Effects of irradiation on LGAD devices with high excess current

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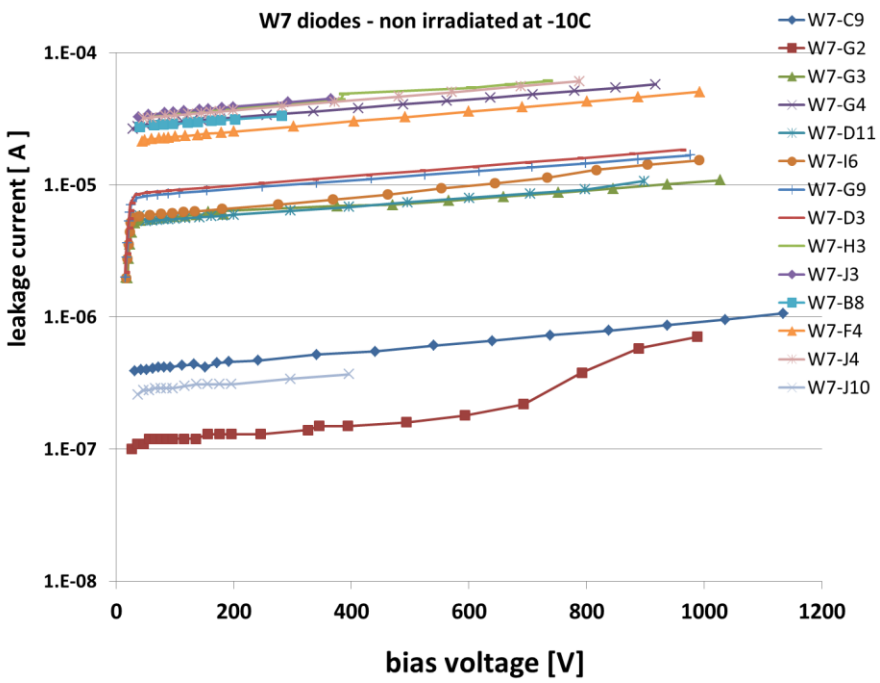
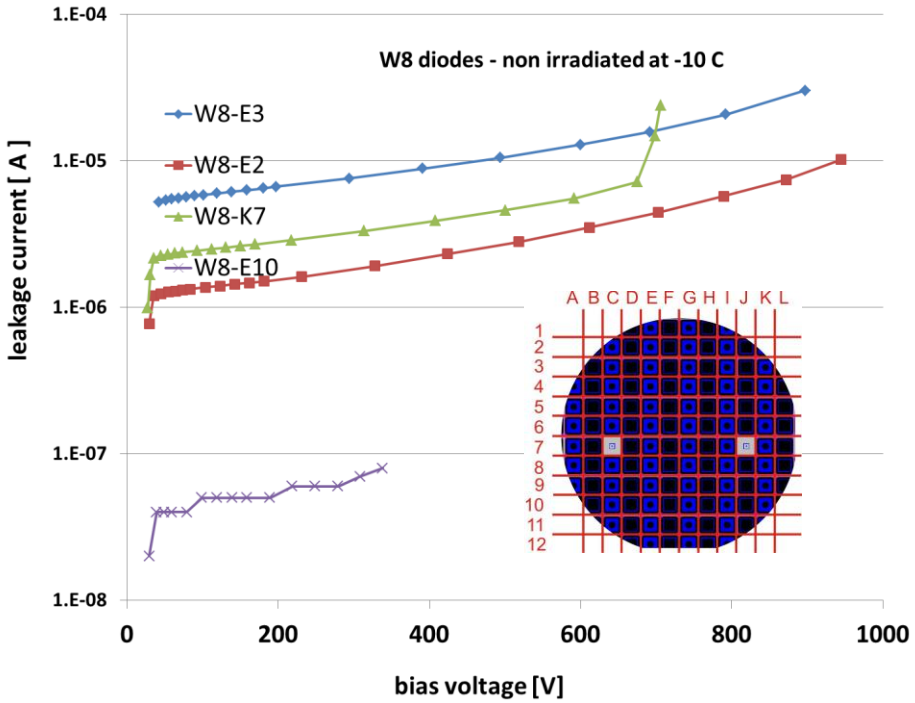
Leakage current before irradiation (R6474)

