Radiation damage in thin LGADs produced by HPK

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on behalf of colleagues from
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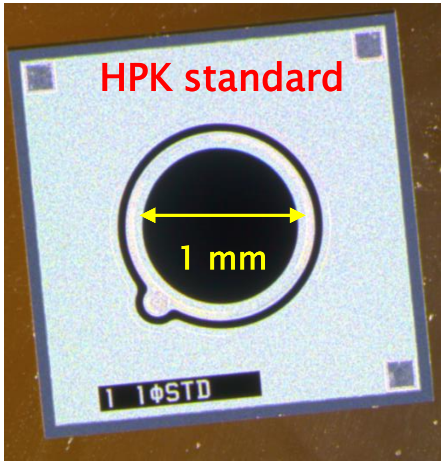
Motivation

- LGADs pioneered by CNM and triggered many interest among other producers (FBK, HPK, Micron, BNL…).
- HPK has a capability to produce large quantities, which may be required for future experiments.
- CNM (also for the FBK run) runs have occasionally higher leakage currents
  - Is it something that depends on process?
  - HPK is known for very “clean” process.
- Can the performance/charge collection after irradiation depend on process:
  - different doping profiles (removal rate depends on concentration)
  - different HV tolerance
- Is effective initial dopant removal related to thickness?
  - removal due to deep traps would depend on thickness (larger volume of thermally generated current)

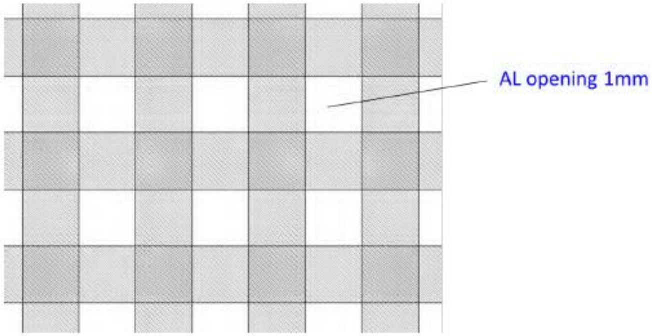
Samples studied

- HPK run
  - 2.5x2.5 mm^2
  - 50 and 80 μm thick (physical thickness 150 μm), high resistivity
  - 4 different dose splits (A,B,C,D)
    - D=highest dose , A=smallest dose
  - high break down voltage (>500 V)
  - 3 different designs in terms of guard rings – only measurements with "standard" will be shown
  - leakage current before irradiation very low [nA]



- Irradiations done in steps:
  - Equivalent fluences 1e14, 3e14, 1e15 cm^{-2}
  - After irradiation samples were annealed for 80min @ 60C

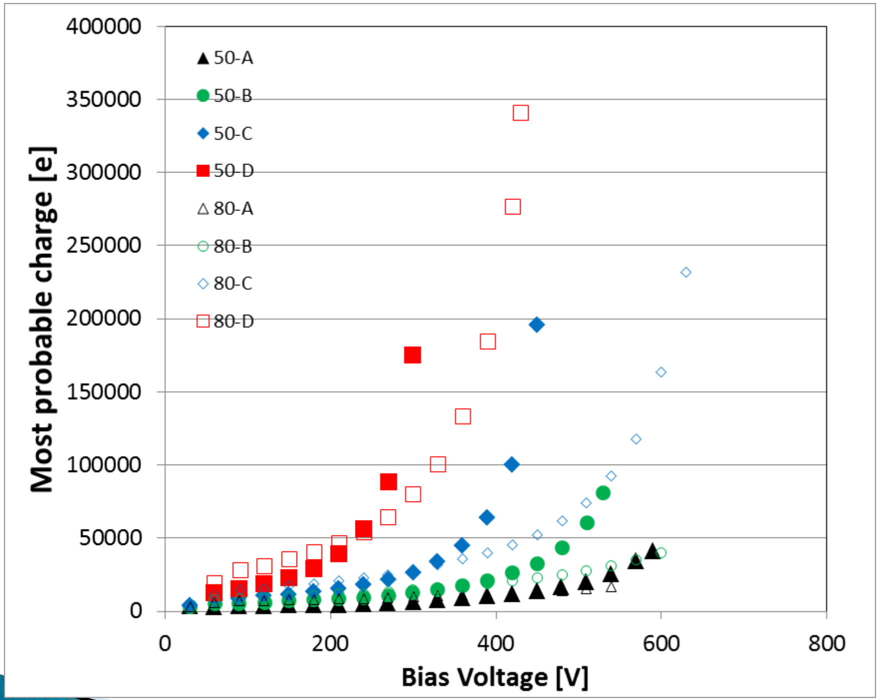
Back side metallization

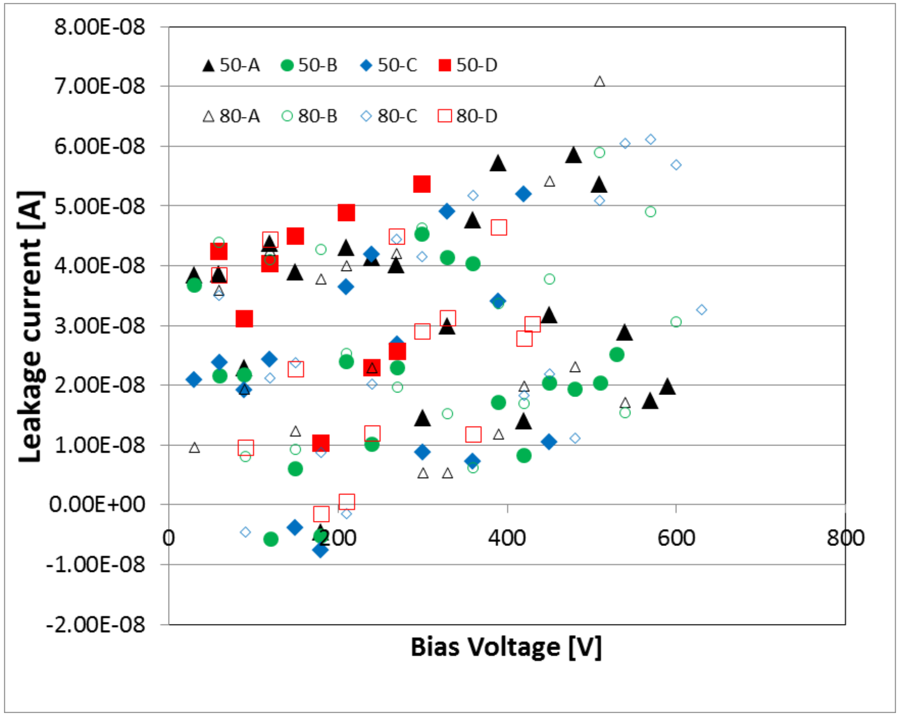


- Measurements performed:
  - CCE (^{90}Sr)
  - TCT (red – 660 nm laser)

