Studies of LGAD diodes in Ljubljana (an update)

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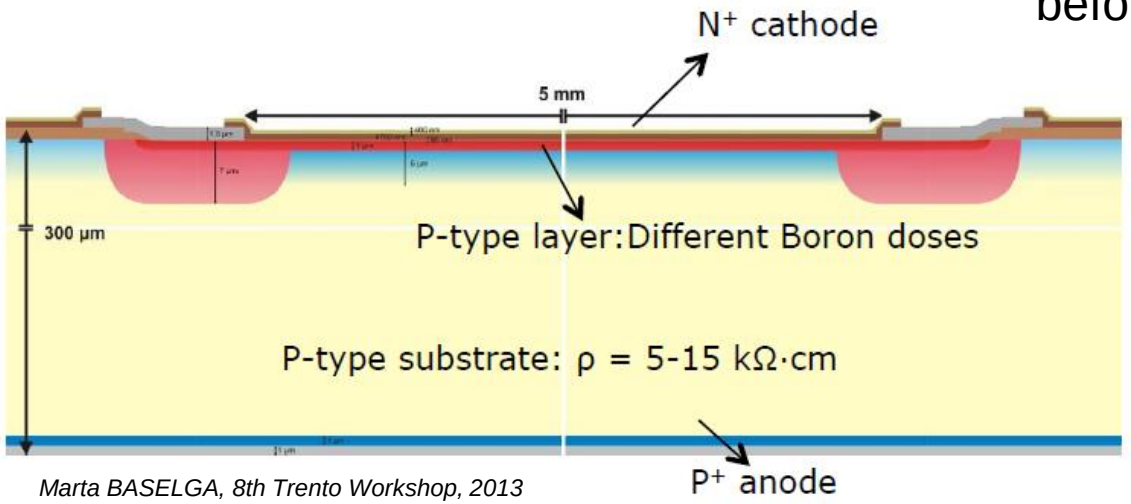
Motivation

It is a follow up from our talk at 22nd RD50 Workshop. Main topics of interest:

- Excess current:
  - Is the excess current in non-irradiated devices correlated with gain?
  - If not, where is it coming from?
  - What is it after irradiations and does it have any influence on CC?
- Gain
  - Is charge collection different for devices with different currents?
  - How does different of W7 and W8 compare after irradiation?
  - Do we see any difference in charge collection between LGAD and normal diodes at 10^{16} cm^{-2}?
  - What is the decrease of gain with fluence for W7 samples, which have lower gain?

Samples

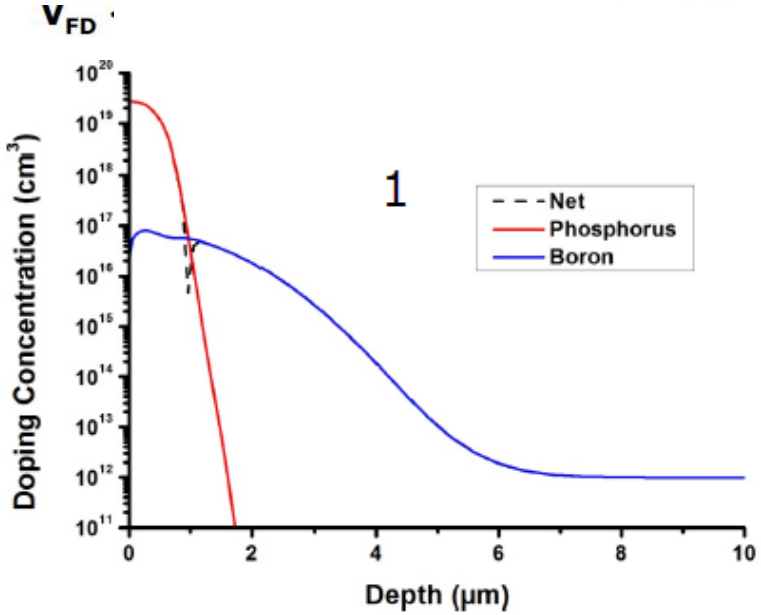
Avalanche multiplication already before irradiation – APD concept.



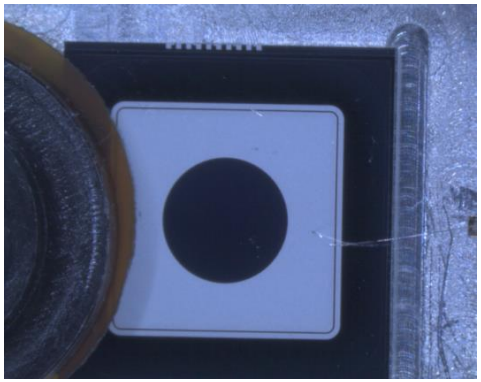
Marta BASELGA, 8th Trento Workshop, 2013

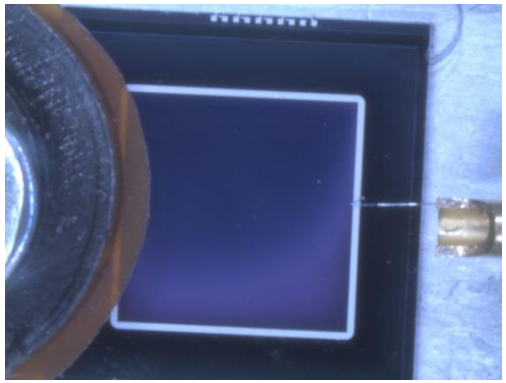
n^{++} - p^{+} - p – p^{+} stucture

$10^{16\text{-}17}$ cm^{-3} – much larger than in the bulk. Large N_{eff} provokes avalanche multiplication by impact ionization.

