TCAD simulation of silicon detectors
A validation tool for the development of LGAD

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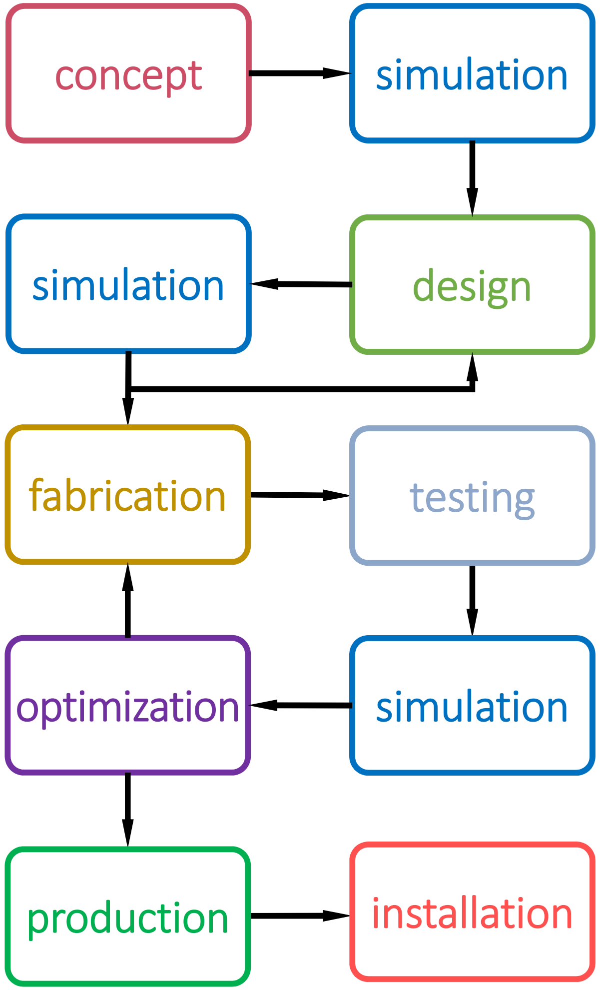
Motivation

- **Device-level simulation**, as well as measuring and testing, is widely known to have a crucial role in the process of **particle detector design and optimization**
- This work is aimed to **develop a robust numerical framework** for **LGAD simulation**
- We would like to achieve this result by **calibrating the physical parameters** on a wide set of experimental data
- By validating models and simulations on available data we intend to obtain a predicting tool allowing to **design new generations of radiation-resistant LGAD devices**



Summary

1. Simulation setup
    - gain calculation procedure, description of avalanche models, empirical acceptor removal
2. Model calibration on *pin* diodes
    - laser/heavy-ion beam for MIP calibration on irradiated 50 µm diodes by CNM and HPK
3. LGAD simulations
    - unirradiated 50 µm by HPK at room temperature
    - irradiated 300 µm by FBK (UFSD-1) and 50 µm by HPK
    - gain versus temperature in unirradiated LGAD by HPK
    - gain versus fluence in irradiated LGAD by HPK
4. UFSD-2 production by FBK with Boron and Gallium (preliminary)
    - measured/simulated $I(V)$ characteristics with B implantation
    - simulated $G(V)$ characteristics with Ga implantation

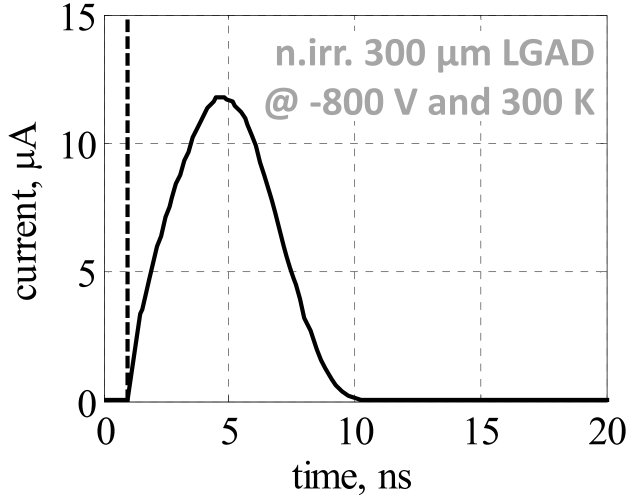
Simulation setup

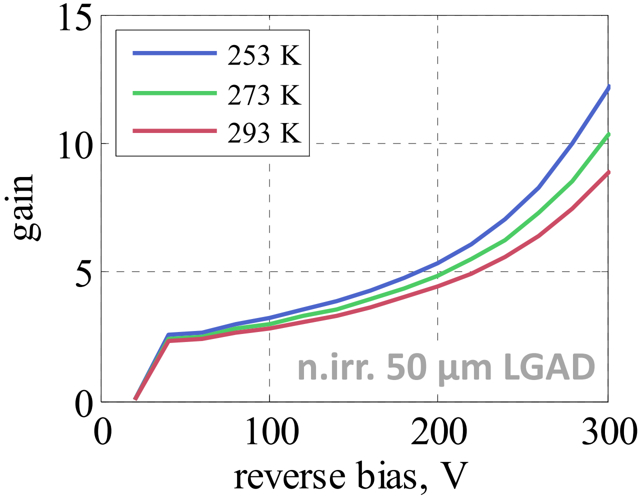
Gain calculation in TCAD Synopsys *Sentaurus Device*:

- The signal is stimulated through focused **laser** or **heavy-ion** beam
- Then the pulse response is time-integrated to obtain the **collected charge**
- By carrying out the same procedure either on diode w/o gain and on LGAD one can find the **gain** as

$$G(V) = \frac{Q_{\mathrm{LGAD}}(V)}{Q_{pin}(V)}$$

- Different well-known **avalanche models** have been used to compute $G(V)$





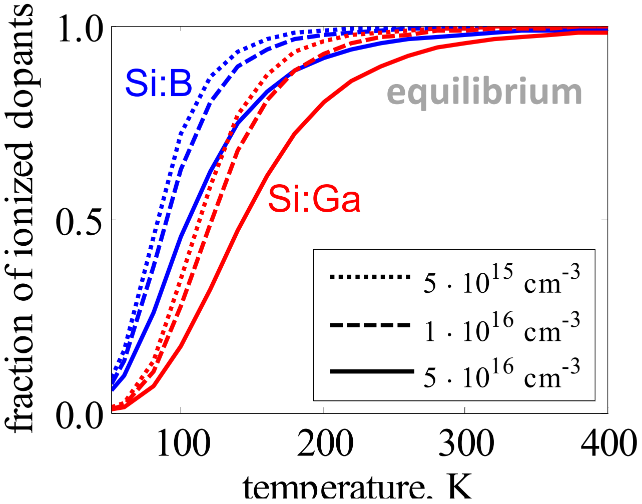
Simulation setup

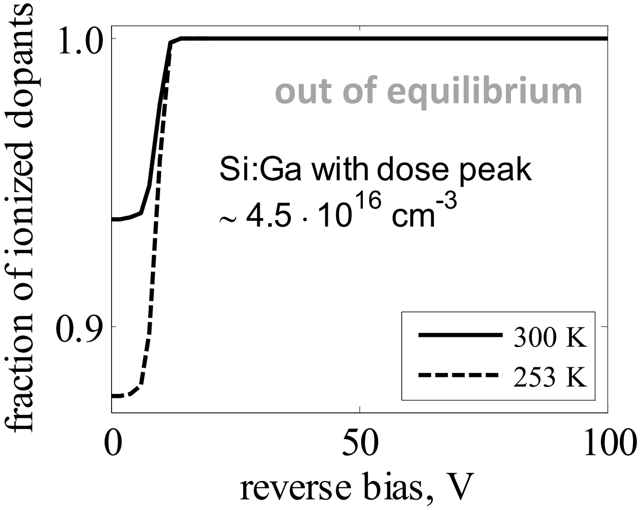
The generation/recombination (GR) models accounted for in the simulation are:

- **Avalanche** generation
- **Shockley-Read-Hall** (SRH)
- **Band-to-band tunneling** (BTBT)

where van Overstraeten-de Man, Massey and Okuto-Crowell multiplication formalisms have been alternatively included.
Since Massey model is not present among the built-in functions of Sentaurus, it has been added as a **PMI routine in C++**

Also a study on **incomplete ionization** of dopants has been performed, confirming that the electric field provides the energy required to activate almost all dopants





Simulation setup

The three avalanche models are all based on a **Chynoweth-like expression** of electron/hole **ionization coefficients** $\alpha_{n,p}$

$$\alpha_{n,p}(E) = \gamma \cdot A_{n,p} \cdot \exp\left(-\gamma \frac{B_{n,p}}{E}\right)$$

where

⇒ **van Overstraeten-de Man:**

$A_n = 7.030 \times 10^5\ \mathrm{cm}^{-1}$ $B_n = 1.231 \times 10^6\ \mathrm{V/cm}$

$A'_p = 1.582 \times 10^6\ \mathrm{cm}^{-1}$ $B'_p = 2.036 \times 10^6\ \mathrm{V/cm}$ low-field

$A''_p = 6.710 \times 10^5\ \mathrm{cm}^{-1}$ $B''_p = 1.693 \times 10^6\ \mathrm{V/cm}$ high-field

Simulation setup

The three avalanche models are all based on a **Chynoweth-like expression** of electron/hole **ionization coefficients** $\alpha_{n,p}$

$$\alpha_{n,p}(E) = A_{n,p} \cdot \exp\left(-\frac{B_{n,p}(T)}{E}\right)$$

where

⇒ **Massey:**

$$A_n = 4.43 \times 10^5\ \mathrm{cm}^{-1} \qquad B_n(T) = C_n + D_n \cdot T$$

$$A_p = 1.13 \times 10^6\ \mathrm{cm}^{-1} \qquad B_p(T) = C_p + D_p \cdot T$$

$$C_n = 9.66 \times 10^5\ \mathrm{V \cdot cm^{-1}} \qquad C_p = 1.71 \times 10^6\ \mathrm{V \cdot cm^{-1}}$$

$$D_n = 4.99 \times 10^2\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}} \qquad D_p = 1.09 \times 10^3\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}}$$

Simulation setup

The three avalanche models are all based on a **Chynoweth-like expression** of electron/hole **ionization coefficients** $\alpha_{n,p}$

$$\alpha_{n,p}(E) = A_{n,p} \cdot \left(1 + (T - 300)C_{n,p}\right) \cdot E \cdot \exp\left(-\left(\frac{B_{n,p} \cdot \left(1 + (T - 300)D_{n,p}\right)}{E}\right)^2\right)$$

where

⇒ **Okuto-Crowell:**

$A_n = 0.426\ \mathrm{V}^{-1}$

$A_p = 0.243\ \mathrm{V}^{-1}$

$C_n = 3.05 \times 10^{-4}\ \mathrm{K}^{-1}$

$D_n = 6.86 \times 10^{-4}\ \mathrm{K}^{-1}$

$B_n = 4.81 \times 10^{5}\ \mathrm{V/cm}$

$B_p = 6.53 \times 10^{5}\ \mathrm{V/cm}$

$C_p = 5.35 \times 10^{-4}\ \mathrm{K}^{-1}$

$D_p = 5.67 \times 10^{-4}\ \mathrm{K}^{-1}$

Simulation setup

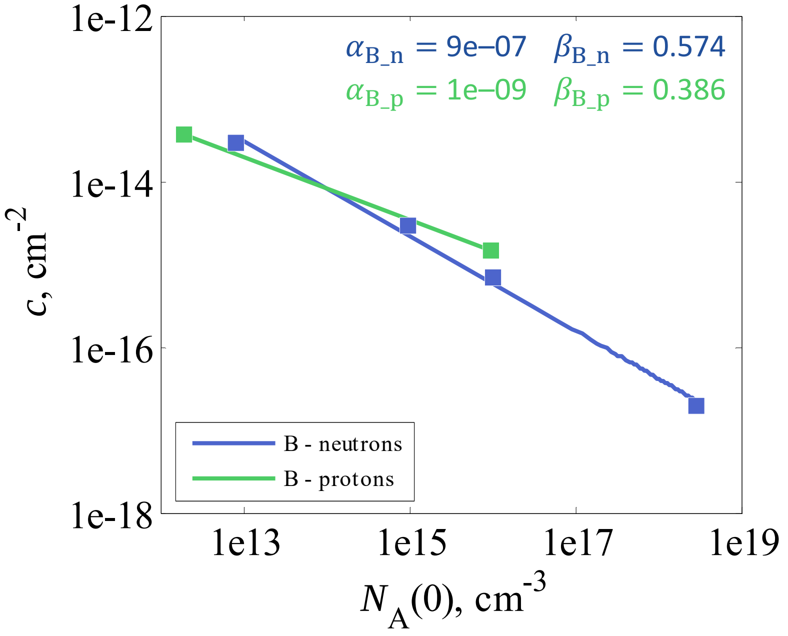
Concerning the **effects of radiation** we used the empirical law

