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Correlation between charge and current gain in LGADs

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Motivation

- Understanding the generation current gain and charge gain in LGADs is important for understanding the operation of LGADs.
- What is the underlaying physics reason for difference in gain for charge and current?
- Leakage current is correlated with gain and is much easier to measure - therefore can be practical to know the correlation
- These studies lead to a fast QA procedure using TCT system for fast and reliable measurements of LGADs (see Petja's talk)

Gain – leakage current and charge

Why are/can be G_I and G_Q different ?

$$\left.\begin{aligned} I_{leak} &= G_I\, I_{gen} \\ Q_{LGAD} &= G_Q\, Q_{PIN} \end{aligned}\right\}$$

If G_I=G_Q : $Q_{LGAD} = \frac{I_{leak}}{I_{gen}} Q_{pin}$

Measurement difficulties:

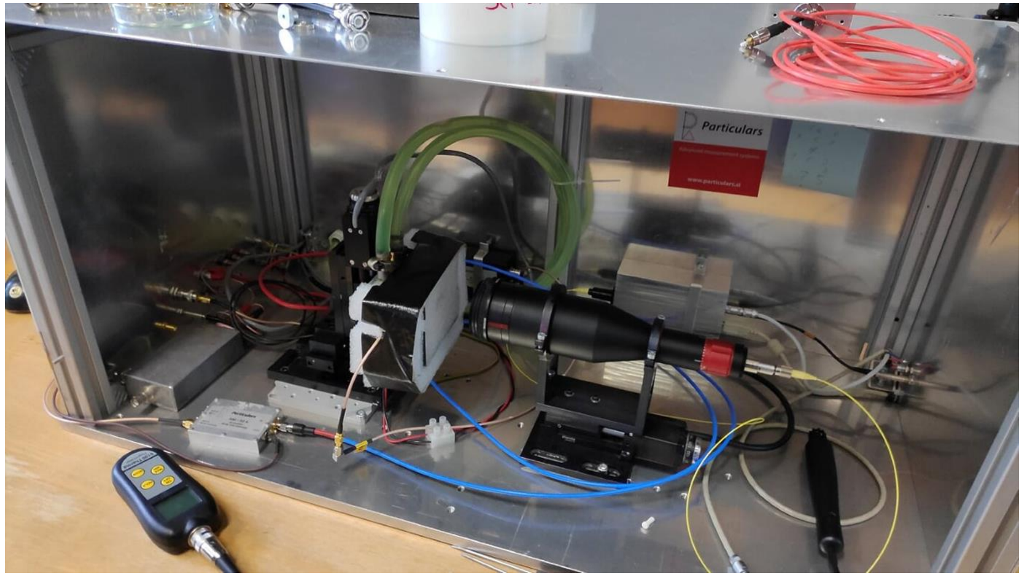
- Annealing uncertainty and temperature effects
  - It is crucial to either measure the I_{gen} (PIN) or be sure of annealing history and measurement temperature
- trapping: $Q_{pin,nirr} > Q_{pin}$ - **definition** of gain with or without trapping :
  - If $Q_{pin,nirr}$ is used the gain is underestimated in irradiated sensors
  - If $Q_{pin,irr}$ is used one should always measure it first

Device related reasons for the difference:

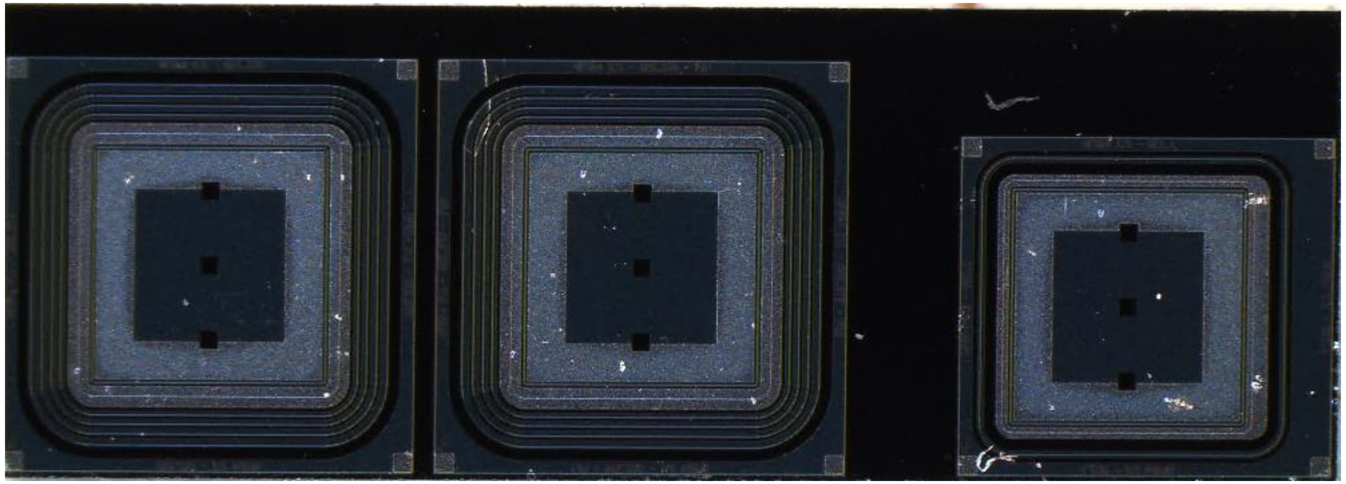
- Gains for G_I and G_Q are not the same – screening effects (NIMA 1046 (167669) , NIMA 1031 (166530) , Frontiers in physics 10 (877577), sensors 22 (1080))
  - leakage is coming from all over the bulk and in generally the density of carriers, even for substantial leakage is small
  - density of carriers for mip/laser track is much larger
- Leakage is measured on the time scale of several tens ms unlike for charge measured on 1 ns scale – detrapping
  - charge detrapped on the time scale of several tens ms (primary generated and multiplied) contributes to leakage
  - de-trapping time constants are much longer than drift times.

