X defect after ^{60}Co- γ irradiation

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Outline:

- Material properties
- Experimental methods
- Measurements
- Conclusion

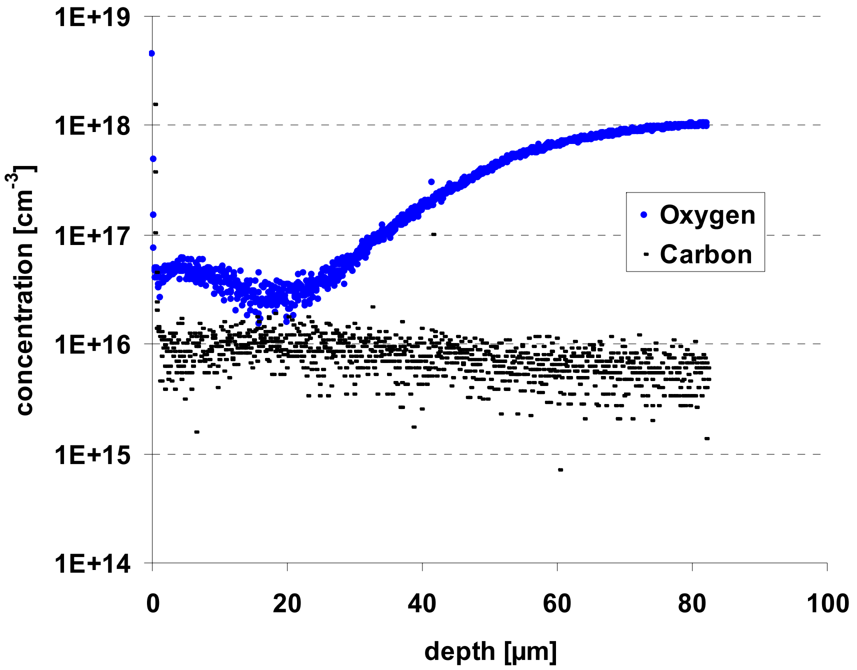
Material

DOFZ: Wacker Siltronic <111>, n/P, 2-5 kΩcm, 285±10μm, CiS process, 24, 48, 72 h /1150°C

Epi/Cz: <111>, n/P, 50 Ωcm, 50 μm on 300 μm Cz-substrate, CiS process

Sample	**SIMS [O]**
DOFZ 24h/1150°C	$6 \cdot 10^{16}$ cm^{-3}
DOFZ 48h/1150°C	$1 \cdot 10^{17}$ cm^{-3}
DOFZ 72h/1150°C	$1.2 \cdot 10^{17}$ cm^{-3}
Epi/Cz	$9 \cdot 10^{16}$ cm^{-3}

Carbon concentration for all materials at detection limit [C] ≈ $5.7 \cdot 10^{15}$ cm^{-3}



Experimental Methods

Irradiation source:

Brookhaven National Laboratory for ^{60}Co- γ -photons

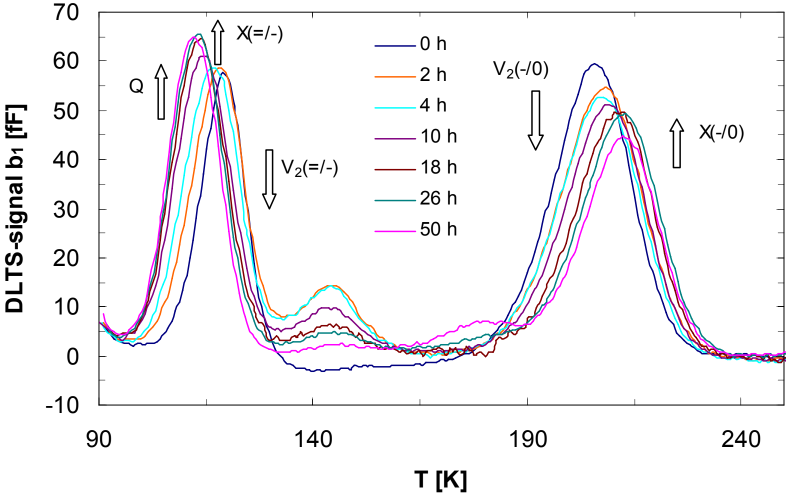
I. Defect characterisation by C-DLTFS/High Resolution DLTS for samples with same irradiation dose but different oxygen content. Shown DLTS-spectra were measured with U_R=20V, t_p=100ms, T_W=200ms.

II. Defect characterisation by TSC for samples with same irradiation dose but different annealing temperature.

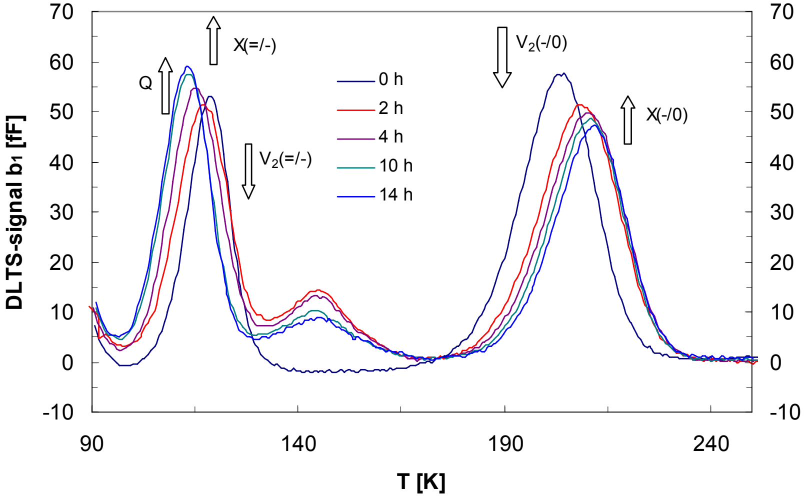
III. Defect characterisation by TSC for samples with same annealing temperature but different irradiation dose.

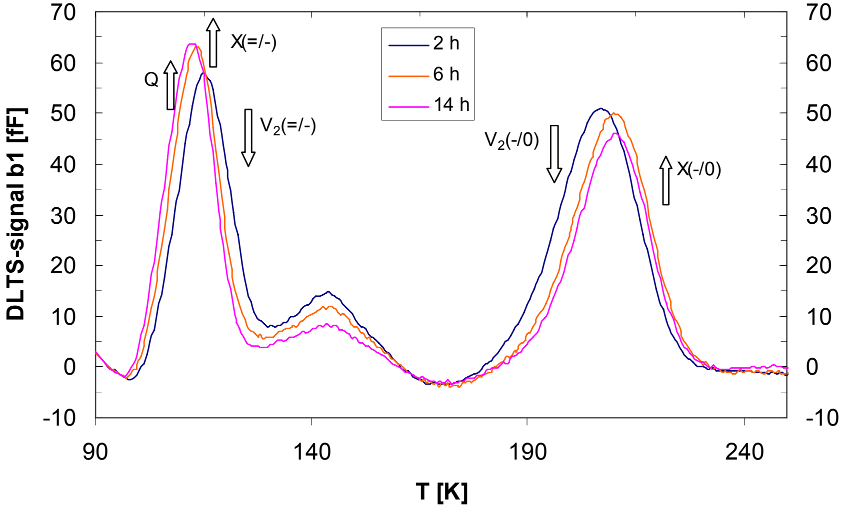
I) Same irradiation dose – different oxygenation time (DOFZ technology)

