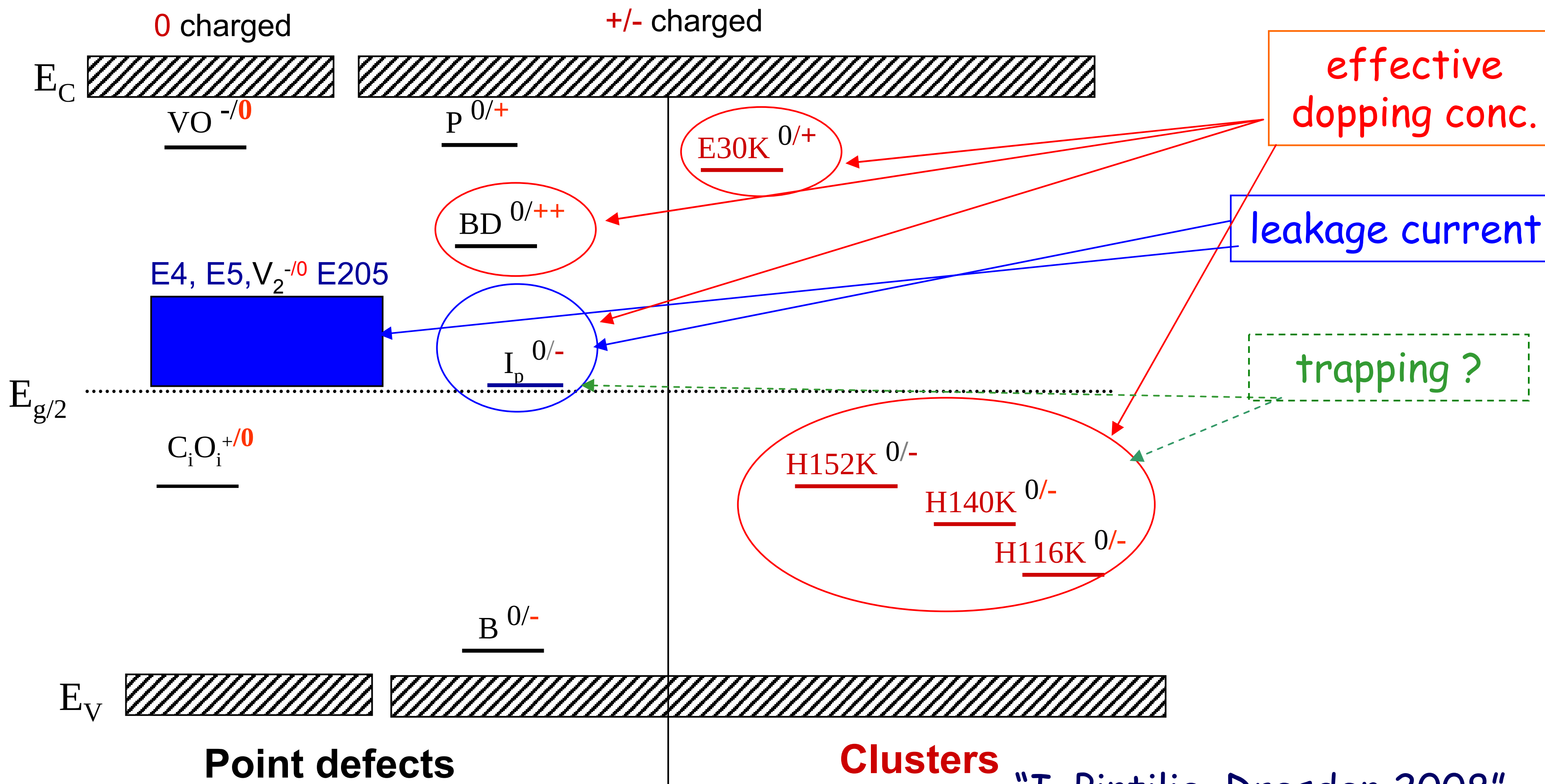


For the development of more radiation hard Si detectors:

- **Knowledge of defect kinetics**
- **Correlation of microscopic with macroscopic properties of the detector for optimizing the Si growth and processing technology**

Overview of radiation induced defects

At room temperature:
- Change of the effective doping concentration
- Generation of leakage current
- Increase of charge carrier trapping



"I. Pintilie, Dresden 2008"

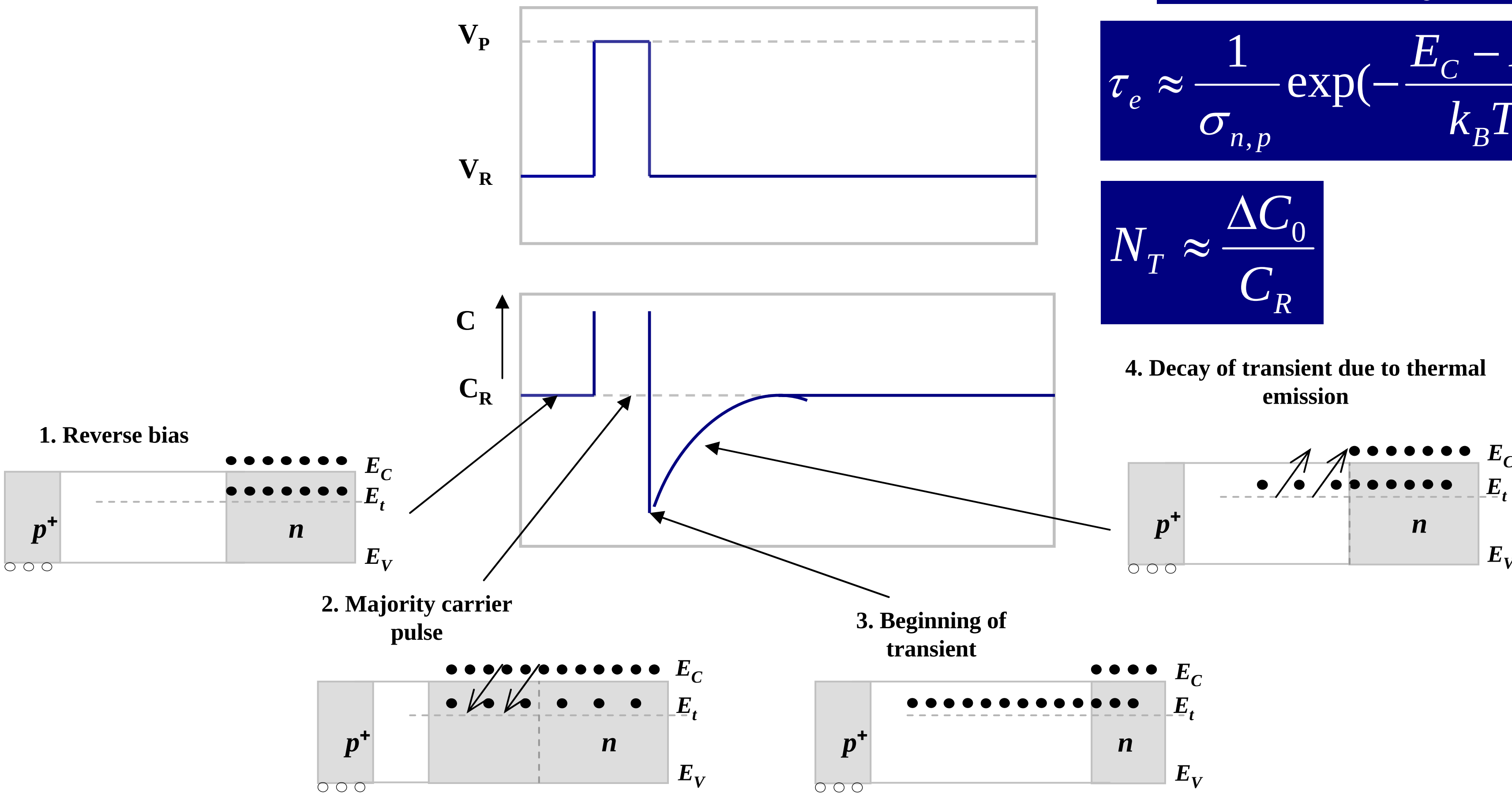
Capacitance Deep Level Transient Spectroscopy

