TSC studies on n- and p-type MCZ Si pad detectors irradiated with neutrons up to 10^{16} n/cm^2

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Samples and irradiation

-Material: n-type magnetic Czochralski silicon 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^{14}-10^{15} n_{eq}/cm^2 1MeV equivalent neutron
-Annealing: 1 year room temperature

-Material: p-type magnetic Czochralski silicon 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 1MeV equivalent neutron
-Annealing: few days room temperature (+ 80min 80°C)

Measurement Techniques

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.**

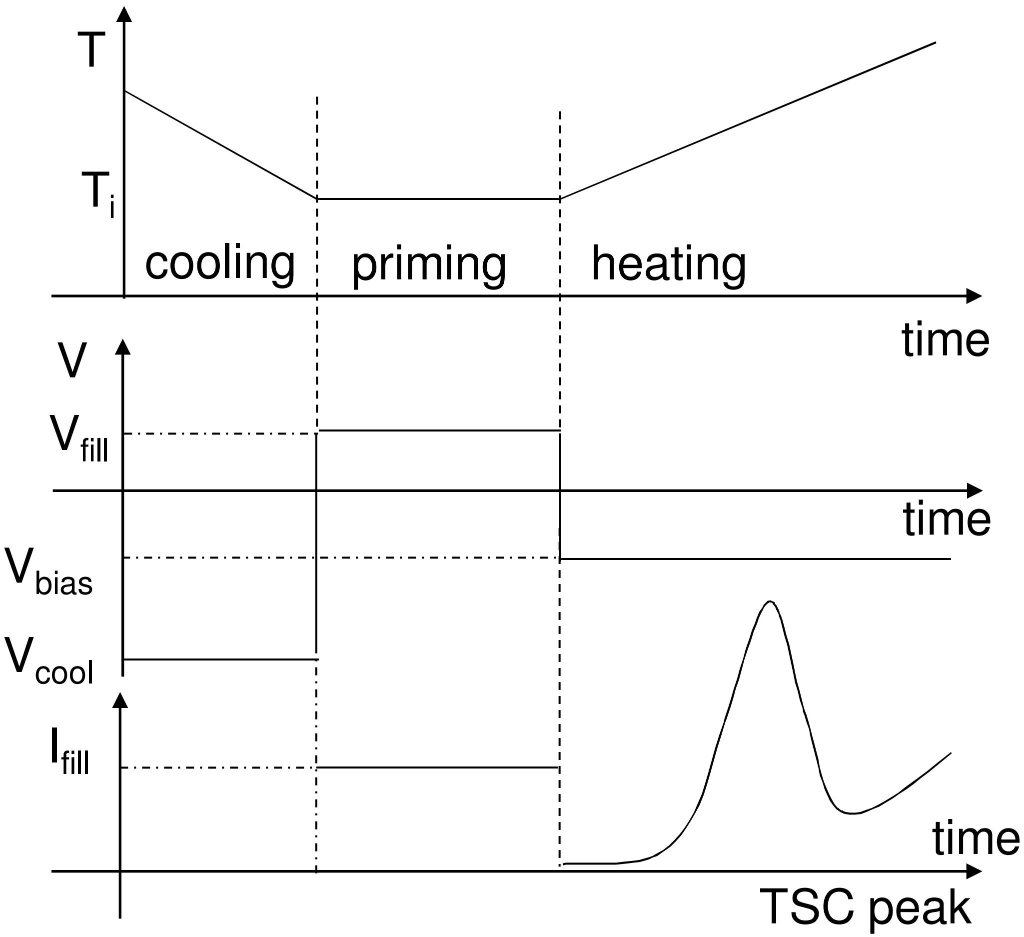
2. **Zero Bias Thermally Stimulated Currents measured at high fluence in the high temperature range (100-200K), to avoid background current subtraction, and increase resolution in deep levels analysis. Used in all T range to study the residual electric field due to charged defects.**

Aims:

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

TSC and ZB-TSC (→ same as TSC but $V_{bias} = 0$)

The method: procedure and symbols



Common procedures:

Current priming

-Cooling with applied reverse V_{cool} or null bias

-Forward voltage applied V_{fill} at T_i

-TSC with V_{bias} or null bias (ZB-TSC)

Optical priming

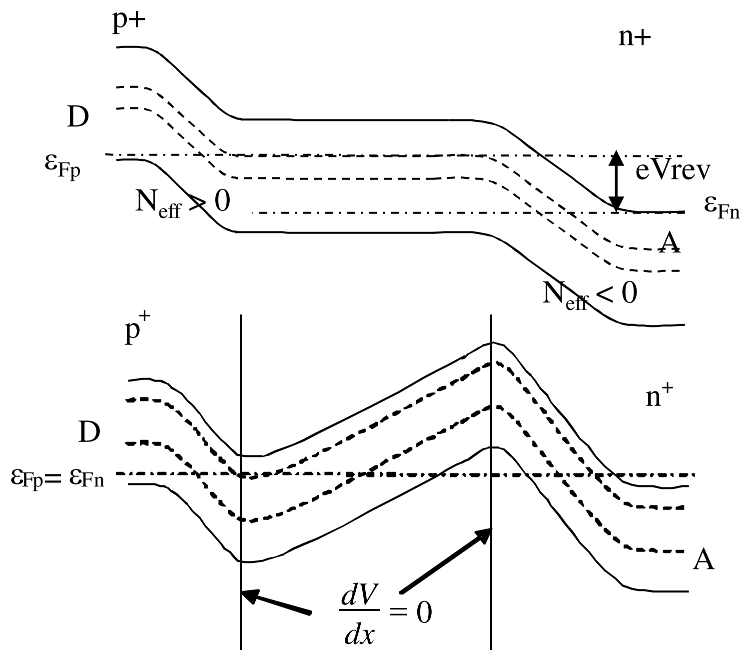
-illumination with optical source and V_{fill} at T_i

-TSC with Vbias or null bias (ZB-TSC)

ZBTSC: More on the Experimental procedure

1. **Priming** provide an injection of carriers which are trapped at energy levels, according to an asymmetrical distribution induced by external polarization (V_{bias}).

2. At low temperature **electrodes are short-circuited**: the carriers at electrodes and in bulk redistribute themselves in order to establish zero voltage and zero field boundary conditions. Charge frozen at low temperature → non-uniform electric field and non-monotonous potential distribution with minima and maxima corresponding to zero electric-field planes settle.



Zero-field planes

Example: double junction in irradiated p-on-n Si (voltages measured at n^+ respect to p^+). Charge distribution not shown.

3. ZBTSC scan (heating): system brought back to the fundamental equilibrium state. Charge redistribute into the volume and charge injection occurs at the electrodes, giving rise to current detected in the external circuit. Charge relaxation during heating scan can be discussed in terms of motion of the zero electric-field planes along the sample thickness.

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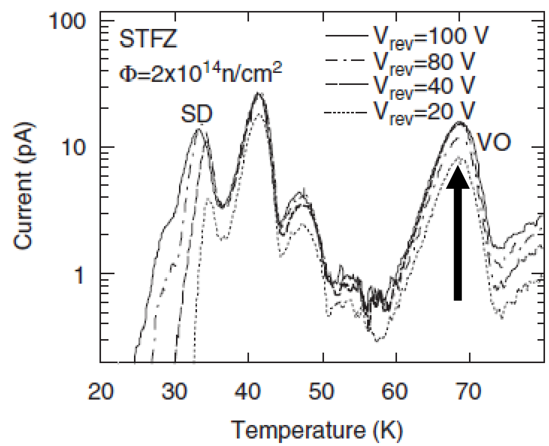
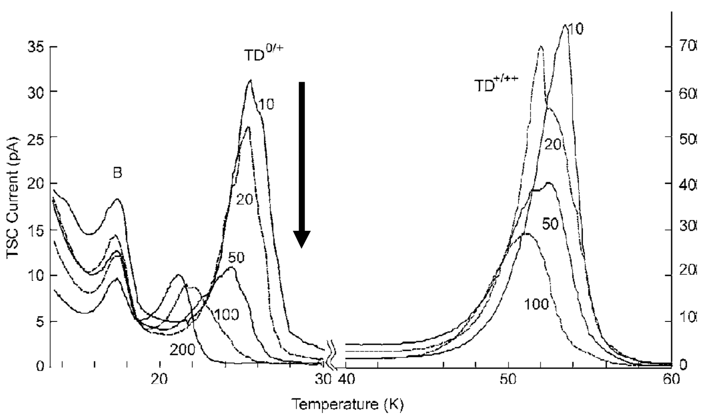
Problems ancountered in TSC after priming

