HIPPOCRATICA CIVITAS STUDIUM SALERNI

Dipartimento di Ingegneria Industriale

AS BeST

A 7-Beryllium electron capture STudy for nuclear and solid state physics

Ph.D. School – Nuclear Physics meets Electronic Technology

Capacitive techniques for the defect characterization of semiconductor devices

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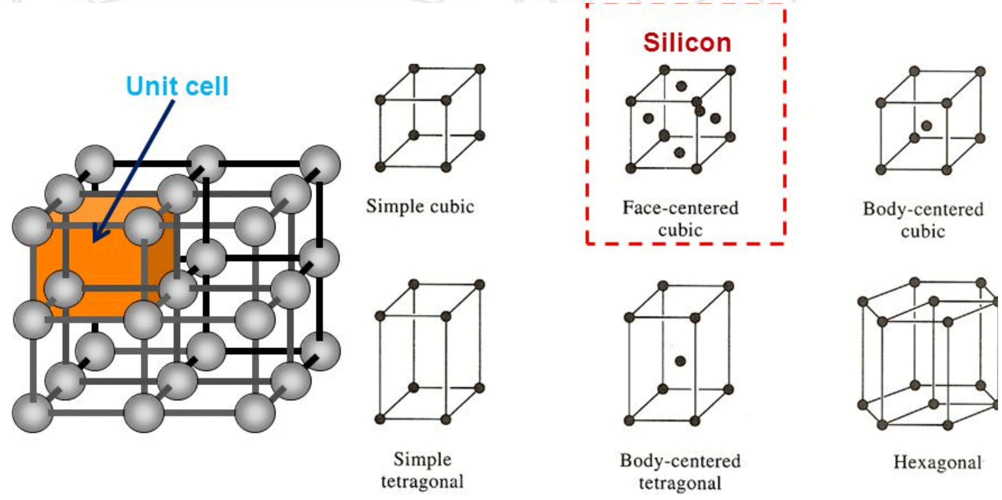
Outline

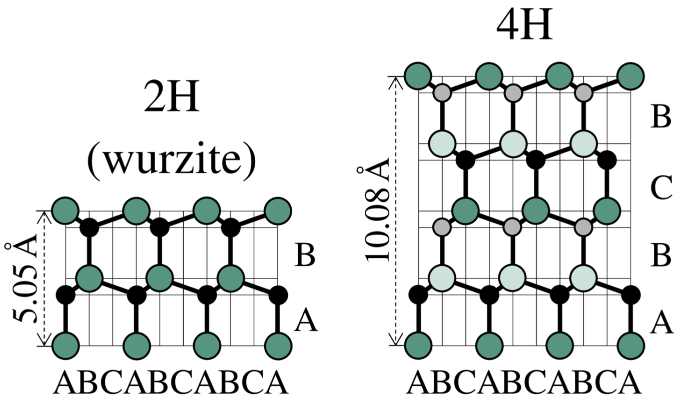
- What is a defect in a semiconductor?
- Electrical effects of the traps
- Capacitive techniques to measure a defect
- Examples

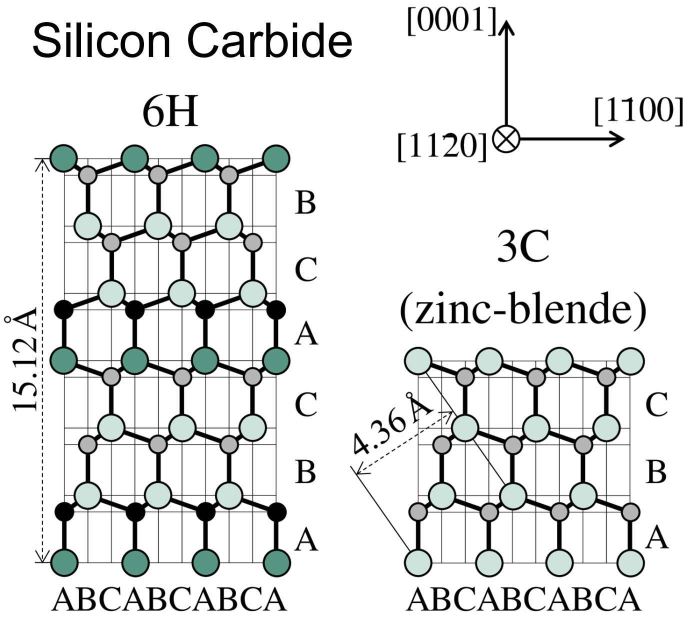
Cristal structure of a semiconductor

- Crystal structure is the atomic distribution into the space
- Each semiconductor has its own and defines the physical properties



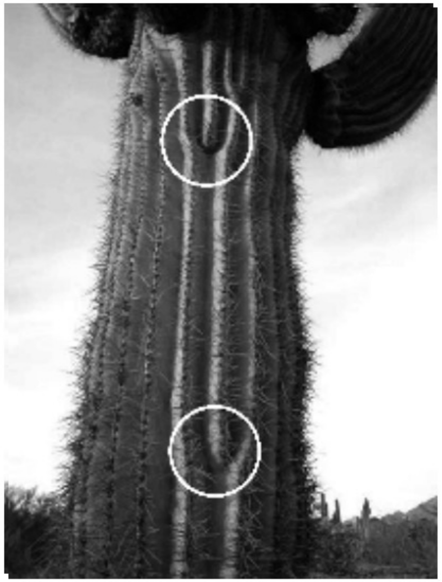
Silicon Carbide

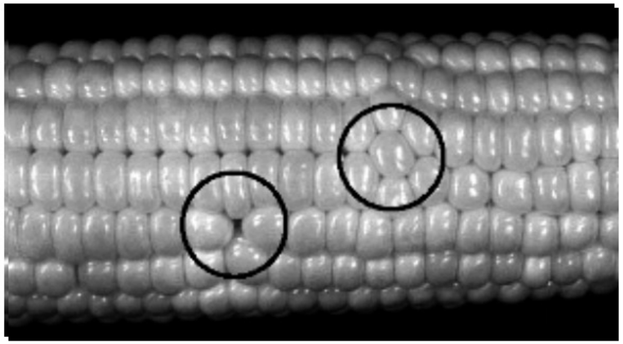




What is a defect?

- The defect is an imperfection of the regular crystalline structure of a semiconductor atom-by-atom
- The nature is full of examples
- Defects can be also intentional to achieve a lower energy state (reduction of mechanical stress) or to have a better material (steel).

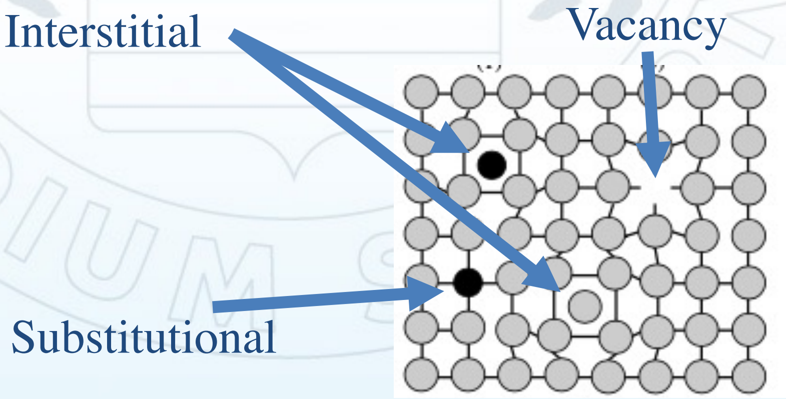




Defects of a semiconductor

- All semiconductors contain defects:
  - foreign atoms (impurities)
  - crystalline defects
- Impurities are:
  - intentionally introduced: improve the performance of the device
    - dopant atoms (shallow-level impurities);
    - recombination centers (deep-level impurities) to reduce the device lifetime;
    - deep-level impurities to increase the substrate resistivity.
  - unintentionally incorporated during crystal growth and device processing: the performance of the device gets worse

