Development and application of analysis software for a current based defect characterization technique (TSC) in irradiated silicon sensors

EP-DT
Detector Technologies

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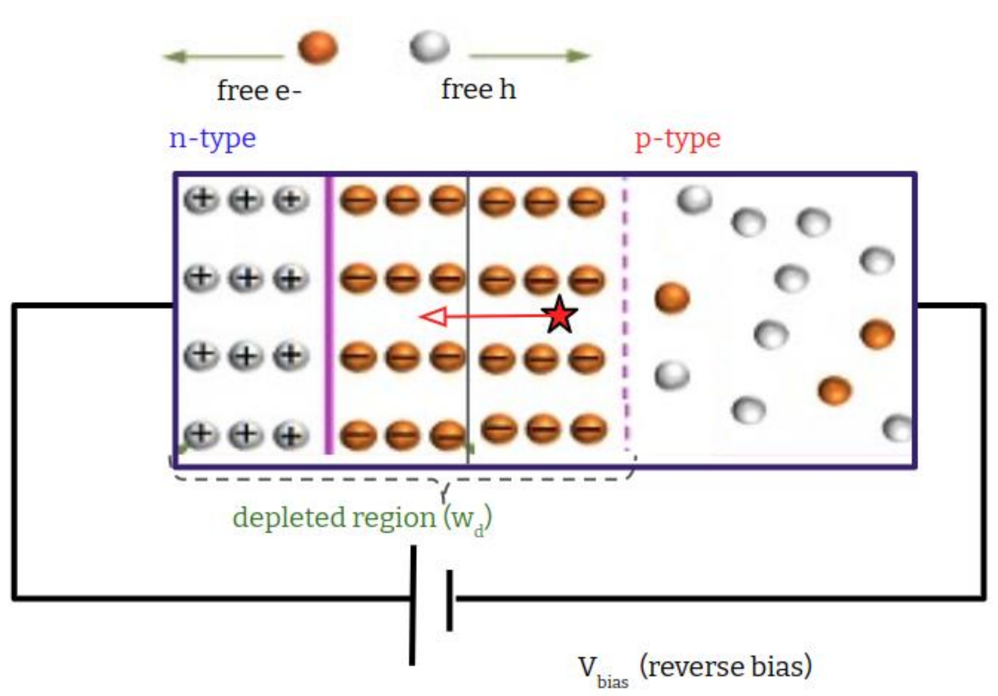
ABSTRACT

With the **T**hermally **S**timulated **C**urrent technique (**TSC**) one can classify defects in irradiated silicon-based detectors by the characteristic current peak they emit while releasing charge carriers. Simulations that reproduce the charge carrier generation and trapping within a device enable us to further characterize the trap behavior under various conditions e.g., differing voltage bias and trap filling temperature. Additionally, the use of software to analyze the TSC spectra facilitates the characterization and classification of observed defects.
The focus of the project lies on developing the here presented Python-based software by additional features for TSC scan simulation and fitting and also by debugging the existing simulation approach.

INTRODUCTION

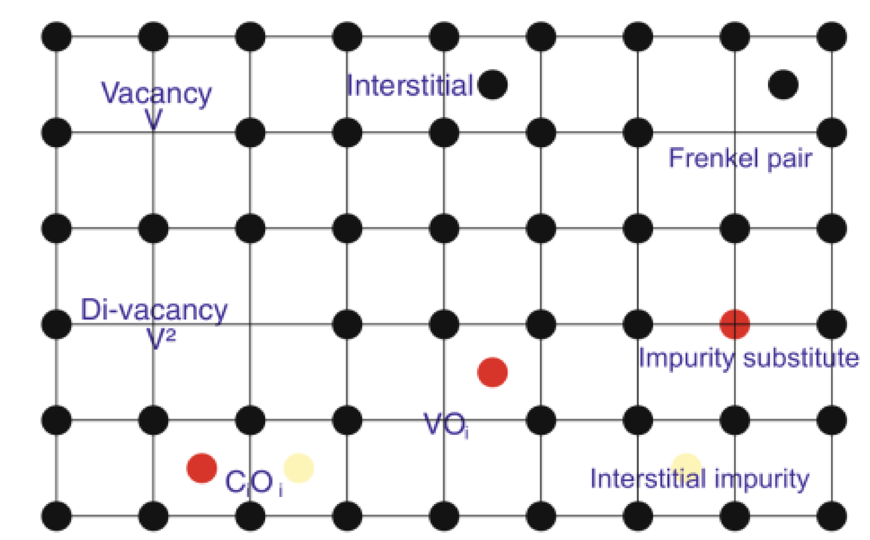
Silicon-based sensors operated in the high radiation environment of the CERN-LHC undergo a degradation in performance that is determined by defects formed during particle-interaction with the Si-crystal. In future LHC upgrades higher radiation fields pose a severe challenge to operation. A currently undergoing study of this degradation is targeting the 'acceptor removal effect' (ARE), which describes an observed deactivation of active boron in irradiated p-type Si-devices. The characterization of radiation induced defects in prototype sensors using the thermally simulated current technique (TSC) is a key step to get a deep inside and a profound understanding of such detector degradation mechanism like the ARE and allows in the next step to counteract them.

