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NUMERICAL SIMULATION OF LOW GAIN AVALANCHE DETECTOR

Presented by:

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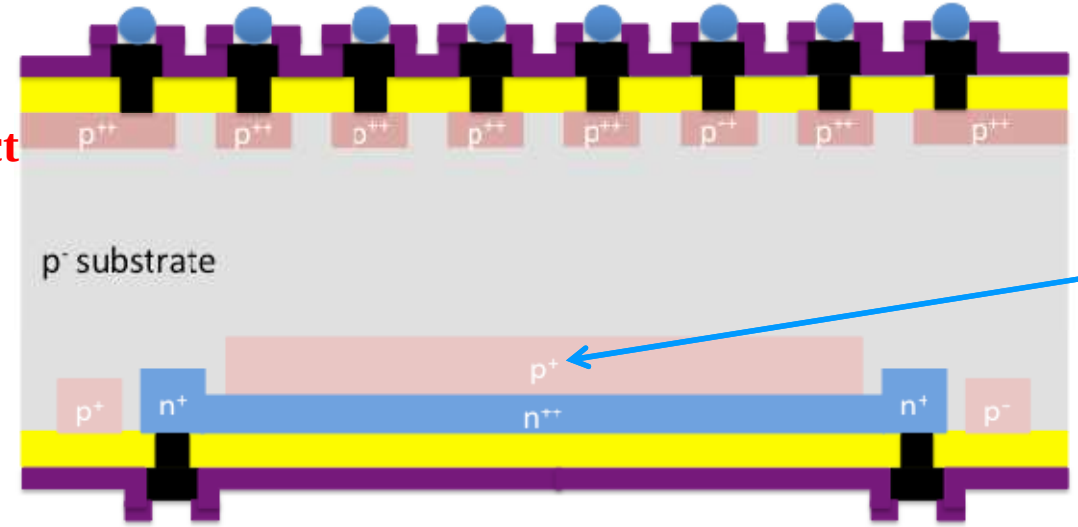
Outline

- Overview of LGAD technology
- Aim of this work
- Simulation tool
- Simulation and results
- Conclusion and future work

Double-sided pixelated LGAD

G.-F. Dalla et.al , RESMDD', 2014

UFSD, INFN project



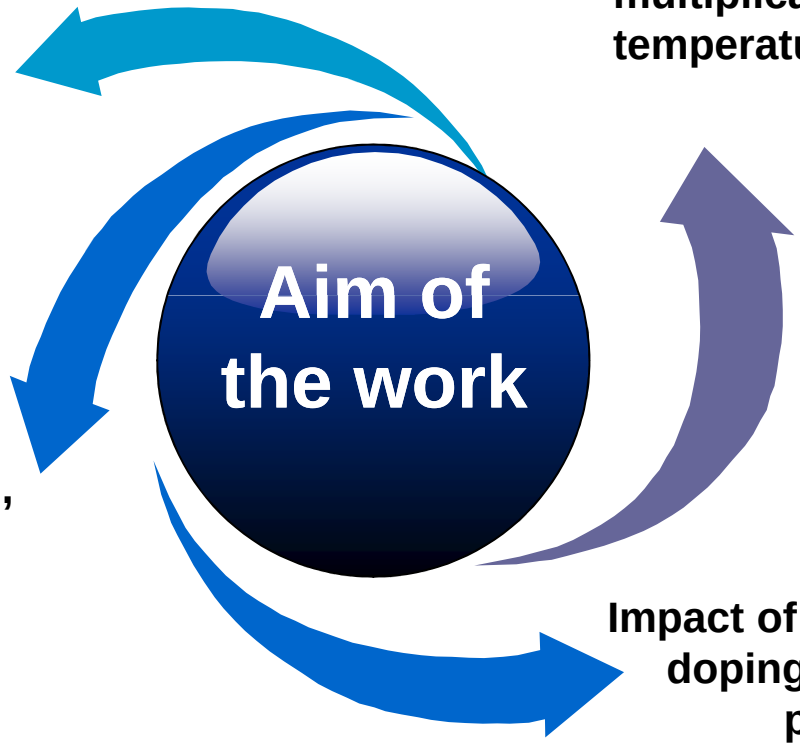
P-type Multiplication layer

- Multiplication region in the back of the device
- Pixel side is simple, gain side more complex (4 ion implantations)
- Pixels to obtain spatial resolution
- Pixel need to be bump bonded to a read out electronic chip

Aim of the work

Development of numerical tool for LGAD analysis

Study of the dependence of multiplication gain on temperature variation



Analytical Multiplication gain, noise factor and breakdown voltage.

Impact of multiplication region doping profiles on LGAD performance.