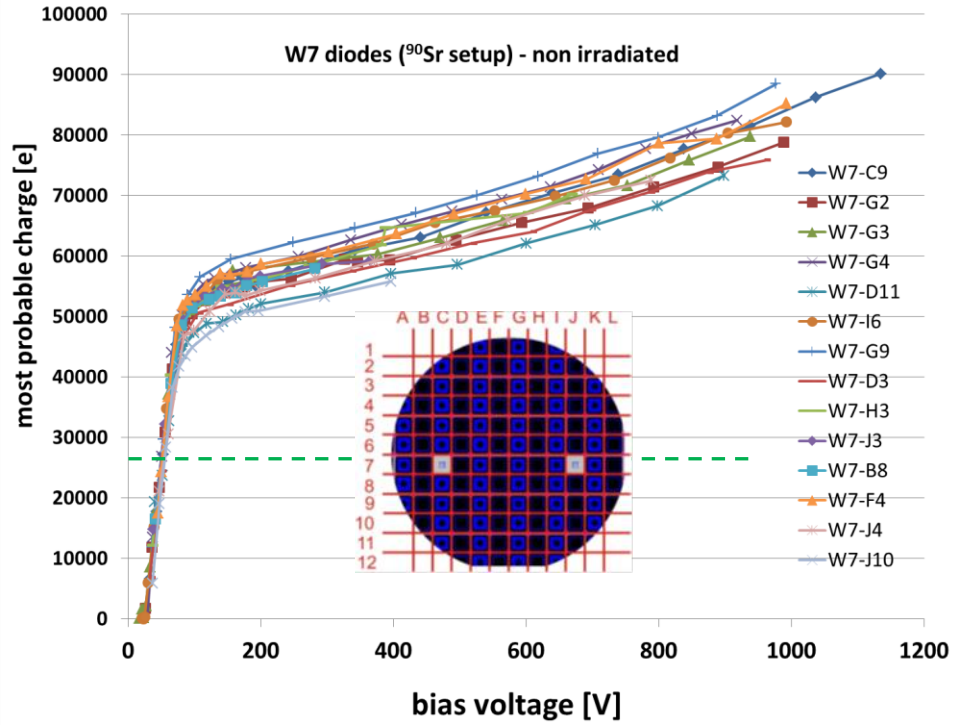


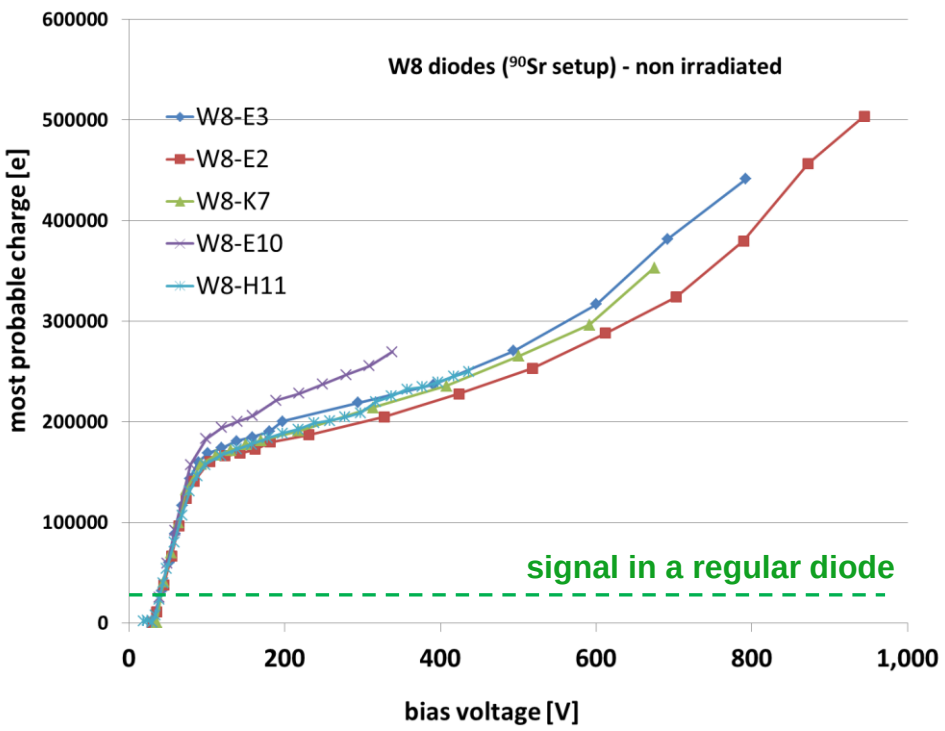
How do the diodes (pad detectors) behave before and after irradiation?





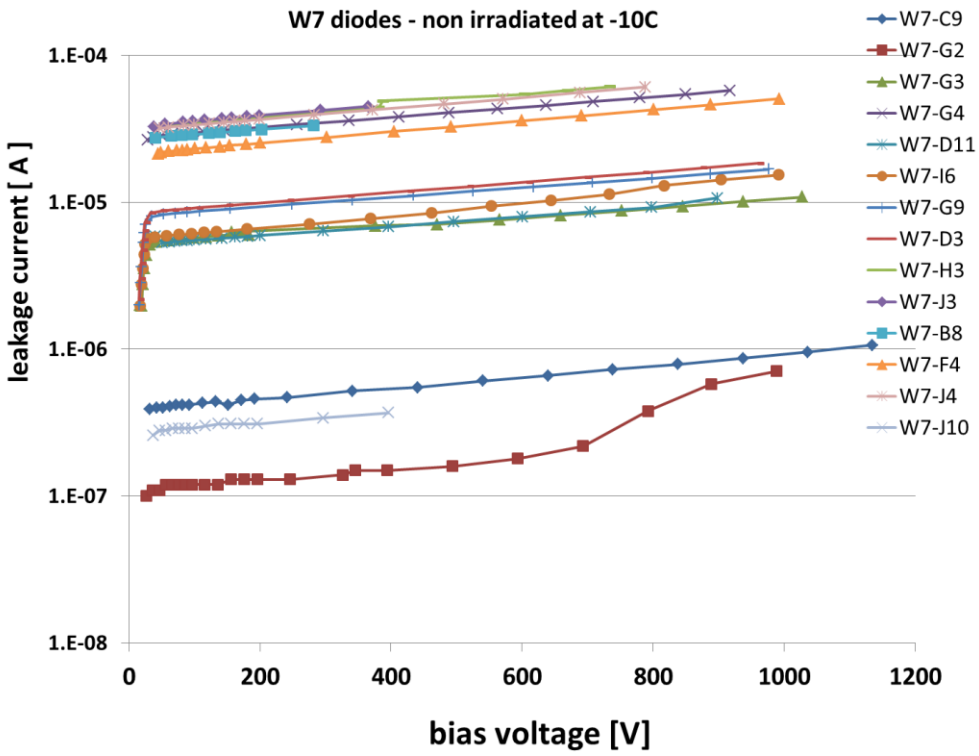
Charge collection of diodes from W7 and W8

