

# GAIN-LAYER PROJECT

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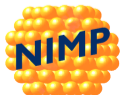
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4<sup>th</sup> DRD3, CERN, November 12<sup>th</sup>, 2025

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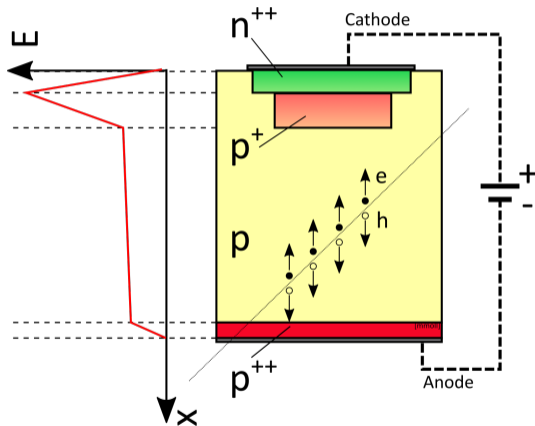


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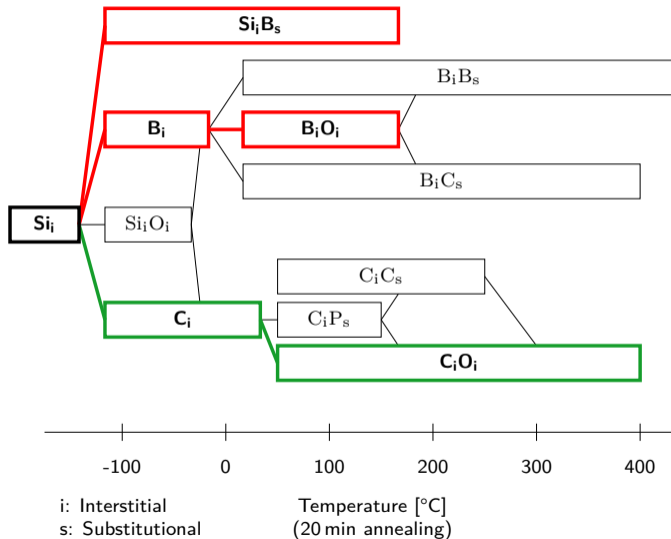
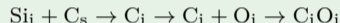


# It's all fun and gain until the Boron gets removed

Low Gain Avalanche Diodes (LGADs)



- ▶ PIN diode with built-in amplification
  - ▶ Gain achieved by implanting layer with high doping (Boron) concentration
  - ▶ Results in very strong electric field  
⇒ Avalanche & amplification
  - ▶ Large & fast signals
- 
- ▶ Gain layer degrades with irradiation until it is fully removed
  - ▶ De-activation of doping in gain layer?
  - ⇒ Is the Acceptor Removal Effect the main culprit?

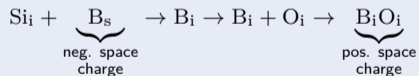
 **$B_iO_i$  formation** **$C_iO_i$  formation**

- ▶ Some defects are detrimental for detector performance ( $B_iO_i$ )
- ▶ Some are not so bad ( $C_iO_i$ )
- ▶ The formation of  $Si_iB_s$  has been proposed in literature as an alternative to the formation of  $B_i$

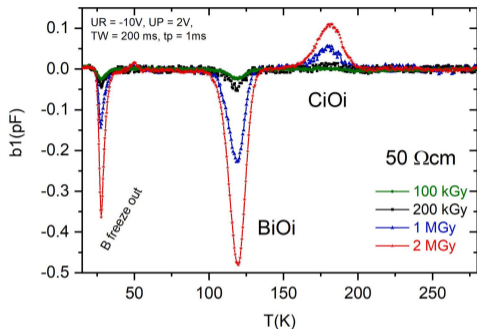
- ▶ Acceptor Removal Effect is the apparent deactivation of acceptor dopants (Boron) by radiation
- ▶ Observed macroscopically as a change in the effective doping concentration  $N_{\text{eff}}$  and gain-layer degradation

### Current understanding

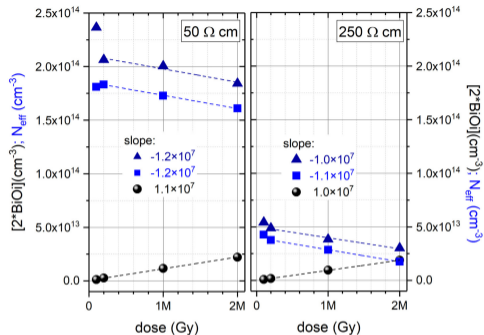
- ▶ Boron dopant on lattice site  $B_s$  provides negative space charge
- ▶  $B_s$  is kicked-out by migrating Silicon atoms
- ▶ Becomes interstitial  $B_i$
- ▶  $B_i$  is highly mobile and forms together with Oxygen interstitial impurity  $O_i$  the  $B_iO_i$  defect
- ▶  $B_iO_i$  provides positive space charge



- ▶ Removal of 1 Boron atom results in formation of  $B_iO_i$ , which essentially compensates a second Boron dopant
- ▶ Effective doping concentration  $N_{\text{eff}}$  should anti-correlate with twice the  $B_iO_i$  concentration
- ▶ Can we see this in measurements?



