# Study of point- and cluster-defects in radiation-damaged silicon

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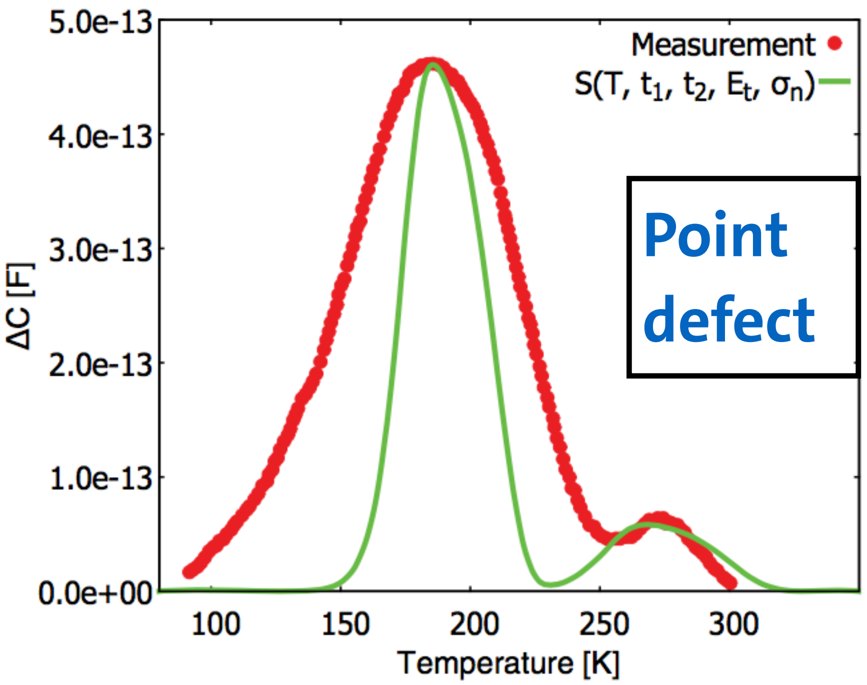
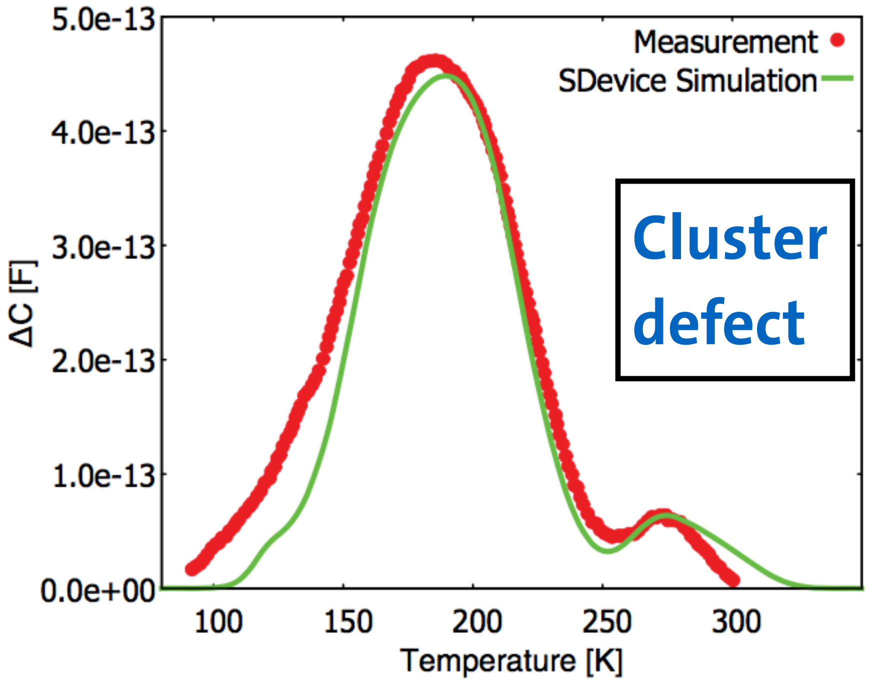
# INTRODUCTION

- Irradiations of silicon can produce **point**-like and **cluster** defects
- The **peak shape** of cluster-related defects recorded by **TSC** or **DLTS** differs significantly from those of point-like defects (measured peaks are broader compared to point-defects)
- Problem was studied by A. Scheinemann and A. Schenk e.g. on dislocation loops (DLs) due to ion implantation in CMOS devices

**[A. Scheinemann, A. Schenk, Phys. Stat. Solidi A211, No.1, 136-142 (2014)+ PhD Scheinemann]**



DLTS spectrum of DL compared with analytical theory for point defects:



DLTS simulation of DL taking into account the Coulomb repulsion energy

## In this talk

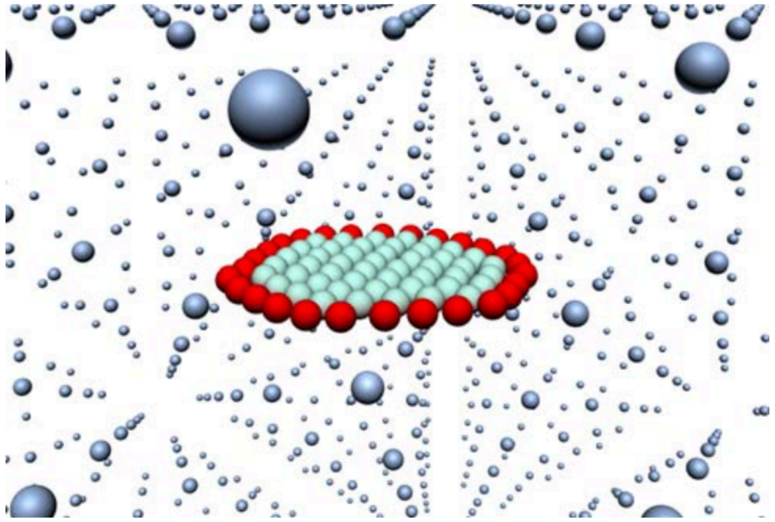
- Application to silicon irradiated with electrons with **3.5 - 27 MeV** kinetic energy

➡ Formation of cluster defects is expected above 7 MeV

# MODEL

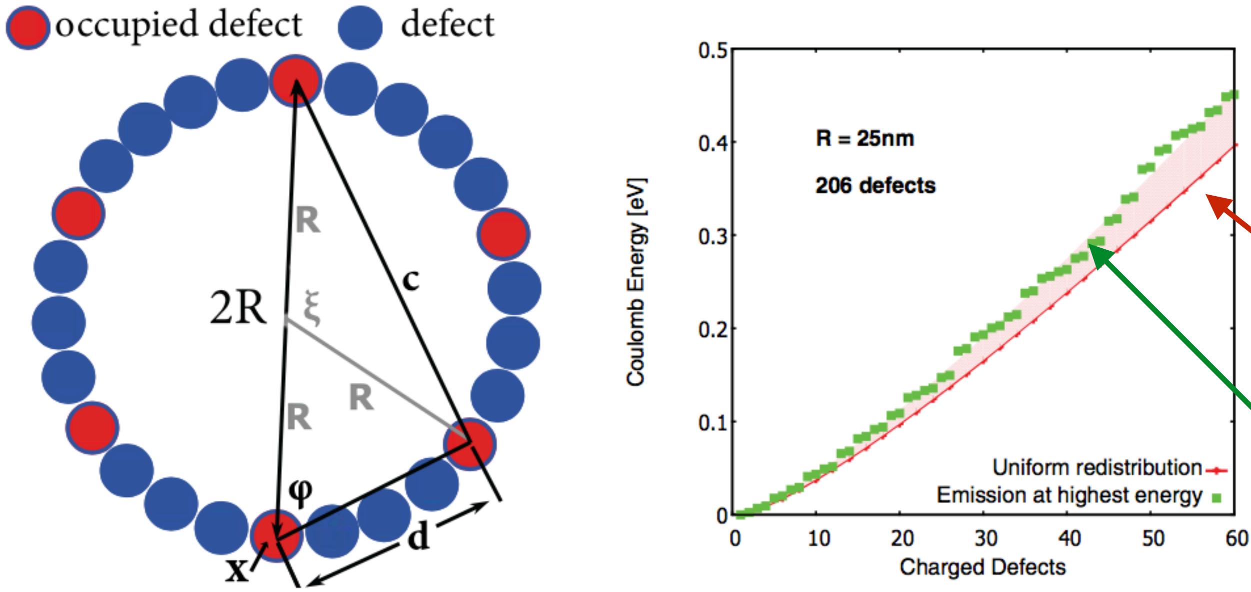
## Assumptions:

Cluster → **accumulation** of point defects
→ change of **local potential** depending on fraction of filled states
→ activation energy $E_a$ of defects **depends on occupation**
→ time (and T) dependence



[A. Scheinemann, A. Schenk, Phys. Stat. Solidi A211, No.1, 136-142 (2014)]