- Principle of operation: capacitance transients measurements in function of temperature
- Requirements: Trap concentration « Doping concentration → $\Phi_{max} < 10^{12} cm^{-2}$

$$C(t) = \Delta C_0 \exp(-\frac{t}{\tau_e}) + C_R$$

$$\tau_e \approx \frac{1}{\sigma_{n,p}} \exp(-\frac{E_C - E_T}{k_B T})$$

$$N_T \approx \frac{\Delta C_0}{C_R}$$

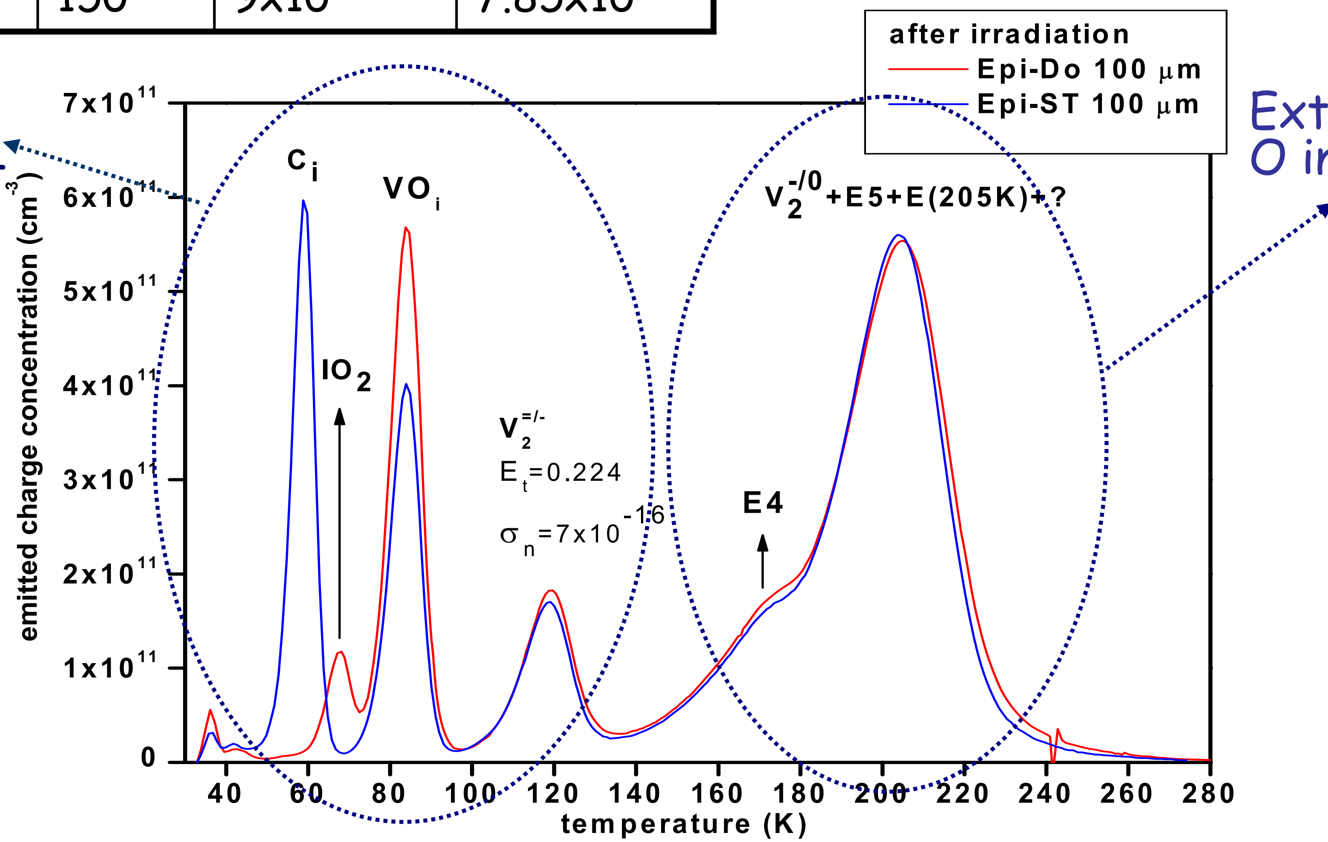


Analyzed samples

n-type Si	d [µm]	‹O› [cm^{-3}]	N_{eff} [cm^{-3}]
Epi-DO	100	2.7×10^{17}	1.44×10^{13}
Epi-DO	150	1.4×10^{17}	8.12×10^{12}
Epi-ST	100	5.4×10^{16}	1.51×10^{13}
Epi-ST	150	9×10^{15}	7.85×10^{12}