IMPURITIES

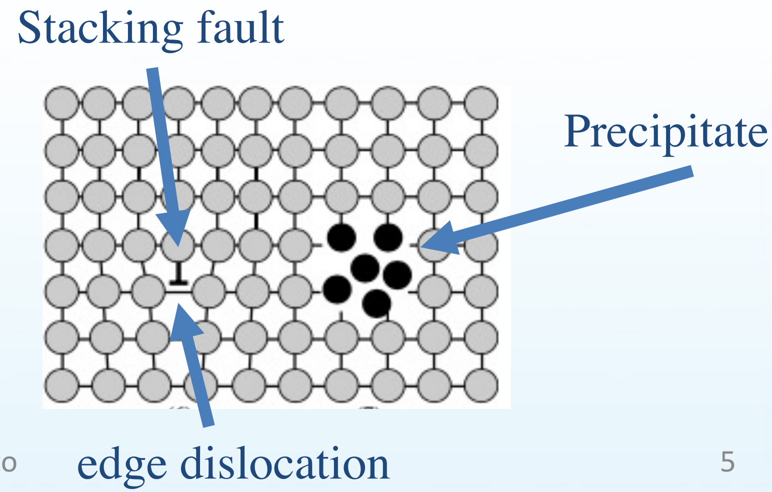


Interstitial

Vacancy

Substitutional

CRYSTALLINE DEFECTS



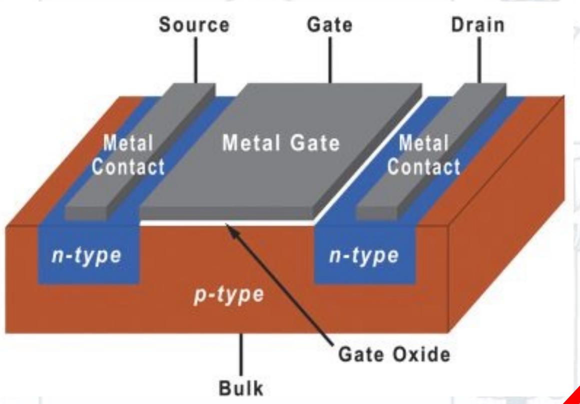
Stacking fault

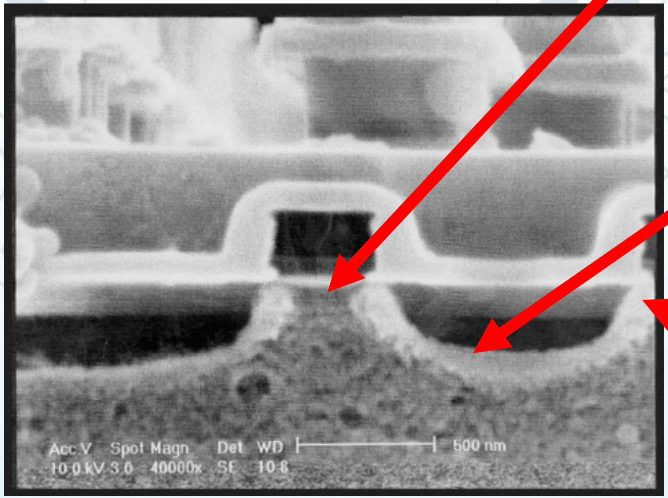
Precipitate

edge dislocation

Defects and the electron devices

- Nowadays Silicon is grown very pure ($<10^{10}$cm^{-3}), but process fabrication can introduce concentration of metals of around 10^{10}-10^{12}cm^{-3}
- They affect the reliability of the device, for example oxide failure of a MOSFET

