Defect spectroscopy studies on irradiated LGADs

EP-DT-DD
Detector Technologies
Detector Development

Anja Himmerlich, Nuria Castello-Mor, Esteban Curras Rivera,
Yana Gurimskaya, Vendula Maulerova-Subert, Michael Moll
CERN, Switzerland

Ioana Pintilie
NIMP, Bucharest-Magurele, Romania

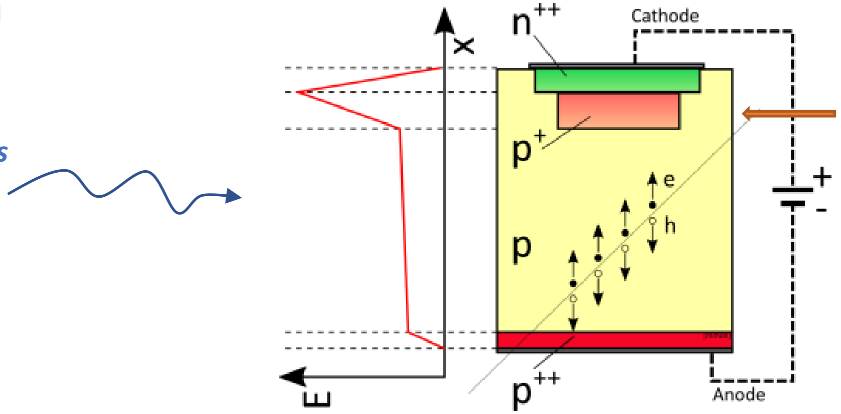
Chuan Liao, Eckhart Fretwurst, Joern Schwandt
University Hamburg, Germany

Leonid Makarenko
Belarusian State University, Minsk, Belarus

03.03.2022 *anja.himmerlich@cern.ch*

Motivation

High energy particles
(n, p^+, e^- ...)



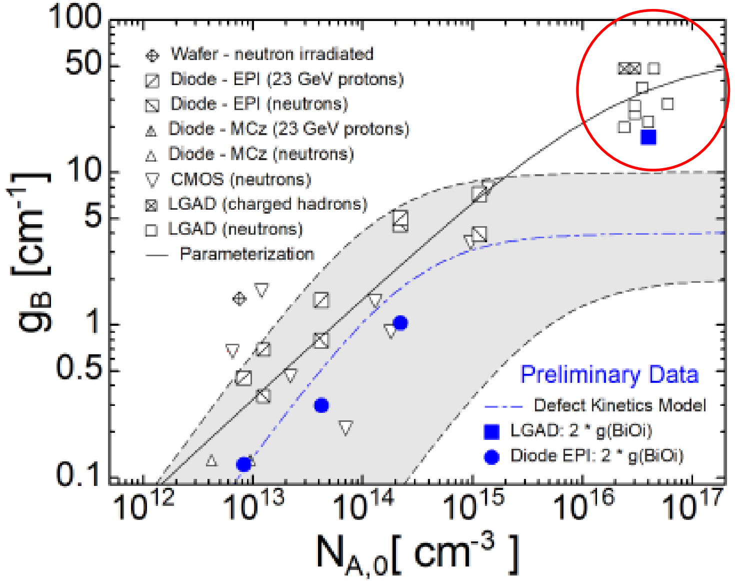
highly boron-doped gain layer (1E+17 cm-3)

- ☐ *radiation induced degradation of the highly boron-doped gain-layer (deactivation at fluences > 1-2 E+15 n_{eq}/cm^2)*
- ☐ *decrease of the signal gain with increasing particle fluence*

„boron deactivation“

*⟹ ACCEPTOR REMOVAL EFFECT by **BiOi** formation*

Boron-removal IR vs. initial boron concentration



LGADs

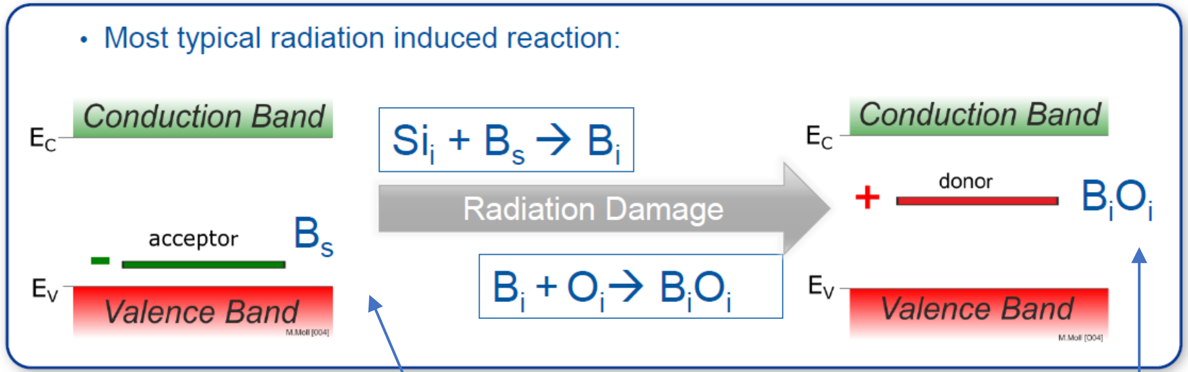
Torino Parametrization: Ferrero et al. NIMA 919 (2019) 16-26

← ***defect kinetics model*** *(almost all intersitials go into BiOi or CiOi)*

Moll, PoS 2019 VERTEX

introduction rate (IR): $gB = \frac{defect\ concentration}{fluence}$

- Most typical radiation induced reaction:



*induce **negative** space charge*

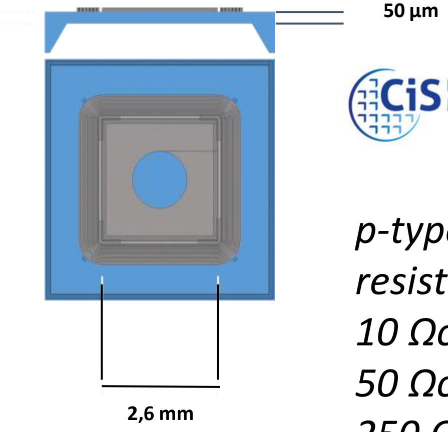
*induce **positive** space charge*

What other defect formation mechanism lead to the deactivation of acceptors?

Can we get information about gain-layer defects by using defect spectroscopy methodes like DLTS or TSC?

Samples

p-type Si diodes (n^+p):



CiS Forschungsinstitut für Mikrosensorik GmbH

p-type Si of different resistivity:
10 Ωcm
50 Ωcm
250 Ωcm
1kΩcm

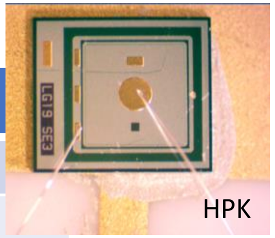
Material:
Standard EPI diodes
area = (2.632 x 2.632) mm²
nominal active thickness = 50 µm
guard rings
passivation with openings for conection;
on back and front side openings for light injection

Neutron irradiation up to 1E+14 n/cm²

CNM & HPK LGADs & PiNs

Neutron irradiated

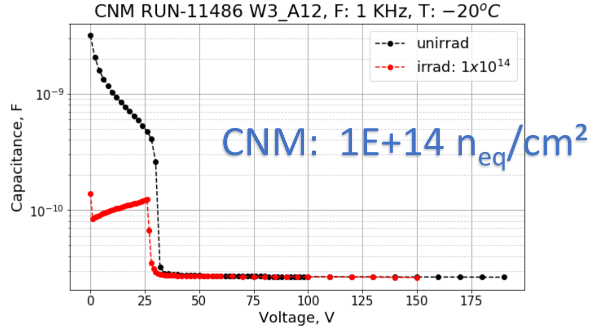
	fluence (n_{eq}/cm^2)	U_{depl} (V)
LGAD - HPK W36 S3	1E+13	~ 50
PiN – HPK W42 S4	1E+13	~ 5
LGAD – CNM W2	1E+14	~ 30
LGAD – CNM W3	1E+14	~ 30
PiN – CNM W2	1E+14	~ 2
LGAD – CNM W2	1E+15	



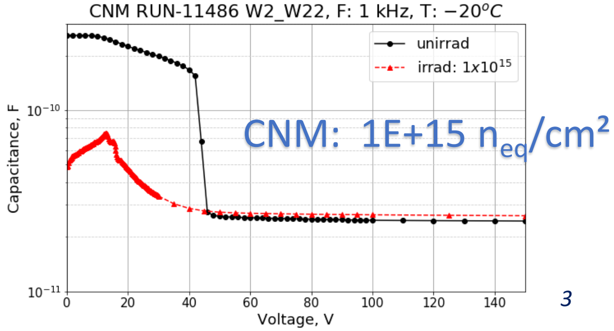
HPK

CNM LGADs: SOI –wafer *(run11486) – (351 µm thick):*
B-doped active p-type layer: resistivity > 5000 Ωcm, 50 µm
oxide layer (1 µm)
p-type support-wafer (B-doped, 300 µm, low resistivity)
area = 0.09 cm²

HPK LGADs:
B-doped active p-type layer: 50 µm
support wafer thickness: 300 µm
area = (1.3 x 1.3) mm²



CNM: 1E+14 n_{eq}/cm^2

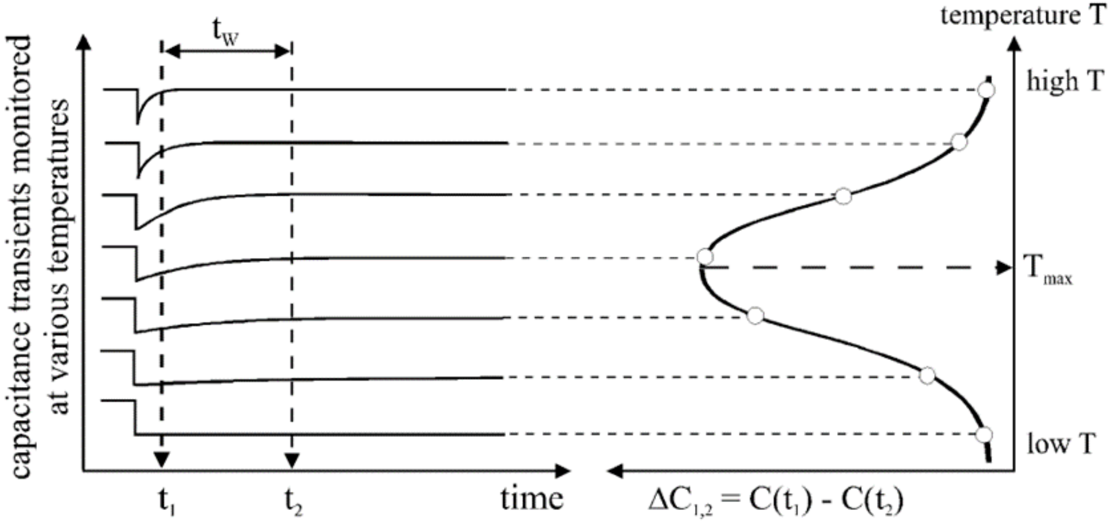


CNM: 1E+15 n_{eq}/cm^2

DLTS

DLTS: Deep Level Transient Spectroscopy

(1) Junction under reverse bias @ different temperatures→ defect states unoccupied
(2) Injection pulse (electrical or optical) → injection of minority and/or majority carriers → occupation of defect levels
(3) Junction under reverse bias → charge carriers thermally emitted → change in capacitance (capacitance transients)