$\Phi_p = 6.4\times10^{11}$ cm^{-2}

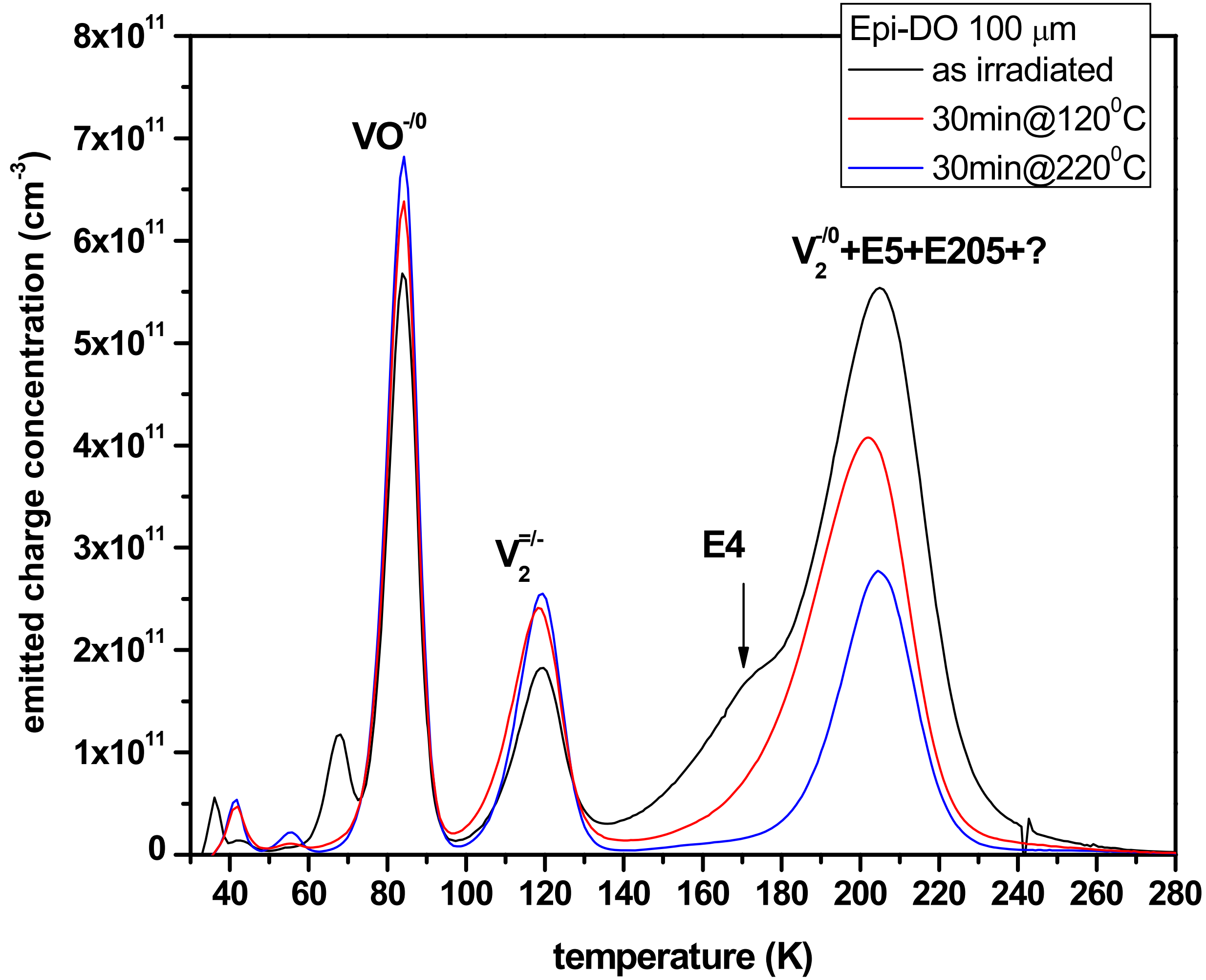
Point defects O dependent



Extended defects O independent

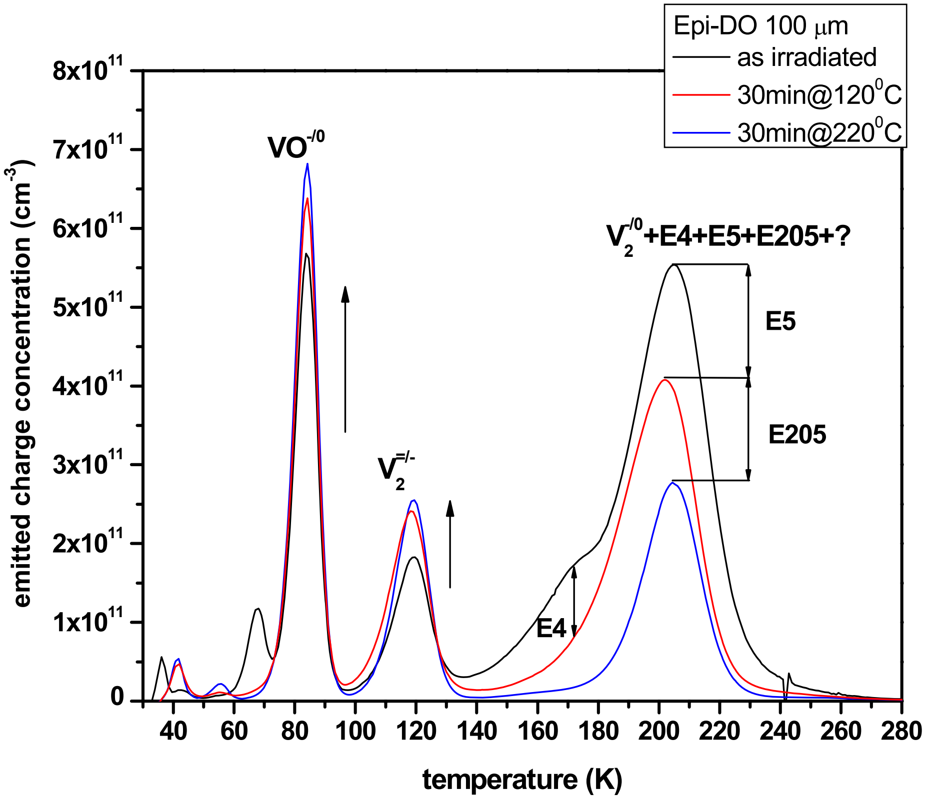
Annealing of clusters

- Isochronal annealing => 30 minutes thermal treatment at different temperatures