Normally the peak height increases with increasing bias voltage

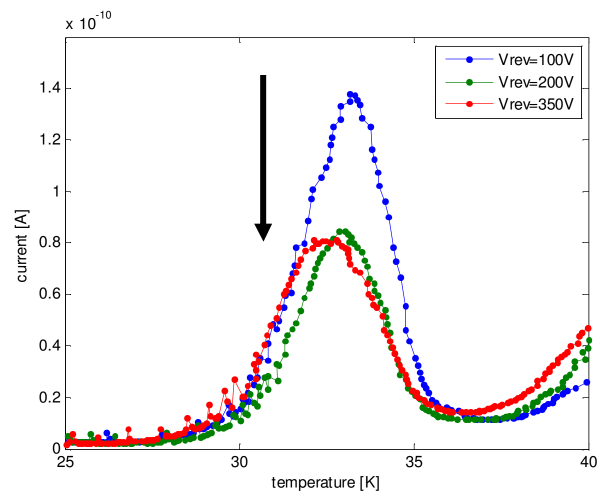


Scaringella et al. *Nucl. Instrum Meth A* **570** (2007) 322–329

In some case it decreases



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



TSC peak saturation does not correspond to full volume emission

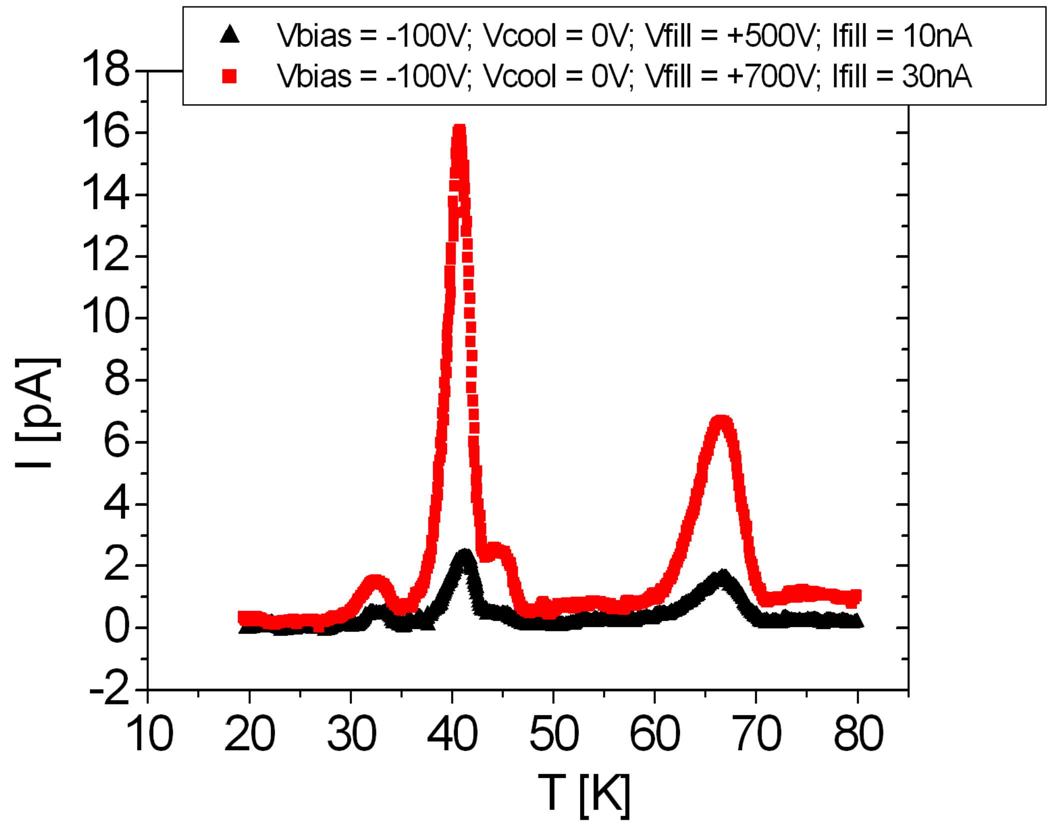
Experimental results obtained with different TSC and ZB-TSC parameters I_{fill}, V_{cool}, V_{bias}

A - Forward current priming

n-on-p $\Phi=10^{15}$ n_{eq}/cm^2 annealed 80 min @80°C

With same V_{cool} and V_{bias} TSC peaks height always increases with the filling current.

Increasing I_{fill} more charges are trapped at defects, so TSC and ZB-TSC emission is higher



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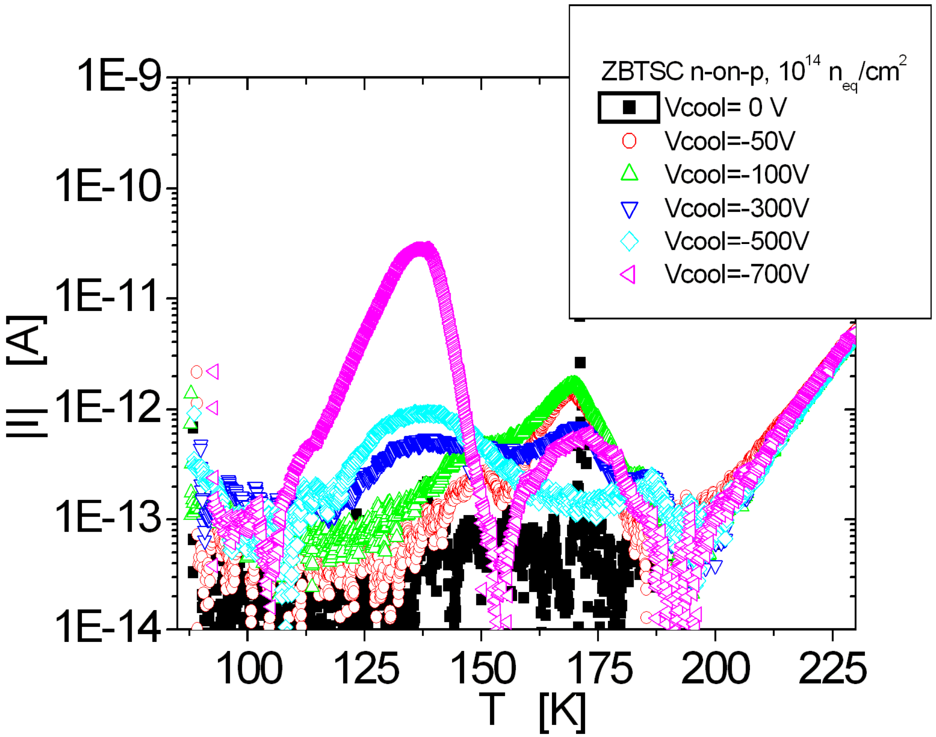
ZB-TSC peaks height increases with increasing V_{cool} (zero V_{bias} and I_{fill})



Cooling under reverse bias build-up a residual field (opposite to the cooling voltage), due to the charges frozen in the radiation induced traps. This field increases with V_{cool} and it drives the first emission of charge during the ZB-TSC.

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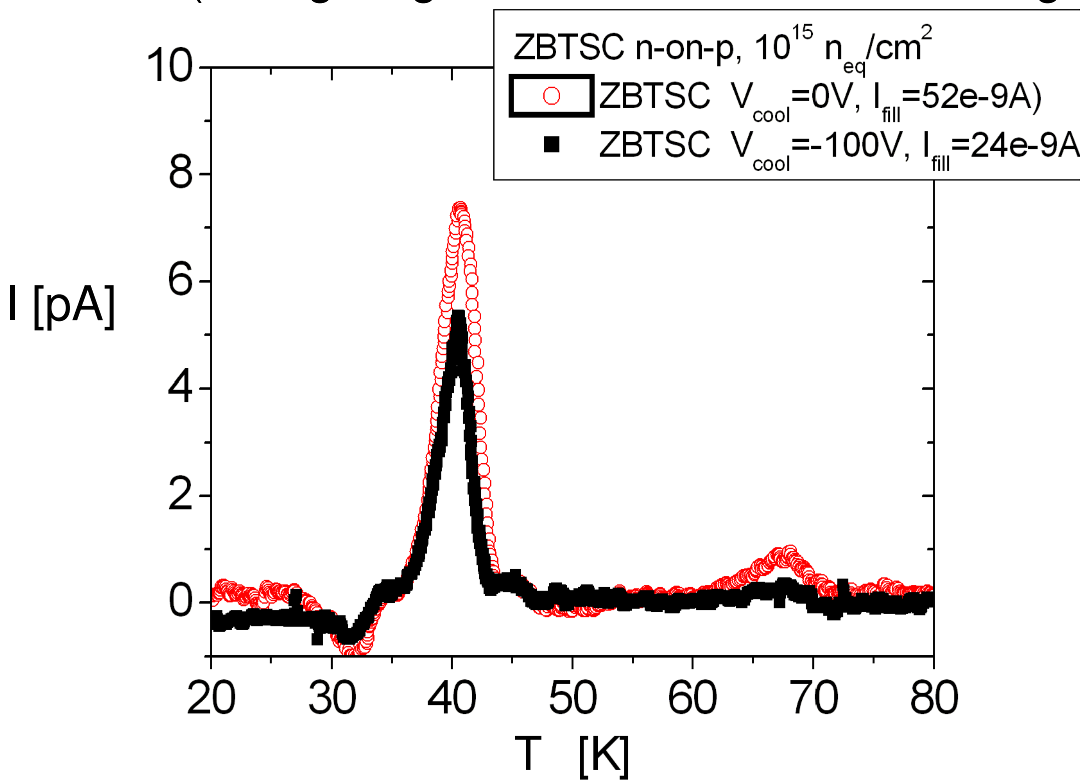
When applying I_{fill}

1) I_{fill} decrease when $|V_{cool}|$ increase
2) ZB-TSC peak height mainly determined by I_{fill}
   (altough higher residual field because higher $|V_{cool}|$)



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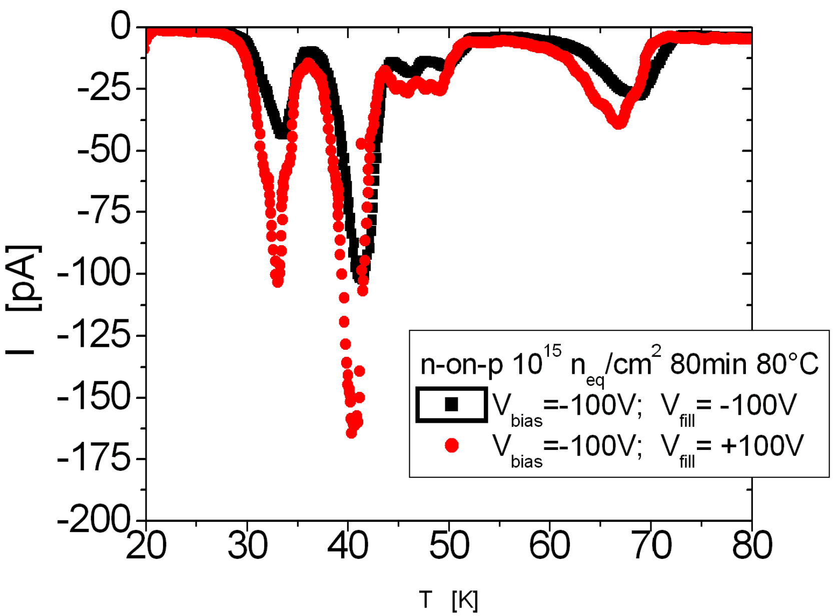
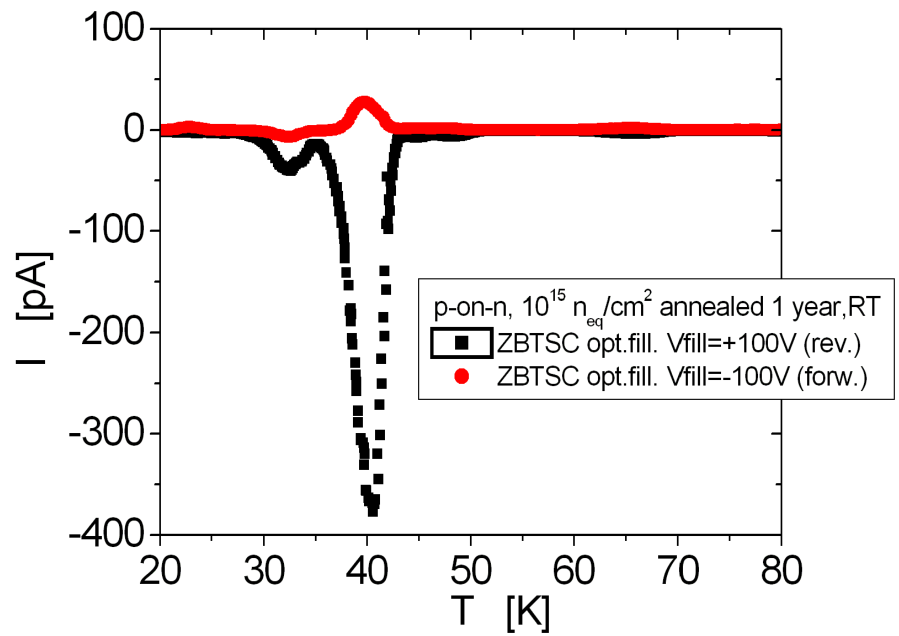
B - Optical priming (λ= 850nm)