Moll thesis 1999

Defect parameters:
activation energy
capture cross section
defect concentrations

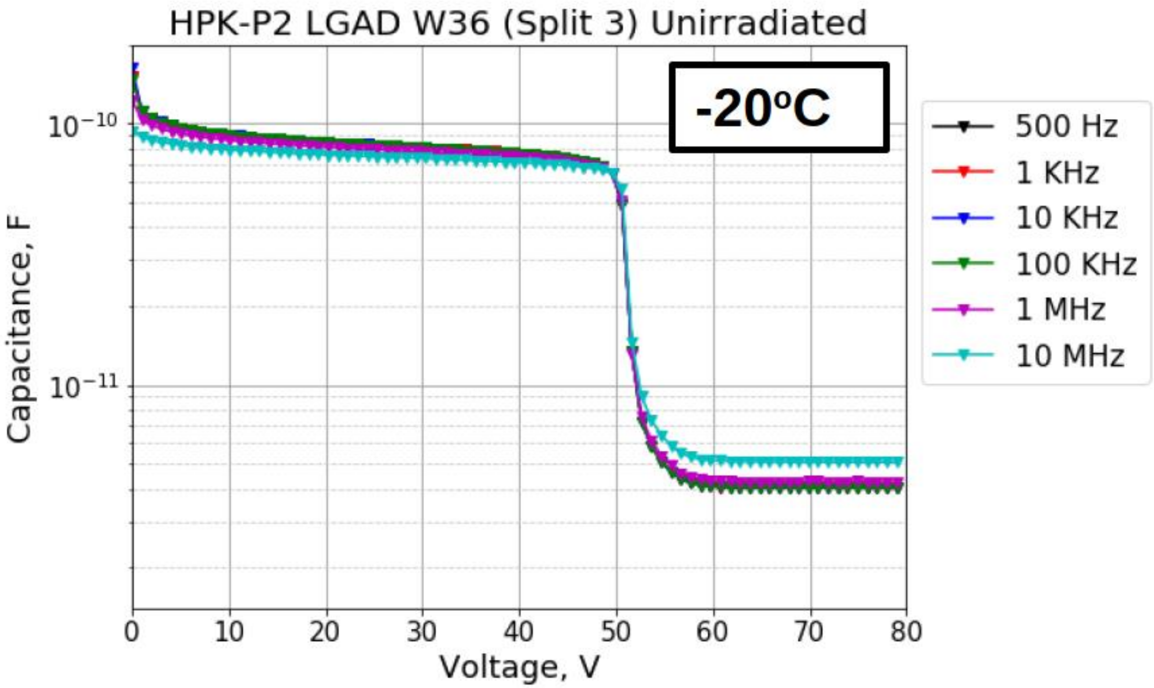
DLTS limited to defect concentrations
$N_t \approx 0.1\text{-}0.3 * N_{doping}$

Is DLTS capable to characterize defects in neutron irradiated LGADs ?

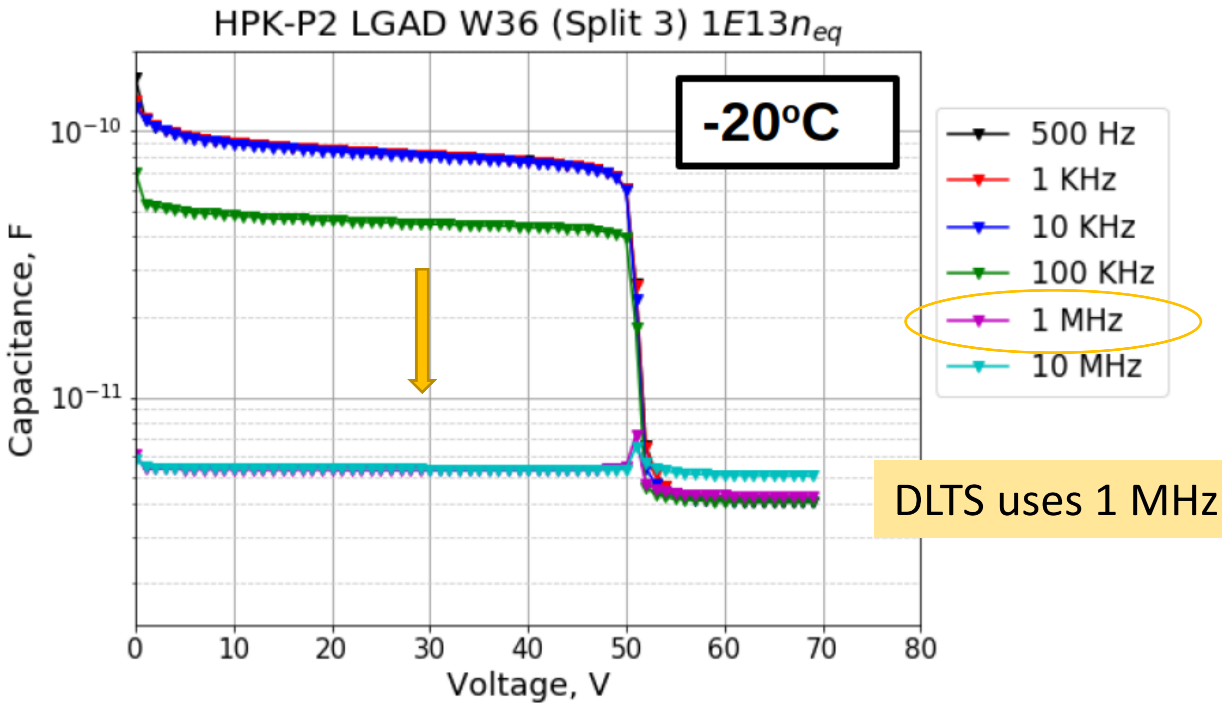
Frequency dependence

LGAD – HPK (1E+13 n_{eq}/cm^2)

unirradiated



irradiated



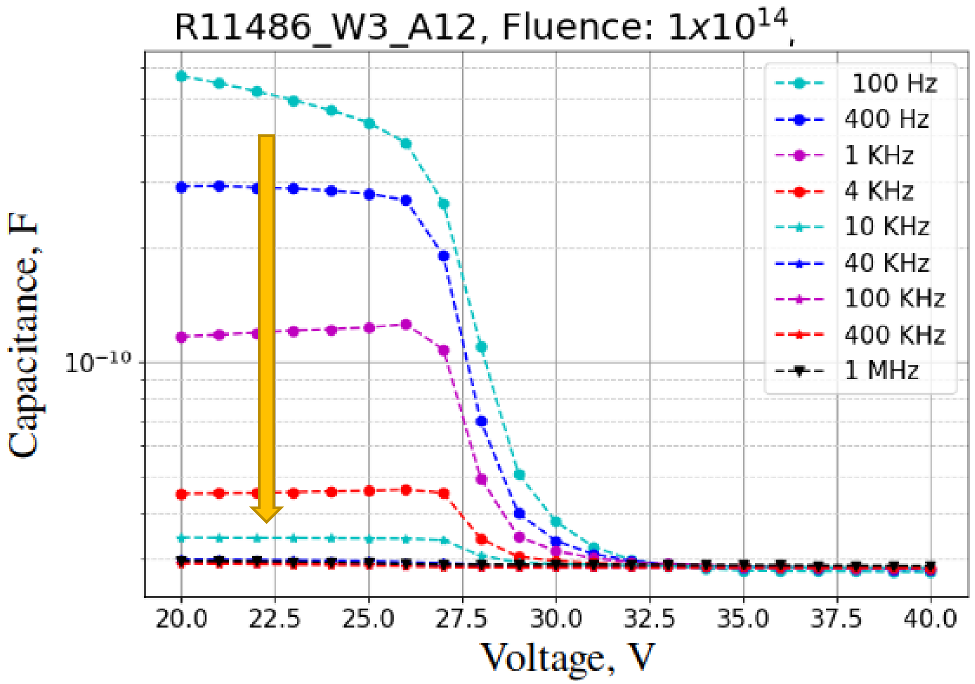
DLTS uses 1 MHz

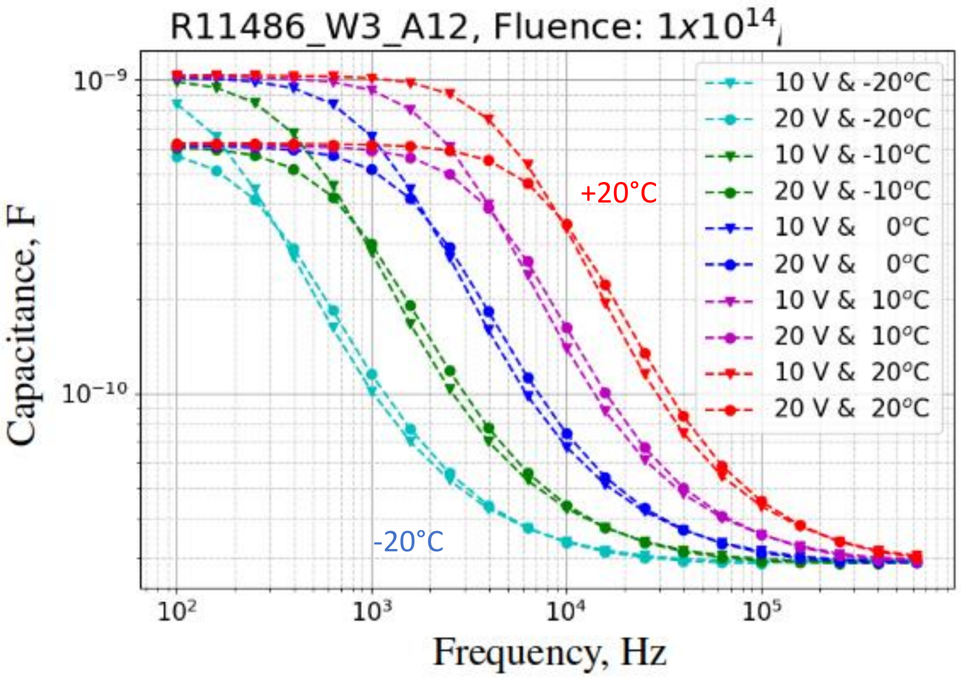
after irradiation: capacitance drops at higher measurement frequencies

Is DLTS capable to characterize defects in neutron irradiated LGADs ?