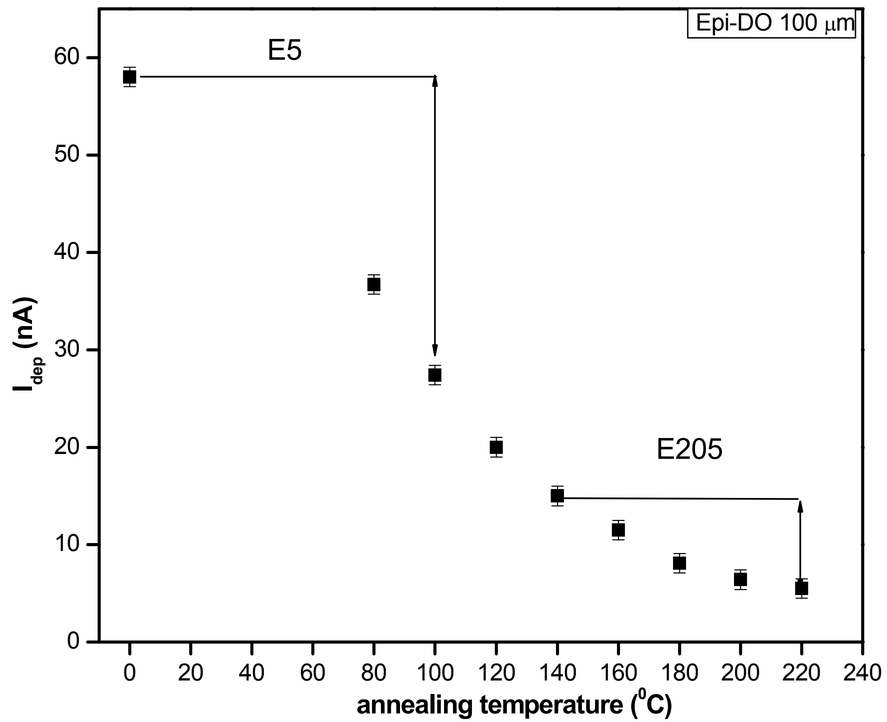


Annealing of clusters

Cluster annealing

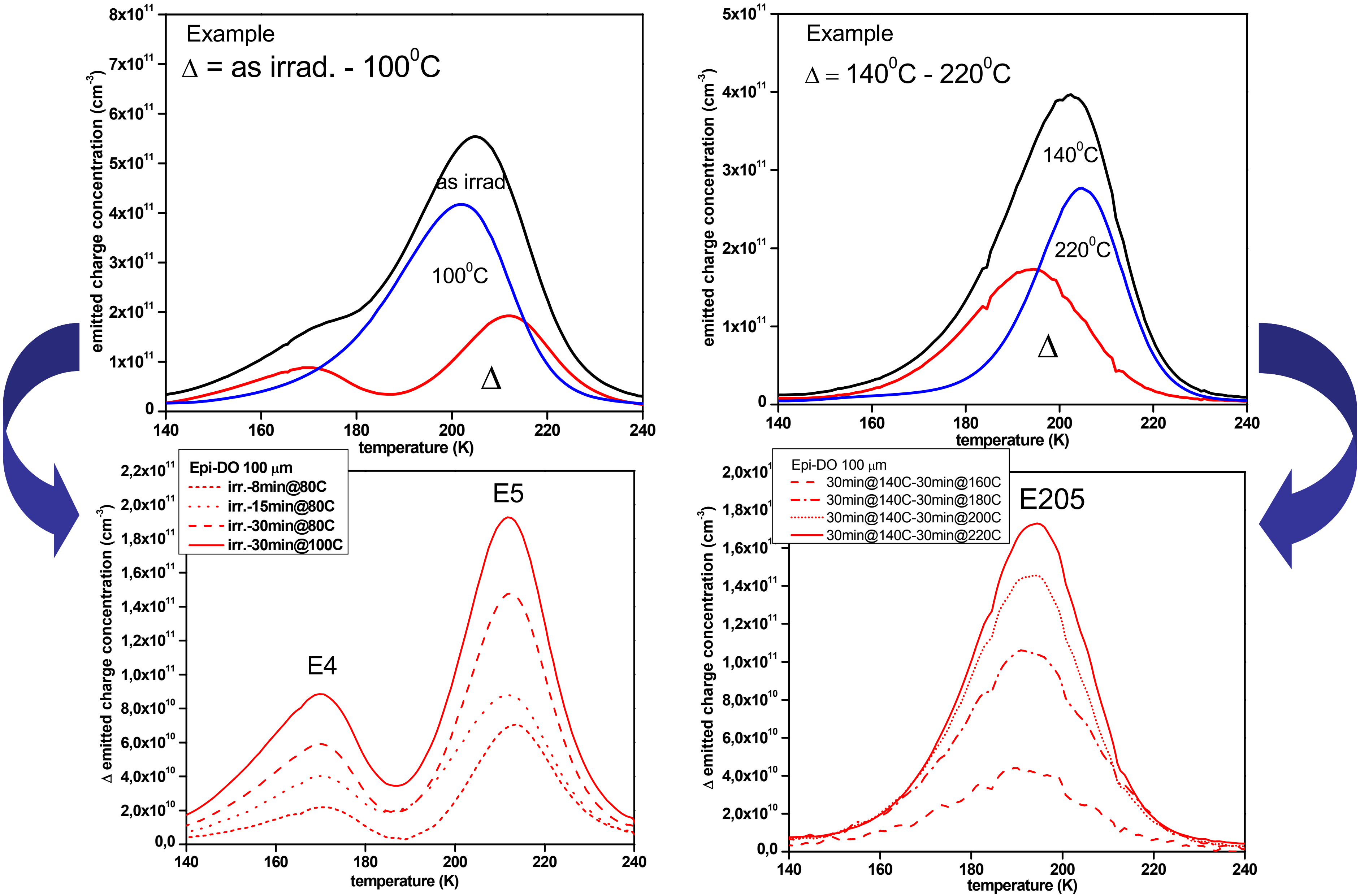


Leakage current annealing

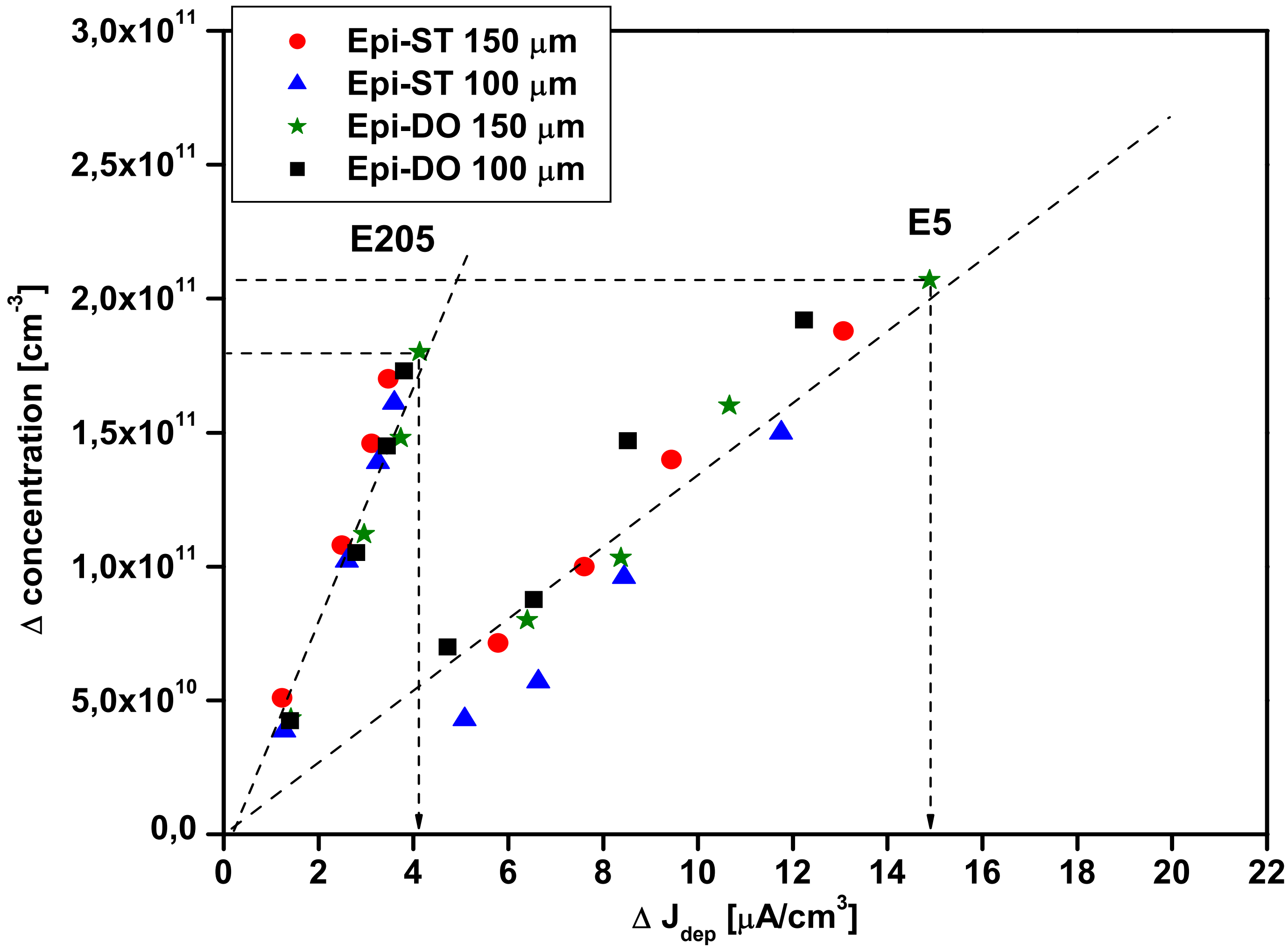


Indication of similar annealing behavior of E5 and E205 clusters and of leakage current => dedicated study for correlation

