First Irradiation Studies of the novel nLGAD Concept

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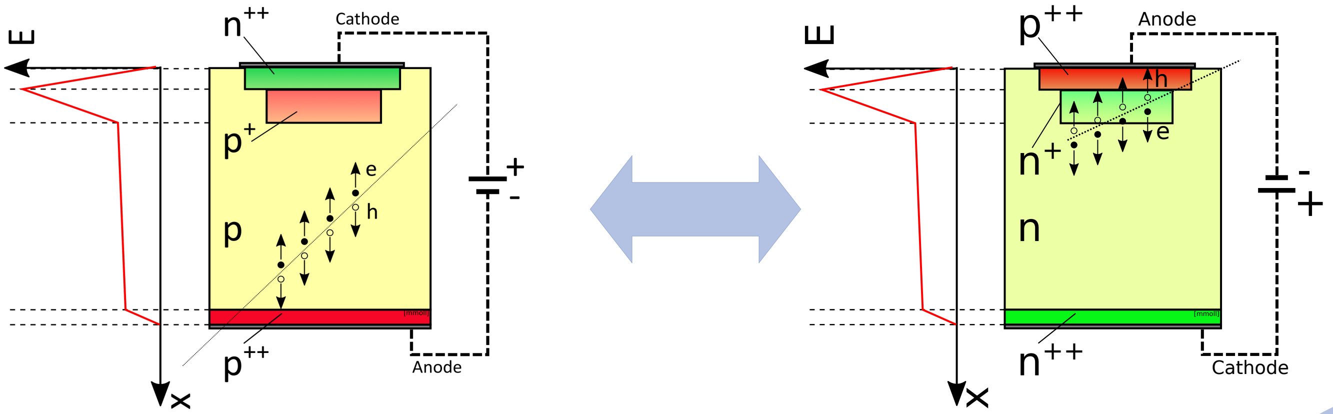
Overview

- **The novel nLGAD concept**
  - Devices under test
- **Irradiation campaigns**
  - High fluence
  - Low fluence
- **Electrical characterization of the devices after irradiation**
- **Laser characterization**
  - Transient Current Technique with UV laser
  - Two Photon Absorption - TCT

The nLGAD Concept

- LGADs implemented as $n^{++}-p^{+}-p$, show outstanding performance for high-energy charged particle detection
- HEP LGADs show poor detection performance for low penetrating particles. Thus, the novel nLGAD concept was designed and fabricated at IMB-CNM [1]
- Applications: low-energy protons, soft X-rays, UV
- Synergy with HEP R&D: the compensated LGAD concept [2] and donor removal in the gain layer



The novel nLGAD concept

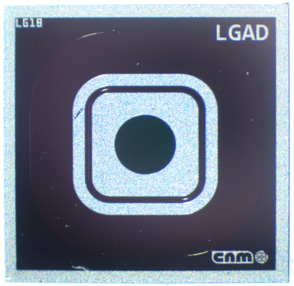
Opposite conductivity type compared to the HEP LGAD layers

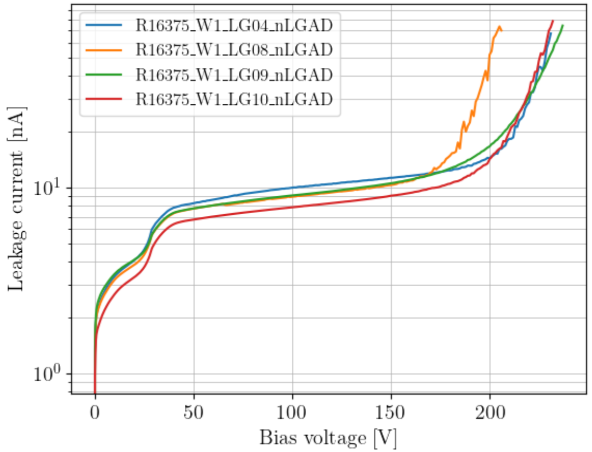
Difference in multiplication mechanism for holes and electrons

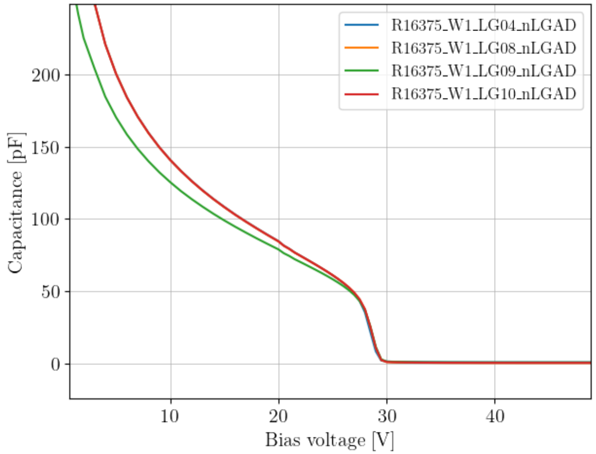
Detection performance is optimized for low penetrating particles