Experimental setup

- Samples from FBK4.0 – Wafer 9 were used 2xLGAD+PIN on the same die (50 μm thick active layer)
- Shallow GL design, with high B concentration and standard carbon dose
  - V_{gl}~24 V, V_{bd}~180 V, I@0.8V_{bd}~120 nA, V_{fd}~35 V
  - "CH-BL" diffusion
- Samples were irradiated with neutrons to 4,8,15,25e14 cm^{-2} and annealed for 80 min @ 60C before measurements



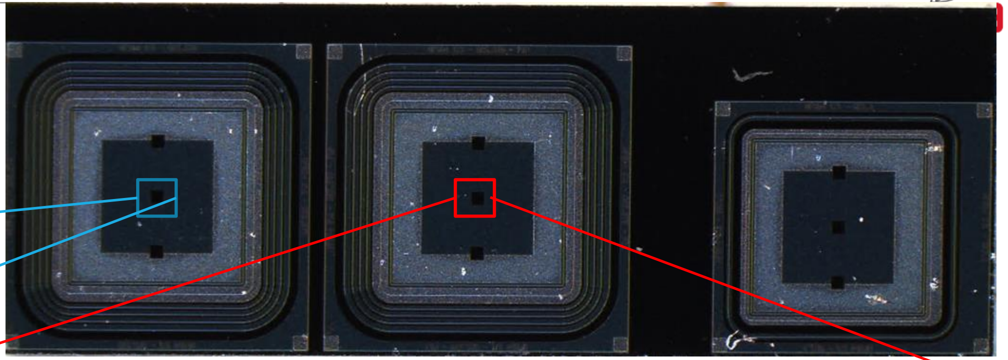
samples glued to housing to ensure good thermal contact

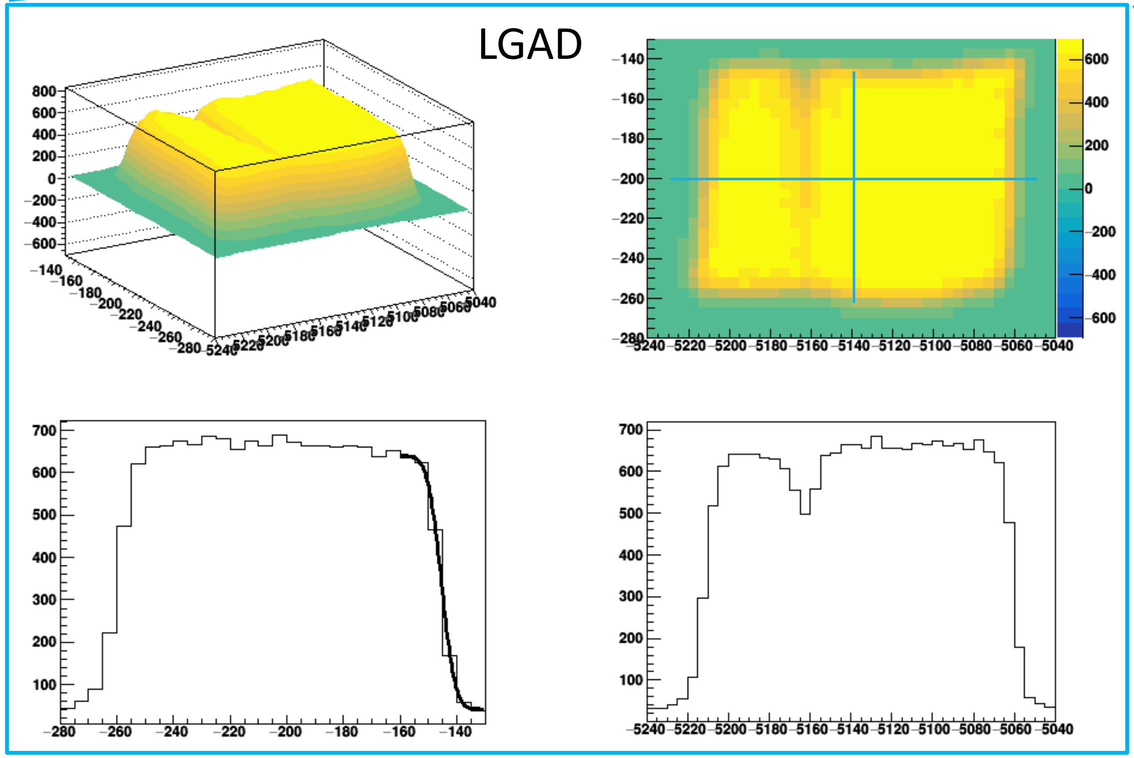


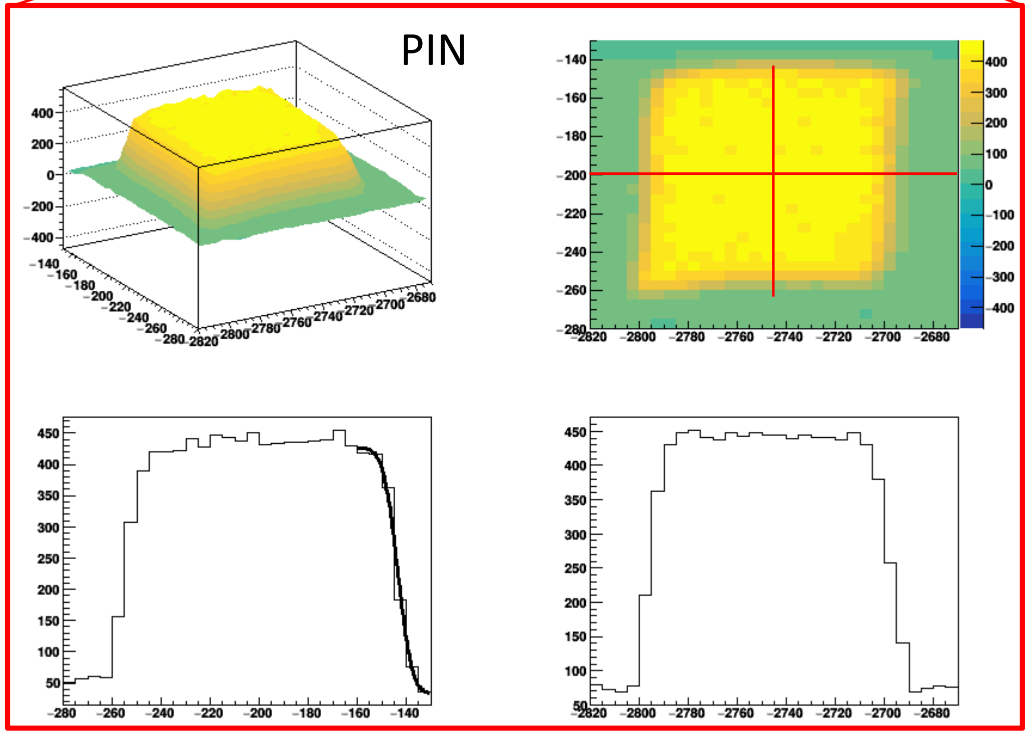
- Scanning-TCT at University of Niš and JSI were used
  - 0,4,8e14 cm^{-2} were measured at room temperature at EF Niš with 660 nm and 1064 nm
  - 15,25e14 cm^{-2} were measured at 20C and -30C at JSI with 1064 nm
- Beam split monitor (1064 nm) was used to allow for accurate measurements of injected charge