- ▶ DLTS measurements of  $\gamma$ -irradiated Silicon diodes
- ▶ Identify  $B_iO_i$  defect
- ▶ Concentration increases with irradiation dose



- ▶ Measure change in  $N_{\text{eff}}$  with dose (blue points)
- ▶ Change with radiation is linear, with slope  $-1$
- ▶ Two times  $B_iO_i$  concentration versus dose is linear with slope 1 (black points)

ANJA HIMMERLICH ET AL.: Defects and acceptor removal in <sup>60</sup>Co  $\gamma$ -irradiated p-type silicon [10.1016/j.nima.2025.170886](https://doi.org/10.1016/j.nima.2025.170886)

- ▶ Studies have shown the expected behaviour of  $N_{\text{eff}}$  with  $\text{B}_i\text{O}_i$  concentration
- ▶ Problem: All studies were carried out on high resistivity material ( $50 \Omega \text{ cm}$  to  $\text{k}\Omega \text{ cm}$ )
- ▶ LGAD gain-layer is typically  $1\text{--}10 \Omega \text{ cm}$
- ▶ Does the same process happen at these much higher doping concentrations?

## Motivation

- ▶ Study of radiation-induced degradation of gain-layer in LGADs
- ▶ We want to gain an understanding on the defect level

## Problem

- ▶ It is impossible to directly investigate the gain-layer of a LGAD with DLTS and TSC measurements

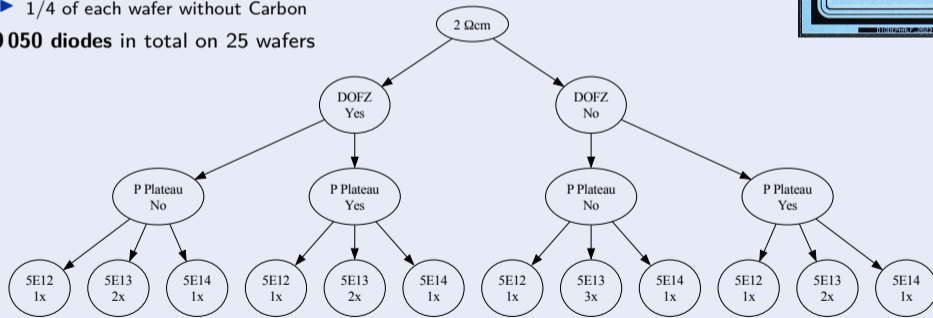
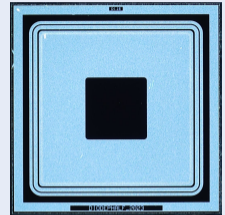
## Solution

- ▶ We produced a specific set of diodes for defect spectroscopy measurements
- ▶ The bulks mimic a gain-layer, i.e. they have a very high doping concentration

## Goals

- ▶ Understand the acceptor removal effect (ARE) in irradiated gain-layer of LGADs
- ▶ Parametrise the ARE for various Boron, Phosphorus, Carbon and Oxygen concentrations and irradiations
- ▶ Find defect engineering solutions to maximise the radiation-hardness of gain-layers

- ▶  $p$ -type Silicon pad diodes, FZ and DOFZ wafers
- ▶  $2\ \Omega\ \text{cm}$  ( $6.5 \cdot 10^{15}\ \text{cm}^{-3}$ ) and  $10\ \Omega\ \text{cm}$  ( $1.3 \cdot 10^{15}\ \text{cm}^{-3}$ ) wafers,  $250\ \mu\text{m}$  and  $525\ \mu\text{m}$  thickness respectively
- ▶ Large diodes  $6.25\ \text{mm}^2$ , small diodes  $1.56\ \text{mm}^2$
- ▶ Phosphorus plateau co-doping for some wafers
- ▶ 3 Carbon implantation doses:  $5 \cdot 10^{12}\ \text{cm}^{-2}$ ,  $5 \cdot 10^{13}\ \text{cm}^{-2}$  and  $5 \cdot 10^{14}\ \text{cm}^{-2}$ 
  - ▶ 1/4 of each wafer without Carbon
- ▶ **19 050 diodes** in total on 25 wafers

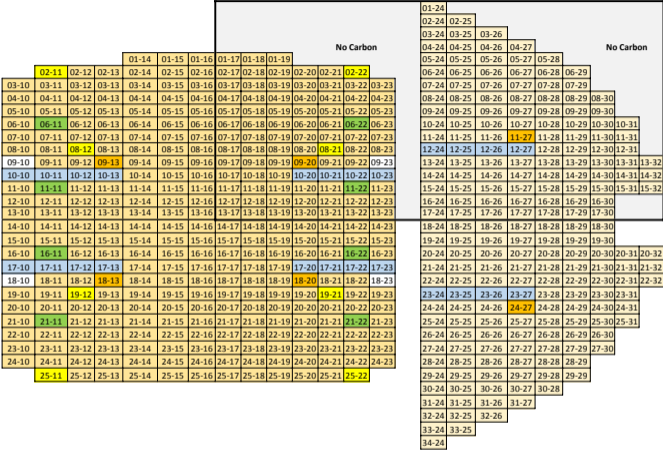
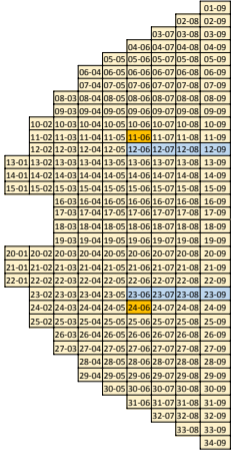


