D•E
Dipartimento di Energetica
"Sergio Stecco"

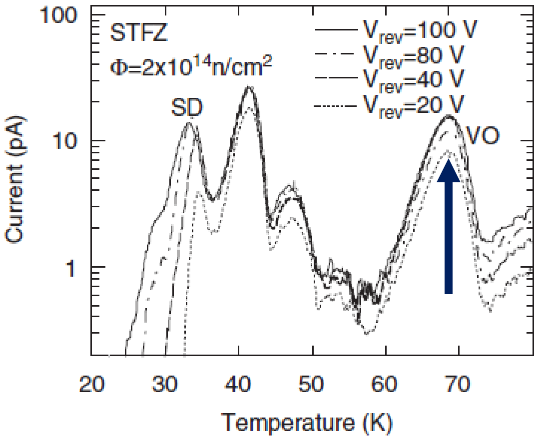
Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors

R. Mori, M. Scaringella, M. Bruzzi
Università degli Studi di Firenze and Istituto Nazionale di Fisica Nucleare

2010

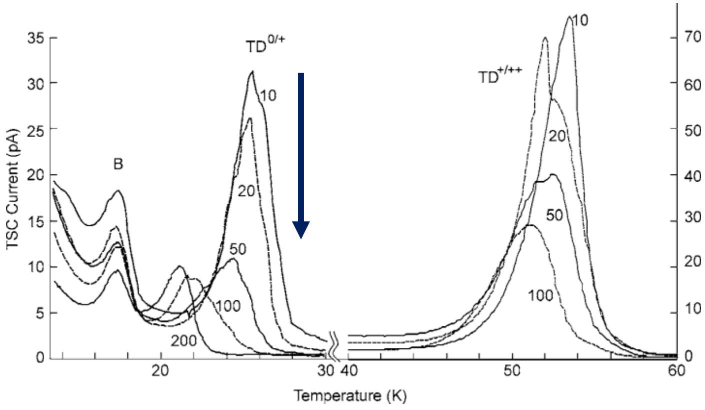
Introduction:
Problems encountered in TSC after priming

Normally the peak height increases with increasing bias voltage

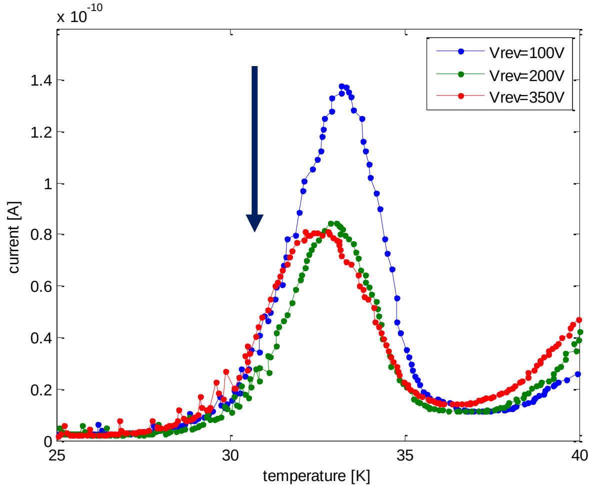


Scaringella et al. *Nucl. Instrum Meth A* **570** (2007) 322–329

In some case it decreases



Bruzzi et al. *J. Appl. Phys.* **99** (2006) 093706



TSC peak saturation does not correspond to full volume emission

Materials and methods

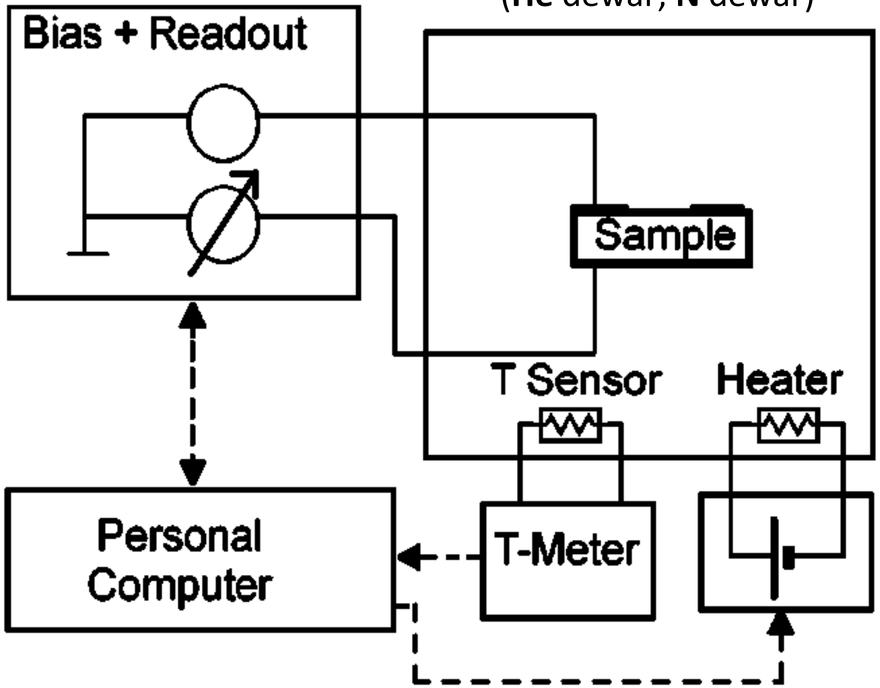
- Samples
  - Material: n-type MCz Si produced by Okmetic (Finland) with 900 Ωcm resistivity, <100> orientation and 280μm thickness.
  - Devices: p-on-n planar diodes 0.5x0.5cm^2
  - Procurement: WODEAN, Thanks to E. Fretwurst, G. Lindstroem
  - Irradiation: reactor neutrons at the Jozef Stefan Institute, Ljubljana
  - Fluence: 10^{13}-10^{14}-10^{15} n_{eq}/cm^2
  - Annealing: 1 year RT

  - Material: p-type MCz Si produced by Okmetic (Finland) with 2k Ωcm resistivity, <100> orientation and 280μm thickness
  - devices: n-on-p square diodes 0.5x0.5cm^2
  - Procurement: SMART, Thanks to D. Creanza, N. Pacifico
  - Irradiation: reactor neutrons at the Jozef Stefan Institute, Ljubljana
  - Fluence: 10^{14}-10^{16} 1/cm^2
  - Annealing: few days RT (+ 80min 80° C)

Materials and methods

- Set-up
  - He dewar: T=[5K,RT]
  - N dewar: T=[90K,RT]

(**He** dewar; **N** dewar)



Materials and methods

1. Thermally Stimulated Currents with cryogenic equipments: measurements performed on liquid He vapors, to ensure stable temperatures down to 4.2K minimize thermal inertia and mismatch.

2. Zero Bias Thermally Stimulated Currents measured at high fluence in the high temperature range (100-200K), to avoid background current subtraction, and increase resolution in deep levels analysis. Used in all T range to study residual electric field and charge of defects.

Issues:

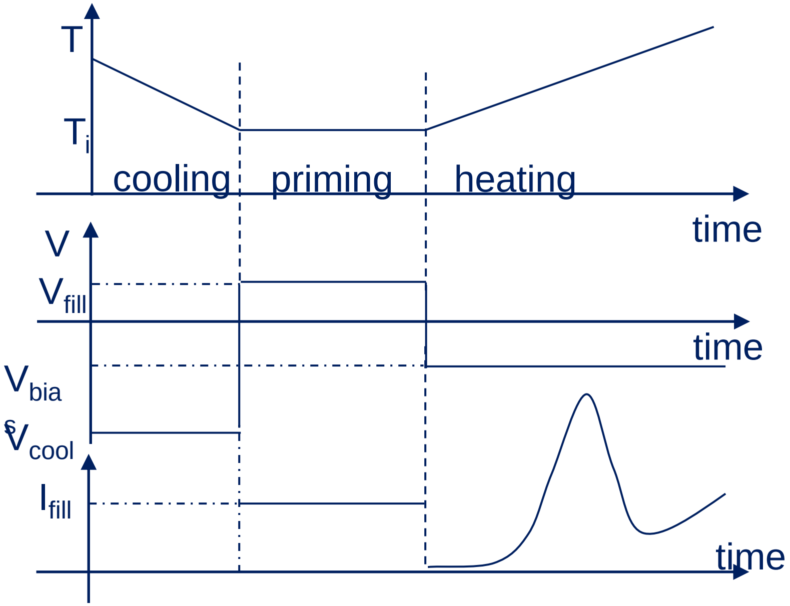
(a) Optimize the priming procedure to evidence radiation induced defects and correctly evaluate their concentration;
(b) Get information about electric field distribution;
(c) Correlate defects with transport properties.

Materials and methods

- TSC
  - Priming:
    - Forward current priming:
      - Cooling from Tp0 down to Tfill under polarization Vcool
      - Filling at Tfill with polarization Vfill: Ifill
    - Optical priming:
      - Cooling down to Tfill
      - Illumination at Tfill with IR LED (λ=850nm, full penetration) with polarization Vfill
  - Stimulation
    - Thermal scan
      - Apply bias voltage Vbias (*TSC*)

      or

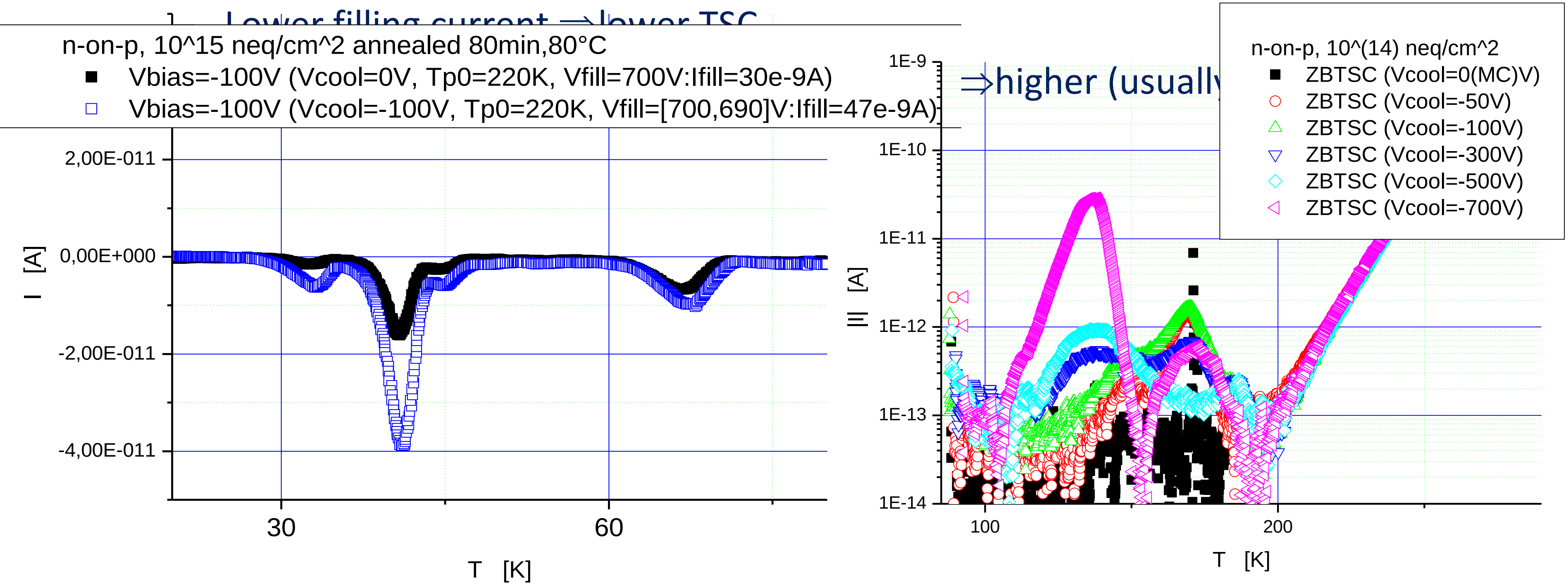
      - Apply 0V (*ZBTSC*)
      - Heating to Tmax