Scanning the area and working point

- Different windows were investigated (no difference found)
- Centre of the pixel investigated
- Beam focused to around 10 μm to achieve densities of ionization as close to the one of the mip as possible

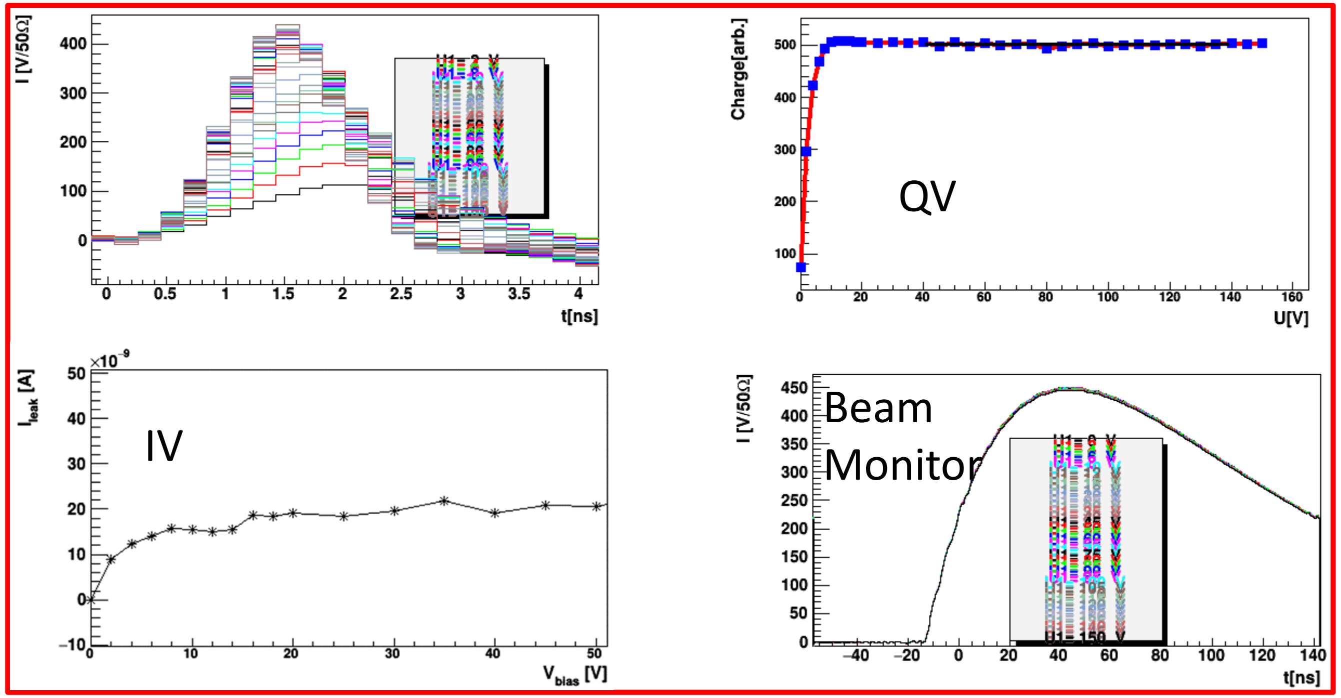


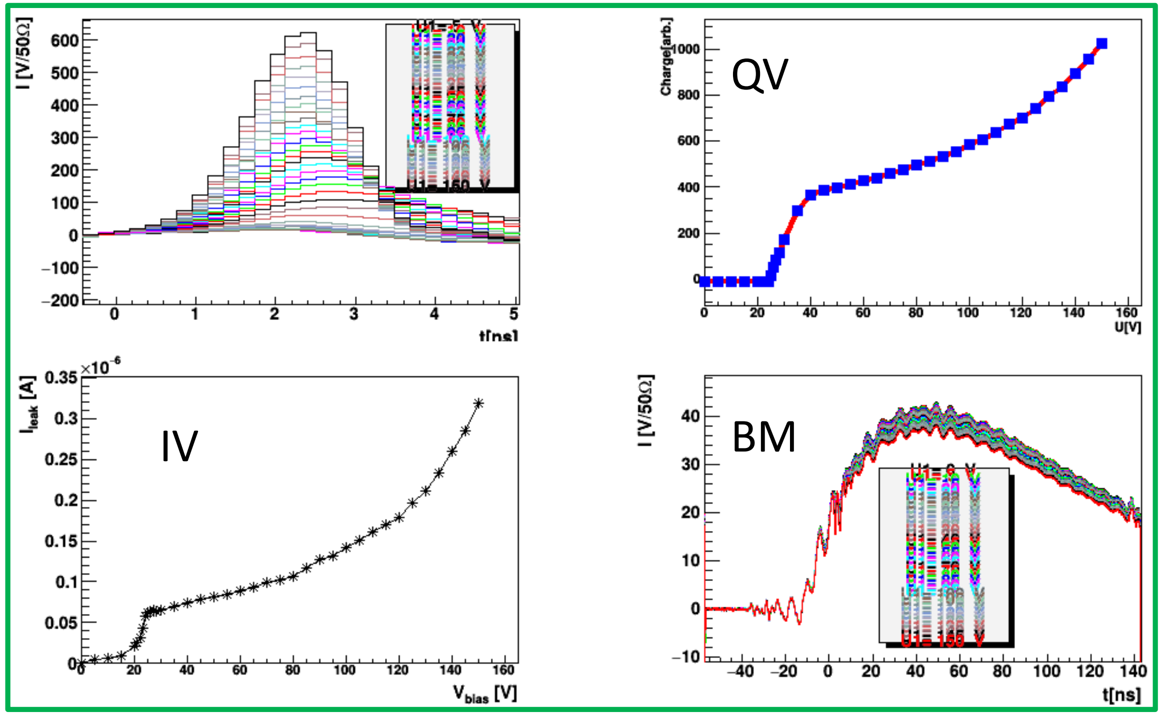




Analysis approach – non-irradiated sample

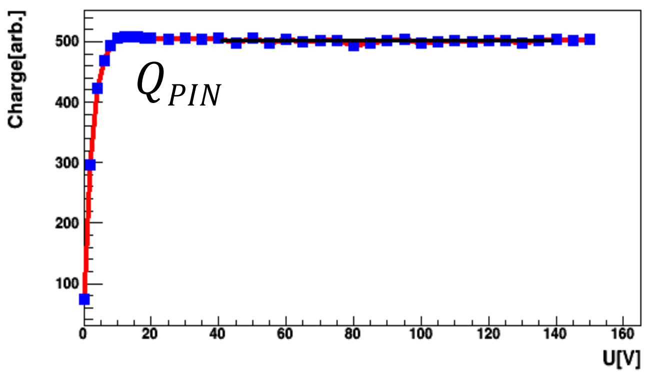
- we look at the signals (waveforms) and integrate them on short time scale [0,5 ns] for collected charge
- current is measured with Keithley 237 (PS and current measure) with GR floating –> source of uncertainty
- Beam monitor is used to measure the relative amount of charge between different samples