HPK samples – before irradiation

- Very low current (not accurately measured in the setup)
- Expected shape of the charge vs. voltage curve
  - intersection of 50 and 80 μm curves (for lower V_{bias} 80 μm is better – primary charges, for large V_{bias} 50 μm is better – larger gain at the same gain
  - a clear effect of different multiplication layer doping (D->A)
  - higher break down for lower charge multiplication layer doping





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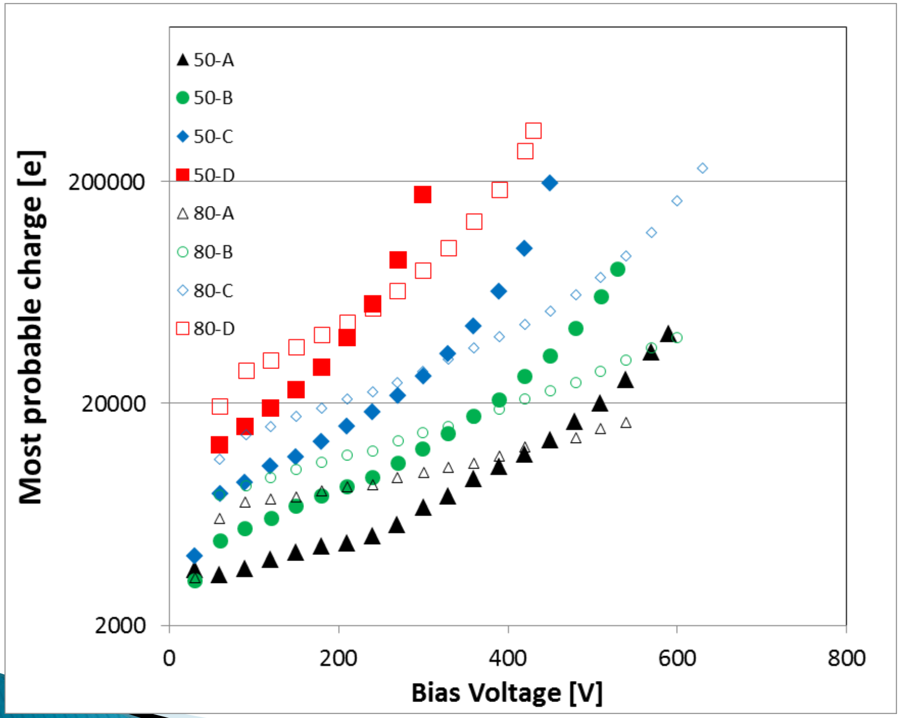
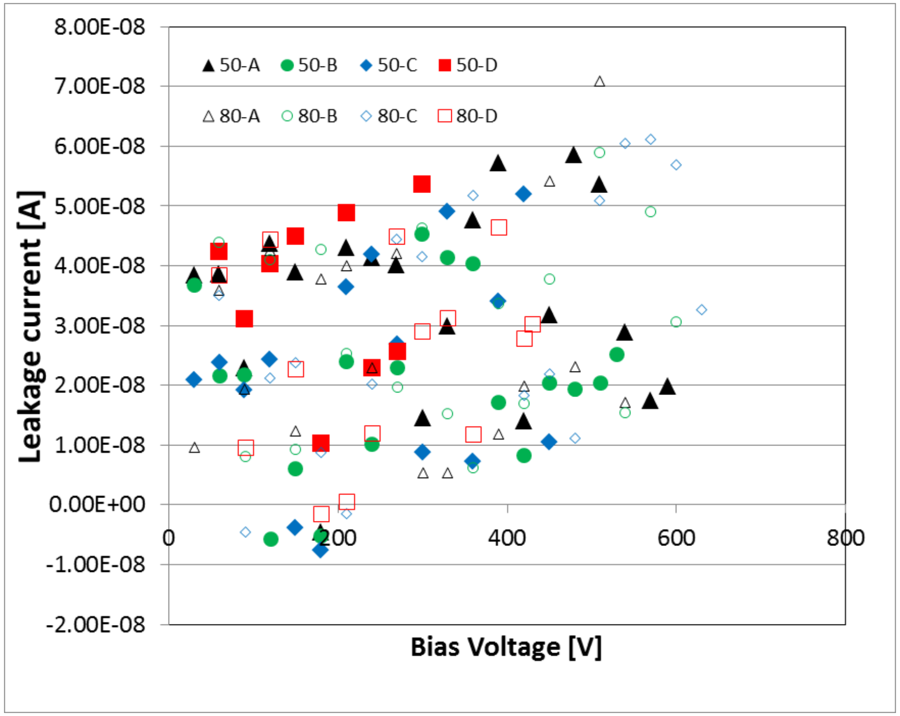
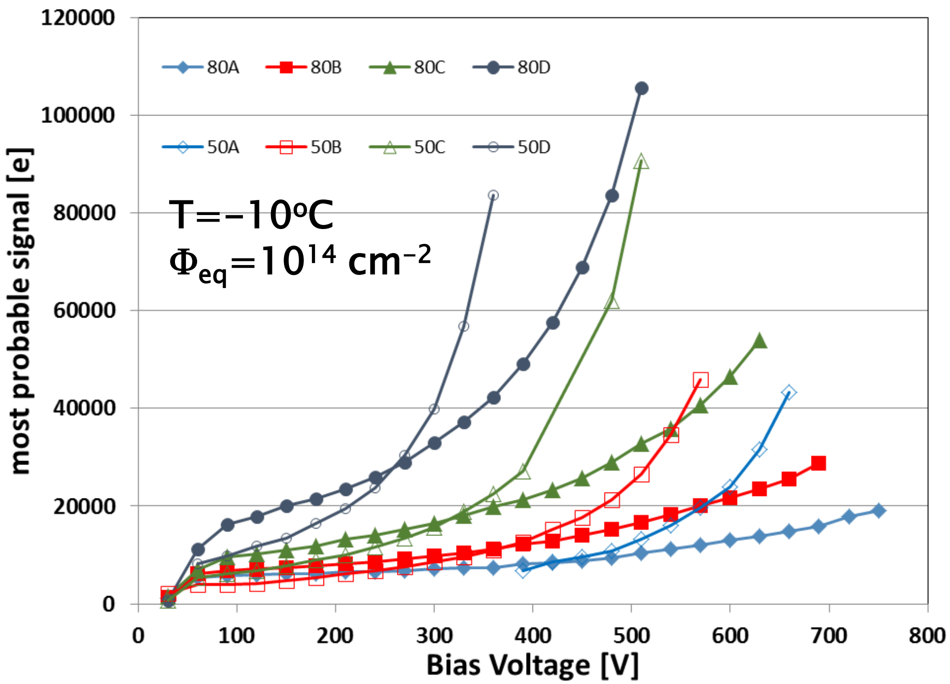
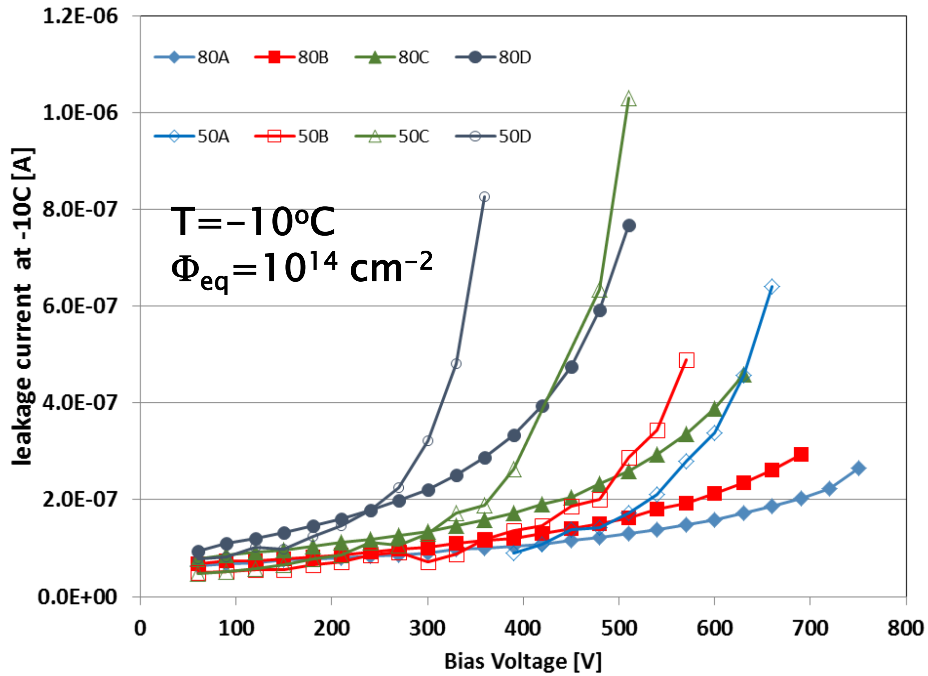