Devices Under Test

- Sample info:
  - n-type
  - Resistivity > 1 kΩcm
  - Thickness 275 μm, Active area 1.3 x 1.3 mm^2 or 1 x 1 mm^2 (samples with and without opening in the metallization)
  - As can be seen from IV/CV characteristics before irradiation: V_{gl} ~ 30 V, breakdown ~ 200 V before irradiation







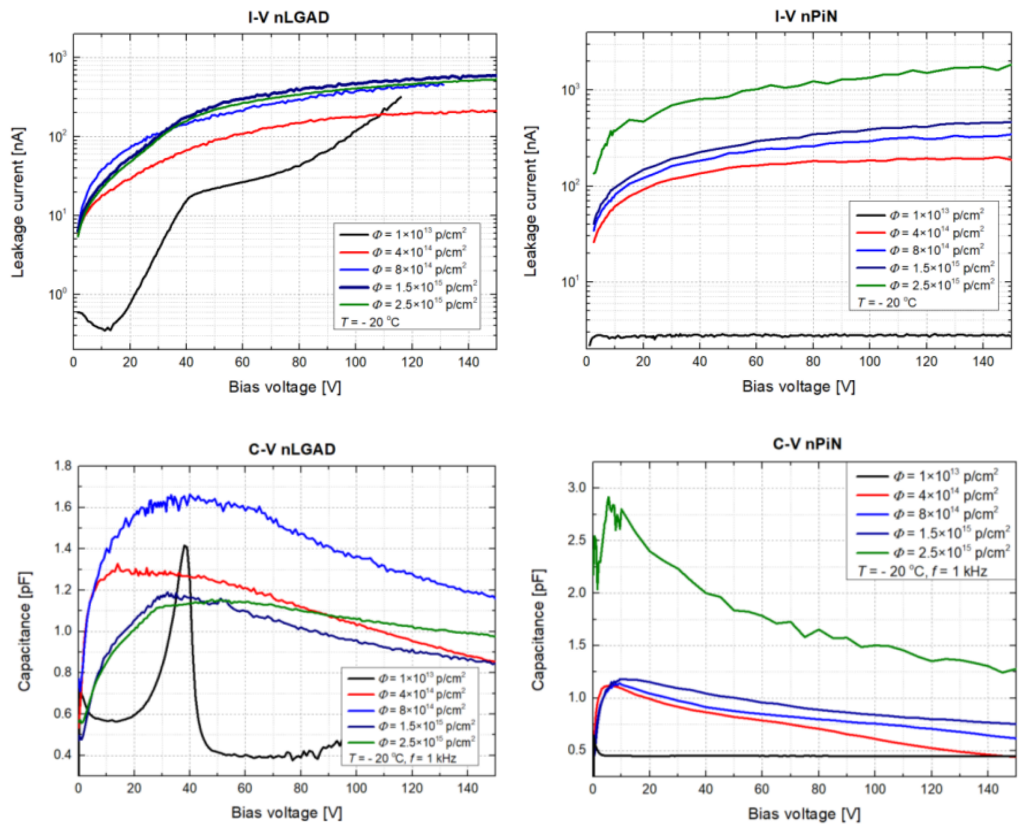
High Fluence Irradiation

- First irradiation campaign with nLGADs: HEP fluences from $1 \cdot 10^{13}$ p/cm^2 up to $2.5 \cdot 10^{15}$ p/cm^2
- 23 GeV protons from PS-IRRAD (CERN)

High fluence step-by-step irradiation		
Sample type	**Name**	**Fluence [p/cm^2]**
nLGAD	R16375_W1_51015_nLGAD	$1 \cdot 10^{13}$
	R16375_W1_51019_nLGAD	$4 \cdot 10^{14}$
	R16375_W1_51042_nLGAD	$8 \cdot 10^{14}$
	R16375_W1_51044_nLGAD	$1.5 \cdot 10^{15}$
	R16375_W1_51058_nLGAD	$2.5 \cdot 10^{15}$
PiN	R16375_W4_51004_PiN	$1 \cdot 10^{13}$
	R16375_W4_51043_PiN	$4 \cdot 10^{14}$
	R16375_W4_51044_PiN	$8 \cdot 10^{14}$
	R16375_W4_51082_PiN	$1.5 \cdot 10^{15}$
	R16375_W4_51083_PiN	$2.5 \cdot 10^{15}$

High Fluence Irradiation

- First measurements of nLGADs irradiated to HEP fluences performed within the scope of a CERN summer student project in our group
- No characteristic gain layer depletion anymore
- Unexpected effects like decreasing leakage current after 200 V
- **Probably fluences too high!** We suspect type-inverison, that affects the shapes of the curves compared to HEP LGADs
- For more information on the *High Fluence Irradiation*: have a look at the summer student report [3]