Dependence of TSC peak heights on bias voltage applied during illumination (V_{fill})





Reverse voltage gives lower TSC and higher ZB-TSC with respect to forward voltage

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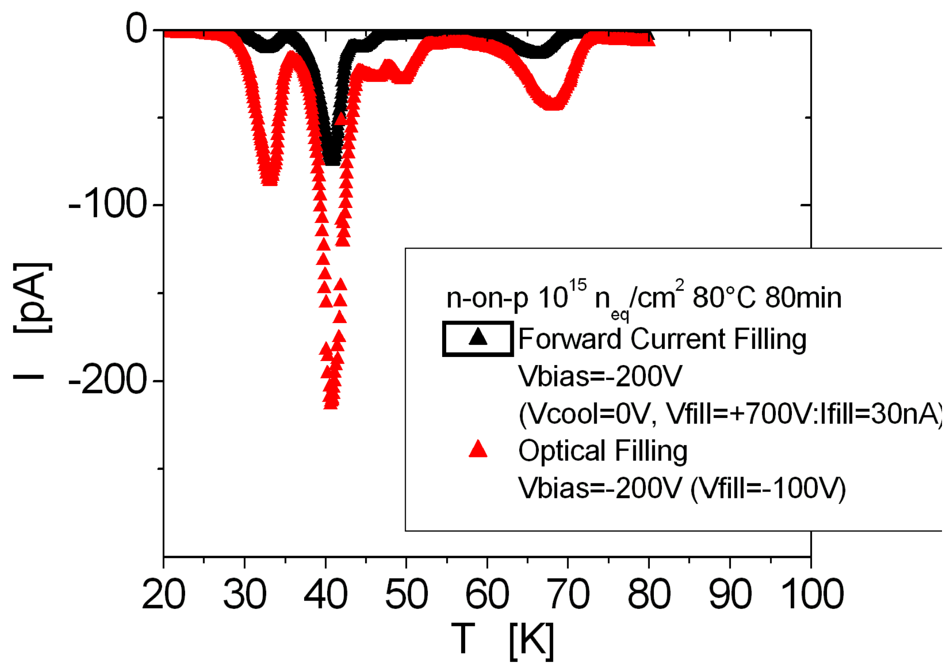
Comparison between forward current and optical priming



In heavily irradiated samples optical priming can be much more efficient than forward current priming

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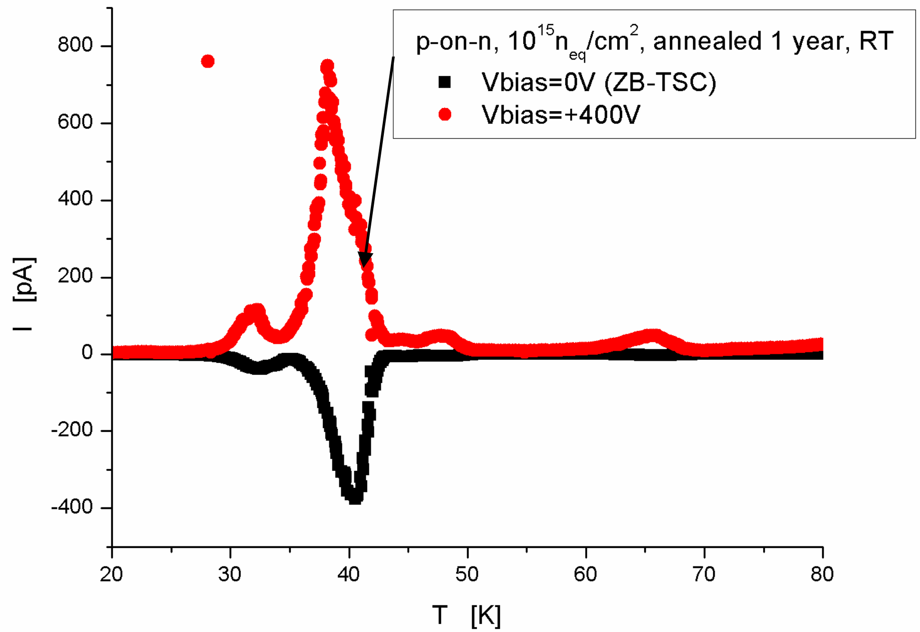
Effects of the residual field in a TSC

1)

Optical filling with reverse bias (Vfill =+100V): evidence of residual field setup. TSC discontinuity reflects the residual field in the bulk. It's the same residual field that drives the ZB-TSC!



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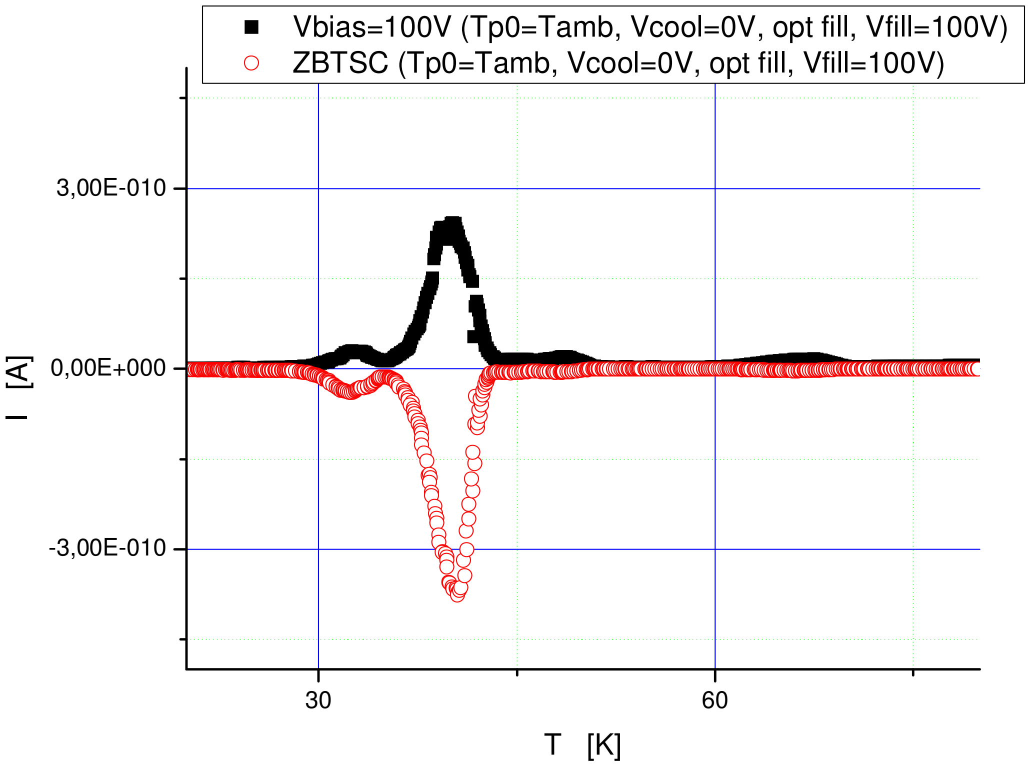
2)



The intensity of the current from the residual electric field can be higher than the one observed in a standard TSC

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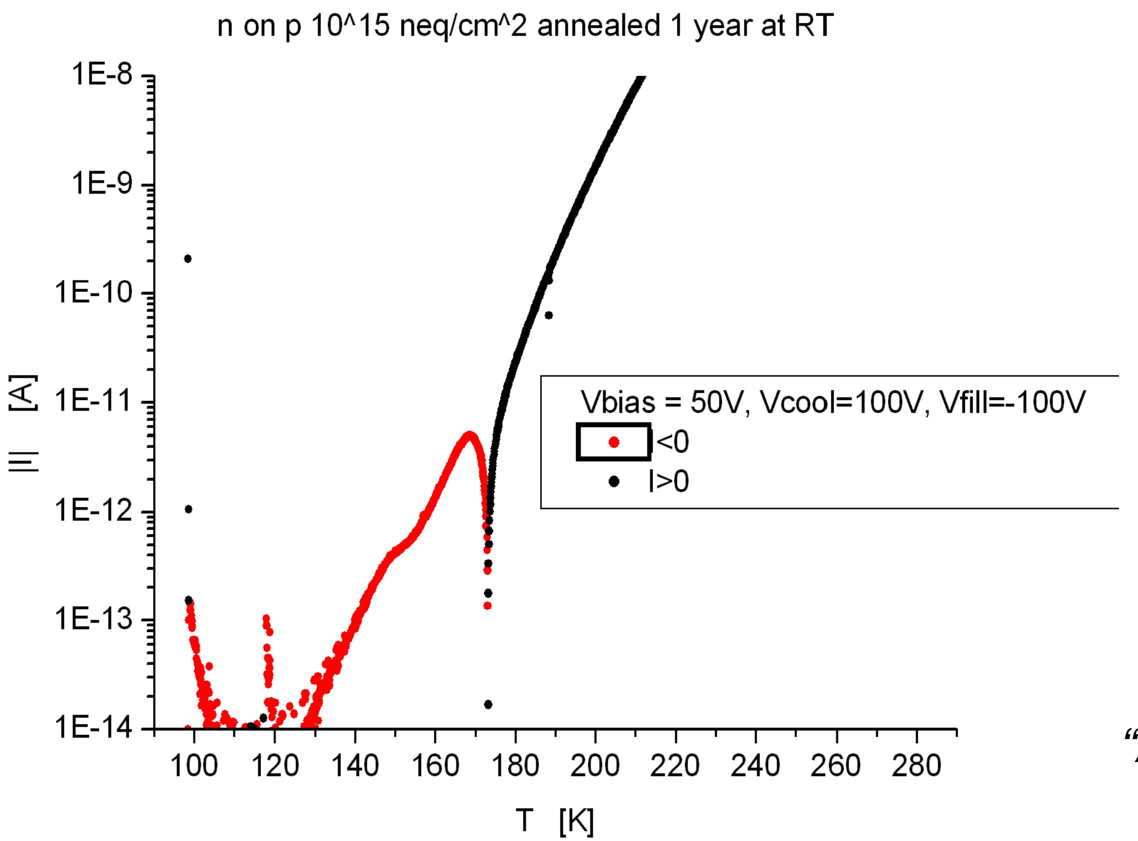
3) Forward current priming, TSC with Vbias < Vcool. Residual field can be so high to give evidence of an opposite current in a TSC!