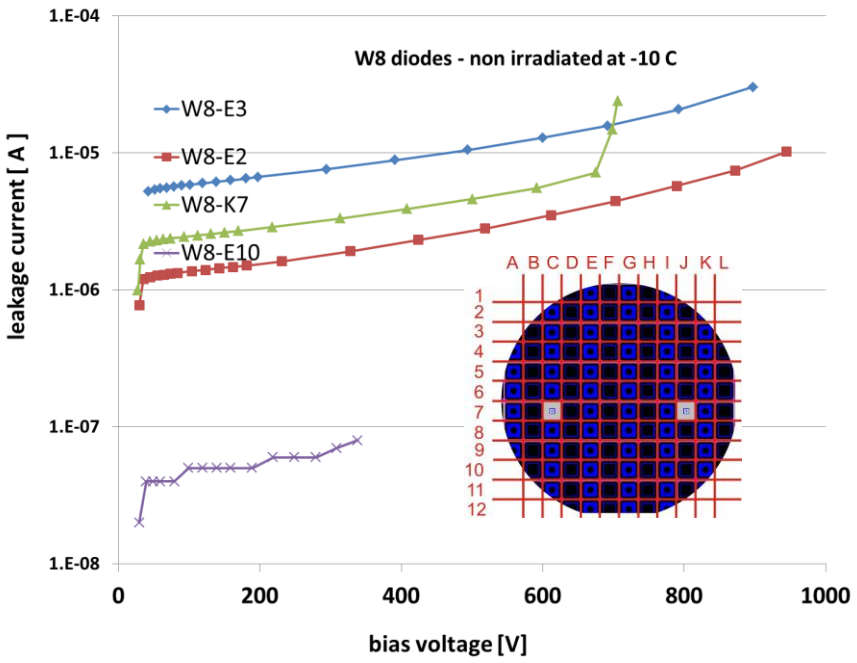




- **No apparent difference in gain for W7 and W8, although devices have different currents.**
- Weak, if any, dependence on position of the sample on the wafer
- Very good stability of some diodes up to >1000 V.
- For W8 samples the gain at >900 V is difficult to measure – amplifier saturates due to too large signals – note steeper increase of gain for U>500V.

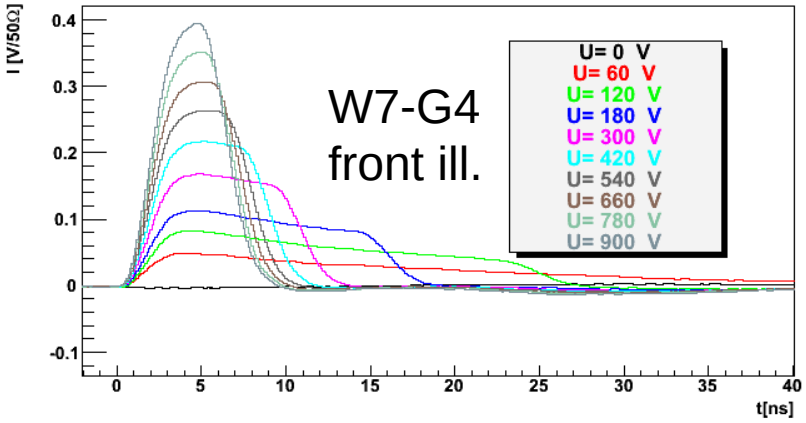
Current during CCE measurements at -10ºC



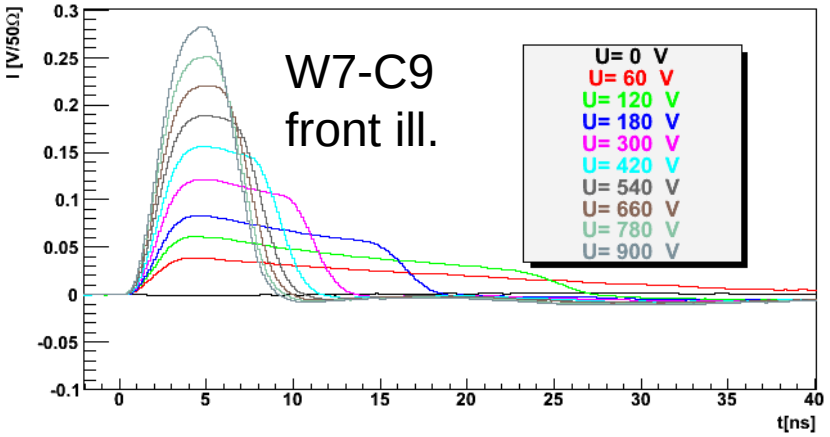


- Current at lower temperatures is still high - higher than expected for generation current!
- Devices have current spread in the range of 2-3 orders of magnitude.