Measurements performed by
M. Biveinytė

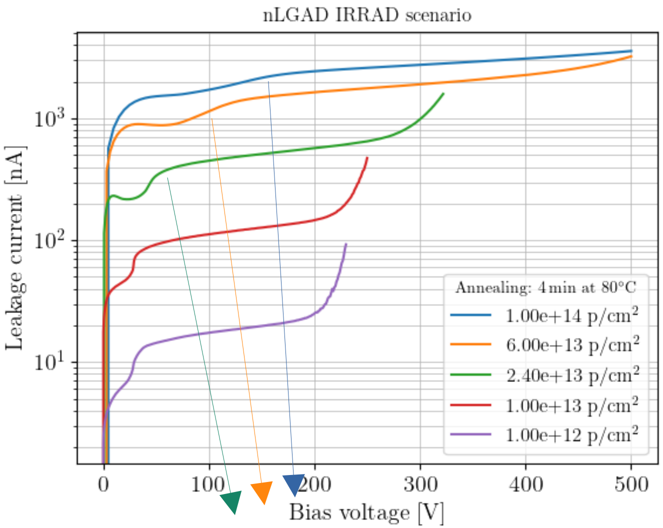
Low Fluence Irradiation

- Fluences of the 1st irradiation campaign were too high for studies on this devices
- We performed a step-by-step irradiation with one nLGAD and one reference PiN, starting from $1 \cdot 10^{12}$ p/cm^2 and adding up to a final fluence of $1 \cdot 10^{14}$ p/cm^2 with measurements in between
- 23 GeV protons from PS-IRRAD (CERN)
- Samples with metal opening used → laser characterization can be performed

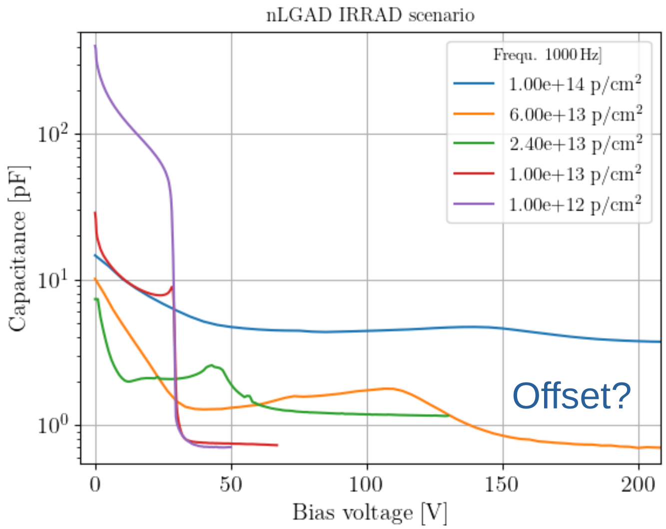
Low fluence step-by-step irradiation		
Sample type	**Name**	**Fluence [p/cm²]**
nLGAD	R16375_W1_LG04_nLGAD	• $1 \cdot 10^{12}$ • $2 \cdot 10^{12}$ • $4 \cdot 10^{12}$ • $6 \cdot 10^{12}$ • $8 \cdot 10^{12}$ • $1 \cdot 10^{13}$ • $2.4 \cdot 10^{13}$ • $6 \cdot 10^{13}$ • $1 \cdot 10^{14}$
PiN	R16375_W1_LG16_PiN	

Electrical Characterization

- Measured at 20ºC; Annealing: 4 min at 80ºC; CV Measurement frequency: 1000 Hz
- Change in IV/CV characteristics:
  - From $1 \cdot 10^{12}$ p/cm^2 to $1 \cdot 10^{13}$ p/cm^2 no big changes (therefore not all curves displayed → backup)
  - Assumption for "dip" in IV at $2.4 \cdot 10^{13}$ p/cm^2 (κ = 0.62 → $1.5 \cdot 10^{13}$ n_{eq}) : type-inversion, field starts building from the back
  - Shift of breakdown for two largest fluences connected to reduced impact ionization (→ gain)?