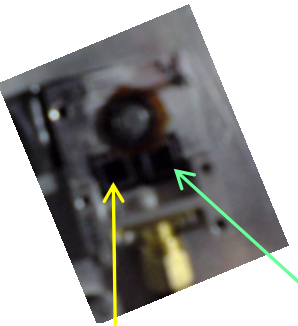


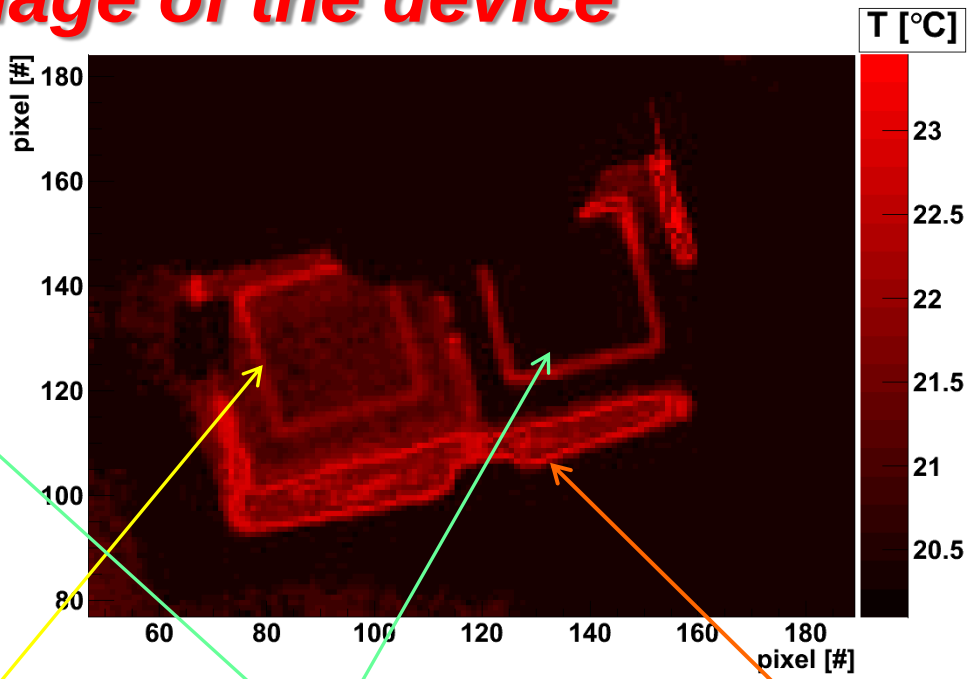


Devices **have current spread in the range of 2-3 orders of magnitude** and show **no apparent gain variation over the wafer.**

What is the reason for it and how much it affects the device performance after irradiation?

IR image of the device





Cooling surface to which the housing (see left picture) is mounted is **at 20°C** measured with Pt-100

Investigated detector: biased 900V, I=104.7 μA, few degrees warmer than non biased detector.

Reference detector (never biased)

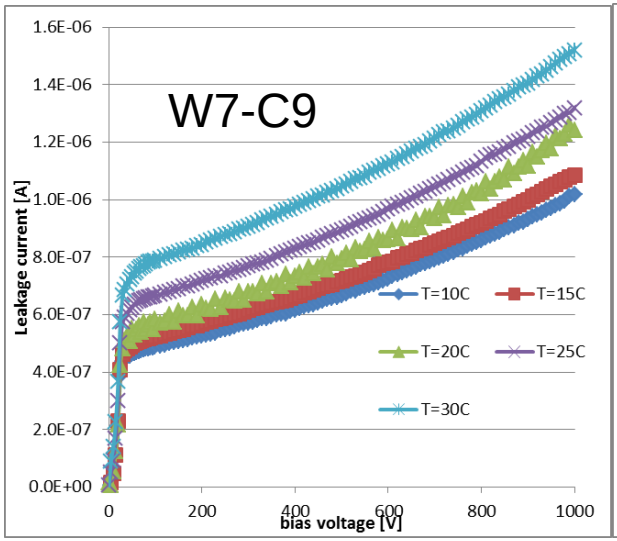
Refractive surface of the detector housing box not (not well) covered!

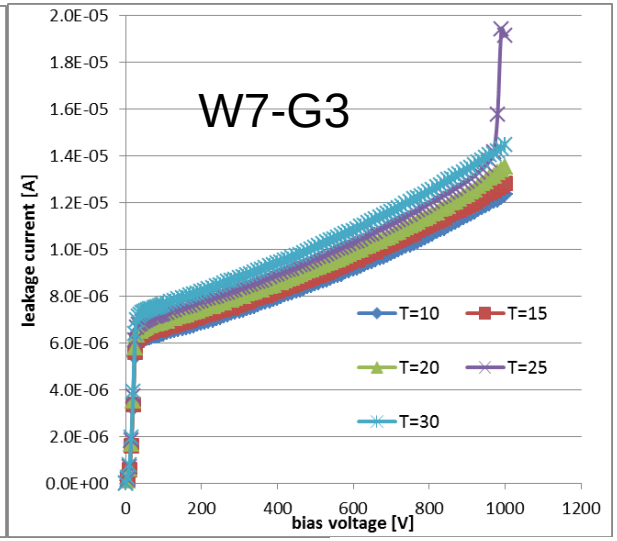
Investigated detector (not biased)

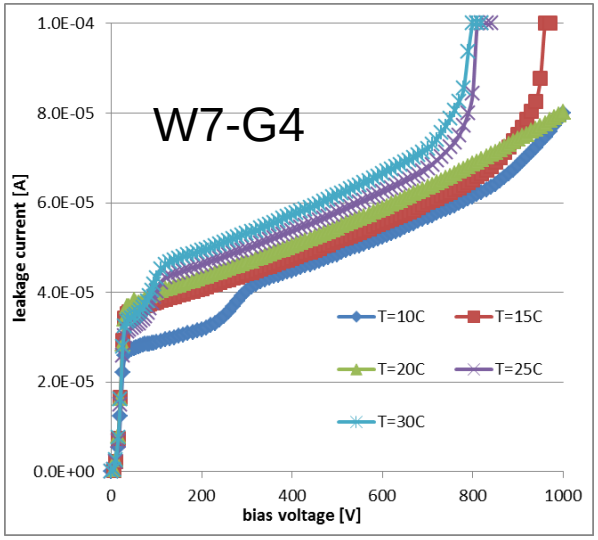
The IR image shows more or less uniform temperature over the sample i.e. no hot spots of larger gradients observed.

To exclude JTE as the source of higher current better images are required.

Temperature dependence of the current







The additional/excess current is not due to the bulk generation current. Same gain and significantly different current points to origin of the current outside bulk.

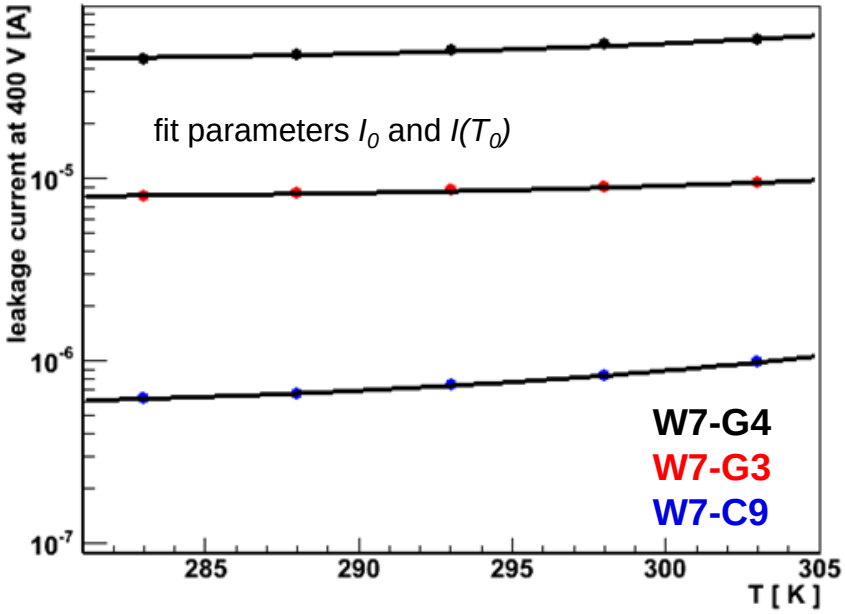
How to probe it?