"Against the tide"

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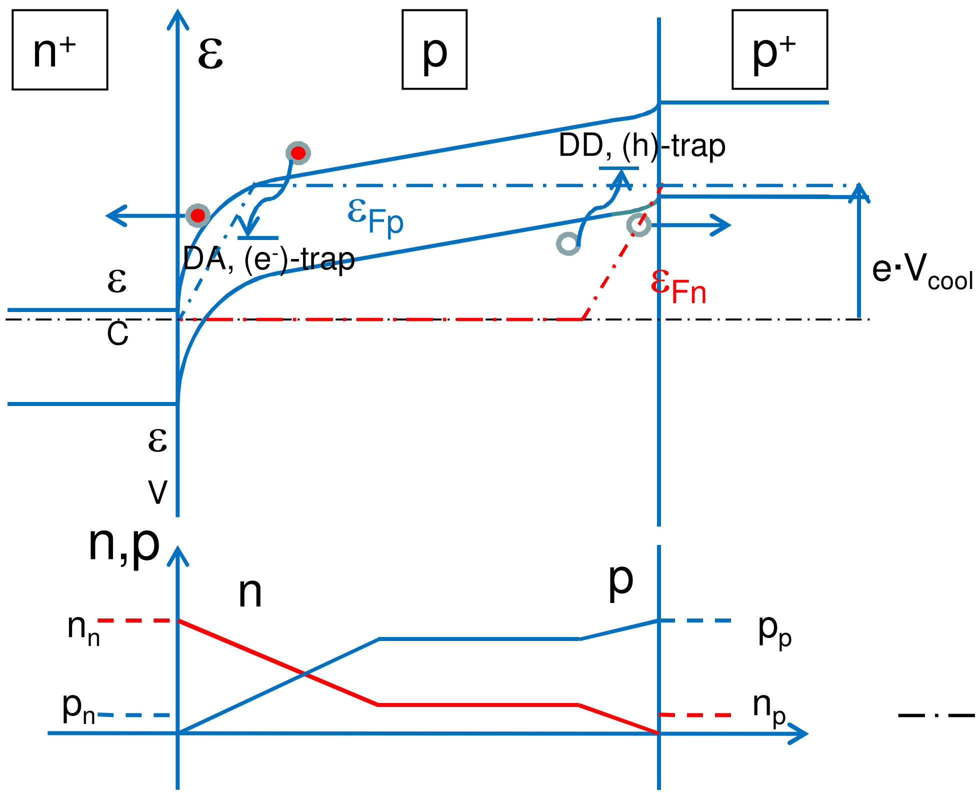
Discussion: explain results with a band diagram model

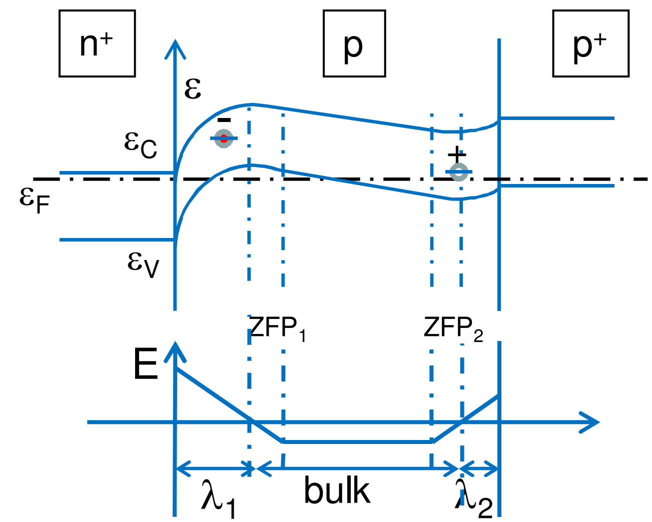
A -Forward current priming

COOLING (reverse bias)

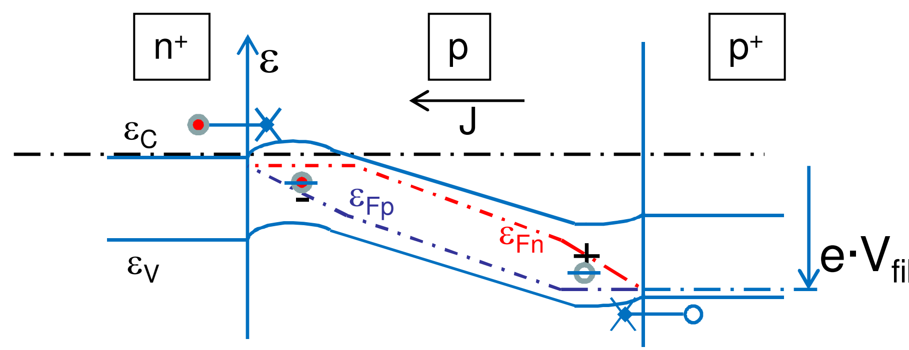


Free carriers during reverse bias

FROZEN CHARGE DISTRIBUTION (0 bias)



FORWARD FILLING



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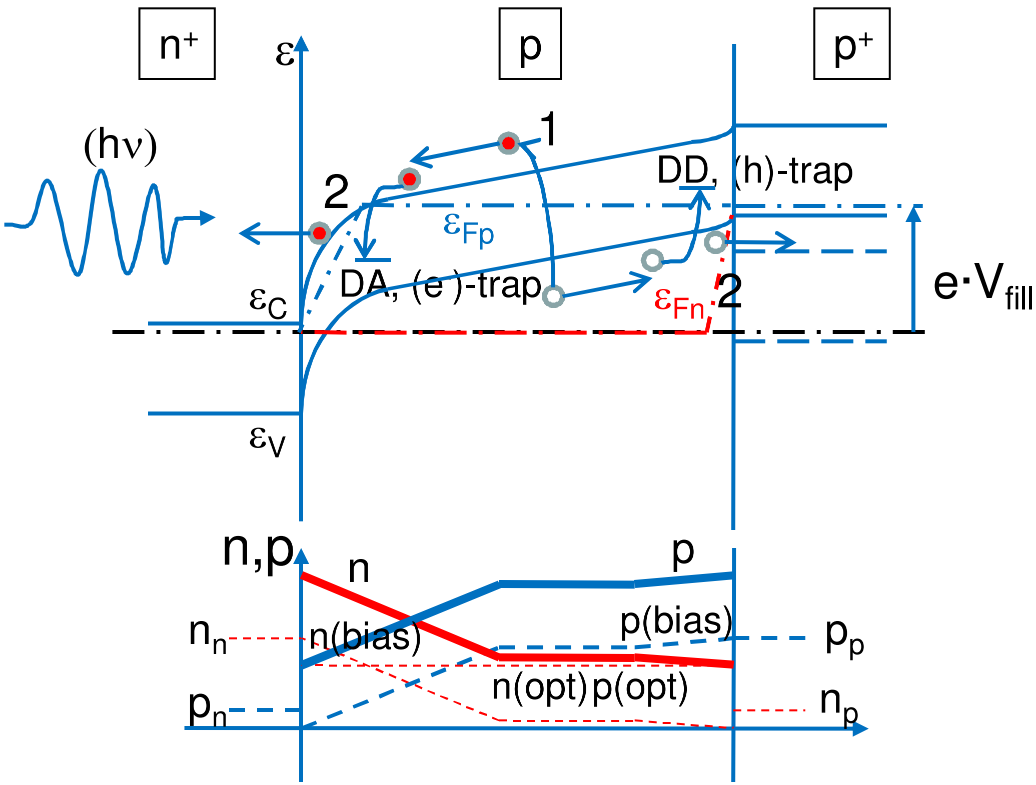
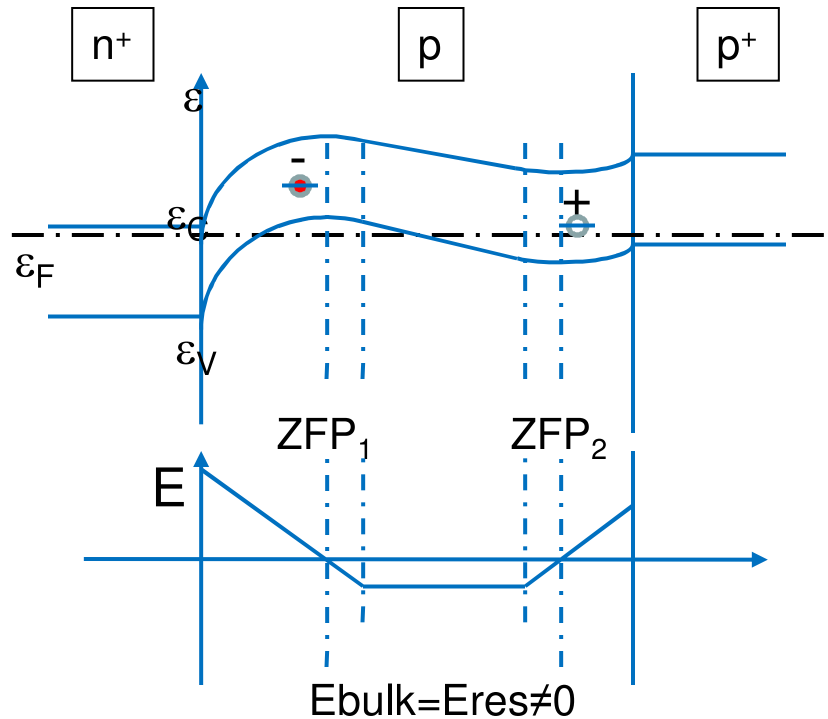
B-OPTICAL PRIMING