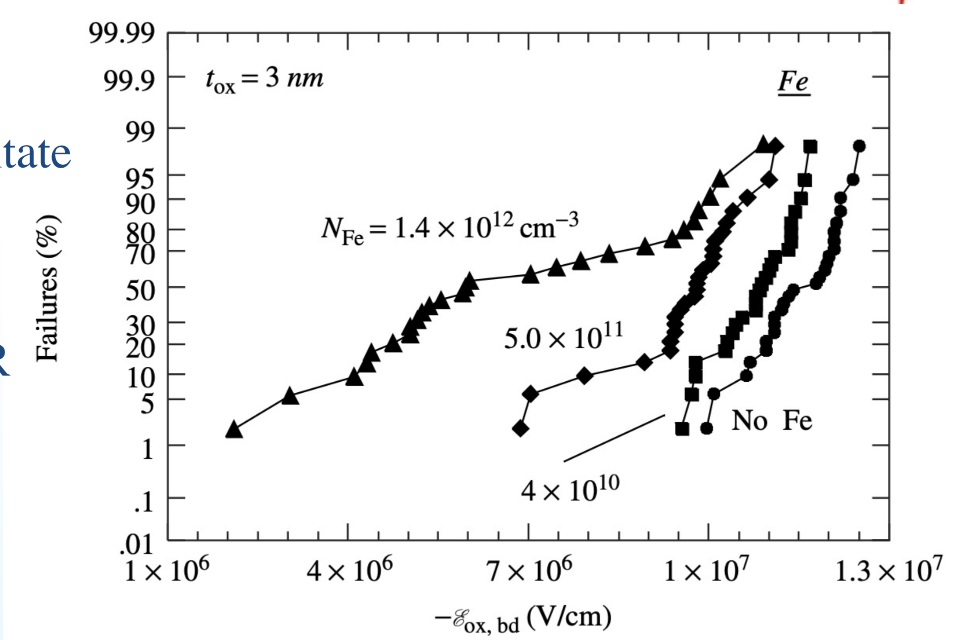




Metal precipitate

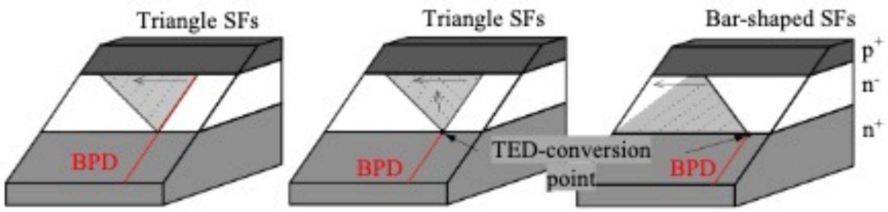
SCR

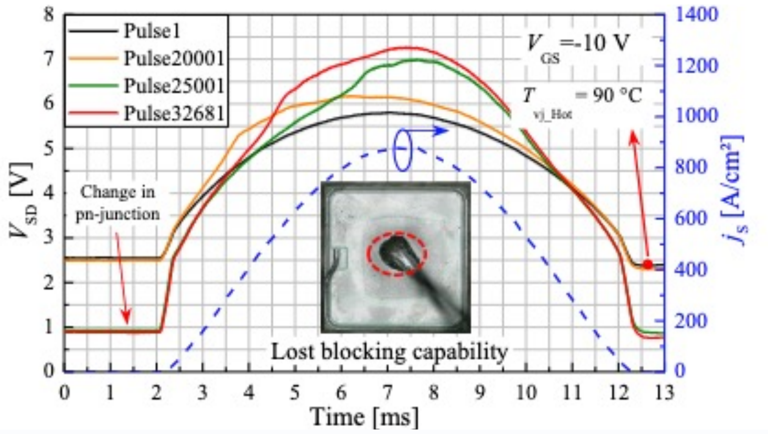
Stress

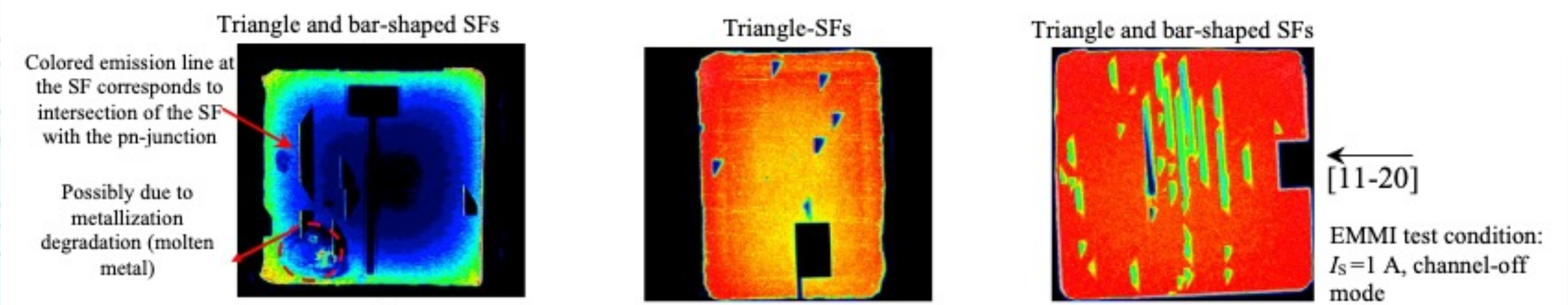


Defects and the electron devices

- 4H-SiC bipolar degradation: the minority charge carriers (holes) might reach the substrate and cause electron-hole recombination in or close to it, which exhibits a certain energy activating the growth of SFs at BPDs or other BPD conversion points.



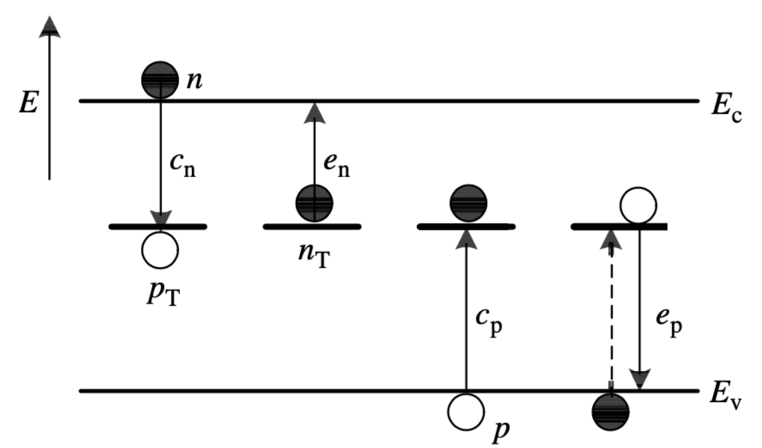




A way to quantify the defects

Electron energy band diagram – Graphical representation

- Band diagram of a pure crystal: no energy level in the band-gap
- When the periodicity of the crystal is perturbed, a discrete energy level is introduced (E_T), named defects or generation-recombination (G-R) centres or traps.
- Four events are possible between charge carriers and traps



Charge carriers: n (electron) – p (hole)
Traps: N_T (impurities)

$c_{n(p)}$: capture coefficient for electron (hole)
$e_{n(p)}$: emission coefficient for electron (hole)

G-R mechanism

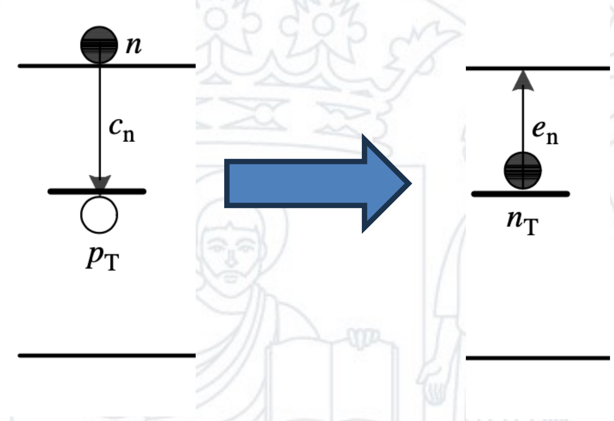
Recombination

Generation

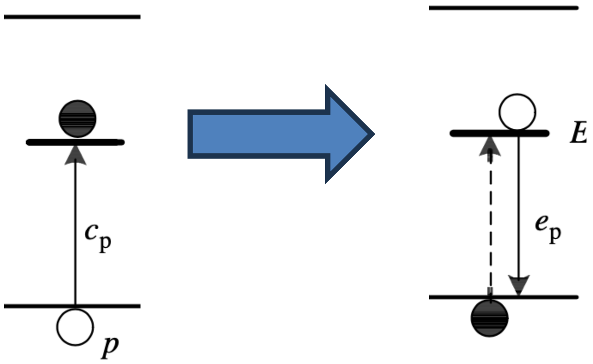
- The impurity is a G-R center and both bands are involved
- This mechanism is related to the lifetime of the charge carriers: relevant parameter for electron devices
- The energy level is in the middle of the band-gap