## A taste of Silicon: Now in six exciting flavours!



Flavour	Resistivity [ $\Omega$ cm]	DOFZ	Phosphorus Plateau	Carbon [ $\text{cm}^{-2}$ ]
A	2	no	no	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$
B	2	no	yes	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$
C	2	yes	no	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$
D	2	yes	yes	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$
E	10	no	no	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$
F	10	yes	no	$0, 5 \cdot 10^{12}, 5 \cdot 10^{13}, 5 \cdot 10^{14}$

# Wafer Layout



Wafer Info	
Name	CIS-xx-yy
Resistivity	xx Ωcm
DOFZ	yes / no
P Plateau	yes / no
Carbon Dose	xx 1/cm <sup>2</sup>
Thickness	2 Ωcm: 250 μm
Thickness	10.2 Ωcm: 525 μm

SMALL DIODES	carbon			no carbon		
	dies	424	318	106		
standard small	404	303	101			
large backside window	16	12	4			
no metal/Hall	0	0	0			
sims	0	0	0			
CLT01TF	0	0	0			
long backside window	4	3	1			

BIG DIODES	carbon			no carbon		
	dies	338	252	86		
standard big	298	222	76			
large backside window	16	12	4			
no metal/Hall	8	6	2			
sims	8	6	2			
CLT01TF	4	3	1			
long backside window	4	3	1			

# Status of the Project

*Measurements taken – explanations pending*



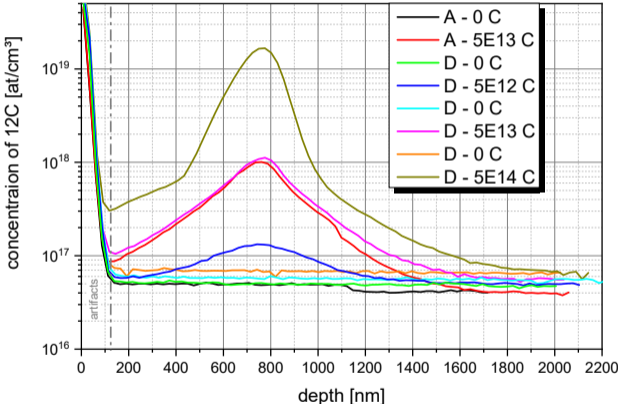
- ▶ All diodes were produced at CiS and are now stored at CERN SSD group (in charge of distribution)
- ▶ Initial set of (unirradiated) diodes was distributed to participating institutes
- ▶ IV, CV and DLTS measurements were performed on the unirradiated diodes
- ▶ SIMS measurements were carried out on dedicated diodes of all flavours
- ▶ Hall measurements started
- ▶ Fourier-transform infrared spectroscopy (FTIR) measurements planned
- ▶ First irradiation campaign was carried out at CERN,  $2 \cdot 10^{14}$  p/cm<sup>2</sup> at PS-IRRAD
  - ▶ DLTS measurements ongoing
  - ▶ Measuring multiple annealing steps

- ▶ SIMS measurements were carried out on dedicated structures at CiS
  - ▶ So-far only measured for the  $2\ \Omega\ \text{cm}$  diodes
- 
- ▶ Phosphorus doping ( $n^{++}$  implant) as expected
  - ▶ Phosphorus plateau (compensation doping) as expected
  - ▶ Carbon and Oxygen: see next slides



- ▶ Flavour A: FZ
- ▶ Flavour D: DOFZ, w/ Phosphorus

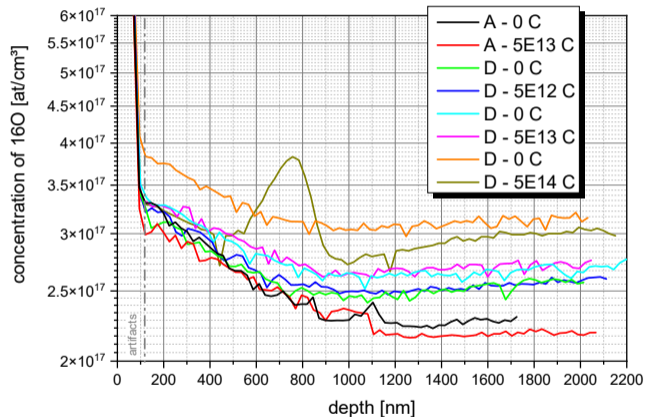
- ▶ Carbon implantation at expected depth
- ▶ Increased concentration for higher implantation doses
- ▶ No (extra) Carbon for w/o Carbon diodes



- ▶ Flavour A: FZ
- ▶ Flavour D: DOFZ, w/ Phosphorus

- ▶ DOFZ diodes have higher Oxygen concentration than FZ diodes

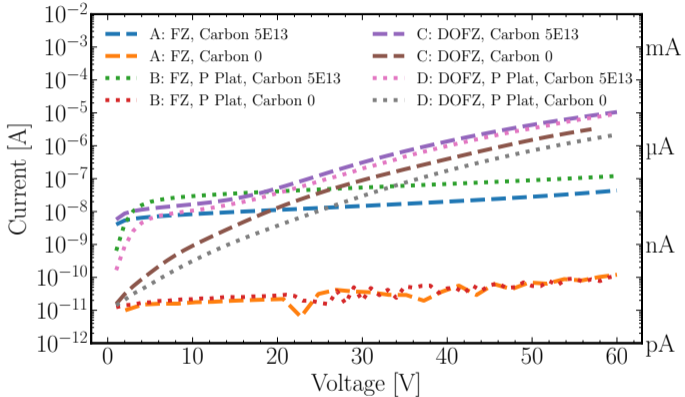
- ▶ Highest Carbon implantation has unexpected Oxygen peak at 700 nm depth
- ▶ Unclear increase of *base* Oxygen concentration with higher Carbon implantation (only for flavour D)