bulk generation current

$$I(T) = I_0 + I(T_0) * \left(\frac{T}{T0}\right)^2 * \exp\left(-\frac{E_a}{k_b}(1/T - 1/T_0)\right)$$

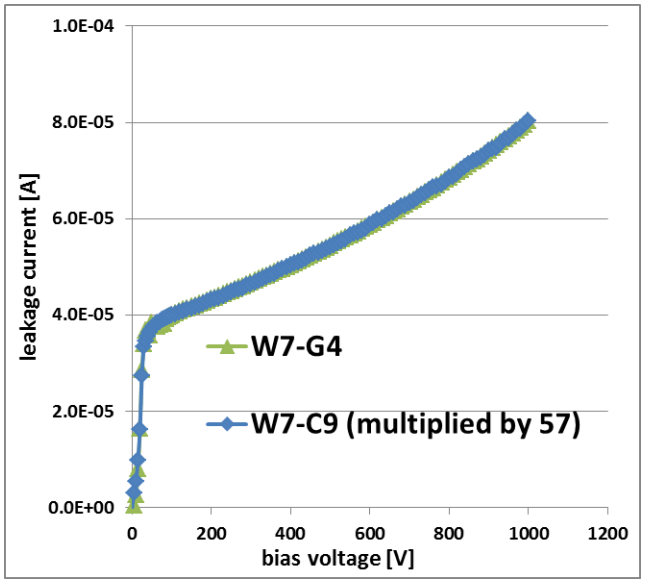
excess current

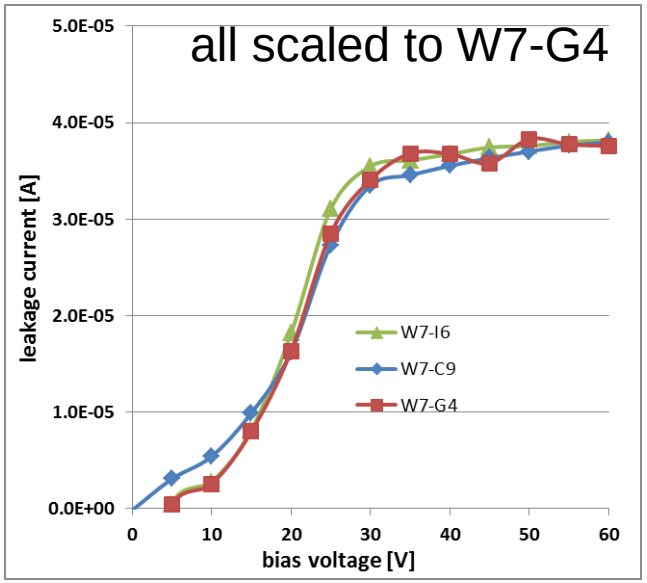
The equation fit the data well with $I(T_0)<=1$ μA!
The main difference between samples is in ***I_0*** *!*



Possible reasons for excess current

- Electron injection: no field before full depletion at the back (I-V curve), excess of positive space charge after irradiation even before multiplication
- Bulk generation: current should increase substantially from 30-90 V – strong dependence on temperature expected
- Generation at the border p-p^+: temperature dependence
- Generation at the p^+-n^{++}: depletion of the multiplication layer, temperature dependence
- Hole injection at Al-n^{++}: same behavior of both types of diodes (full metallization/no metallization), I-V