## Dislocation loop (DL): Potential energy vs. occupation



a) Loop Geometry b) Coulomb Energy

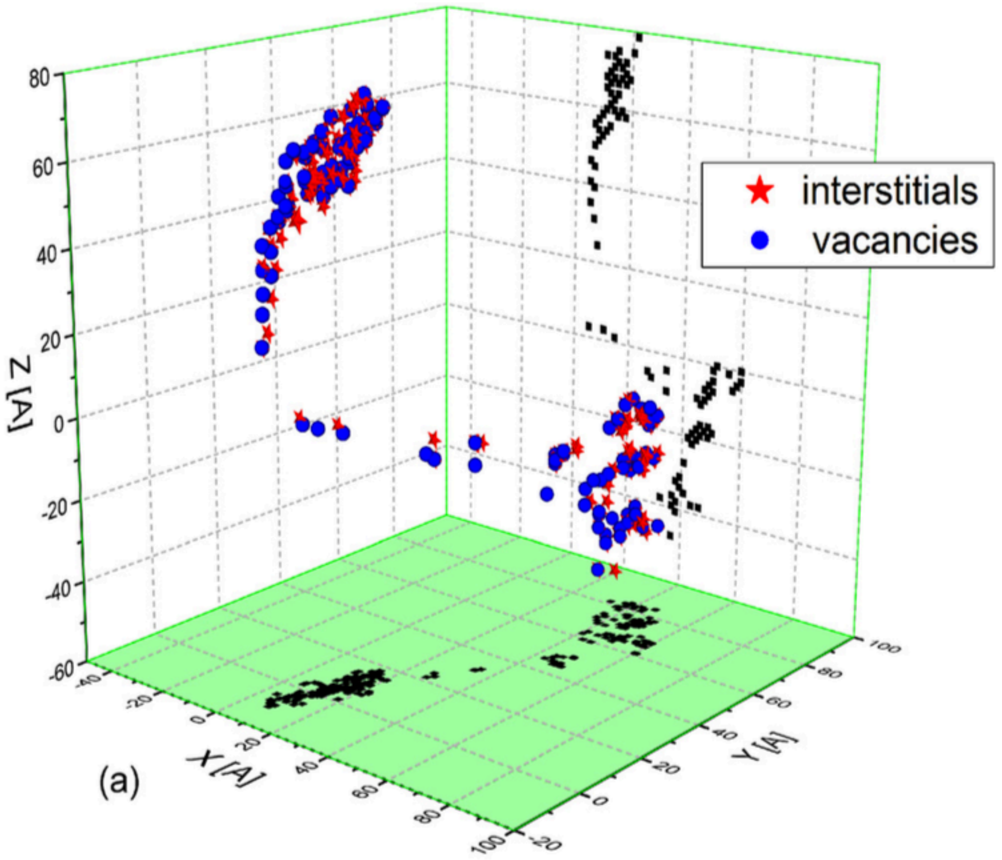
uniform redistribution

emission at highest energy

**Figure 2** (a) Schematic view of DL periphery partially occupied by captured carriers with geometry used to derive the Coulomb contribution to the defect level. (b) Deviations between the assumption that captured carriers can redistribute instantaneously along the dislocation loop (solid line) and the case where they are bound to their site while capture and emission probabilities vary along the periphery of the defect with the local Coulomb energy contribution (square symbols). The shaded area indicates 15% difference from the original analytical expression.

# MODEL

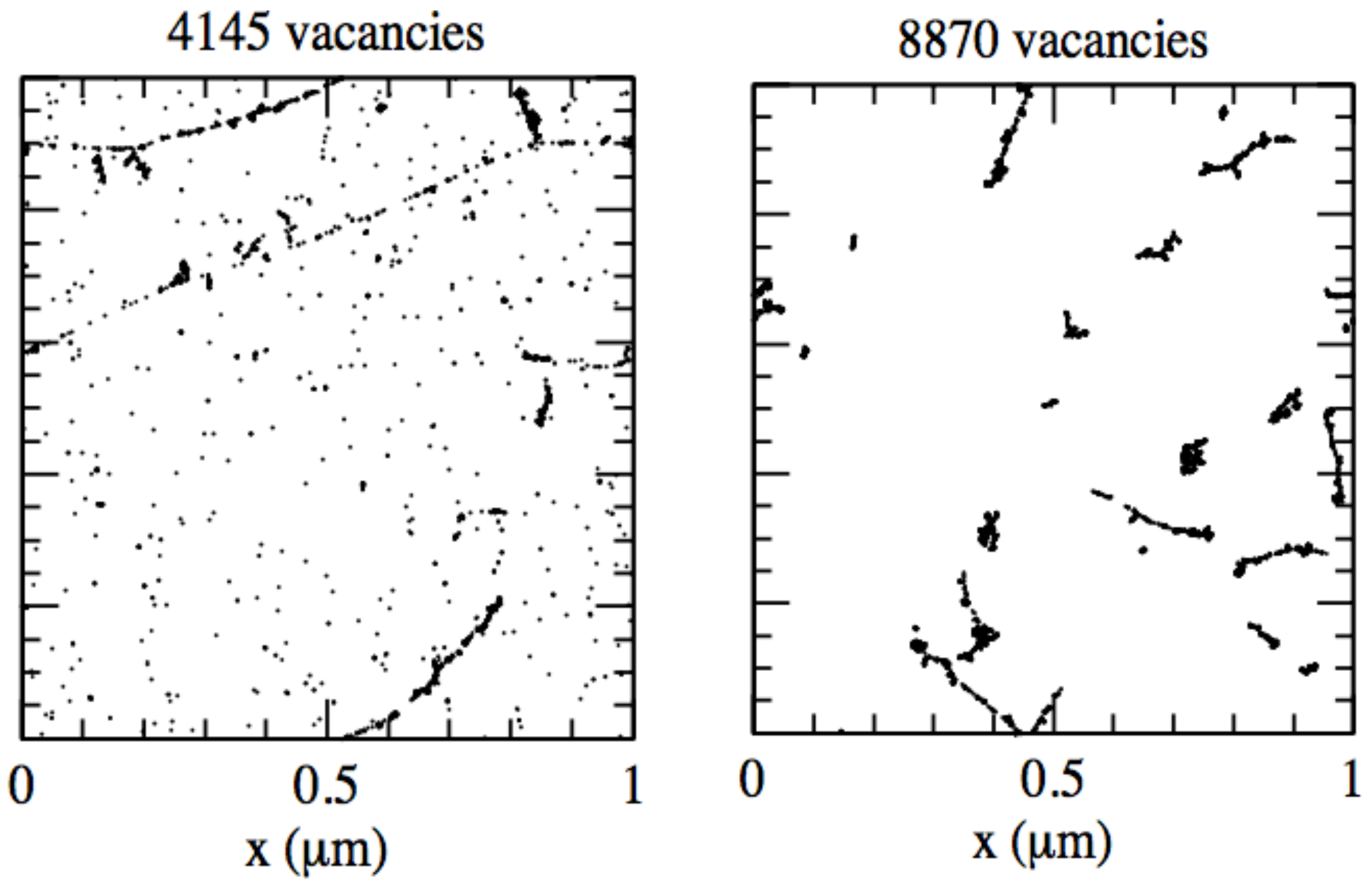
**TCAS** simulation of a collision cascade for a **20 keV PKA** after recombination of close Frenkel pairs:



[R. Radu et al., JAP 117, 164503 (2015)]

Initial distribution of vacancies after $\Phi_{eq} = 10^{14}\ \mathrm{cm}^{-2}$

**24 GeV/c protons** **1 MeV neutrons**



[M. Huhtinen, NIM A 491, (2002) 194]

**→distribution of vacancies and interstitials approx. straight line**

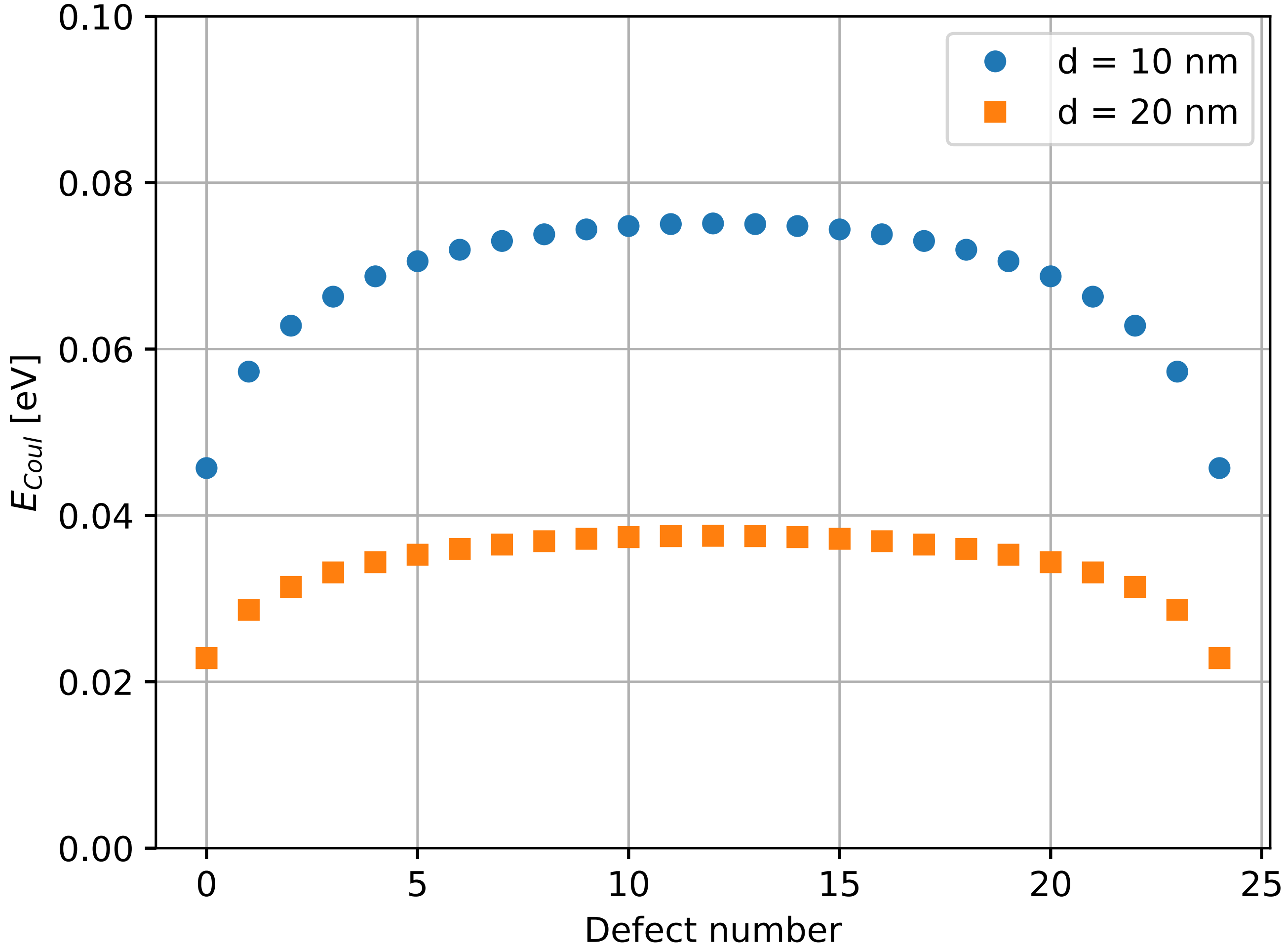
# MODEL

**Assume:**

n **uniformly spaced** point defects on a straight line,
deep acceptor, negatively charged
→ **Coulomb repulsion**