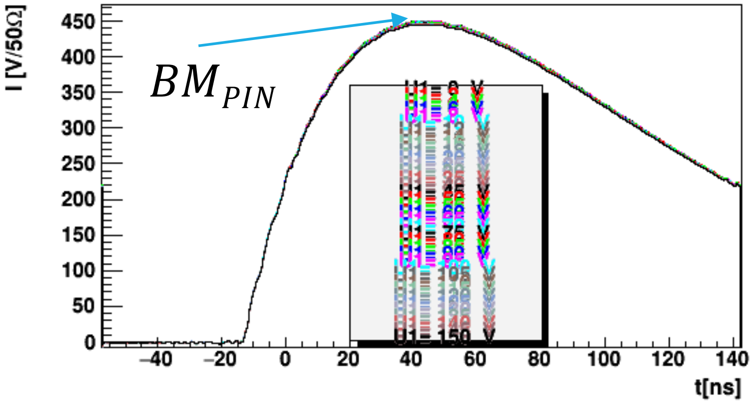


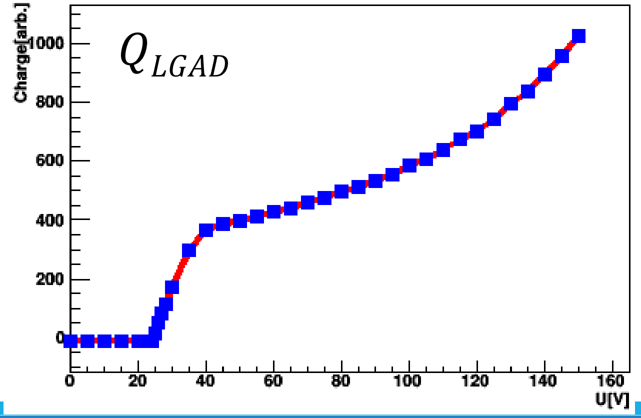


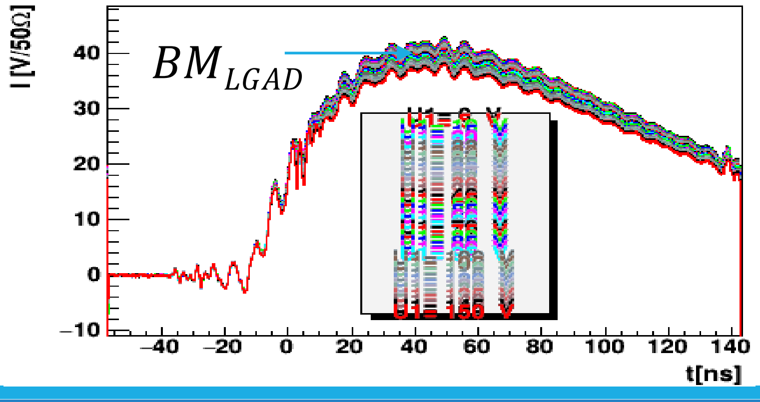
Calculation of the G_I and G_Q

- Signal from PIN – average over the 100 V above the full depletion voltage
- Signal from LGAD – taken at every voltage point above the full depletion voltage
- Peaks of the BM output for both LGAD and PIN (laser power needed adjustment to exploit full dynamic range of DRS)