Trapping mechanism

Electron trapping



Hole trapping

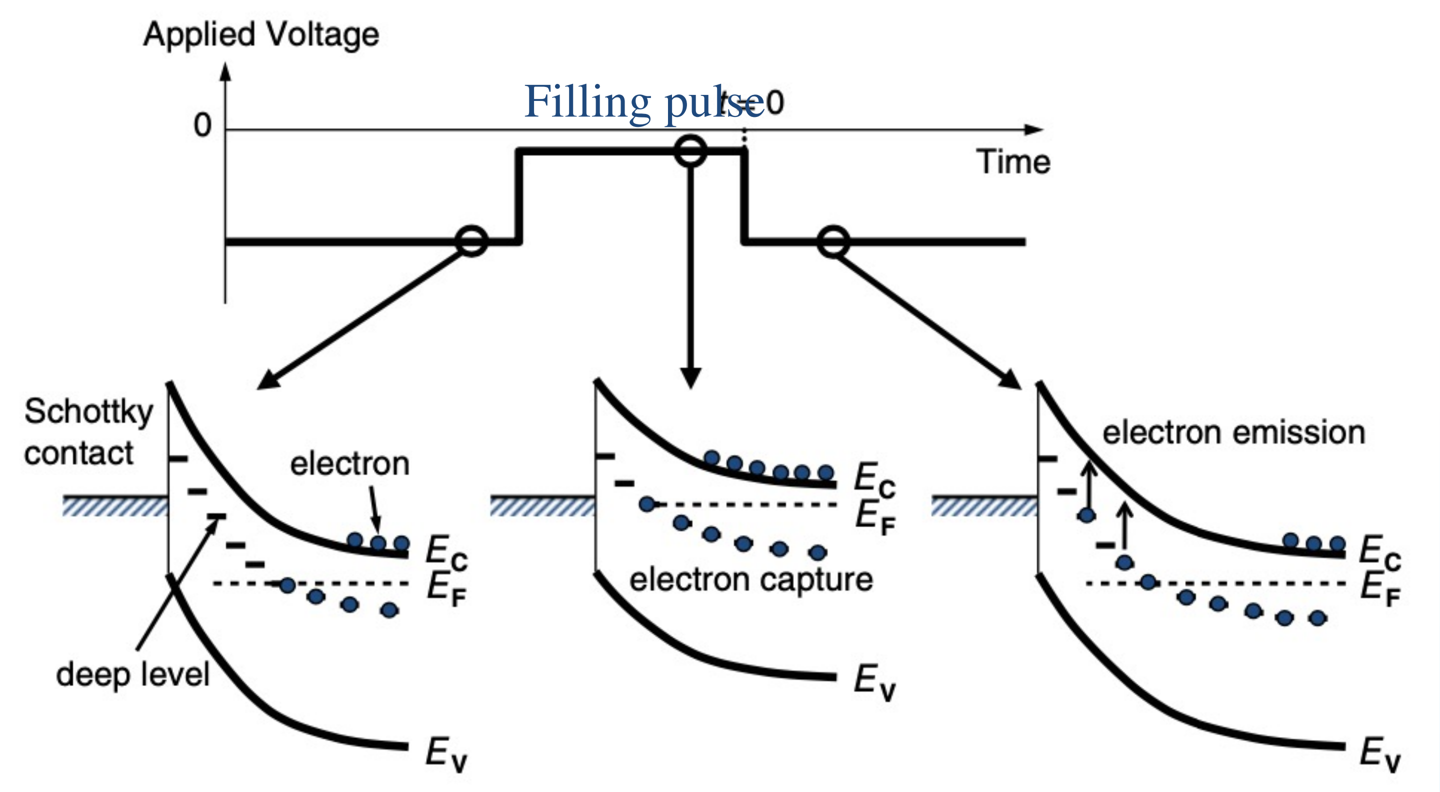


- A carrier is captured and emitted back to the same band
- The impurity is a Trap
- The energy level is close to the band edges:
  - E_T near E_C: capture and emission rate for electron dominate to hole ones
  - E_T near E_V: capture and emission rate for hole dominate to electron ones

Sample excitation

- A junction is required in order to have a space charge region (Schottky, pin, MOS) used to move the Fermi level
- An external voltage is applied and varies during the time

Filling pulse



Mathematical description

- The electron density in the conduction band is increased by electron emission and is diminished by electron capture.
- The electron time rate of change due to G-R mechanisms is

$$\frac{dn}{dt}\Big|_{G-R} = e_n n_T - c_n n p_T$$

- The emission rate e_n [1/s] represents the electrons emitted per second from electron-occupied G-R centers
- The capture rate $c_n n$ [cm^3/s] represents the density of electrons captured per second from the conduction band
- c_n is the capture coefficient and depends on electron capture cross-section and the thermal velocity

$$c_n = \sigma_n v_{th}$$

- Similarly, for the hole:

$$\frac{dp}{dt}\Big|_{G-R} = e_p p_T - c_p p n_T$$

Mathematical description

- When hole and electron are emitted and/or captured, the trap occupancy changes with a rate

$$\frac{dn_T}{dt}\Big|_{G-R} = \frac{dp}{dt} - \frac{dn}{dt} = (c_n n + e_p)(N_T - n_T) - (c_p p + e_n)n_T$$

- In the case of a n-type the hole are negligible and a solution can be found

$$n_T(t) = n_T(0)\exp\left(-\frac{t}{\tau_1}\right) + \frac{(e_p + c_n n)N_T}{e_n + c_n n + e_p}\left(1 - \exp\left(-\frac{t}{\tau_1}\right)\right)$$

- For a relevant trap in the upper half of the band gap, i.e. $e_n >> e_p$, further approximation is assumed
  - Emission process: $n_T(t) = n_T(0)\exp\left(-\frac{t}{\tau_e}\right) \approx N_T \exp\left(-\frac{t}{\tau_e}\right)$ with $\tau_e = 1/e_n$
  - Capture process: $n_T(t) = N_T - (N_T - n_T(0))\exp\left(-\frac{t}{\tau_c}\right)$ with $\tau_c = 1/c_n n$, $n_T = \frac{e_p}{e_n + e_p}N_T$

Macroscopic measurements

- With impurities being charged or neutral, and with electrons or holes emitted or captured, any measurement that detects charged species can be used for their characterization
- The measurable electrical quantity is the junction capacitance
- It can change by applying an external voltage and depends on the net charge
- In the case of only electron trap density, the capacitance is given by

$$C(t) = \sqrt{\frac{\varepsilon_S q\{N_D - n_T(t)\}}{2(V_d - V_R)}} = C_{st}\sqrt{1 - \frac{n_T(t)}{N_D}} = C_{st}\sqrt{1 - \frac{N_T \exp(-t/\tau_e)}{N_D}}$$

where $C_{st} = \sqrt{\frac{\varepsilon_S q N_D}{2(V_d - V_R)}}$ is the steady-state capacitance

- When the trap density is lower than doping concentration, one obtains

$$C(t) \cong C_{st}\left\{1 - \frac{N_T \exp\left(-t/\tau_e\right)}{2N_D}\right\}$$

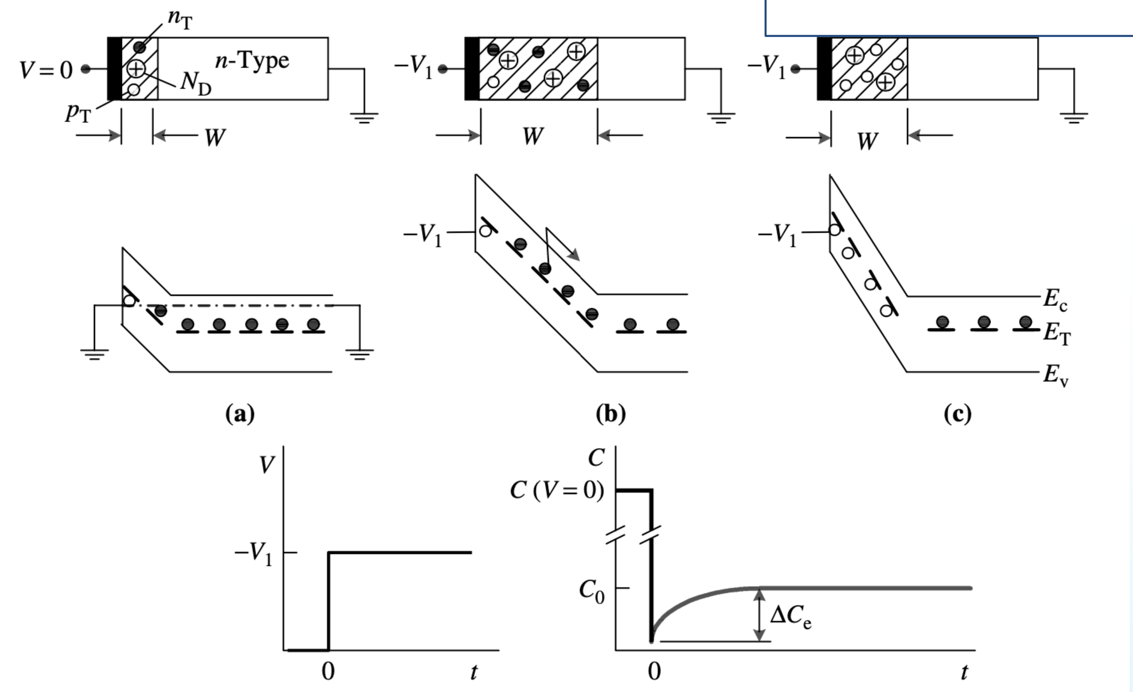
Emission of majority carriers

- By applying an external voltage, one can change the charge in the SCR and a transient is observed

$$C(t) \cong C_{st}\left\{1 - \frac{N_T \exp(-t/\tau_e)}{2N_D}\right\}$$

- For the emission process

$$\boxed{C(\infty) - C(t) = \frac{n_T(0)}{2N_D} C_0 \exp\left(-\frac{t}{\tau_e}\right)}$$