**Energy scale:** $E_{Coul} = \frac{q_0}{4\pi\epsilon_0\epsilon_{Si}d} = 0.121\,\mathrm{eV/d[nm]}$

**Example:** n = 25 (arbitrary), distance between 2 charged defects d = 10/20 nm

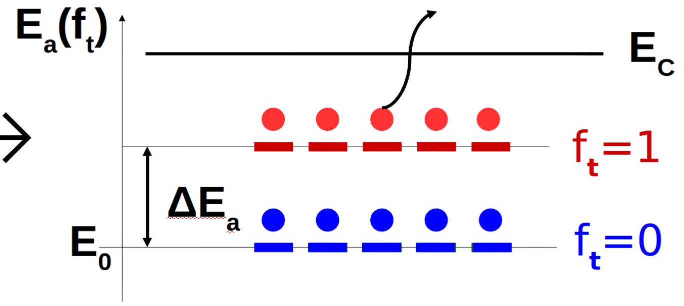


$$E_{Coul}(i) = \frac{q_0}{4\pi\epsilon_s\epsilon_0 d}\sum_{\substack{j=0\\ j\neq i}}^{n-1}\frac{1}{|\,j-i\,|}$$

# MODEL

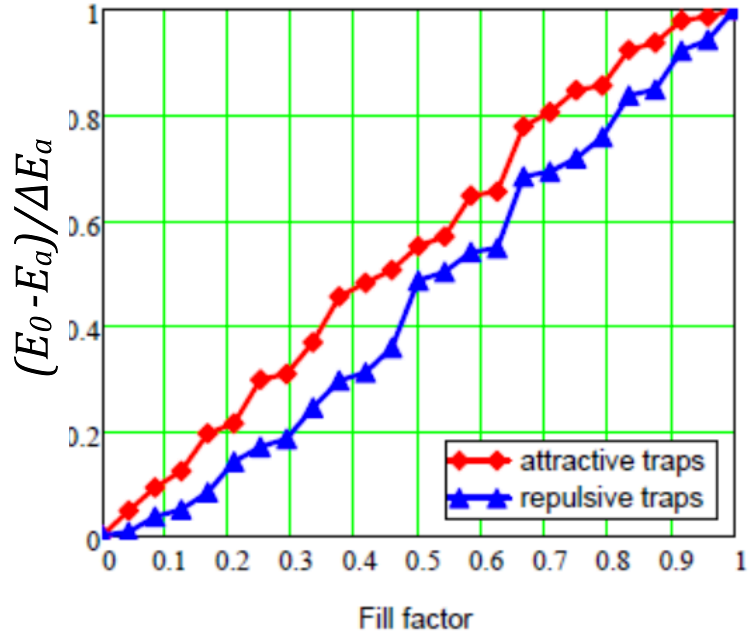
## Procedure:

- **All** n defect states **occupied** → calculate Coulomb energy $E_{Coul}(n_t)$
  → $E_a(n_t) = E_0 - E_{Coul}(n_t) = E_{min}$; fill factor $f_t = n_t/n = 1$
- Carrier with **highest** energy is **emitted** →
  $E_a(n_t-1) = E_0 - E_{Coul}(n_t-1)$ ; $f_t = (n_t-1)/n$
- **New** $E_{Coul}$ for **every** left carrier → carrier with **highest** $E_{Coul}$ **emitted**
  → $E_a(n_t-2)$
- **Successive** calculation of $E_{Coul}(i)$ until **last carrier emitted** → $E_{Coul}(1) = 0$
  → $E_a(0) = E_0 = E_{max}$; $f_t = 0$

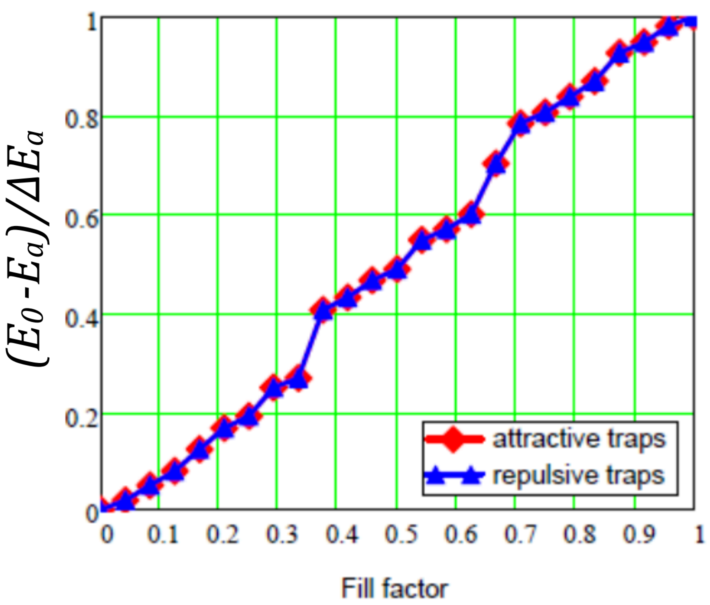


$$E_a(f_t) = E_0 - \Delta E_a \cdot f_t$$

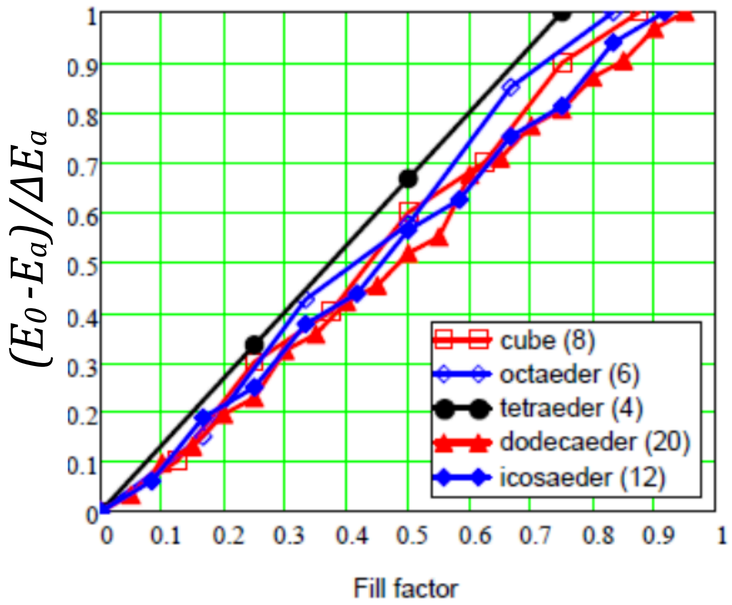
### Lines with 25 charges



### Ring with 25 charges



### Platonic bodies



**$E_a(f_t)$ is approximately linear in $f_t$ and independent of cluster topology**

# TSC MODEL FOR CLUSTER-DEFECTS

**Implement $E_a(f_t)$ in TSC calculation, e.g. for acceptor traps (SRH-statistics):**

**TSCurrent:**

$$I_{TSC}(T) = \frac{q_0 \cdot A \cdot d}{2} \cdot e(T) \cdot f_t(T) \cdot \boxed{N_t}$$

Density of defects in all clusters

**Emission rate:**

$$e(T) = \sigma_n \cdot v_{th,n}(T) \cdot N_C(T) \cdot \exp\left(-\frac{E_a\left(f_t\right)}{k_B T}\right)$$

**Fraction of filled states:**

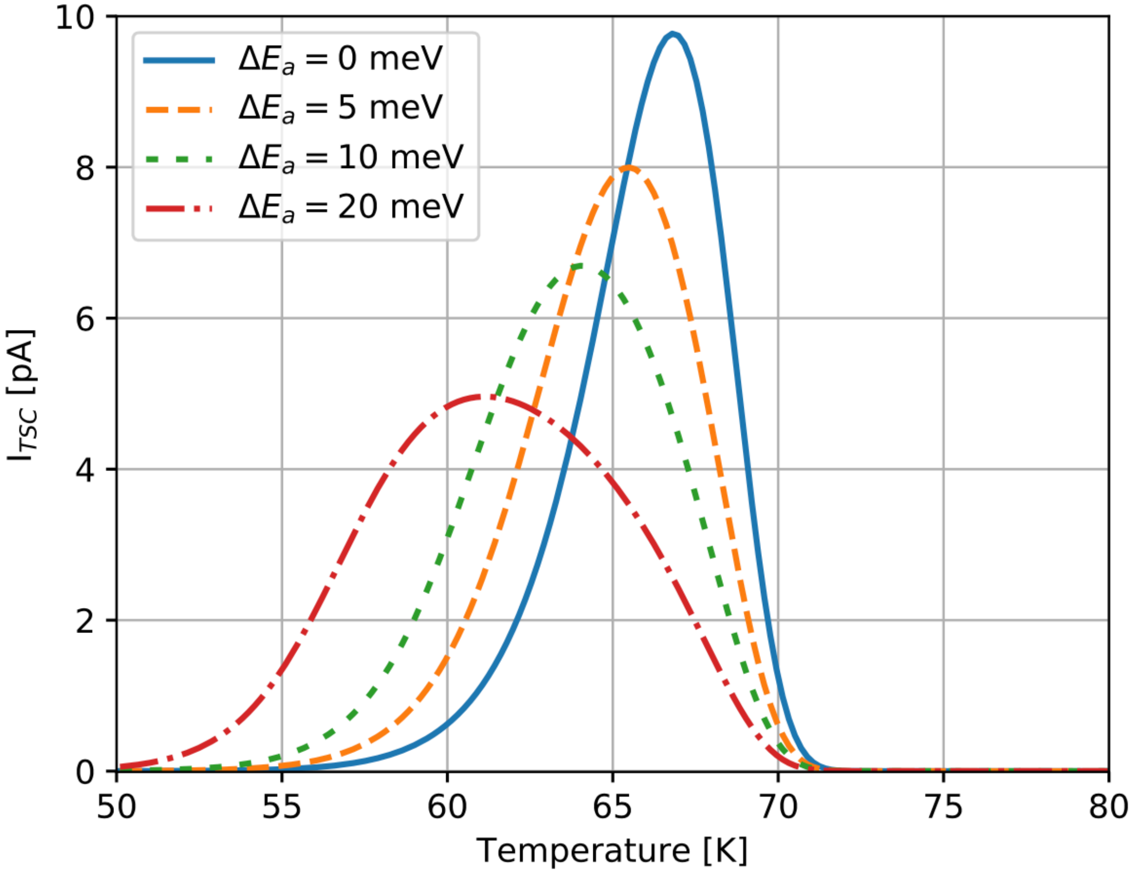
$$f_t(T) = \exp\left(-\frac{1}{\beta}\int_{T_0}^{T} e(T')\,dT'\right)$$