$$N_A(\phi) = g_{\mathrm{eff}} \cdot \phi + N_A(0) \cdot \mathrm{e}^{-c(N_A(0)) \cdot \phi} \qquad (1)$$

accounting for both **acceptor creation** and **initial acceptor removal** mechanisms, where ϕ is the fluence and $g_{\mathrm{eff}} \cong 0.02\ \mathrm{cm}^{-1}$.

Before performing the simulation, doping profiles are recomputed according to Eq. (1) through a *local correction* (in space) of the coefficient c which derives from a fit of the form

$$c(N_A(0), x) = \alpha \cdot N_A(0, x)^{-\beta}$$



Simulation setup

Other transport models implemented in the drift-diffusion (DD) framework are the **Shockley-Read-Hall (SRH)** process, with generation rate

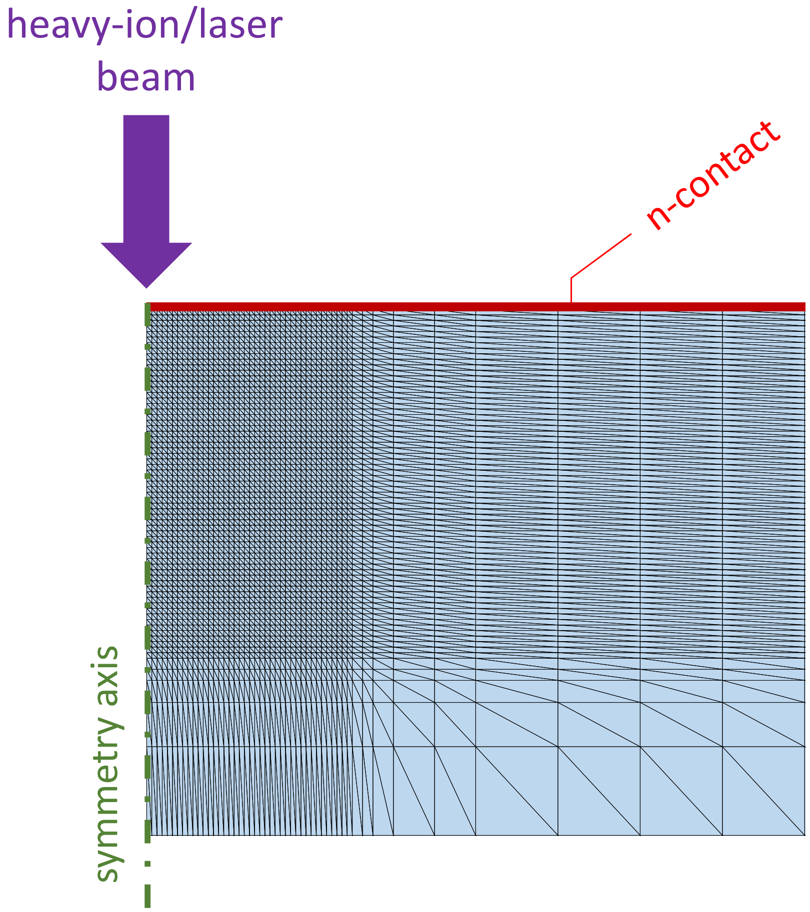
$$G_{\mathrm{SRH}} = \frac{n \cdot p - n_i^2}{\tau_p\big(n - n_i \cdot \exp(-E_t/k_{\mathrm{B}}T)\big) + \tau_n\big(p - n_i \cdot \exp(E_t/k_{\mathrm{B}}T)\big)}$$

and the **band-to-band tunneling (BTBT)**, where the rate is

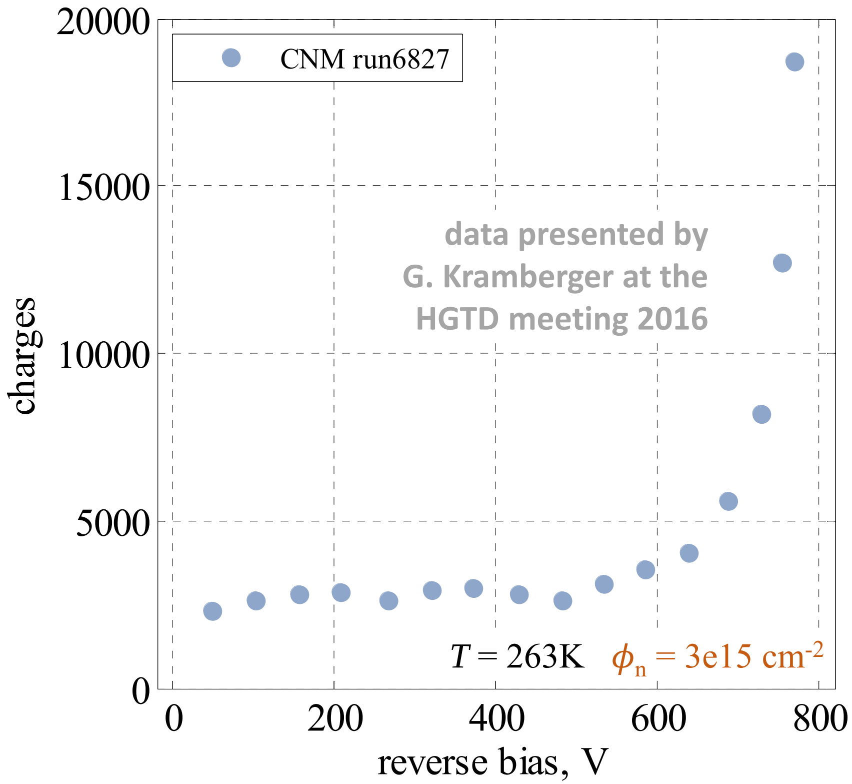
$$G_{\mathrm{BTBT}}(E) = A \cdot E^2 \cdot \exp\left(-\frac{B}{E}\right)$$