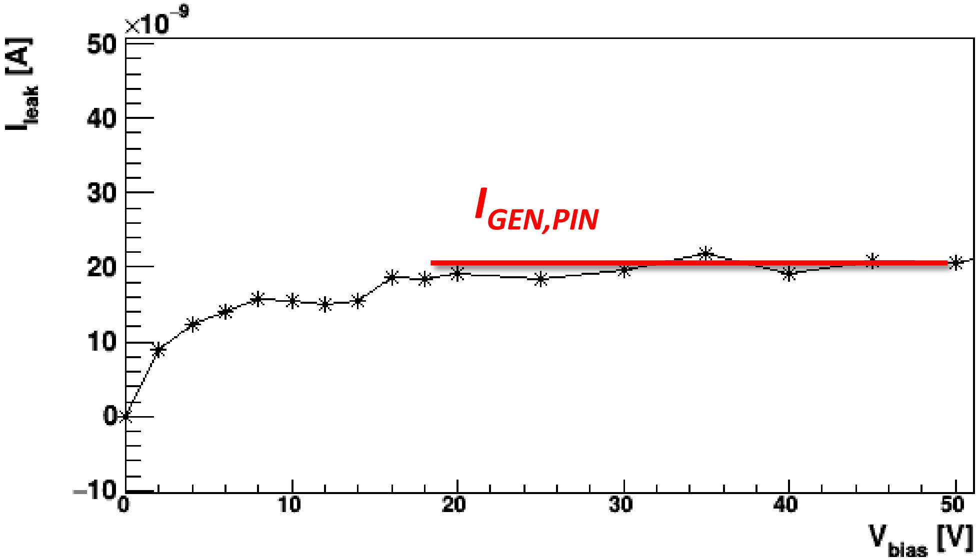


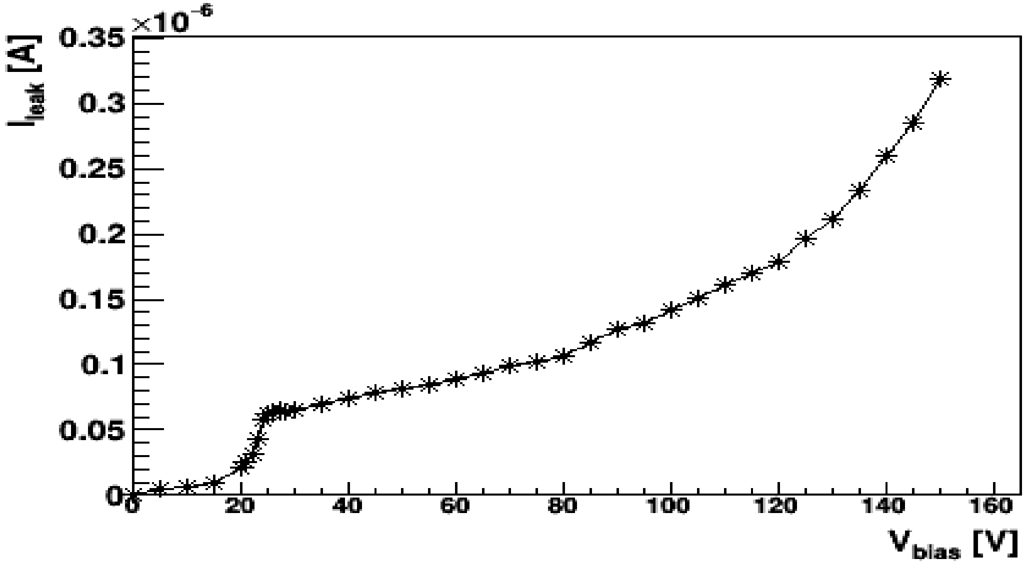


$$G_Q = \frac{Q_{LGAD}}{Q_{PIN}} \frac{BM_{PIN}}{BM_{LGAD}}$$

Note that laser fluctuation is larger at very low pulse energies needed for LGAD samples.

Calculation of the G_I



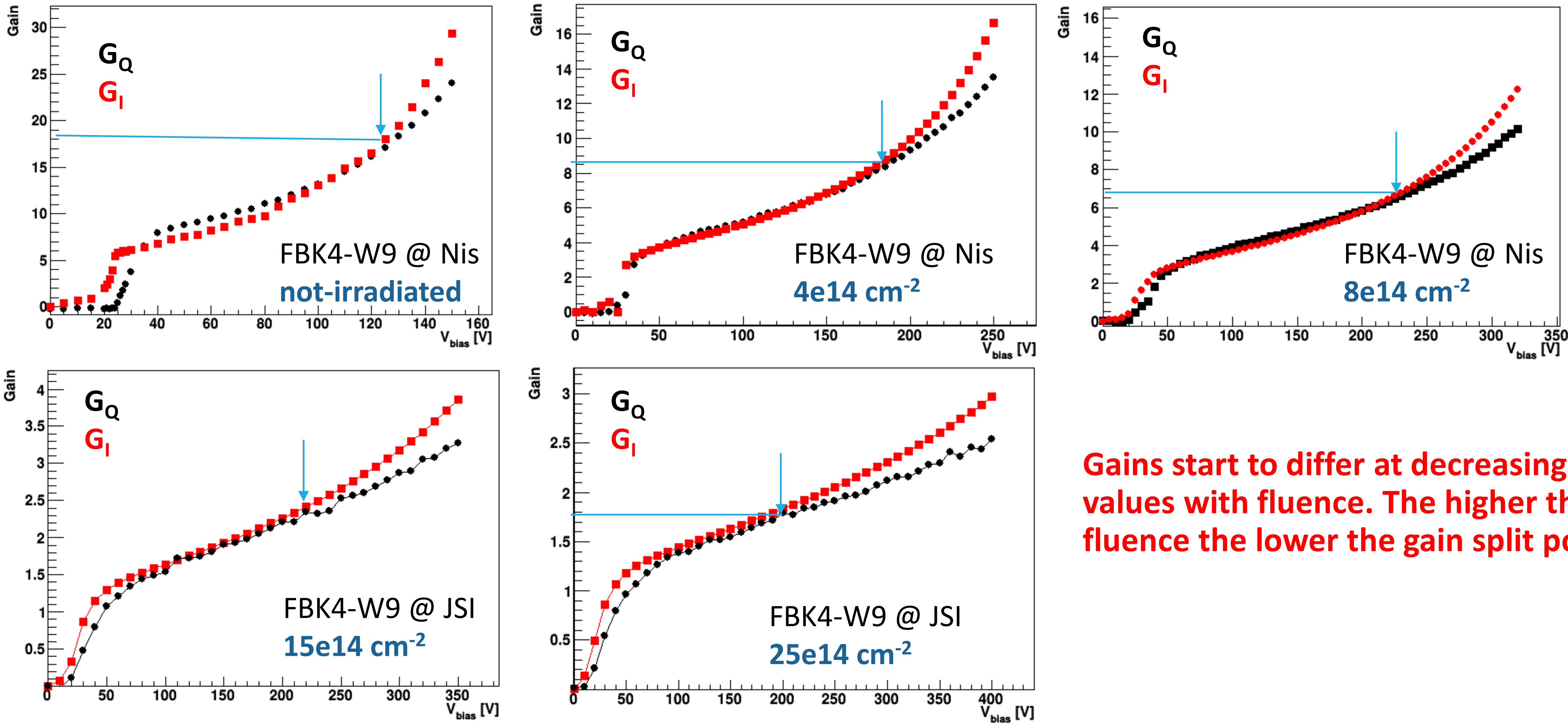


Procedure:

- Extract the Vfd from Q-V plot, average I for 30V over the V_{fd}
  - Guard current is not measured
  - I_{gen} is best measured at V_{fd} and to average out the fluctuations and prevent the at higher voltages contributions to the leakage current others than generation current
  - If any deviation in temperature was observed during both measurements it was taken into account according to standard scaling of I_{leak} with temperature.
- The temperature is not crucial as the generation current is the same for both and does not affect the ratio of the currents – only if the T changes between both measurements on the die (scan direction was from high to low voltage)