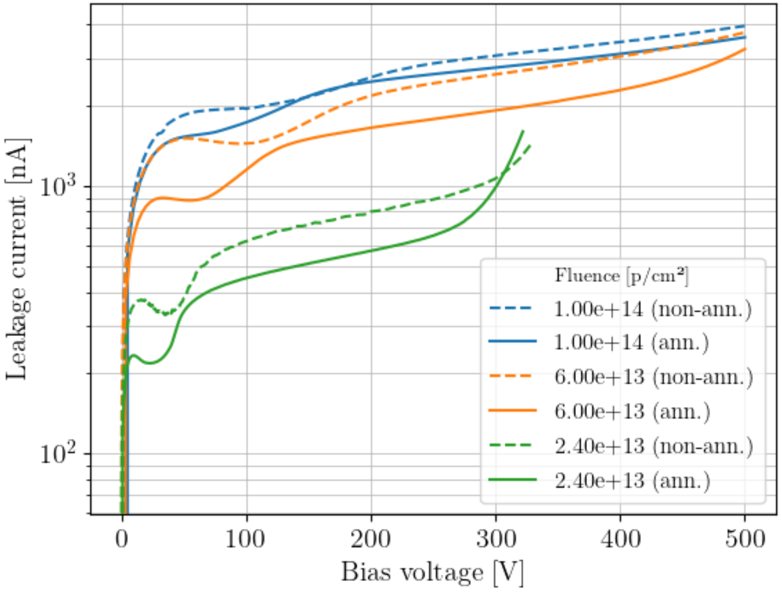


"Dip" appears at 2.4e14 p/cm^2 around V_{gl} and then flattens out



Electrical Characterization II

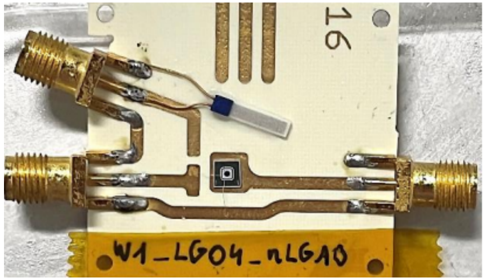
- Annealing after every irradiation step for 4 min at 80ºC
- Not only leakage current decreases with annealing, but also position of the “dip” indicating type-inversion changes

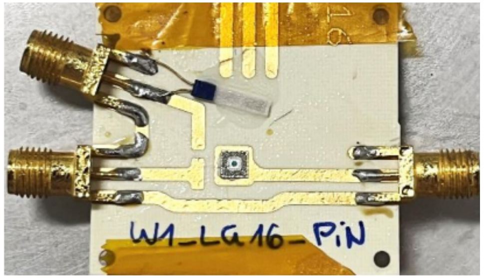


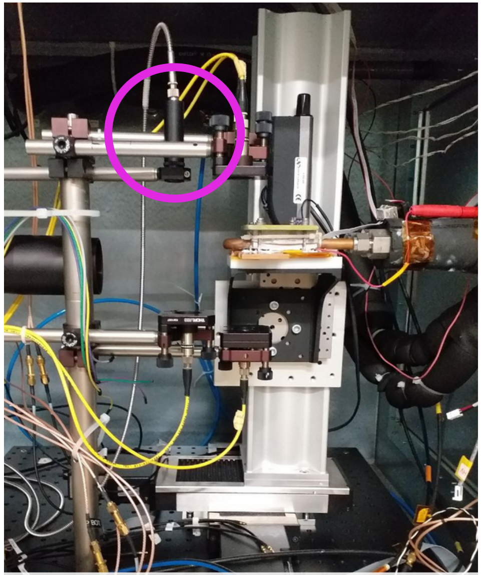
UV TCT

- **In nLGADs:**

  Gain (IR) < Gain (UV) because electrons mainly trigger the avalanche mechanism for UV, which is low penetrating in silicon, and holes for IR (impact ionization rate is higher for electrons than for holes)
- UV laser installed at the TCT setup at the SSD lab (CERN)
- Wavelength of the laser: λ = 375 nm





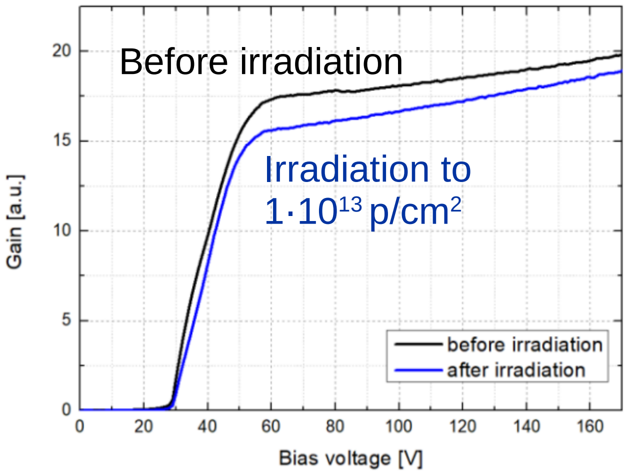


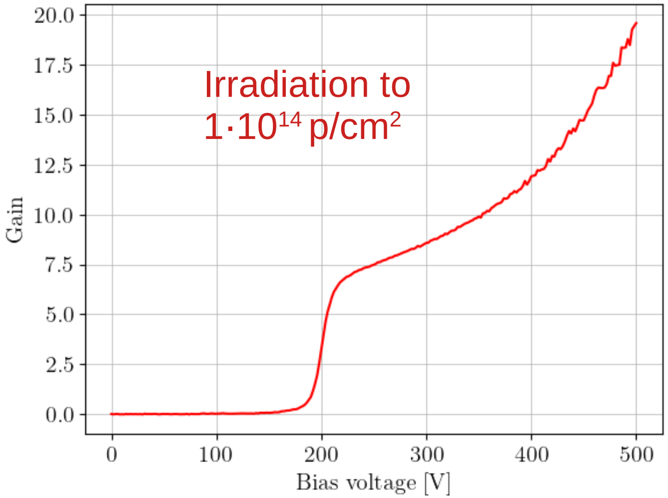
TCT optical system and linear stage

UV TCT: Gain

- Collected charge of nLGAD / Collected charge of PiN: $Gain[V] = \frac{CC_{LAGD}[V]}{CC_{PIN}[V \geq V_{FD}]}$