Moreover, the three-levels **Perugia model** for trap formation is also included (two acceptor traps and one donor trap, with **$E_C - E_{t1}$ = 0.42 eV**, **$E_C - E_{t2}$ = 0.46 eV** and **$E_{t3} - E_V$ = 0.36 eV**)

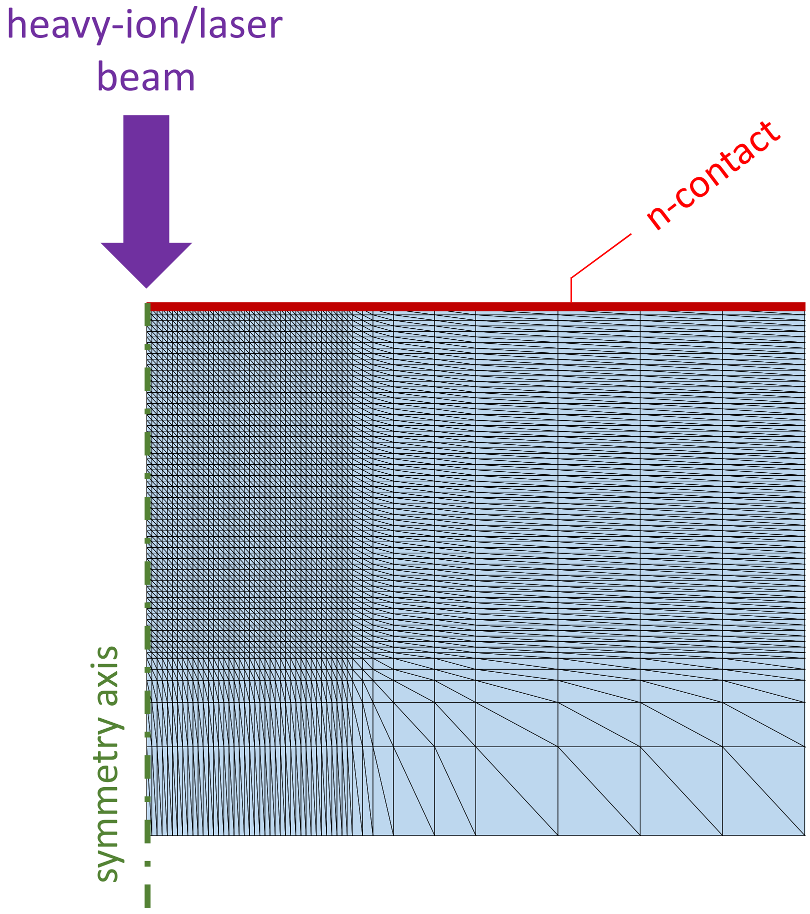
Model calibration



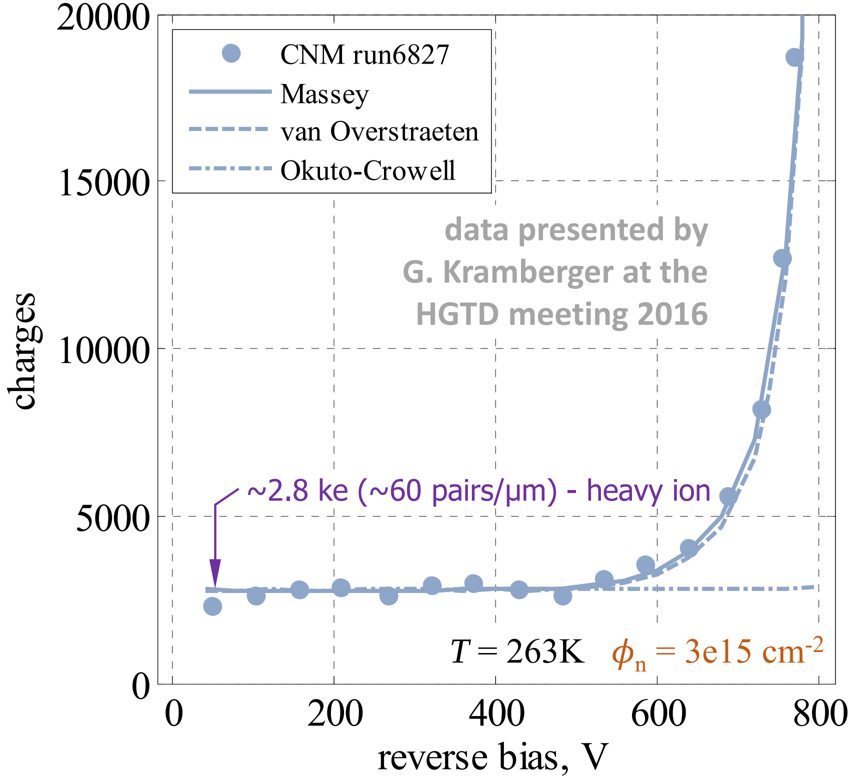
MIP calibration on measurements of irradiated 50 µm *pin* diode by **CNM**