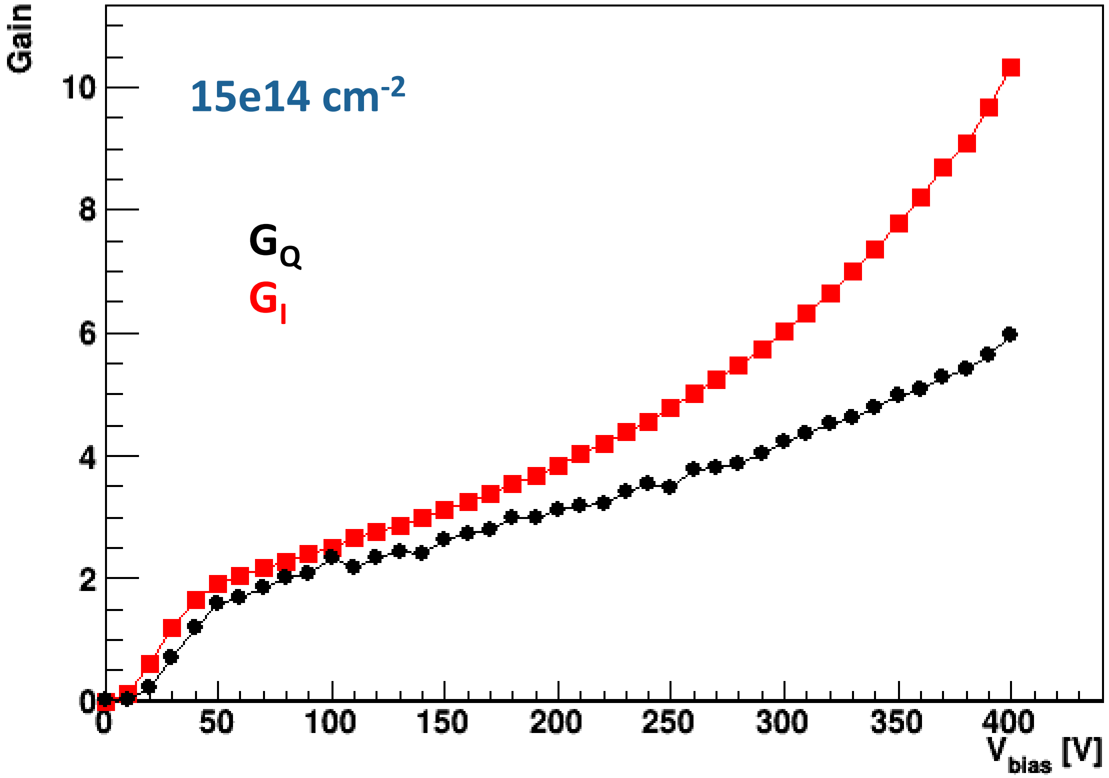
$$G_I = \frac{I_{LGAD}(V)}{I_{GEN,\,PIN}}$$

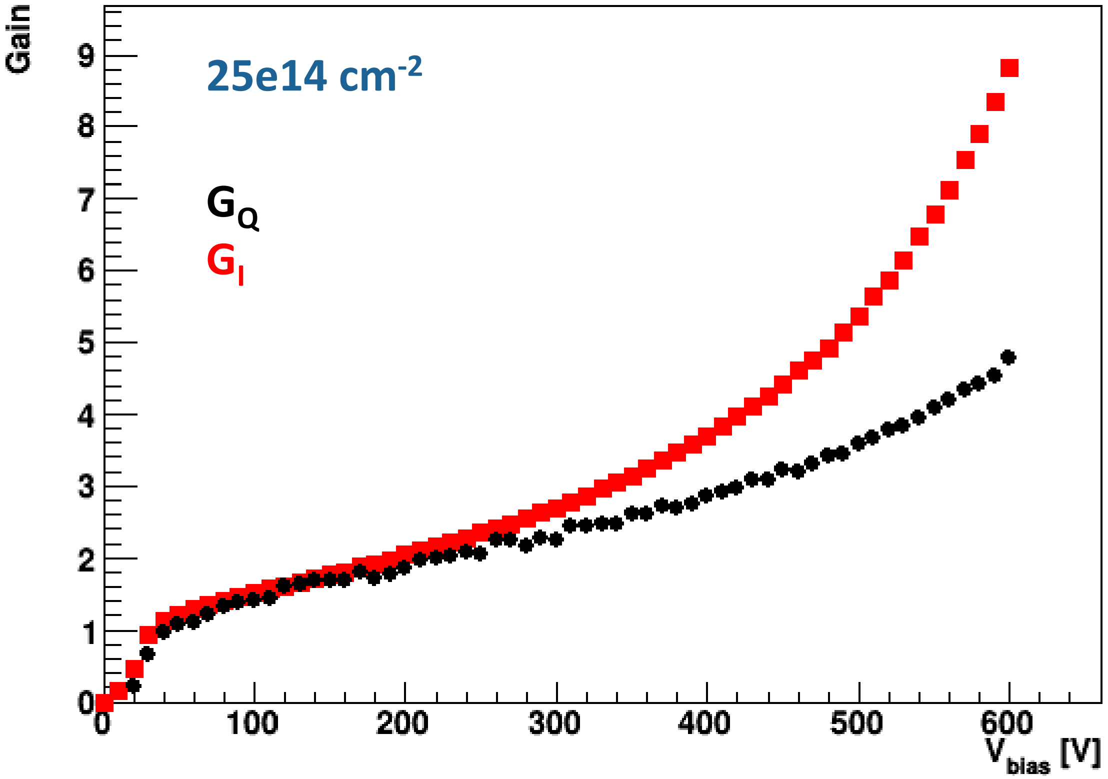
G_I and G_Q at room temperature



Gains start to differ at decreasing values with fluence. The higher the fluence the lower the gain split point.