[O_i]= 6 · 10^{16} cm^{-3}



[O_i]= 1 · 10^{17} cm^{-3}



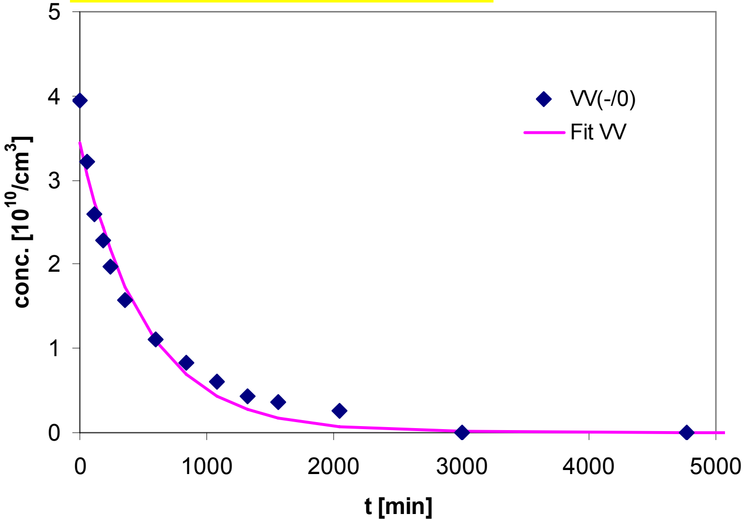


[O_i]= 1.2 · 10^{17} cm^{-3}

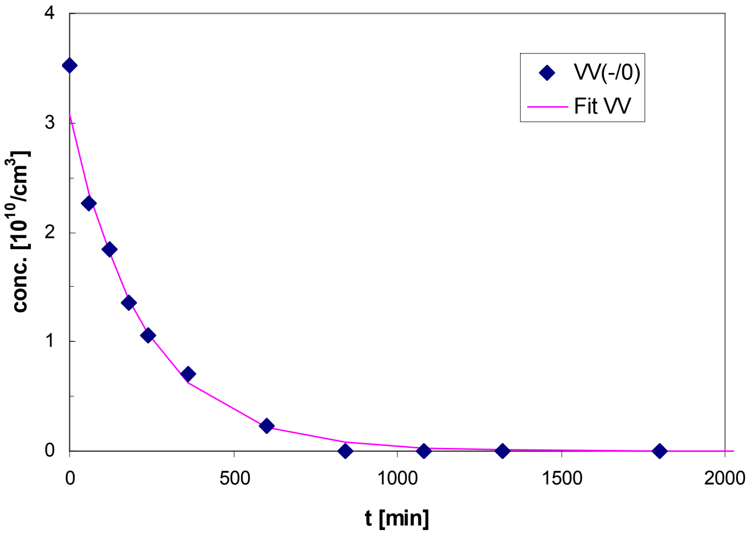
spectra after electron injection of DOFZ – diodes irradiated with 4 Mrad annealed at 250°C.

annealing out of V_2 and formation of X

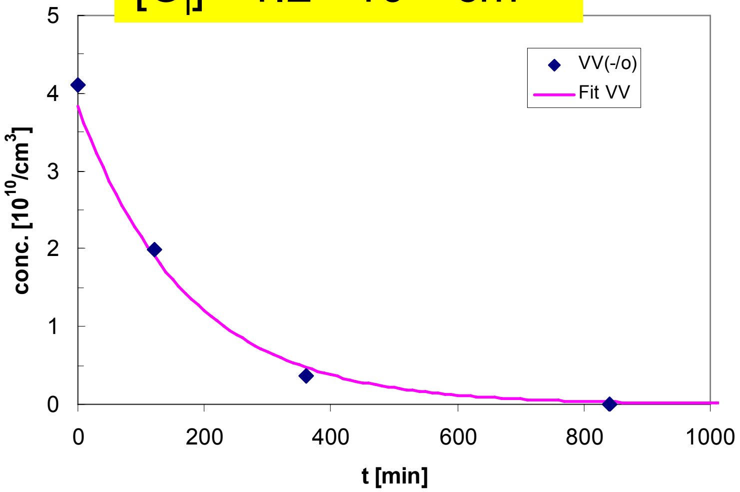
$[O_i]= 6 \cdot 10^{16}$ cm^{-3}



$[O_i]= 1 \cdot 10^{17}$ cm^{-3}



$[O_i]= 1.2 \cdot 10^{17}$ cm^{-3}

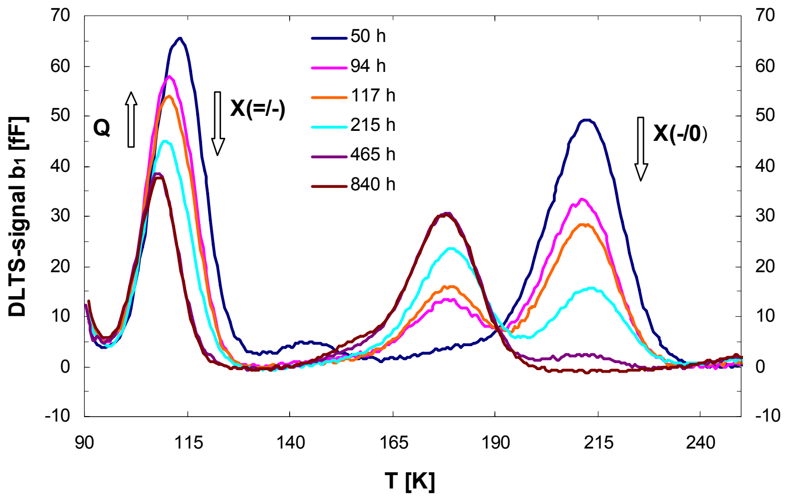


Time dependence of **V_2** concentration in DOFZ-diodes during annealing at 250°C.