Frequency dependence

LGAD – CNM (1E+14 n_{eq}/cm^2)





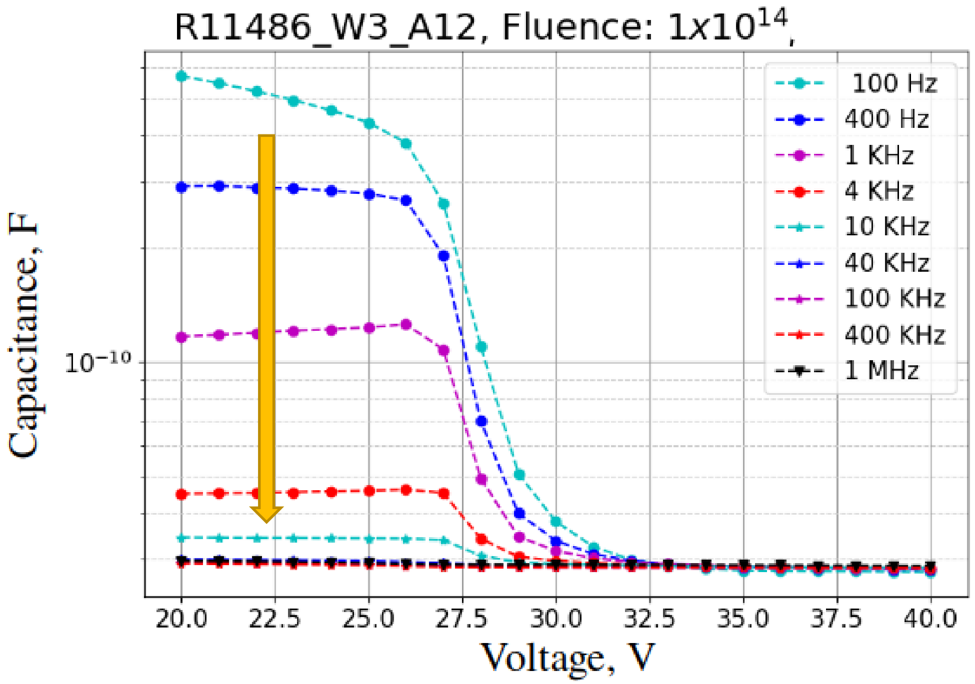
↑F → ↓C

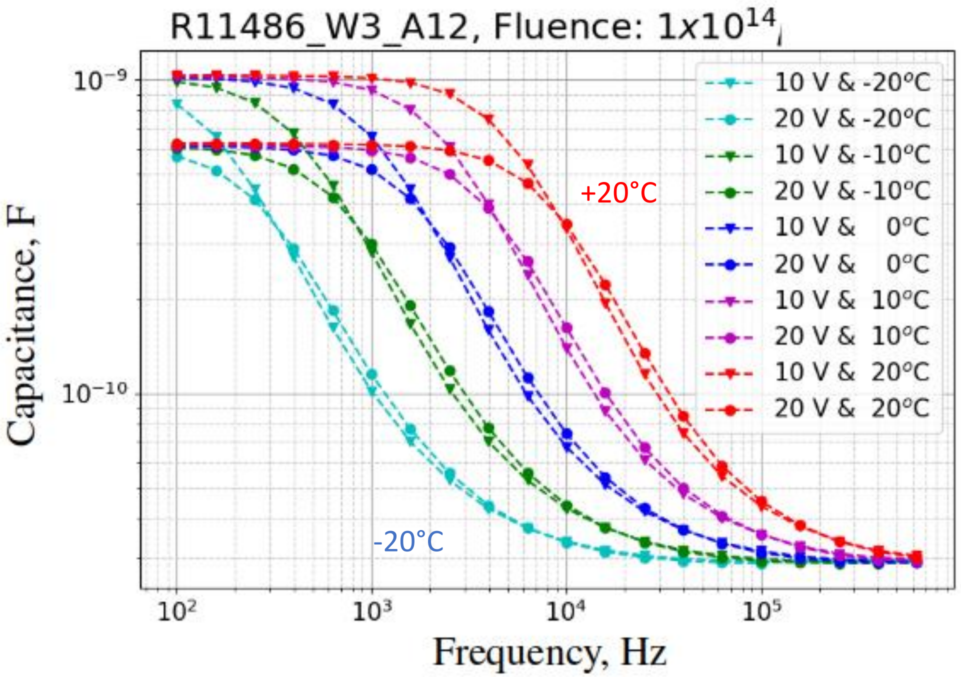
↑T → ↑C

Is DLTS capable to characterize defects in neutron irradiated LGADs ?

Frequency dependence

LGAD – CNM (1E+14 n_{eq}/cm^2)





↑F → ↓C

↑T → ↑C

DLTS defect characterization:
performed at
low T (> 20K) and high frequency (1MHz)

Capacitance in the GL drops to the bulk value

Results from DLTS measurements *<u>are not reliable</u>*
⟹ measuring defects in the GL was not successful using DLTS

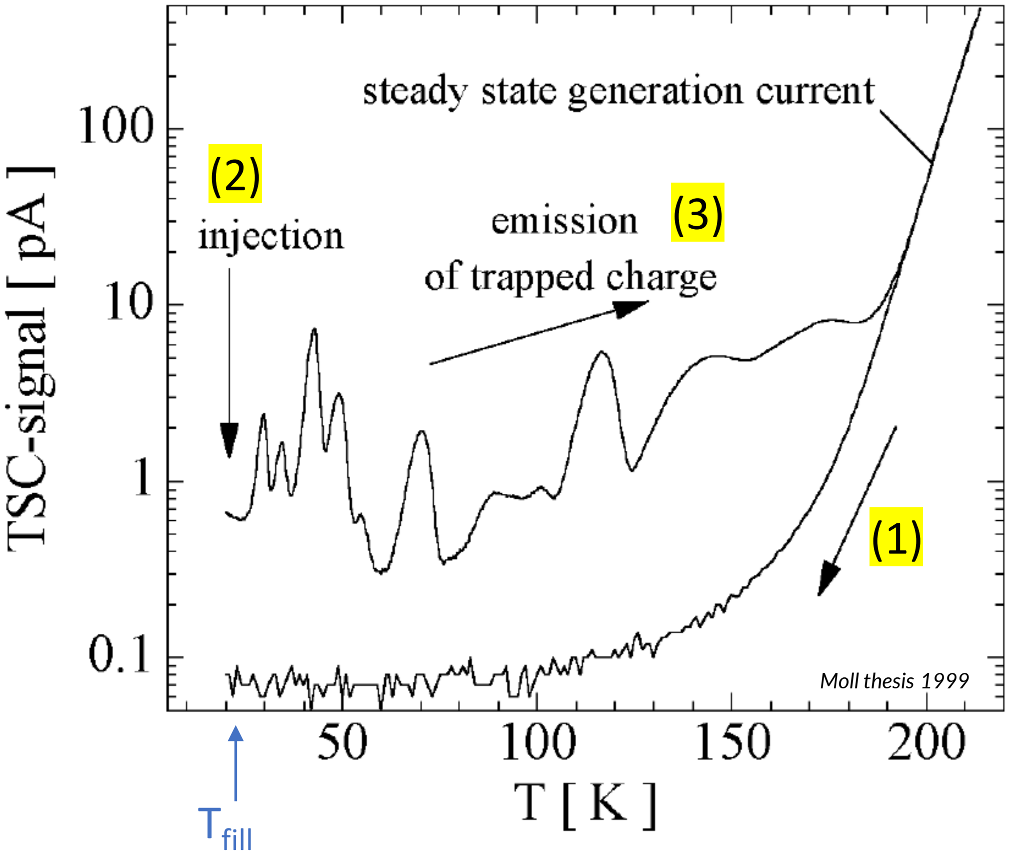
TSC studies

TSC: Thermally Stimulated Current

(1) Cooling down to T_{fill}:
junction under reverse bias → defect states free of charge carriers

(2) Filling @ T_{fill}:
Electrical (or optical) Injection pulse → injection of minority and/or majority carriers
→ occupation of defect levels in dependency of their individual capture cross-section for electrons and holes at T_{fill}

(3) Heating at a constant heating rate:
junction under reverse bias & temperature raised
→ monitoring the discharging current due to thermal emission from defect levels



Moll thesis 1999

Defect concentration calculation using the integrated peak area:

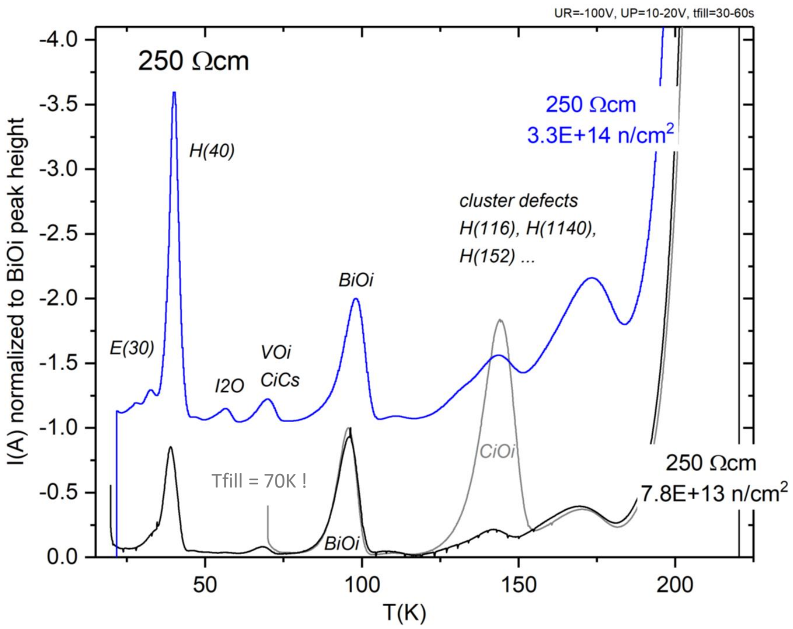
$$n_{t,0} = 2\frac{Q_t}{q_0 A W}$$

Defect studies on neutron irradiated p-type EPI diodes

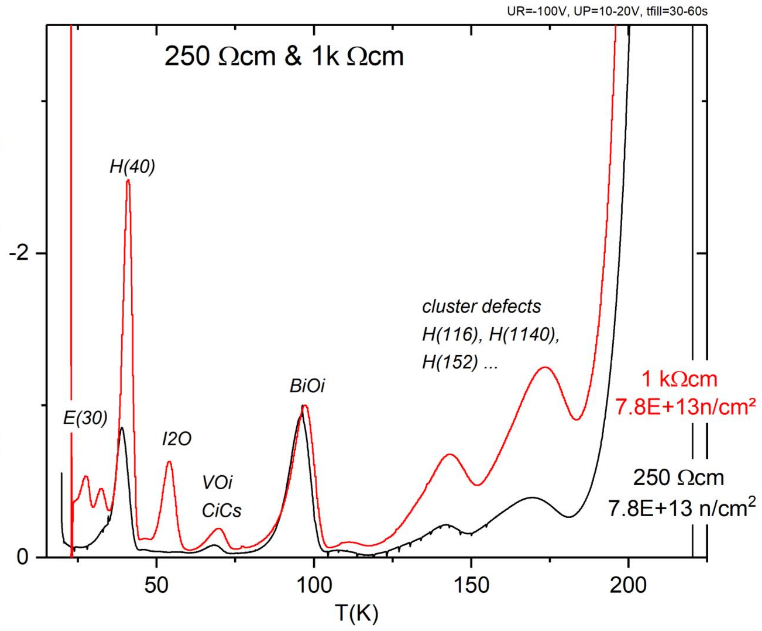
$$\mathrm{IR} = \frac{defect\ concentration}{fluence}$$