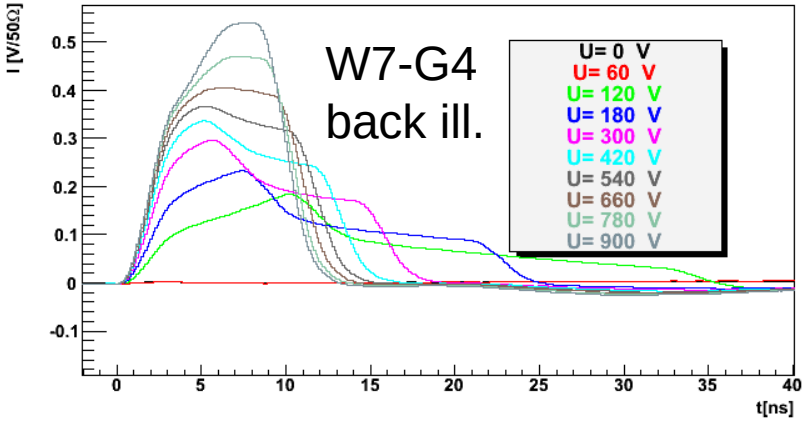
TCT for diodes from W7

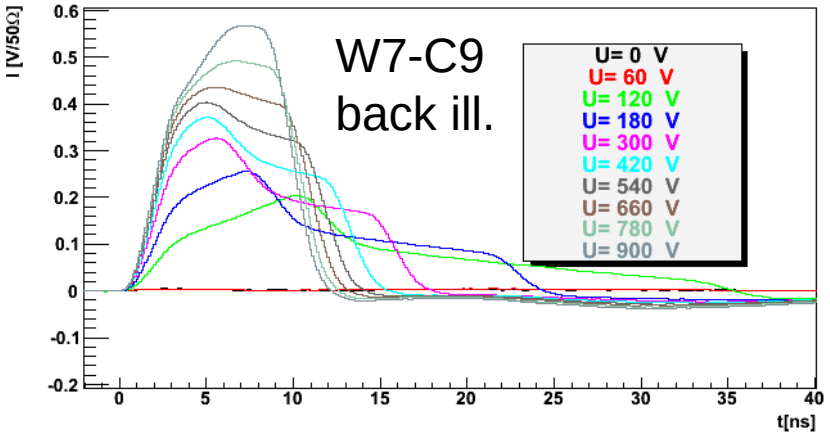


I<1 μA



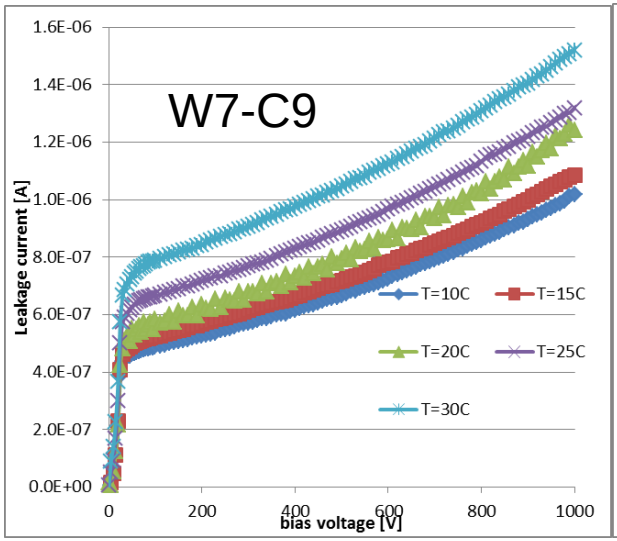
I~50 μA

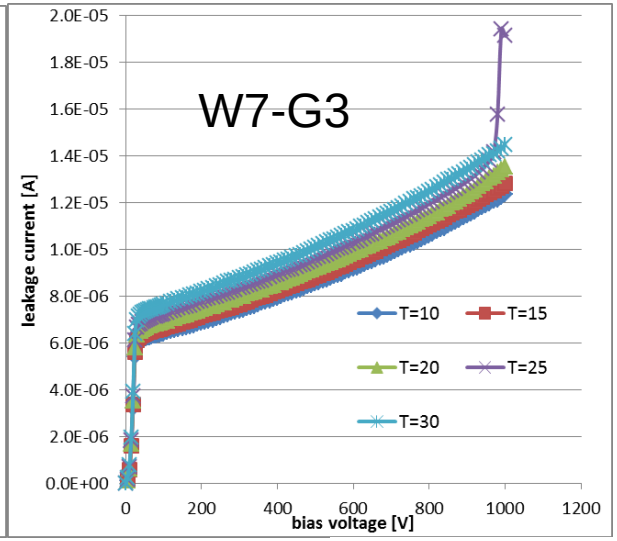


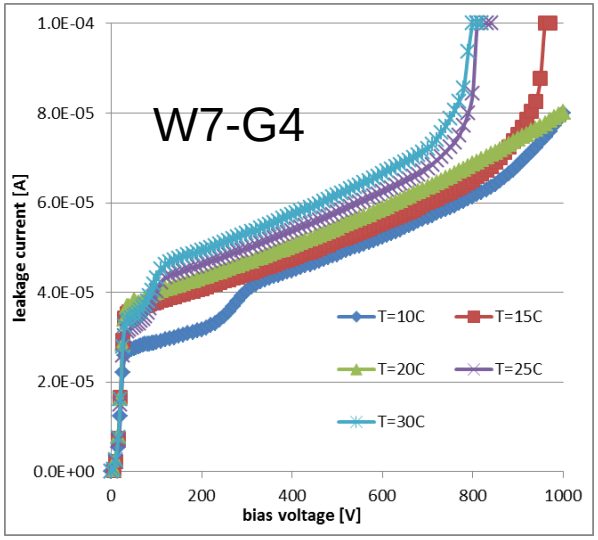


- Almost **identical signals for all W7 samples (all were measured)**: excess current has no influence on signal formation for non-irradiated samples
- The shape of the current after back injection is as expected for multiplication: 1. electron drift – 2. multiplication – 3. hole drift ; note that for low bias : $v_e \sim 3 \cdot v_h$

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.

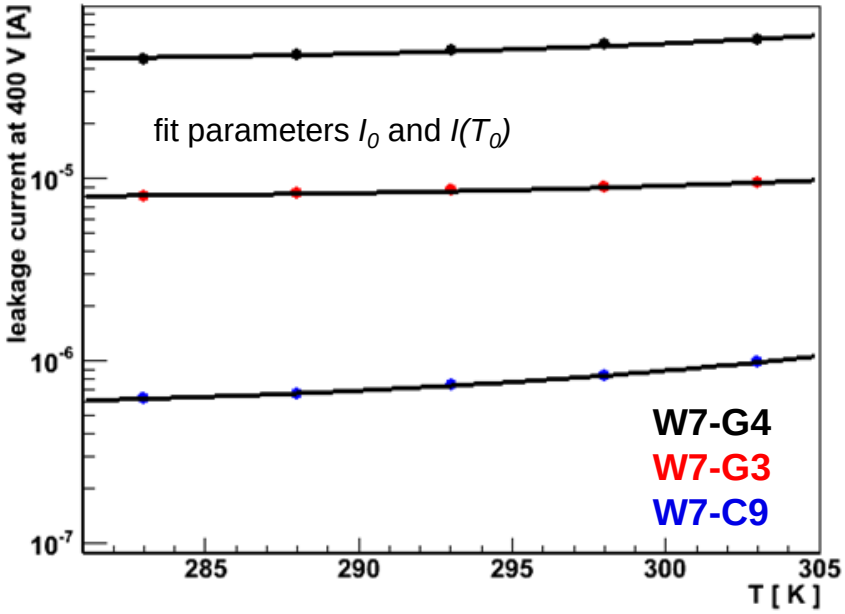
How to probe it?