$$\Delta C_e = \frac{n_T(0)}{2N_D} C_0$$

Final manipulation

- Principle of detailed balance: under equilibrium conditions each fundamental process and its inverse must balance independently from any other process that may be occurring inside the material
- Assumption: the emission and capture coefficients remain equal to their equilibrium values under non-equilibrium condition

$$\tau_e = 1/e_n$$

$$e_n = c_n n_1; e_p = c_p p_1$$

$$c_n = \sigma_n v_{th}$$

$$\tau_c = 1/c_n n$$

$$n_1 = n_i \exp((E_T - E_i)/kT); p_1 = n_i \exp(-(E_T - E_i)/kT)$$

$$\tau_e = \frac{\exp((E_i - E_T)/kT)}{\sigma_n v_{th} n_i} = \frac{\exp((E_c - E_T)/kT)}{\sigma_n v_{th} N_c}$$

$$\boxed{\tau_e T^2 = \frac{\exp((E_c - E_T)/kT)}{\gamma_n \sigma_n}}$$

$$v_{th} = \sqrt{\frac{3kT}{m_n}} \quad N_c = 2\left(\frac{2\pi m_n kT}{h^2}\right)^{3/2}$$

$$\gamma_n = (v_{th}/T^{1/2})(N_c/T^{3/2}) = 3.25 \times 10^{21}(m_n/m_o) \ \text{cm}^{-2}\text{s}^{-1}\text{K}^{-2}$$

Deep-Level Transient Spectroscopy DLTS

Deep-Level Transient Spectroscopy DLTS

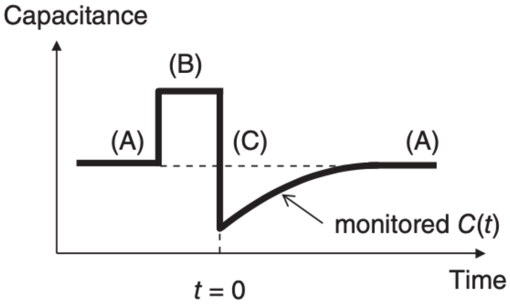
- DLTS is a technique to extract the energy level (E_T) and the cross section (σ) of a trap
- The technique is merely a method to extract a maximum in a decaying waveform
- The assumptions are:
  - C-t curve has a transient with a single decay rate;
  - a processing of the transient produces a maximum output for selected decay rate;
  - the maximum output is obtained when the rate of the decay is equal to the rate window of a boxcar average;
  - for the same rate window and varying the temperature, a peak appears in the capacitance versus temperature plot because the decay rate depends on the temperature.

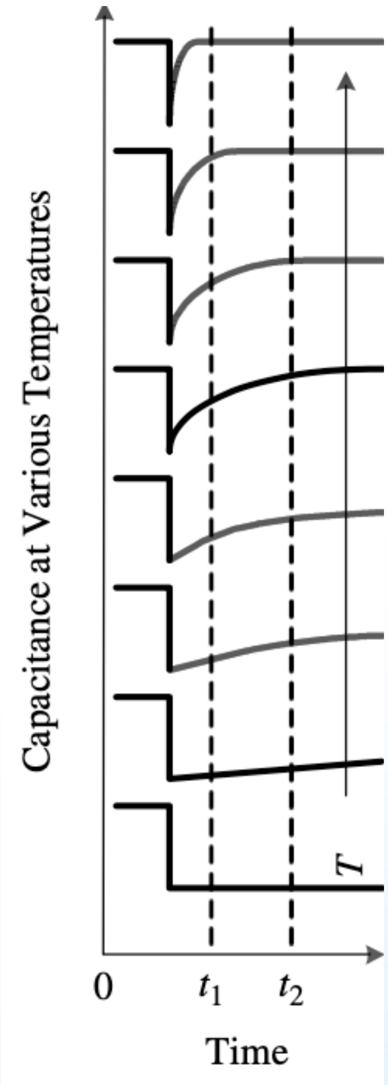
DLTS basic concept

- The transient of the capacitance is exponential and depends on:
  - Doping concentration (N_D)
  - Trap density occupied by electron (n_T)
  - Constant time (τ_e)
- The constant time decreases with the temperature and depends on the E_T and the cross section σ_n of the trap

$$C(t) = C_0\left[1 - \frac{n_T(0)}{2N_D}\exp\left(-\frac{t}{\tau_e}\right)\right]$$

$$\tau_e = \frac{\exp((E_c - E_T)/kT)}{\gamma_n \sigma_n T^2}$$





Weighted function

- The capacitance decay waveform is corrupted with noise and a technique to clean it is necessary
- The DLTS is a correlation technique:
  1. the input signal is multiplied by a reference signal, named weighting function w(t)
  2. the product is filtered (averaged) by a linear filter (integrator or a low-pass filter)

$$\delta C = \frac{1}{T}\int_0^T f(t)w(t)\,dt = \frac{C_0}{T}\int_0^T \left(1 - \frac{n_T(0)}{2N_D}\exp\left(-\frac{t}{\tau_e}\right)\right) w(t)\,dt$$

- The properties of such a correlator depend strongly on the w(t) and on the filtering method

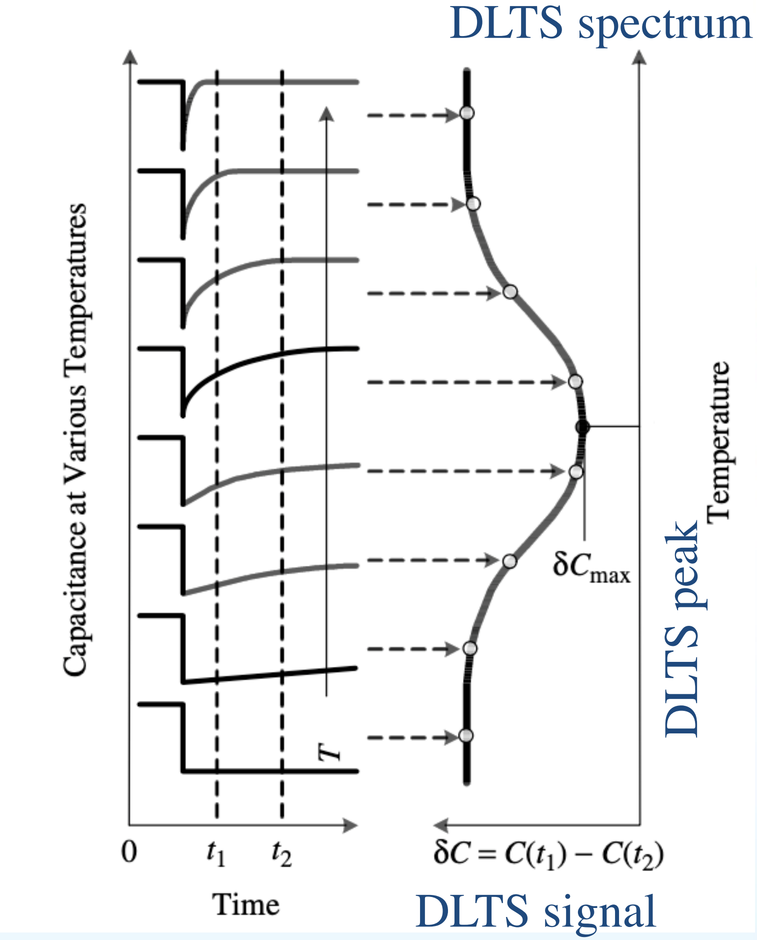
Boxcar DLTS

1. At each T, C-t curve is sampled at times $t=t_1$ and $t=t_2$ and the capacitances are subtracted

$$C(t) = C_0\left[1 - \frac{n_T(0)}{2N_D}\exp\left(-\frac{t}{\tau_e}\right)\right]$$

$$w(t) = \delta(t - t_1) - \delta(t - t_2)$$

$$\delta C = C(t_1) - C(t_2) = \frac{n_T(0)}{2N_D}C_0\left(\exp\left(-\frac{t_2}{\tau_e}\right) - \exp\left(-\frac{t_1}{\tau_e}\right)\right)$$