EPI-diodes:

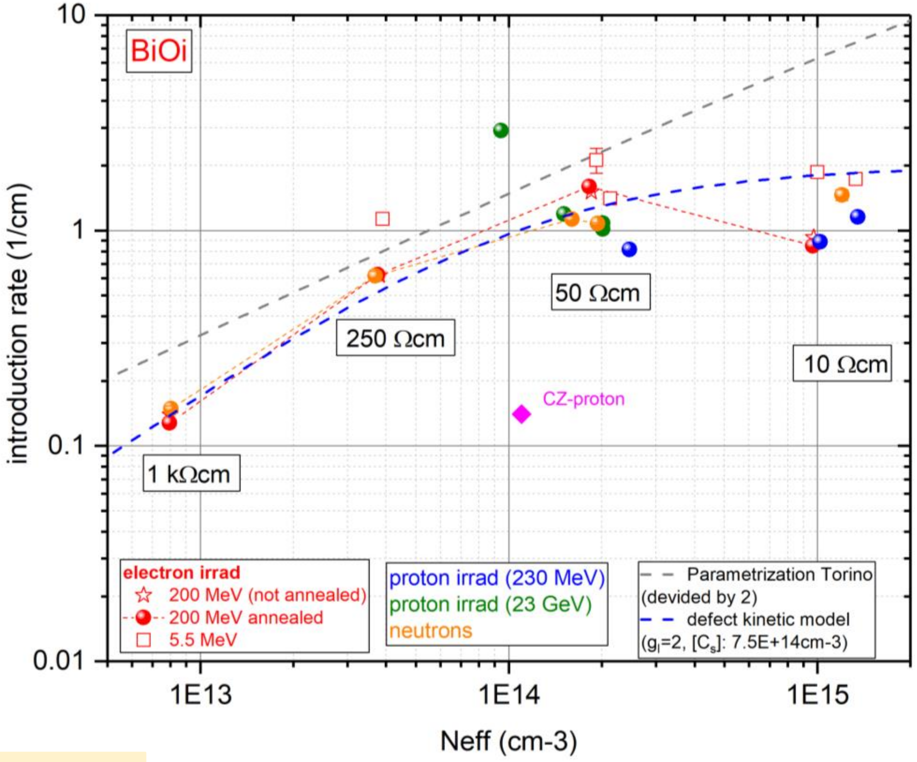
same B-doping different fluence



same fluence different B-doping



IR rate vs. initial B-concentration:



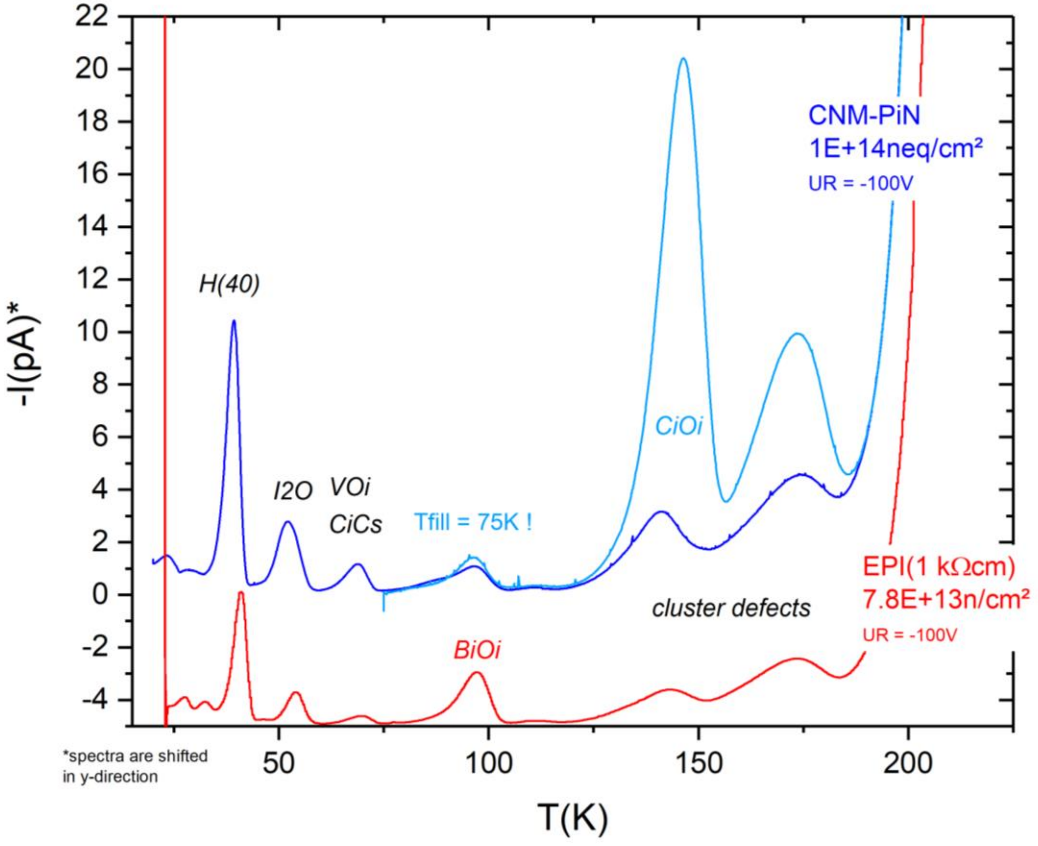
- ☐ higher fluence: defect ratio changes (e.g. more cluster related defects)
- ☐ low resistivity material: BiOi defect dominates
- ☐ BiOi concentration increases with fluence
- ☐ IR dependence on fluence and N_{eff} (increase if ϕ < 1E+14 n_{eq}/cm² & N_{eff} < 2E+14 cm^{-3})

For details of the parametrization see:

- *Moll, PoS 2019 VERTEX*
- *Ferrero et al. NIMA 919 (2019) 16-26*

TSC studies on neutron irradiated PiN diodes

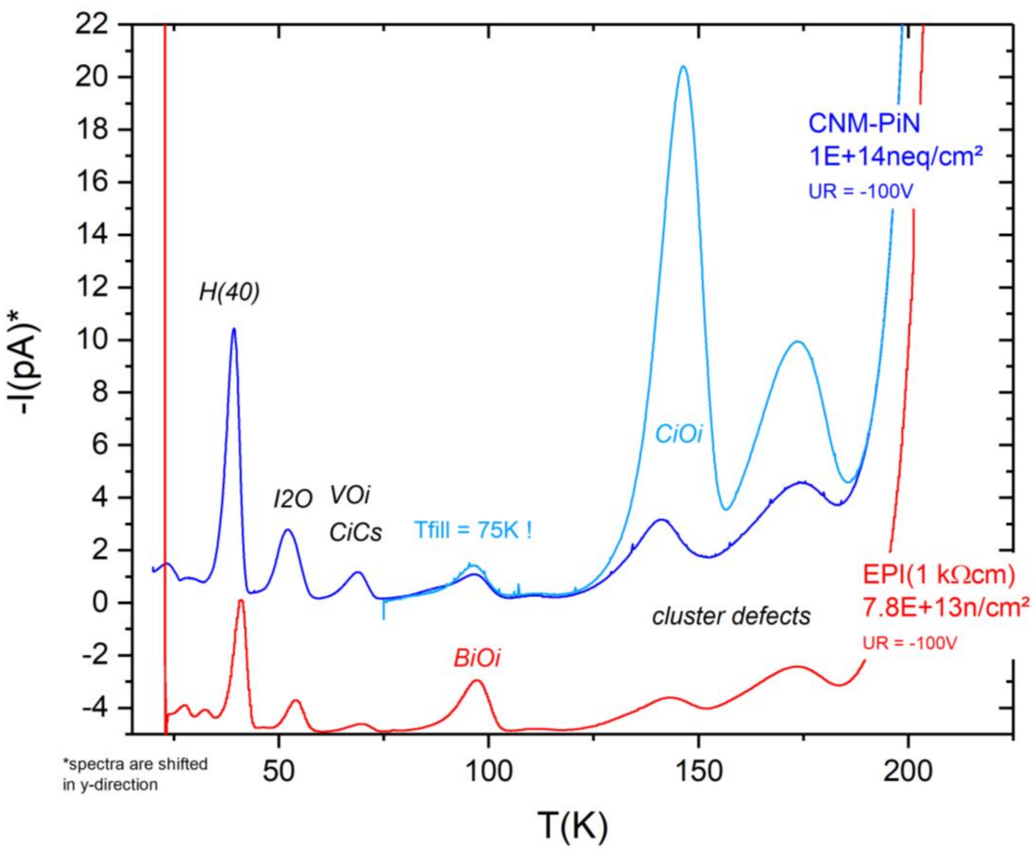
Comparison PiN diode and EPI pad diode (PiN-diode: higher fluence!!)

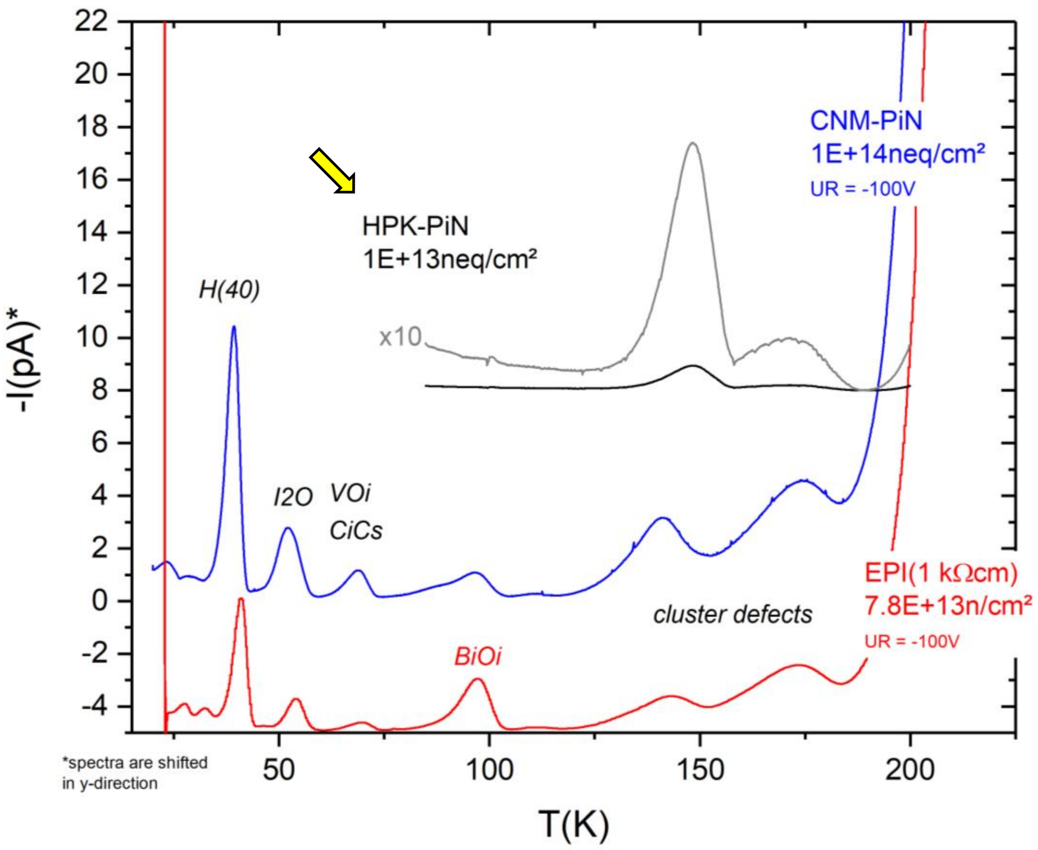


- ☐ Comparable defects formed

TSC studies on neutron irradiated PiN diodes

Comparison PiN diode and EPI pad diode (PiN-diode: higher fluence!!)