**with $\beta$ the heating rate**

**Effective energy:**

$$E_a\left(f_t\right) = E_0 - \Delta E_a \cdot f_t$$

**Example:**



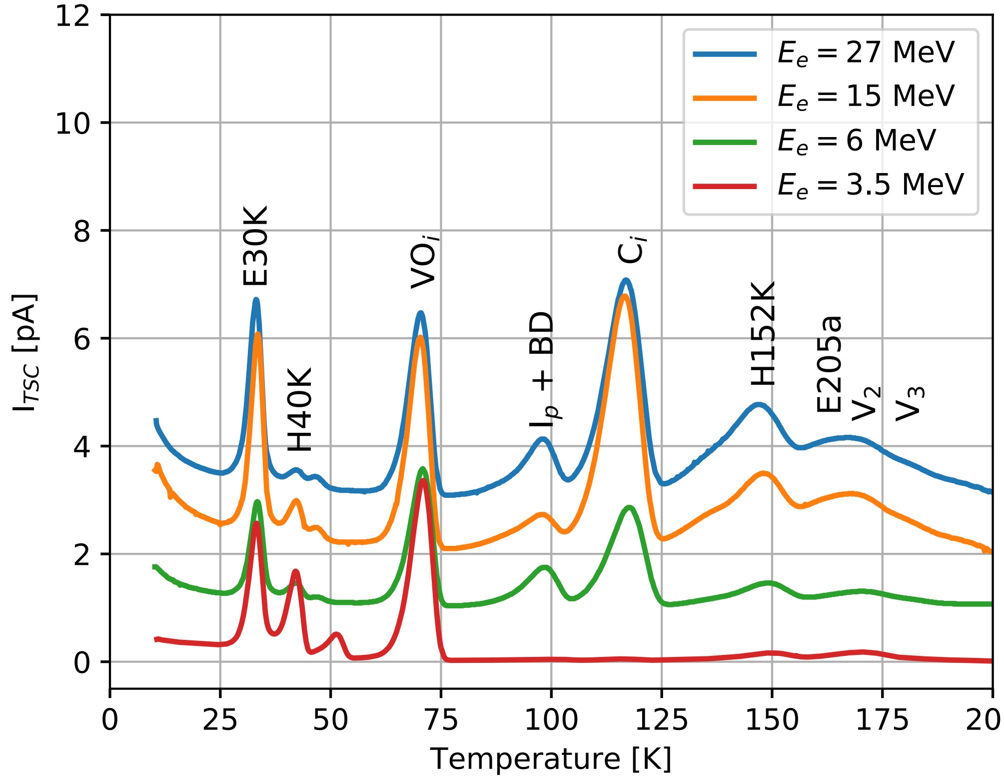
**The T-dependence of the effective energy $E_a$ via $f_t(T)$ leads to a shift and broadening of the TSC-peak**

Calculations for
$N_t = 5 \cdot 10^{11}$ cm$^{-3}$
$\sigma_n = 5 \cdot 10^{-14}$ cm$^{-2}$
$E_0 = 0.175$ eV
$T_0 = 10$ K

# ELECTRON-IRRADIATED DIODES

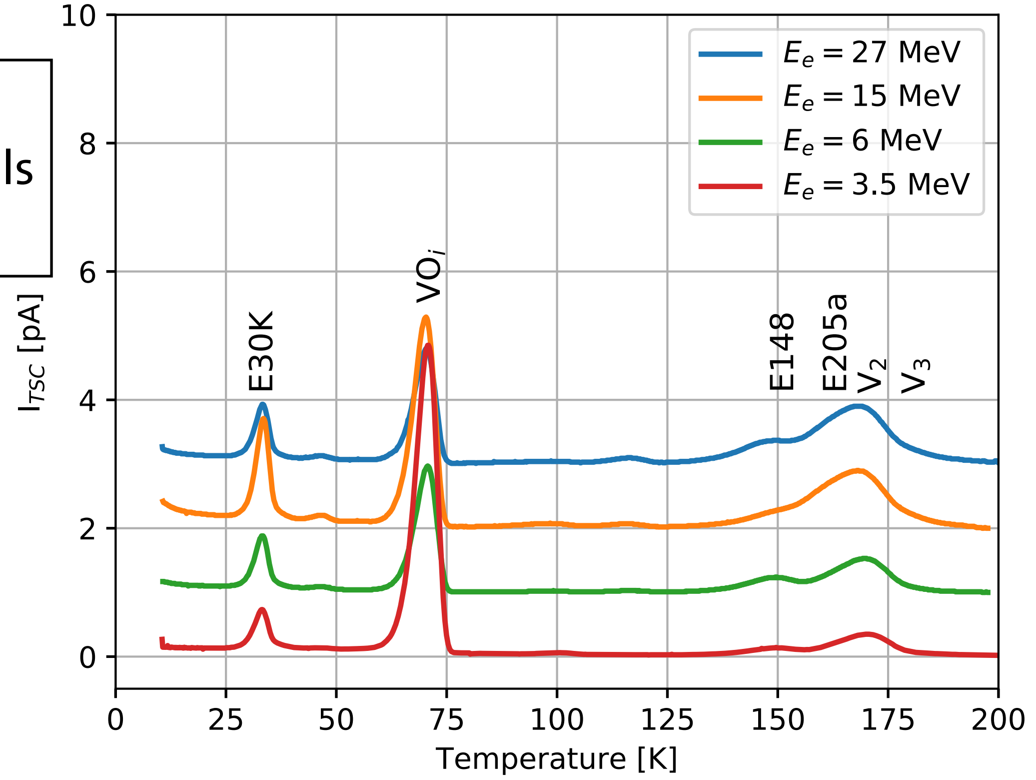
- **Samples:** FZ n-type pad diodes of 0.25 cm$^2$ area and 283 µm thickness
- **Irradiation:** With electrons of 3.5, 6, 15 and 27 MeV kinetic energy
- **TSC measurements (Phd thesis R. Radu + R. Radu et al., JAP 117, 164503 (2015)):**
  - For 15 MeV isochronal annealing for $\Delta t$ =30 min at $T_{ann}$ = 80 -280°C, in 20°C steps
  - After annealing of 30 min at $T_{ann}$ = 80°C for the other energies

**TSC spectra after 30min@80°C**



For clarity, individual signals shifted by 1 pA

**TSC spectra after 30min@80°C**



**- Trap filling at $T_0$ = 10 K with forward current**
**➡Electrons and holes traps are visible**
**- $I_{TSC}$ normalised to fluence $\Phi_{eq} = 10^{14}$ cm$^{-2}$**

**- Trap filling at $T_0$ = 10 K with light**
**➡Only electrons traps are visible**

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# VACANCY-OXYGEN DEFECT

RD50

**Vacancy-oxygen ($VO_i$) defect:**

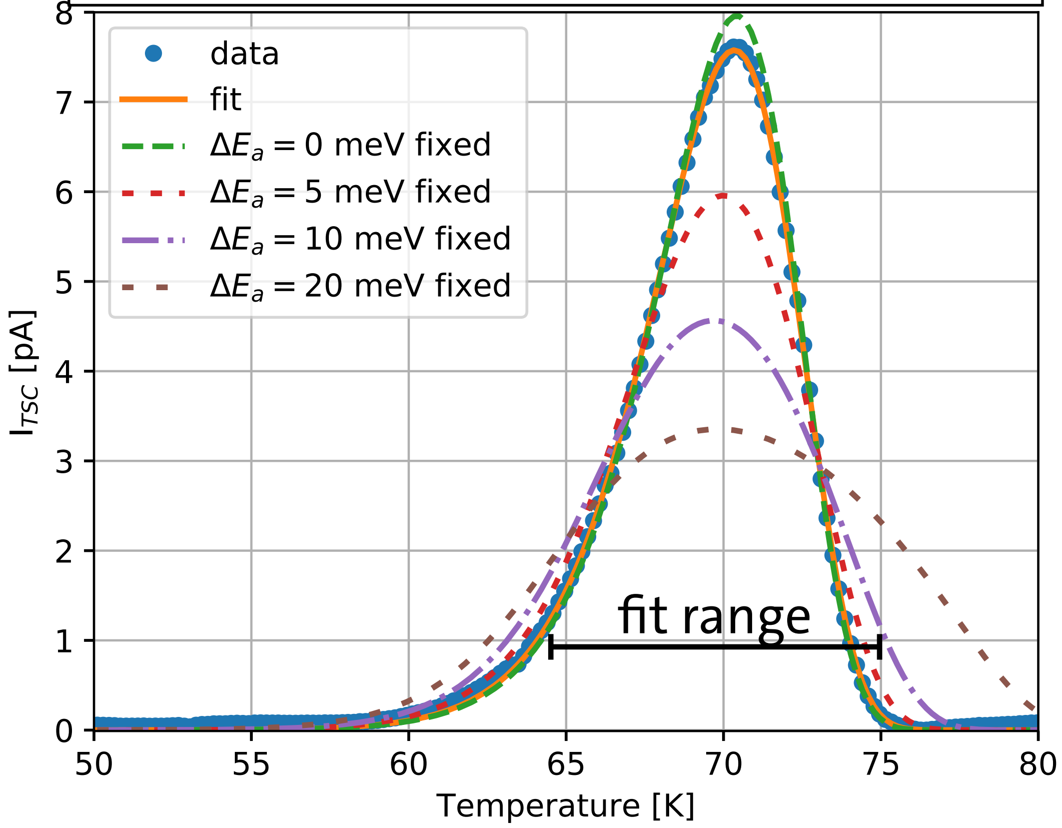
- Acceptor at approx. 70 K
- Known to be point-like defect
- Energy level at $E_C$ - 0.176 eV
- $\sigma_n \approx 7.9 \cdot 10^{-15}$ cm$^{-2}$