Model calibration



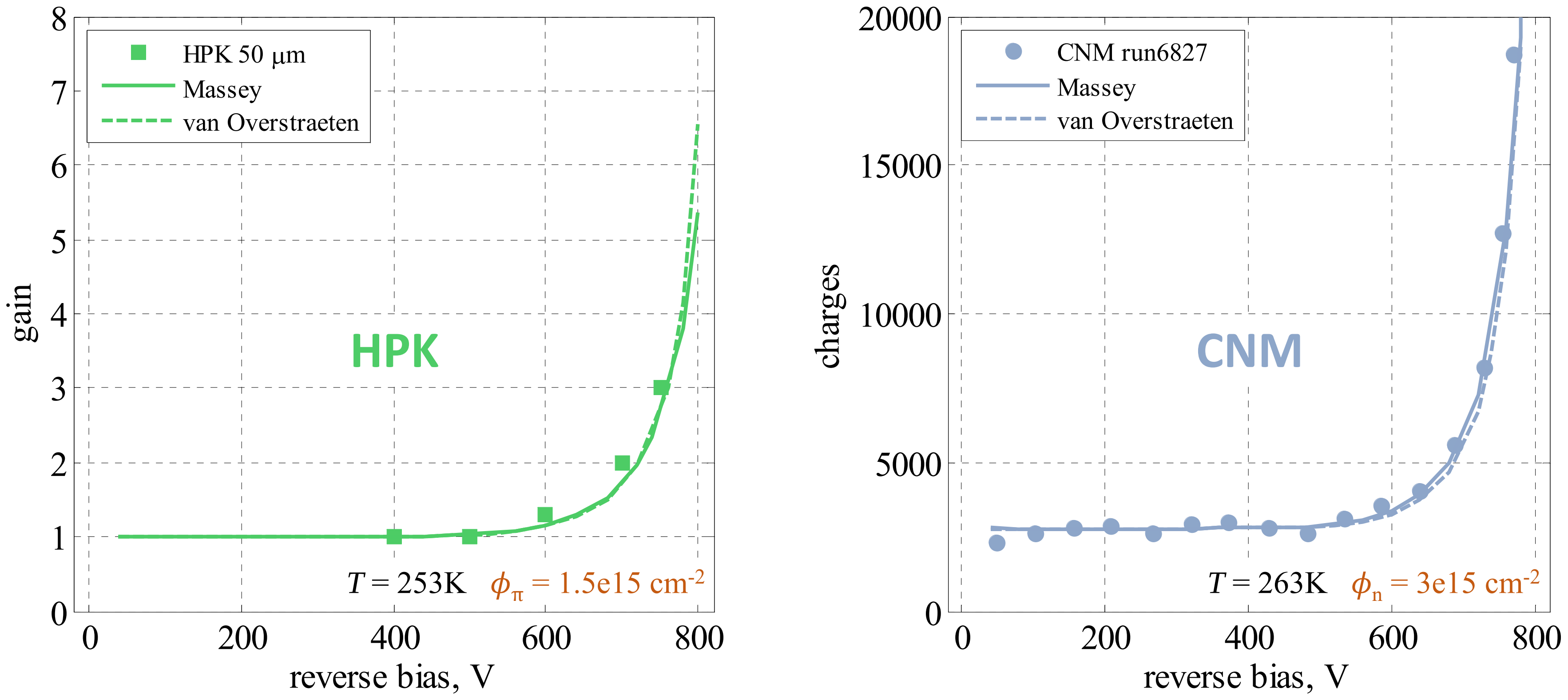
MIP calibration on measurements of irradiated 50 µm *pin* diode by **CNM**



data presented by G. Kramberger at the HGTD meeting 2016

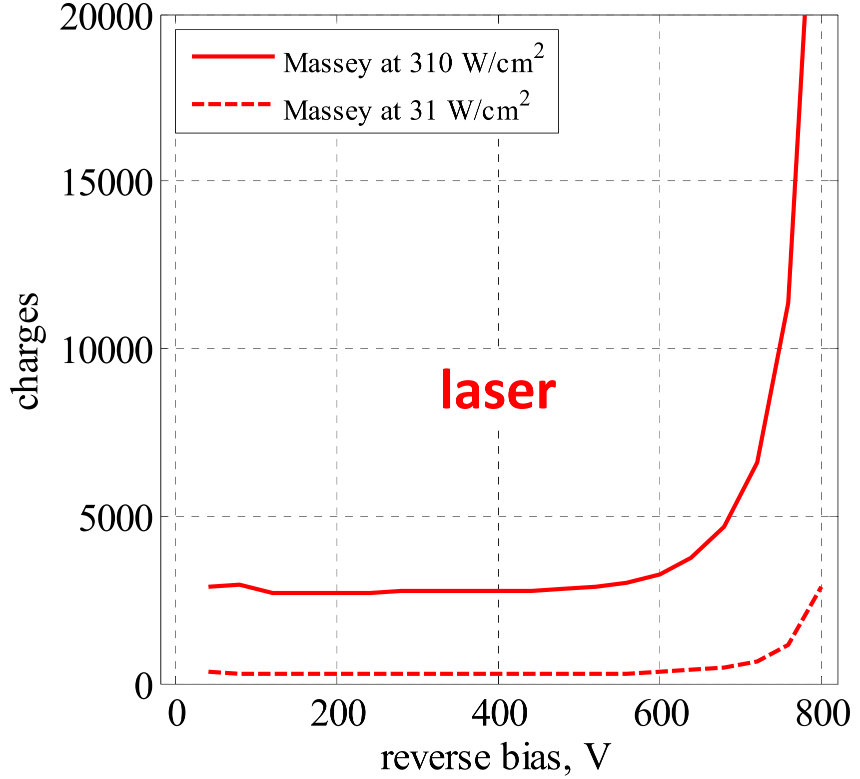
Model calibration

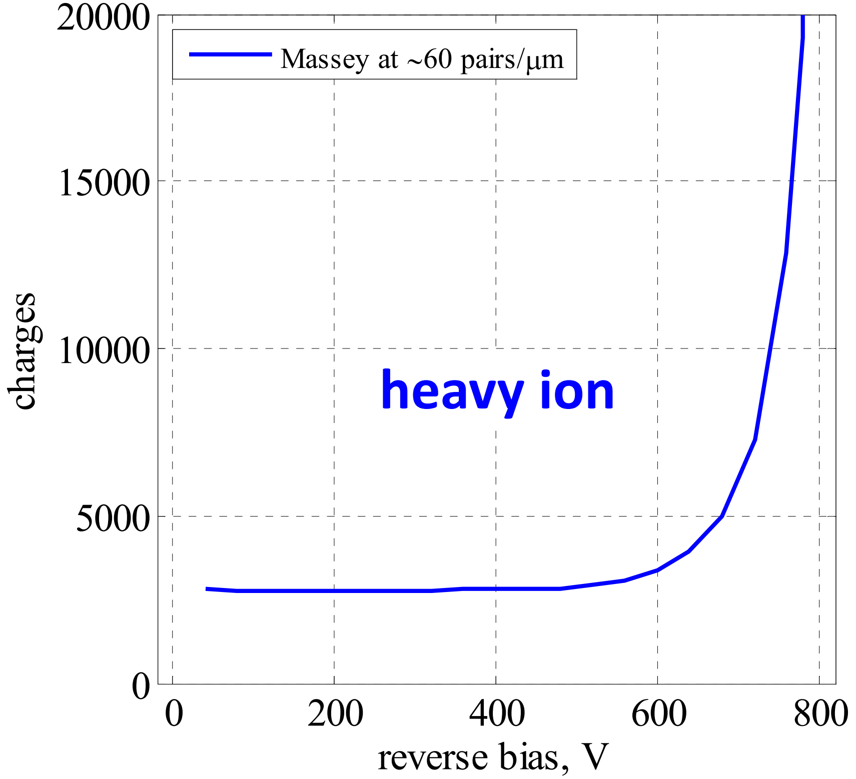
The same simulation performed also on a *pin* from **HPK 50 µm**