- T is slowly scanned
- The device is repetitively pulsed between zero and reverse bias

Extracting time constant

- The maximum time constant ($\tau_{e,max}$) is obtained differentiating the DLTS signal with respect to τ_e and equaling it to zero
- $\tau_{e,max}$ at δC_{max} is

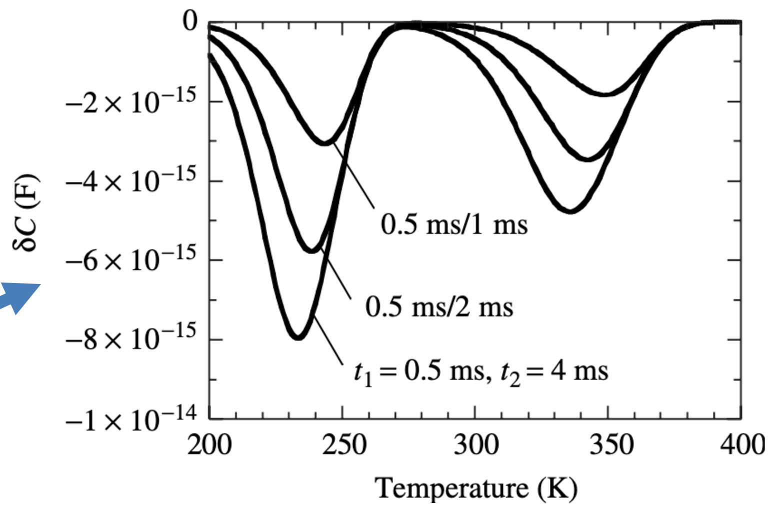
$$\tau_{e,\max} = \frac{t_2 - t_1}{\ln(t_2/t_1)}$$

2. For each rate window, namely each pair (t_1,t_2), single values of $\tau_{e,max}$ and T_m are obtained and collected in the Arrhenius plot $ln(\tau_{e,max} T_m^2)$ *vs.* $1/T$
3. The steps 1. and 2. are repeated for another rate window in order to have another point in the Arrhenius plot

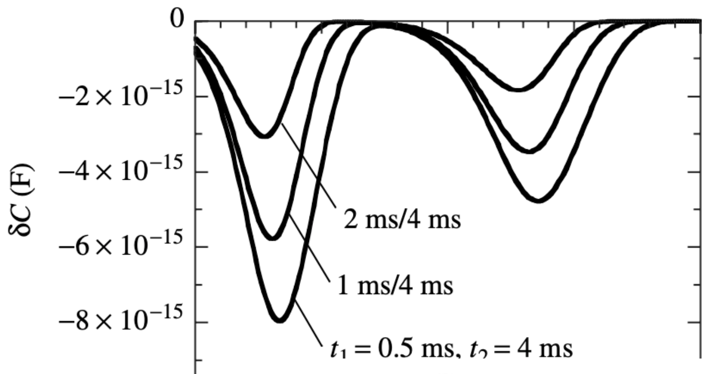
- The relation between w(t) and $\tau_{e,max}$ is independent from the capacitance and the baseline

Effect of the rate window

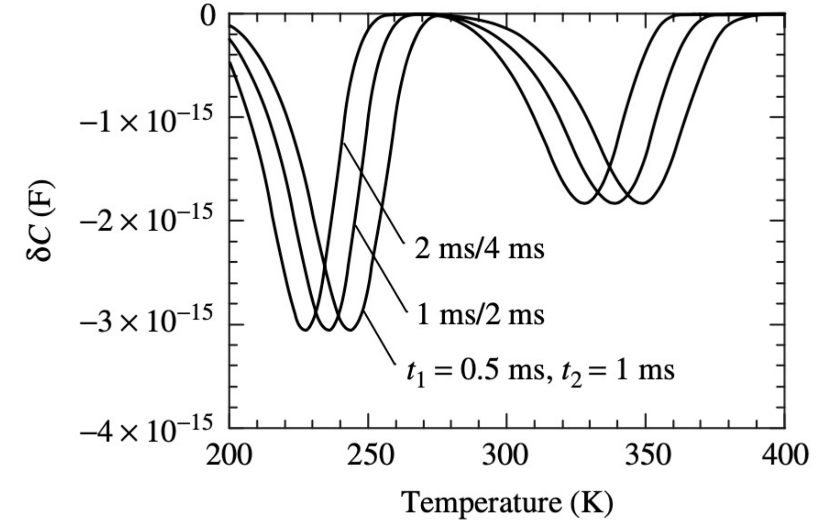
- To create the Arrhenius plot, the rate windows must be varied:
  1. t_1 fixed and t_2 varied



  2. t_2 fixed and t_1 varied



  3. t_2/t_1 fixed and t_1 - t_2 varied



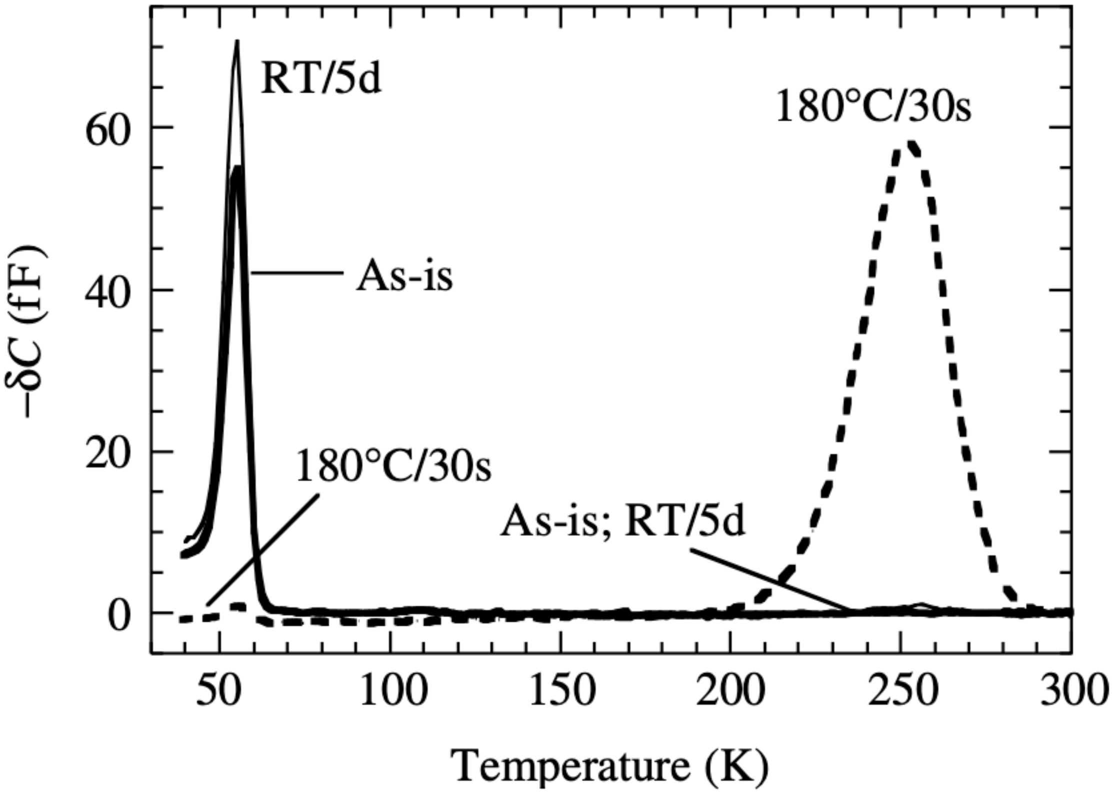
$C_0 = 4.9\times10^{-12}F$, $N_D = 10^{15}\ \text{cm}^{-3}$