- Different depletion voltage after type-inversion, for same range not comparable (before irradiation sensor reaches breakdown before $1 \cdot 10^{14}$ p/cm^2 sensor even is fully depleted at ~200V)
- (Conditions slightly different: not irradiated and $1 \cdot 10^{13}$ p/cm^2 measured at +20ºC; due to higher leakage current $1 \cdot 10^{14}$ p/cm^2 measured at -20ºC)



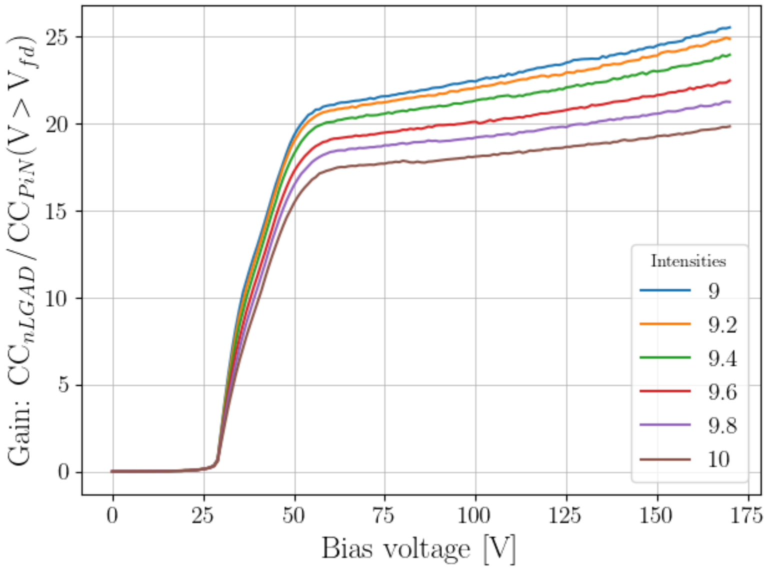


Measurements performed by M. Biveinytė

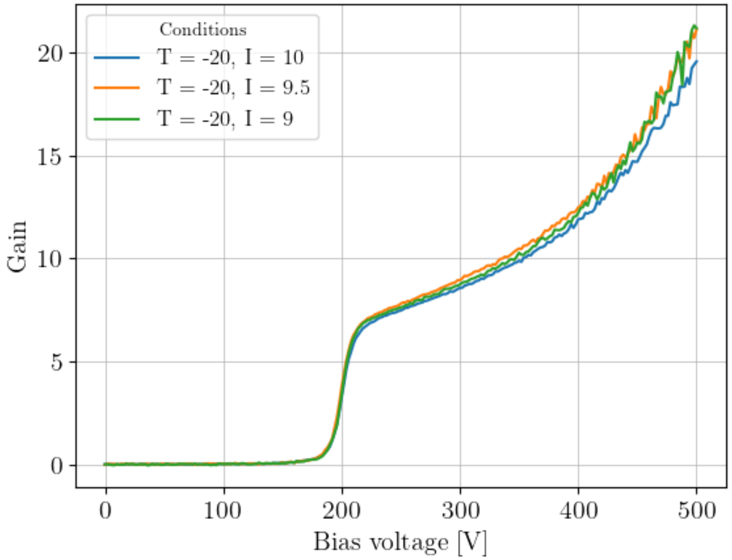
UV TCT: Gain Suppression

- Gain suppression with increasing intensity visible for the non-irradiated nLGAD
- Not strongly pronounced for the $1 \cdot 10^{14}$ p/cm^2 sensor
- Min. intensity with UV laser ~ 30 fC, max. intensity ~ 59 fC deposited in the sensor