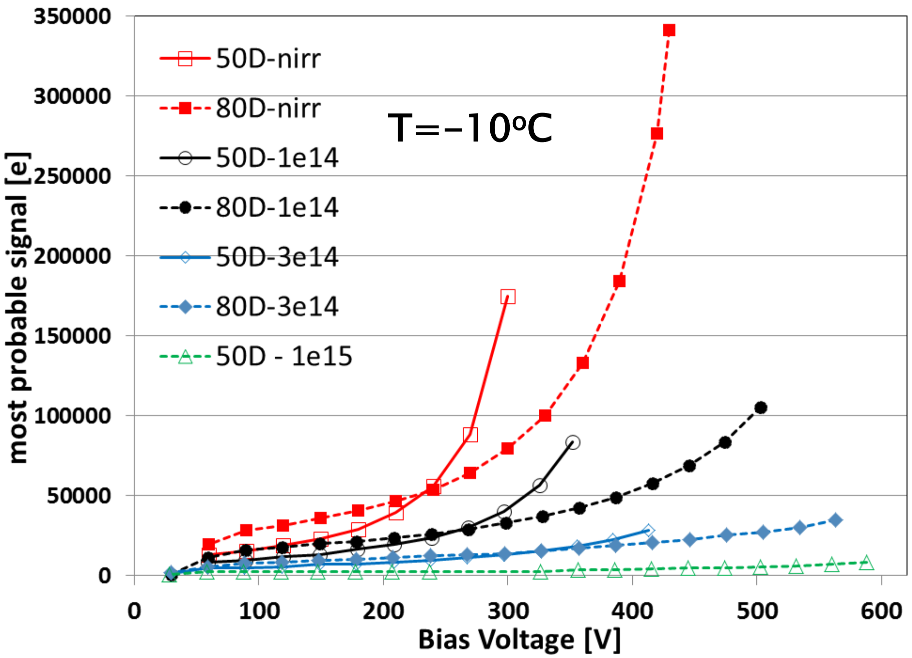
HPK samples (irradiated)