$E_c - E_{T1} = 0.37$ eV $\sigma_{n1} = 10^{-15}\ \text{cm}^2$ $N_{T1} = 5\times10^{12}\ \text{cm}^{-3}$

$E_c - E_{T2} = 0.6$ eV, $\sigma_{n2} = 5\times10^{-15}\ \text{cm}^2$, $N_{T2} = 2\times10^{12}$

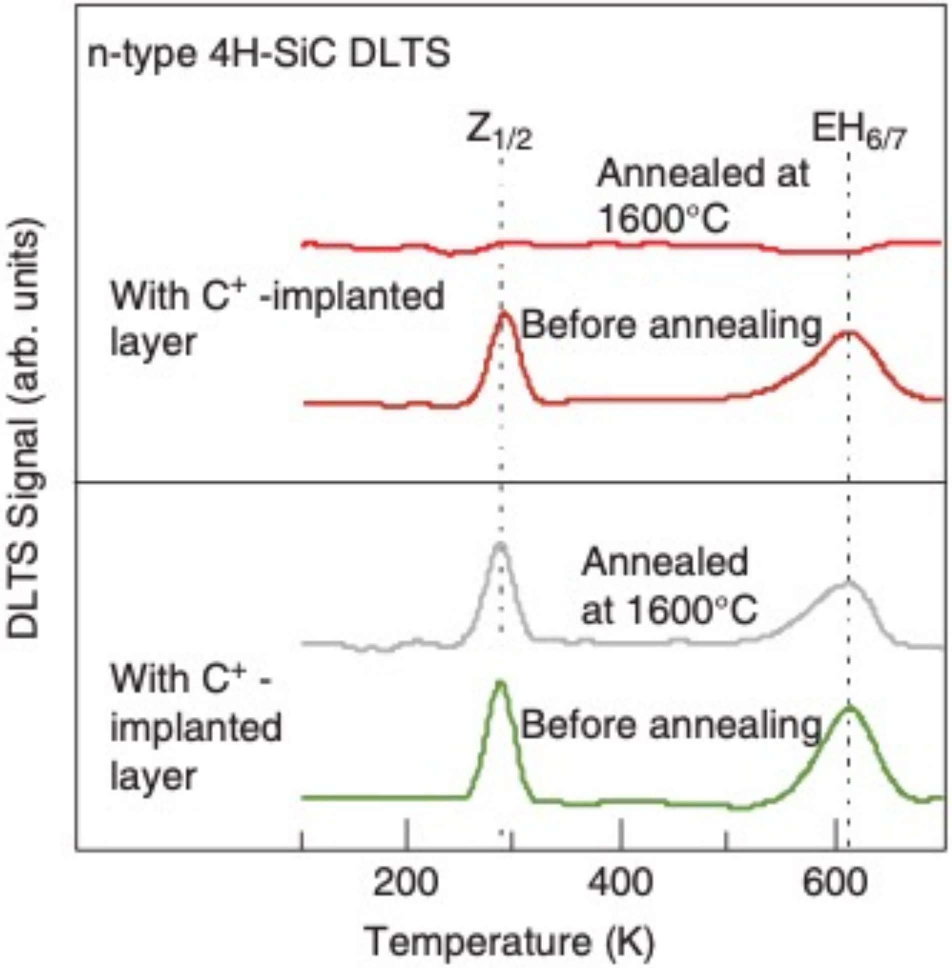
Example of DLTS spectrum

- The DLTS spectrum of Fe-B in Silicon crystal



Example of DLTS spectrum

- The DLTS spectrum of intrinsic defects in 4H-SiC crystal:
  - $Z_{1/2}$ ($E_C - 0.63eV$)
  - $EH_{6/7}$ ($E_C - 1.55eV$)



Extraction procedure

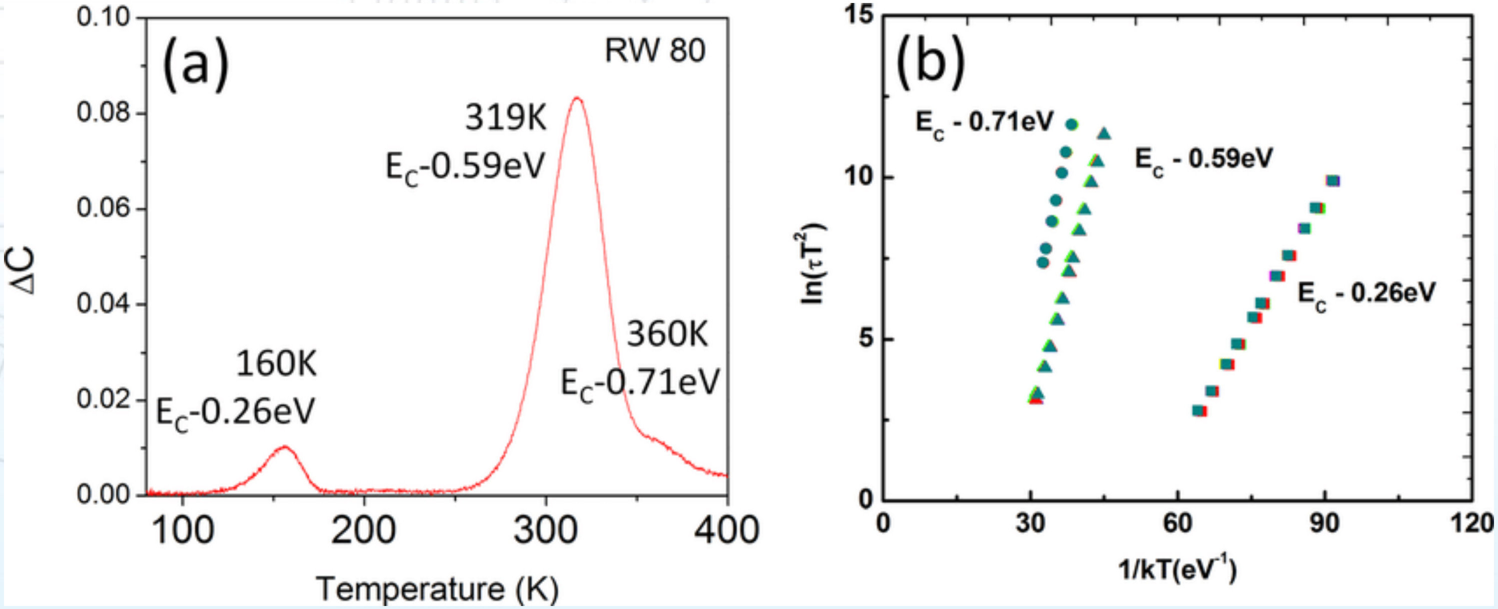
- Once the Arrhenius plot is obtained, the trap characteristics parameters can be extracted:

$$\tau_e = \frac{\exp((E_c - E_T)/kT)}{\gamma_n \sigma_n T^2}$$

$$\ln\left(\tau_{e,max} T_m^2\right) = \frac{E_C - E_T}{k_B T} - \ln(\sigma_n \gamma_n) = \mathrm{A}\,\frac{1}{k_B T} + \mathrm{B}$$