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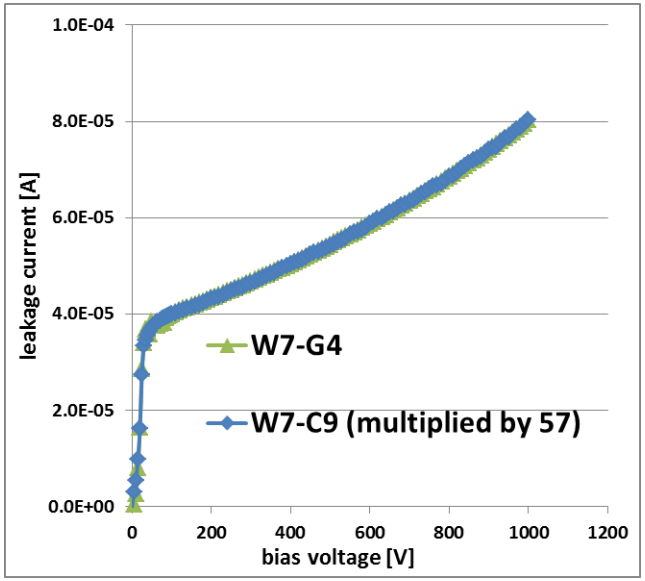
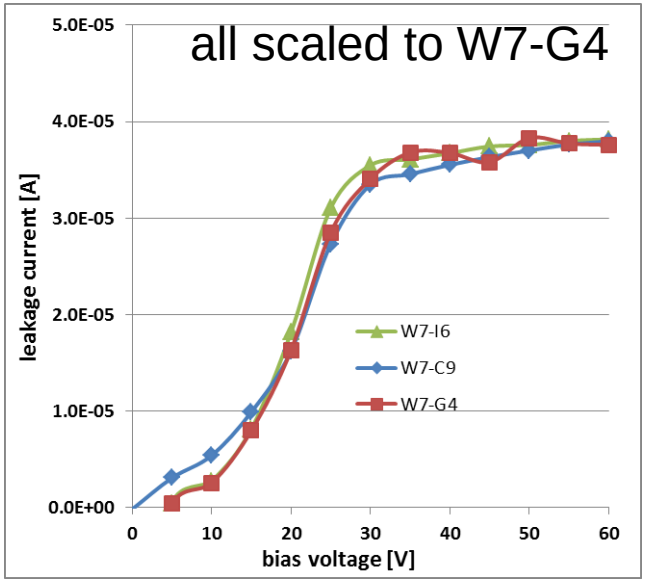
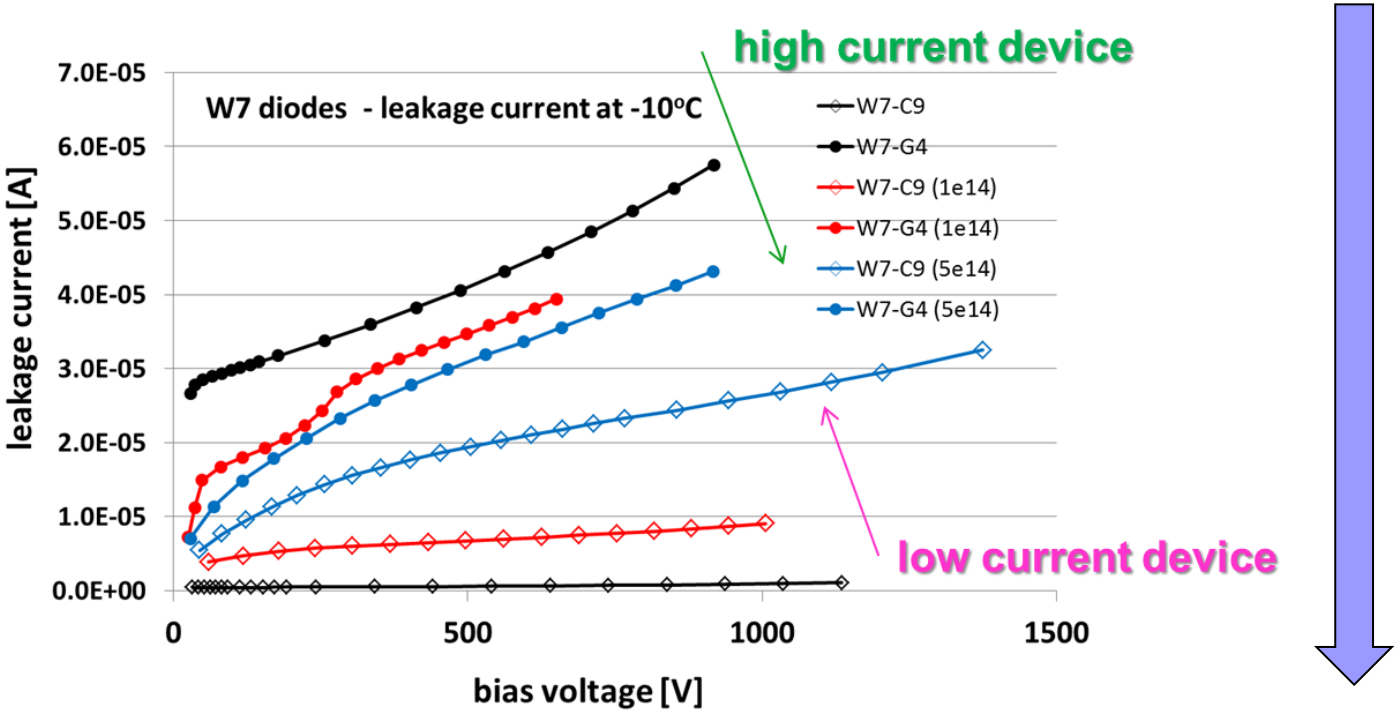




How does it behave with irradiation?

The excess current changes with irradiation – gets smaller with irradiation, but doesn't disappear - the reduction of total leakage with fluence



If it remains substantial it can effect the space charge and this should point to what it is

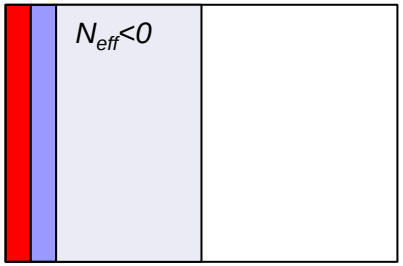
- **hole current**
- **electron current**

Effects of radiation in case of high hole current

Low current device (<=1 μA @ V_{fd}):
hole concentration in the bulk has smaller impact on effective space charge

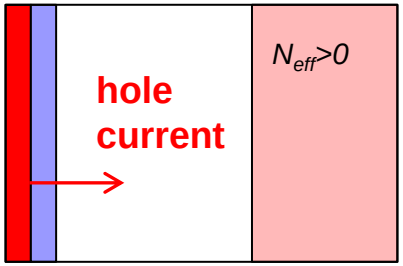
High current device (>10 μA @ V_{fd}):
substantial free hole concentration (either from hole injection or multiplication) with an impact on space charge