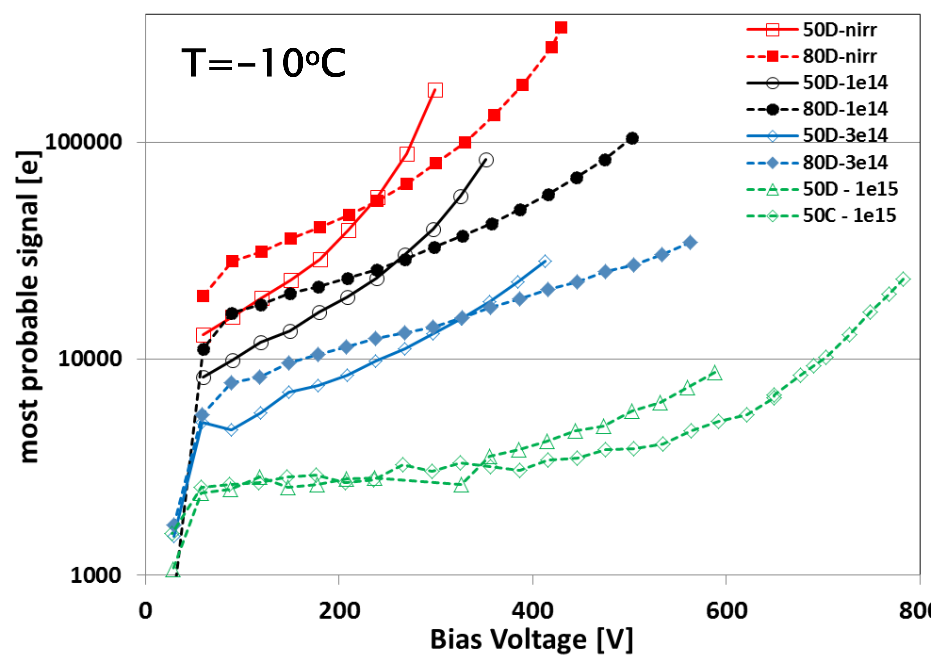




- Perfect correlation between current and most probable signal from both sensors
- Signal loss similar to CNM and FBK.
- Less micro discharges (no warning of breakdown – we lost one of the samples)

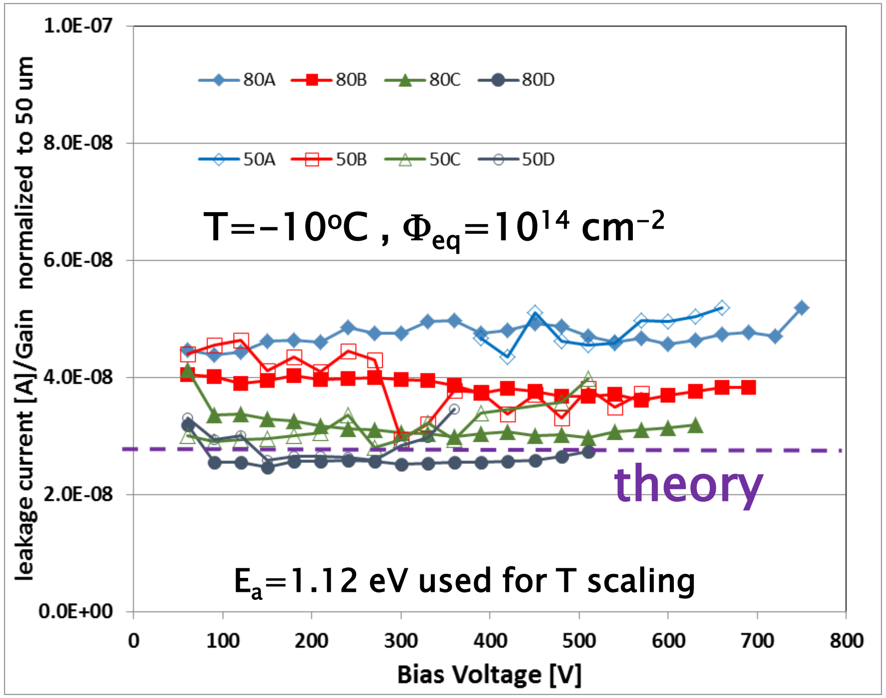
Charge dependence on voltage

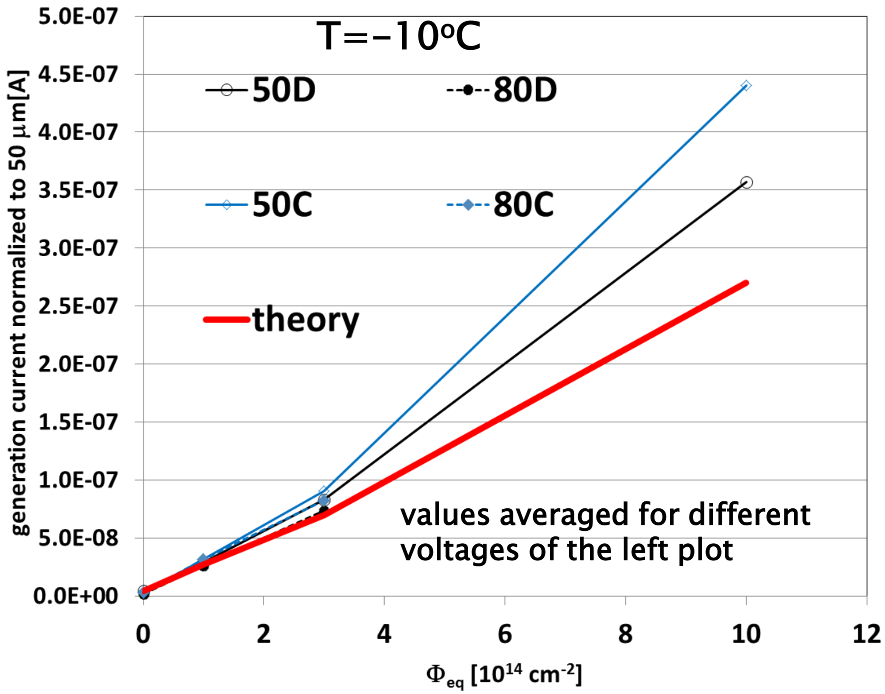




- The characteristic shape as for CNM
  - Decrease of charge at low voltages – disappearance of multiplication layer
  - smaller slope of charge increase
- "Break-even" voltage for 50 and 80 μm is shifted to large voltages as expected
- Perfect current behavior – basically one can extract the gain from current measurements alone