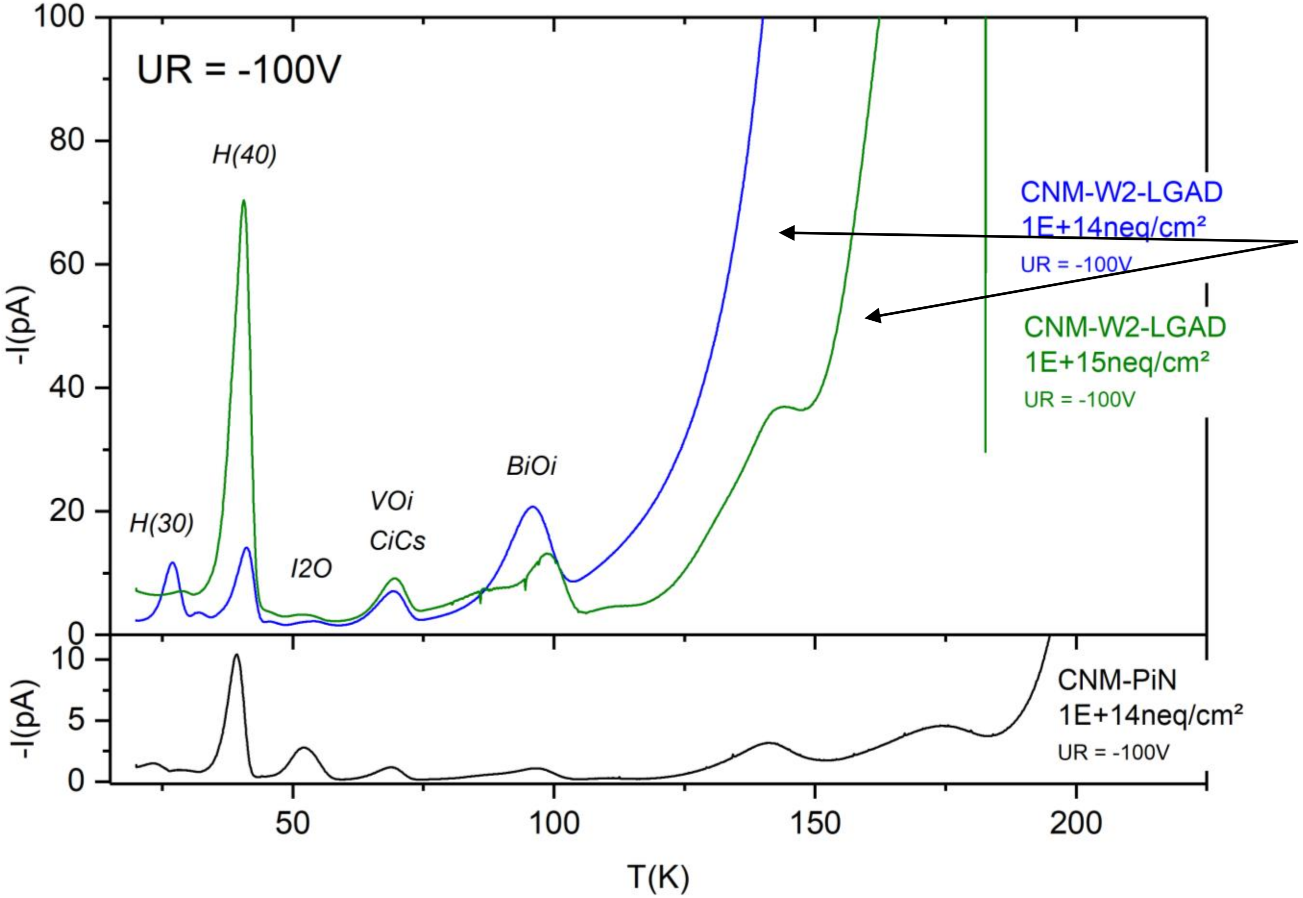




- ☐ HPK PiN lower fluence: significantly less defects detected (defects in the T-range of 125K - 200K)

TSC studies on neutron irradiated LGADs (depletion of the full device)

Comparison LGADs with PiN diode (depletion over the full device):



☐ identification of radiation induced defects possible

Charge carrier amplification:

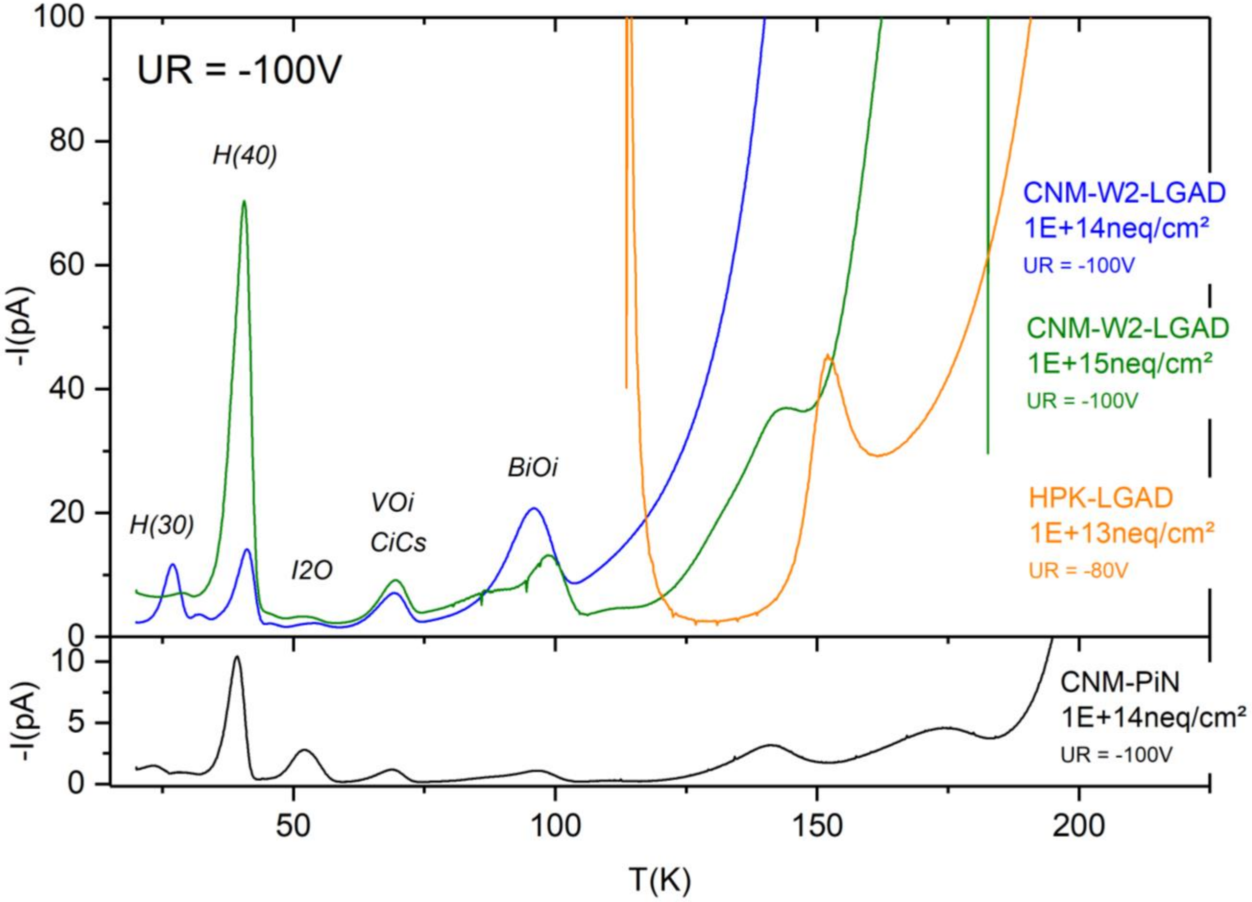
☐ background leakage current starts to increase already at T < 150K:
⇒ *defect levels in this range not detectable*

☐ current amplification in the LGAD (even at low T):
… in dependency of the gain-layer deactivation due to radiation
⇒ *exact determination of the defects concentrations not possible*

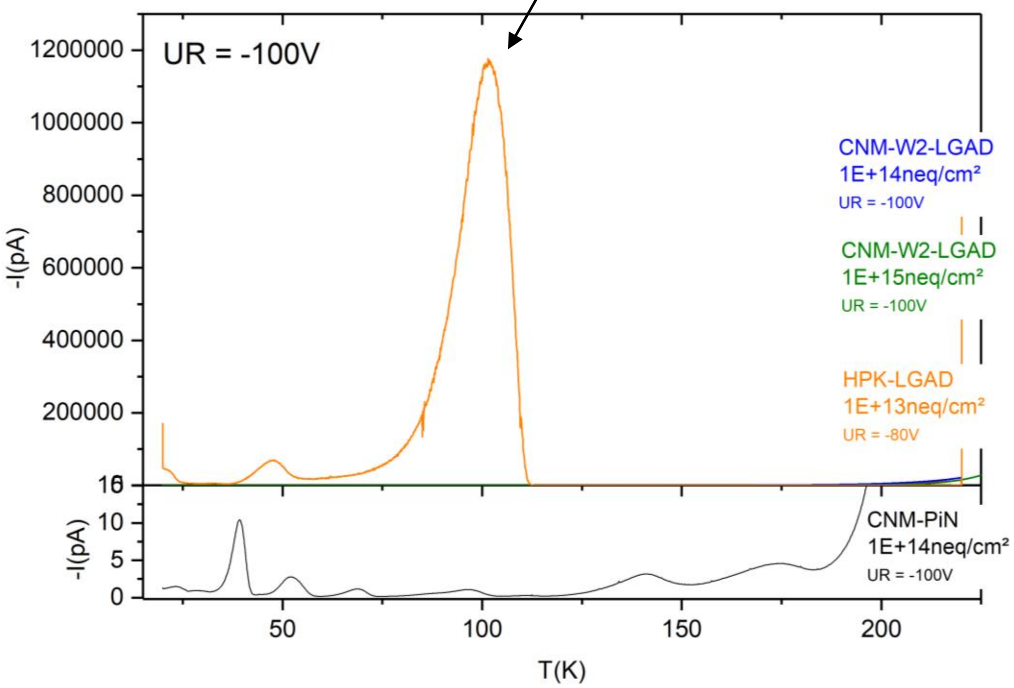
!! BiOi-IR ~ 1.8 cm^{-1} (lower fluence)
BiOi-IR ~ 0.2 cm^{-1} (higher fluence)

☐ signal mainly from the bulk (?)