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*** !



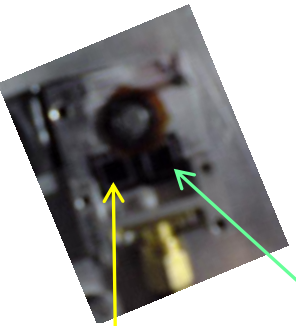
Where does the excess current (I_0) come from?

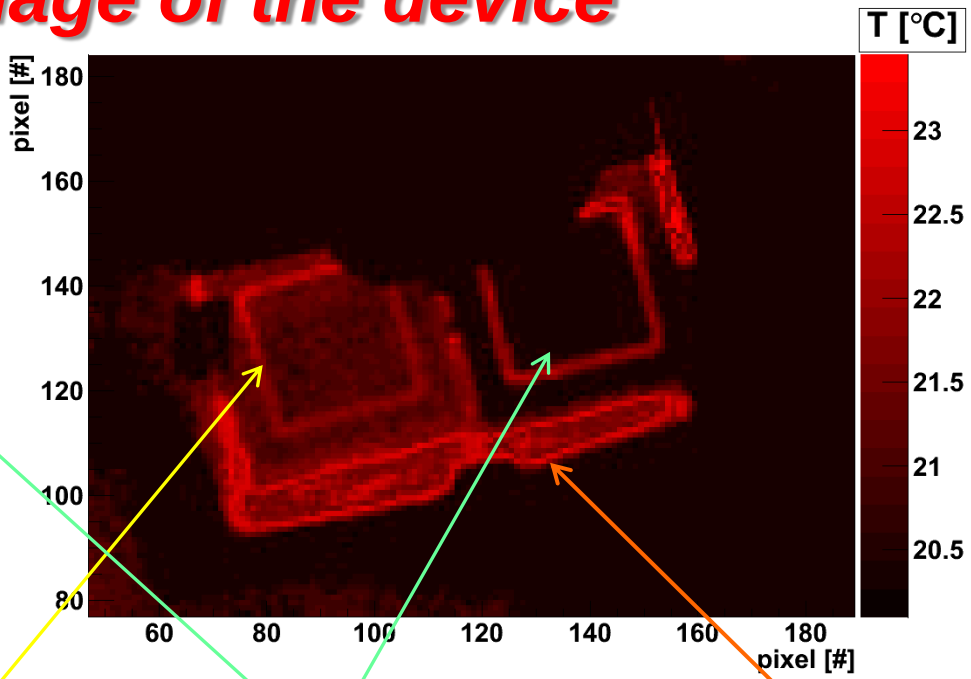
- Possible reasons for high current:
  - injection of the electrons from the back side (supported by the similar shape of the I-V and CCE-V for all sensors)
  - hot spots - JTE/edges
  - Any other …

- Excess current should result in heating of the sample when biased. Any obvious hot spots should appear in the IR image of the sensor. In order to be accurate two sensors were put together – one biased (W7-G4) and one not (W7-G3) of the same type. The latter serves for the reference as the precise absolute determination of the sample temperature is difficult for different materials.

Note that this is our first attempt with an IR-imager which is in addition not meant for such purposes.

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!

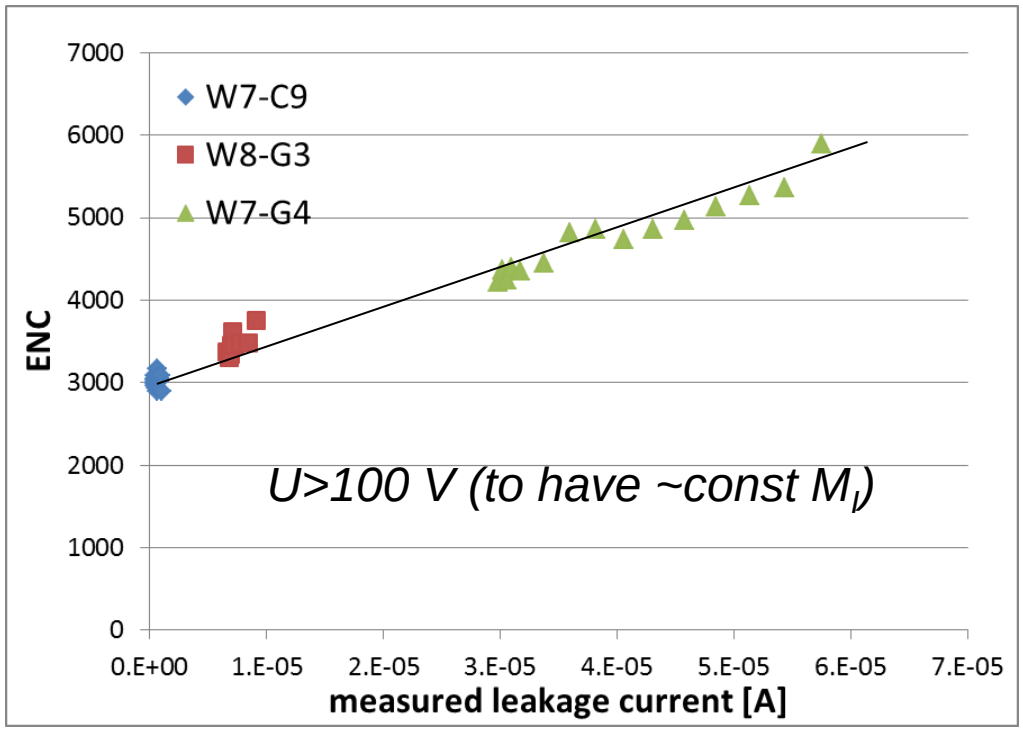
Investigated detector (not biased)

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.