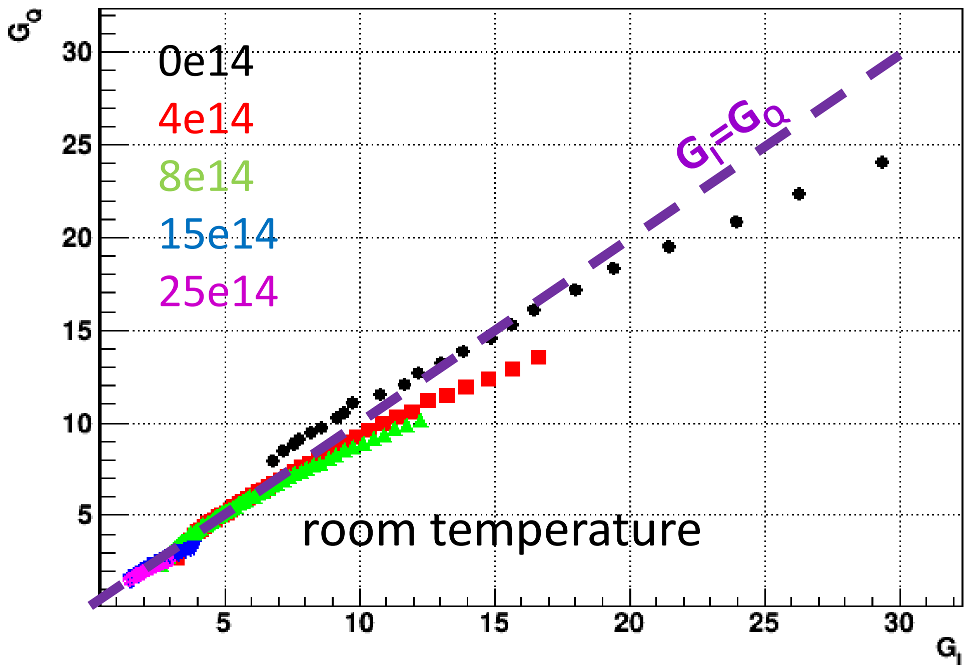
G_I and G_Q at -30°C

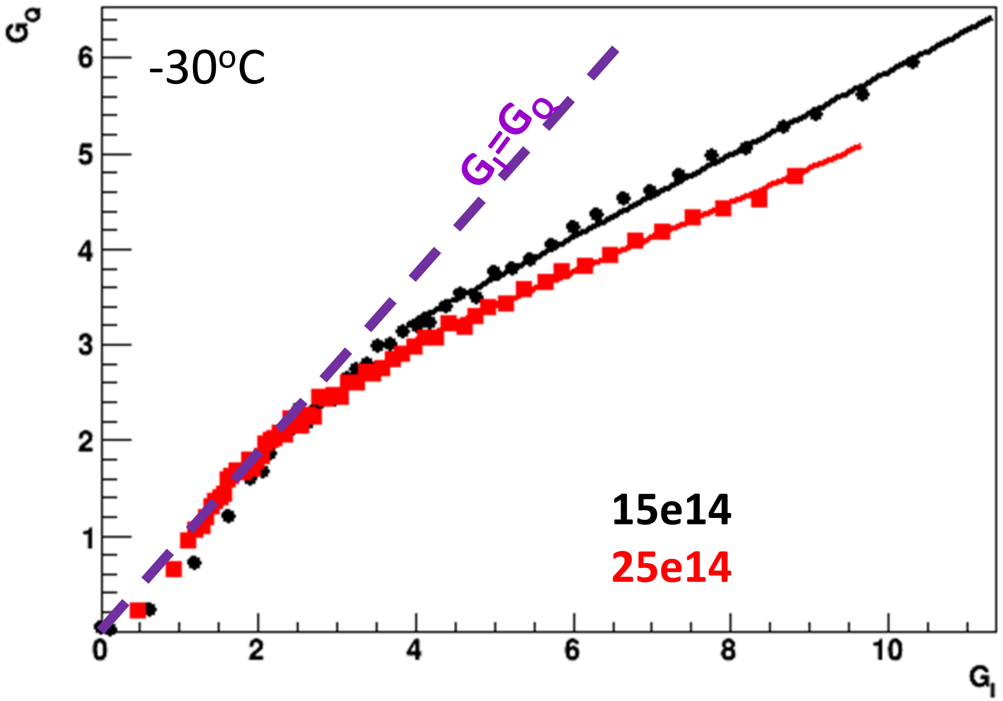




- Lower temperatures allowed much larger voltage range and split is much more evident at higher gains/bias voltages
- The difference can not come due to de-trapping of the trapped charge – to large – only ~10% of charge is trapped
- Somewhat lower gain than expected from some ^{90}Sr measurements

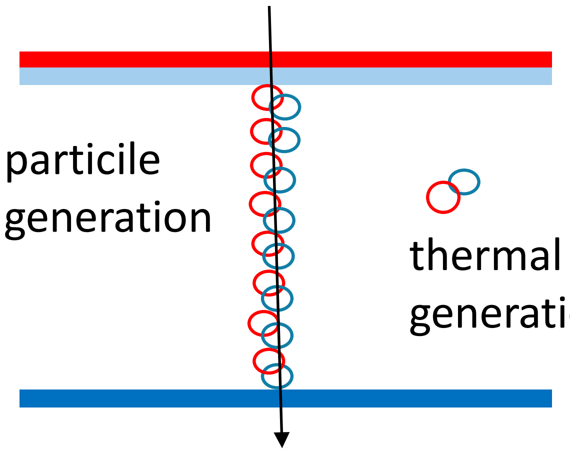
$G_Q(G_I)$ curves – correlation





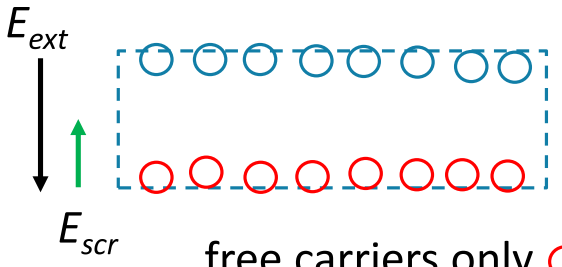
- At room temperature the slope for non-irradiated detector differs from G_I=G_Q only at high gain
- After moderate irradiation the G_I=G_Q breaks down earlier
- At -30°C the deviation form G_I=G_Q becomes larger and the ratio G_Q/G_I becomes smaller

Possible reasons for shape of G_Q-G_I



Non-irradiated case

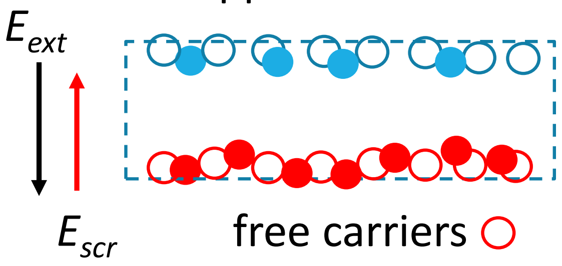
after the arrival of first electrons steady state is established



free carriers only

Irradiated case

after the arrival of first electrons steady state is established with carriers trapped on defects