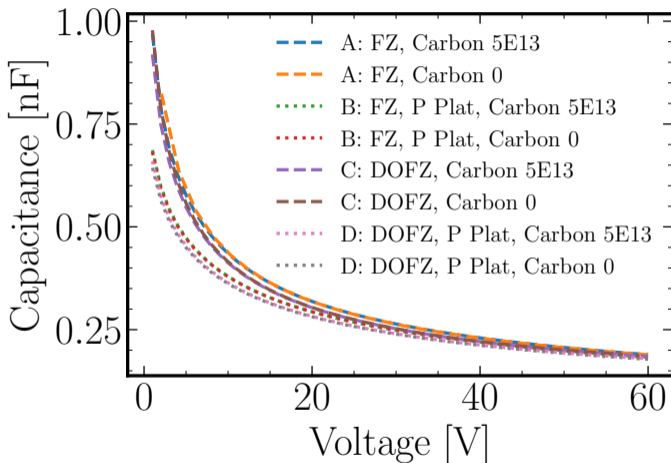
# Before Irradiation: IV ( $2 \Omega \text{ cm}$ )



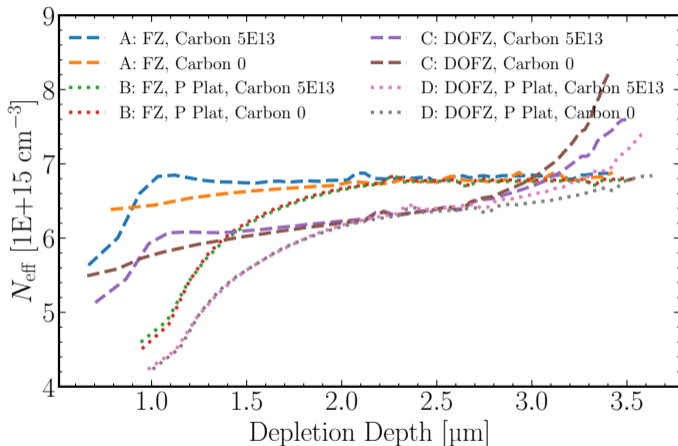
- ▶ DOFZ has larger currents than FZ
- ▶ w/ Carbon has larger currents
- ▶ No consistent effect of Phosphorus



- ▶ w/ Phosphorus consistently lower capacitance
- ▶ All flavours deplete nicely
- ▶ Full depletion would be at around 300 kV
- ▶  $\sim 1.5 \mu\text{m}$  depletion depth @10 V (DLTS measurement voltage)



- ▶ Compensation from Phosphorus visible (blue vs green curve)
- ▶ Carbon causes compensation(?) close to surface (blue vs orange curve)
- ▶ Effect of Carbon only visible without Phosphorus plateau (green and red curve identical)
- ▶ FZ consistently higher  $N_{\text{eff}}$  than DOFZ (blue vs purple curve)



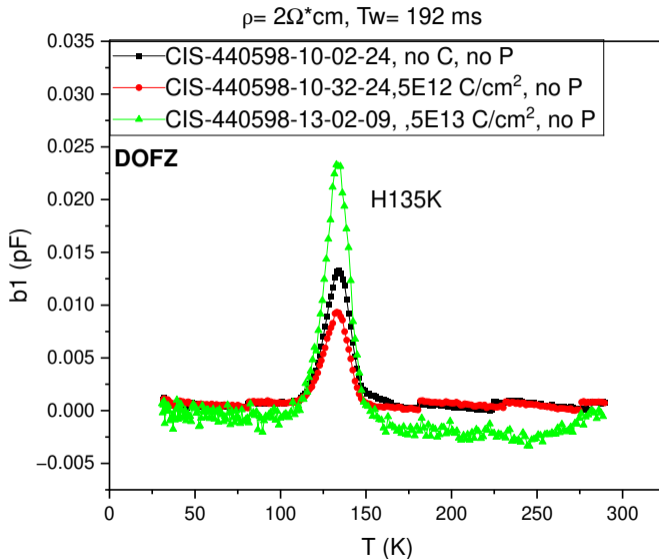
- ▶ All measurements show that the diodes are of excellent quality
- ▶ No early breakdowns, expected depletion behaviour
- ▶ Some effects of the flavours are observed
- ▶ Similar results seen by the other institutes as well

- ▶ DLTS measurements on unirradiated diodes were carried out by CERN, NIMP and Vilnius institutes
- ▶ Diodes work nicely with DLTS
- ▶ Overall agreement between measurements at different institutes
  - ▶ We have defined a standard set of measurement conditions for DLTS measurements

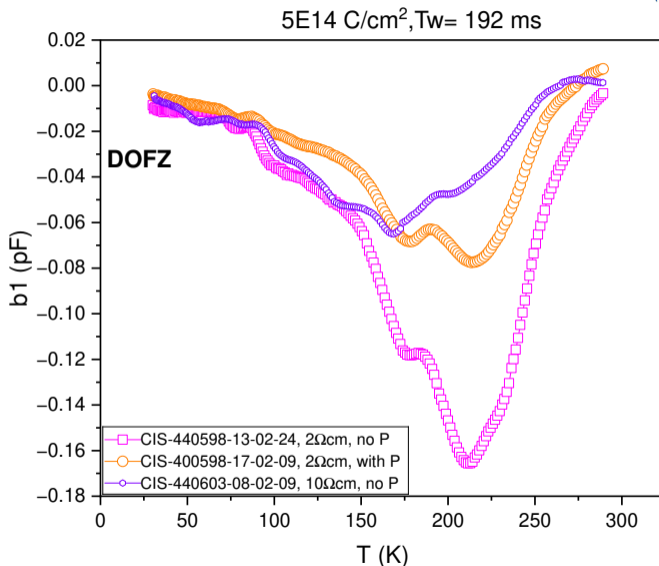
#### DLTS Standard Measurement Conditions