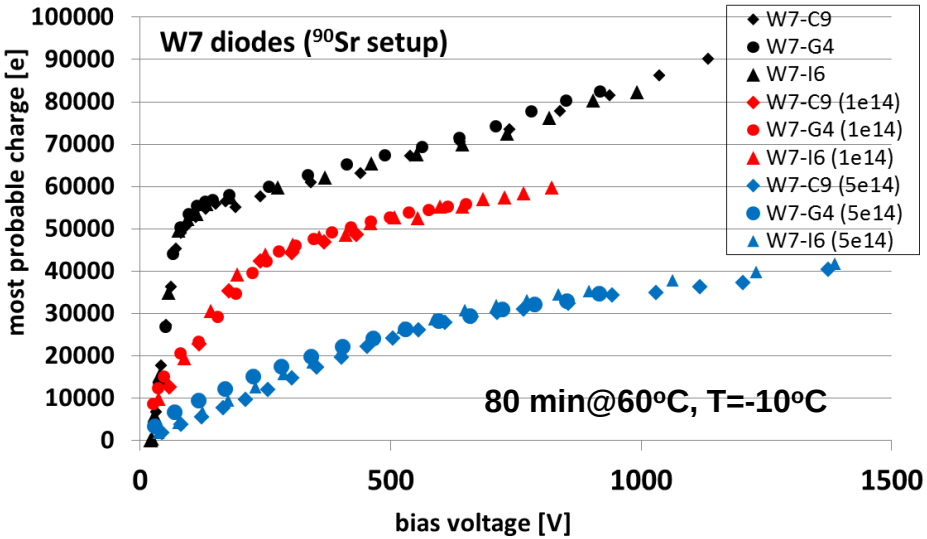
Noise measurements

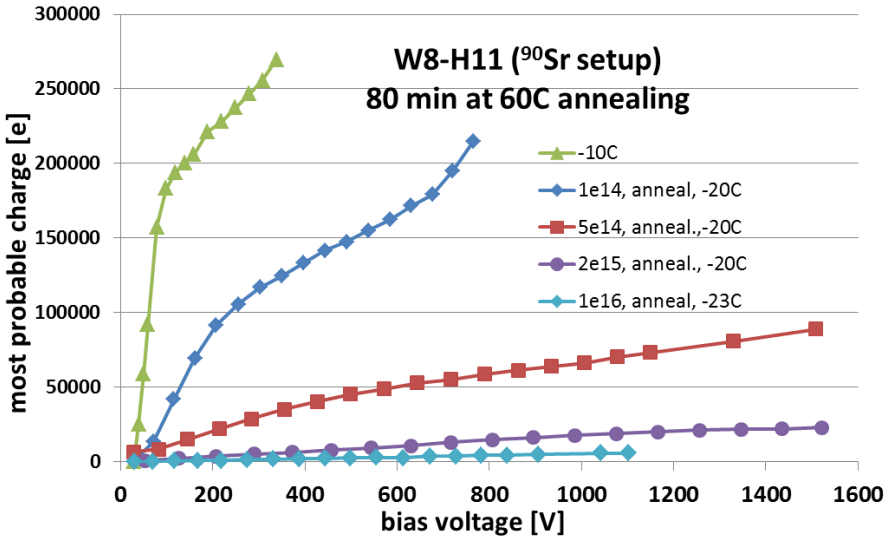
- The measured noise is in agreement with the expectationxs (see talk from last RD50 workshop) with $M_I=M_Q$~2-3 for W7
- This is a strong indicator that excess current undergoes multiplication. If this was not the case the *noise vs. current* plot would have a different shape (more sqrt than linear dependence)
- Question: if it undergoes multiplication with appropriate factor can it be at JTE?



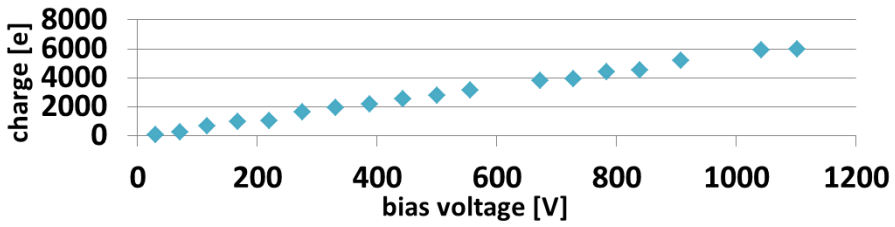
CCE of irradiated detectors

- Detectors irradiated with neutrons in steps with annealing at 60°C in-between
  - W8 from 1,5,20,100·10^{14} cm^{-2}
  - W7 from 1,5·10^{14} cm^{-2}
- Selected detectors from W7 wafers: W7-C9 (~1 μA), W7-I6 (~10 μA), W7-G4 (100 μA) which have different currents were irradiated together to both fluences