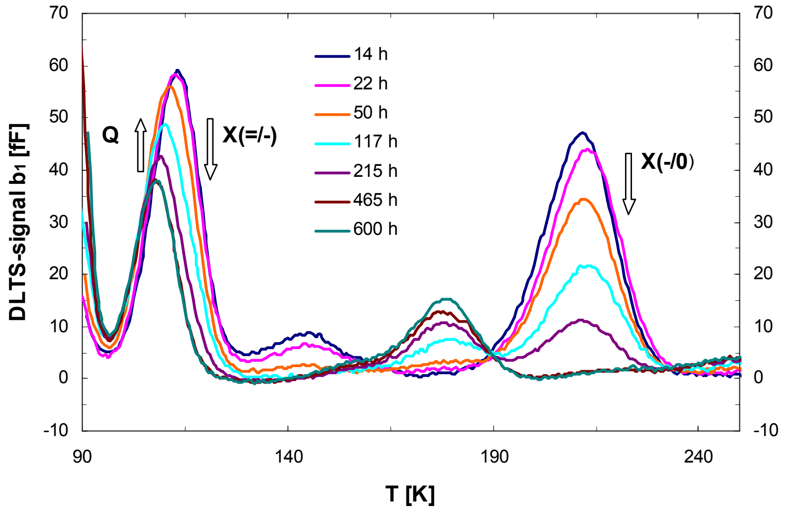
annealing of V_2

$$N_t = N_0 \bullet \exp\left(-\frac{t-t_0}{\tau}\right)$$

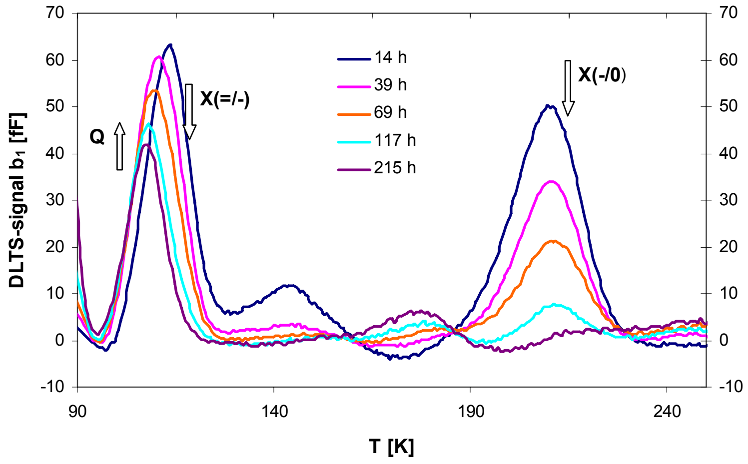
$[O_i]= 6 \cdot 10^{16}\ cm^{-3}$



$[O_i]= 1 \cdot 10^{17}\ cm^{-3}$



$[O_i]= 1.2 \cdot 10^{17}\ cm^{-3}$

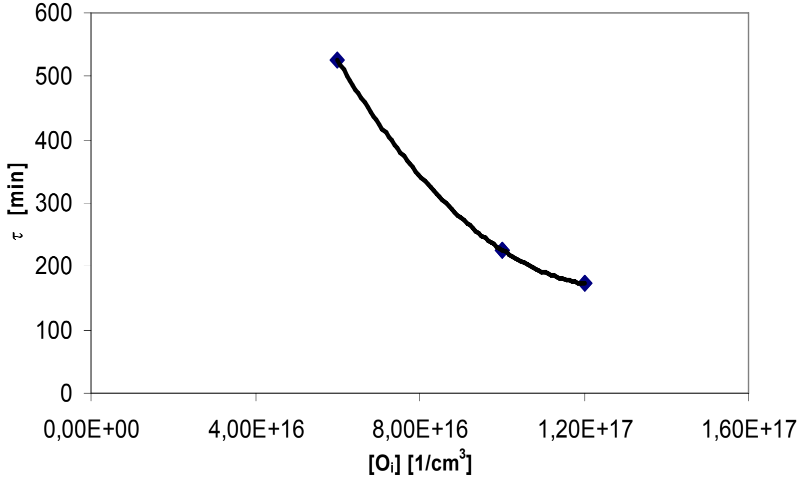


spectra after electron injection of DOFZ – diodes irradiated with 4 Mrad annealed at 250°C.

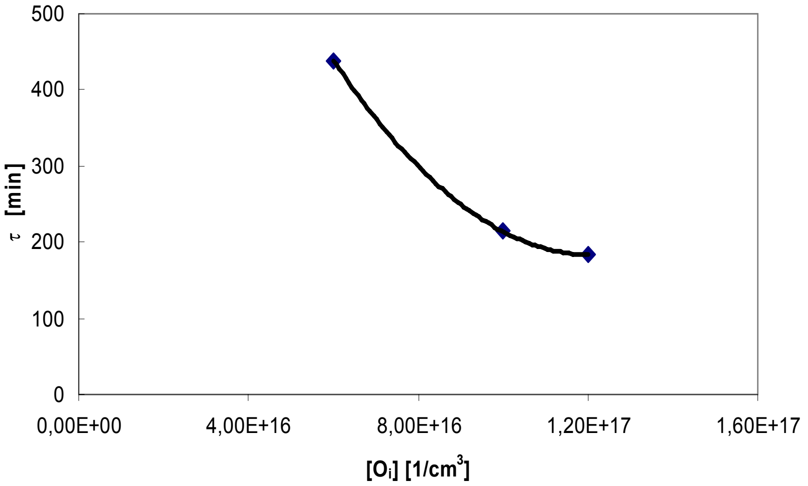
annealing of X

$$N_t = N_0 \cdot \frac{1/\tau_1}{1/\tau_2 - 1/\tau_1} \cdot \left(\exp\left(-\frac{t-t_0}{\tau_1} \right) - \exp\left(-\frac{t-t_0}{\tau_2} \right) \right)$$

annealing of V_2



formation of X



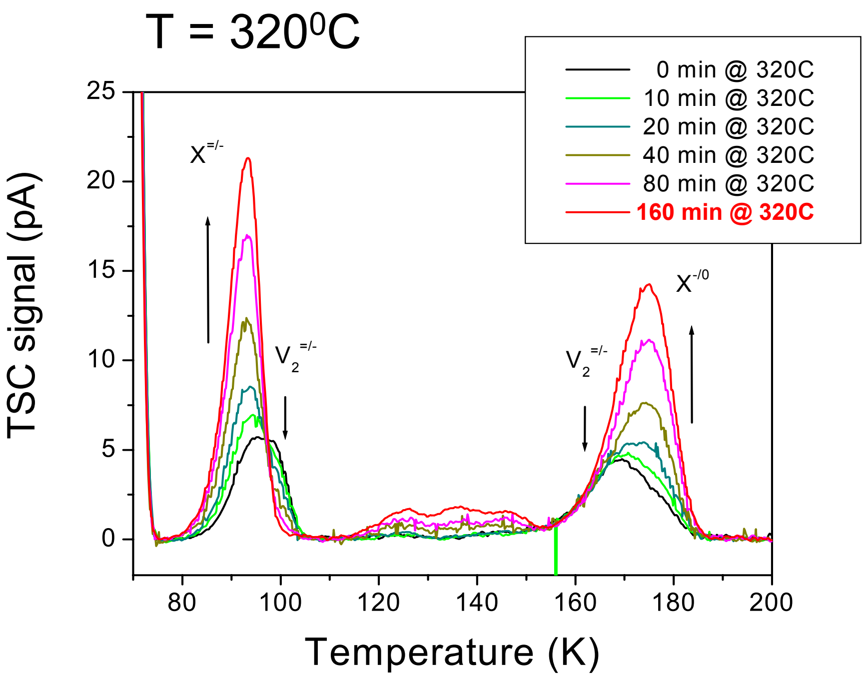
For $k = 1/\tau \longrightarrow k = a \cdot x^b$ with $b \approx 1.5$

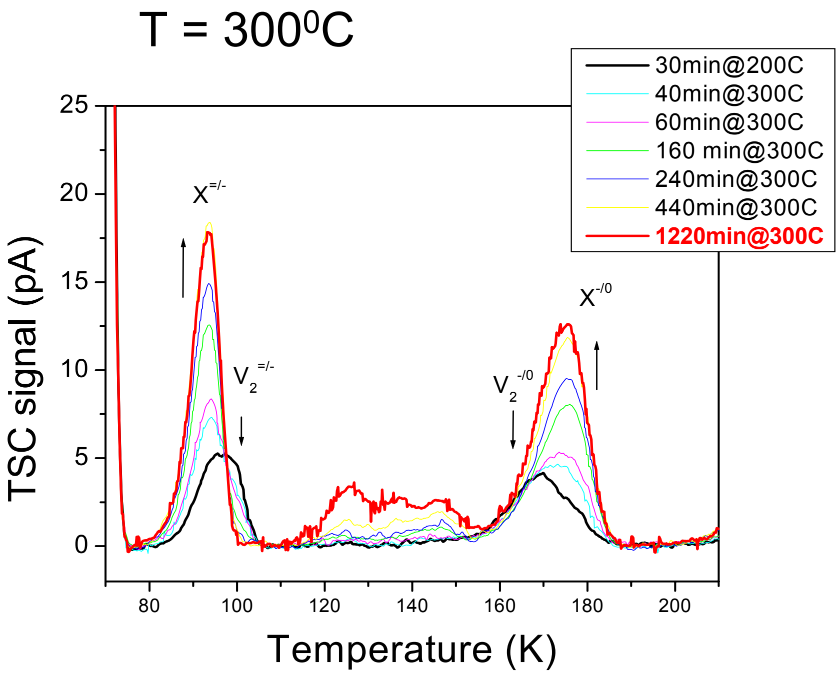
$\Rightarrow$ Non linear dependence of [X] on [O_i]