DETECTORS & DEFECTS



A simple silicon detector can be seen as two differently dopped silicon layers brought into contact, forming a p-n-junction. The recombination process of holes and electrons creates a depletion zone which prevents charge flow in thermal equilibrium by exerting a potential on the charge carrier. With a reversed bias applied the width of the depletion zone ***W*** can be modulated.

Due to the expose to radiation, defects are formed in the crystalline structure of the silicon detector. The first defects are formed by vacancies and interstitials (Frenkel pair) which can than further interact with impurities or dopants to form defects like, **CiOi**, **BiOi** and **VO**.

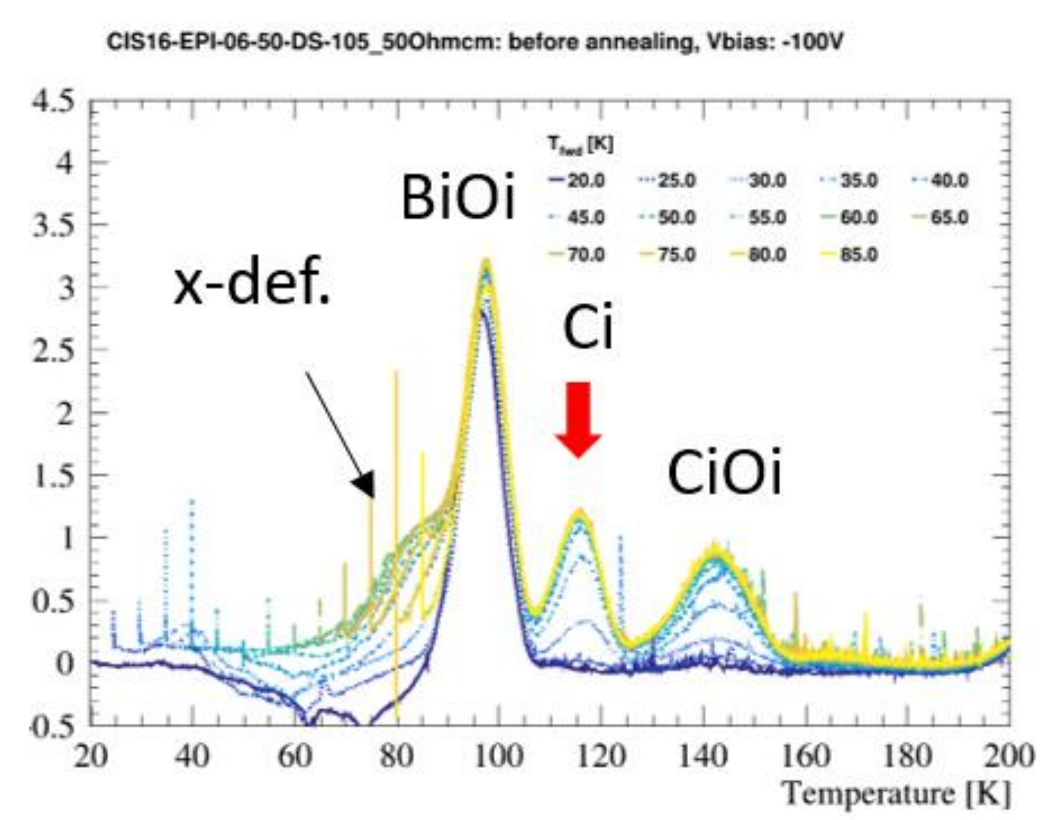


Simplified illustration of typical radiation-induced defects in a silicon crystal lattice. F. Hartmann. Evolution of silicon sensor technology in particle physics. Springer, Berlin Heidelberg, 2009.