} **from literature**

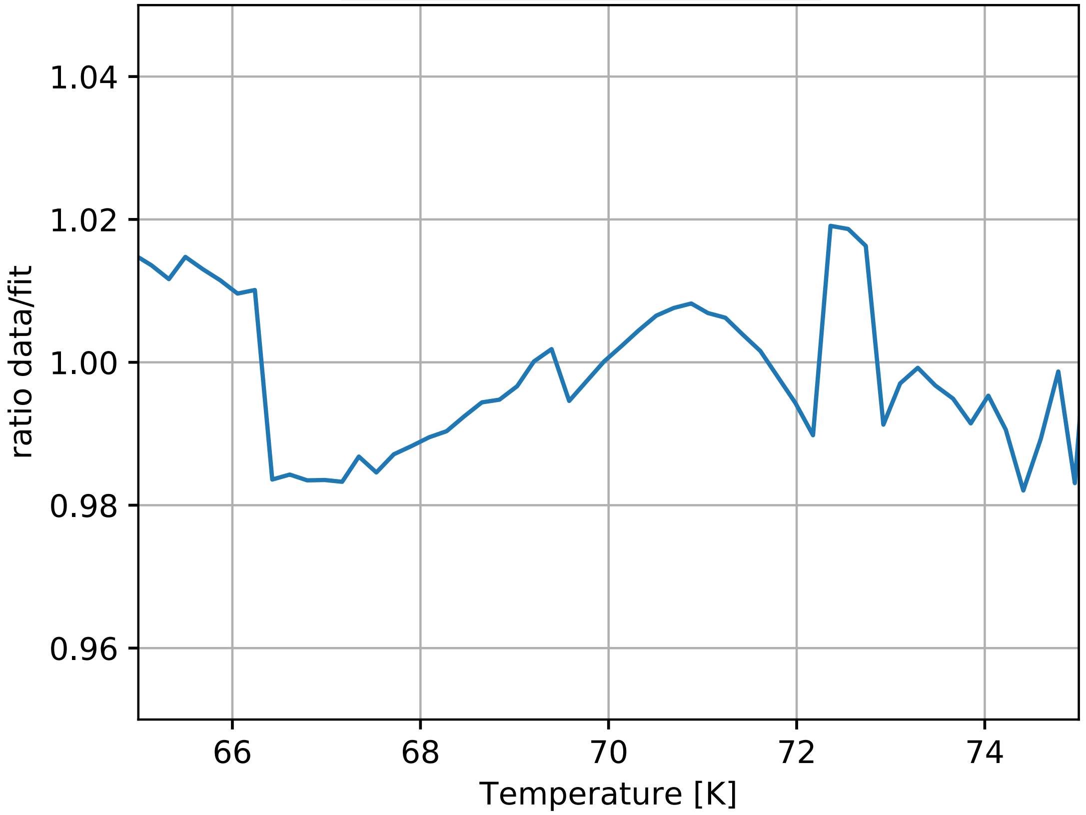
**Ansatz:**

- Fit cluster model
- Free parameters: $N_t$, $\sigma_n$, $\Delta E_a$
- $\delta I/I = 1\,\%$ uncertainty

**TSC for 27 MeV and $\Phi = 4 \cdot 10^{14}$ cm$^{-2}$**



**Ratio of data/fit**



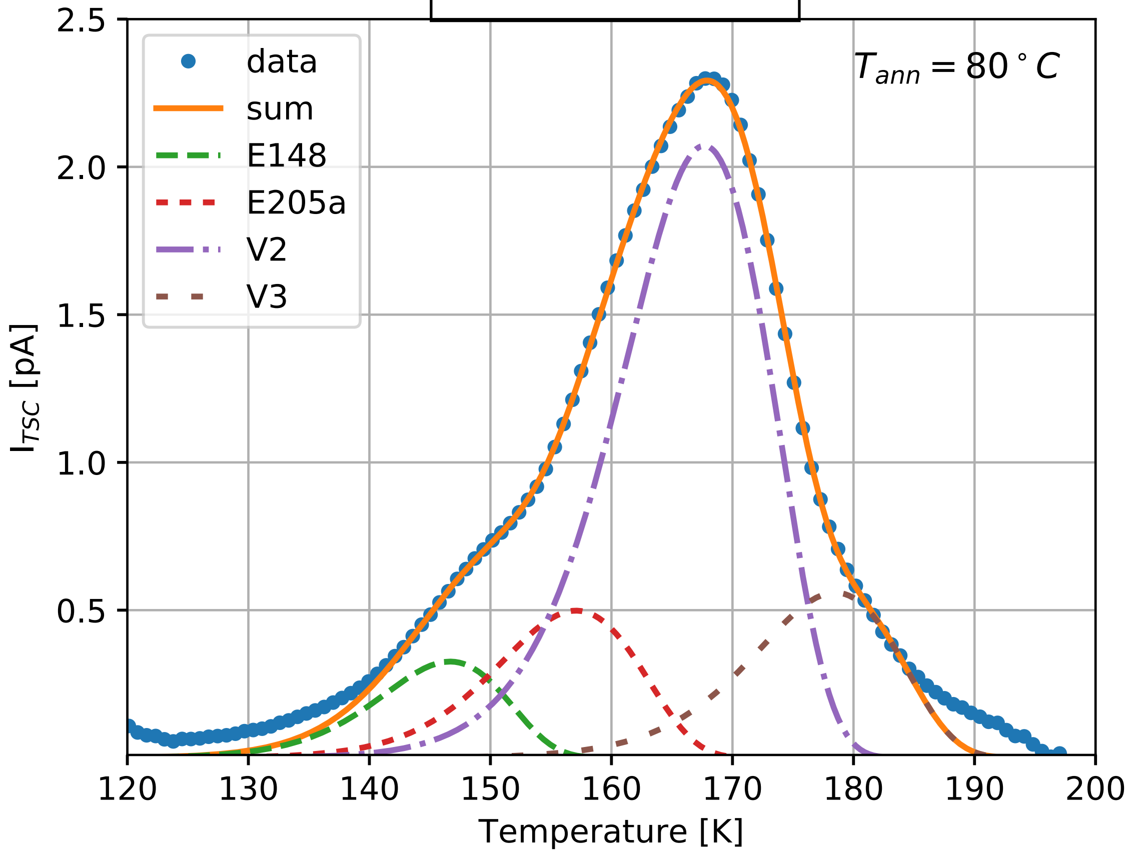
**Fit in the range of 64.5 K to 75.0 K results in $\Delta E_a$ = 0.9 meV and $\sigma_n = 7.99 \cdot 10^{-15}$ cm$^{-2}$ with $\chi^2$ / ndf = 61.4/48. Fits with fixed $\Delta E_a$ values, which differ significantly from zero are excluded. → SRH provides a good description of point defects**

# ISOCHRONAL ANNEALING

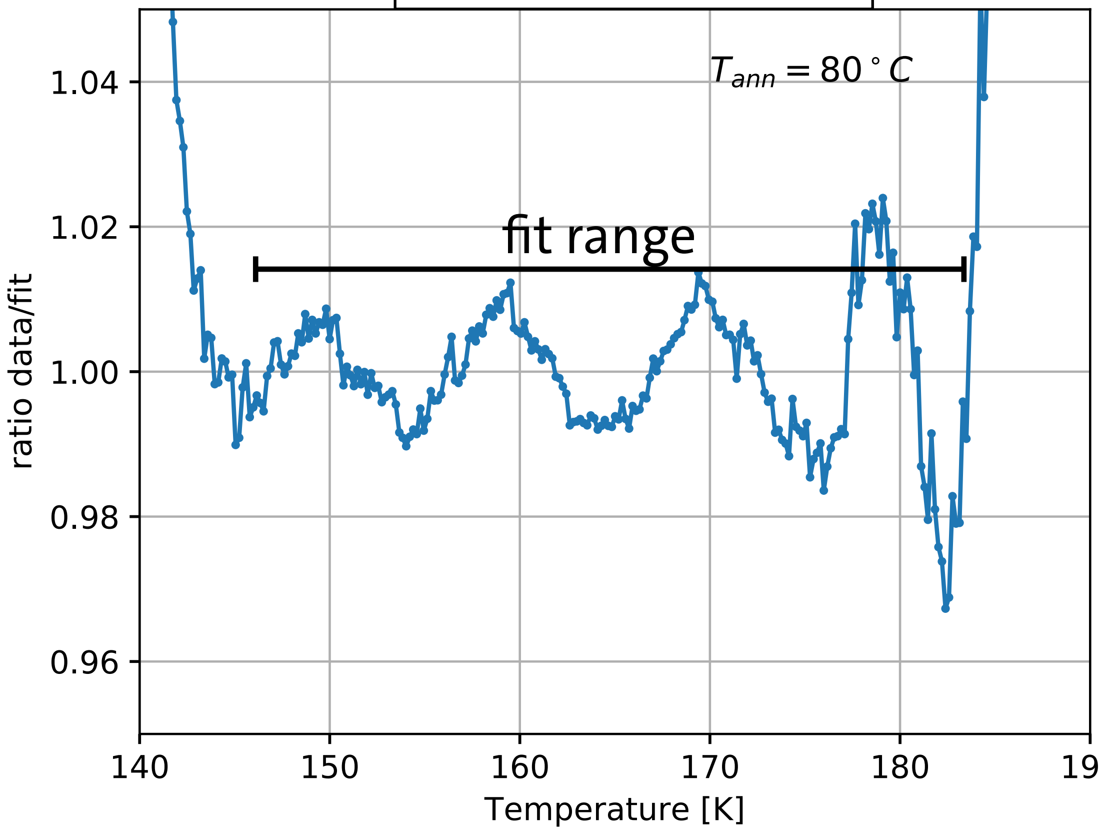
## Isochronal annealing for 15 MeV and $\Phi = 2.6 \cdot 10^{14}$ cm$^{-2}$