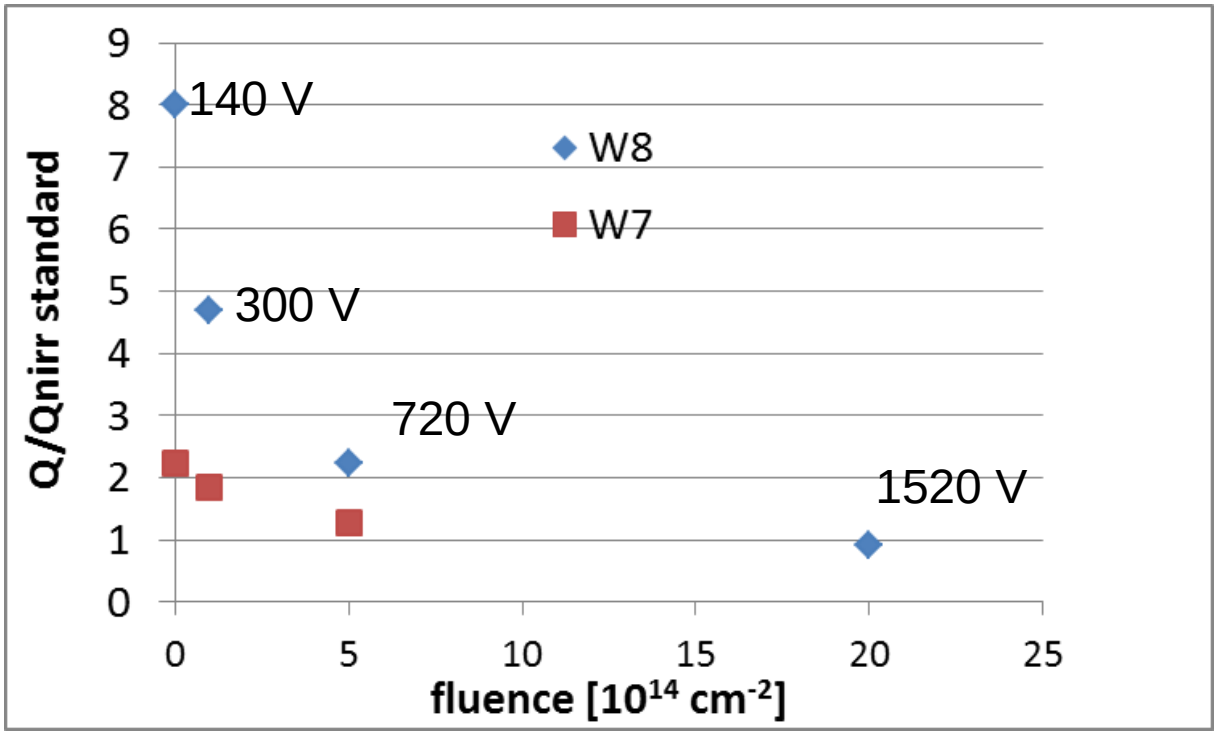




- W7 – full depletion voltage can be nicely observed
- W8 around 6000 e collected at 10^{16} cm^{-2} , which is still slightly more than for normal diode
- There is almost no influence of CCE of devices on the initial current for W7– some difference at lower bias voltages at 5·10^{14} cm^{-2}.

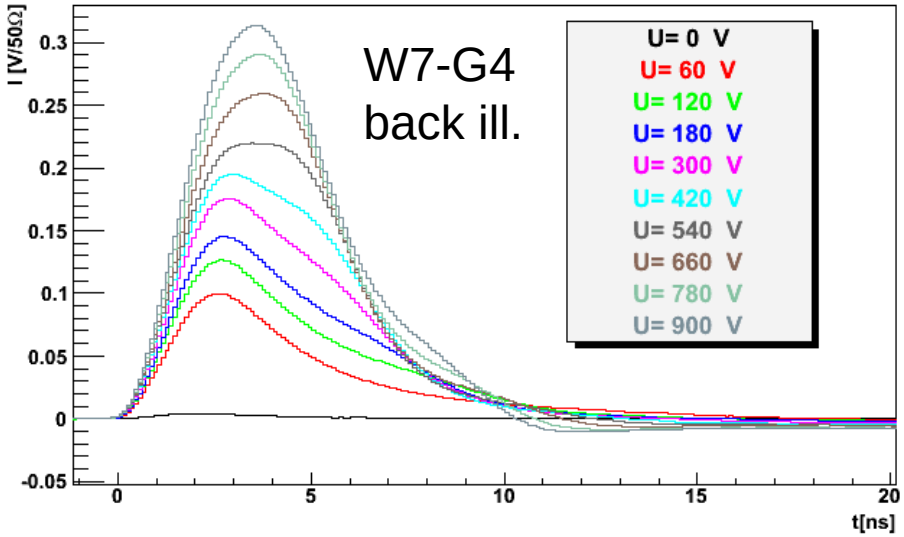


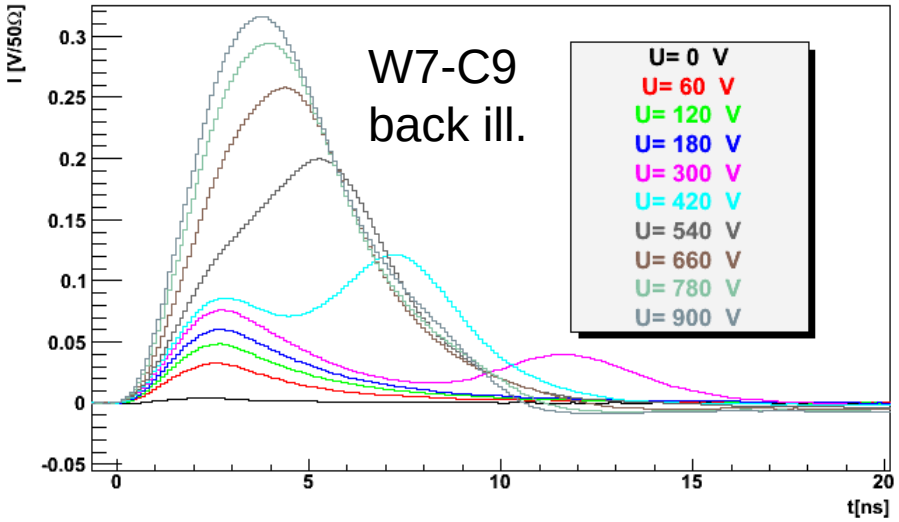
CCE of irradiated detectors



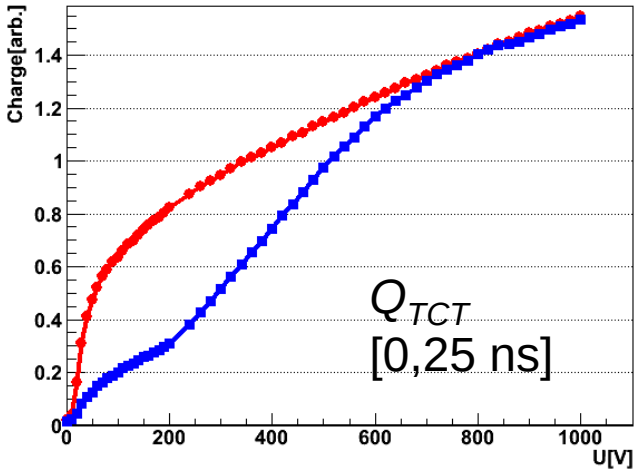
- Charge multiplication measured at ~V_{fd} (similar for W7 and W8) decreases with fluence.
- As the trapping is not that severe the dominant decrease should come from decrease of multiplication
  - acceptor removal (see the morning talk)
  - trapped holes reduce the field in the multiplication region (can be probed by TCT)