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: varying priming

- Forward current priming: varying Ifill, Vcool
  - Lower filling current ⇒lower TSC

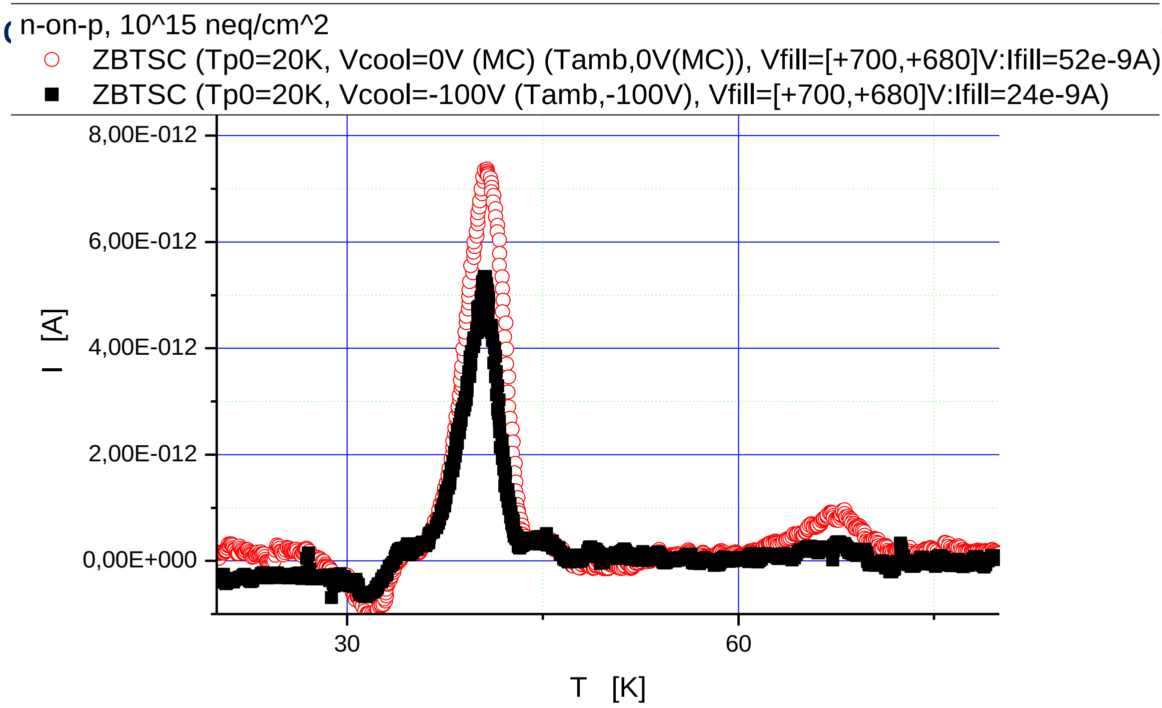


⇒higher (usually

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: varying priming

- Forward current priming: varying Ifill (independent of Vcool)
- Filling (dual field)



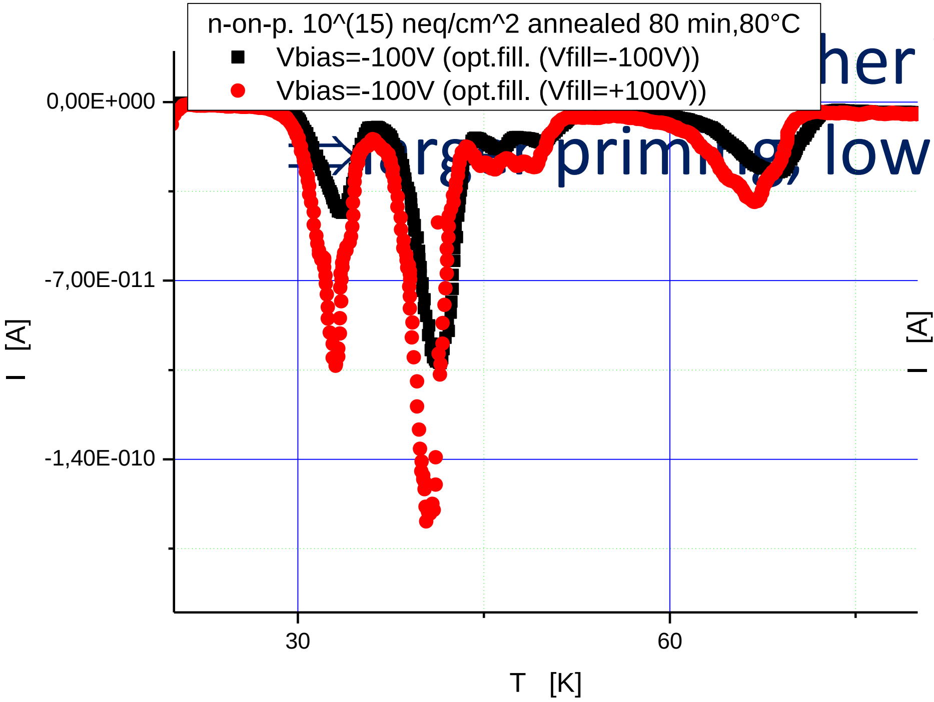
R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

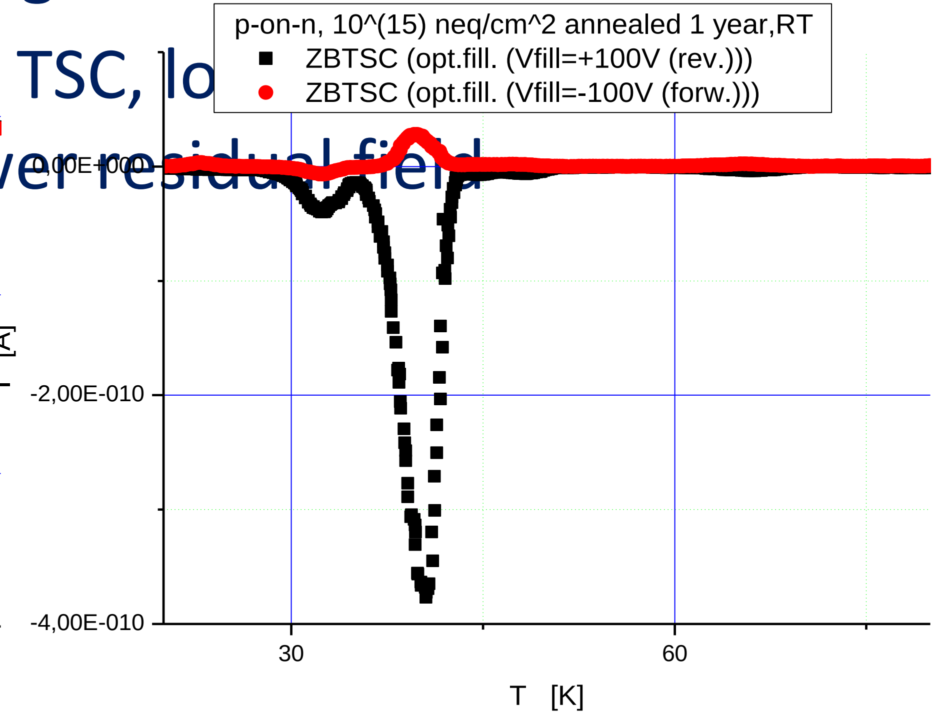
Experimental results: varying priming

- Optical priming: varying Vfill

her TSC, lo

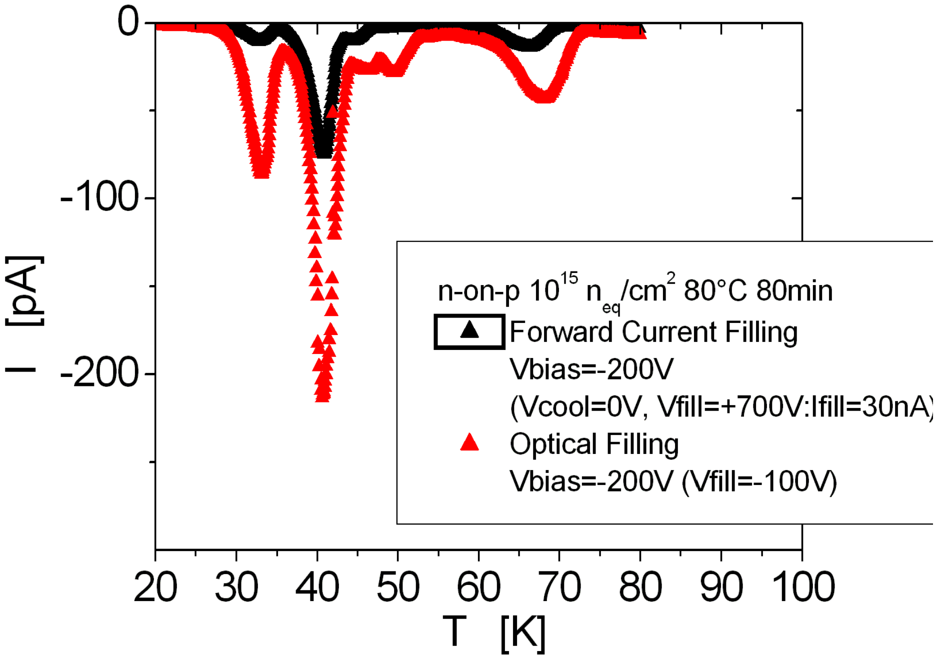
⇒ larger priming, lower residual field





Experimental results: varying priming

- Varying procedure: forward current- vs. optical-priming
- Higher e

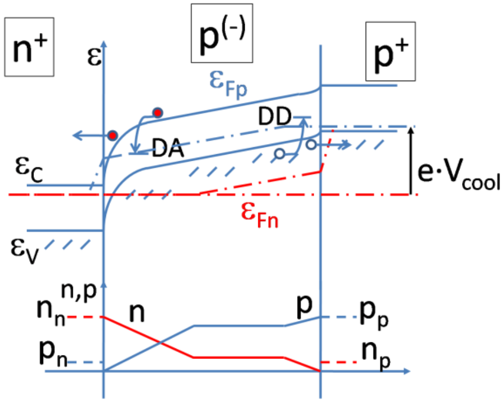


R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors RD50 workshop, 31 May-01 June 2010, Barcelona