- ▶ Reverse bias  $U_R = 10\text{ V}$
- ▶ Pulse bias  $U_P = -2\text{ V}$  (forward) for majority & minority or  $0.6\text{ V}$  (reverse) for majority carrier only injection
- ▶ Pulse duration  $t_P = 100\text{ ms}$
- ▶ Time windows  $T_W = 19.2\text{ ms}$ ,  $192\text{ ms}$  and  $1920\text{ ms}$

- ▶ The spectra look more or less identical for all flavours
- ▶ All diodes have the hole trap *H135K*
- ▶ Not yet identified with a known defect
- ▶ Not responsible for leakage current generation, since activation energy is quite small  $\sim 0.27$  eV, compared to mid-bandgap
- ▶ Concentration affected by flavour and Carbon concentration not consistently



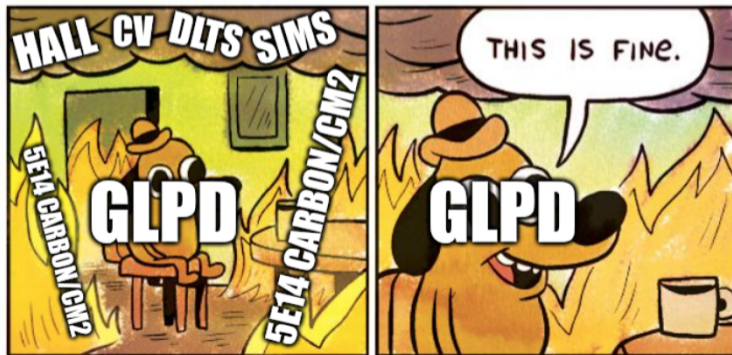
- ▶ Observed only for largest Carbon dose  $5 \cdot 10^{14} \text{ cm}^{-2}$
- ▶ Negative peaks appear for majority carrier only injection (should not happen)
- ▶ Appears irrespective of flavour
- ▶ Not understood why this happens



$5 \cdot 10^{14} \text{ cm}^{-2}$  Carbon dose

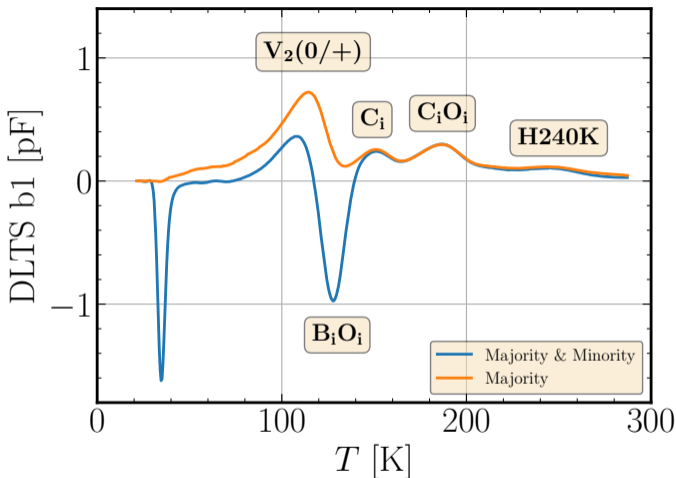
- ▶ SIMS measurement show weird peak in Oxygen concentration
- ▶ Hall measurements show weird results
- ▶ Doping profiles from CV measurements show weird peaks
- ▶ Unirradiated DLTS has minority carrier peaks for majority carrier injection

⇒ Further investigations needed

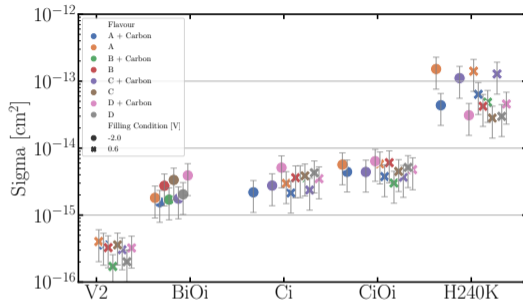
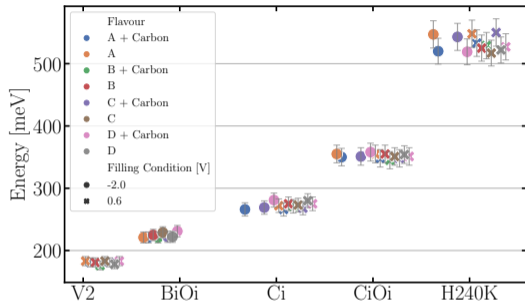