II) Epi/Cz material - similar irradiation dose and annealing at diferent T

X center: Annealing - Formation

Dose: 520 Mrad



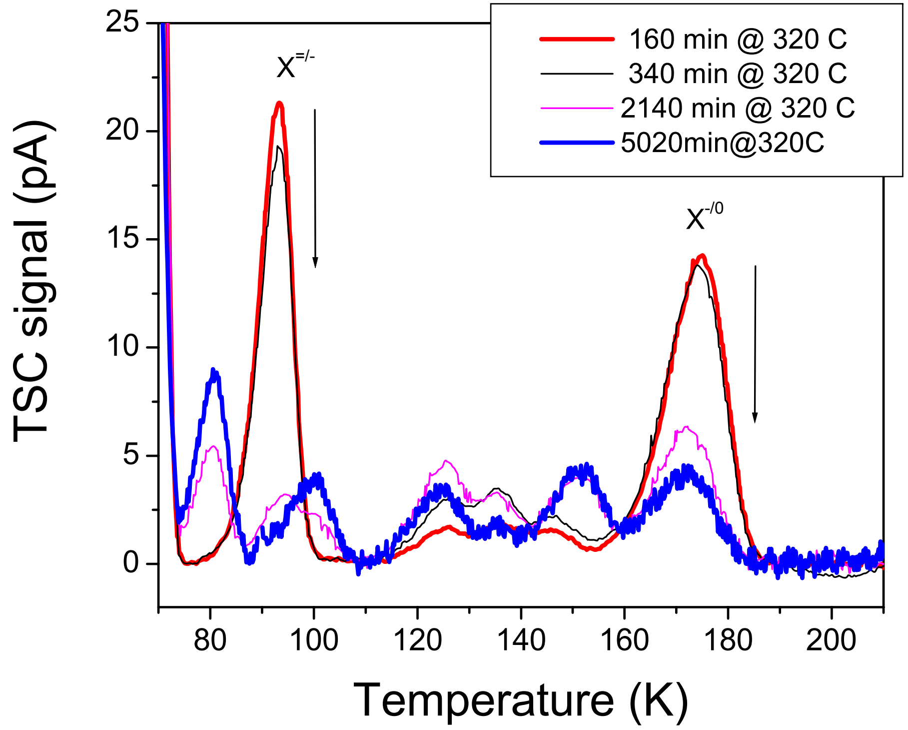


Increasing the annealing temperature *[X]* increases although *[V_2]* is the same ⇒ The contribution of other defect/impurity becomes important at high T