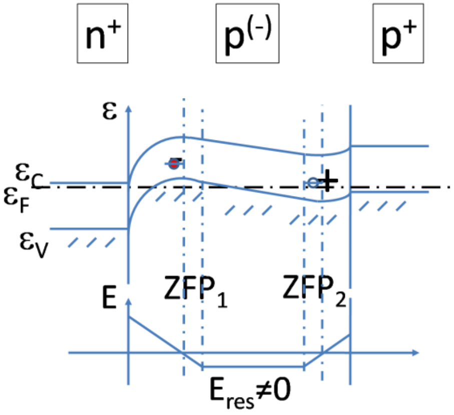
Discussion

- Priming mechanisms
  - Forward current priming

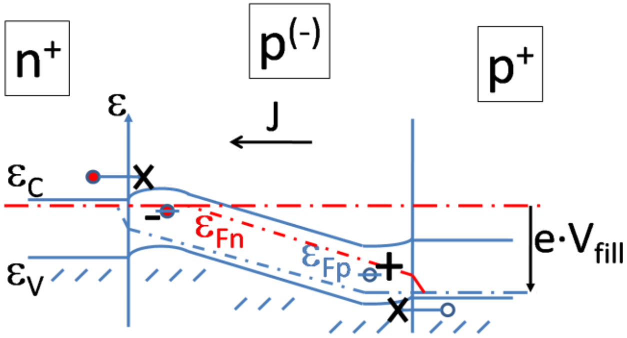
Reverse cooling



Metastable condition



Forward filling



- Space charge enlargement during cooling*
- Asymmetrical filling leading to DJ**

$$\frac{dJ}{dx} = -\frac{d\rho}{dt}$$

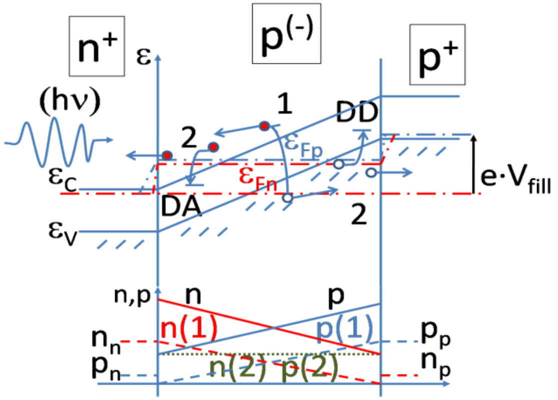
*Simmons and Taylor, JAP, 1972

**Eremin et al., NIMA, 2002

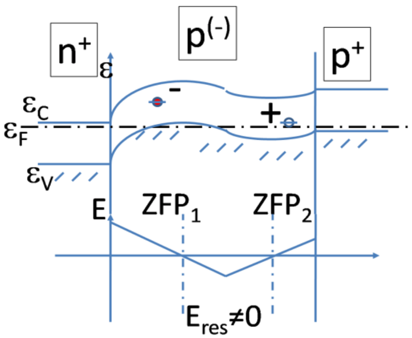
Discussion

- Priming mechanisms
  - Optical priming

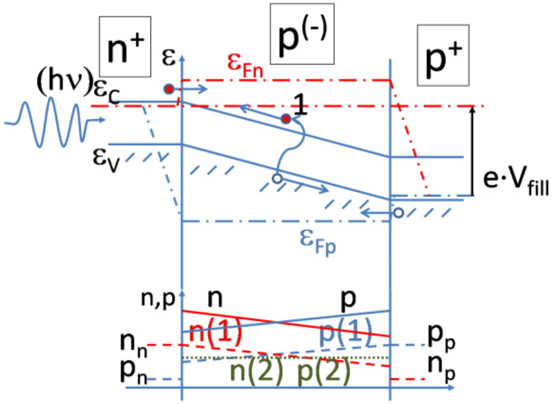
Reverse filling



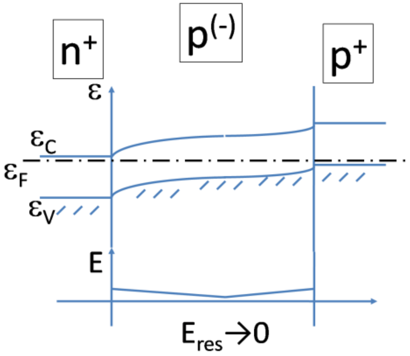
Metastable condition



Forward filling



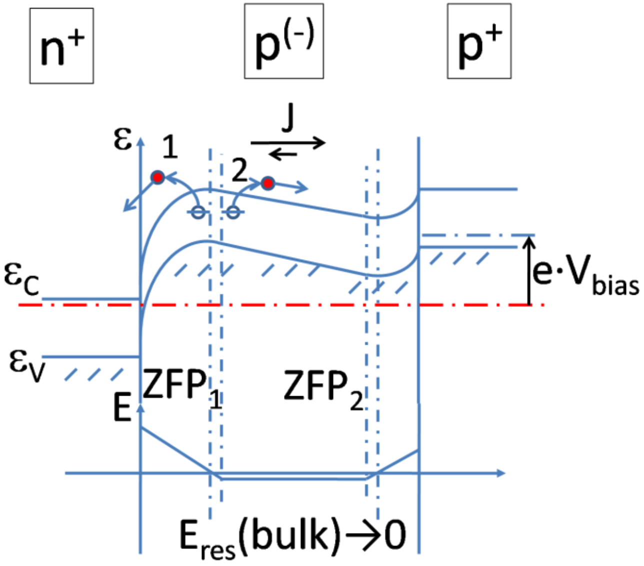
Metastable condition



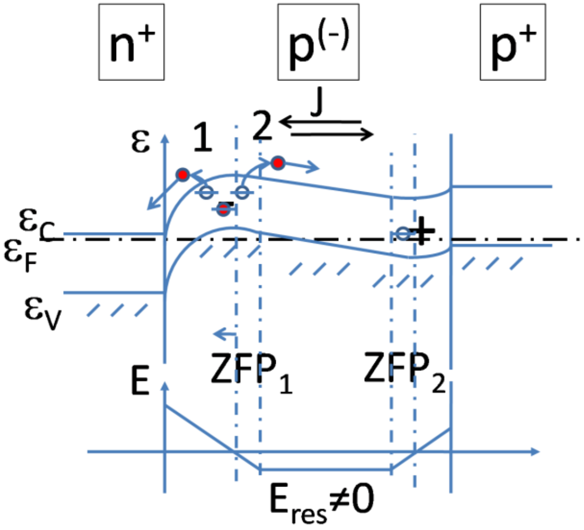
R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors RD50 workshop, 31 May-01 June 2010, Barcelona

Discussion

- Stimulation
  - TSC



  - ZBTSC



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors RD50 workshop, 31 May-01 June 2010, Barcelona

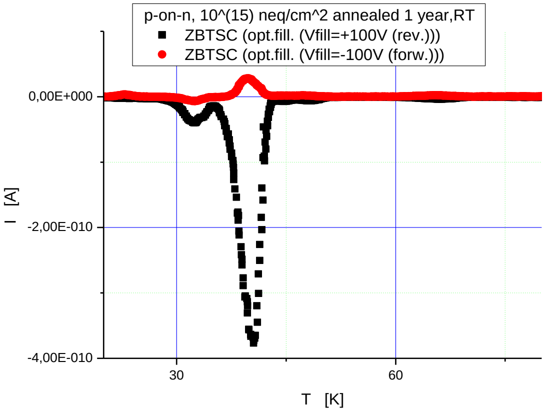
Discussion

– On the priming procedure:

Negligible ZBTSC means:

a) Null priming

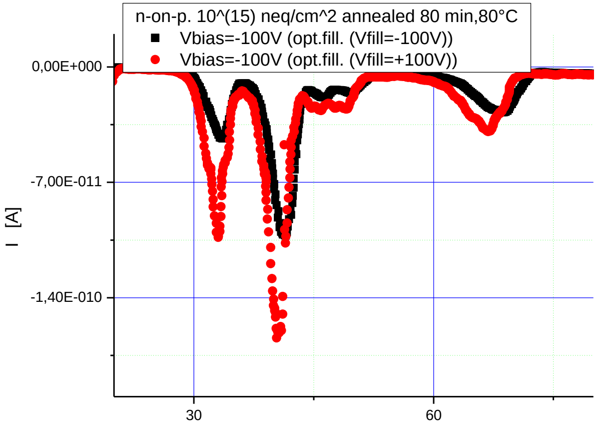
b) Uniform priming



If TSC after same priming is not negligible:

– There is priming

and it is uniform!!!



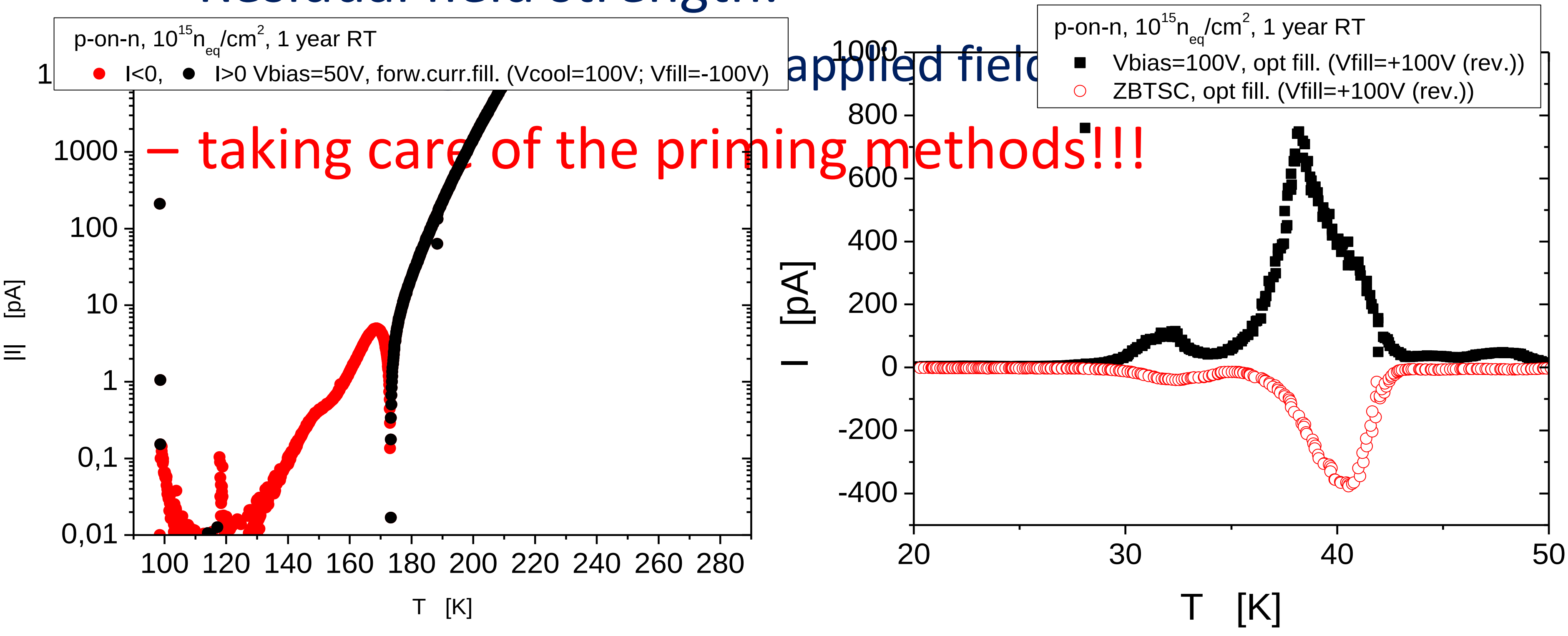
R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results:
particular phenomena from priming conditions