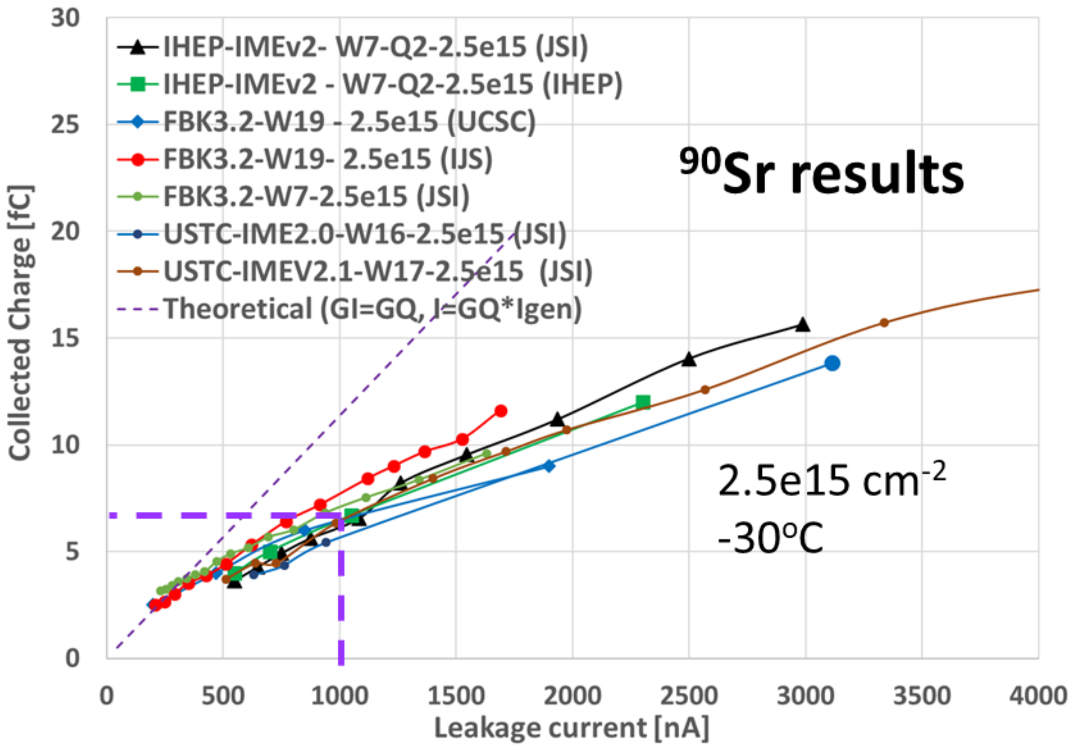
free carriers
+
trapped carriers

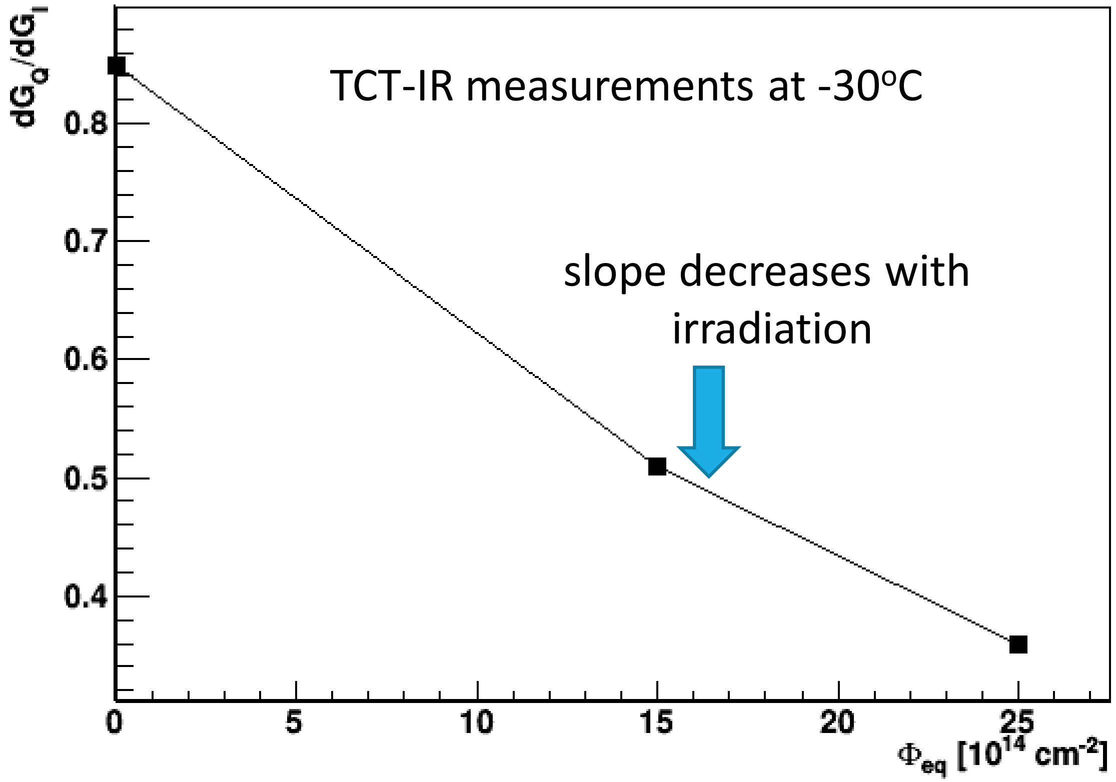
- For non-irradiated sensors only free carriers screening applies
- For irradiated sensors trapping of the holes (high density of defects) modifies the field even more and leads to larger screening – as it affects G_Q more than G_I .
- Can trapping of thermally generated carries can have an effect to “polarization” of the gain layer?

$$p = \frac{I_{leak}}{e_0 v_{sat,p} S} \sim 10^{-4} \mu m^{-3}$$

leakage current increase of carrier density is much smaller that that of the particles $> 10\ \mu m^{-3}$, but it is accumulated over longer period of time and it depends on de-trapping

What about the particle measurements?





Seen also in the charge collection measurements – theoretically calculated gain assuming G_I=G_Q and $I_{leak}=G_I \cdot I_{gen}$ should be much larger than that measured with ^{90}Sr electrons

Conclusions

- A correlation between G_I and G_Q was studied on a set of PIN+LGAD sensors from FBK4.0 – W9 wafer (shallow gain layer) with TCT
- For non-irradiated devices a deviation from $G_I=G_Q$ is observed only at very high gains (voltages) and is attributed to charge screening effects observed before
- For irradiated devices at room temperature the gain at which the relation $G_I=G_Q$ breaks decreases
- The ratio G_Q/G_I decreases with fluence at given gain , which is in agreement with ^{90}Sr measurements
- It seems that "field-quenching", due to trapped holes is the likely the reason

Next steps:

- Using red laser (much larger density of carriers in the gain layer – shallower deposition) will reveal the correctness of the conclusions shown here – studies ongoing in Niš and will be analysed soon
- TB measurements for angled tracks after irradiation
- A model will be derived to account free carrier screening and in addition

BACKUP

2.5e15 cm^{-2} at room temperature - example of irradiated plots