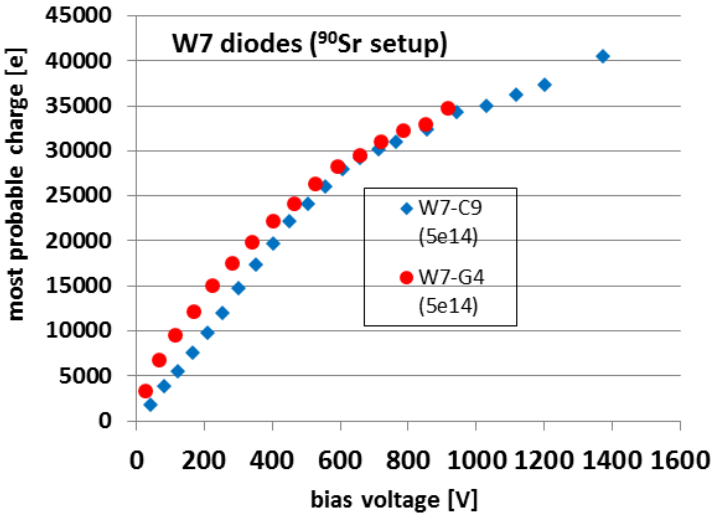
TCT for irradiated diodes from W7





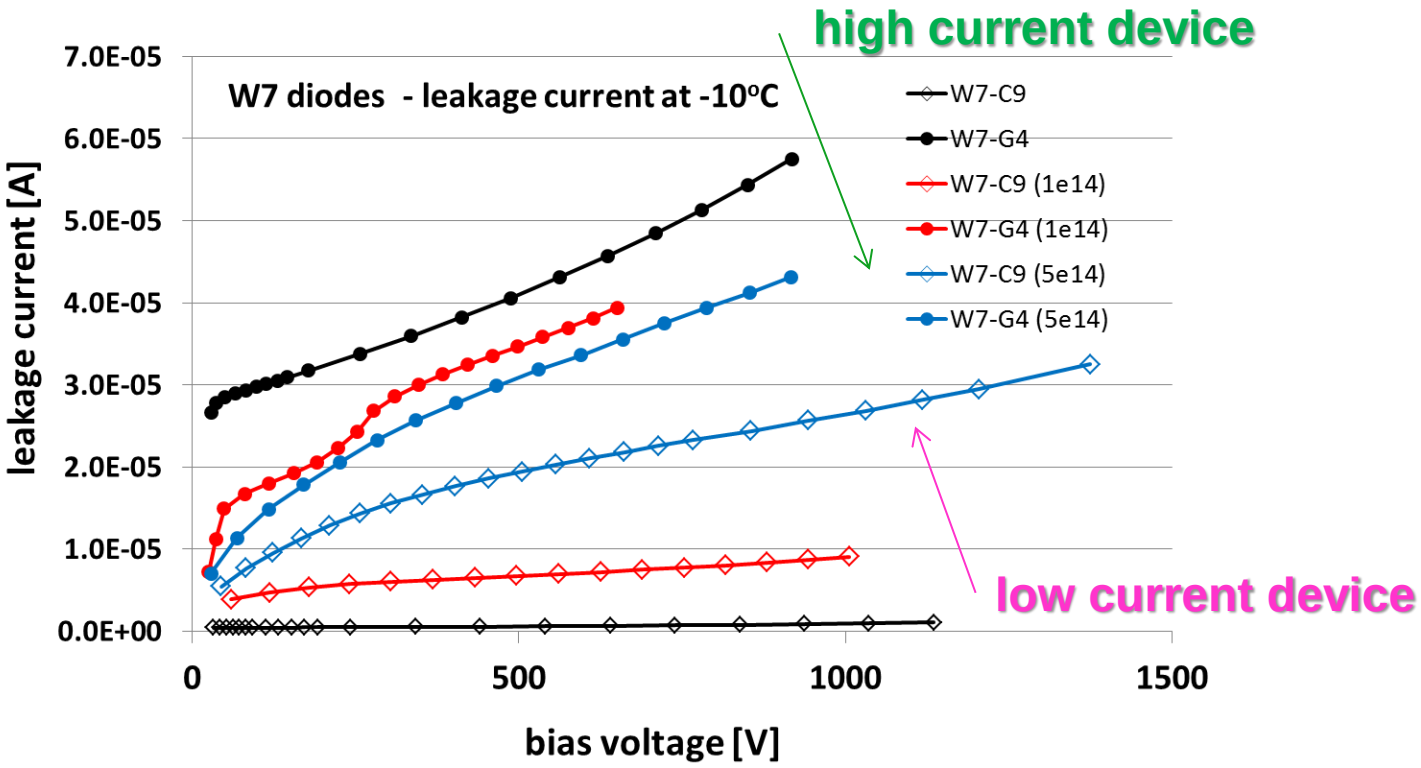
- There is a difference between W7-G4 (high current) and W7-I6 (med. current), W7-C9 (low current)
- It seems that larger electric field is present in the bulk for large current devices at lower voltages– do free carriers modify electric field?





Leakage current of irradiated W7 detectors

- The leakage current increases as expected (reduction of M_l and increase of I_{gen}) for W7-C9 device
- For the "high current" devices the **leakage current decreases at moderate fluences**:
  - reduction of M_l
  - deactivation/decrease of injection centers ???



Conclusions

Current:

- larger dark current in the detectors is not due to larger gain
- the excess current is not related to bulk generation current – doesn't scale in the same way with temperature
- it seems that the excess current is not due to some hot spots but it is uniformly distributed over the surface (not conclusive for IR image yet)
- noise measurements indicate the excess current undergoes multiplication
- after irradiations to moderate fluences the current decreases for high current devices and increases for low current devices

Gain:

- for W8 multiplication seems to increase faster for approx.. U>500 V until it actually saturates our amplifier.
- gain does not depend much also on sample position on the wafer (for sensors sent to us) and is constant within around 10% for all measured devices
- "excess" current has no impact on induced current shape before irradiation and it has some after irradiation
- radiation significantly decreases the performance, due to loss of multiplication and less due to trapping