– Residual field strength:

applied fiel

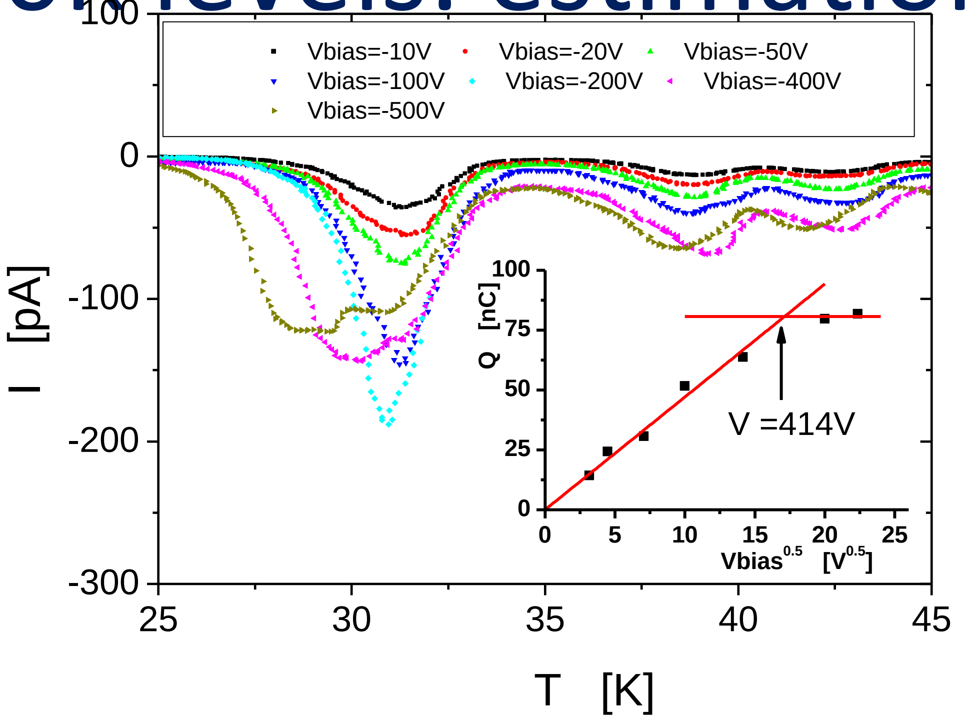
– taking care of the priming methods!!!



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: defect studies

–SD30K levels: estimations

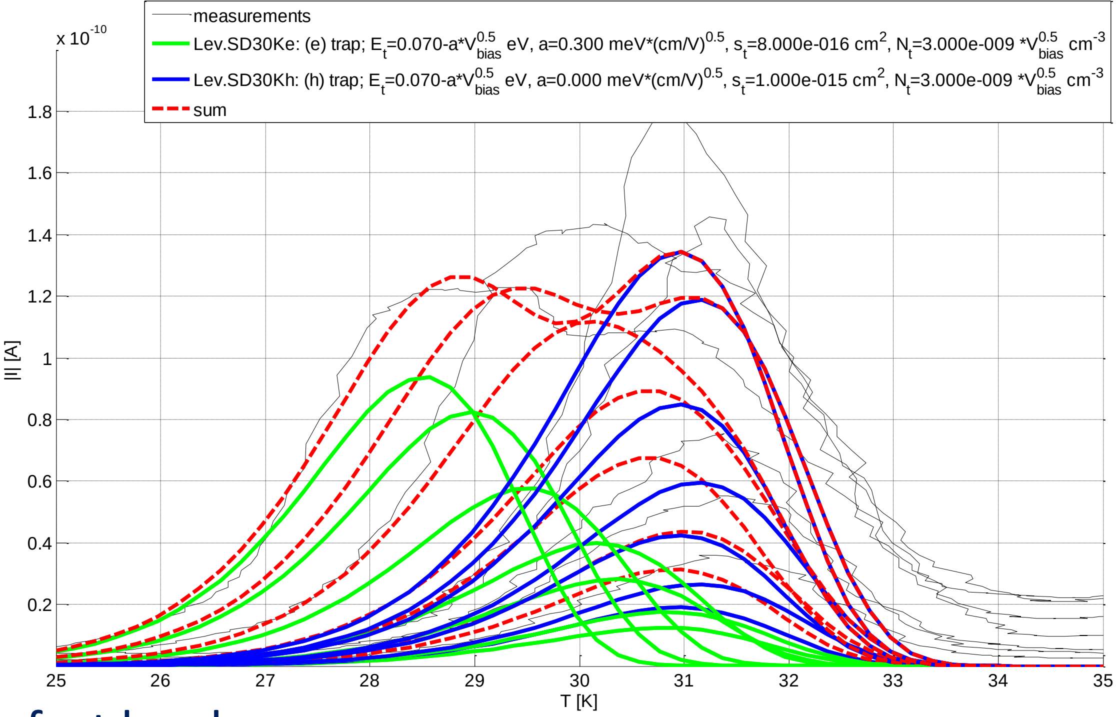


We studied the 30K shallow defect in irradiated MCZ Si using the correct priming procedure. Now emitted charge increases with square root of bias up to saturation for V~Vdep.

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: defect studies

-SD30K: two main components



- Defect levels:

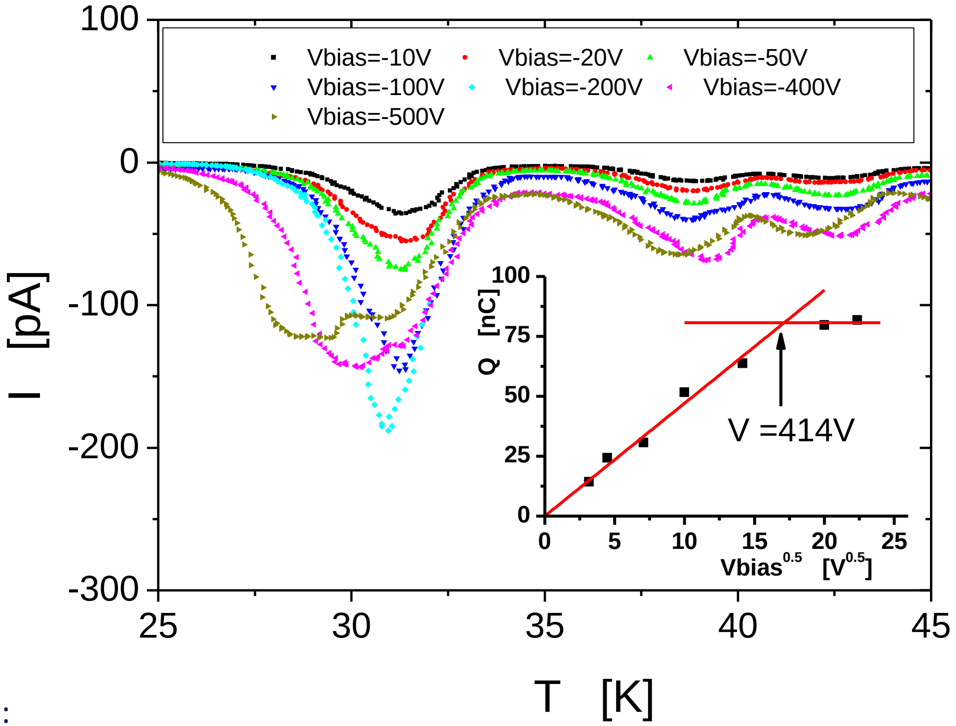
One (green) shows Poole-Frenkel effect thus it is charged at RT, contributes to Neff

The other (blu) shows no P-F, does not contribute to the effective doping

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: defect studies

– SD30K levels: estimations



- N_t estimation:
  - From charge at saturation: [SD30K levels] ≅Q_{sat}/Vol. ≅$2.388 \cdot 10^{14}$cm^{-3} →reliable
  - From fits: [SD30K charged]~ $2 \cdot 10^{13}$cm^{-3}; [SD30K not charged]~ $3 \cdot 10^{13}$cm^{-3} →confirm
- V_{dep} estimation, from Q_{sat}: V_{dep}~414V ($V_{dep}^{(nominal)}$=378V) →reliable
- V_{dep} evaluation from [SD30K charged]≡Neff: V_{dep}≈5kV!!!→?!?→ shallow level compensates other negatively charged defects usually responsible of type inversion!!!

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Experimental results: TSC and ZBTSC

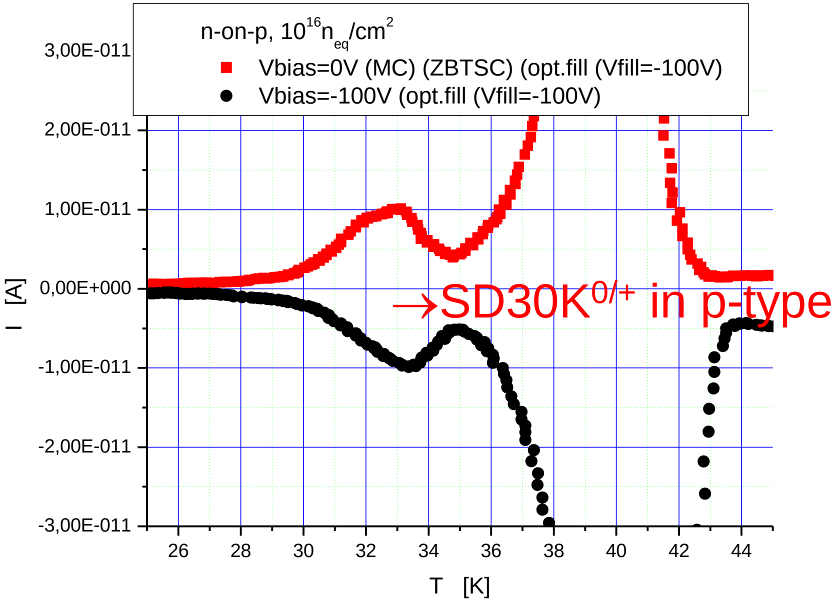
A comparison between TSC and ZBTSC allows one to evaluate the kind of carrier released by the trap:

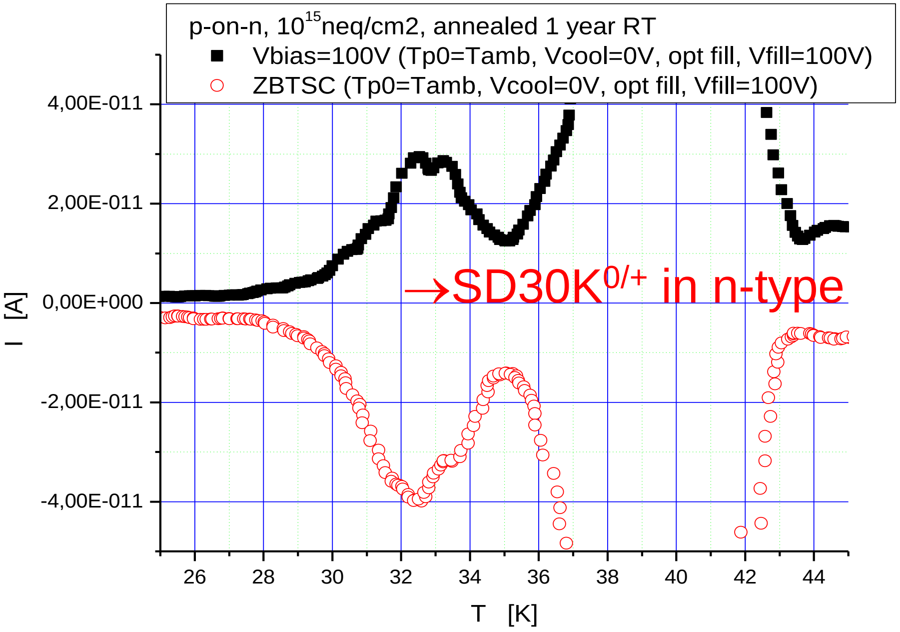
- Electron emission:
  - negative SCR (p-type) ⇒ field reduction ⇒ ZBTSC peak delayed during T scan with respect to TSC peak
  - Positive SCR (n-type) ⇒ field increase ⇒ peak anticipated
- Hole emission:
  - negative SCR (p-type) ⇒ field reduction ⇒ peak delayed
  - Positive SCR (n-type) ⇒ field increase ⇒ peak anticipated