$V_{fd}<V_{bias}$



After irradiation the depletion grows mainly from the front

$V_{fd}<V_{bias}$

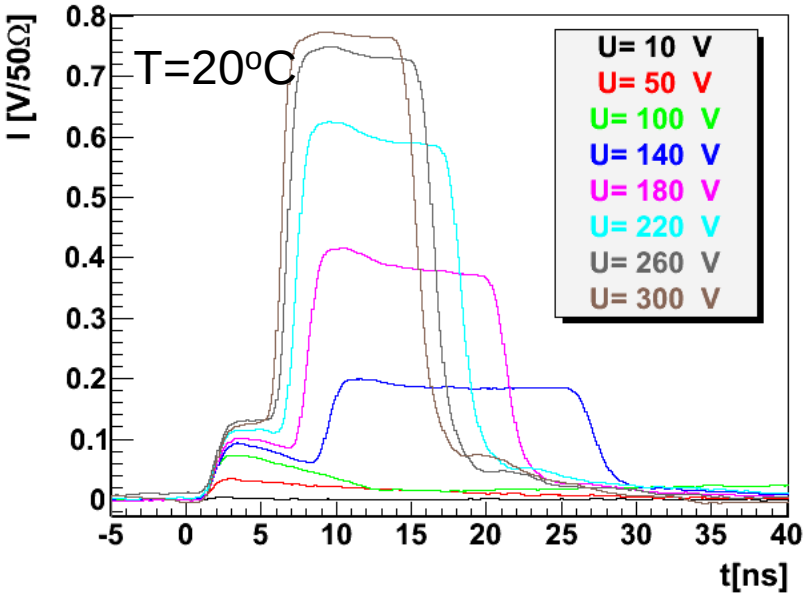


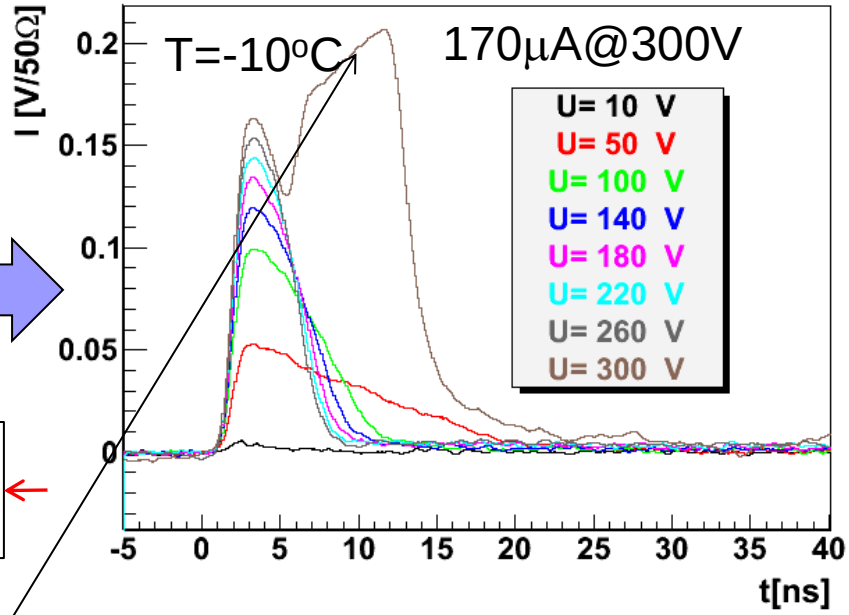
After irradiation the depletion grows from the back

- No difference in space charge before irradiation – deep traps are absent and $p<N_{eff}$
- Excess holes in addition with holes from multiplication can affect the space charge after irradiation
- As it is not temperature dependent, but the occupation probability of traps is, **a large temperature dependence of space charge is expected**

Effects of radiation

Device with irradiated with neutrons to 10^{14} cm^{-2} (R7062 W5-J10 device)





Back illumination – electron injection:
$V<V_{fd}$ – shape of induced current indicates $N_{eff}>0$ – decrease with time **(BEFORE CM)**
$V>V_{fd}$ – depletion of multiplication layer starts – appearance of current from multiplication – increase with time (clearly seen at T=-10ºC)

Large dependence on temperature:
excess current doesn't depend on temperature but de-trapping does = conformation of expectations for temperature weakly dependent excess current

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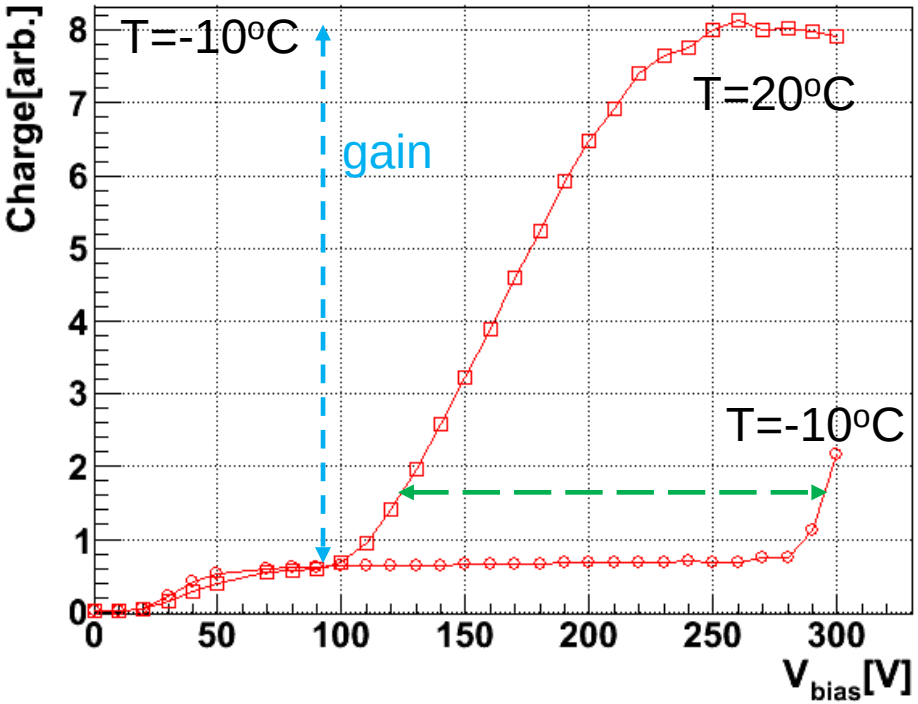
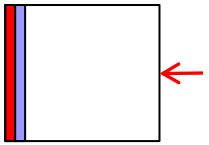