Investigation of E4, E5 and E205 clusters



Correlation between leakage current and concentration



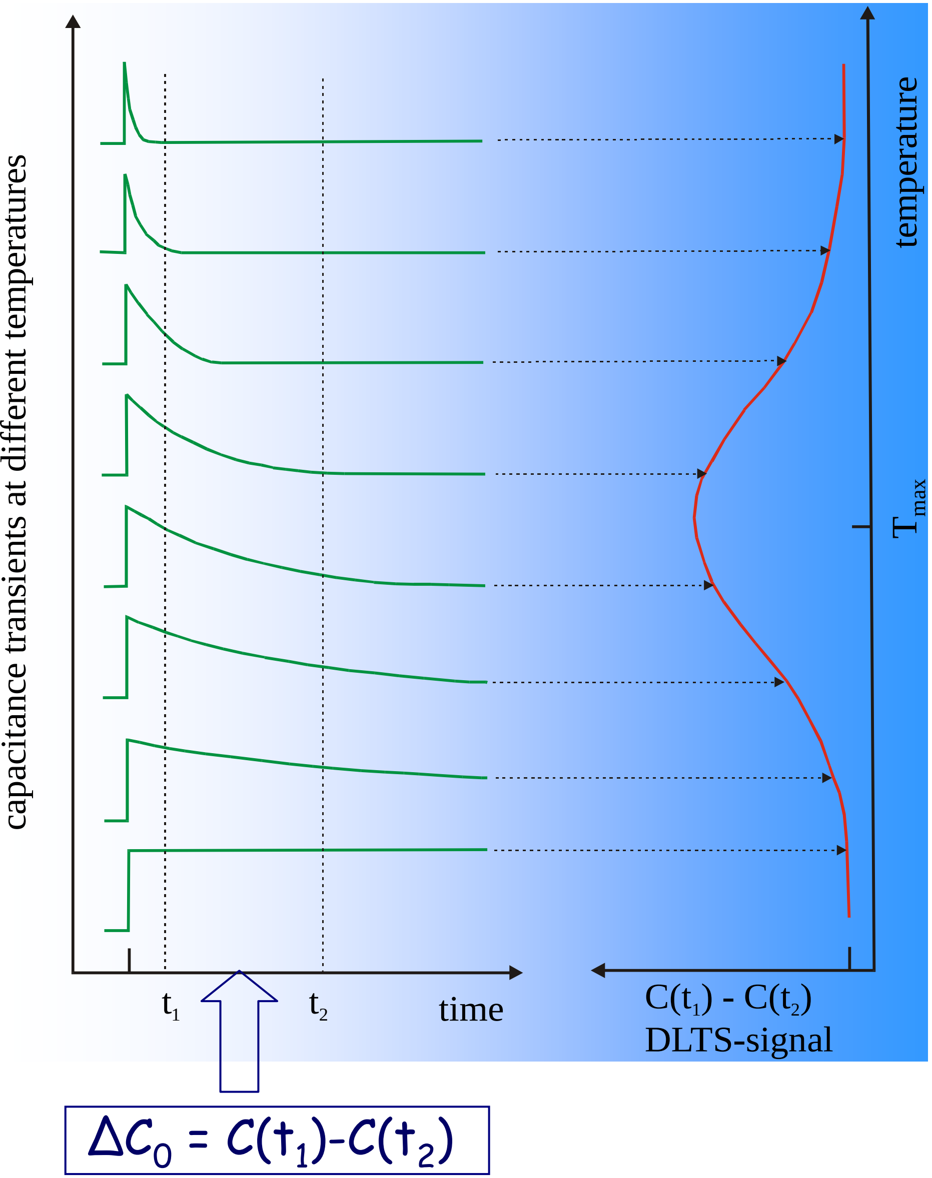
➢E5 has greater impact than E205

➢No dependence on O concentration

Conclusions

- A direct correlation between each of the E5 and E 205 defect concentration and the leakage current was evidenced
- The generation of E4, E5 and E205 defect clusters does not depend on O concentration
- E4 and E5 annealed out together (100 C) suggesting that they can be two charge states of the same defect cluster
- E205 annealed out at higher temperature (220C)

Capacitance Deep Level Transient Spectroscopy



Extraction of parameters : several temperature scans with different $T_W = t_2 - t_1$ → Arrhenius plot :

$$\frac{1}{\tau_e} = \sigma_{n,p} v_{th,n,p} N_{C,V} \exp\left(-\frac{E_C - E_T}{k_B T}\right)$$

→ E_t extracted from slope of the Arrhenius plot

→ σ_n from the intercept with ordinate

→ Trap concentration:

$$N_T = 2N_D \frac{\Delta C_0}{C_R}$$

Deep level transient spectroscopy for determination of charge carrier traps parameters in irradiated sensors

Cristina Pirvutoiu

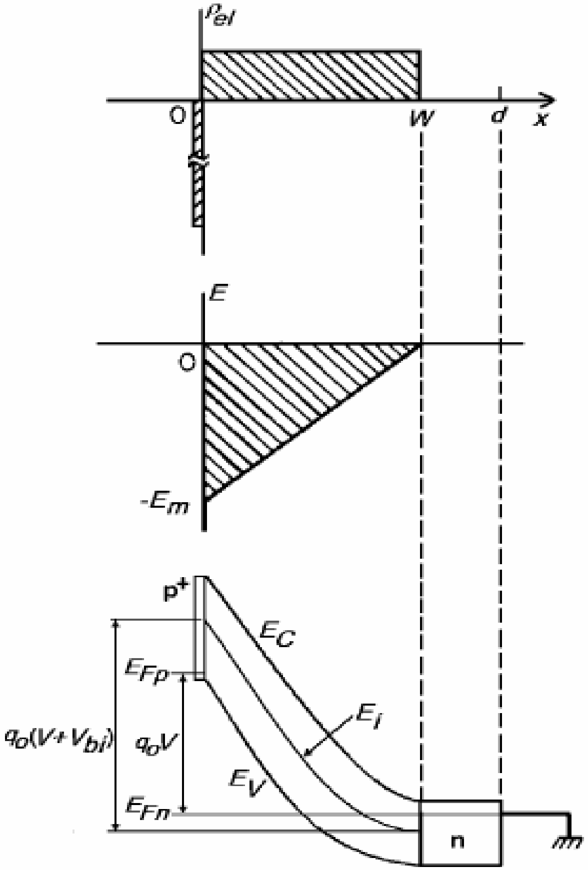
Outline

- Motivation
- Operation principles of silicon detectors
- Shockley-Read-Hall statistics
- Deep level transient spectroscopy
- Analyzed samples
- Annealing studies of clusters
- Correlation between leakage current and defect concentration
- Conclusions

Motivation

- **To develop Silicon detectors** able to operate in the conditions imposed by S-LHC
- **Damage mechanism:** due to Non Ionizing Energy Loss → dislocation of Si atoms (interstitials), empty lattice sites (vacancies), interaction with impurities (O, C) form defects that introduce energy levels in the band gap
- **Radiation damage effects on sensors:**
  - change in effective doping concentration – change in the full depletion voltage
  - increase of leakage current
  - deterioration of charge collection efficiency: part of the drifting charge, created by ionizing particle, is temporarily trapped by the defects generated by irradiation

Operation principles of silicon detectors



- Neutrality of the system:

$$N_{A,p}x_p = N_{D,n}x_n$$

- Usually p^+-n junction: $N_{A,p} >> N_{D,n}$

$$w = x_p + x_n \approx x_n = \sqrt{\frac{\varepsilon\varepsilon_0(V_{bi}+V)}{e_0 N_{D,n}}}$$

- If $N_{D,n}$ comparable with $N_{A,n}$ than $N_{D,n}$ must be replaced with effective dopant concentration $N_{eff} = | N_{D,n} - N_{A,n} |$

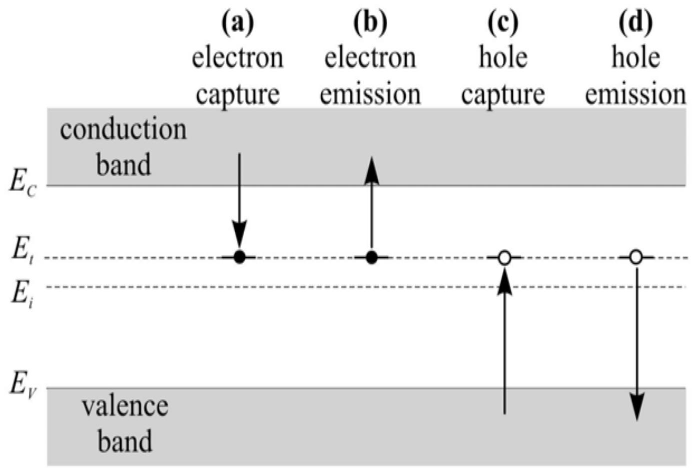
$$w(V) \propto \sqrt{V/N_{eff}}$$

- Desired detector operation voltage $V >$ full depletion voltage V_{FD}
- Si detector: a diode operated under reverse bias where the depleted region acts like ionization chamber
- Capacitance

$$\left.\begin{array}{l} C(V) = \frac{dQ}{dV} \\ Q = e_0 N_{eff} A w \end{array}\right\} \Rightarrow C(V) = \frac{\varepsilon\varepsilon_0 A}{w}$$