- ▶ Test campaign to gauge proper fluence levels for DLTS measurements
  - ▶ Set of all flavours were irradiated to  $2 \cdot 10^{14}$  p/cm<sup>2</sup> at PS-IRRAD (23 GeV protons, 0.62 hardness-factor)
  - ▶ For each flavour, one diode with and one without Carbon (only  $5 \cdot 10^{13}$  cm<sup>-2</sup>)
- 
- ▶ Both resistivities were irradiated
    - ▶ For the 10 Ω cm diodes, fluence level was too high for DLTS measurements
  - ▶ All (2 Ω cm) diodes were measured after irradiation with DLTS
    - ▶ Before annealing
    - ▶ After 60 °C for 30 min
    - ▶ After 60 °C for 80 min
    - ▶ After 60 °C for 200 min (measurements ongoing)

- ▶ Spectra look practically the same for all flavours, albeit peak heights
- ▶ Forward and reverse bias injection always measured to probe for electron and hole traps
- ▶ Extraction of defect parameters on next slides



📄 Identification of the V<sub>2</sub>(0/+): NIELS SORGENFREI ET AL.: *On the nature and charge state of the X-Defect, a radiation-induced Silicon defect with field-enhanced charge carrier emission* [10.1016/j.nima.2025.171133](https://doi.org/10.1016/j.nima.2025.171133)



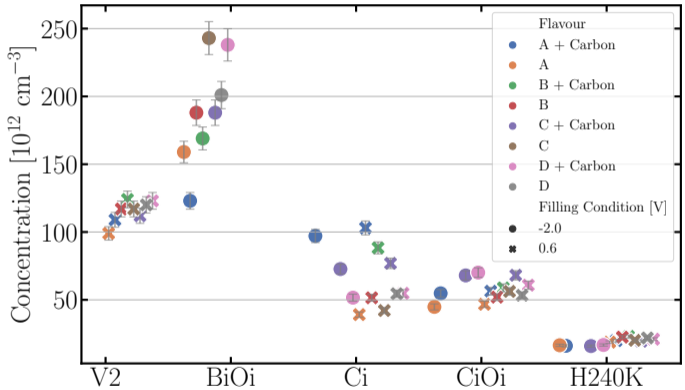
- ▶ Activation energies and capture cross-section are consistent throughout all flavours
- ▶ No differences observed between w/ or w/o Carbon
- ▶ No difference observed for forward or reverse bias injection

# After Proton Irradiation: DLTS



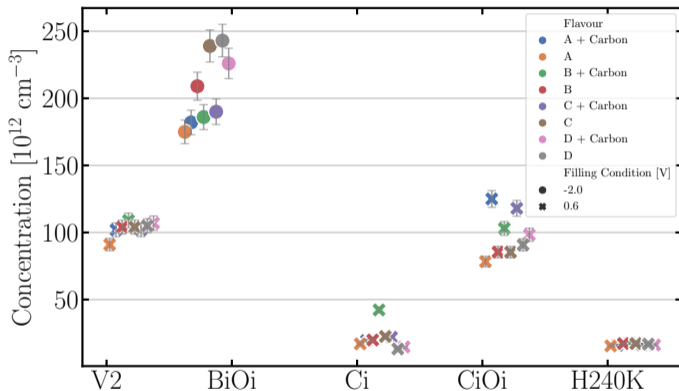
- ▶ Concentrations of investigated defects for different flavours
- ▶ No difference for  $V_2(0/+)$  and  $H240K$  observed
- ▶ Strong differences for  $B_iO_i$
- ▶  $C_i$  anneals to  $C_iO_i$  at room temp
- ▶  $C_i$  &  $C_iO_i$  varies, but should be checked after stable annealing stage is reached

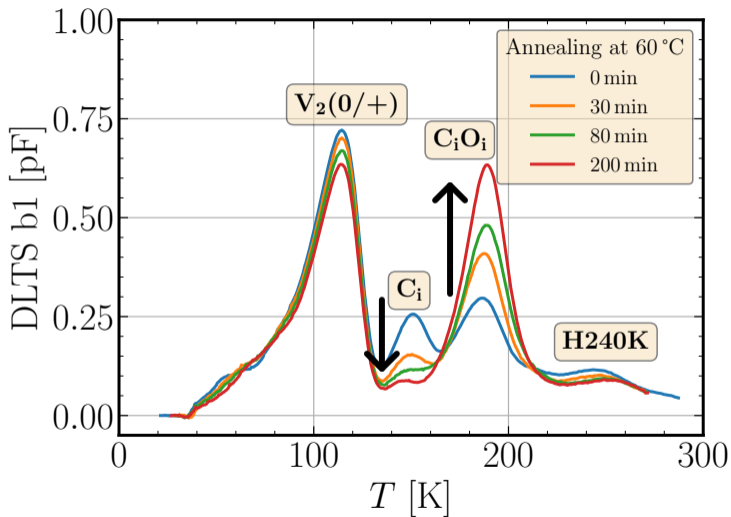
Flavour	Res. [ $\Omega$ cm]	DOFZ	P Plateau
A	2	no	no
B	2	no	yes
C	2	yes	no
D	2	yes	yes



- ▶ Reduced  $C_i$  and increased  $C_iO_i$  concentrations
- ▶  $C_i$  anneals into  $C_iO_i$

Flavour	Res. [ $\Omega$ cm]	DOFZ	P Plateau
A	2	no	no
B	2	no	yes
C	2	yes	no
D	2	yes	yes





- ▶ Comparison of annealing times at 60 °C
- ▶  $C_i$  shrinks,  $C_iO_i$  increases
- ▶ Concentration of  $C_i$  goes into  $C_iO_i$

## Acceptor Removal Effect

- ▶ Main mechanism behind gain layer degradation of LGADs
- ▶ Current understanding says formation of  $B_iO_i$  is the problem