- Fit cluster model for E148, E205a, $V_2$, $V_3$ with energies $E_0$ from literature
- Free parameters are $N_t$, $\sigma_n$, $\Delta E_a$
- Additional assumption: **Same** $\Delta E_a$ for E148 and $V_3$ and **same** $\Delta E_a$ for E205a and $V_2$

**TSC for 80°C**



**Ratio of data/fit**



| Defect | $E_0$ [eV] | $\Delta E_a$ [meV] | $\sigma_n$ [cm$^{-2}$] | $N_t$[cm$^{-3}$] |
|---|---|---|---|---|
| E148 | 0.359 | 4.3 | 4.6E-16 | 4.3E+10 |
| E205a | 0.393 | 7.6 | 6.0E-16 | 7.3E+10 |
| $V_2$ | 0.424 | 7.6 | 7.0E-16 | 7.0E+11 |
| $V_3$ | 0.456 | 4.3 | 9.7E-16 | 8.5E+10 |

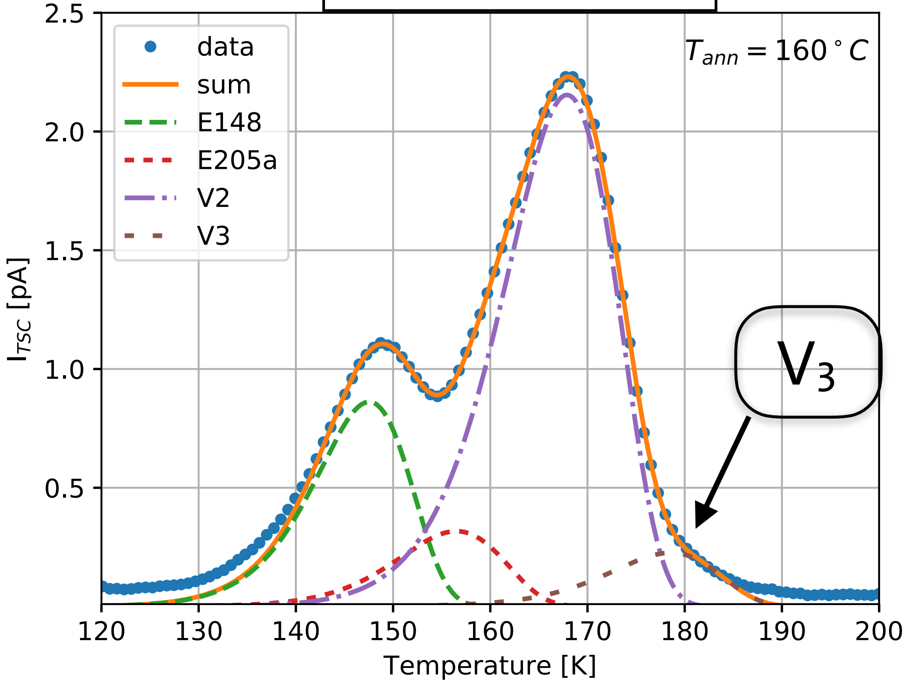
**Fit in range of 144.1 K to 184.6 K**
**$\chi^2$ / ndf = 228/211**
**Systematics from temperature ramp**

# ISOCHRONAL ANNEALING

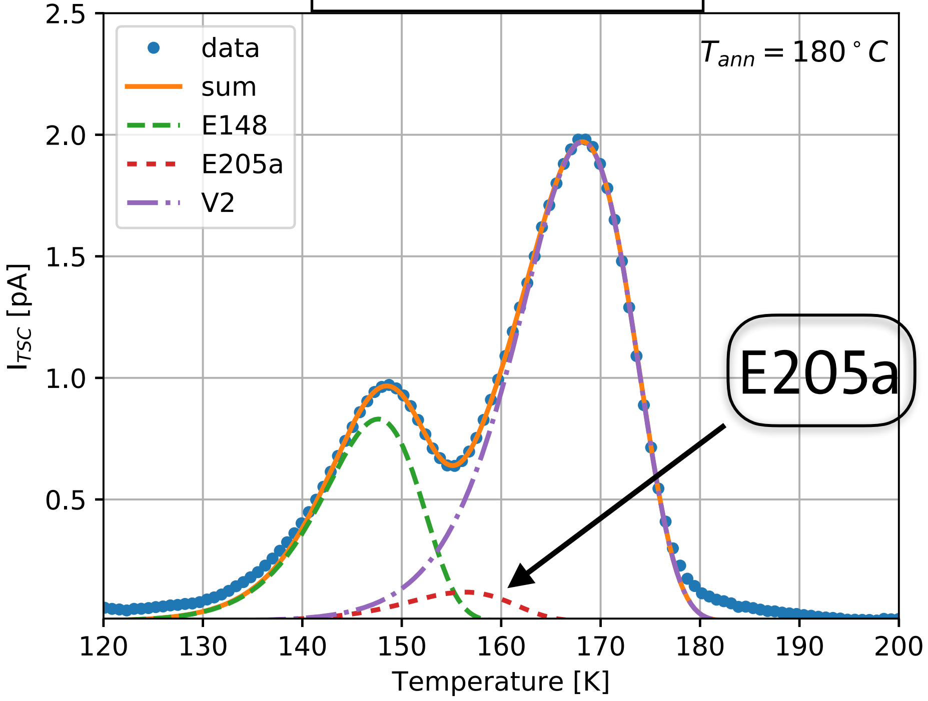
## TSC for 15 MeV isochronal annealing

- Annealing out of $V_3$ at 180°C
- Annealing out of E205a at 200°C
- Fit ranges:
  - 160 °C: 144 - 185 K
  - 180 °C: 141 - 176 K
  - 280 °C: 138 - 178 K