OPTICAL EXCITATION (reverse bias)



metastable condition afterwards



- n(opt),p(opt): ALMOST UNIFORM
- n(bias),p(bias): ASYMMETRIC

=> n,p: ASYMMETRIC

<u>- Residual field present</u>

<u>- Only a portion of the volume is filled</u>

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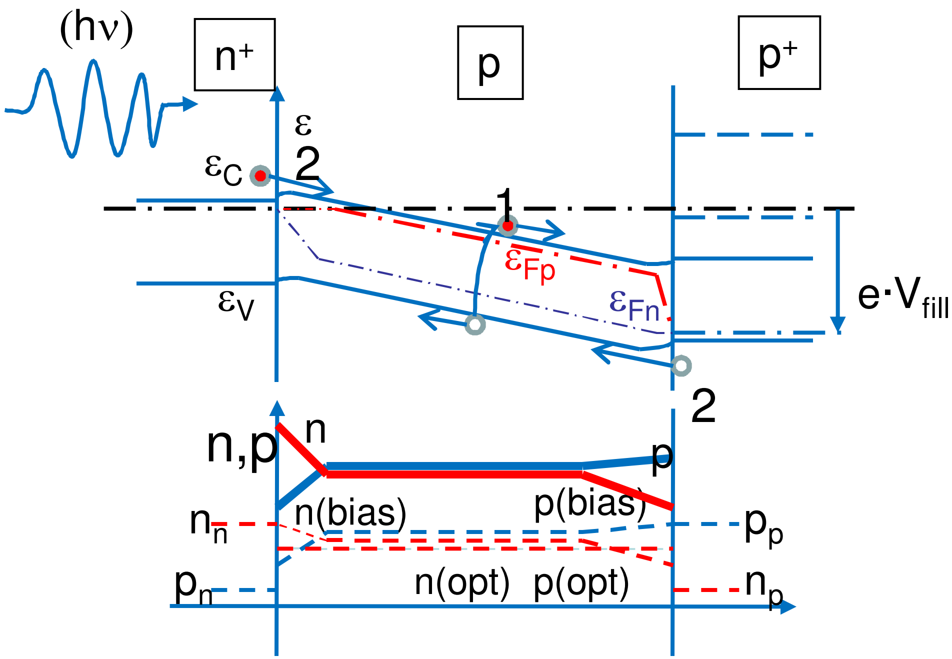
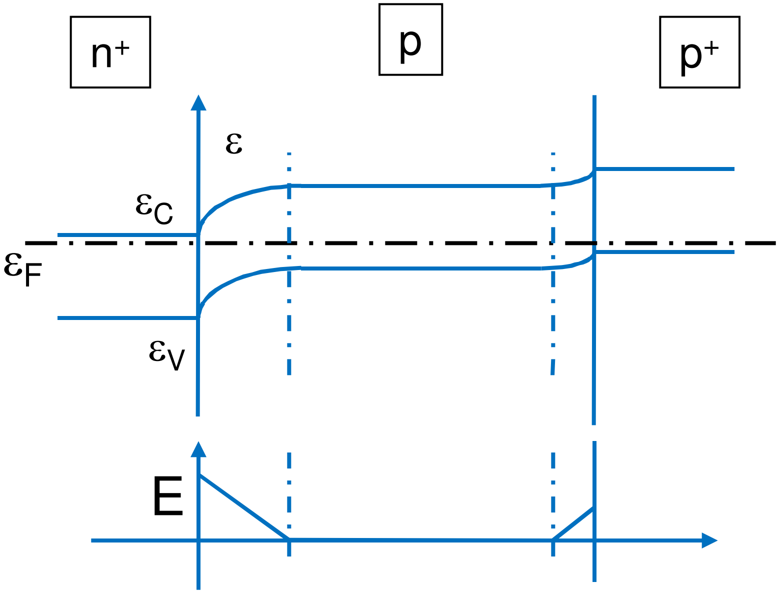
OPTICAL EXCITATION (forward bias)



metastable condition afterwards



Ebulk=Eres→0

-n(opt),p(opt), n(bias),p(bias): ALMOST UNIFORM
=> n,p: SYMMETRIC

- Residual field very low
- Almost uniform priming

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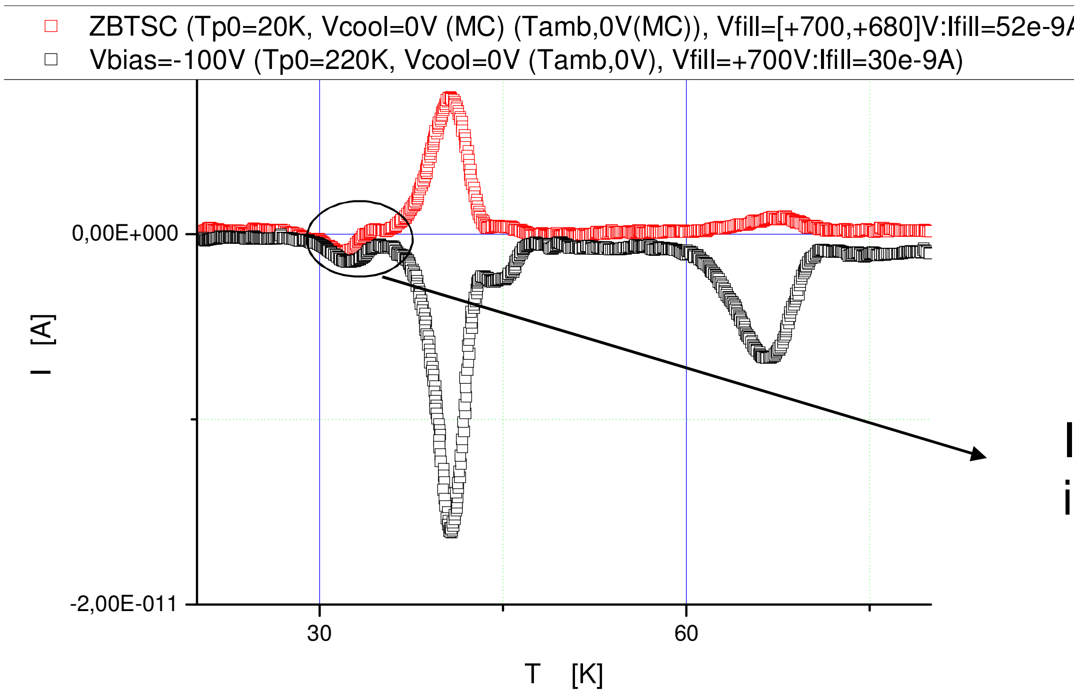
Observations about current sign in ZBTSC

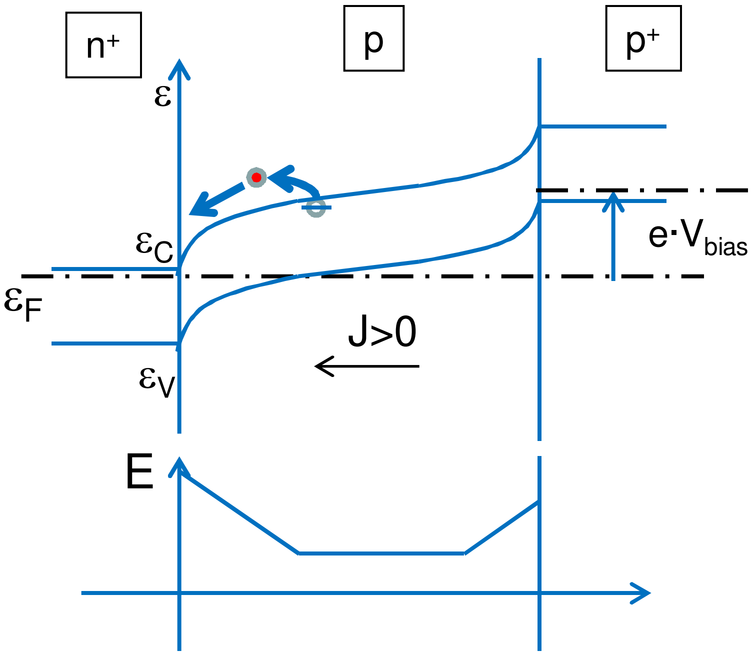
Usually the sign of the ZB-TSC is opposite to the TSC, under the same priming conditions



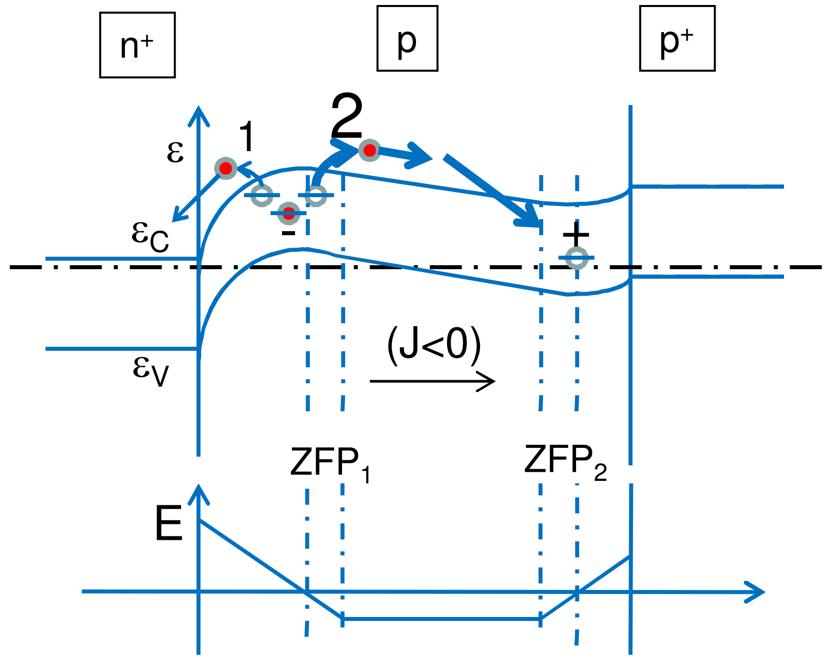
In some cases the sign is the same

EMISSION

TSC



ZBTSC



The sign of the current depends on the dominating emission mechanism

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ZERO-FIELD PLANES

$x_i(t)$ Position of the zero field plane (ZFP)