Leakage & Generation currents



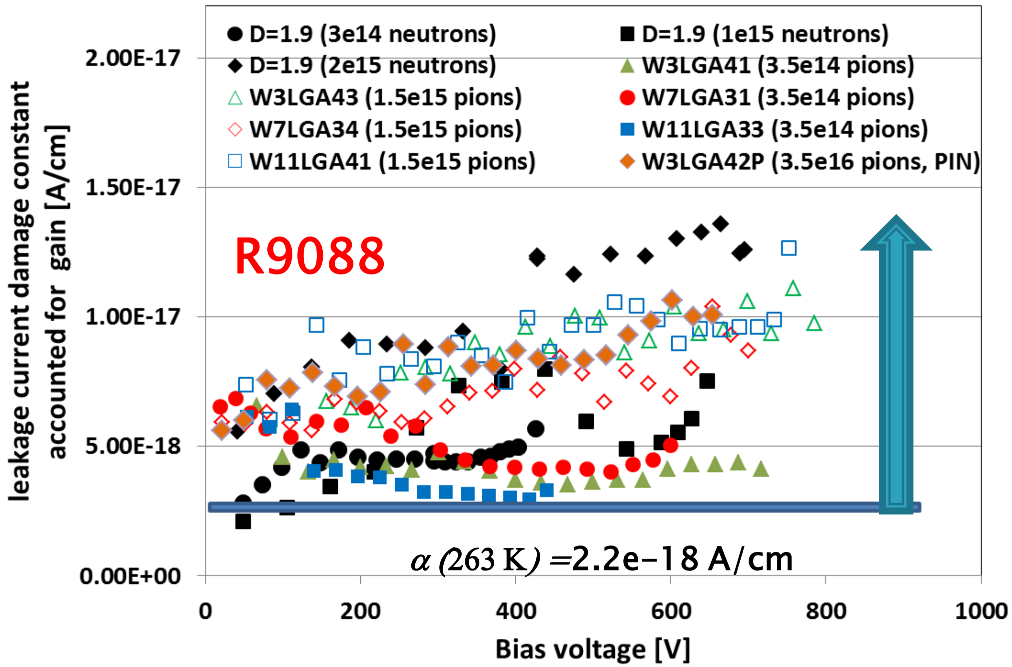


$$I_{gen} = \frac{I_{meas}}{M_I} \quad , \quad \text{gain} \approx\sim M_I$$

$$I_{gen,theory} = \alpha(-10^0\mathrm{C}) \cdot S \cdot w \cdot \Phi_{eq} + I_0$$

Very good agreement between predicted and measured current – excess current seen in CNM and FBK is probably related to the process.

Leakage current comparison with CNM



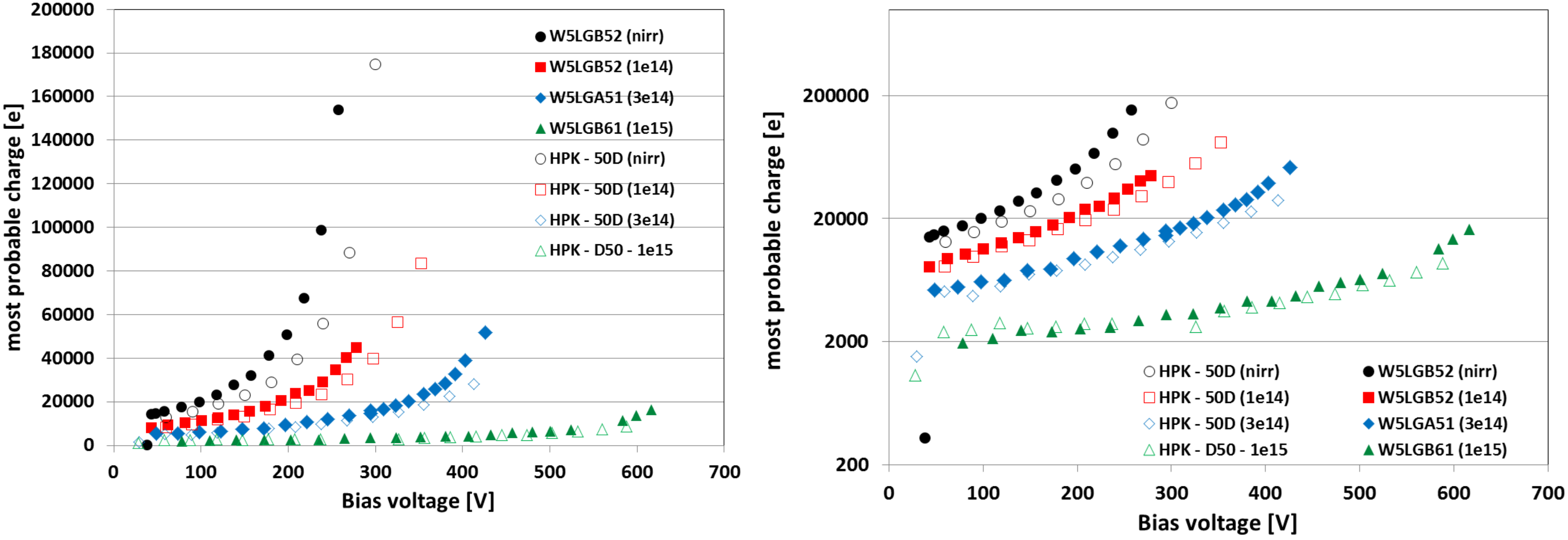
$$\alpha = \frac{I_{gen}}{S \cdot d} = \frac{I}{S \cdot d \cdot M_I} = \frac{I}{S \cdot d} \cdot \frac{Q_{no,gain}}{Q_{LGAD}}$$

Measured leakage currents are higher than expected for factor 2-4

- possibly larger temperature than measured (T is not measured on the sensor)
- leakage current gain can be larger than that for the charge collection
- surface current contribution is not separated in these measurements
- we still don't understand fully the origin of the dark current before irradiation

Probably not related to multiplication mechanism as control samples show same behavior