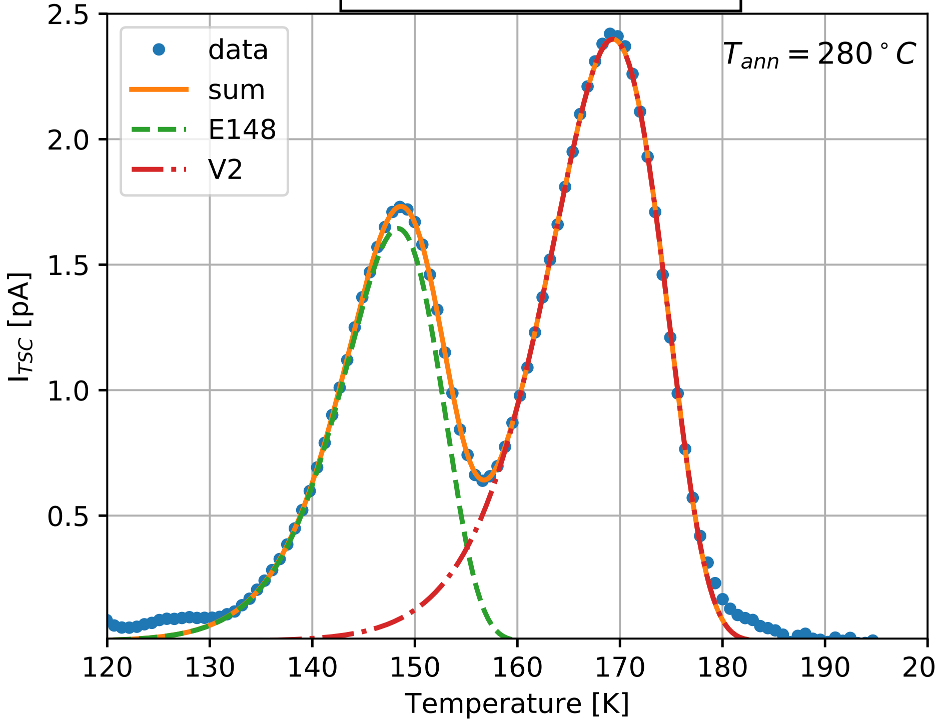
### TSC for 160°C



### TSC for 180°C

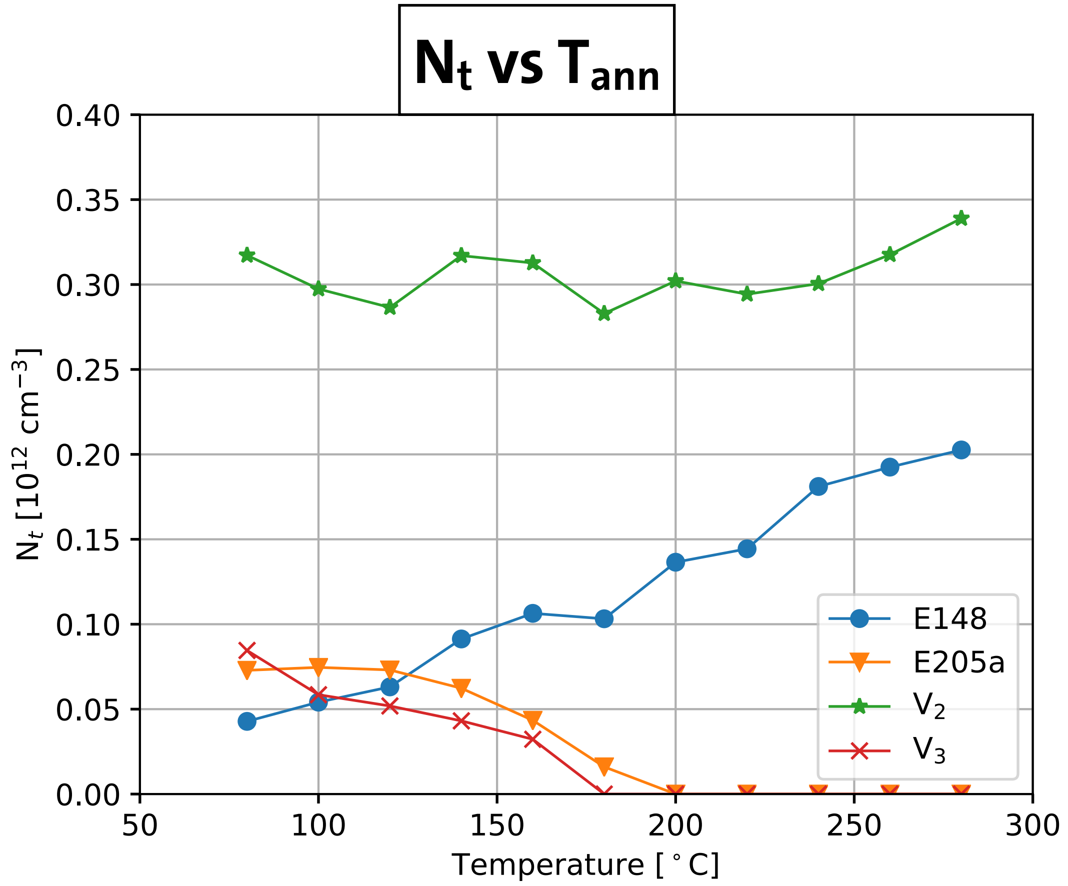


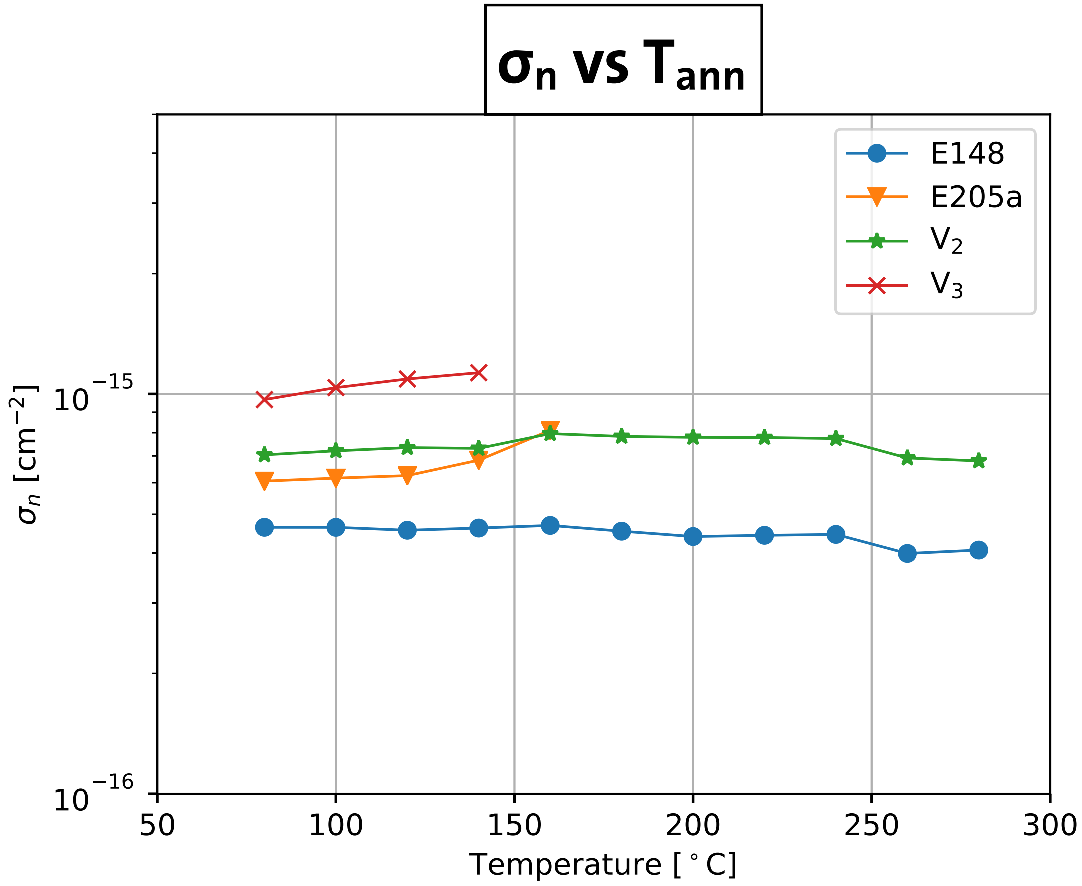
### TSC for 280°C



# ISOCHRONAL ANNEALING

## Fit results for trap concentrations and cross sections:





- Annealing out of E205a and $V_3$
- $V_2$ concentration nearly constant
- E148 concentration increases

- Only small variation of the cross sections as function of $T_{ann}$

# ISOCHRONAL ANNEALING

## Model description of fit results for $\Delta E_a$ as function of $T_{ann}$ (first order process):

Exponential decrease of $\Delta E_a$ at given annealing step (assumes 1st order effect!):

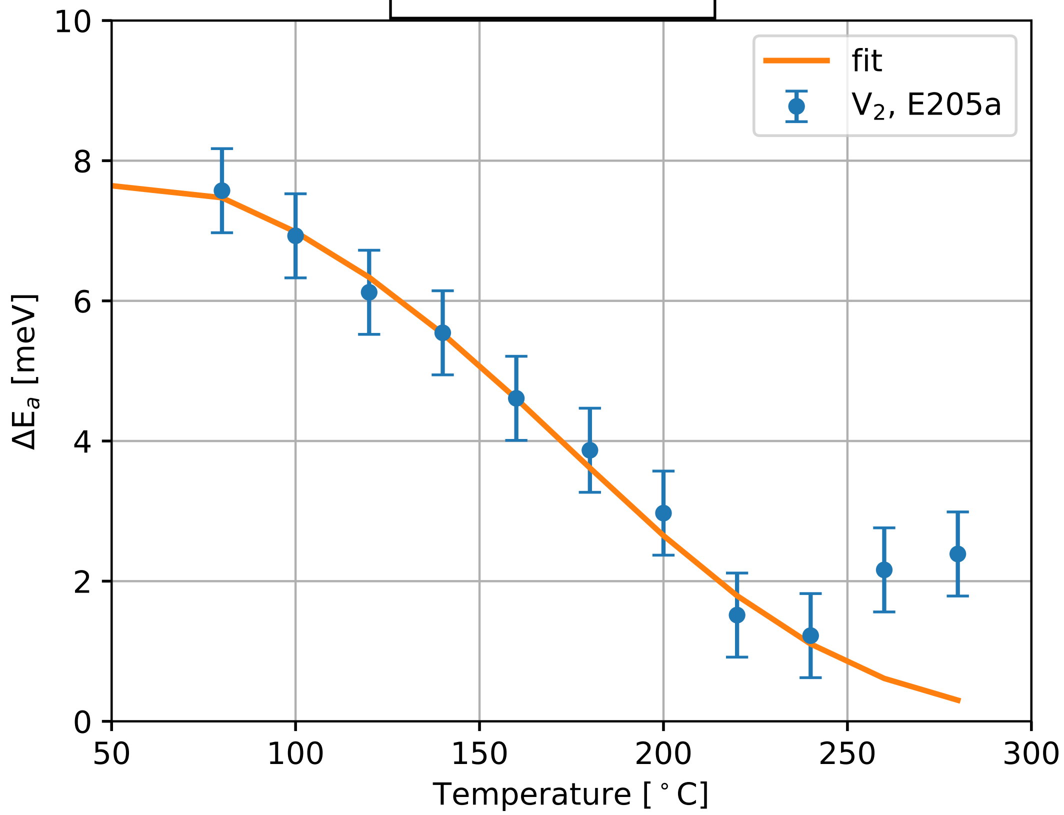
$$\Delta E_a(T,t) = \Delta E_a(T,0) \cdot \exp\left(-t/\tau_{ann}(T)\right) \quad \text{with} \quad 1/\tau_{ann}(T) = k_0 \cdot \exp\left(-E_A/k_B \cdot T\right)$$

$$\Delta E_a(T_i,0) = \Delta E_a(T_{i-1},\Delta t) \quad \text{with} \quad \Delta t \quad \text{the isochronal annealing time}$$