Experimental results: TSC and ZBTSC

For the shallow level at 30K we find **electron emission**:

- negative SCR (p-type) ⇒ field reduction ⇒ peak delayed
- Positive SCR (n-type) ⇒ field increase ⇒ peak anticipated





R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

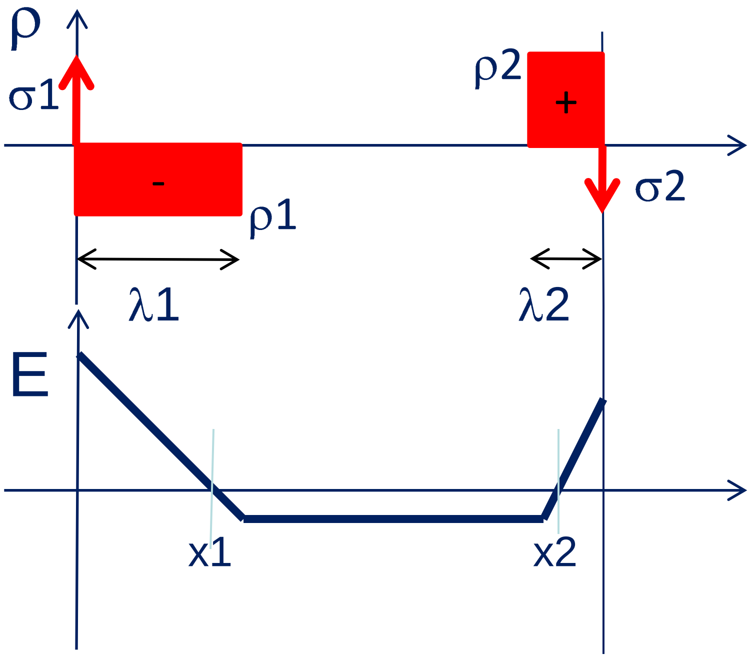
Work in progress

We are working on a model taking into account of fundamental relations:

- Poisson equation
- Continuity equation
- Current definition
- Boundary conditions:
    - » $E(0^-)=0$
    - » $E(d^+)=0$
    - » $q(\phi(d)-\phi(0))=\varepsilon_g$

$\Rightarrow$Relation between differentials

- Zero-field plane definition



$$\mathrm{d}\sigma_1 - (\lambda_1 \mathrm{d}\rho_1 + \rho_1 \mathrm{d}\lambda_1) + (\lambda_2 \mathrm{d}\rho_2 + \rho_2 \mathrm{d}\lambda_2) - \mathrm{d}\sigma_2 = 0$$

$$\mathrm{d}\sigma_1 - (\lambda_1 \mathrm{d}\rho_1 + \rho_1 \mathrm{d}\lambda_1) - \left(\frac{\lambda_1^2}{2d}\mathrm{d}\rho_1 + \frac{\rho_1\lambda_1}{d}\mathrm{d}\lambda_1\right) - \left(\frac{\lambda_2^2}{2d}\mathrm{d}\rho_2 + \frac{\rho_2\lambda_2}{d}\mathrm{d}\lambda_2\right) = 0$$

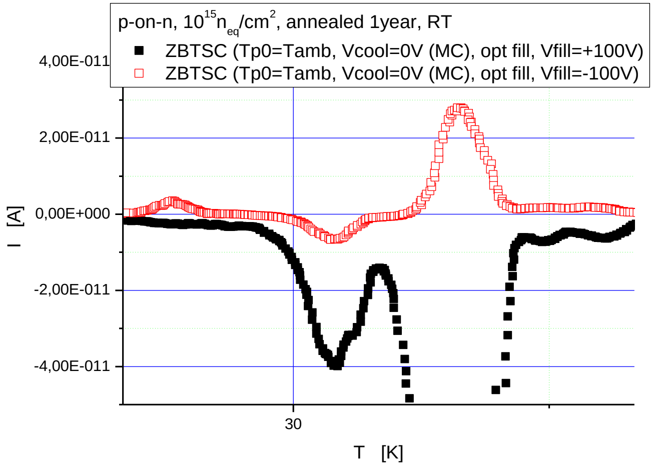
$$\mathrm{d}x_1 = \left(\mathrm{d}\lambda_1 - \frac{\lambda_1}{d}\mathrm{d}\lambda_1\right) - \left(\lambda_2 - \frac{\lambda_2^2}{2d}\right)\left(\frac{\rho_1 \mathrm{d}\rho_2 - \rho_2 \mathrm{d}\rho_1}{\rho_1^2}\right) - \left(\frac{\rho_2}{\rho_1}\right)\left(\mathrm{d}\lambda_1 - \frac{\lambda_1}{d}\mathrm{d}\lambda_1\right)$$

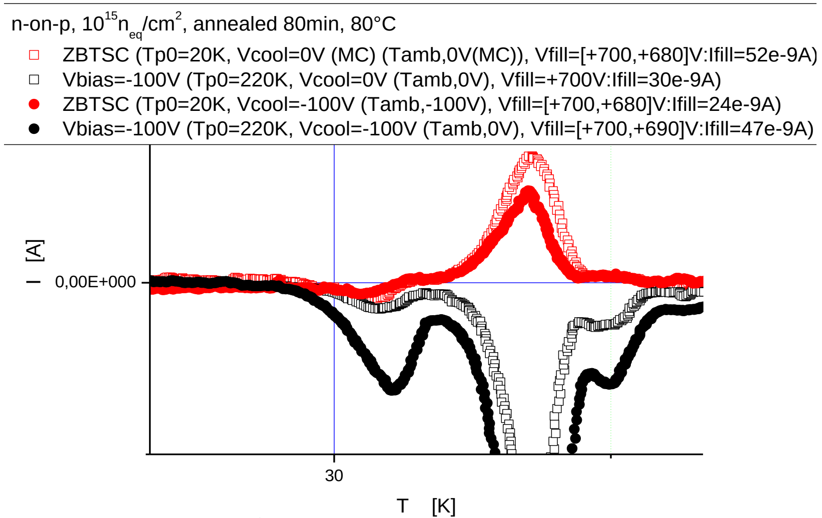
$$\Rightarrow J \approx \rho_1 \frac{\mathrm{d}x_1}{\mathrm{d}t}$$

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona

Discussion

1. Measurements suggest:





- Negative (independently on priming and type)

2. Model infer:

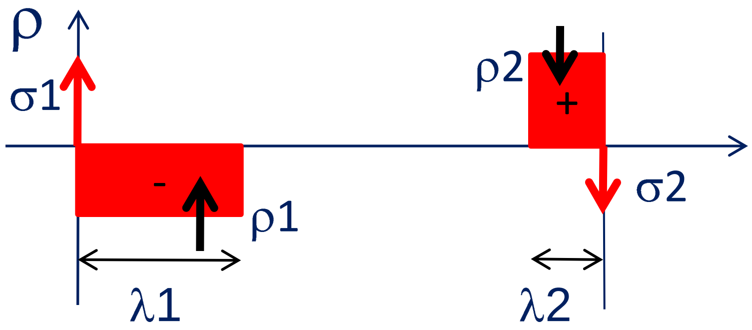
- Hp.s:-SD30K emission, recombination in the bulk

$$\begin{cases} d\rho_2 < 0 \\ d\rho_1 < 0 \end{cases}$$

$$J < 0 \quad \Rightarrow \quad \rho_1\lambda_1 > \rho_2\lambda_2$$

- And relation with trap type!?

⇒WORK IN PROGRESS



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors RD50 workshop, 31 May-01 June 2010, Barcelona

Conclusions

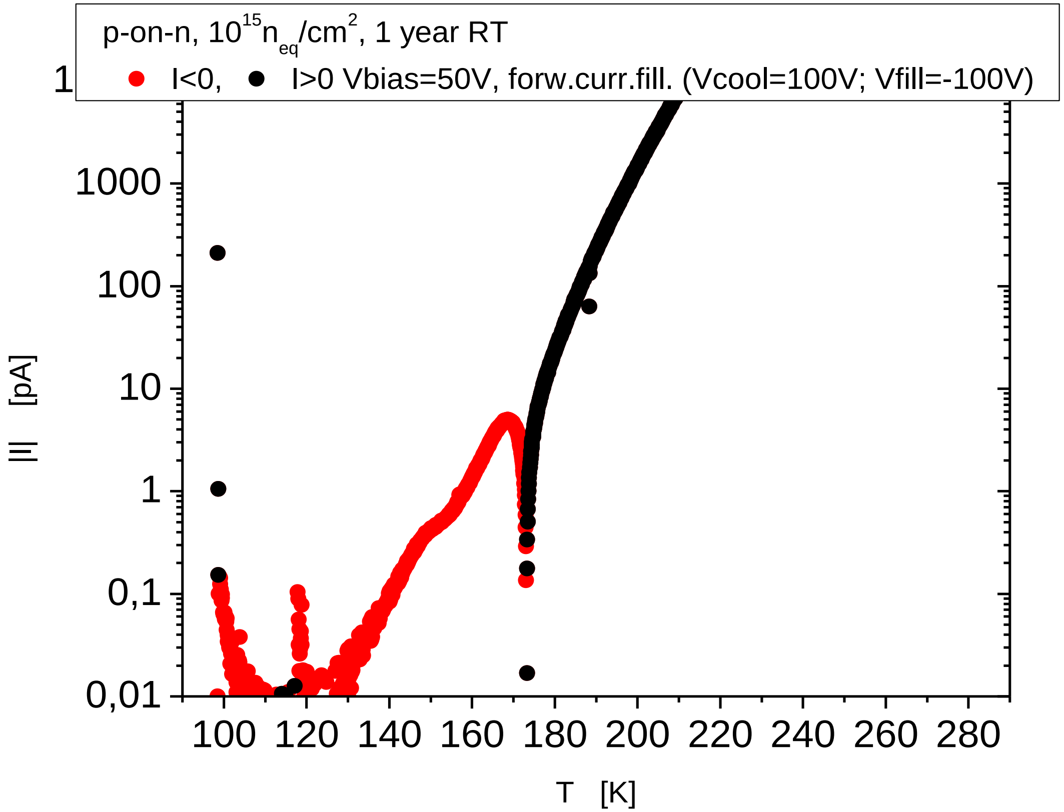
We studied both p- and n-type MCz Si pad detectors after irradiation with reactor neutrons up to 10^{15}cm^{-2}.

-Priming procedures were investigated to optimize the visualization of traps by TSC and to evidence the electric field distribution within the irradiated device. Best priming process found is optical priming in forward polarization (to be checked without polarization).

-The various features observed experimentally by changing the operative parameters are qualitatively described by band diagrams. Best description accounts for the presence of a residual electric field (polarization of the irradiated Si bulk) due to charges frozen at traps in bulk and barriers close to the electrodes. Residual electric field in the bulk can be so high, in highly irradiated device, to dominate the current emission both in TSC and ZB-TSC.