$$J(t) = -a\rho[x_i(t),t]\frac{dx_i(t)}{dt} + ai[x_i(t),t]$$

If field induced current dominates

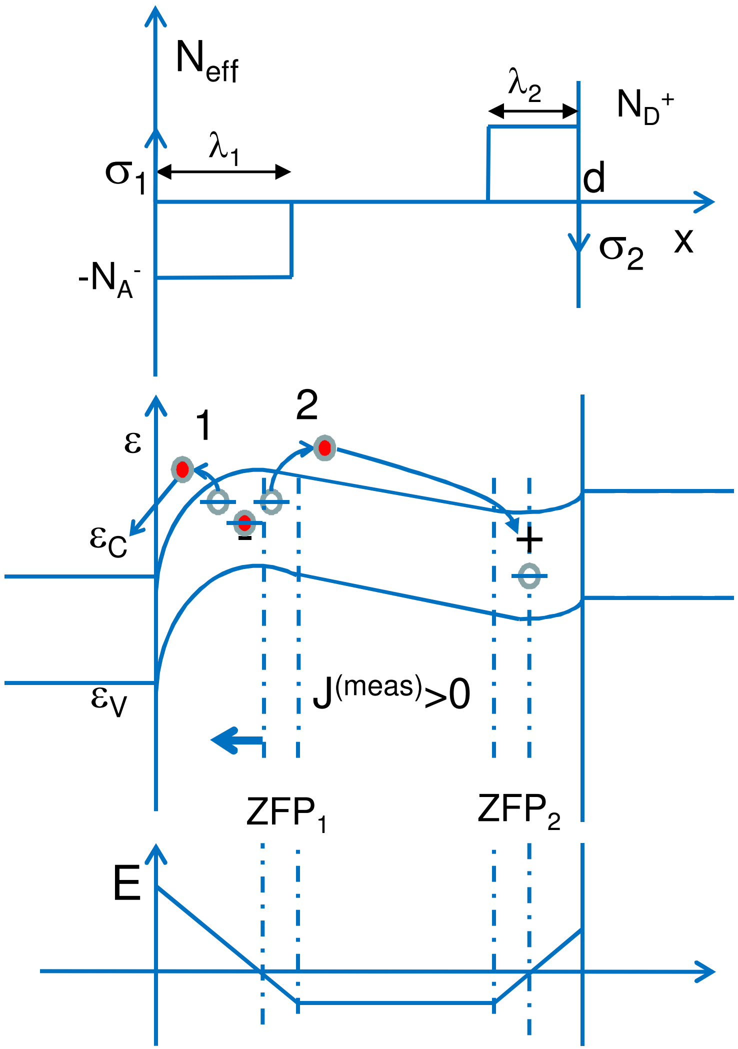
$$J(t) = -a\rho[x_i(t),t]\frac{dx_i(t)}{dt}$$

REF: Gross B. and M.M. Perlman, *J. Appl. Phys.*, Vol. 43, No. 3, March 1972

The sign of the current is determined by:

- The sign of the charge density at the ZFP
- The motion direction of the ZFP

Possible mechanisms for electron emission in p-type



$$x_{ZFP1} = \lambda_1 - \frac{1}{2d}\left(\lambda_1^{\,2} + \frac{k_2}{k_1}\lambda_2^{\,2}\right)$$

$$k_1 = q\frac{N_A^-}{\varepsilon}$$

$$k_2 = q\frac{N_D^+}{\varepsilon}$$

Case 1

$$k_1' < k_1 \quad k_2' = k_2 \qquad x_{ZFP1}' < x_{ZFP1}$$

$$J < 0$$

Case 2

$$k_1'' < k_1 \quad k_2'' < k_2$$

a $x_{ZFP1}'' < x_{ZFP1},\ J < 0$ if $N_A^-\lambda_1 < N_D^+\lambda_2$

b $x_{ZFP1}'' > x_{ZFP1},\ J > 0$ if $N_A^-\lambda_1 > N_D^+\lambda_2$

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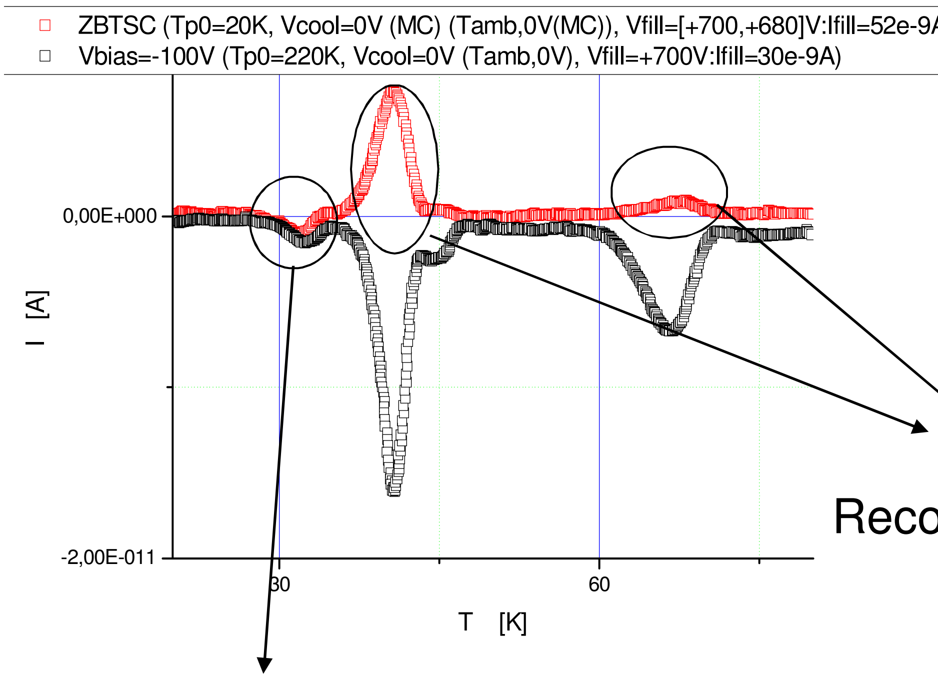

Recombination inside the bulk and $N_A\lambda_1 > N_D\lambda_2$

Recombination outside the bulk or
Recombination inside and $N_A\lambda_1 < N_D\lambda_2$

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Summary

We studied both p- and n-type MCz Si pad detectors after irradiation with reactor neutrons up to 10^{15}-$10^{16}cm^{-2}$.

-TSC and ZB-TSC were carried out to inspect radiation-induced defects.

-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 frozen charged traps in the 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.

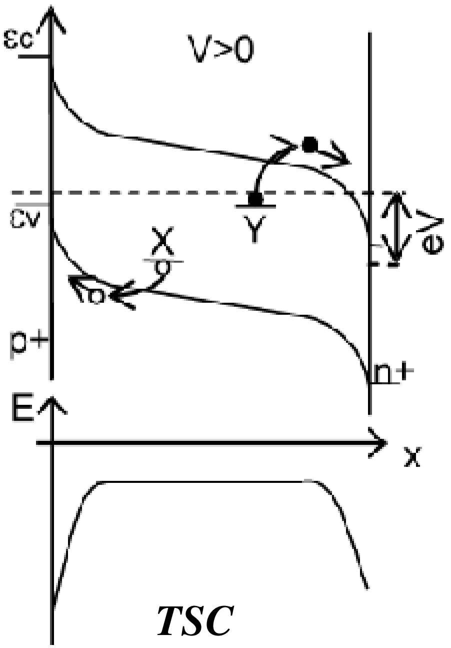
-The sign of the ZB-TSC current is discussed in terms of possible emission mechanisms. In most practical cases the residual field, revealed by the ZB-TSC, is opposed to the external bias voltage in a TSC scan.

spares

TSC vs. ZB-TSC

Example: double junction in irradiated p-on-n Si (Voltages measured at n^+ respect to p^+, currents positive when flowing from n^+ to p+) ; X hole trap Y electron trap.

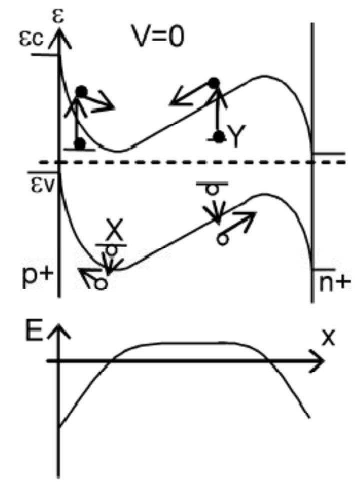
TSC



TSC

Sample reverse-biased: electric field always with same sign. As a consequence, emitted electrons and holes, regardless of the region from which they are emitted, produce a positive current.

ZB-TSC



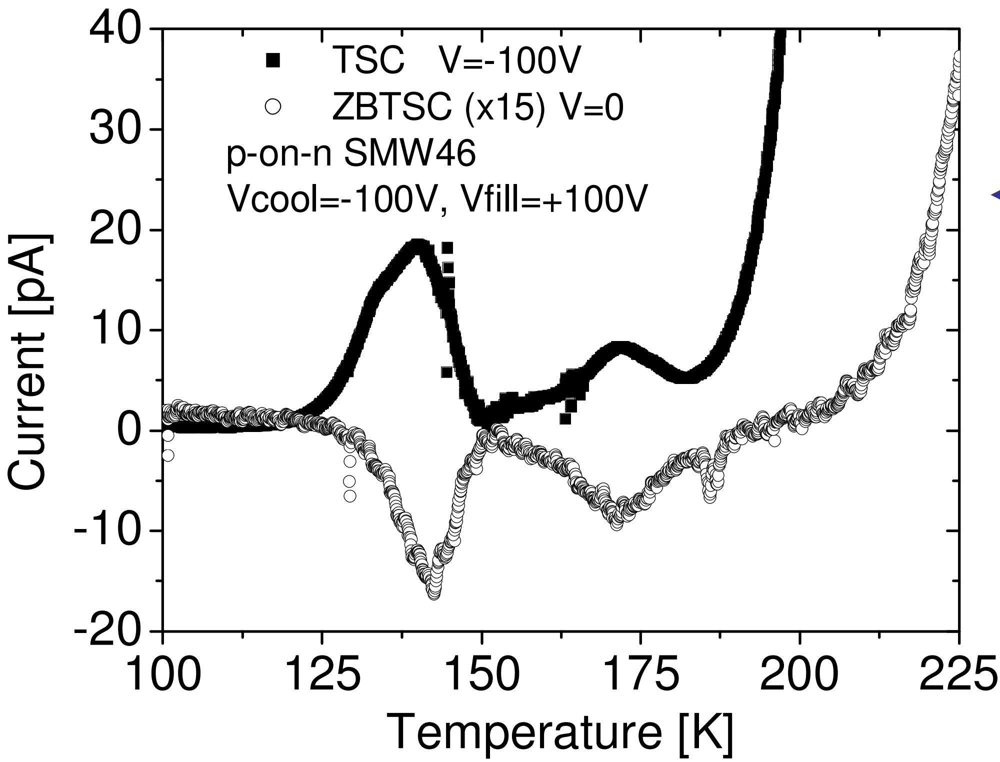
Electric field changes sign inside the bulk. Traps emitting close to p^+ or n^+ interfaces give rise to a positive current; those emitting in the bulk will produce a negative current. These two contributions, whose intensity is related to electric field rearrangement during emission, are summed up in the overall measured current. Current sign depends on which components dominate.