## Gain-Layer Project

- ▶ Large quantity (**19050**) of diodes produced for defect spectroscopy
- ▶ Bulks mimic gain-layer of LGADs
- ▶ Different flavours to check effects of Carbon, Boron, Oxygen and Phosphorus content
- ▶ First proton irradiation campaign completed, annealing study ongoing

## Outlook

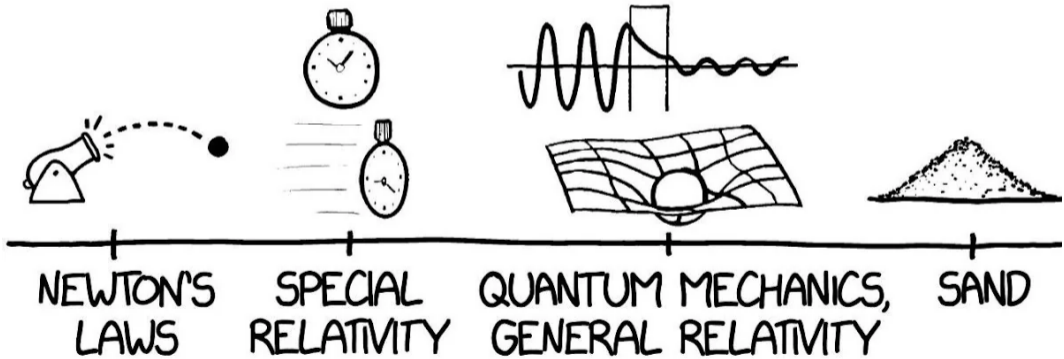
- ▶ Neutron irradiation campaign for DLTS: 4 fluences, all flavours, all Carbon doses, 240 diodes
  - ▶ Additional proton irradiation campaign for DLTS: more fluences, 240 diodes
  - ▶ Neutron irradiation campaign for macroscopic investigations (IV, CV), 96 diodes
- ⇒ Study fluence effects & parametrise ARE

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

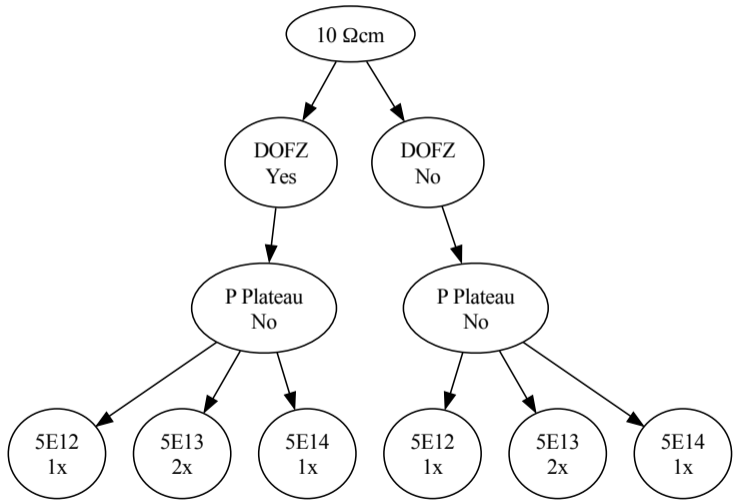
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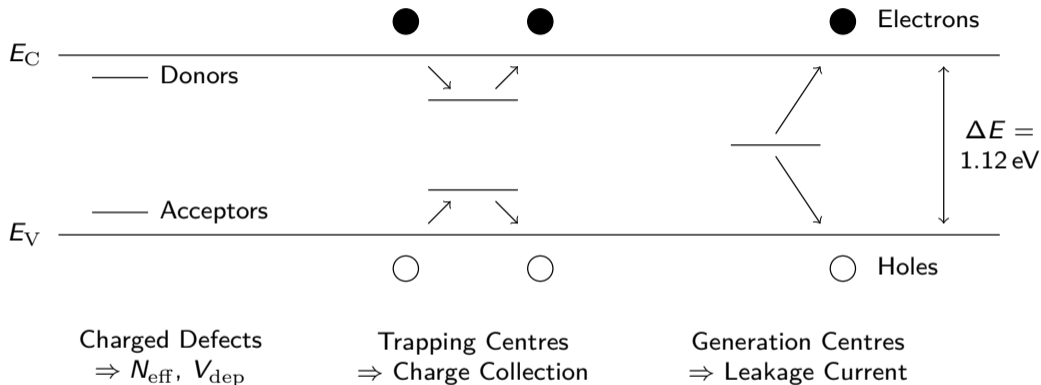
# AREAS OF PHYSICS BY DIFFICULTY

HARDER →



# 10 Ω cm diodes flavour tree





By knowing capture-cross sections  $\sigma_{n,p}$ , activation energy  $E_A$  and the defect concentration  $N_t$ , impact on the detector can be simulated

Investigate **macroscopic** properties

## Current-Voltage &amp; Capacitance-Voltage Characteristics

- ▶ Current and capacitance at a certain voltage?
- ▶ What is  $N_{\text{eff}}$ ? What is the doping profile?
- ▶ What is the full depletion voltage?