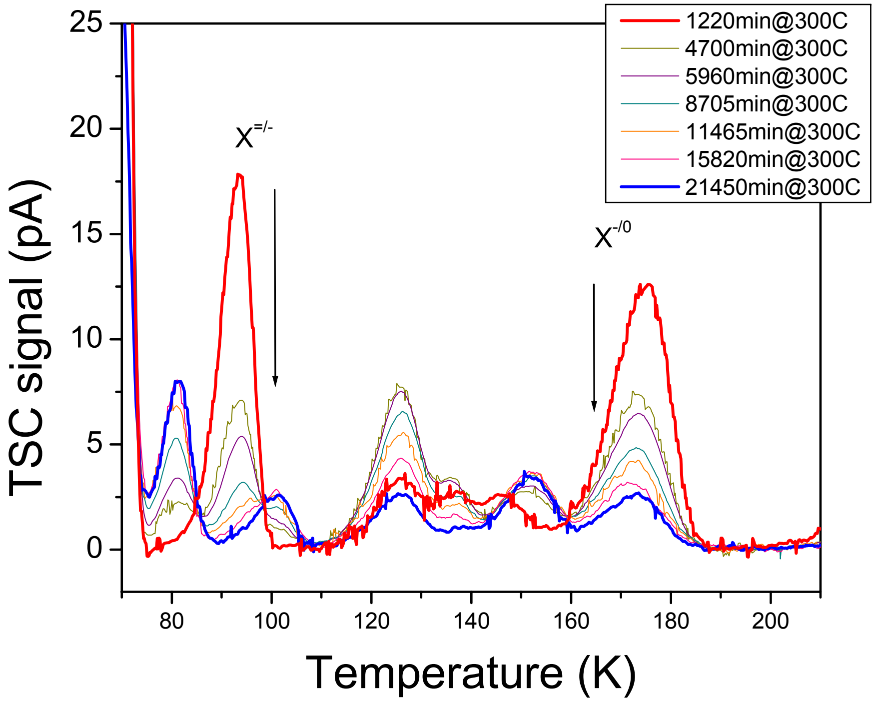
X center: Annealing - OUT

Dose: 520 Mrad

T = 320^0C



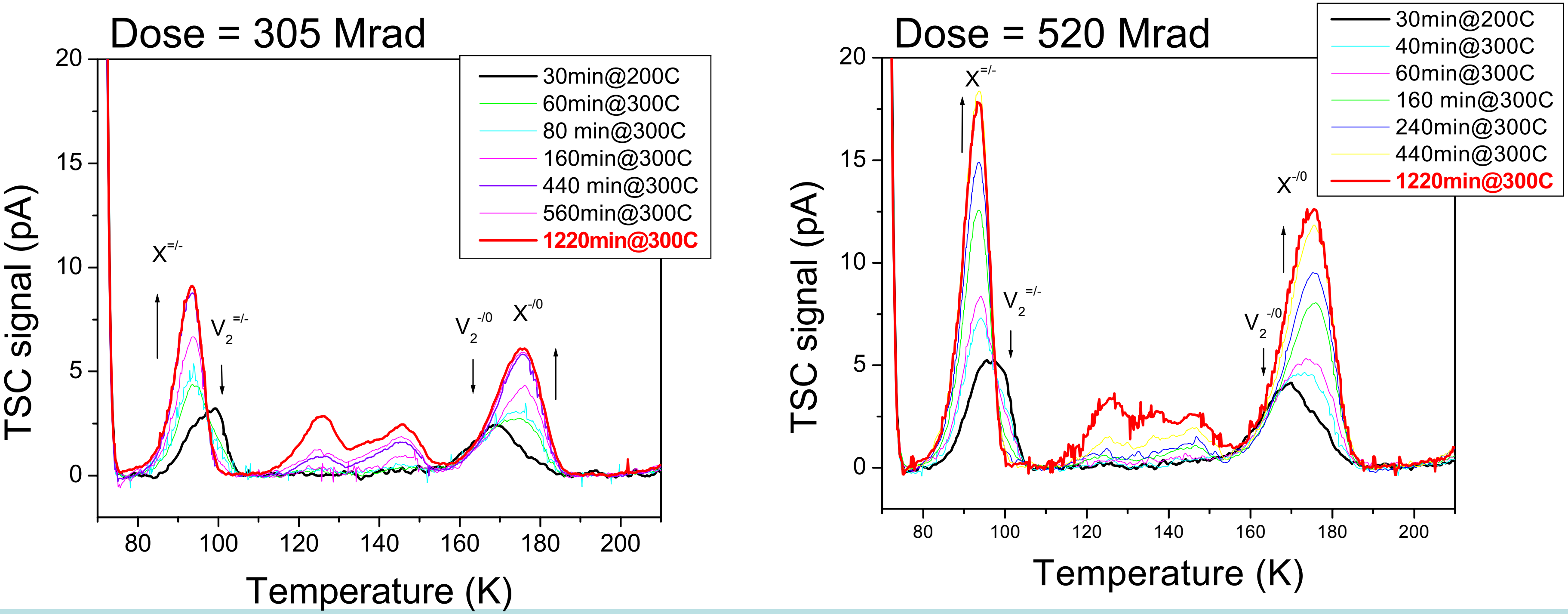
T = 300^0C



III)Epi/Cz material - Same annealing T but different irradiation doses

X center: Annealing - Formation

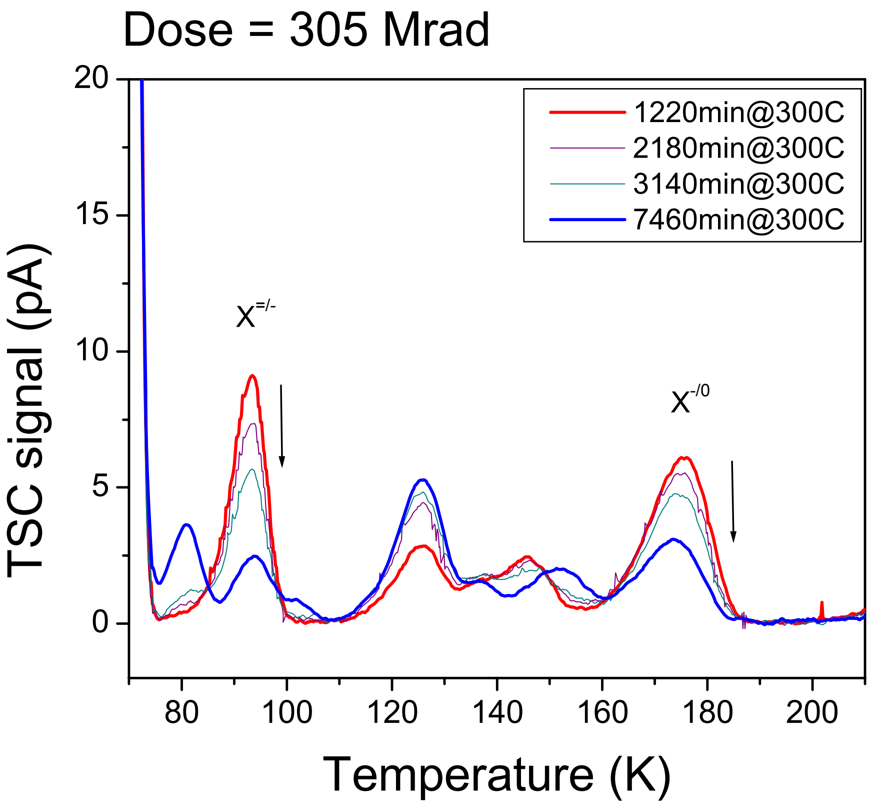
T = 300 ^{0}C



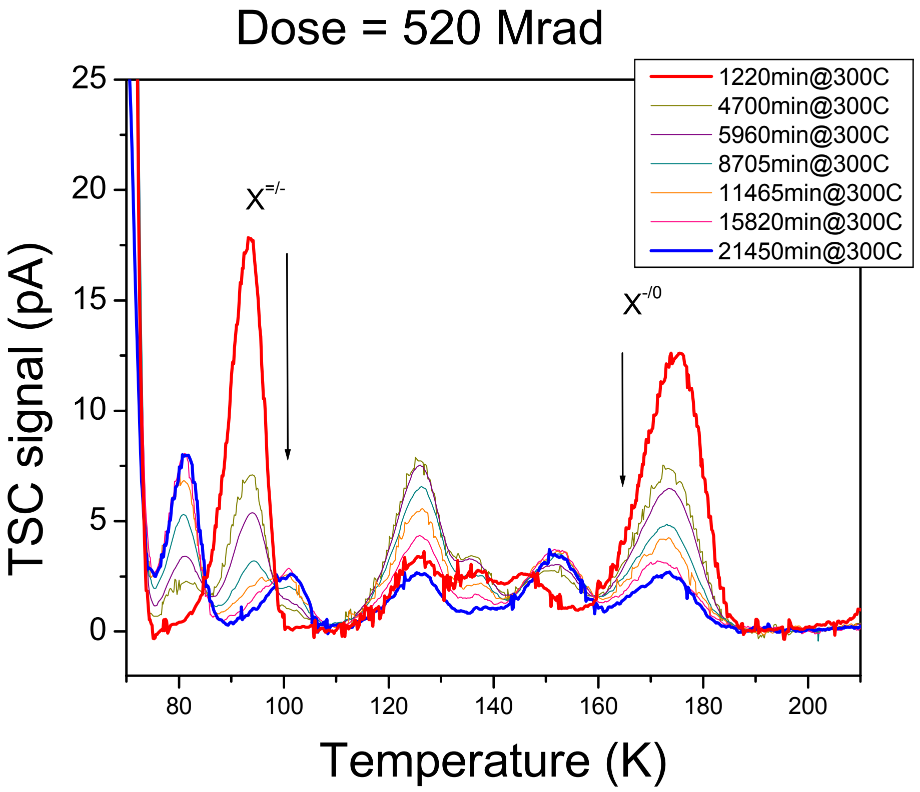
Increasing the irradiation dose *[X]* increases more than due to *[V_2]* ⇒ the involvement of other radiation induced defect (like VO center) in the formation of X centers is possible

X center: Annealing - OUT

T = 300 ^{0}C



Dose = 305 Mrad



Dose = 520 Mrad

Reactions for the formation of V_2O_2

During irradiation*

- in dimer riched silicon
and for high doses -

V_2O_2 - defect generated via a second order process

A) $V + O_2 \rightarrow VO_2$ not electrically active

$VO_2 + V \rightarrow \mathbf{V_2O_2^A}$ electrically active

After irradiation - During annealing at T>200 ⁰C

B) $V_2 + O_2 \rightarrow \mathbf{V_2O_2^B}$

C) $VO + VO \rightarrow \mathbf{V_2O_2^C}$

$$[V_2O_2](t,T) = \underbrace{[V_2O_2^A](Dose)}_{\text{generation during irradiation at RT}} + [V_2O_2^B](t,T) + [V_2O_2^C](t,T)$$

generation during irradiation at RT

generation during annealing at high T

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* see I.Pintilie – 5th- RD50 workshop, Florence 2004 – for generation of X center via a second order proces