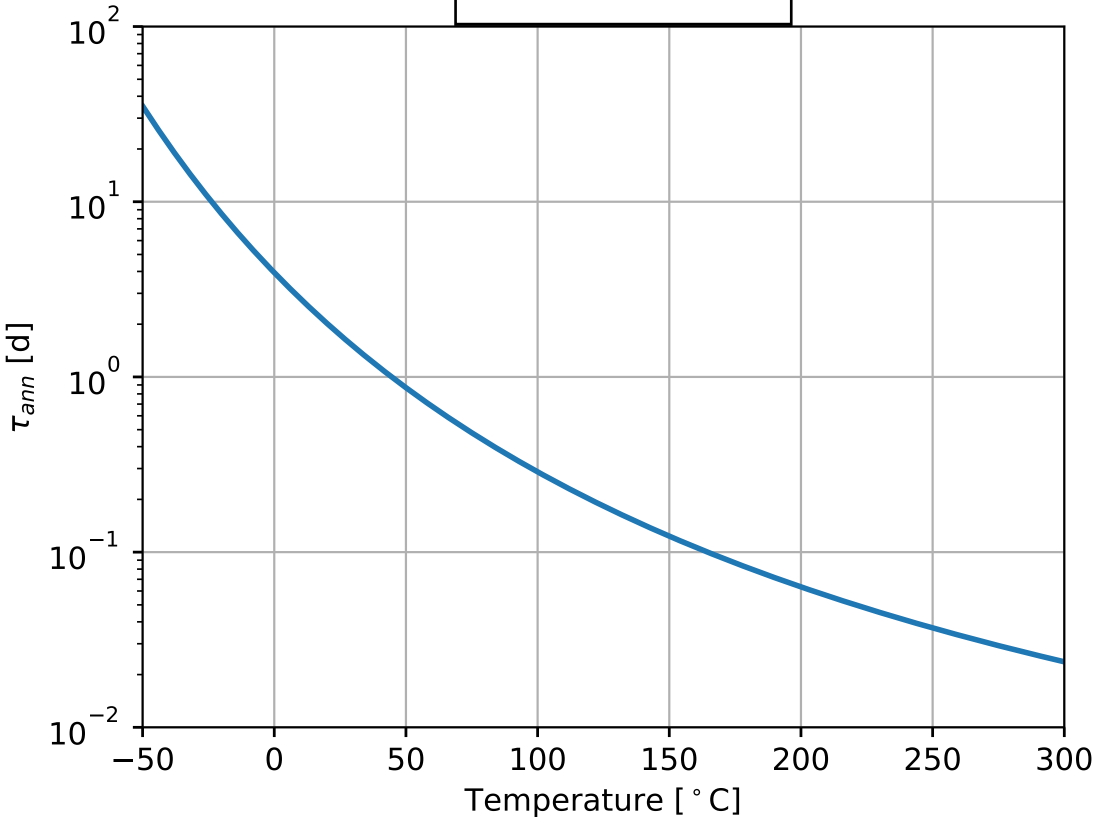
$$\Rightarrow \; \Delta E_a(T_i) = \Delta E_a(T_{i-1}) \cdot \exp\left(-\Delta t/\tau_{ann}(T_i)\right)$$

$E_A$ activation energy of cluster annealing

**$\Delta E_a$ vs $T_{ann}$**



**$\tau_{ann}$ vs $T_{ann}$**



- **Fit excluding 260°C and 280°C data**
- **$E_A$ = 0.23 eV and $k_0 = 5.15 \cdot 10^{-2}\,s^{-1}$**

- **For low temperatures annealing time constant much smaller than expected**

**➡ Further investigations needed**

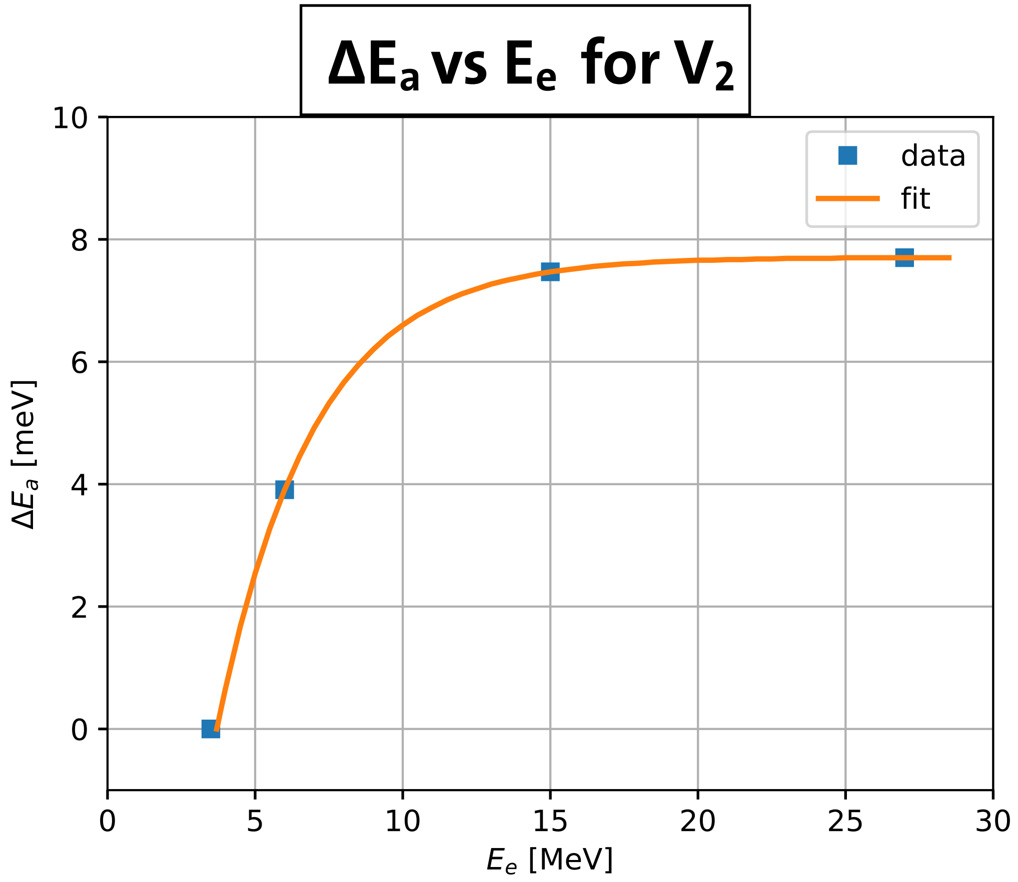
# CLUSTER FORMATION

## Electron-energy dependence of cluster formation :

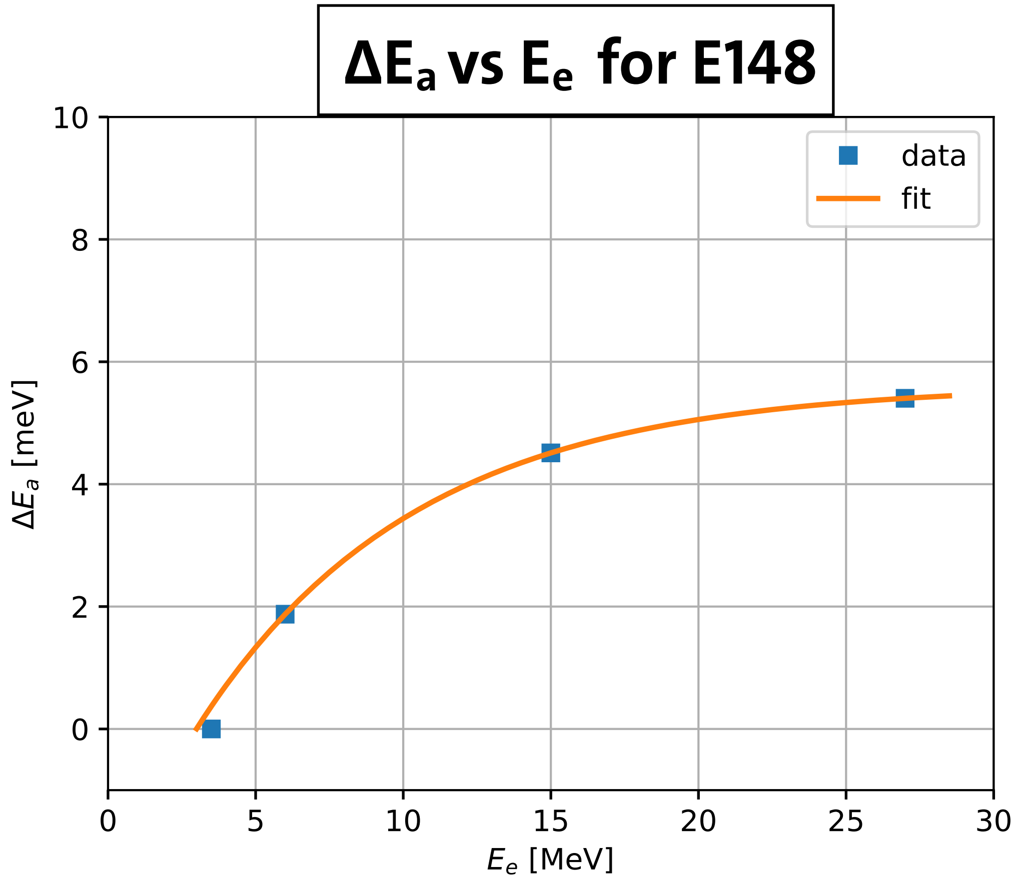
**Parametrisation for $E_e > E_{th}$ :**

$$\Delta E_a = A \cdot \left[1 - \exp\left(\frac{E_e - E_{th}}{\gamma_e}\right)\right]$$

**with threshold energy $E_{th}$**



**$\Delta E_a$ vs $E_e$ for $V_2$**



**$\Delta E_a$ vs $E_e$ for E148**

**Extracted threshold energies:**

- **$V_2$ : $E_{th}$ = 3.7 MeV (A = 7.7 meV, $\gamma_e$ = 3.2 MeV)**
- **E148 : $E_{th}$ = 3.0 MeV (A = 5.6 meV, $\gamma_e$ = 7.4 MeV)**

# SUMMARY

1. Model within SRH statistics developed, which allows describing point + cluster defects
2. Model applied to TSC data with light injection for pad diodes irradiated by electrons with $E_e$ = 3.5 - 27 MeV where cluster formation is expected for $E_e \geq 7$ MeV
3. Analysis $VO_i$: confirm point defects
4. Analysis region 0.35- 0.5 eV from the conduction band edge, where there are 4 overlapping states:
   - evidence for cluster defects
   - as function of annealing, change of concentration + dissociation of clusters
5. Assuming a first order effect for modelling the T-dependence of cluster dissociation indicates significant effects at room T and even at -30°C. However, more work needed.

**Thank you for your attention!**

# Backup