-The method has been applied to the shallow level at 30K. A reliable trap concentration was found (2x1013cm-3), electron-trap nature of defect was determined by comparison of TSC and ZBTSC emissions. Results indicate that this defect is main responsible of compensation in heavily irradiated MCZ Si detectors.

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
RD50 workshop, 31 May-01 June 2010, Barcelona



It remember.

M. Bruzzi, D. Menichelli, R. Mori, M. Scaringella , TSC on n- and p-type MCz silicon diodes after irradiation with neutrons up to 10^{15}-10^{16} n/cm^2
13° RD50 Workshop, 3-5 June 2009, Freiburg24

Spares

- Useful references
- References on methods and on mechanisms
- References on results
- Addictional results
- Discussion on model

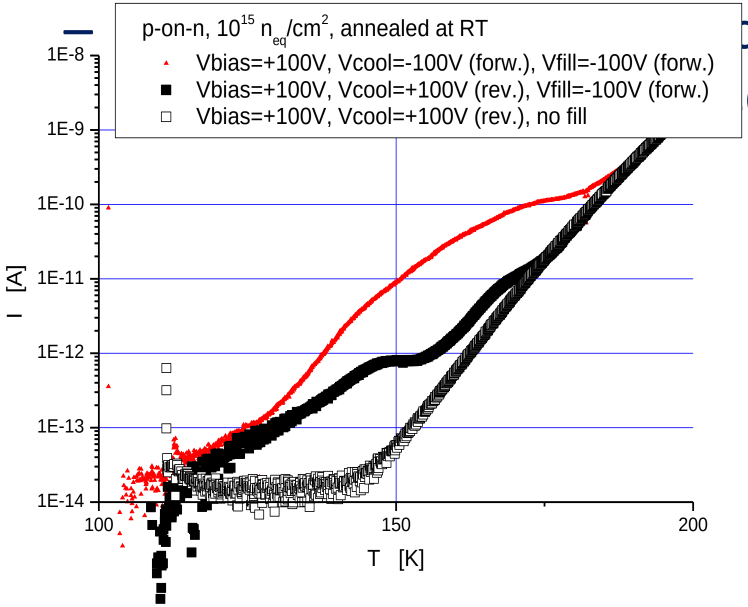
Spares: introduction

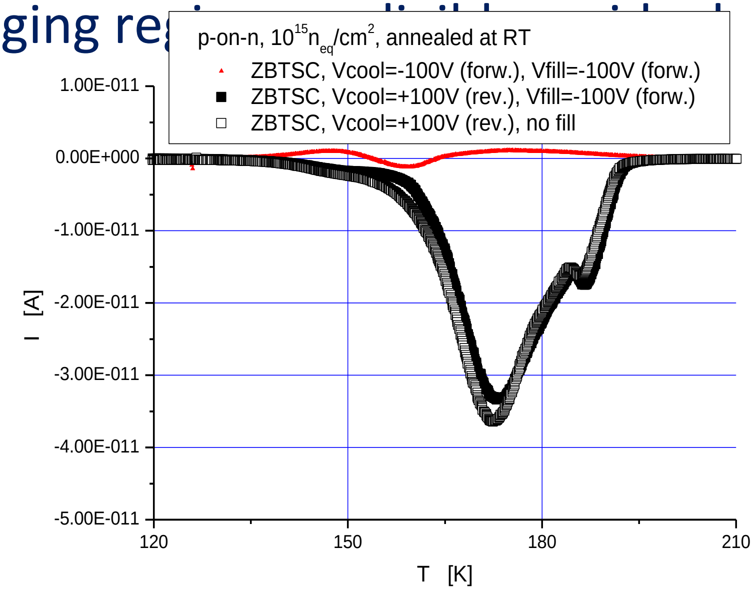
- What they (and you) have said more about
  - On the role of contacts:
    - "It should be noted that the space charge is always concentrated near the electrodes and consequently the role of contact phenomena in the behaviour of TSD currents is sufficient."*
    - "the fast retrapping case, when the influence of the contacts on the TSDC curve is more apparent"**
  - On the interpretation of measurements:
    - "starting polarity of the discharging current is different for various irradiation times, depending on the degree of filling of the traps."***
    - "the integral of the external current measures only a small fraction of the charge lost. This arises because the space charge which is driven deeper into the material contributes to a displacement current at x=0 which is a significant fraction of the conduction current at that point and opposed it in direction."****
  - On how should be the priming for:
    - "the observation of an external current requires not only a time changing density of trapped charge but also a change in the relative distribution of trapped charge to give a time-changing zero-field point."*****
    - "The calculation illustrate the important fact that the largest fraction of the total charge is observed externally when the initial charge is located within one half of the thickness of the sample."*****
  - On the target of the investigations:
    - "The external measurements of current and charge transferred between the electrodes is found to depend strongly on the ratio of transport-to-trapping times. [...] For large values of this parameter, a significant fraction of the internal charge can be observed externally, and the externally measured quantities become relatively easy to interpret in terms of the release and retrapping of carriers within the insulator."*****

**Kostsova and Kostsov, JPD, 2008*
***Kostsova and Salman, PSS, 1995*
****Petre et al., JAP, 1994*
*****Wintle, JAP, 1971*
******Monteith and Hauser, JAP, 1967*

Spares: experimental results: varying priming

- Forward current priming: varying Vcool
- [illegible] charging reg[illegible] C

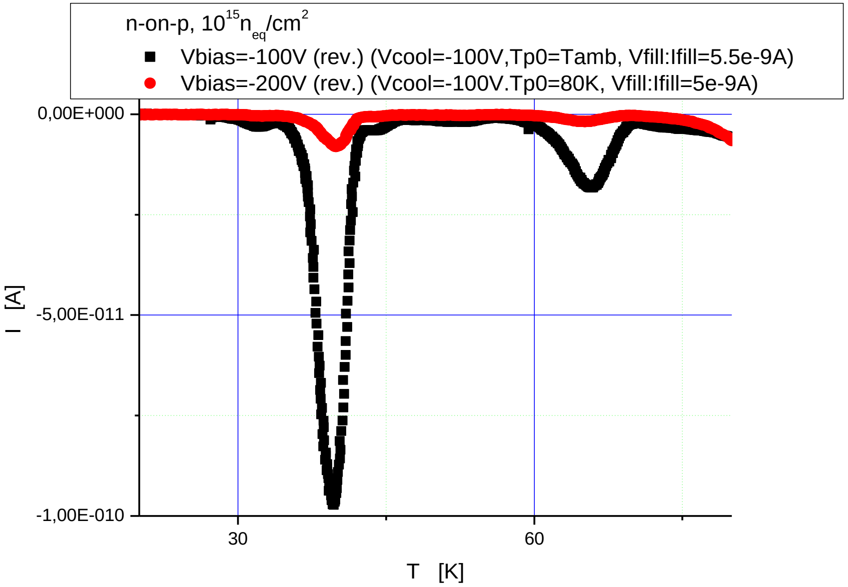


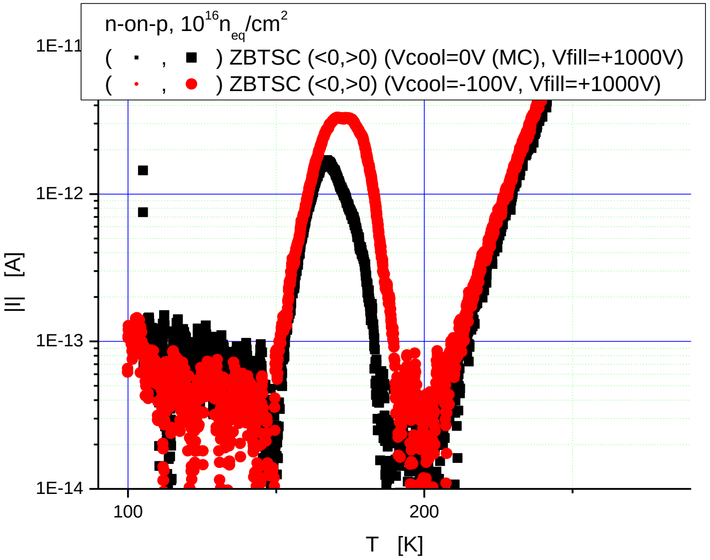


R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: varying priming

- Forward current priming: varying methods (Tp0 and Tfill)



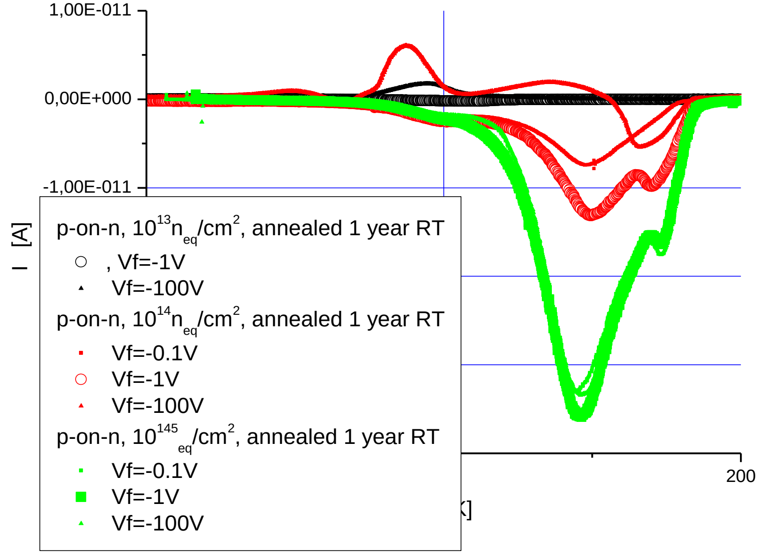


- Higher temperature of reverse polarization ⇒higher residual field
- Lower temperature of forward filling ⇒lower current⇒higher effects of residual field
- Effects are highlighted in ZBTSC ⇒residual field is the protagonist

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: varying priming

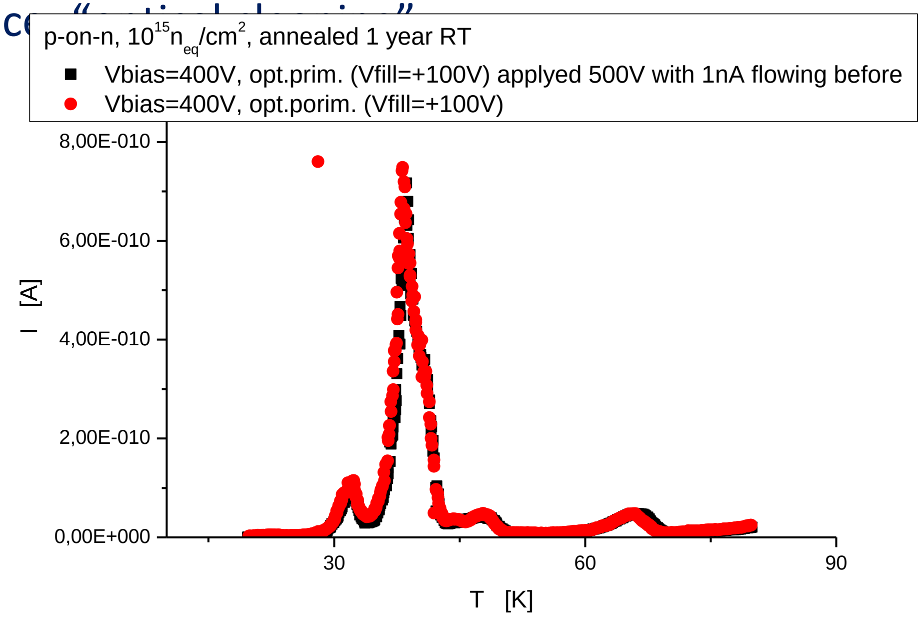
- Varying irradiation fluence
- Effects increase, increasing fluence ⇒higher space charge, higher residual field