Model calibration

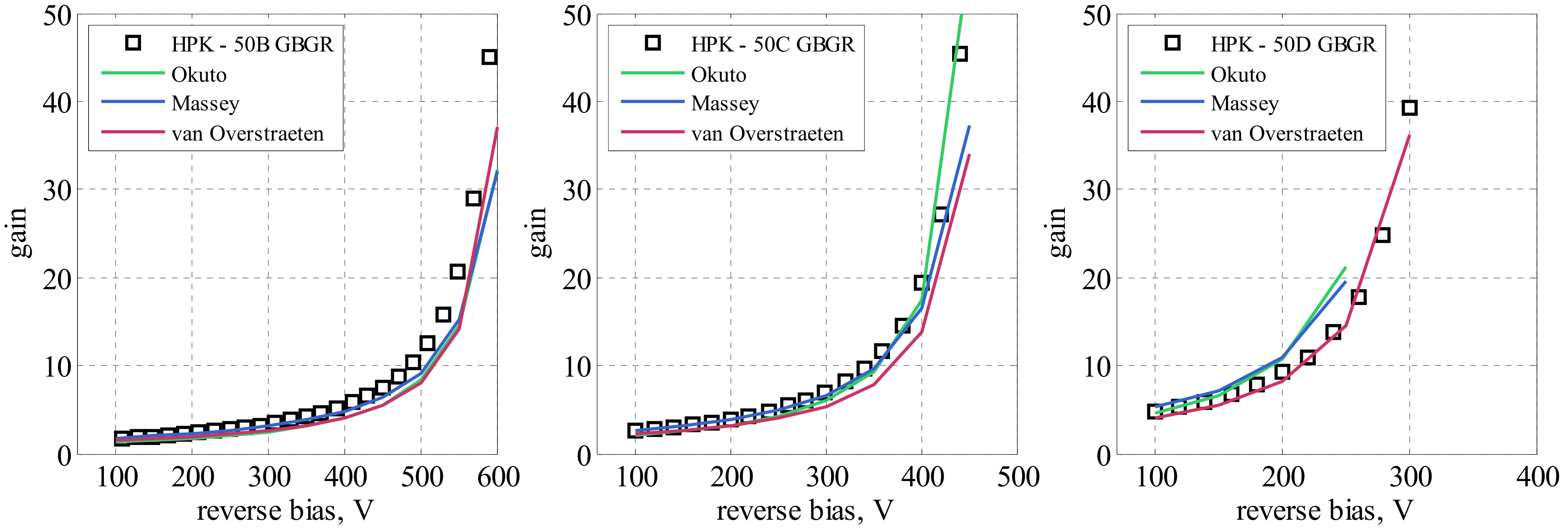
Massey model on **CNM run6827**: Comparison between **laser beam** (1060 nm) at different energies and, again, **heavy ion beam** at 60 pairs/µm





LGAD simulation - I

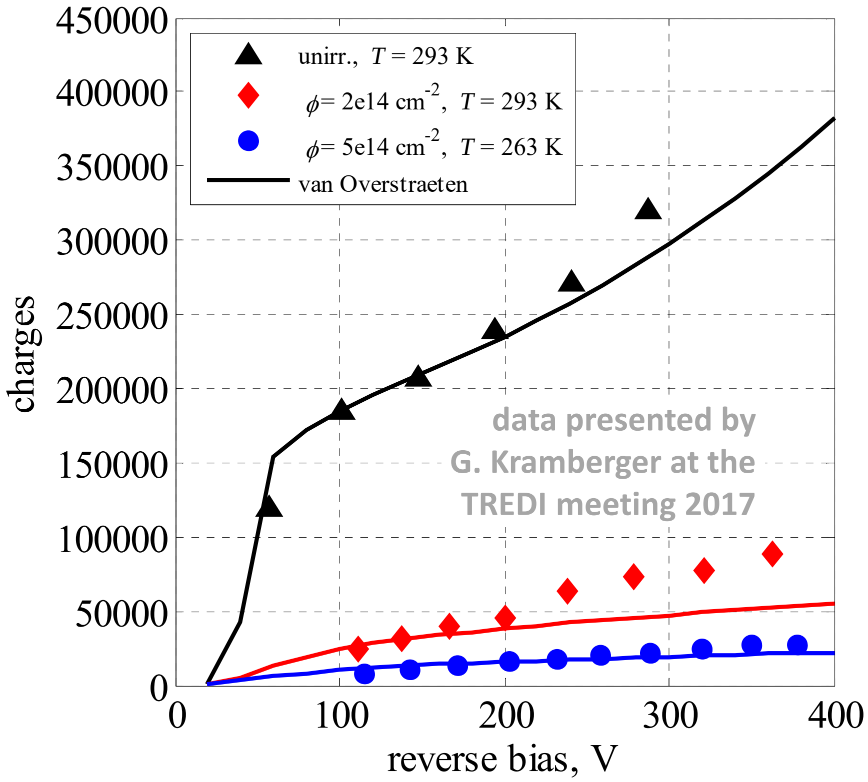
Unirradiated 50 µm by HPK at room temperature



- gain measurements from **HPK**
- simulated laser at **310 W/cm^2**
- simulation of both ***pin*** and **LGAD** diodes