Shockley-Read-Hall statistics

- Occupation of a defect states of concentration N_t, energy level E_t and average occupation probability P_t
  - density of occupied defects: $n_t = N_t P_t$
  - density of unoccupied defects: $p_t = (N_t - n_t)(1 - p_t)$
- Change of a defect occupancy possible by
  - electron capture with rate $R_n = c_n n p_t$
  - electron emission with rate $G_n = e_n n_t$
  - hole capture with rate $R_p = c_p p n_t$
  - hole emission with rate $G_p = e_p p_t$



$$c_n = \sigma_n \left\langle v_{th,n} \right\rangle$$

$$c_p = \sigma_p \left\langle v_{th,p} \right\rangle$$

$$e_n = N_c c_n \exp\left(-\frac{E_c - E_t}{k_B T}\right)$$

$$e_p = N_v c_p \exp\left(\frac{E_v - E_t}{k_B T}\right)$$

Rate equations

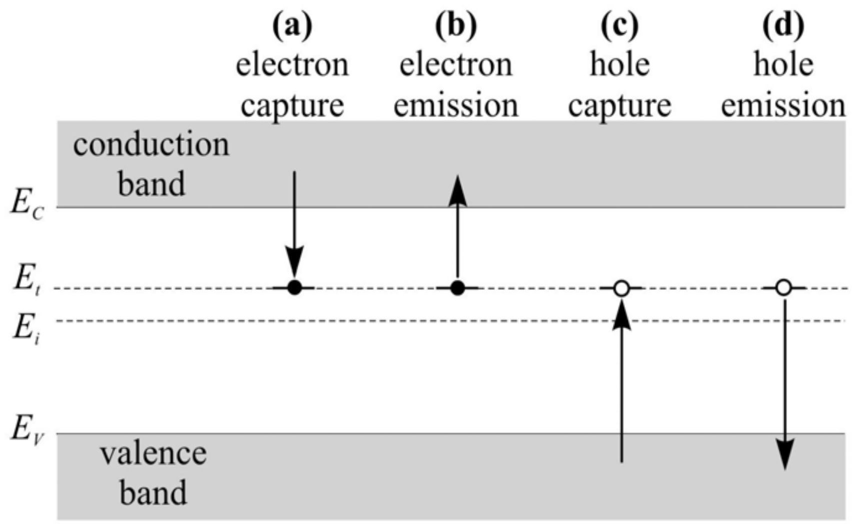
- The change of the defect ocupancy is given by rate eqs.:

$$\frac{dn_t}{dt} = \overbrace{(e_p p_t - c_p p n_t)}^{\text{hole excess generation rate}} - \overbrace{(e_n n_t - c_n n p_t)}^{\text{electron excess generation rate}}$$

$$\frac{dp_t}{dt} = -\frac{dn_t}{dt}$$

$$\frac{dn_c}{dt} = e_n n_t + c_n n p_t$$

$$\frac{dn_v}{dt} = e_p p_t - c_p p n_t$$



Shockley-Read-Hall statistics

- **Thermal equilibrium**
  - P_t = Fermi-Dirac function
  - $dn_c/dt = dp_v/dt = dn_t/dt = 0$
  - **no current** → no net flow of electrones or holes between conduction and valence band → $R_p = G_p$, $R_n = G_n$

- **Space charge region in steady state**

  steady state → *only* $dn_t/dt = 0$

$$\frac{dn_t}{dt} = -e_n n_t + c_n n p_t - c_p p n_t + e_p p_t = 0$$

⇒

$$n_t^{acceptor}(T) = N_T \frac{c_n(T)n + e_p(T)}{e_n(T) + e_p(t) + c_n(T)n + c_p(T)p}$$

$$N_{eff} = \sum_{donor} p_t(T) - \sum_{acceptor} n_t(T)$$

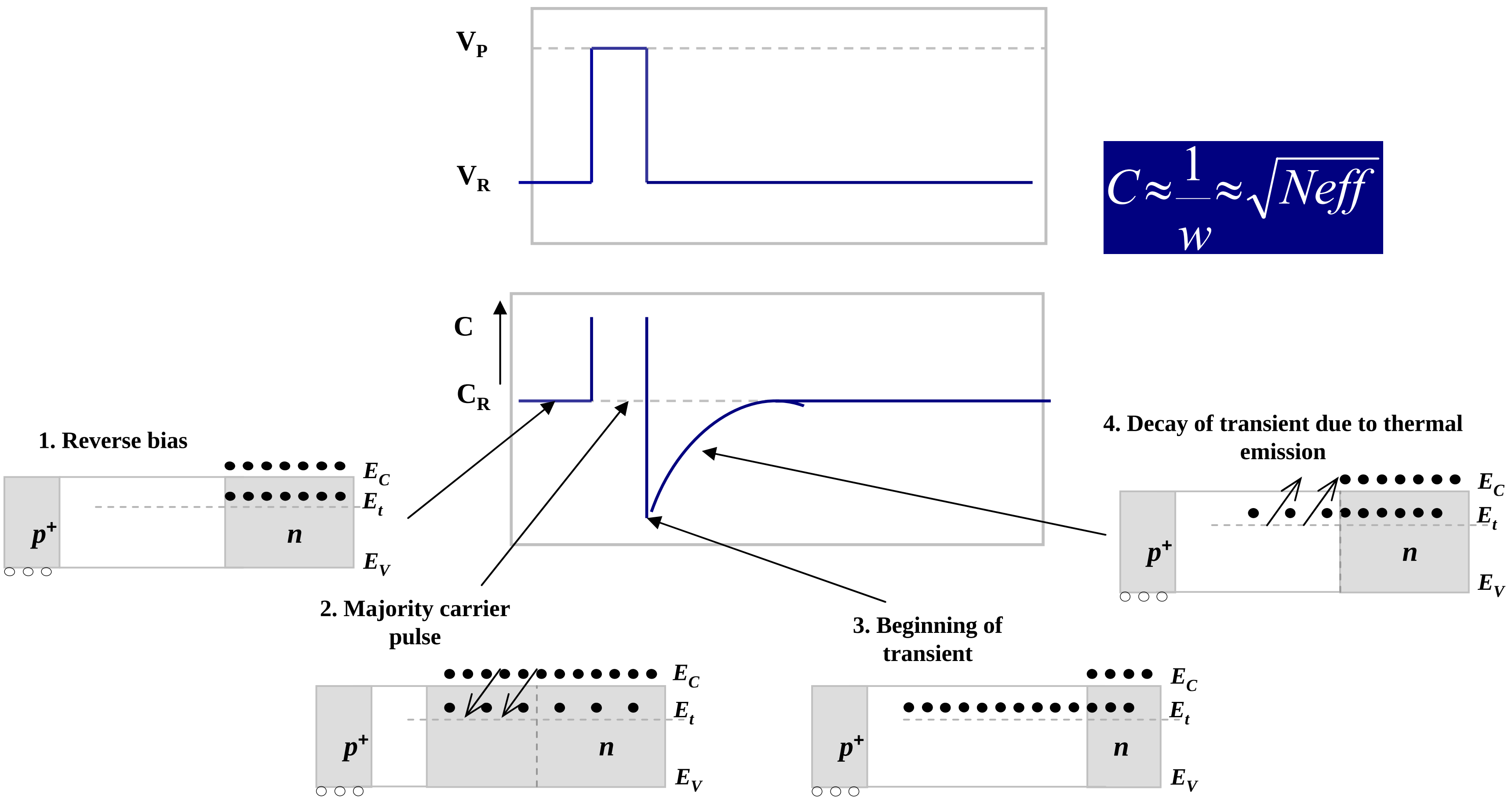
$$p_t^{donor}(T) = N_T \frac{c_p(T)p + e_n(T)}{e_n(T) + e_p(t) + c_n(T)n + c_p(T)p}$$

$$I_{leakage}(T) = e_0 A d\left(\frac{dn_c}{dt} + \frac{dn_v}{dt}\right) = e_0 A d\left(\sum_{acceptor} e_n(T) n_t(T) + \sum_{donor} e_p(T) n_t(T)\right)$$