## Transient Current Technique &amp; Radioactive Source &amp; Testbeam

- ▶ Use lasers, radioactive sources or accelerator beams to deposit energy in sensor
- ▶ Measure charge collection efficiency before and after irradiation
- ▶ Observe electric field shapes

Investigate **microscopic** properties

## Defect Spectroscopy

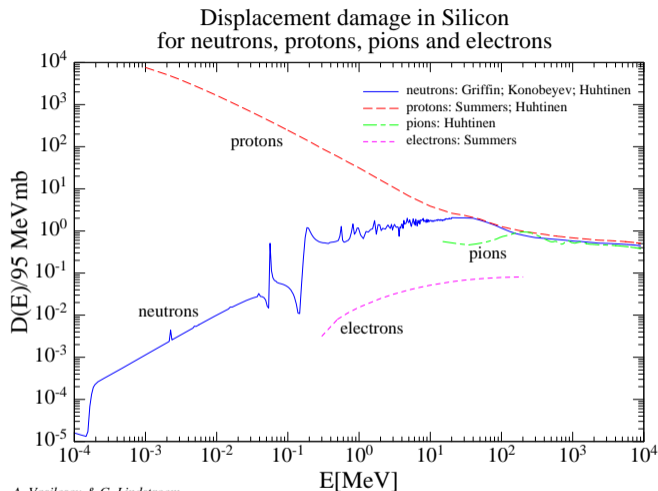
- ▶ Measure defect parameters
- ▶ Capture-cross section, energy level, concentration
- ▶ Observe new defect types after irradiation or increased concentration of intrinsic defects


## Methods

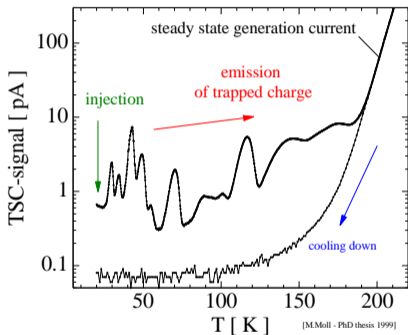
- ▶ Measure current or capacitance due to de-trapping of charges from defects
- ▶ Thermally Stimulated Current (TSC)
- ▶ Deep-Level Transient Spectroscopy (DLTS)

Match microscopic defects with macroscopic properties

- ▶ Scale displacement damage created by different particles of different energies by one factor to a reference of 1 MeV neutron equivalent damage
- ▶ Hardness factor  $k$  is used to scale fluences  $\Phi$  to  $n_{\text{eq}}/\text{cm}^2$
- ▶  $k = \frac{\Phi_{\text{eq}}}{\Phi}$



 A. VASILESCU, G. LINDSTROEM: *Displacement damage in silicon, on-line compilation* [RD50.web.cern.ch/niel](http://RD50.web.cern.ch/niel)



### Method

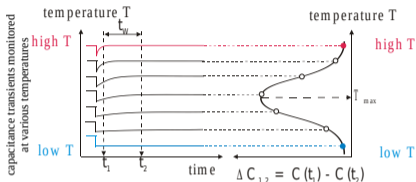
- ▶ Current based technique
- ▶ Measure current due to emission of charges from defects

### Filling recipes

- ▶ Forward biasing → majority & minority carriers
  - ▶ h traps only filled if  $c_p > c_n$
  - ▶ e traps only filled if  $c_n > c_p$
- ▶ 0 V → majority carriers
- ▶ Light injection → majority and/or minority carriers
  - ▶ depends on wavelength (IR or red)
  - ▶ depends on top or bottom injection

### Results

- ▶ Defect concentration  $N_t$  (integrate currents, correlate with depleted volume)
- ▶ Activation energy  $E_A$  (delayed heating method)



## Method

- ▶ Capacitance based technique
- ▶ Measure change in capacitance transients due to de-trapping of charges from defects

## Filling recipes

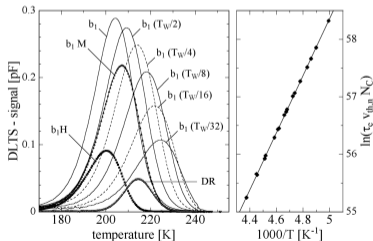
- ▶ Same as TSC

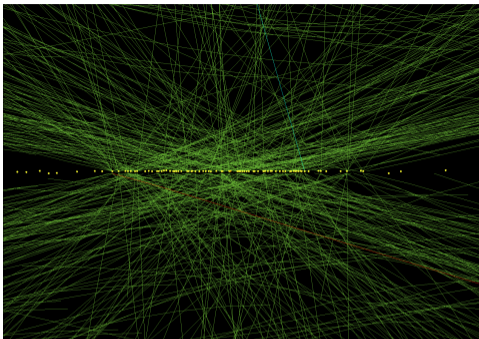
## Results

- ▶ Defect concentration  $N_t$  (Amplitude of capacitance transients)
- ▶ Activation energy  $E_A$  (Arrhenius relation from transients)
- ▶ Capture cross-section  $\sigma$  (Arrhenius relation from transients)

## Related techniques

- ▶ Current DLTS → Current based DLTS
- ▶ Laplace DLTS → Higher precision
- ▶ Difference-DLTS → Field dependence





- ▶ Pile-up poses problems for HL-LHC (and beyond) experiments
- ▶ Increased amount of *simultaneous* collisions makes track identification difficult
- ▶ Disentangle this *simultaneousness* with timing information
- ▶ 4D tracking = 3D tracking + timing information
- ▶ Need for speed (fast detectors)
- ▶ Currently best solution are LGADs
- ▶  $\mathcal{O}(50 \text{ ps})$  time resolution

📄 CMS EXPERIMENT: [cds.cern.ch/record/1479324/](https://cds.cern.ch/record/1479324/)