The simulation tool

- Why Matlab Simulator?
  - Low time-consuming compared to TCAD simulator
  - Fast parametric simulation
  - Fast evaluation of gain and noise factor
- 1D Poisson equation

$$\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

$$\rho = q(N_D^+ - N_A^- + p - n)$$

$$\phi(x) = \phi^i(x) + \lambda^i(x)$$

$$-\frac{d^2\lambda^0}{dx^2} - \frac{1}{\varepsilon}\frac{\partial\rho}{\partial\phi}\bigg|_{\phi^0}\lambda^0 = \frac{\rho(\phi^0)}{\varepsilon} + \frac{d^2\phi(x)}{dx^2}$$

Newton-Raphson

Gauss elimination

The simulation tool

McIntyre model

$$M(x) = \frac{\exp\left(-\int_x^W (\alpha - \beta)dx\right)}{1 - \int_0^W \alpha \exp\left(\int_x^W (\alpha - \beta)dx\right)dx'}$$

Multiplication gain [1]

Ionization integral

$$\int_0^W \alpha \exp\left(\int_x^W (\alpha - \beta)\,dx\right)dx' \approx 1 \Rightarrow \text{ Applied voltage (Vbias)} \approx \text{Breakdown voltage}$$

α and β are expressed by **VanOverstraeten and DeMan model** [2]

[1] R.J. McIntyre, IEEE Trans. Electron Devices 13 (1966) 164.
[2] R. VanOverstraeten and H. DeMan, *Solid-State Electron*, 13(1970) 583.

The simulation tool

Noise current spectral density in an avalanche detector:

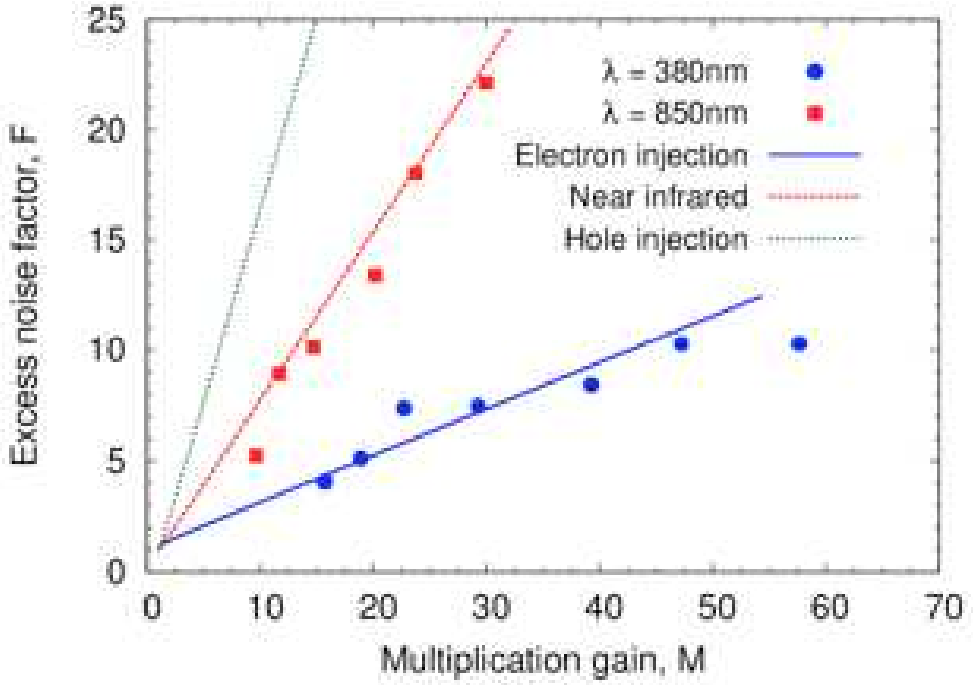
$$S = 2q(I_P + I_D)M^2F$$

Excess noise factor [1]

$$F(x) = 2 + \frac{M(W)\left[2\int_0^W \alpha M^2(x)dx - 1\right]}{M(x)}$$

Excess noise factor can be fit with

$$F = M \cdot k + \left(2 - \frac{1}{M}\right)(1-k) \qquad k = \frac{\beta}{\alpha}$$