Formation of V_2O_2 during annealing at T>200 ^{0}C

B) $V_2 + O_{2i} \rightarrow \mathbf{V_2O_2^B}$

$[V_2]$ ~ Dose

$[O_{2i}]$ – depends on the growth and processing technology

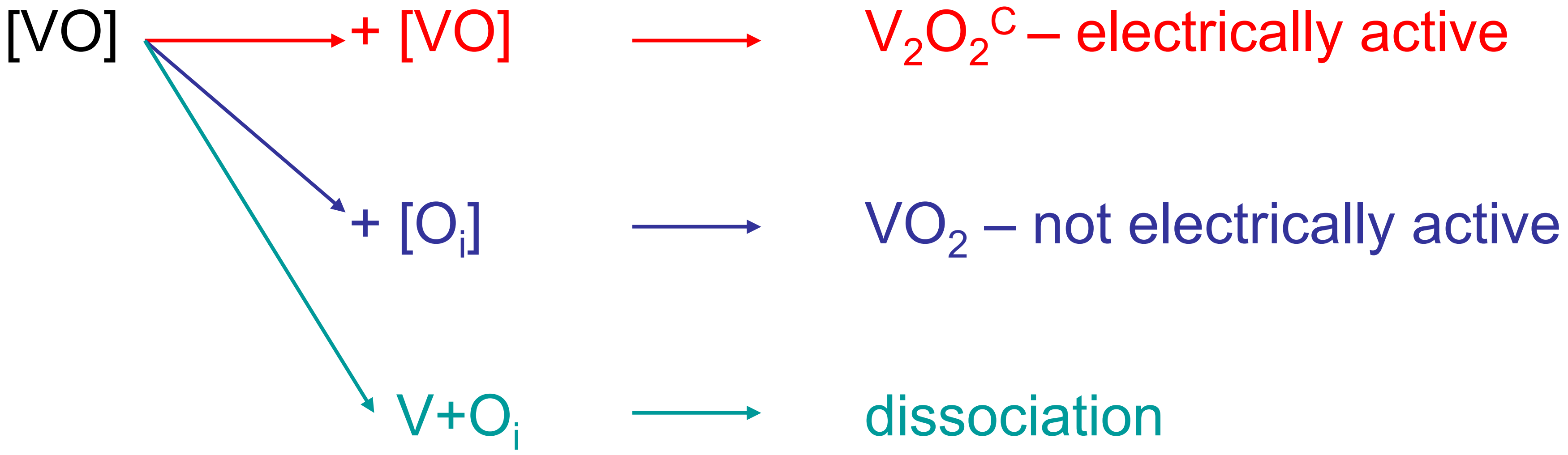
$$\frac{\partial[V_2]}{\partial t} = -4 \cdot \pi \cdot R \cdot (D[O_{2i}](T) + D[V_2](T)) \cdot [V_2] \cdot [O_{2i}]$$

$\mathbf{V_2O_2^B}$

$$[V_2](t,T) = [V_2]_0 \cdot e^{-4\pi R(D[V_2](T)+D[O_{2i}](T))\cdot[O_{2i}]t}; \boxed{[V_2O_2{}^B](t,T) = [V_2]_0 - [V_2](t,T)}$$

C) VO + VO → $V_2O_2^C$

[VO] ~ Dose



[VO] → + [VO] → $V_2O_2^C$ – electrically active

[VO] → + $[O_i]$ → VO_2 – not electrically active

[VO] → $V+O_i$ → dissociation

$VO+VO \rightarrow V_2O_2{}^C$ $VO+O_i \rightarrow VO_2$ $VO \rightarrow V+O_i$

$$\left\{\begin{aligned}
\frac{\partial[VO]}{\partial t} &= -k_1\cdot[VO]^2 - k_2\cdot[O_i]\cdot[VO] - k_3\cdot[VO] \\
\frac{\partial[V_2O_2{}^C]}{\partial t} &= k_1\cdot[VO]^2 \\
\frac{\partial[VO_2]}{\partial t} &= k_2(T)\cdot[VO]\cdot[O_i]
\end{aligned}\right.$$

Annealing out of VO

Formation of V_2O_2 due to VO+VO reaction

Formation of VO_2 via $VO+O_i$ reaction

$$[VO](t,T) = \frac{(k_2(T)\cdot[O_i]+k_3(T))\cdot[VO]_0}{(k_1(T)\cdot[VO]_0+k_2(T)\cdot[O_i]+k_3(T))\cdot e^{(k_2(T)\cdot[O_i]+k_3(T))\cdot t} - k_1(T)\cdot[VO]_0}$$

$V_2O_2{}^C$ (t,T)

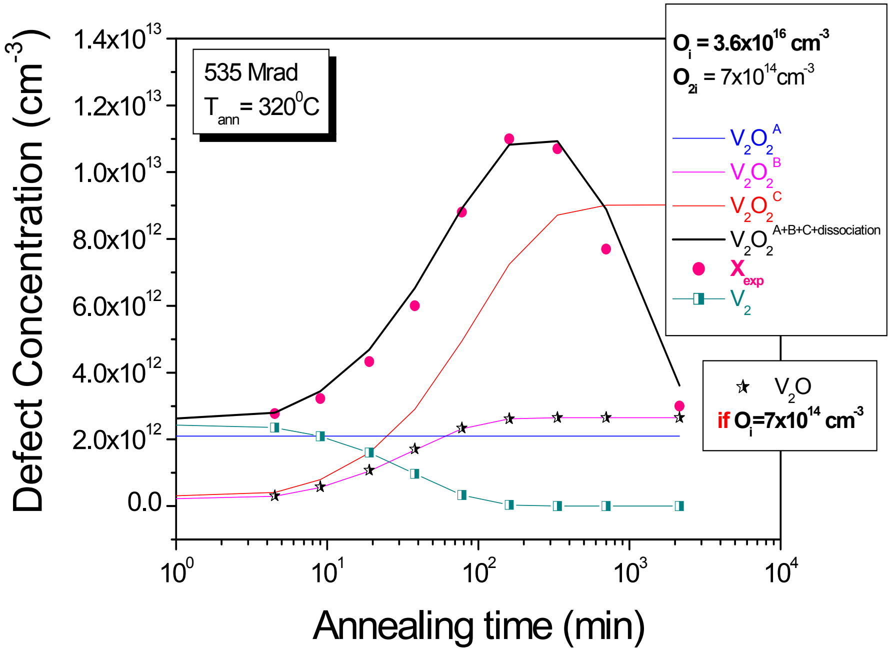
$$\begin{aligned}
[V_2O_2{}^C](t,T) = [VO]_0 + \frac{(k_2(T)\cdot[O_i]+k_3(T))^2\cdot t}{k_1(T)} + \\
+\frac{(k_2(T)\cdot[O_i]+k_3(T))}{k_1(T)}\cdot\ln\frac{(k_2(T)\cdot[O_i]+k_3(T))}{(k_1(T)\cdot[VO]_0+k_2(T)\cdot[O_i]+k_3(T))\cdot e^{(k_2(T)\cdot[O_i]+k_3(T))\cdot t} - k_1(T)\cdot[VO]_0} \\
-\frac{(k_2(T)\cdot[O_i]+k_3(T))\cdot[VO]_0}{(k_1(T)\cdot[VO]_0+k_2(T)\cdot[O_i]+k_3(T))\cdot e^{(k_2(T)\cdot[O_i]+k_3(T))\cdot t} - k_1(T)\cdot[VO]_0}
\end{aligned}$$