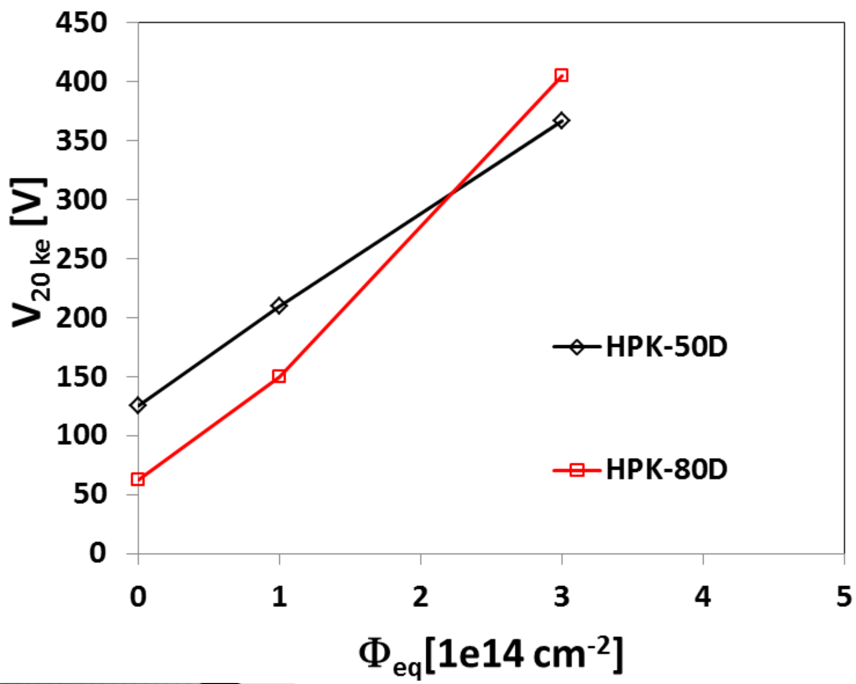
Charge comparison with CNM

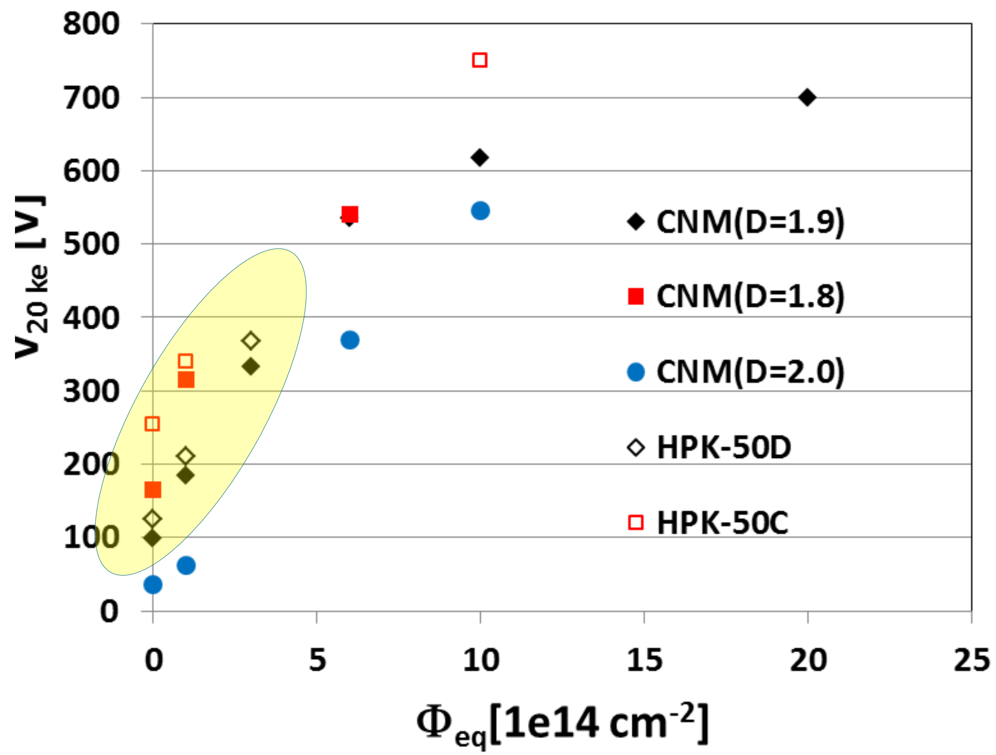


- Good agreement in collected charge between devices from CNM and HPK
  - slightly different thickness (45 μm CNM, 50 μm HPK)
  - possibly different doping profiles ?
- There is not so much "phase space" for reaching certain gain in LGADs and it seems that the performance for a given thickness after irradiations is already determined by initial gain (shown also for FBK devices of standard thickness).

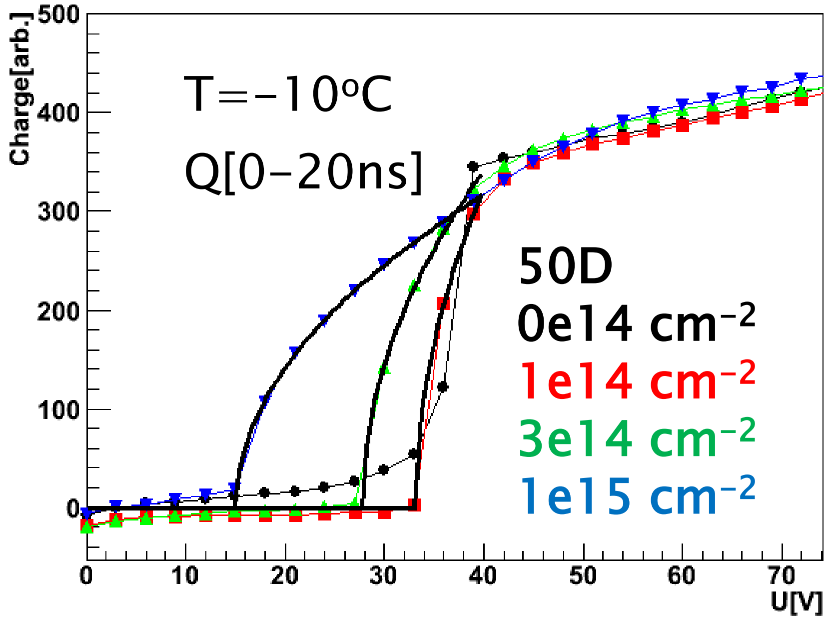
Comparison of performance

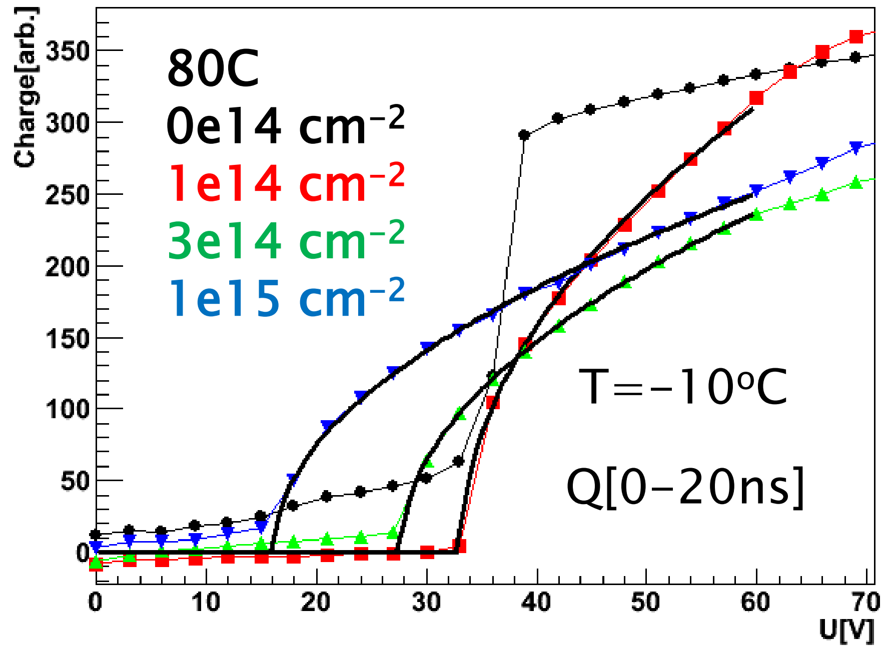
- The timing performance of irradiated thin LGADs depends (noise is controlled) almost entirely on collected charge; **20 ke ≡ 55-60 ps**
- $V_{20ke} \equiv (\sigma_t = 55$ ps) is very similar for HPK and CNM – universal mechanism of gain loss – not process dependent
- Even when **the Landau time walk** is not taken into account for time resolution the thicker detectors exhibit larger V_{20ke} at higher fluences – would be benefit from going to even smaller thicknesses as 50 μm
- Higher doping is beneficial for retaining the LGAD performance at higher fluences.