Electric field contributions in ZBTSC:

a) **built-in** at electrodes;
b) **intrinsic** at traps ionized in the bulk;
c) **offset** due to faible potential differences remaining at electrodes during short-circuit.
d) **Intentional** offset applied to counteract or support emission (quasi-ZBTSC).

Best conditions to observe trap emission must be determined experimentally, by evaluating these components and evaluate their effect on trap emission.

Typically, but non-necessarily, the ZBTSC will flow in the opposite direction of the current that has established the charge distribution during the priming, but the initial direction can be reversed during the thermal scan.



Here signal due to trap emission change sign when changing from TSC to ZBTSC, while current background, due to offset voltage, is always positive.

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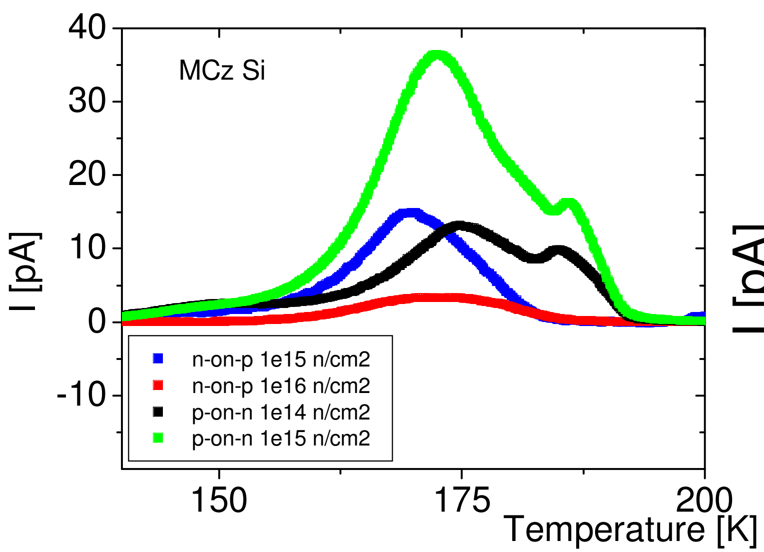
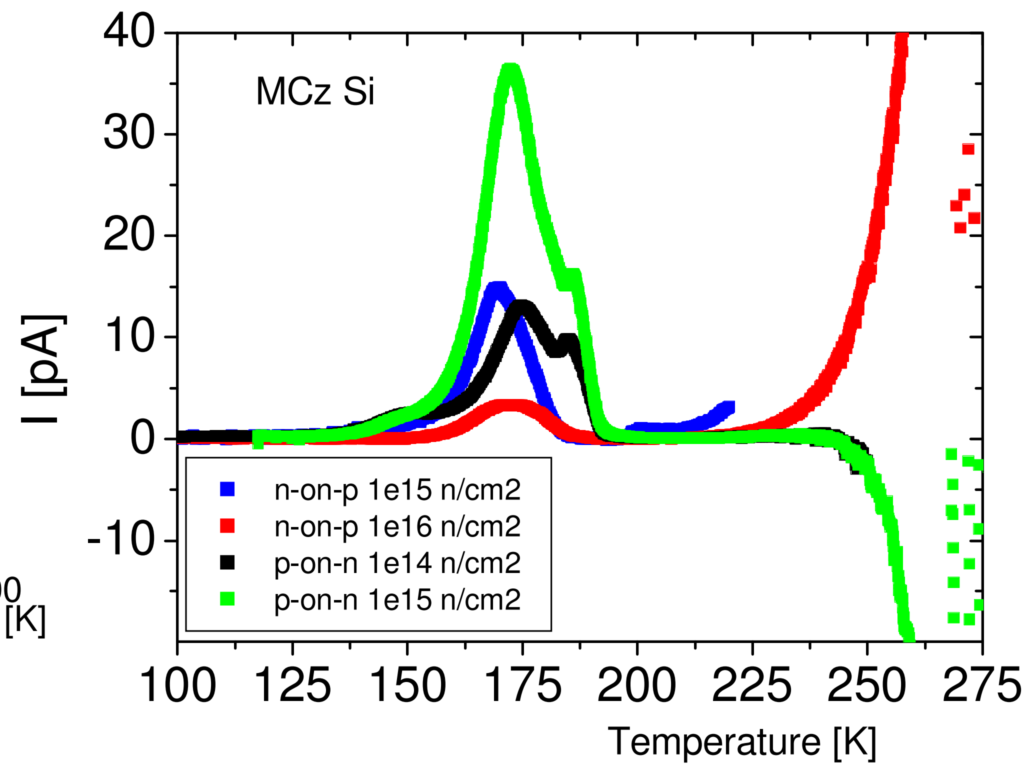
Offset effect on current





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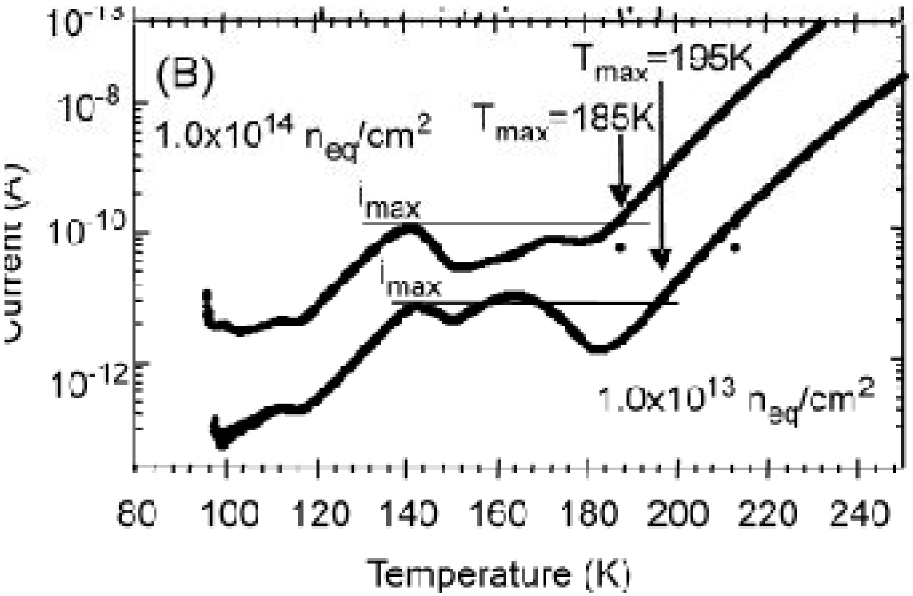
Advantages of ZB-TSC

$$\frac{i_{rev}}{volume} \propto \Phi,$$

$$i_{rev} \propto T^2 \exp(-\varepsilon_g / 2k_B T),$$



In our n-on-p samples:

10^{13}n/cm^2	**T_{max} ~ 195K**
10^{14}n/cm^2	**T_{max} ~ 185K**
10^{15}n/cm^2	**T_{max} ~ 150K**

Deep levels with activation energies close to midgap, important because are believed to be related to extended defects, give TSC signal in the range 180-220K → No reliable evidence for such defects, usually with energies >0.4eV, at high fluences.

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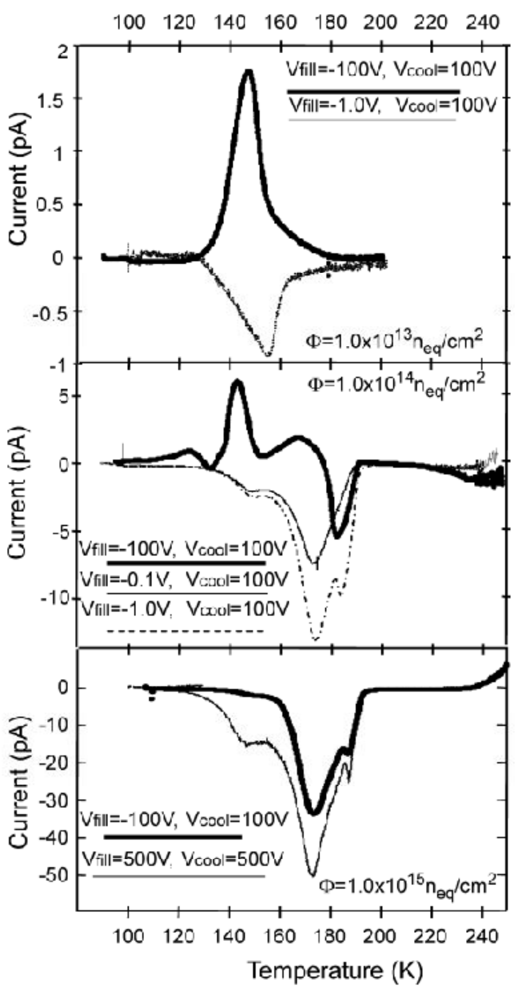
2. Inspection of intrinsic electric field due to charged defects



n-on-p irradiated Si

ZB-TSC measurements performed at different fluences. Thick lines indicate measurements carried out in the following reference conditions: $V=V_{cool}$=100V during the cooling from room temperature to T_0, V=Vfill=-100V to inject carriers at T_0.

At the lowest fluence a positive signal is observed in the range 130-160K. At the intermediate fluence the signal extends up to 190K and its zero-crossings reveal the presence of regions with opposite electric field. At the highest fluence the spectrum is completely dominated by negative components from the bulk.