TSC studies on neutron irradiated LGADs (depletion of the full device)



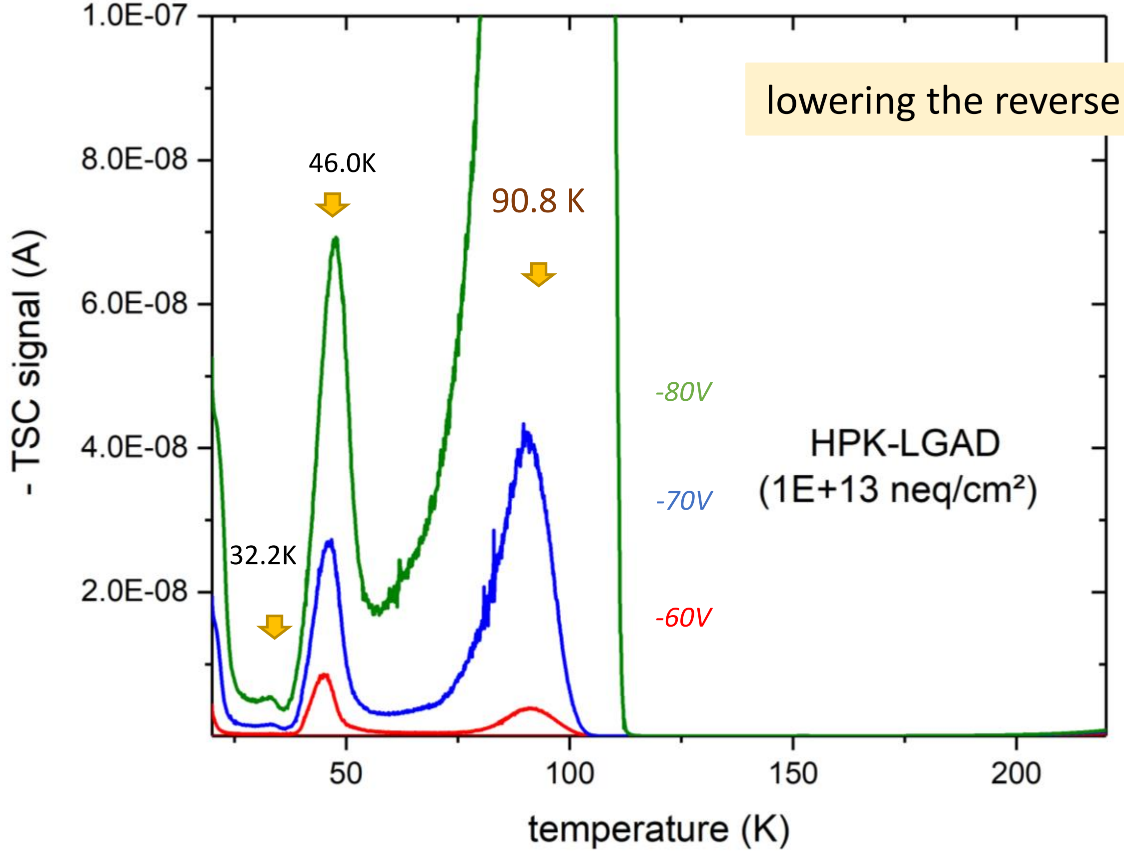
Defect current signal very high (strong amplification effect)



TSC studies on neutron irradiated LGADs (variation of the reverse bias)

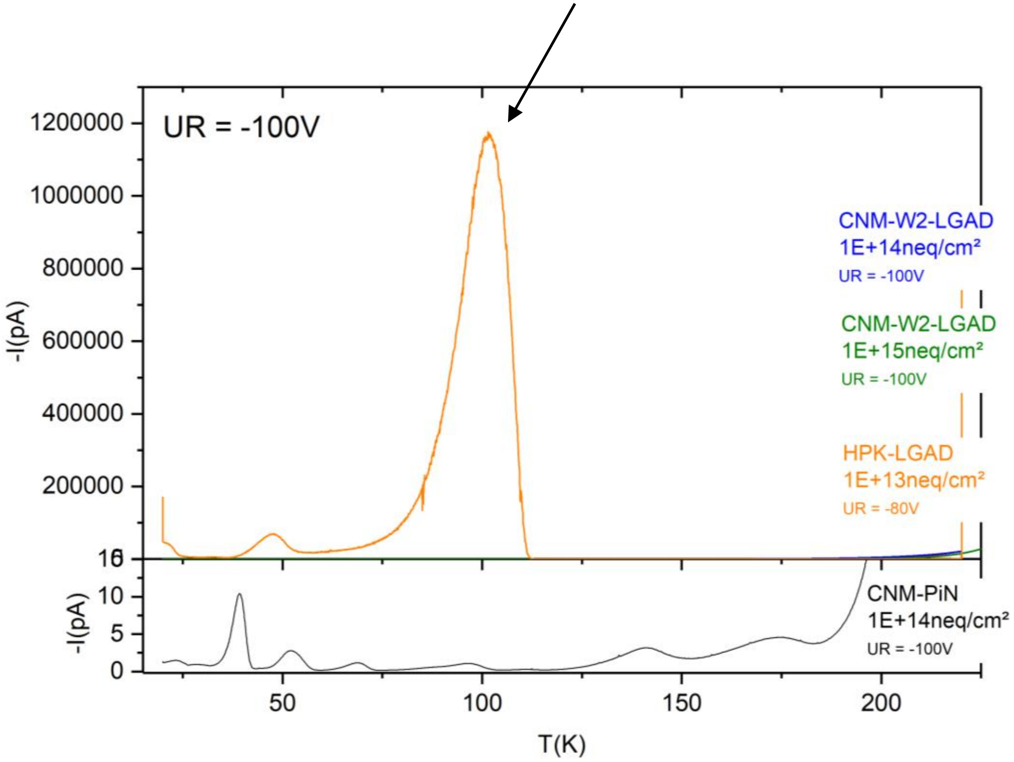
HPK-LGAD: 1E+13 neq/cm²

$U_{GL\text{-}depl.}$: -50V



lowering the reverse bias

Defect current signal very high (strong amplification effect)