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: varying priming

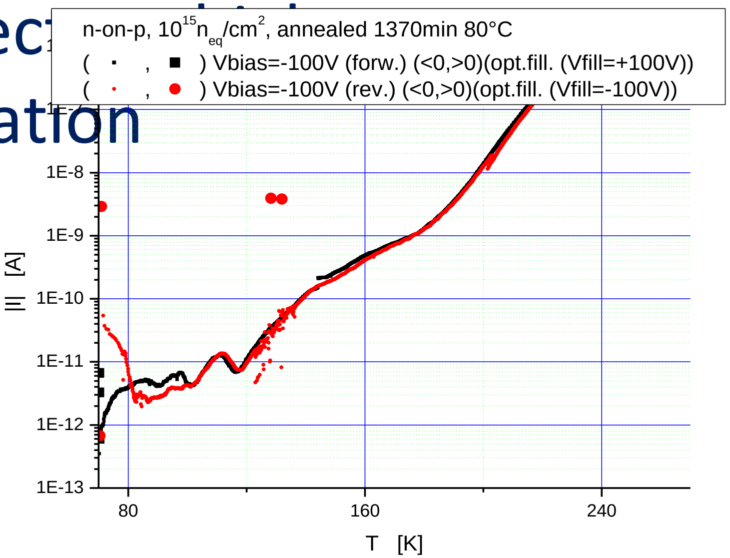
- Optical priming: varying conditions before illumination
- No dependence



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: varying priming

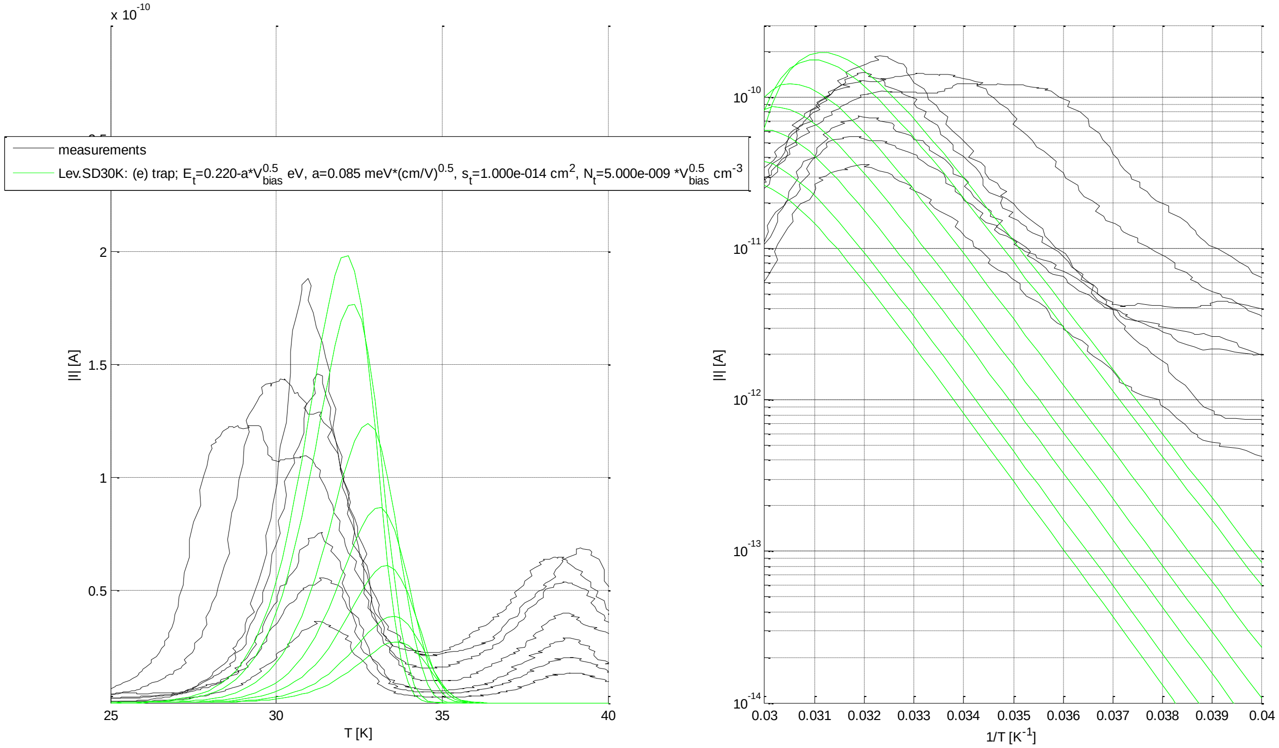
- At different temperatures (same Tfill)
- Lower effec res ⇒residual field relaxation



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: defect studies

- SD30K: fits
  - Scaringella* on MCz, STFZ, proton irradiated

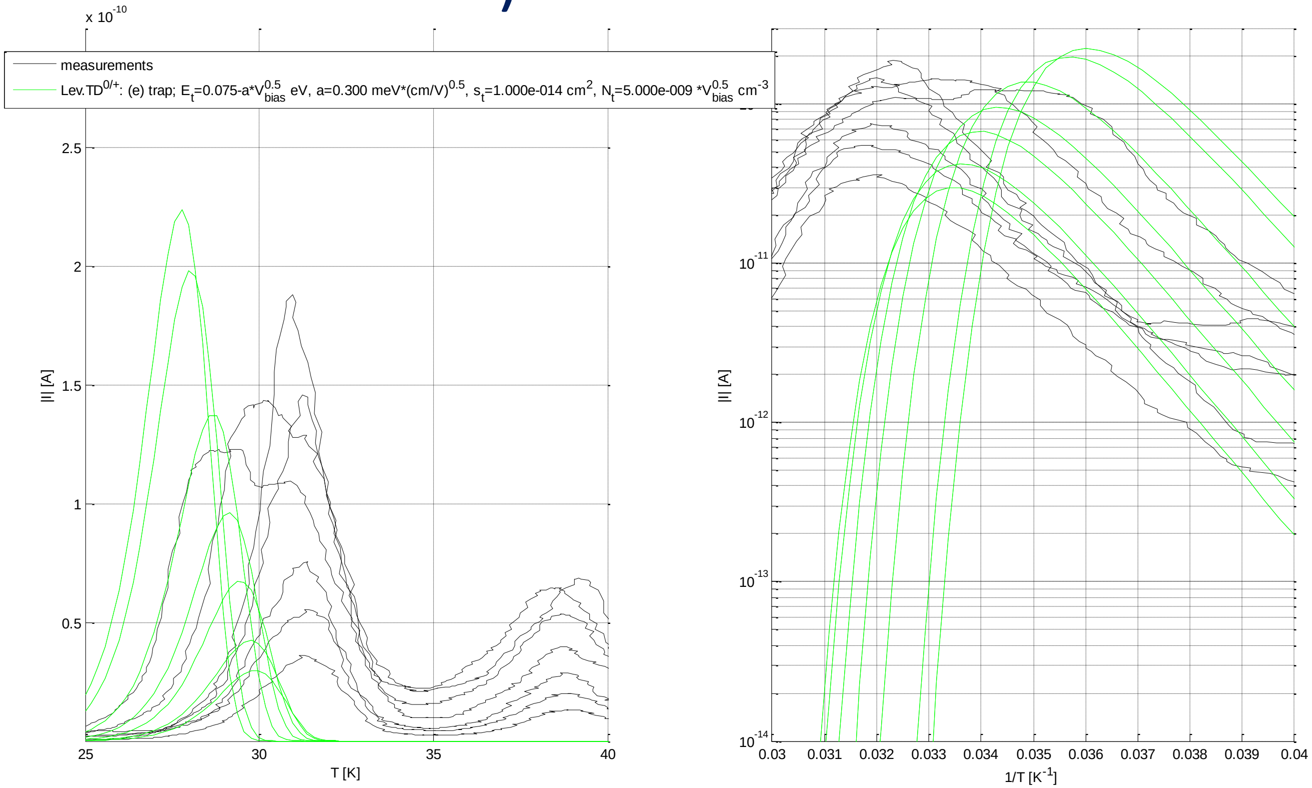


R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: defect studies

Dipartimento di Energetica "Sergio Stecco"

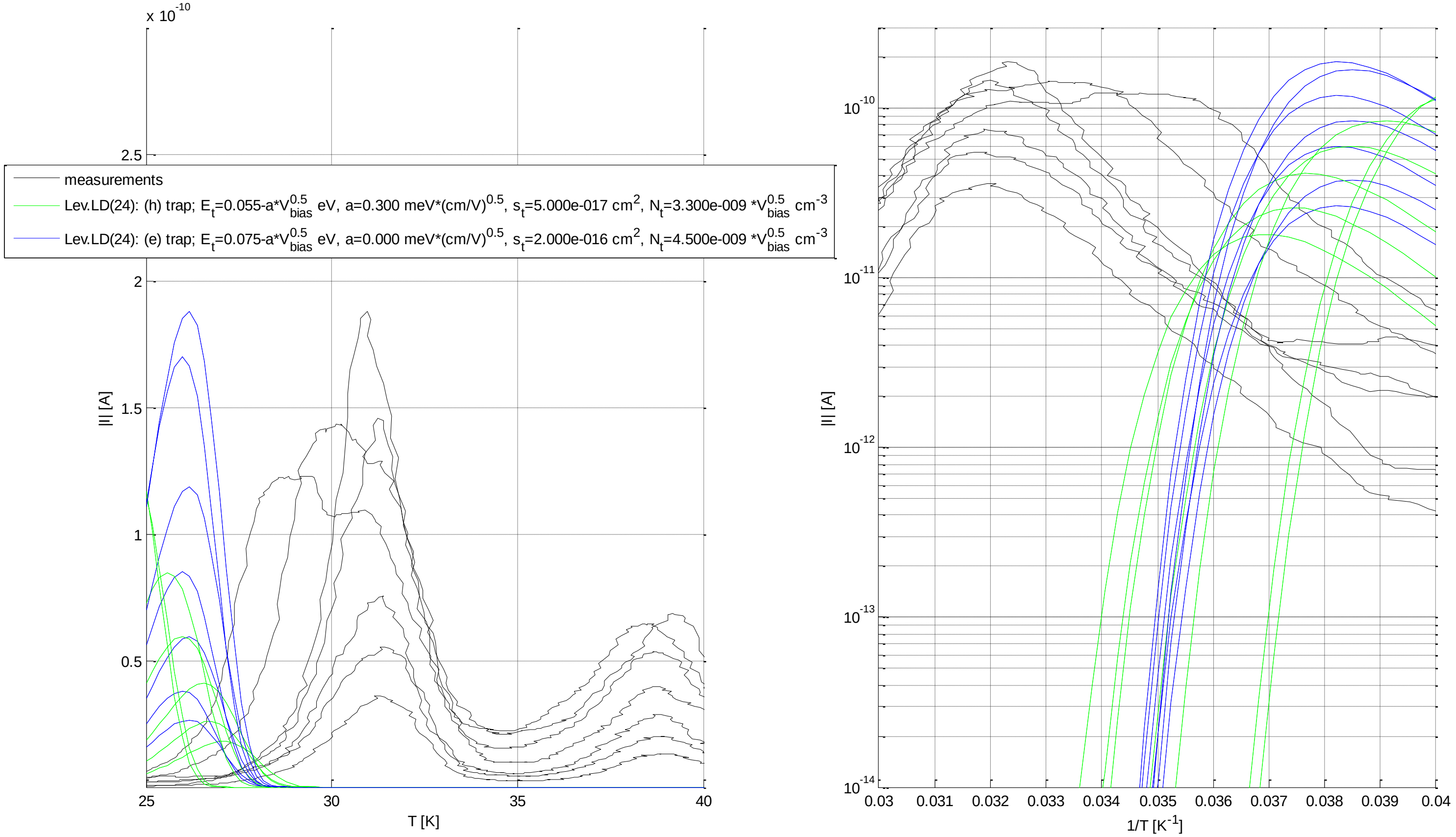
- SD30K: fits
  - Bruzzi* on p-type MCz, (before annealing at 420°C 120min)