Before irradiation



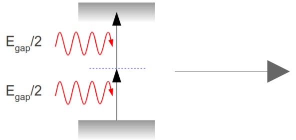
Irradiation to $1 \cdot 10^{14}$ p/cm^2



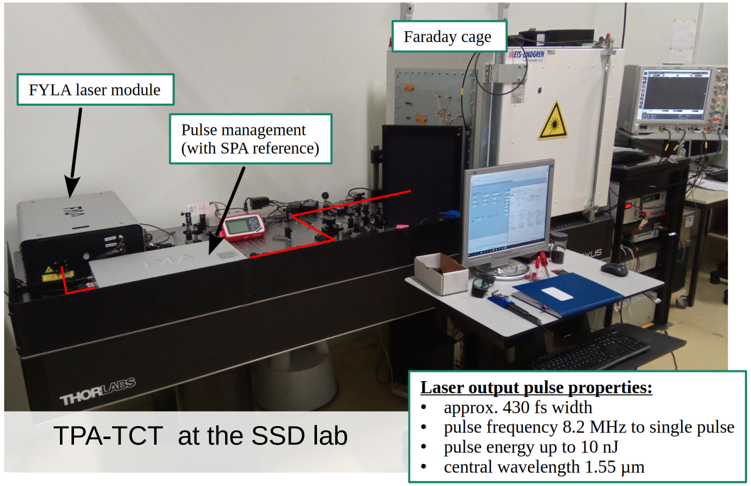
Two Photon Absorption - TCT

- TPA-TCT:
  - No single photon absorption in silicon (1550 nm = 0.8 eV)
  - 2 photons produce one electron-hole pair
  - Point-like energy deposition in focal point
  - 3D spacial resolution! (1 µm x 1 µm x 10 µm)

TPA (1550 nm):
No excitation if $E_{photon} < E_{gap}$ ~ 1 eV. But, if two photons arrive in ~100 attoseconds:

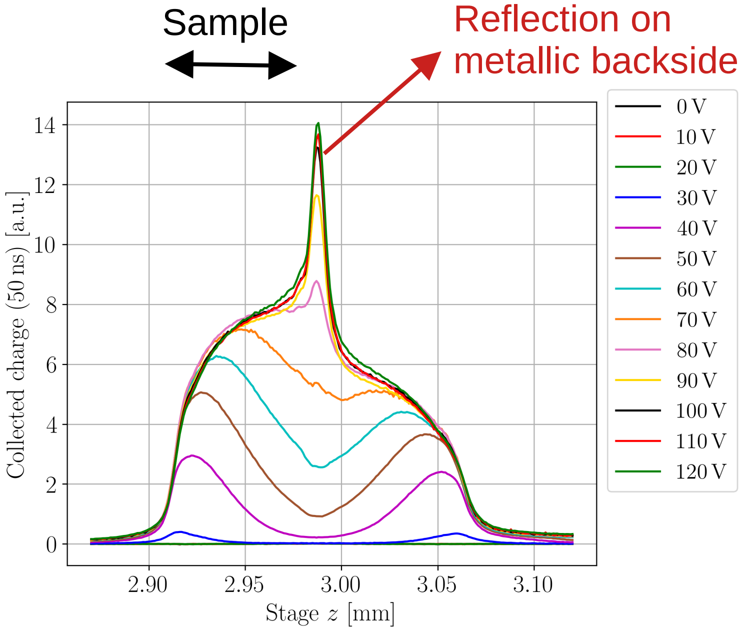


$$\tau_{virtual} \approx \frac{\hbar}{E_{gap}/2} \approx 0.1\, fs$$



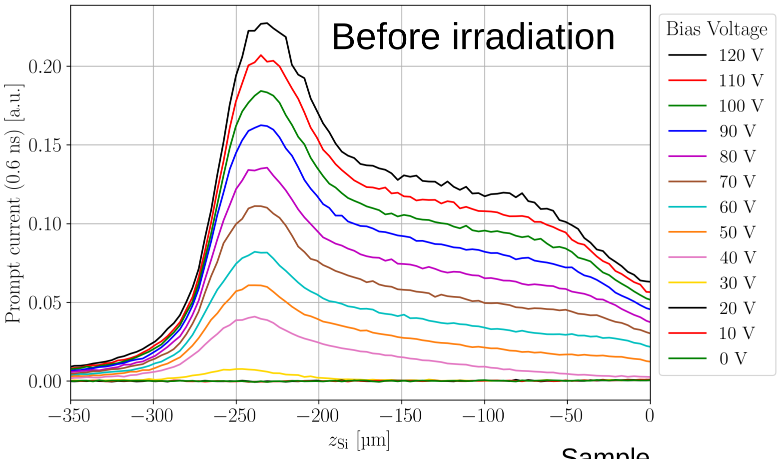
TPA-TCT at the SSD lab

Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm

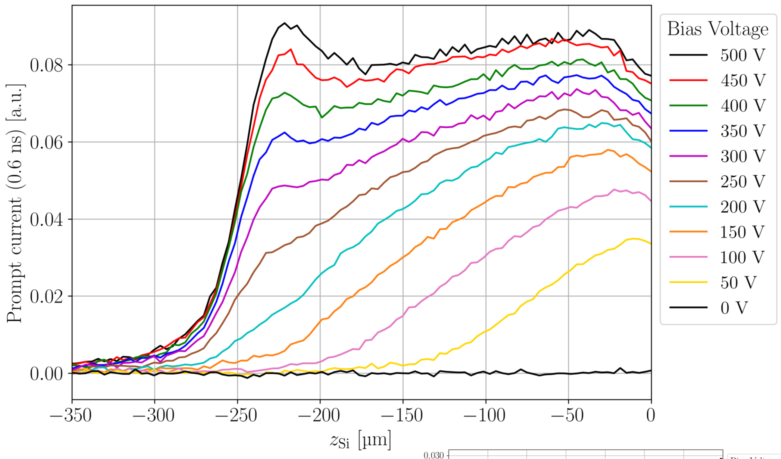


TPA – TCT: Prompt Current

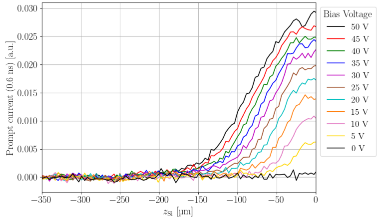
- With TPA-TCT, the prompt current directly after charge generation dependent on the position in the sample can can be measured → investigation of the electric field is possible
- **Space charge sign inversion** after irradiation! Start of depletion from backside
- Different measured voltage ranges are displayed in the comparison before and after irradiation because break down and depletion change strongly with irradiation



Sample backside

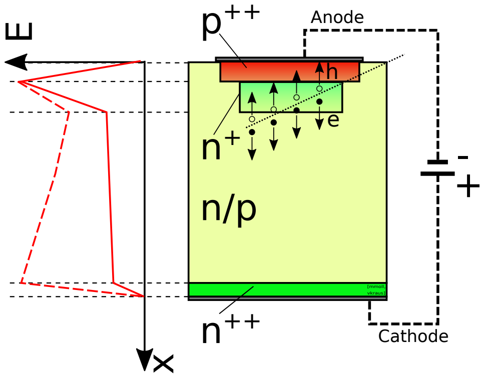


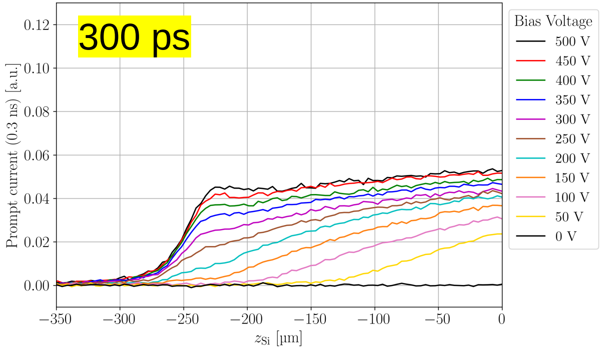
Zoom: 0-50 V

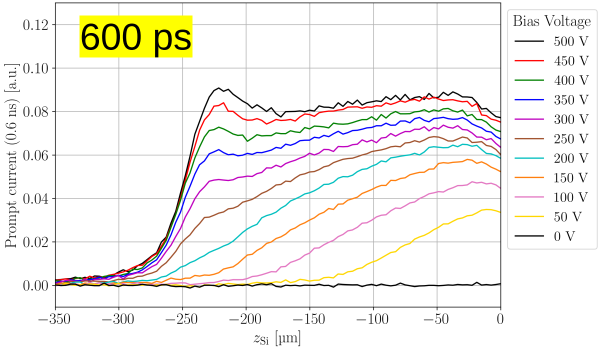


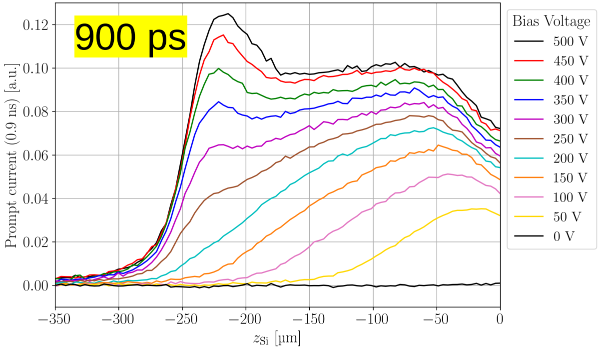
TPA – TCT: Prompt Current Time Dependence

- Different times for the prompt current result in different curves
- Comparison of three times for the $1{\cdot}10^{14}$ p/cm² sample
- For low voltages and short prompt current times, it can clearly be seen that the field starts to build from the backside of the device after irradiation → **junction** at the backside









Summary and Outlook

Summary:

- nLGADs were irradiated with 23 GeV protons
- It is complex to investigate the irradiation induced degradation of the nLGAD gain layer. This arises from complicated field structures after **type-inversion**!
- Type-inversion occurs for the tested devices between $1{\cdot}10^{13}$ p/cm^2 and $2.4{\cdot}10^{13}$ p/cm^2 ($1.5{\cdot}10^{13}$ n_{eq})
- **Shift of depletion voltage**, Gain reduced → n-type gain layer more irradiation “soft” than p-type
- With TPA-TCT: confirmation for **space charge sign inversion** after irradiation! Start of depletion from backside

Outlook:

- Annealing study
- Neutron irradiation (JSI, Ljubljana) of nLGADs is currently underway to complement existing studies by comparing radiation-induced degradation from different particle types
- Possibility to do lower energy proton irradiation (60 MeV)

Thanks for your attention! Questions?