TSC

The **T**hermally **S**timulated **C**urrent technique (**TSC**) is a tool to study these defects in irradiated silicon detectors. A common TSC measurement is performed as follows:

- **Cooling:** The **D**evice **U**nder **T**est (**DUT**) is cooled down to a low temperature (typically 20 K) while applying a reversed bias to the DUT. This way the device is depleted of free charge carries.
- **Filling:** A forward bias is applied to the DUT to fill the defect state at filling temperature with charge carries.
- **Recording:** The DUT is heated with a constant heating rate while being under reversed bias. With increasing temperature, the trapped charges get released resulting in a peak in current. The temperature at which the carries are released is specific for each kind of trap.



The total current measured during a TSC scan is given by

$$I_{TSC} = q_0 A \int_0^{W(t)} \sum_{all\ defects} \frac{e_n(t)n_t(t) + e_p(t)p_t(t)}{2} dx,$$

with the time dependent carrier concentrations ***n*** and ***p*** as well as the emission rates ***e***.
For the analysis for the TSC spectra we assume a fully depleted detector. Therefore, the width of the depletion zone is equal to the detector length. Furthermore, we assume only one charge carrier type being trapped This brings us to the simplified equation for the total current:

$$I_{TSC} = \frac{q_0 A d}{2} e_n(t) n_t(t).$$

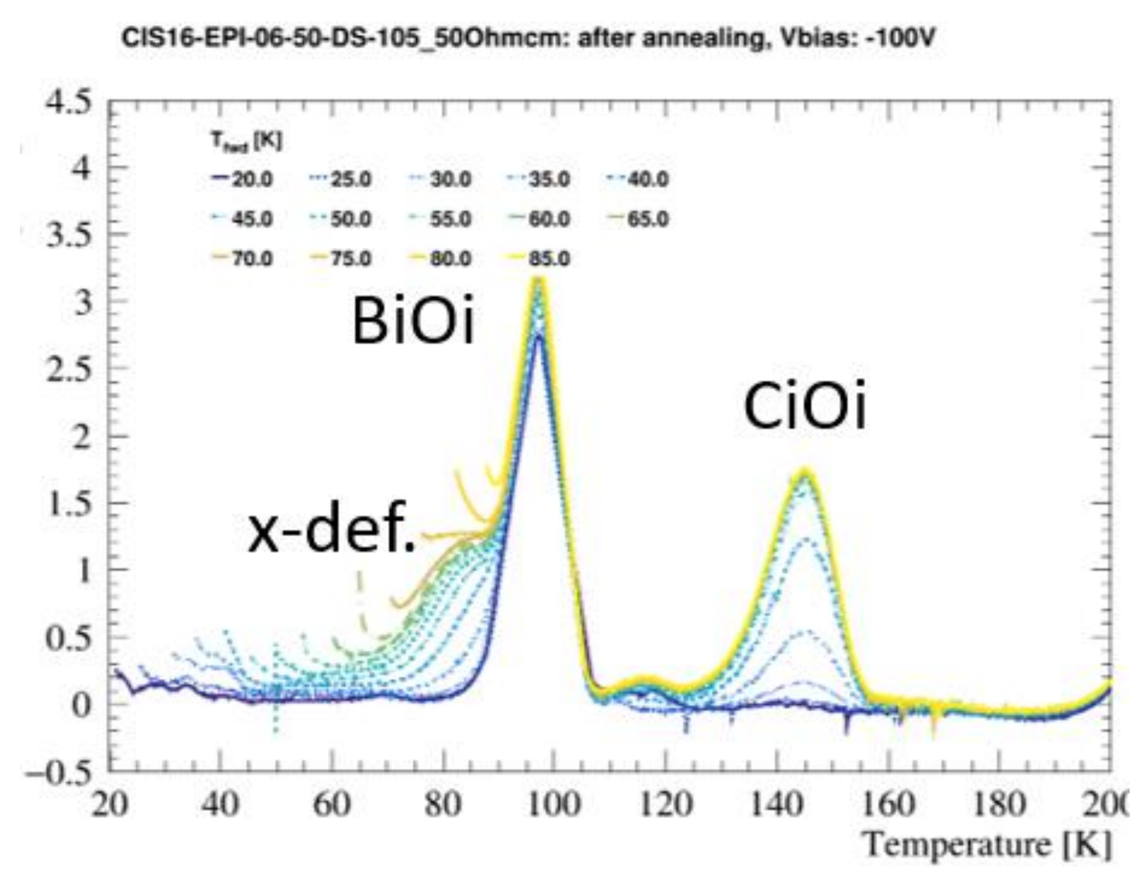
By integrating the current over time, one derives the charge which in turn can be used to calculate the carrier concentration:

$$n_{t,0} = 2\frac{Q_t}{q_0 AW}$$

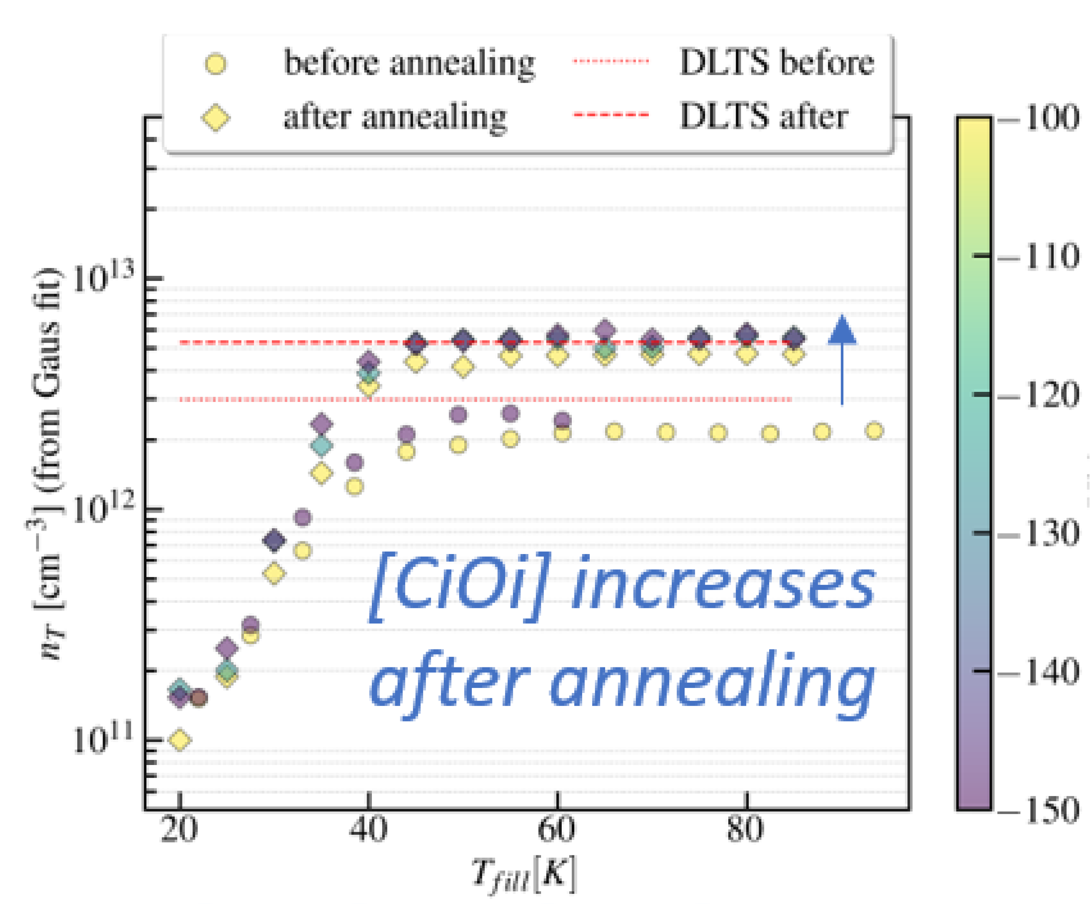
SOFTWARE

To perform analysis on measured TSC spectra we use **pytsc**– a Python3-based software package developed by Nuria Castello-Mor.
Using the theory and computational algorithms following two main tasks can be performed by pytsc:

- Fitting of current peaks in the TSC spectra to obtain characteristic defect parameters with additional optional calculations being executed
- Simulation of TSC spectra using known defect parameter to analyze the impact of different measurement procedures on defect behaviour



The TSC measurement to the left and the one displayed above were both performed on the same detector but one before annealing (left) and the other after (top). By annealing we understand the process of heating up a sensor to stabilize defects as can be seen by the transformation of Ci to CiOi in the sensor after annealing. Both plots are made by using pytsc.



By using pytsc fit function for the CiOi current peak the dependency of the trapped charge carrier concentration to the filling temperature could be determined. Also, it is analytically proofed that the overall concentration of CiOi defects rises.