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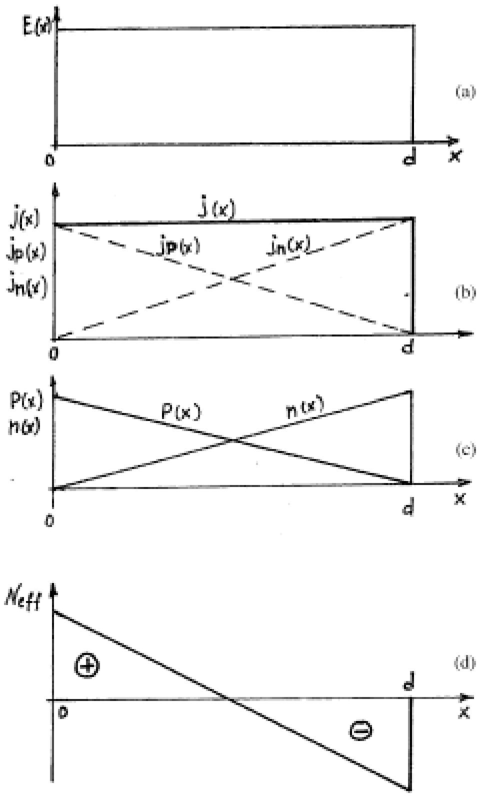
Priming according to an asymmetrical distribution

- Filling of deep levels accordingly to the free carrier distribution settled in reverse biased sample [Eremin *et al.*, NIMA A 476 (2002)]

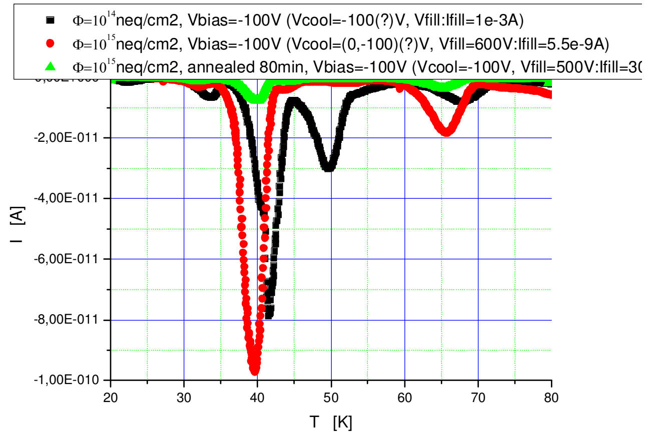


Summary of relations regarding the dependences on priming parameters

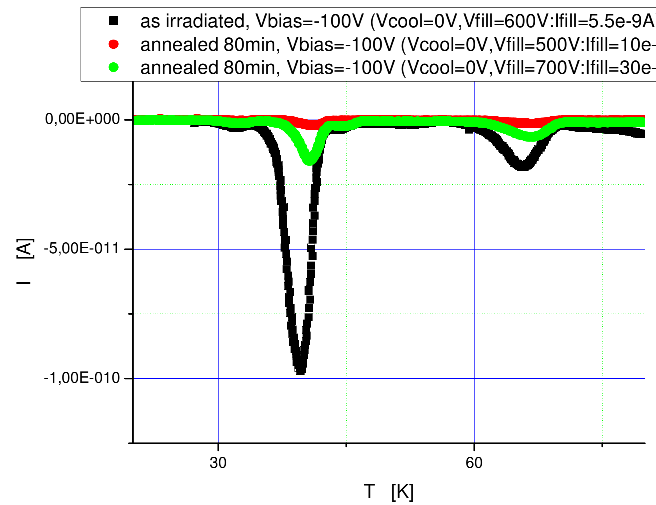
- Forward current priming:
  1. TSC amplitude increase with filling current
  2. Residual electric field increase with cooling voltage
  3. Filling current decrease with cooling voltage increase
- Optical priming:
  1. Reverse filling polarization lower effective than forward
- Optical vs. forward current:
  1. Optical priming more effective than forward current priming

Other dependences

Increasing fluence, Ifill after reverse cooling decrease

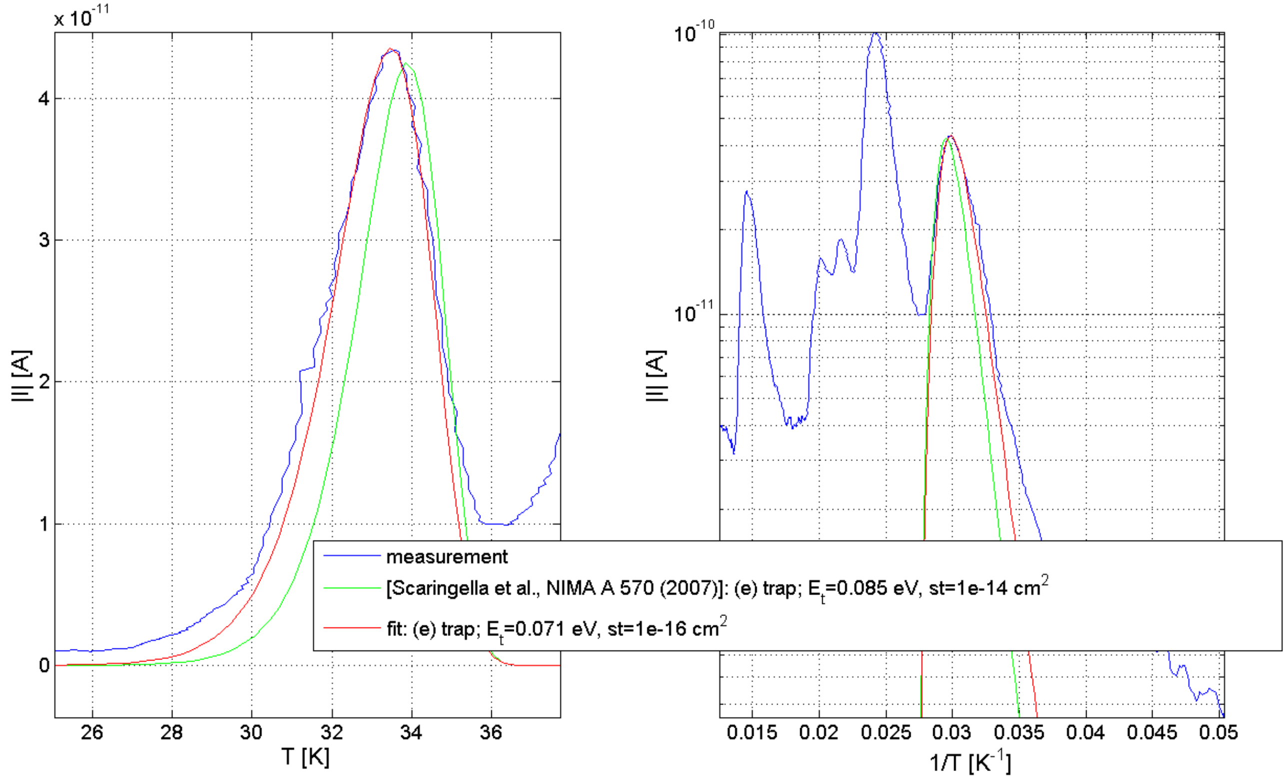


Increasing annealing, Ifill after reverse cooling increase



M. Scaringella, M. Bruzzi, D. Menichelli, R. Mori , TSC studies on n- and p-type MCz silicon pad detectors irradiated with neutrons up to 10^{16} n/cm^2
15° RD50 workshop, 16 November - 18 November 2009, Geneva

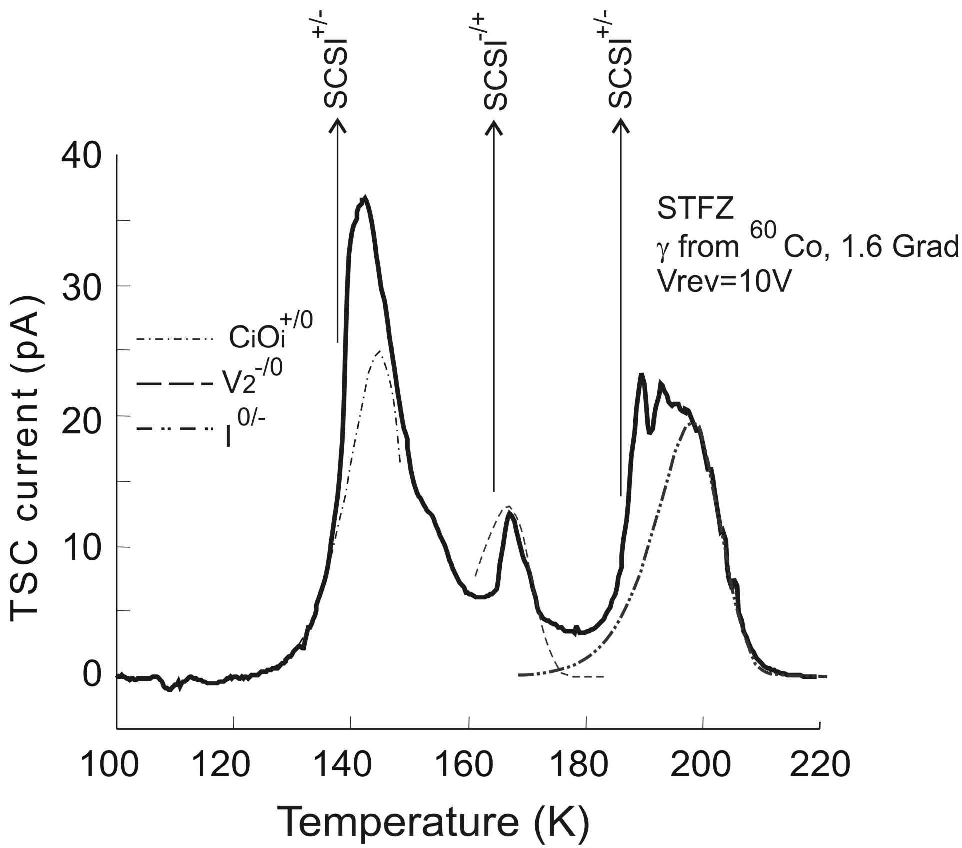
SD30K

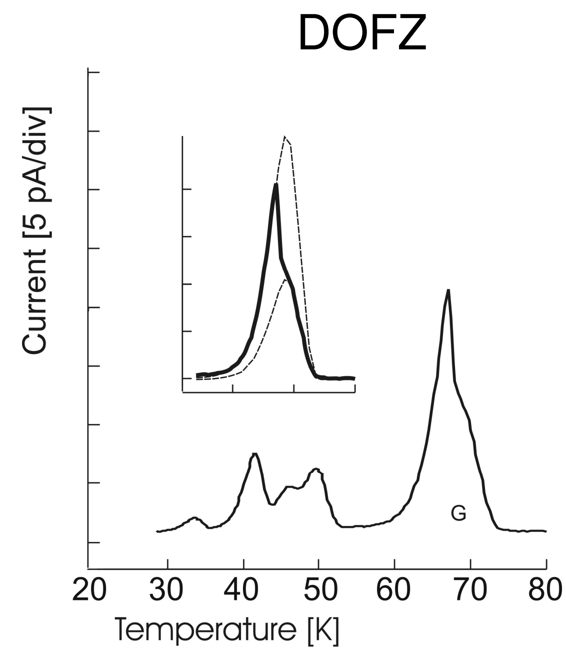


M. Scaringella, M. Bruzzi, D. Menichelli, R. Mori , TSC studies on n- and p-type MCz silicon pad detectors irradiated with neutrons up to 10^{16} n/cm^2
15° RD50 workshop, 16 November - 18 November 2009, Geneva

TSC discontinuities

- Explained as SCSIs [Menichelli *et al.*, APA (2006)]





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