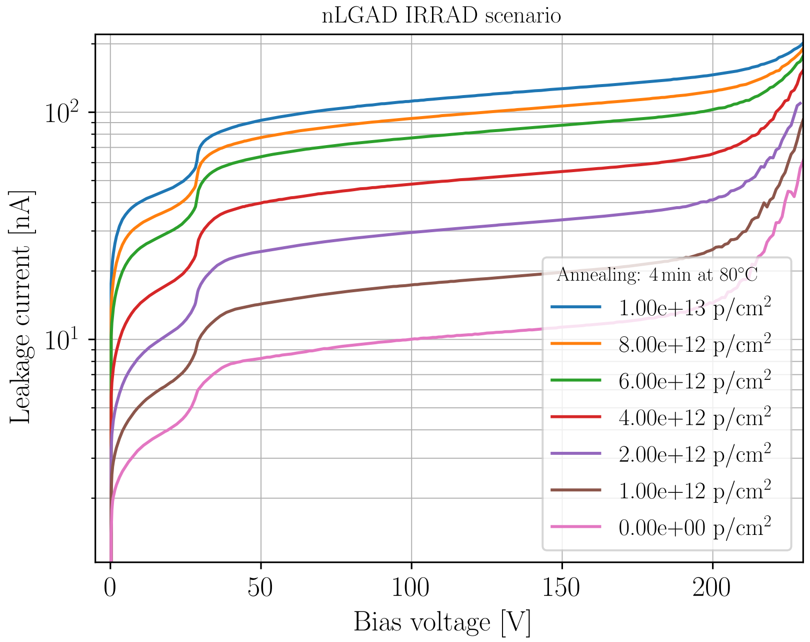
Backup

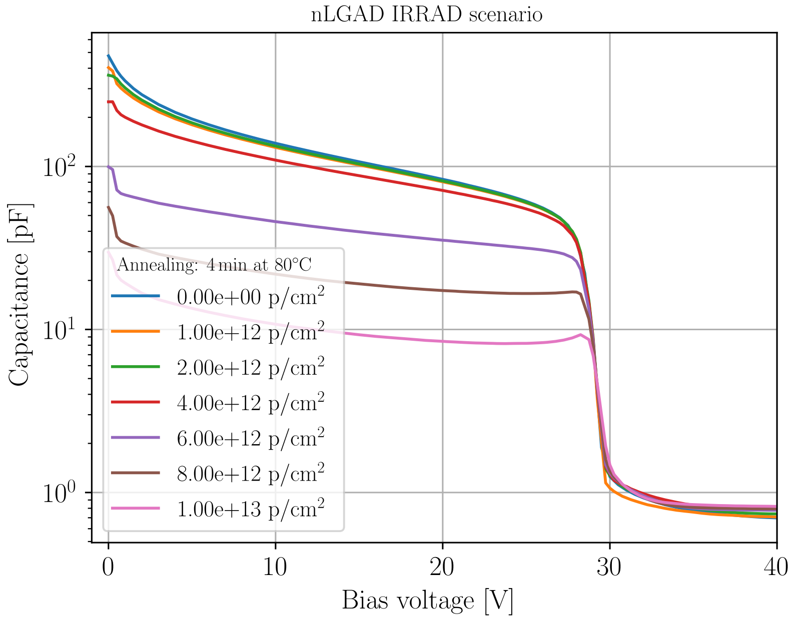
References

- [1] J. Villegas et al. “Gain measurements on NLGAD detectors”. In: *Nuclear Inst. and Methods in Physics Research* Volume 1055 (2023).
- [2] V. Sola et al. “A compensated design of the LGAD gain layer”. In: *Nuclear Inst. and Methods in Physics Research* Volume 1040 (2022).
- [3] M. Biveinyte et al. “Characterization and irradiation studies of n-LGADs”. *CERN-STUDENTS-Note-2024-049* *https://cds.cern.ch/record/2907655*

Electrical Characterization III

- Detailed IV and CV plots of IRRAD step-by-step irradiation for fluences from $1{\cdot}10^{12}$ p/cm^2 to $1{\cdot}10^{13}$ p/cm^2





Impact Ionization

- The impact ionization in the gain layer and therefore breakdown of nLGADs (as in HEP LGADs) is temperature dependent
- Measurements of the leakage current were conducted from -35ºC to +20ºC to show the shift of breakdown towards lower bias voltages with decreasing temperature
- The shift is roughly linear, as also seen in HEP LGADs