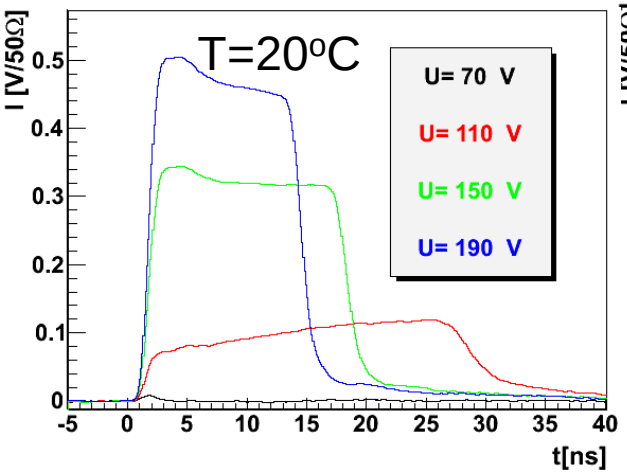
Integration in 40 ns

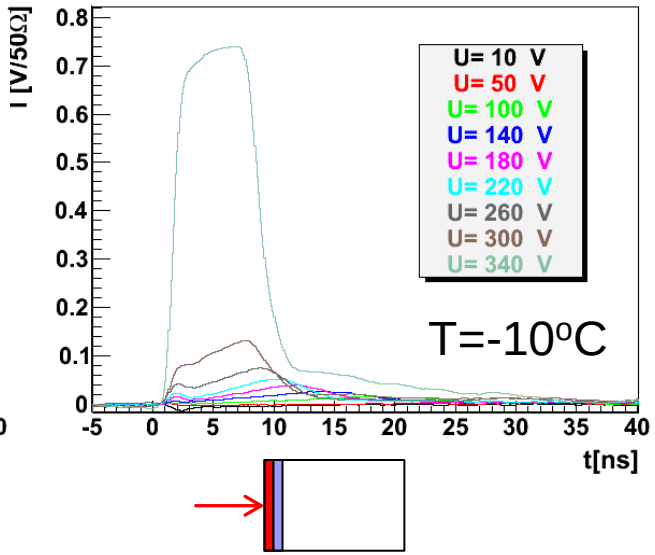
Only after depletion of the entire detector the multiplication layer gets depleted

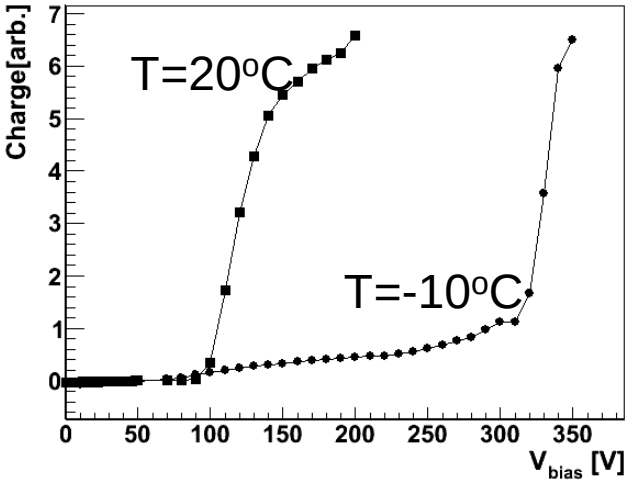
- The gain od the device after 1e14 cm^{-2} can be determined from the plateau before depletion of CM
- The large additional voltage required to trigger multiplication is due voltage drop not only in CM region, but in the entire detector – hence much more additional voltage is required to trigger CM in the case of N_{eff}>0.

Effects of radiation – high current devices

Device with irradiated with neutrons to 10^{14} cm^{-2} (R7062 W5-J10 device)







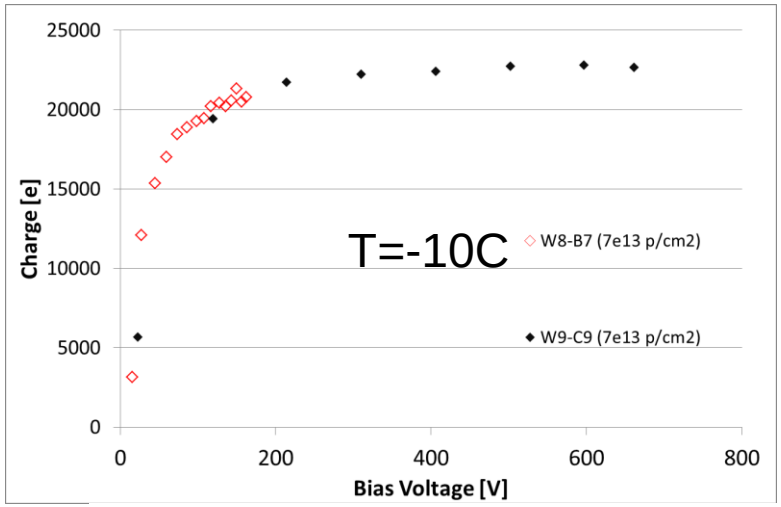
Front illumination – hole injection

Confirmation of the picture obtained for electron injection. Note a well pronounced positive space charge at T=-10C (increasing current after hole injection)

For positive space charge ($N_{eff}>0$) TCT probing of V_{mr} (leg in CV or TCT charge collection plot) doesn't work as the bulk is depleted before the multiplication layer.