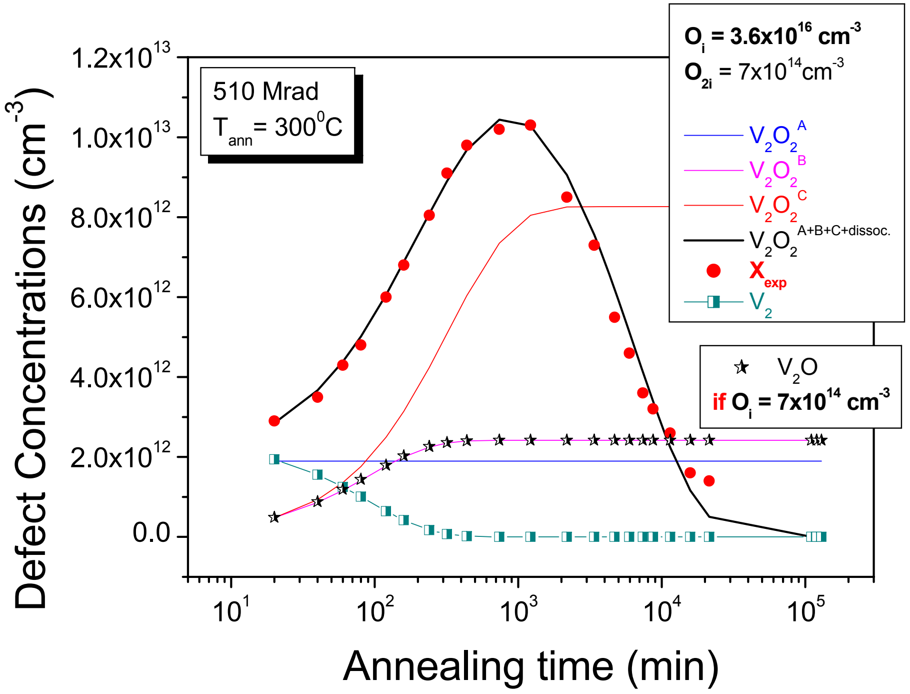
Parameters used for simulations of V_2O_2 formation and dissociation

- $[O_i] = 3.6 \times 10^{16}$ cm^{-3} (from SIMS $[O_i]=9 \times 10^{16}$ cm^{-3})
- $[O_{2d}] = 7 \times 10^{14}$ cm^{-3} (in accordance with previous measurements regarding IO_2 center)
- $[VO] = 1.1 \times 10^{17}$xDose (extrapolation of introduction rate measured with DLTS at lower doses)
- $[V_2]$ and [X] =determined directly from TSC measurements
- $r = 5 \times 10^{-10}$m
- $D_{VO}(T)$=6xexp(-1.8eV/KT) cm^2/s;
- $D_{VV}(T)$=0.1xexp(-1.3eV/KT) cm^2/s;
- $D_{O2d}(T)=3 \times 10^{-4}$xexp(-1.3eV/KT) cm^2/s;
- $D_{oi}(T)$=0.13xexp(-2.53eV/KT) cm^2/s
- $K_3^{\text{VO dissociation}} = 2.1 \times 10^{12}$xexp(-1.94eV/KT) s^{-1};
- $K_4^{\text{V2O2 dissociation}} = 6.1 \times 10^{12}$xexp(-2.1eV/KT) s^{-1} **– fitting parameter** (no references for this parameter)

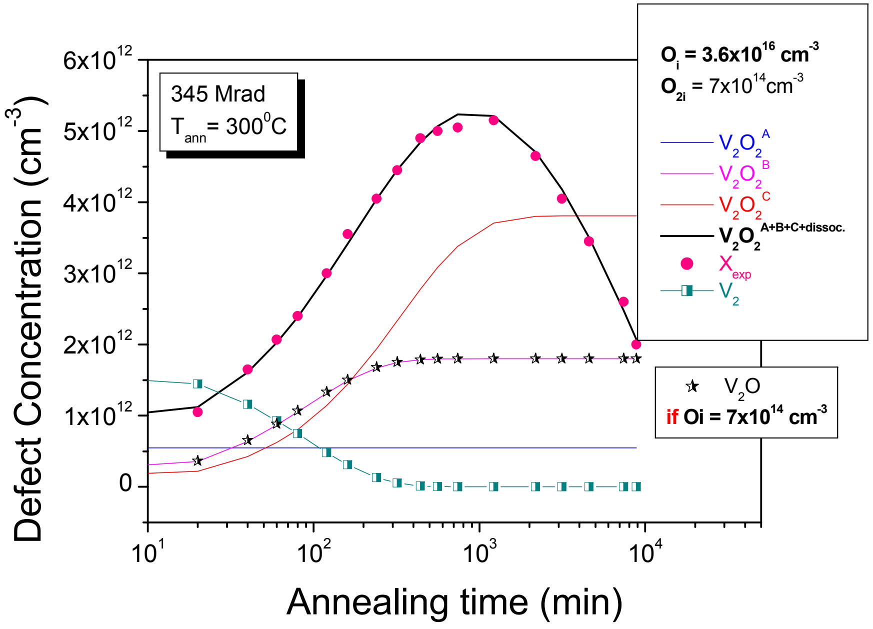
II) Epi/Cz material - similar irradiation dose and annealing at different T