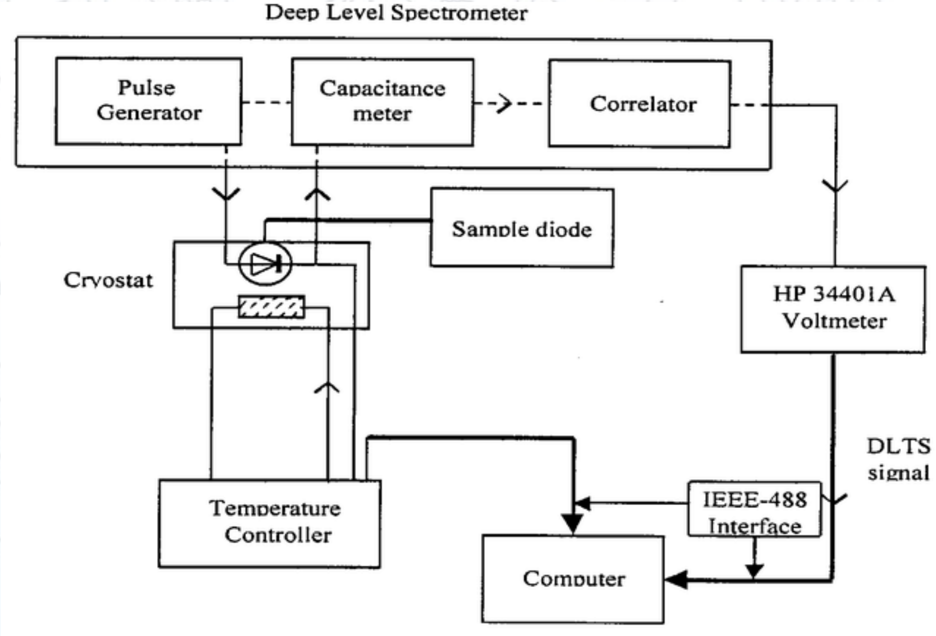
$$\boxed{E_C - E_T = A}$$

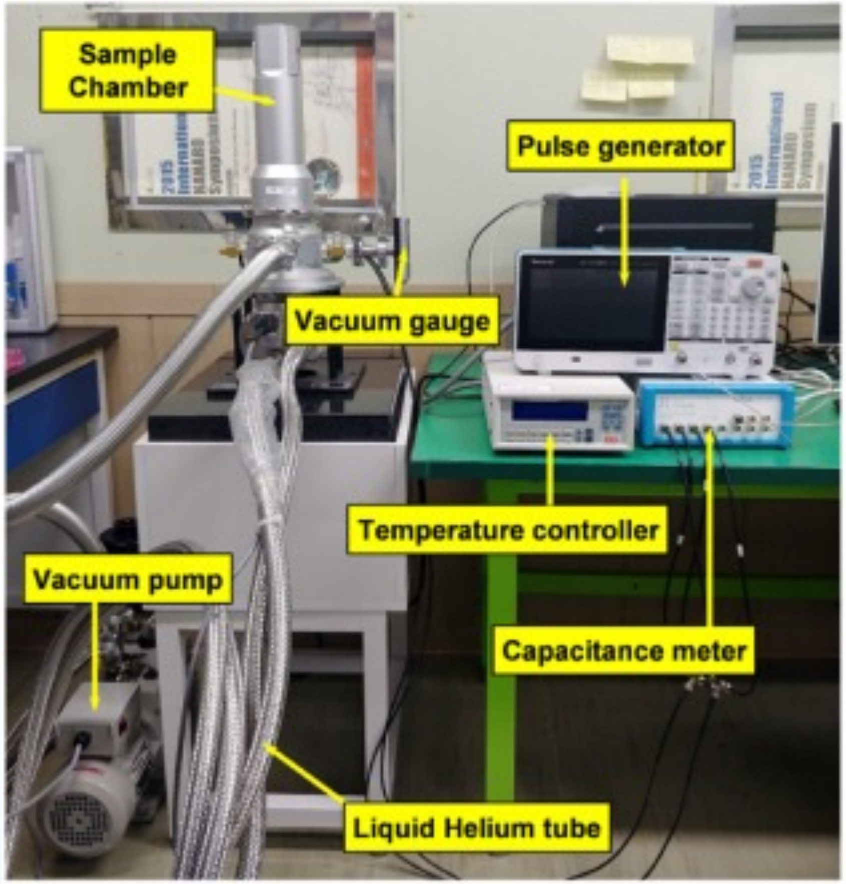
$$\boxed{\sigma_n = \frac{1}{\gamma_n} e^{-B}}$$



DLTS – Measurement set-up

- The DLTS needs:
  - Capacitance meter
  - Pulse generator
  - Cryostat system
  - Acquisition system or correlator



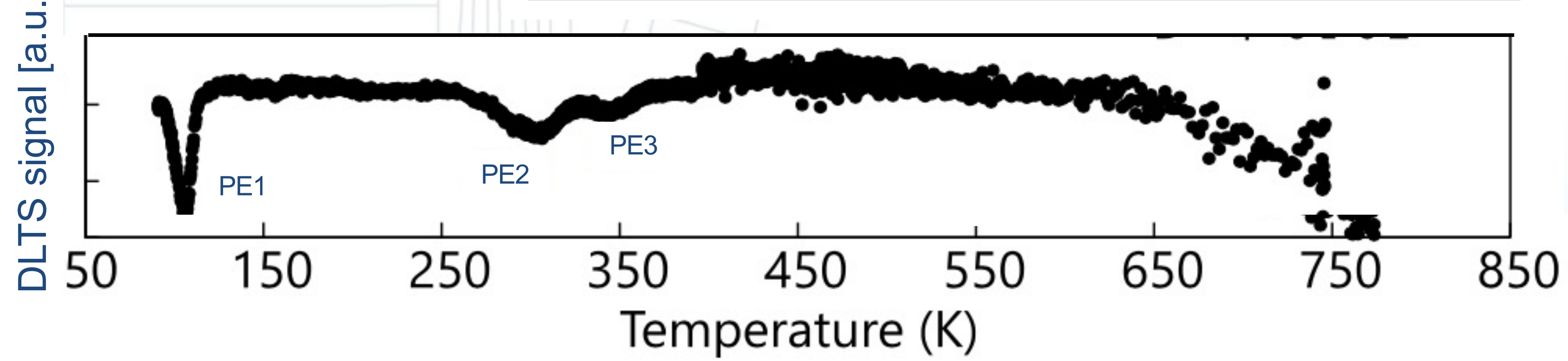


Hands-on: DLTS spectrum Analysis

Exercise

- This afternoon we will simulate a DLTS spectrum.
- Information:
  - 4H-SiC diode with doping concentration of 3.3E14cm^{-3}
  - Rate window of 2
  - Steady-state capacitance of 1pF
  - k_B=8.6E-5, m_n/m_0=0.763, $\gamma_n = 3.25E21 * m_n/m_0$
- Find:
  - t_1
  - Traps parameters

Label	E_A [eV]	σ_∞ [cm^2]	N_T [cm^{-3}]	Corresponding center
PE1	0.17	8.1×10^{-16}	1.6×10^{12}	Ti[29]
PE2	0.41	6.0×10^{-18}	5.6×10^{11}	–
PE3	0.63	1.2×10^{-15}	2.8×10^{11}	$Z_{1/2}$[[29]



Fukaya, S., Yonezawa, Y., Kato, T., & Kato, M. (2022). Depth Distribution of Defects in SiC PiN Diodes Formed Using Ion Implantation or Epitaxial Growth. *physica status solidi (b)*, *259*(9), 2100419.