TASK

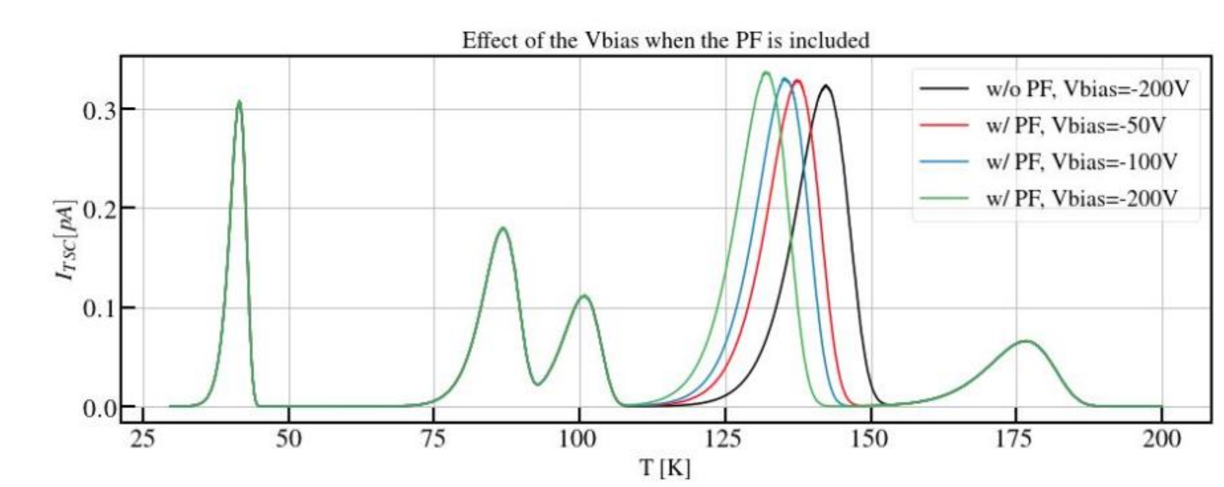
The project's aim lies in improving the pytsc software in respect to the TSC scan simulations.
Currently we can simulate simple scans using known defect parameter. The simulation shall be expanded by the Poole-Frenkel effect – the dependency from the voltage bias of defect activation energy.

```
import pytsc

Neff = 1.3e13
# initialization
scan    = pytsc.trap_fit.TSCScan(Neff, bulk_type=1, fix_Efield=True, thickness_fraction=0.01)

# defect definition
T1 = {'label':'T4','kind':'electron','PF':False,'Ea':0.360, 'Nt':8.88e11, 'Xs':3.22e-15}
T2 = {'label':'T1','kind':'electron','PF':False,'Ea':0.098, 'Nt':2.64e11, 'Xs':1.64e-14}
T3 = {'label':'T2','kind':'electron','PF':False,'Ea':0.196, 'Nt':3.30e11, 'Xs':5.44e-16}
T4 = {'label':'T5','kind':'electron','PF':False,'Ea':0.442, 'Nt':2.27e11, 'Xs':1.22e-15}
T5 = {'label':'T3','kind':'hole',    'PF':False,'Ea':0.252, 'Nt':2.17e11, 'Xs':8.28e-15}

traps = [T1,T2,T3,T4,T5]
scan.set_defects(traps)

# add real tsc scan to load some sensor information, T, ...
scan.add_scan(infile, 25, 250)
```

```
scan.sensor
```

```
[{'Vbias': -200,
  'thickness': 4.9999999999999996e-05,
  'area': 6.25e-06,
  'volume': 3.125e-10,
  'slice_fraction': 0.01,
  'slice_thickness': 5e-07,
  'slice_volume': 3.125e-12,
  'Nslices': 100,
  'x': array([2.500e-07, 7.500e-07, 1.250e-06, 1.750e-06, 2.250e-06, 2.750e-06,
       3.250e-06, 3.750e-06, 4.250e-06, 4.750e-06, 5.250e-06, 5.750e-06,
```

bias voltage
sensor properties



The present implementation of the Poole-Frenkel effect does not match with measurements and thus has to be reviewed regarding the used equations and approximations.

Furthermore, the other simulation-based calculations (e.g., of the intrinsic electric field, charge carrier concentration and depletion depth) will be validated by self-performed TSC measurements and subsequent analysis.
Finally, the software will be added to an existing graphic user interface for TSC analysis.

ACKNOWLEDGEMENTS

The theory presented was extracted from:
Michael Moll. *Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties.* PhD thesis, Hamburg U., 1999.
Elena Maria Donegani. E*nergy-Dependent Proton Damage in Silicon*. PhD thesis, Hamburg U., 2017.

I want to thank Isidre Mateu for creating the GUI used in the SSD group for TSC data analysis.

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