LGAD simulation - II

Irradiated 300 µm by FBK at different fluence and temperature

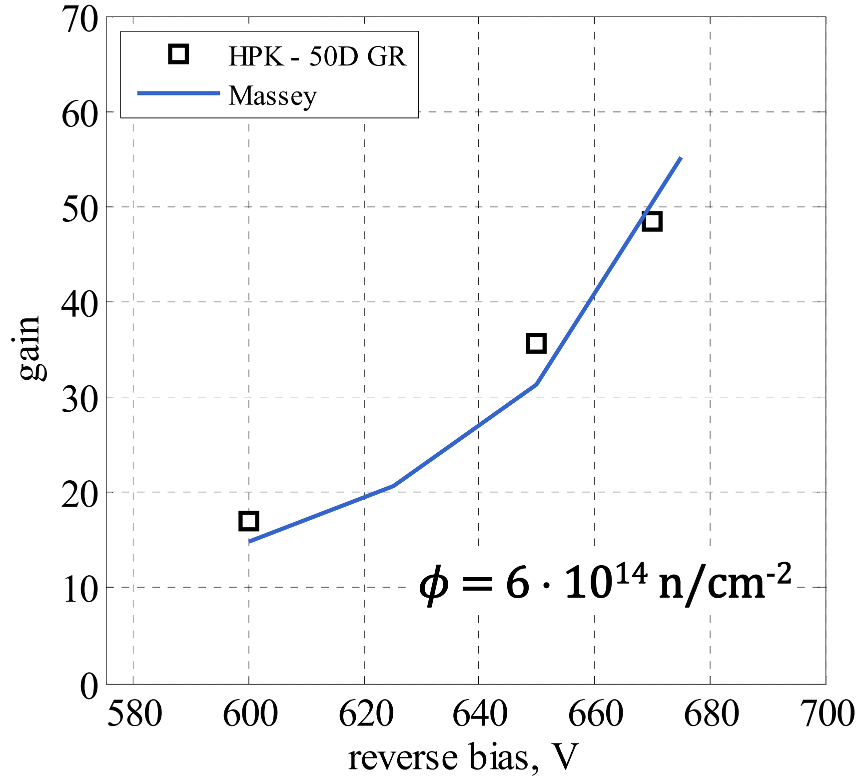


data presented by G. Kramberger at the TREDI meeting 2017

- measurements from **Ljubljana**
- simulated heavy-ion at **~60 pairs/µm**
- **Perugia model** for defects generation
- **acceptor removal** parametrization
- simulation of both ***pin*** and **LGAD** diodes

LGAD simulation - II

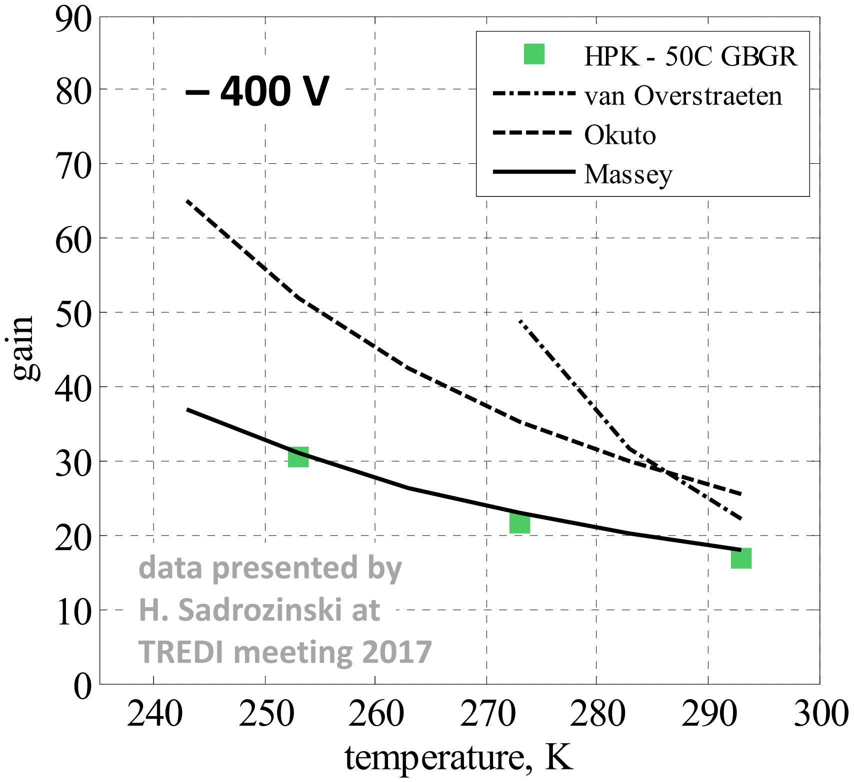
Irradiated 50 µm by HPK at room temperature



- measurements from **Ljubljana**
- simulated laser at **310 W/cm^2**
- **Perugia model** for defects generation
- **acceptor removal** parametrization
- simulation of both ***pin*** and **LGAD** diodes

LGAD simulation - III

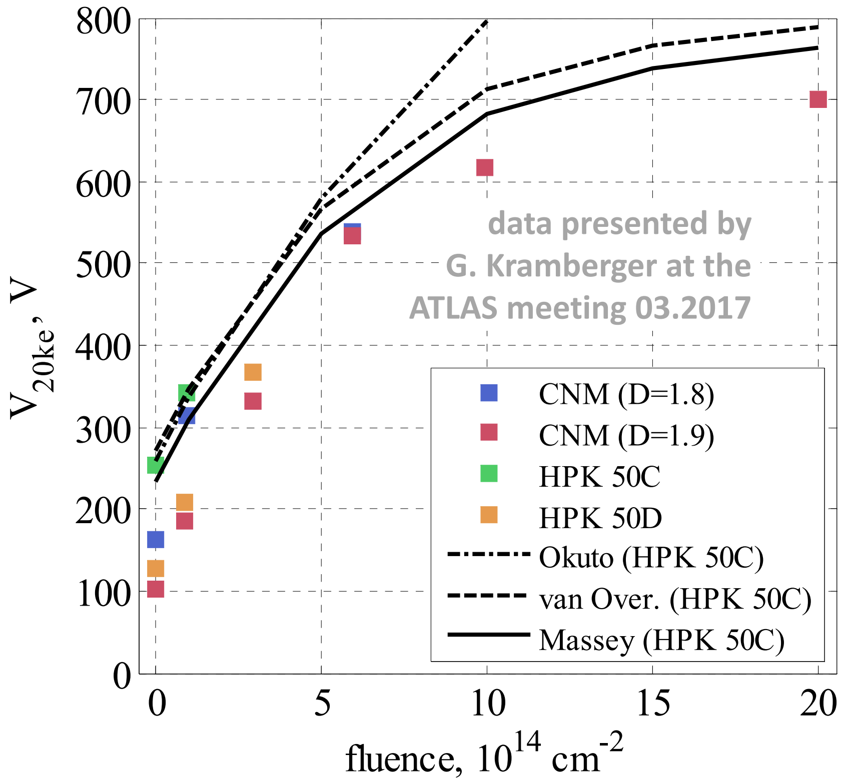
Unirradiated 50 µm by HPK at different temperature