Effect of radiation – proton irradiated device

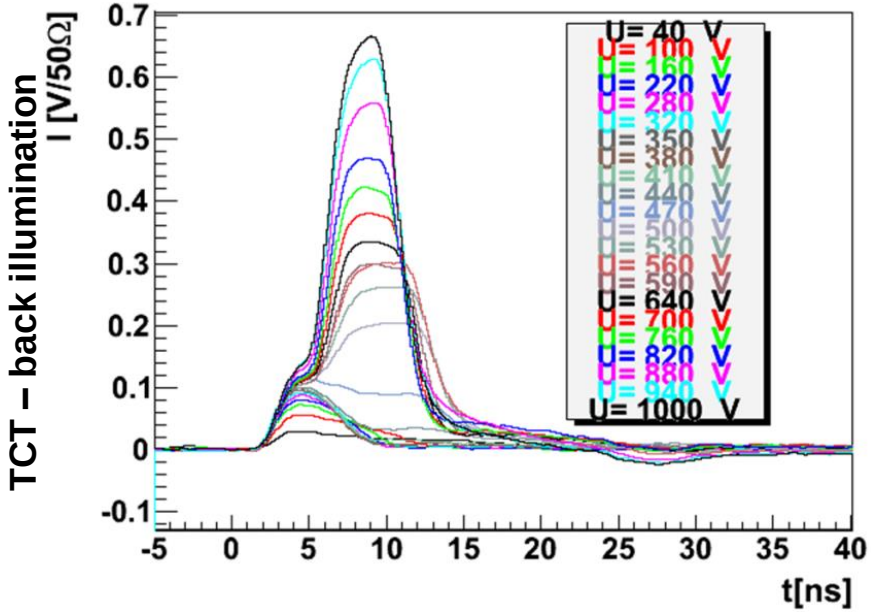
W8-B7 (R6474) - 800 MeV p irradiated device to 7e13 p cm^{-2} (~300 μA@500V)

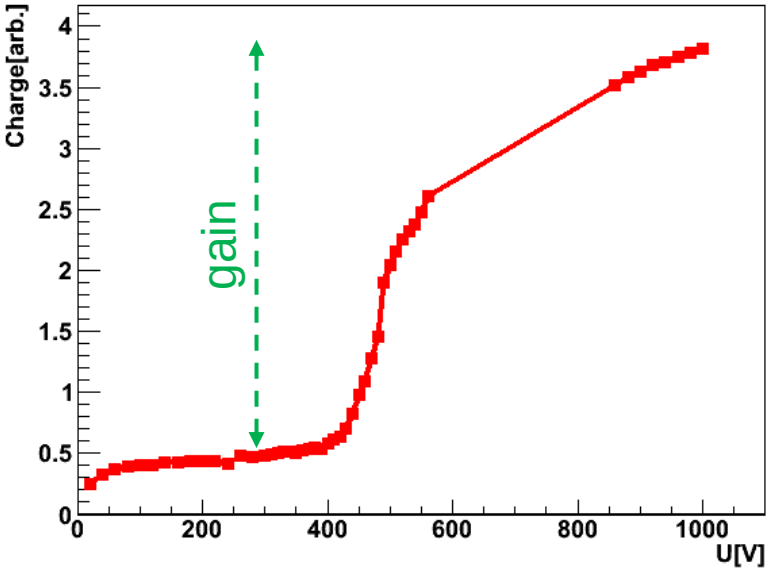


Control sample and LGAD have almost same behavior

High current prevented us to go higher in ^{90}Sr setup, so it seemed (Bucharest meeting) that there was no multiplication already at 7e13 p/cm2.

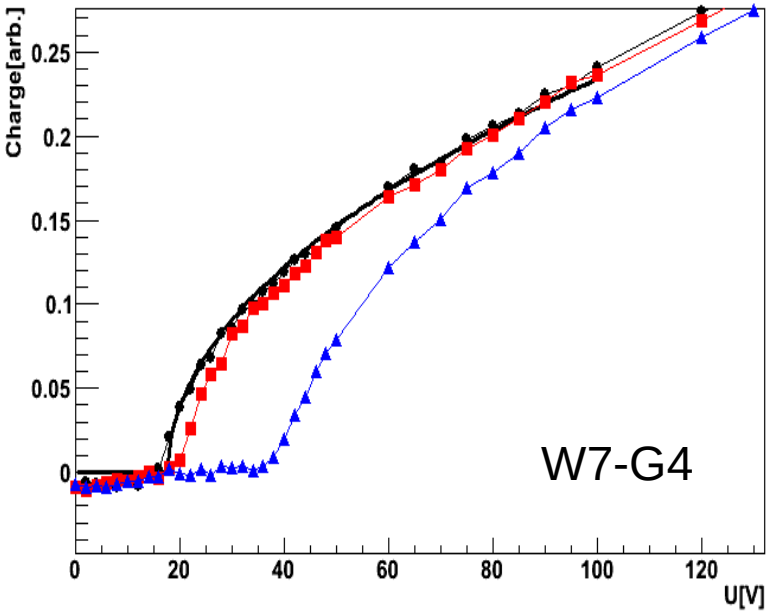
There is multiplication of around 8 at 1000 V, but 400 V is required to start impact ionization (deplete multiplication layer)