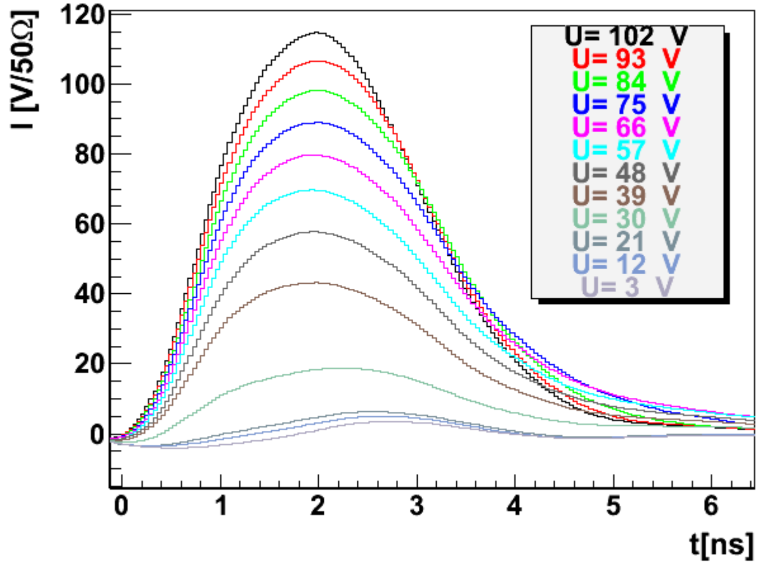


TCT measurements – front illumination



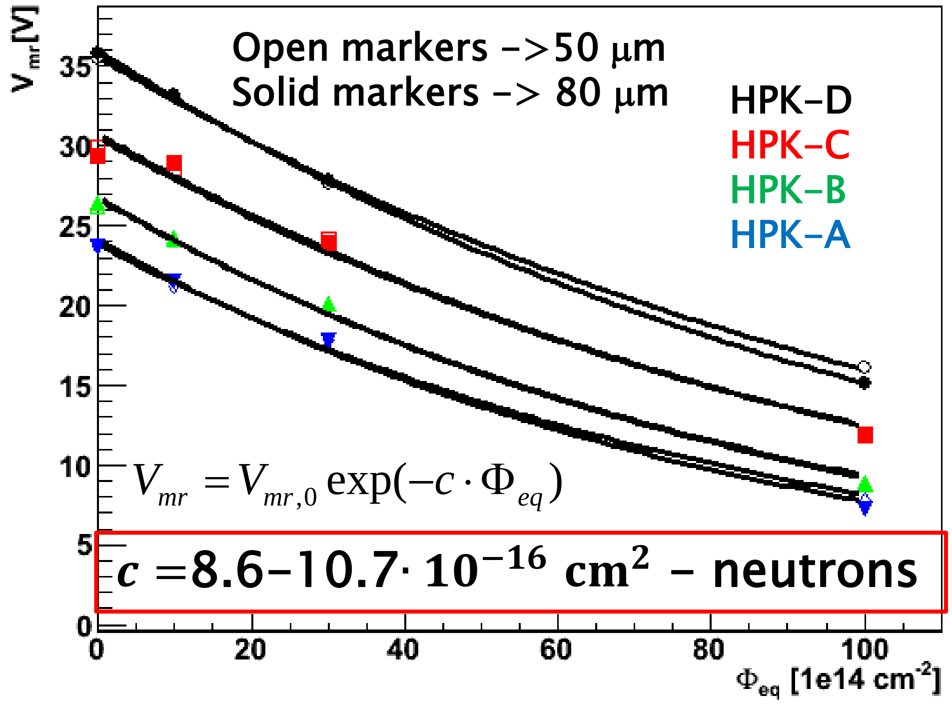


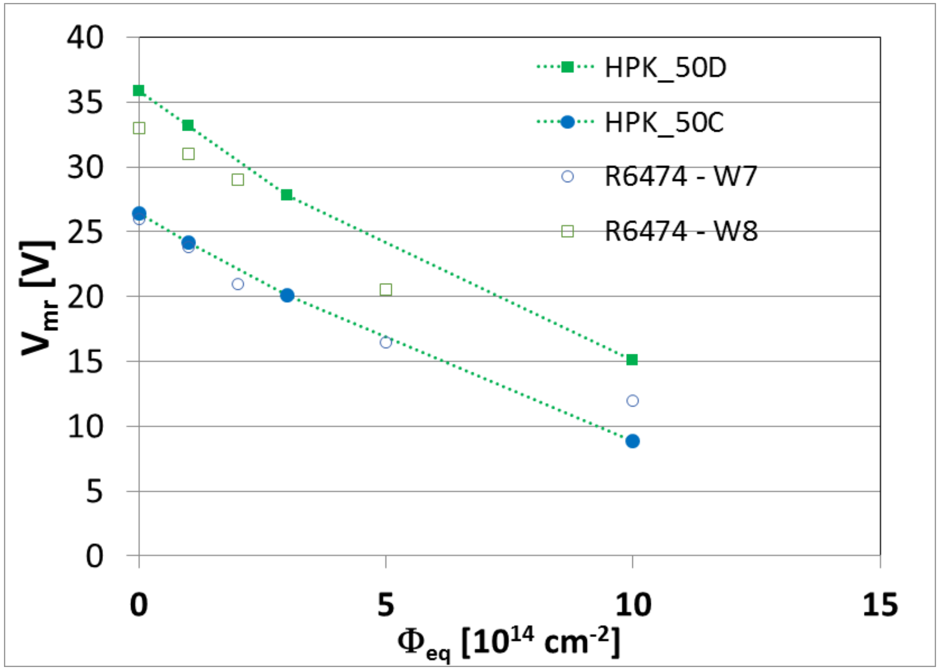
- Evolution of the "foot" voltage V_{mr} shows identical disappearance of gain layer for devices of both thicknesses (should be different if deep traps are also responsible)
- All the devices had low current and evolution of foot was observed for all – no large multiplication that would lead to changed device model after irradiations