- measurements from **Santa Cruz**
- simulated laser at **310 W/cm²**
- simulation of both ***pin*** and **LGAD** diodes

LGAD simulation - IV

Irradiated 50 µm by **HPK** and **CNM** at **different fluence**

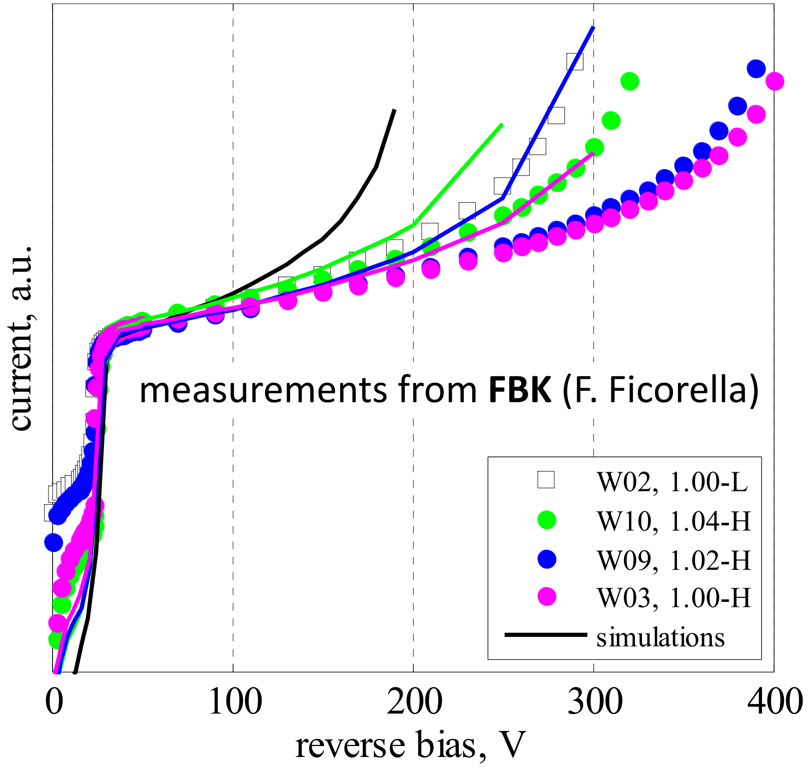


- measurements from **Ljubljana**
- simulated laser at **310 W/cm^2**
- **Perugia model** for defects generation
- **acceptor removal** parametrization
- simulation of both ***pin*** and **LGAD** diodes

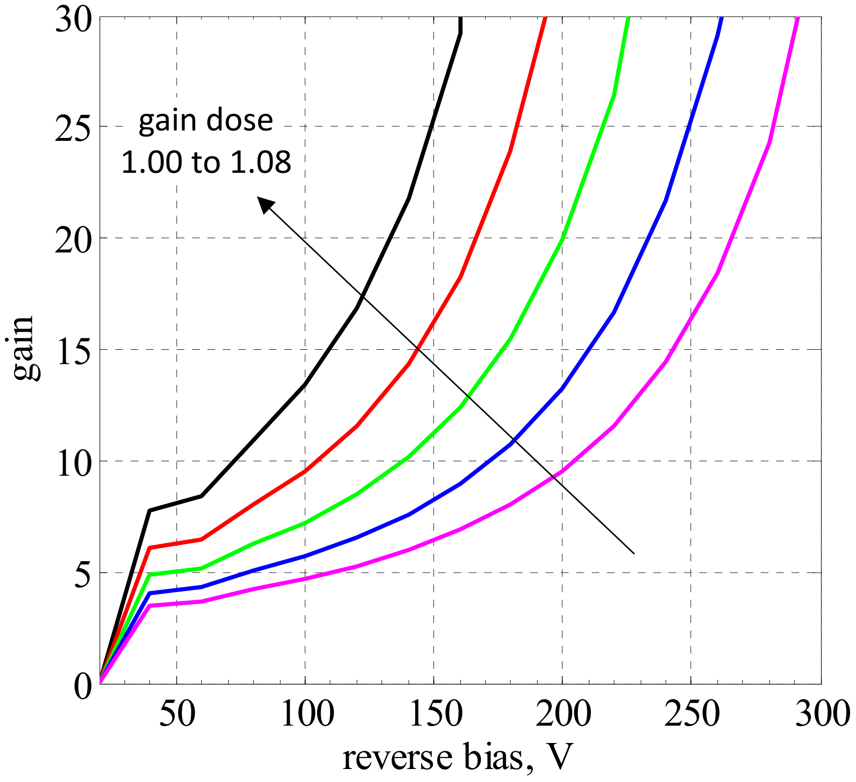
UFSD-2 (preliminary)

About the second production of **50 µm UFSD** by **FBK**

***I*(*V*)** characteristics
with **Boron implantation** at **room-*T***



***G*(*V*)** simulation
with **Gallium implantation** at **room-*T***



Conclusions

We analysed simulations of various LGAD structures fabricated by different foundries starting from a modeling calibration performed on *pin* diodes:

- in general, **Okuto** model seems to **reproduce very poorly** our spectrum of data
- **Massey** and **van Overstraeten** are **highly effective** in reproducing **charges in *pin***
- the choice of a multiplication model is pretty insignificant in LGAD by **HPK**
- **Irradiated** devices by **FBK** and **HPK** are well described by **van Overstraeten** and **Massey** models, respectively
- **Massey** model turned out to be the most accurate in describing the trend of **gain versus temperature and fluence** in several devices from different factories

Probably these differences are due to our uncertainties about critical foundry parameters (doping profiles, defects, irradiation dose, …)

$\Rightarrow$ What's next?

- We are waiting data from **UFSD-2 production** in order to test **multiplication** and **radiation-related** models on **Gallium-doped** and **carbonated** devices

Acknowledgments

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Thank you for your attention!