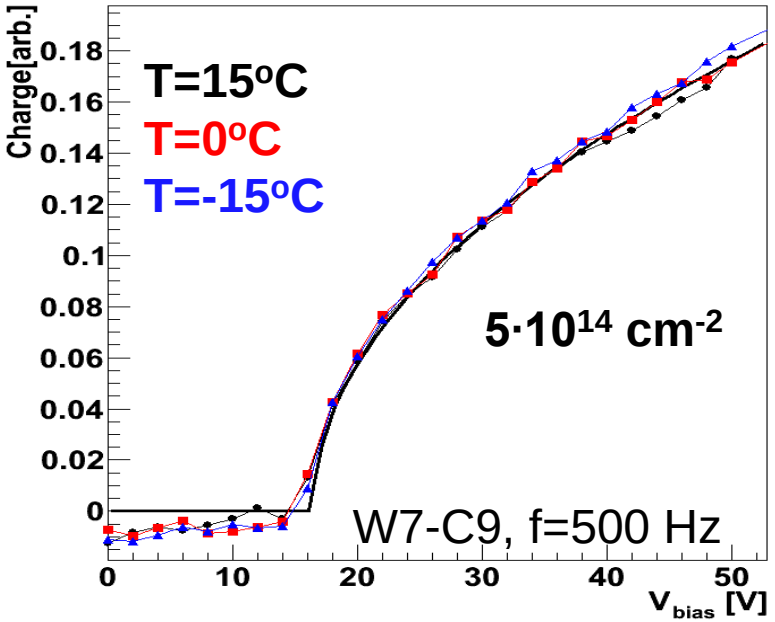




Effect of radiation – neutrons irradiated device

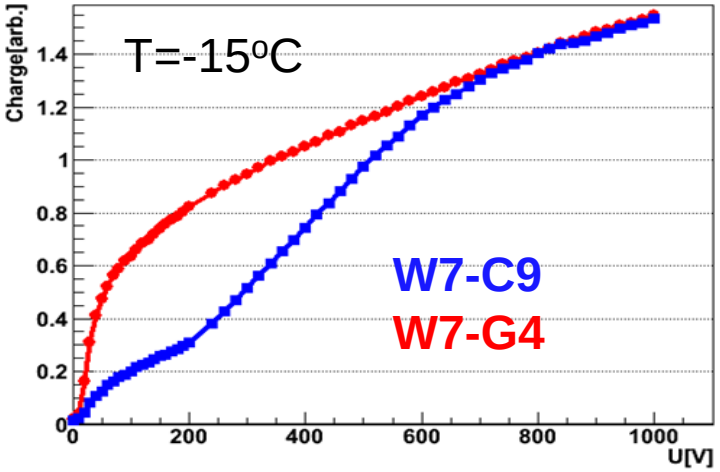
W7 devices (LOW GAIN) with different currents irradiated with neutrons:
W7-C9 low current device, W7-G4 high current device (~50 μA @ 500V)





Front injection shows some temperature dependence, but not large – does W7-G4 deplete at very low voltages? It seems so from back injection.

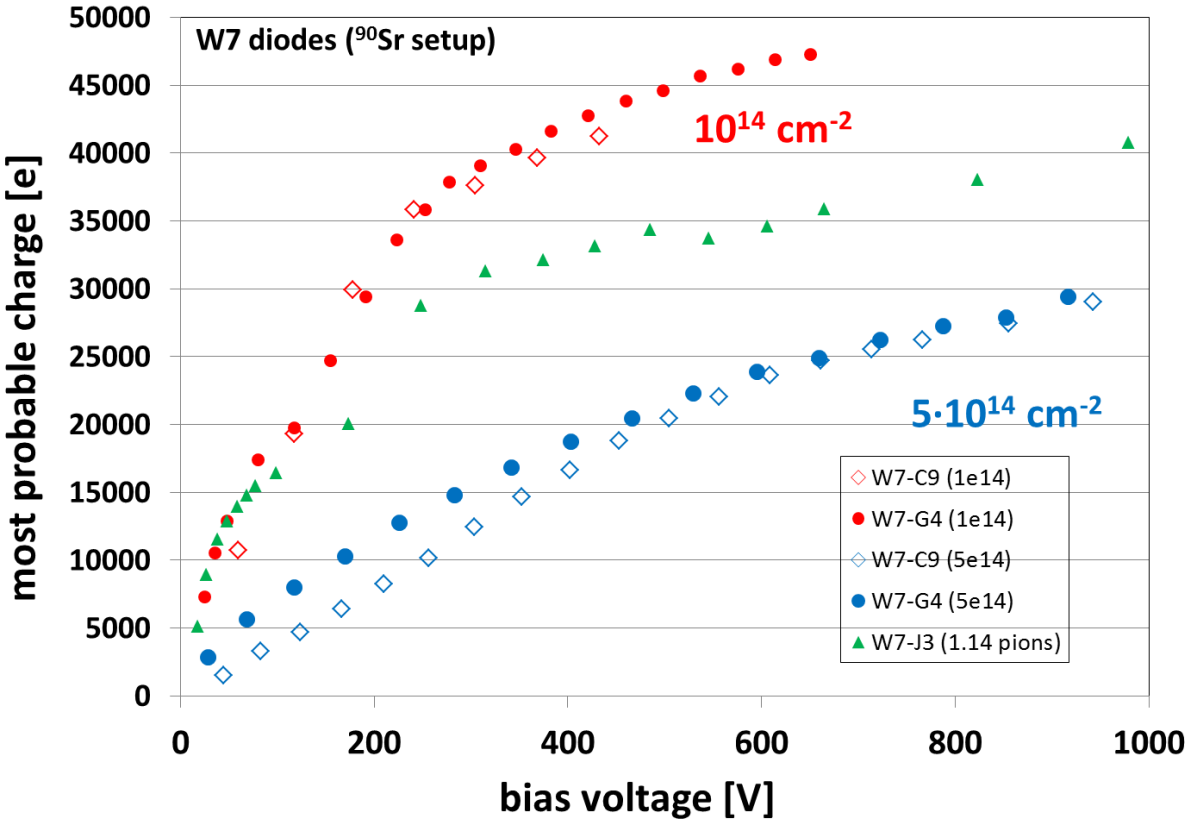
W7-C9 no dependence on T, but back injection shows: Initial 20 V are spent to deplete multiplication layer then depletion of the bulk showing double junction effect



Do we see effect in CCE plots

Low gain devices were selected (W7) with devices of different excess current
W7-G4 high excess current (100 mA)
W7-C9 low excess current (<1 mA)

If you pay attention one can notice the different in Q(V)
Beware – that can be different for segmented devices!



Solid markers – high current device

Open marker – low current device

Conclusions

- It seems that the excess current is dominated by hole current
  - the origin is not known, but it is not localized at a hot spot
  - It is not dependent on temperature (not a generation current?)
- Excess current in LGAD influences the space charge after irradiation
  - It can lead to SCSI which requires higher voltage to deplete the multiplication layer.
  - Space charge is heavily influenced by temperature. which can be explained by almost independent hole concentration (constant current) and strongly dependent de-trapping times
- The behavior is independent on irradiation particle type