Disappearance of gain layer

FRONT 660 nm TCT

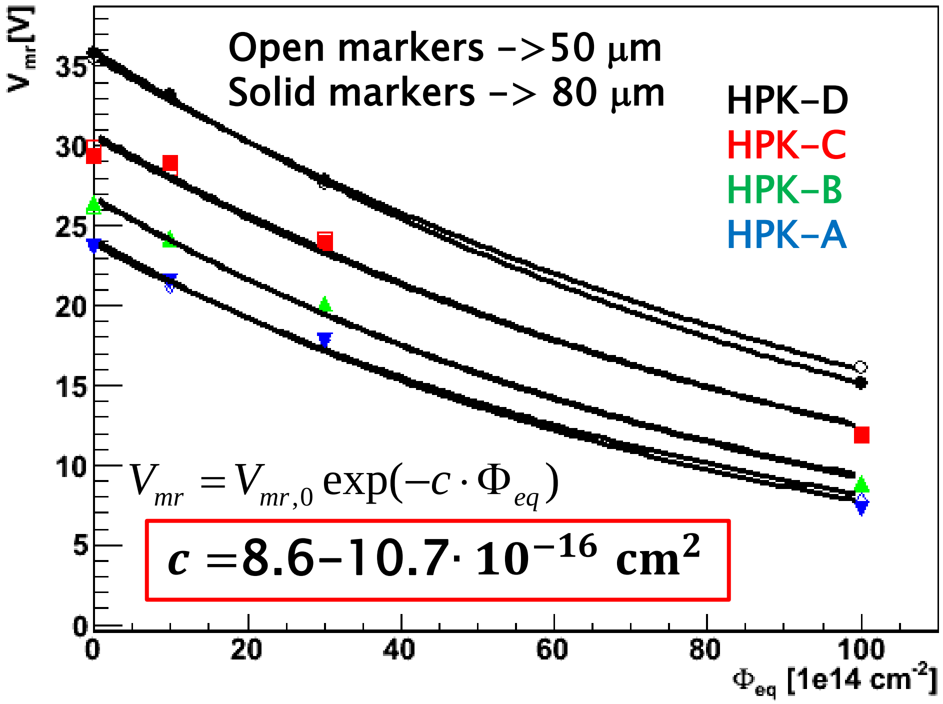


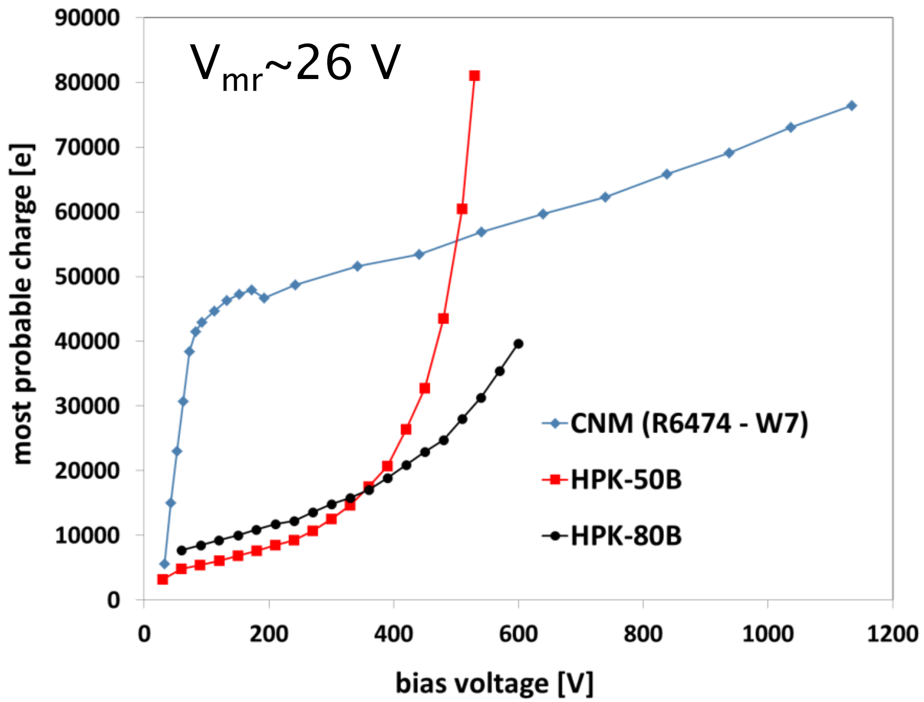


- "Foot" shift to lower values nicely observed (no excess current to blur it).
- "Foot" shift is correlated to gain – note that V_{mr}=26 V gives you G~2.2 (@500V) for 300 μm device and G~8(@500V) for 50 μm device
- $V_{mr}<10$ devices don't clearly exhibit the LGAD behavior in collected charge
- Similar dependence as for CNM 300 μm samples – universal behavior of multiplication layer with fluence – no difference between producers.

Disappearance of gain layer

FRONT TCT – red





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Conclusions

- HPK LGAD sensors perform very much as expected
  - charge collection (50 -> 80 μm, high breakdown)
  - leakage current is very low and follows the prediction (clean process)
- Performance after irradiation:
  - charge collection is very similar to CNM devices of initial gain (no process dependence)
  - at high bias voltages thicker devices (80 μm) are less appropriate -> what is the optimum thickness?
  - leakage current follows $I=M_I \cdot I_{gen}$
- The gain layer disappearance
  - same for 50 and 80 μm devices – influence of deep traps is negligible
  - removal constant is the same as it was measured for CNM devices of standard thickness -> not large enough difference in doping concentration between different dose splits to notice different removal?