Capacitance Deep Level Transient Spectroscopy

➤Principle of operation: capacitance transients measurements as function of temperature

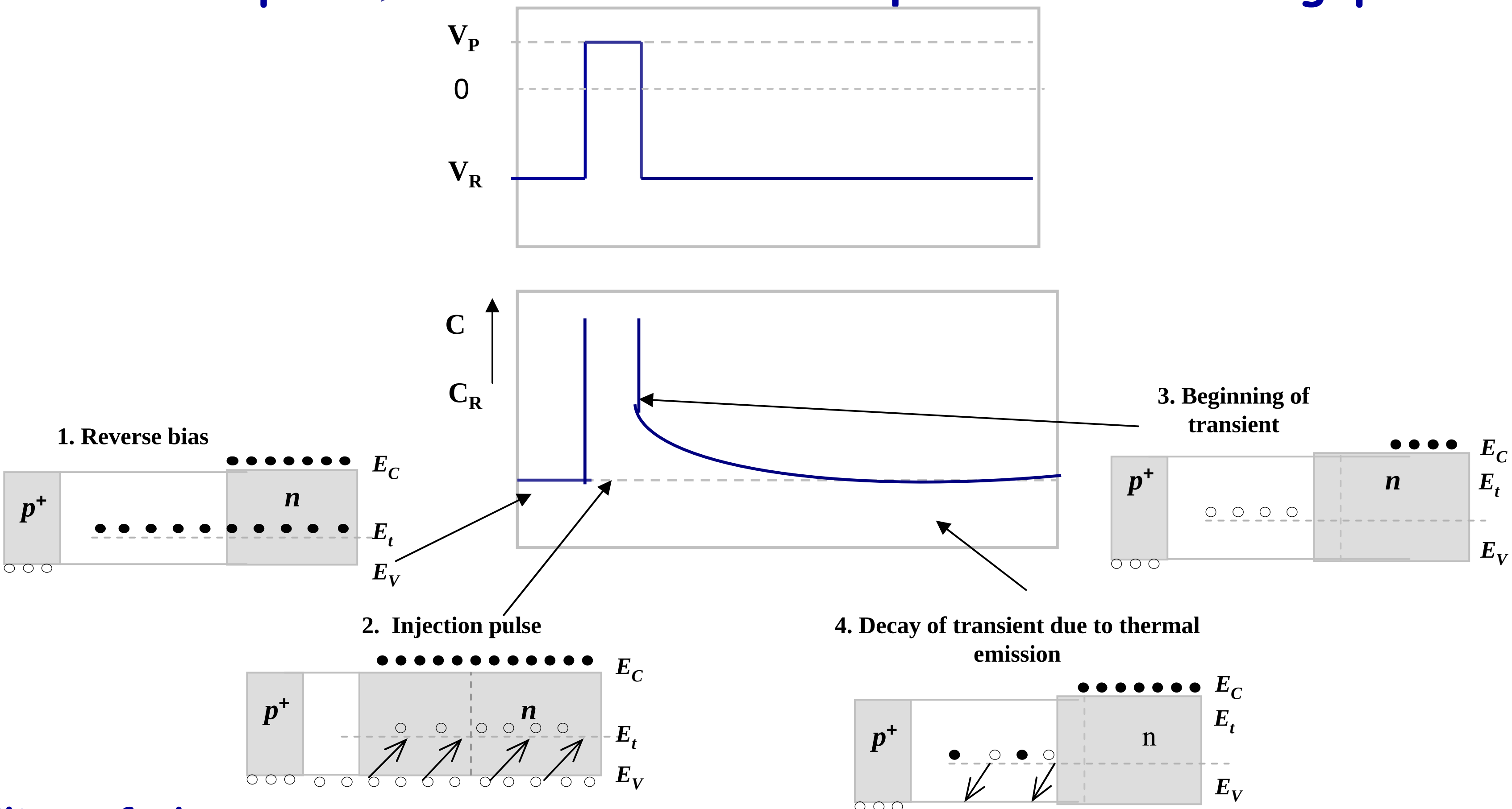
1. Electron trap ⟶ located in the upper half of the band gap:



$$C \approx \frac{1}{w} \approx \sqrt{Neff}$$

Capacitance Deep Level Transient Spectroscopy

2. Hole trap → located in the lower part of the band gap:



Filling of the traps

- By forward bias: electrons and holes injected → trap must have $c_p >> c_n$ for fully filling the hole traps
- By short -λ laser (red) from the n-side → trap with any c_p can be filled with holes

DLTS: determination of trap parameters

Electron trap of acceptor type:

1. Capacitance after the filling pulse

- Effective dopant concentration after the filling pulse

$$N_{eff}(t) = N_D - n_t(t)$$

- Density of occupied traps after the filling pulse

$$\frac{dn_t}{dt} = \overbrace{(e_p p_t - c_p p n_t)}^{\text{hole excess generation rate}} - \overbrace{(e_n n_t - c_n n p_t)}^{\text{electron excess generation rate}}$$

in SCR : $R_n, R_p \sim 0$

electron trap : $e_n >> e_p$

$$\frac{dn_t}{dt} = -e_n n_t$$

$$n_t(t) = N_T \exp\left(-\frac{t}{\tau_e}\right)$$

emission time $\tau_e = 1/e_n$

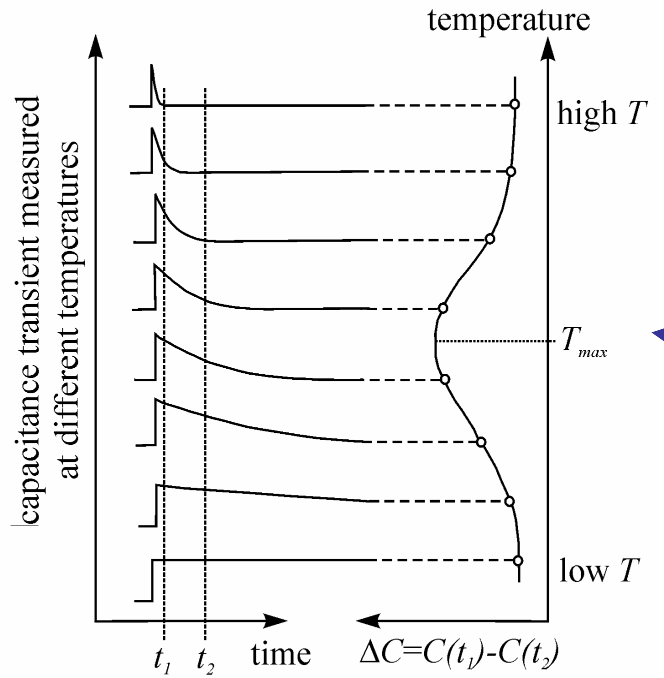
- Capacitance after the filling pulse

$$\Delta C(t) = C(t) - C_R = C_R\sqrt{1 - \frac{n_t(t)}{N_D}} \xrightarrow{\text{usually } N_t << N_D} C_R\left(1 - \frac{n_t(t)}{2N_D}\right)$$

DLTS: determination of trap parameters

2. DLTS spectrum

$$\Delta C = C(t) - C(R) = C_R \frac{N_T}{2N_D}\left(e^{-\frac{t_1}{\tau_e}} - e^{-\frac{t_2}{\tau_e}}\right)$$