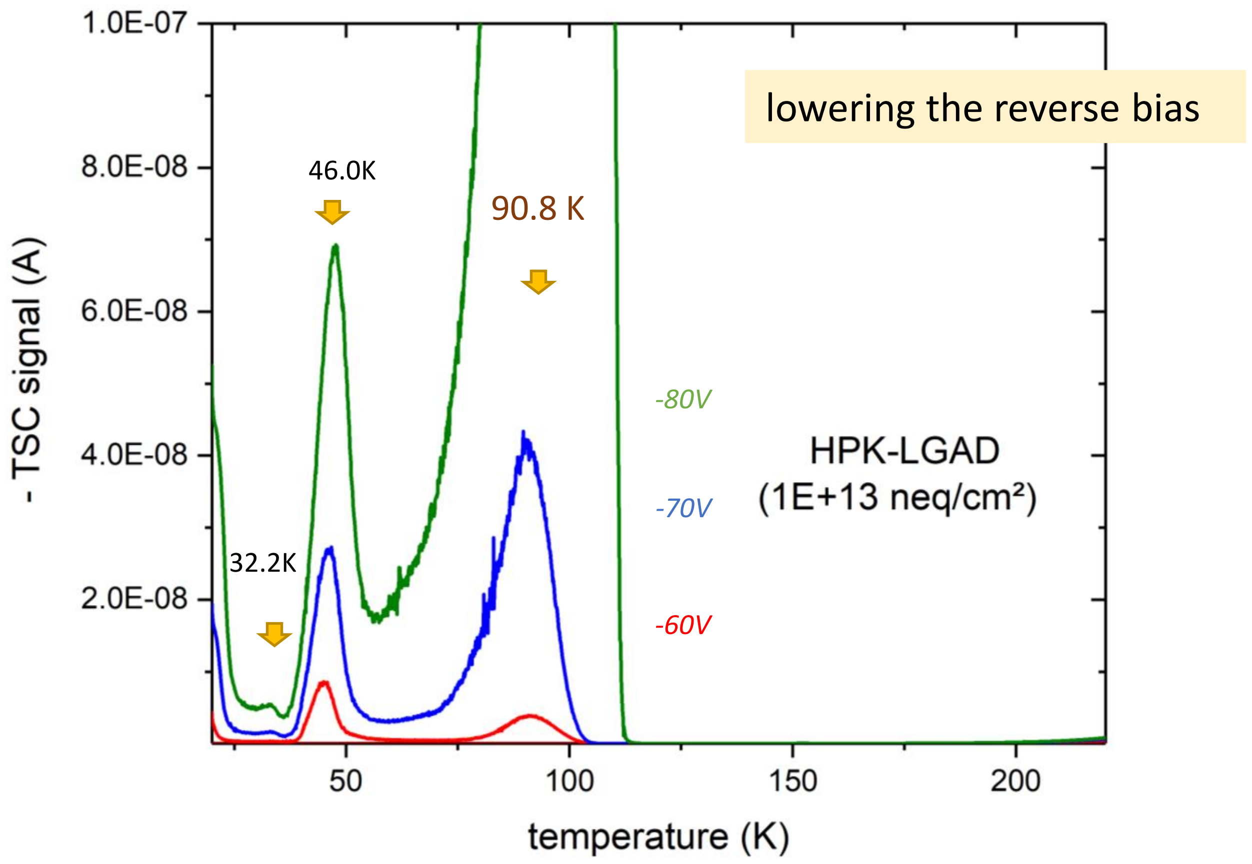
- ☐ defect induced TSC signal decreases

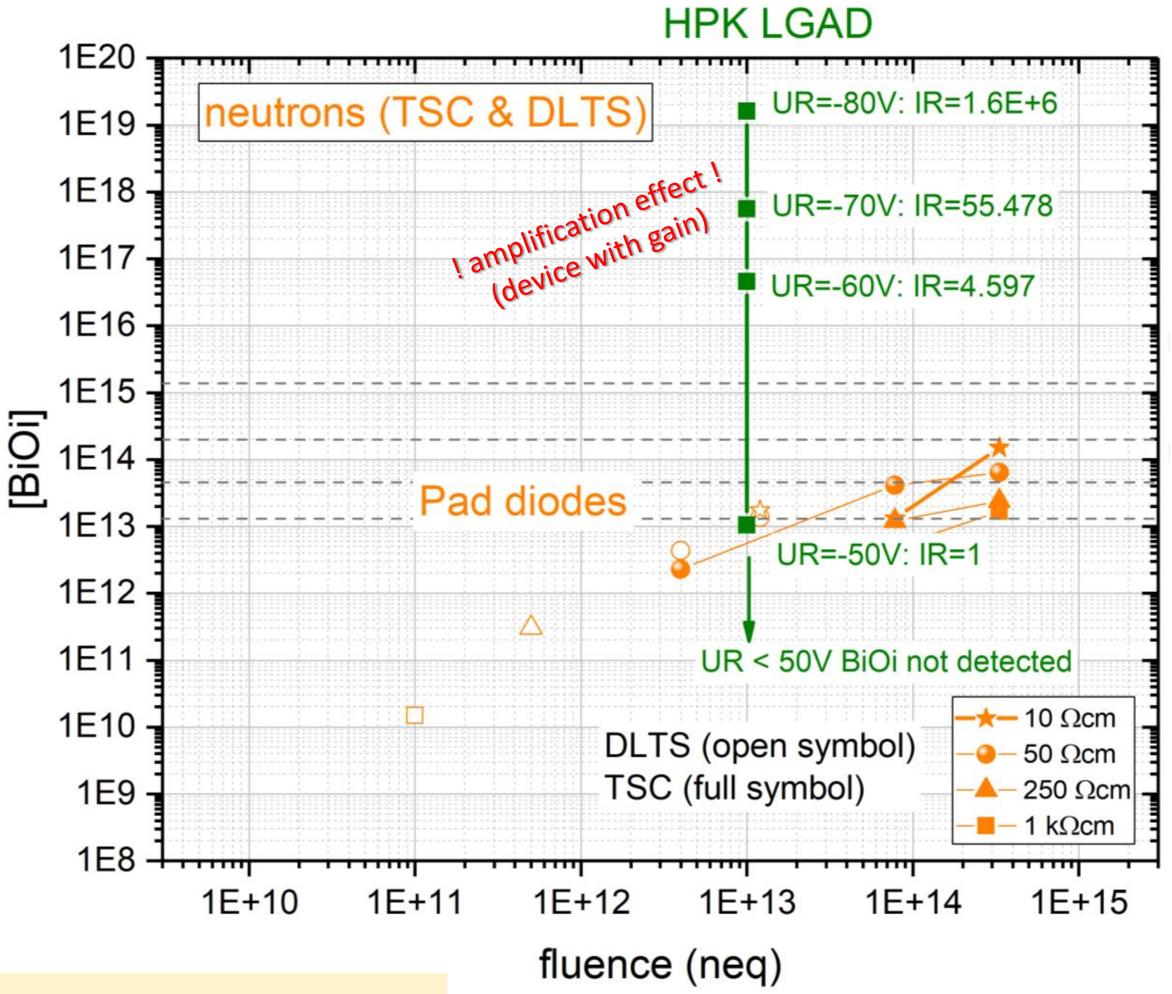
… Defect current signal (90.8K) @ UR=-50V about 1pA ⇒ @ -80V signal about 1.1E+6 higher

TSC studies on neutron irradiated LGADs (variation of the reverse bias)

HPK-LGAD: 1E+13 neq/cm²

$U_{GL\text{-}depl.}$: -50V


lowering the reverse bias



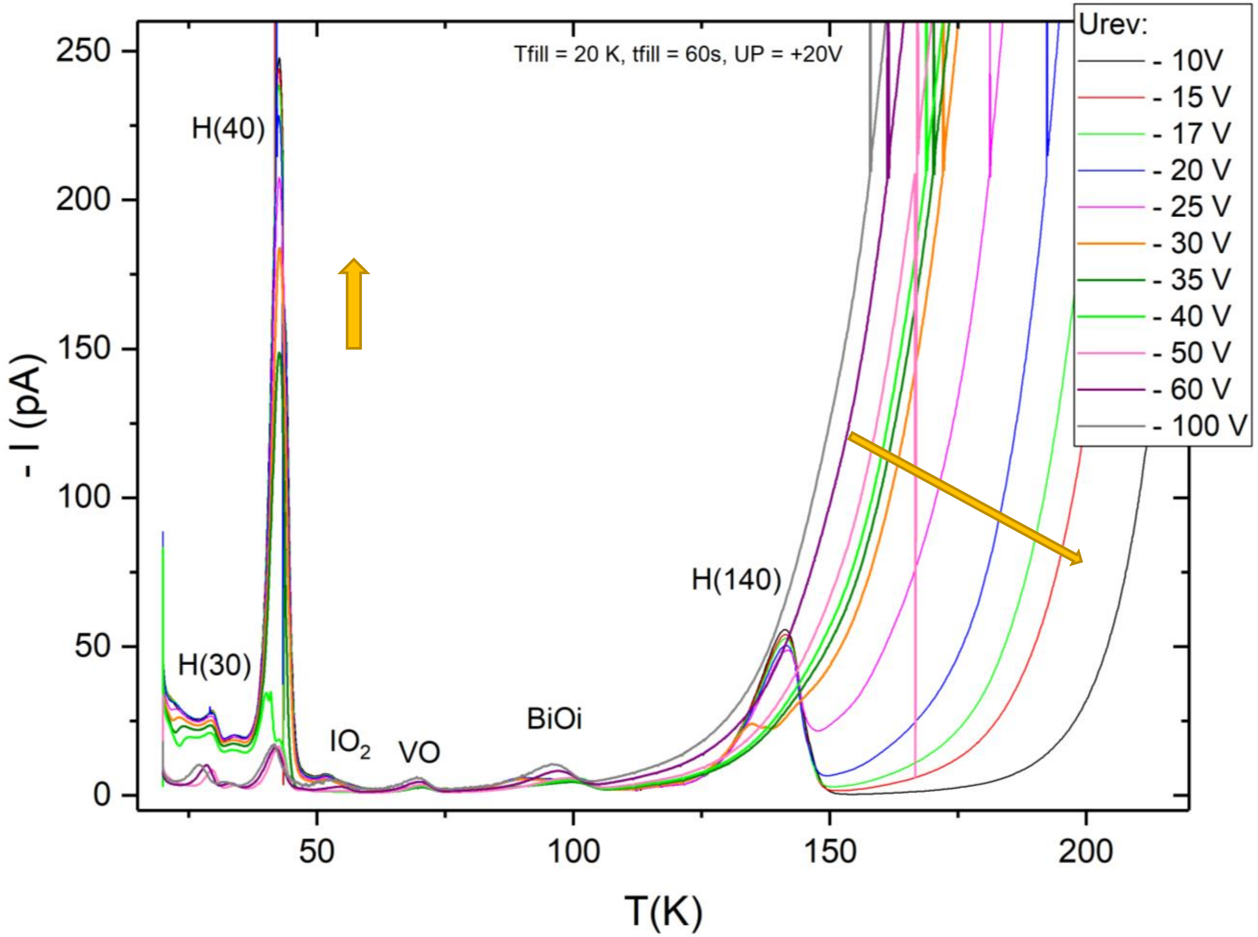
☐ defect induced TSC signal decreases

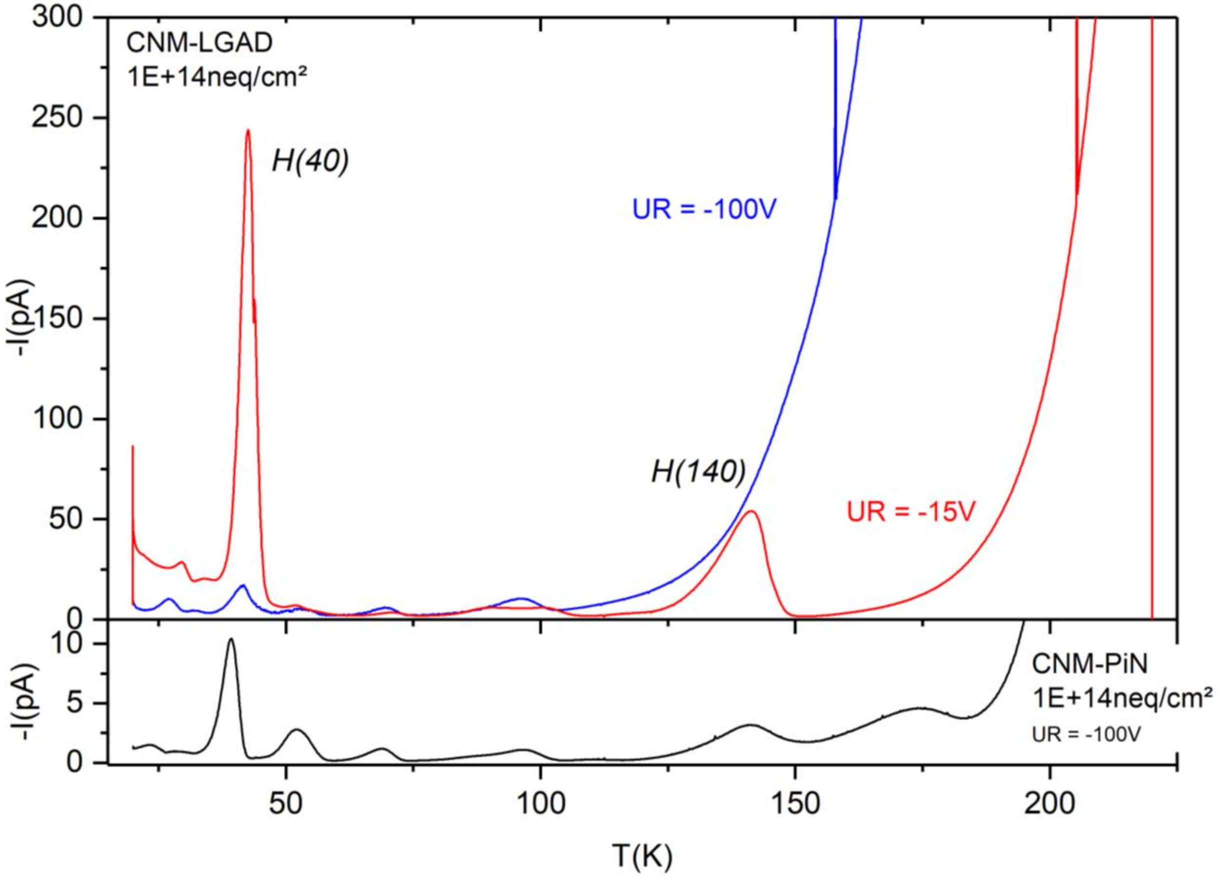
… Defect current signal (90.8K) @ UR=-50V about 1pA ⇒ @ -80V signal about 1.1E+6 higher

TSC studies on neutron irradiated LGADs (variation of the reverse bias)

CNM-LGAD: 1E+14 neq/cm²
$U_{GL\text{-}depl.}$: -30V

lowering the reverse bias:

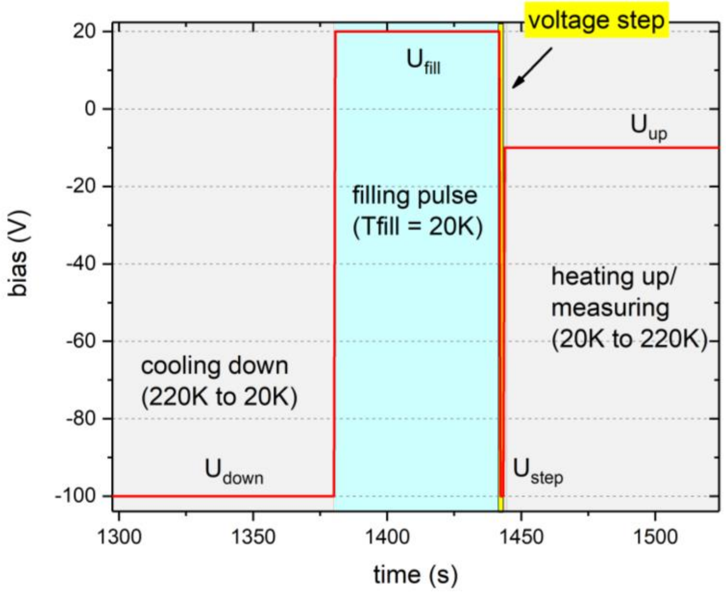




background current amplification decreases

TSC studies on neutron irradiated LGADs (internal fields)

TSC measurement cycle:



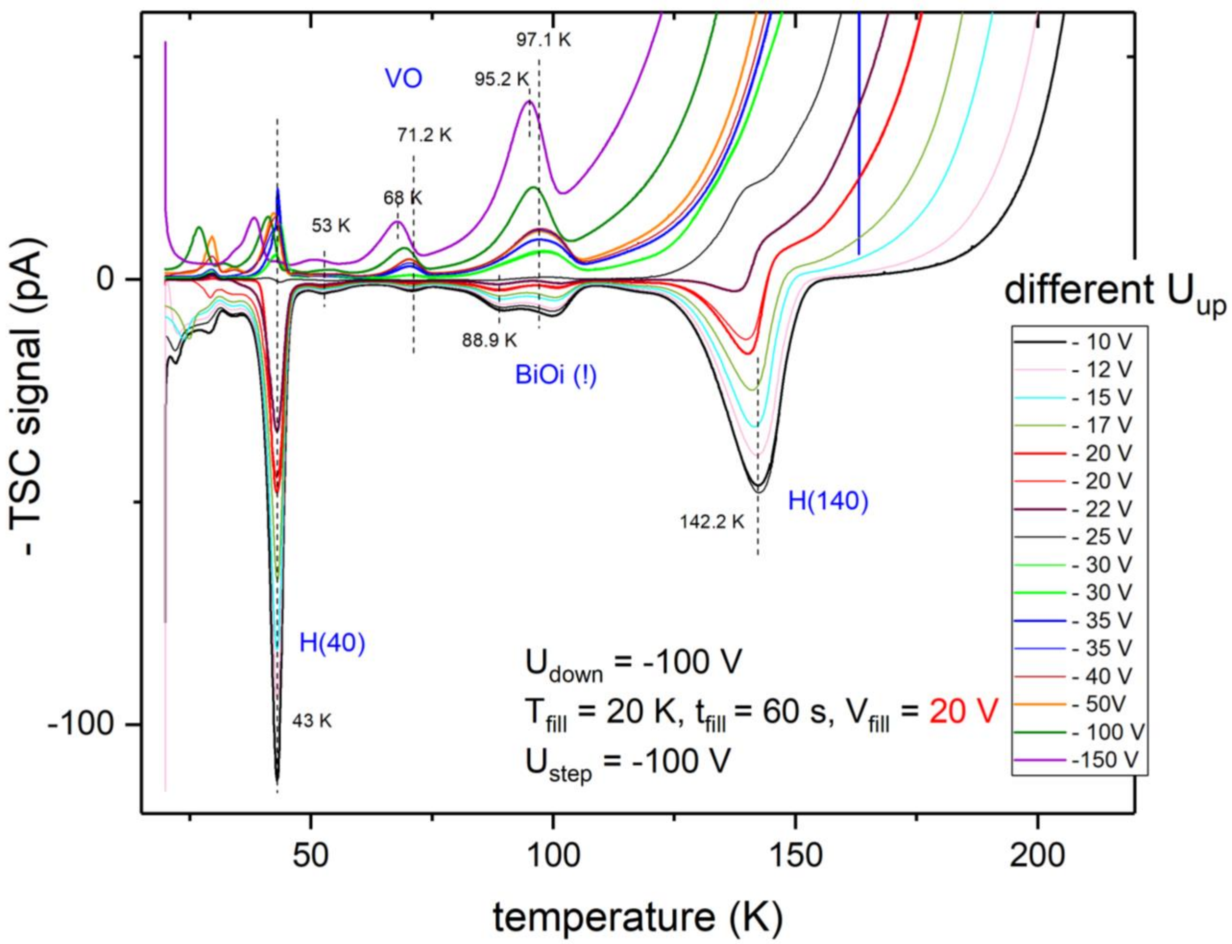
☐ TSC signal intensity & sign depend on the reverse bias U_{up}

☐ Sign changes at U_{up} about - 25 V

☐ If $U_{up} > U_{GL\text{-}depl}$: signal sign as „expected“

CNM – 1E+14 neq/cm^2

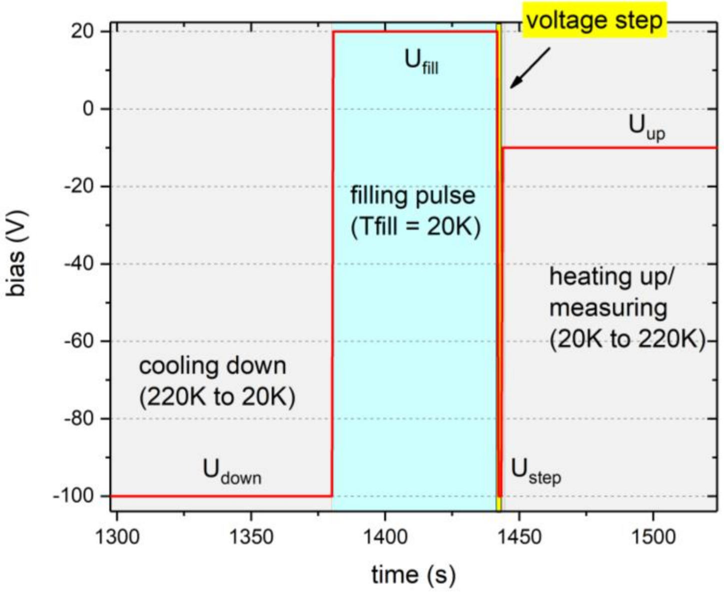
($U_{GL\text{-}depl\text{-}}$ ~ -30V)



03.03.2022 anja.himmerlich@cern.ch

TSC studies on neutron irradiated LGADs (internal fields)

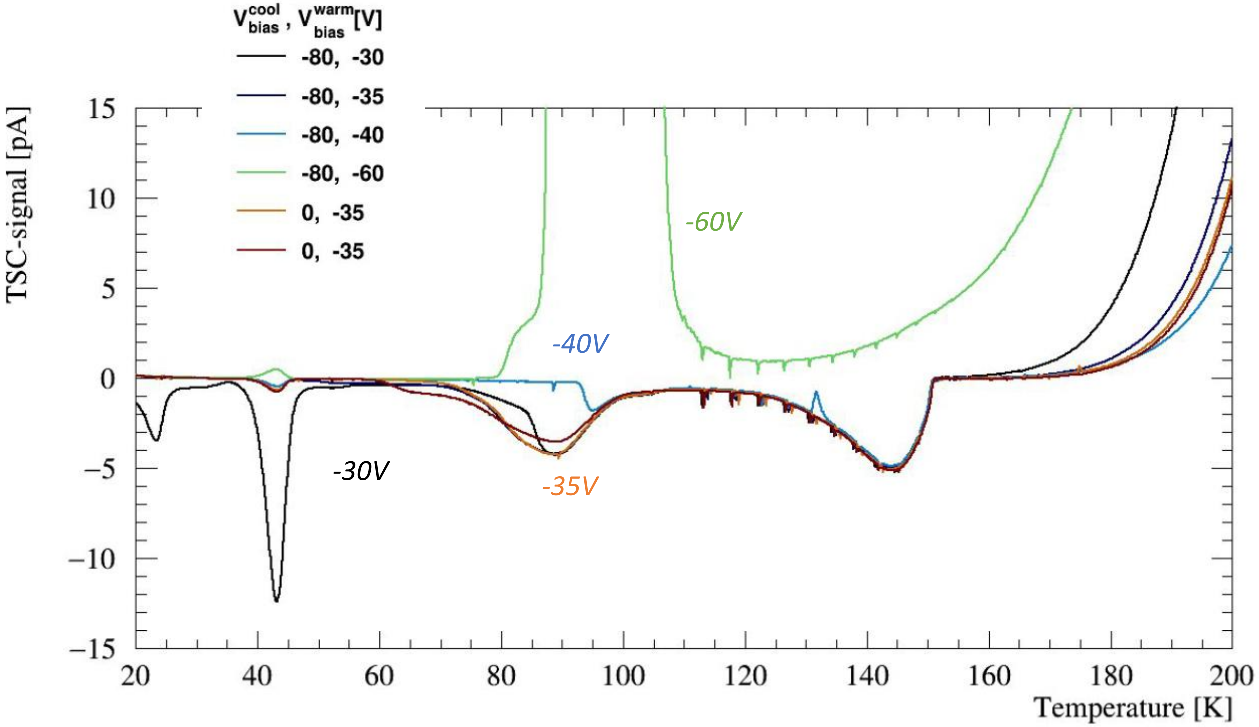
TSC measurement cycle:



„*Changes in the TSC current sign due to* ***internal residual E-fields*** *induced by high defect concentrations after high neutron Irradiation*“
⟹ *M. Bruzzi et al. NIMA 2010 & PoS 2009*

HPK – 1E+13 neq/cm²
($U_{GL\text{-}depl}$ ~ -50V)

- ❑ *Sign change of the TSC signal at U_{up} about - 50 V*



internal electrical polarization fields here observed in irrad. LGADs: induce an inverse current signal

03.03.2022 *anja.himmerlich@cern.ch*

Summary

- DLTS & TSC characterization of HPK & CNM LGADs & PiNs irradiated with neutrons (1E+13 – 1E+15 neq/cm²)

- **DLTS** studies of LGADs restricted by the capacitance drop observed after irradiation

- **TSC:** Identification of irradiation induces defects possible
  ⟹ higher irradiation: more defects & less gain
  ⟹ assignment of defect levels to the gain- or bulk-area is challenging

  ! due to the gain layer:
  pronounced charge multiplication effect & leakage current amplification in the LGADs
    - effect decreases with higher radiation (GL destruction)
    - restrict defect determination & defect concentration determinations
    - gain effects observable also at very low temperatures

- Defect induced internal polarization fields that influence the sign of the TSC current signal

Outlook

*… using defect parameters from DLTS & TSC to **simulate TSC spectra** + **comparison of the PiN & LGAD data***
… ongoing identification of irradiation induced defects that degradate the device performance

… investigate highly irradiated, highly B-doped (1E+17 cm^{-3}) Si pad diodes that mimic the LGAD gain layer

Thank you for your attention!

03.03.2022 anja.himmerlich@cern.ch