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: experimental results: defect studies

- SD30K: fits
  - Menichelli* on DOFZ, STFZ, even unirradiated



R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona

Spares: discussion

- Stimulation mechanisms: modeling ZBTSC
  - Lindmayer *on insulators:

$$x^*: \qquad \int_0^d \mathrm{d}x \int_{x^*}^{x'} n_t(x')\mathrm{d}x'$$

$$\mathrm{d}Q_{ext} = qn_t\mathrm{d}x^* \quad \Rightarrow \quad I_{ext} = \frac{\mathrm{d}Q_{ext}}{\mathrm{d}t} = \frac{qn_t\mathrm{d}x^*}{\mathrm{d}t}$$

  - Monteith** on insulators:

$$Q_{ext} = \mathrm{f}\left(\frac{C_n N_t}{\mu}\right)$$

$$\frac{C_n N_t}{\mu} >> \frac{\varepsilon_t}{k_B T} \quad \Rightarrow \quad I_{ext} \propto \frac{\mathrm{d}n_t}{\mathrm{d}t}$$

  - Gross*** on dielectrics:

$$\varepsilon E(0,t) = \varepsilon E(x,t) - \int_0^x \rho(x',t)\mathrm{d}x' \quad ; \quad x = x^* \quad \Rightarrow \quad \varepsilon E(0,t) = -\int_0^{x^*} \rho(x',t)\mathrm{d}x'$$

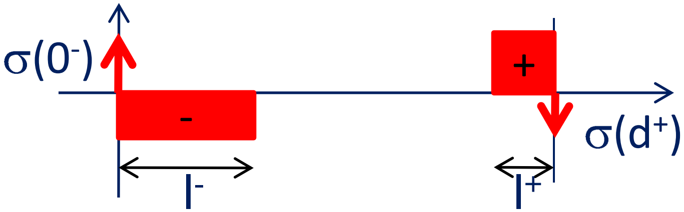
$$j_D(0,t) = \frac{\varepsilon\partial E(0,t)}{\partial t} = -\int_0^{x^*} \frac{\partial\rho(x',t)}{\partial t}\mathrm{d}x' + \rho(x^*,t)\frac{\mathrm{d}x^*}{\mathrm{d}t} = i(x^*,t) - i(0,t) + \rho(x^*,t)\frac{\mathrm{d}x^*}{\mathrm{d}t}$$

$$J = \frac{1}{d}\int_0^d i(x',t)\mathrm{d}x' = j_D(0,t) + i(0,t) = i(x^*,t) + \rho(x^*,t)\frac{\mathrm{d}x^*}{\mathrm{d}t}$$

**Lindmayer, JAP, 1965*
***Monteith and Hauser, JAP, 1967*
****Gross and Perlman, JAP, 1972*

Spares: discussion

- Interpreting measurements:



- Fast and slow relaxing*:
  - Fast relaxation:

$$\sigma(0^-) = \frac{\varepsilon V}{d} - \left[\rho^- l^- - \frac{\rho^- l^{-2} + \rho^+ l^{+2}}{2d}\right] \xrightarrow{V=0} -\left[\rho^- l^- - \frac{\rho^- l^{-2} + \rho^+ l^{+2}}{2d}\right]$$

  - Slow relaxation:

$$\sigma(0^-) = -\left[\rho^- l^- - \frac{\rho^- l^{-2} + \rho^+ l^{+2}}{2d}\right] \xrightarrow{T\uparrow} -\left[\rho_{eq}^- l_{eq}^- - \frac{\rho_{eq}^- l^{-2} + \rho_{eq}^+ l_{eq}^{+2}}{2d}\right]$$

- Trap type distinguish comparing with TSC**:
  - (e^-) emission:

$$\left|E_{space\ charge}\right| : \begin{cases} \uparrow, & \rho > 0 \\ \downarrow, & \rho < 0 \end{cases} \Rightarrow \quad j_{PK} \ : \quad T_{PK} \ : \begin{cases} \downarrow, & \rho > 0 \\ \uparrow, & \rho < 0 \end{cases}$$

*Calderwood, and Scaife, PT Royal Society of London, 1970

**Pintilie, NIMA, 2000

Spares: discussion

- On model:
  - Wintle on dielectrics*: $J(t) \propto [E(d,t)^2 - E(0,t)^2]$
- On measurements:
  - Residual current value**: $J(t) \propto E_{bulk} > E_{applied}$
  - Peak dependence on priming voltage***:

$$\begin{cases} Asymmetry \quad : \quad MAX \quad at \quad V_{dep}/2 \\ Q_t \propto \sqrt{V} \\ E_{anode} \propto V ; E_{cathode} \propto \sqrt{V} \end{cases}$$

$$\Rightarrow I_{redistribution} \propto \begin{cases} Q \propto \sqrt{V} \\ Asymmetry \end{cases} \propto \begin{cases} \sqrt{V}, & V < V_{dep} \\ \to 0, & V > V_{dep} \end{cases} \quad ; \quad I_{injection}^{(anode)} \propto E_{anode} \propto V \quad ; \quad I_{injection}^{(cathode)} \propto E_{cathode} \propto \sqrt{V}$$

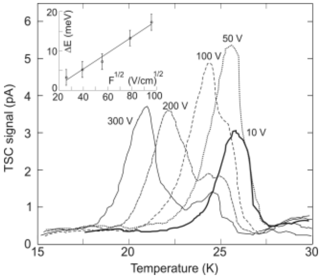
*Wintle, JAP, 1971

**Simmons and Taylor, JAP, 1972

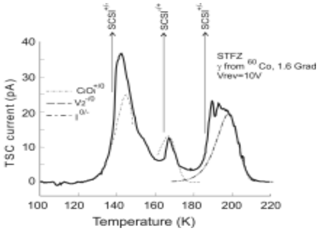
***Kostsova and Kostsov, JPD, 2008

Spares: useful references

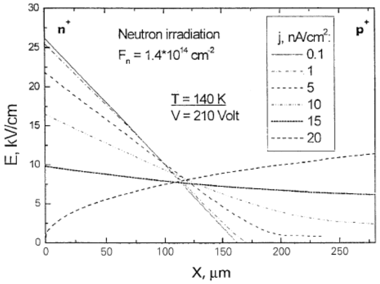
- Pinitilie [Ekstein 2009] group show: Vbias=100V=> Ipk(SD30K)> respect to Vbias 400V on EPIDO
- Bruzzi [Bruzzi 2006]: peak decrease with bias in n-on-p
- Scaringella [Scaringella 2007]: peak increase with bias in p-on-n
- Scaringella [Scaringella 2006]: peak constant with bias in p-on-n



- Scaringella [Scaringella Ph.D. Thesis, Chapt. 5, 2005]: peak decrease with bias in STFZ, DOFZ, p-on-n, irradiated by gamma-rays:



- Eremin [Eremin 2002], from Verbitskaya: increase filling current, more homogeneous electric field distribution and thus filling



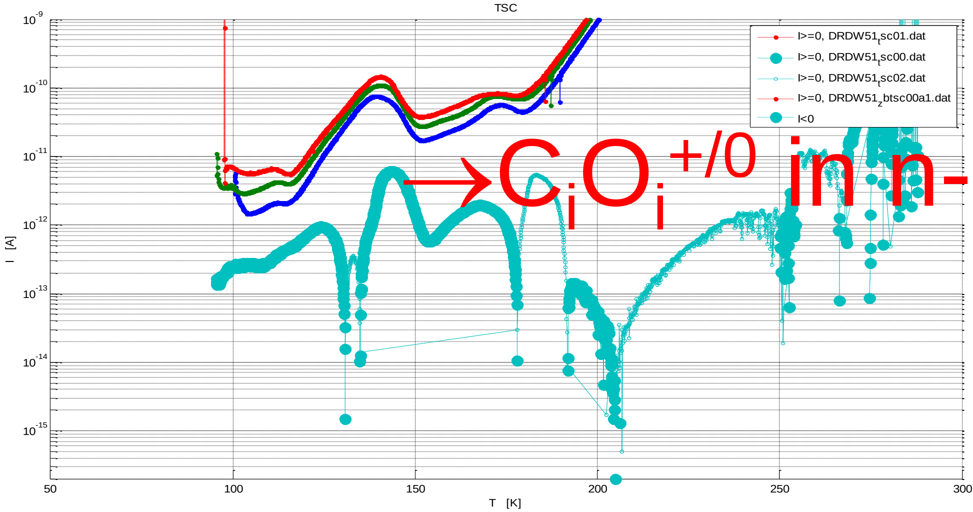
*
**
***
****
*****
******

Experimental results: TSC and ZBTSC

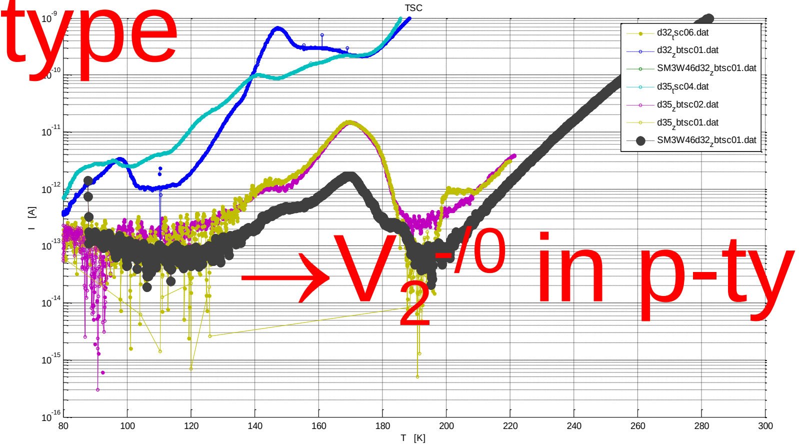
Same for the CiOi and V2 peaks at higher temperature:

  - negative SCR (p-type) ⇒ field reduction ⇒ peak delayed
  - Positive SCR (n-type) ⇒ field increase ⇒ peak anticipated

- Hole emission:
  - negative SCR (p-type) ⇒ field reduction ⇒ peak delayed
  - Positive SCR (n-type) ⇒ field increase ⇒ peak anticipated



$\rightarrow C_iO_i^{+/0}$ in n-type



$\rightarrow V_2^{-/0}$ in p-type

R. Mori, M. Scaringella, M. Bruzzi, Optimization of the priming procedure for thermally stimulated currents with heavily irradiated silicon detectors
WODEAN meeting, 13-14 May 2010, Bucharest – RD50 workshop, 31 May-01 June 2010, Barcelona