High *T*: emission process to fast to be observed

Peak observed at T_{max} where emission time satisfies

$$\tau_e(T_{\max}) = 0.43 \times T_W$$

Low *T*: emission process to slow to be observed

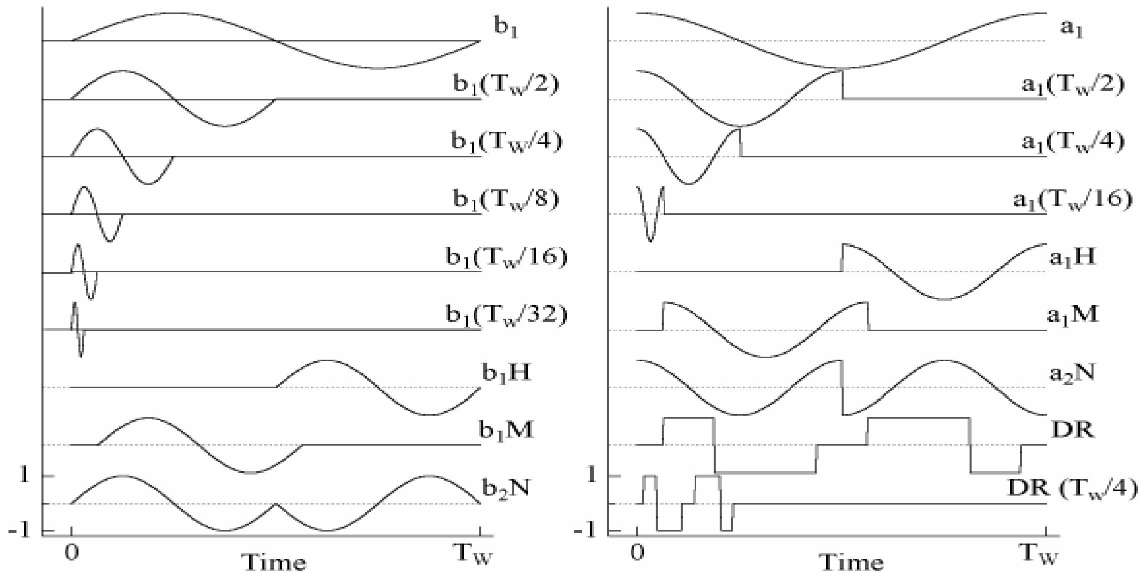
Correlator functions:

- the complete transient is folding with a correlator function

$$b_1 = \frac{2\Delta C}{T_W}\int_0^{T_W} \exp\left(-\frac{t_2+t_1}{\tau_e}\right)\sin\left(\frac{2\pi}{T_W}t\right)dt$$

$$a_1 = \frac{2\Delta C}{T_W}\int_0^{T_W} \exp\left(-\frac{t_2+t_1}{\tau_e}\right)\cos\left(\frac{2\pi}{T_W}t\right)dt$$

DLTS: determination of trap parameters



The correlation functions used for the maximum evaluation

3. Extraction of parameters

- Several temperature scans with different $T_W = t_2 - t_1 \rightarrow$ Arrhenius plot:

$$\ln\left(v_{th,n,p} N_{C,V} \tau_e(T_{max})\right) \text{ versus } 1/T_{max}$$

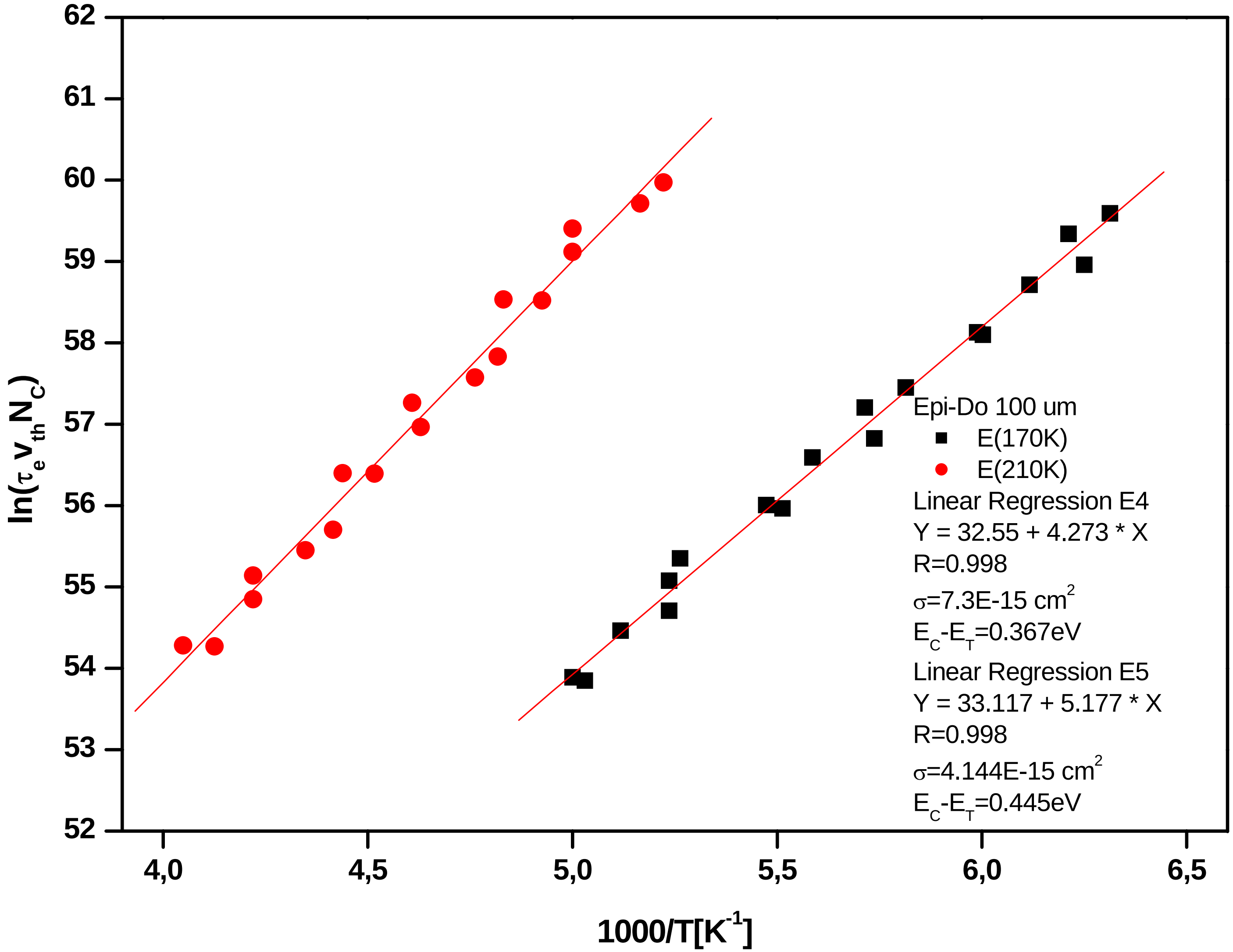
- Connection between e_n and σ_n

$$\ln\left(\tau_e(T) v_{th,n,p} N_{C,V}\right) = \frac{E_C - E_t}{k_B T} - \ln(\sigma_{n,p})$$

- N_t extracted form DLTS peak since $n_t(0) \propto N_t$
- E_t extracted from slope of Arrhenius plot
- σ_n from the intercept of Arrhenius plot with ordinate

DLTS: determination of trap parameters

- Example Arrhenius plot:



Summary

- DLTS → technique for determination of charge carrier traps parameters, based on observing reversely biased detector response to applied light or an abrupt change of biased voltage (filling of traps with holes and/or electrons)

  - DLTS method:
    - Capacitance transient after the filling process is measured
    - Capacitance transient caused by the change of the width of SCR due to emission of carriers that were trapped during the filling
    - During the measurement device must be biased with the voltage lower than full depletion voltage