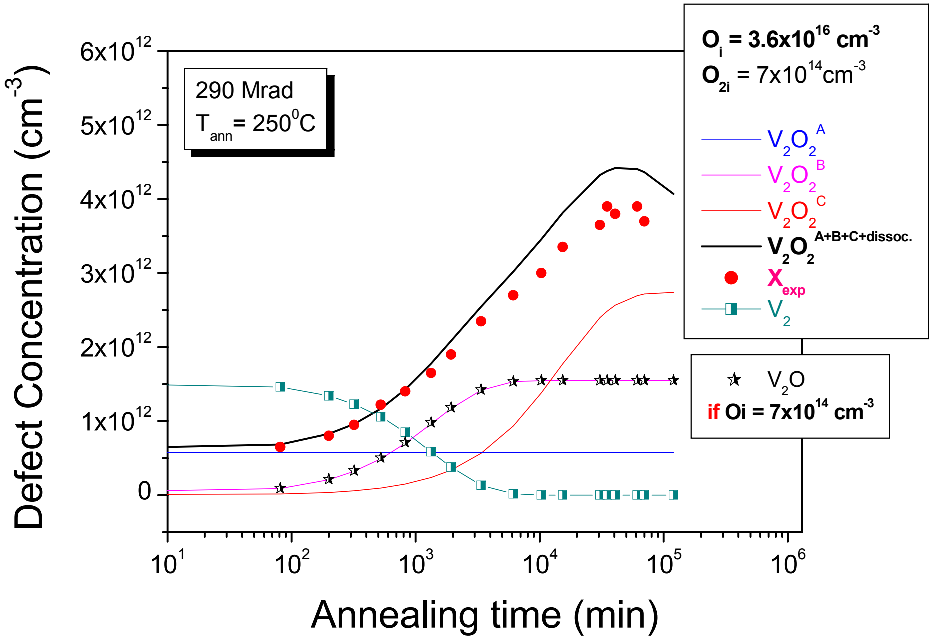
a) Irradiation Dose: 520±10% Mrad





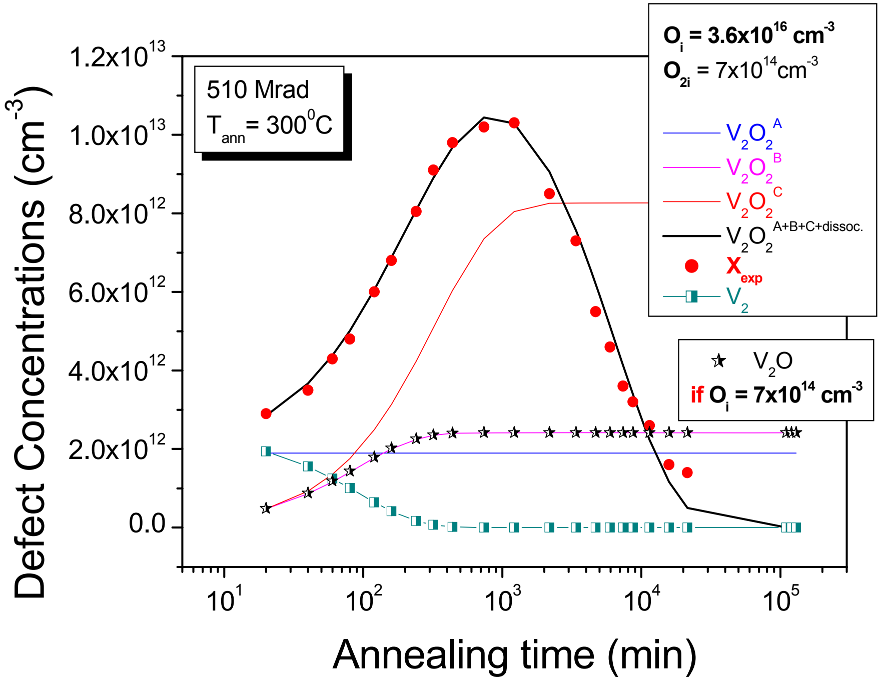
b) Irradiation Dose: 315±10% Mrad

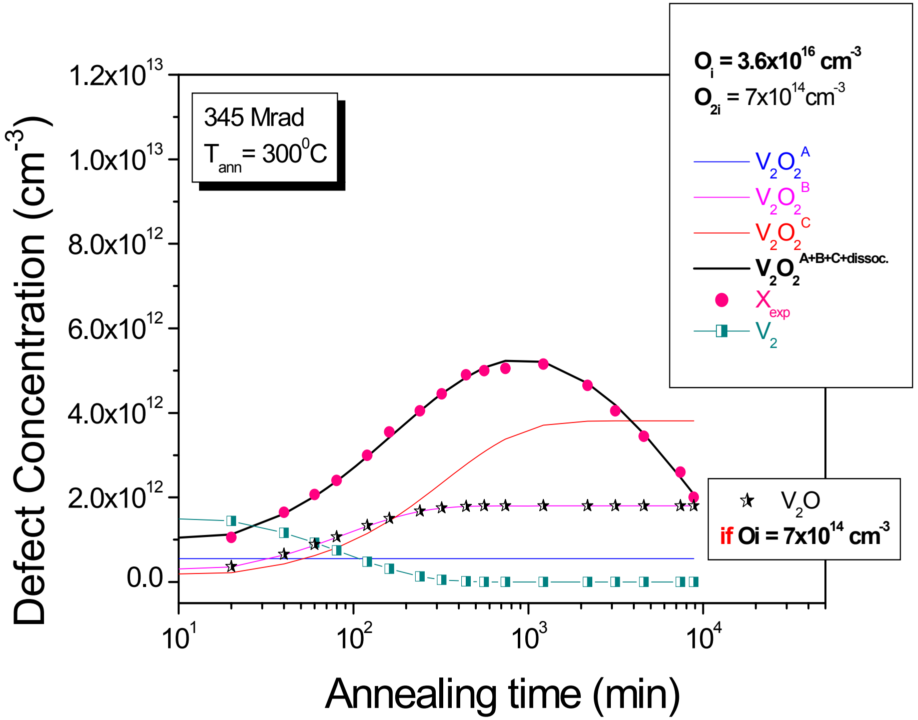




III)Epi/Cz material - Same annealing T but different irradiation doses

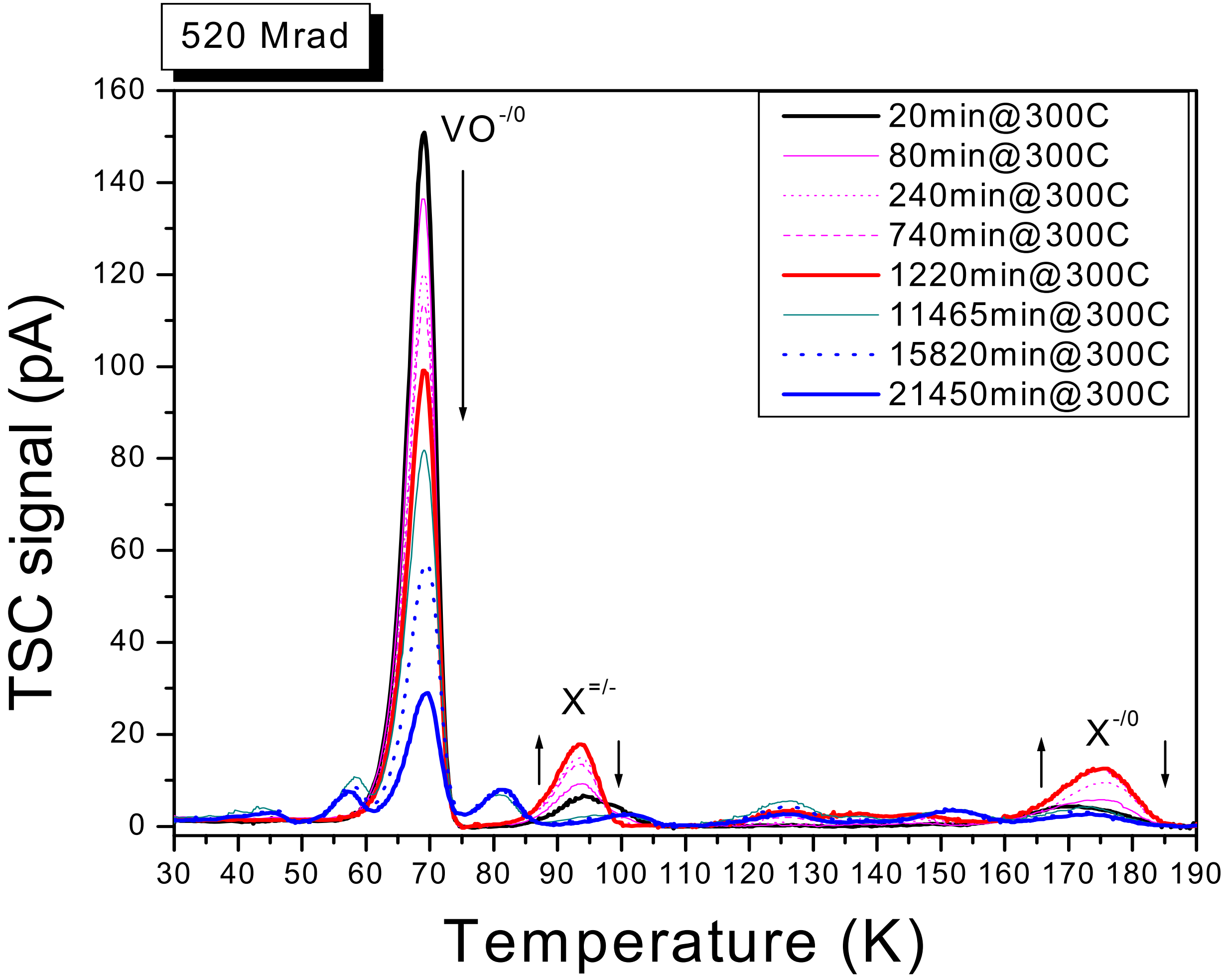
Irradiation dose = 315 ± 10% Mrad





Conclusions

- Non linear dependance of [X] on [O_i]
- X defect can be associated with V_2O_2
- Identification with V_2O would lead to a 50 times lower concentration of O_i or diffusion coef. and activation energy for V_2 from literature are dramatically wrong


520 Mrad
VO$^{-/0}$
X$^{=/-}$
X$^{-/0}$
20min@300C
80min@300C
240min@300C
740min@300C
1220min@300C
11465min@300C
15820min@300C
21450min@300C
TSC signal (pA)
0
20
40
60
80
100
120
140
160
Temperature (K)
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190