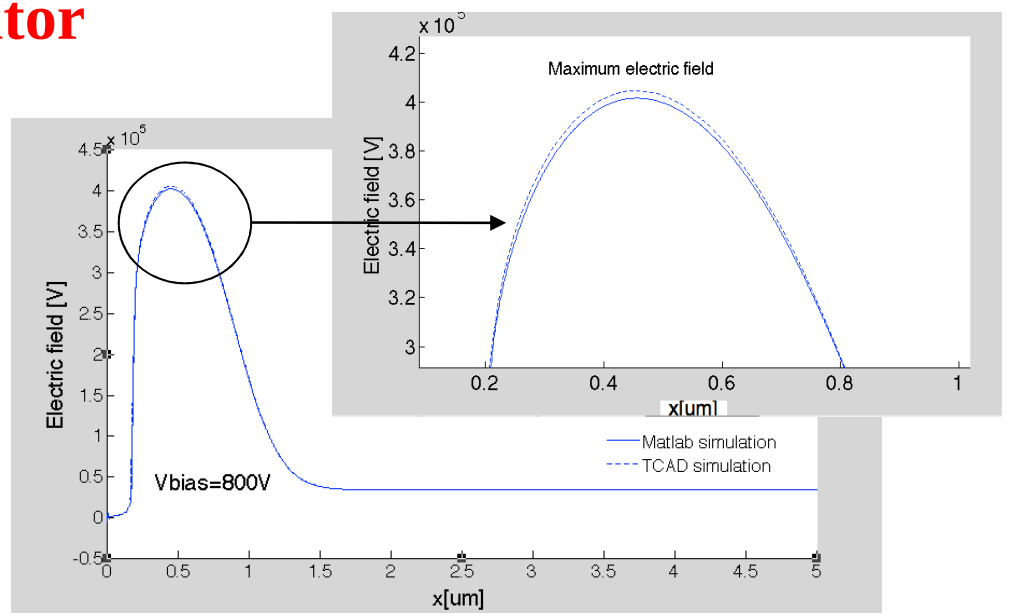
- Electron initiated avalanche: **low F**
- Hole initiated avalanche: **high F**

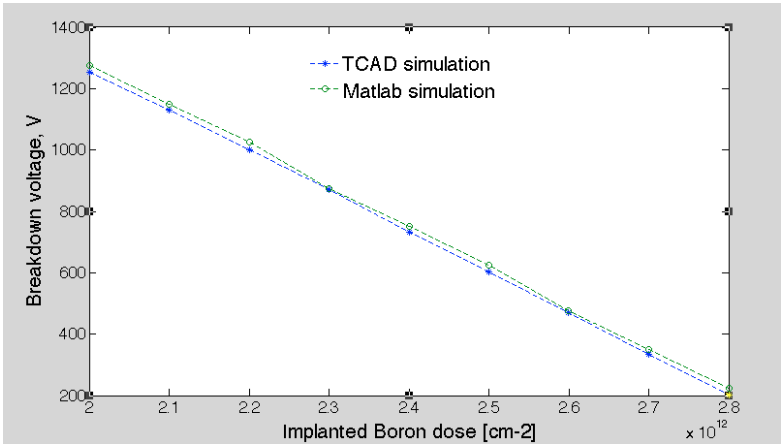
[1] R.J. McIntyre, IEEE Trans. Electron Devices 13 (1966) 164

The simulation tool

Validation with TCAD simulator

Net doping profile → **Solver**





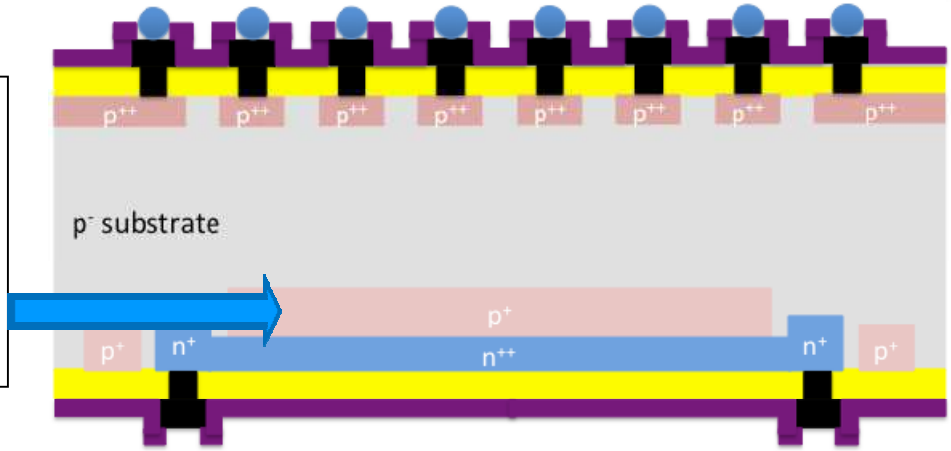
❑ Good agreement with TCAD simulation

Boron and Gallium doping profiles

Net doping profiles

Doping profiles simulated at FBK of the p-region :

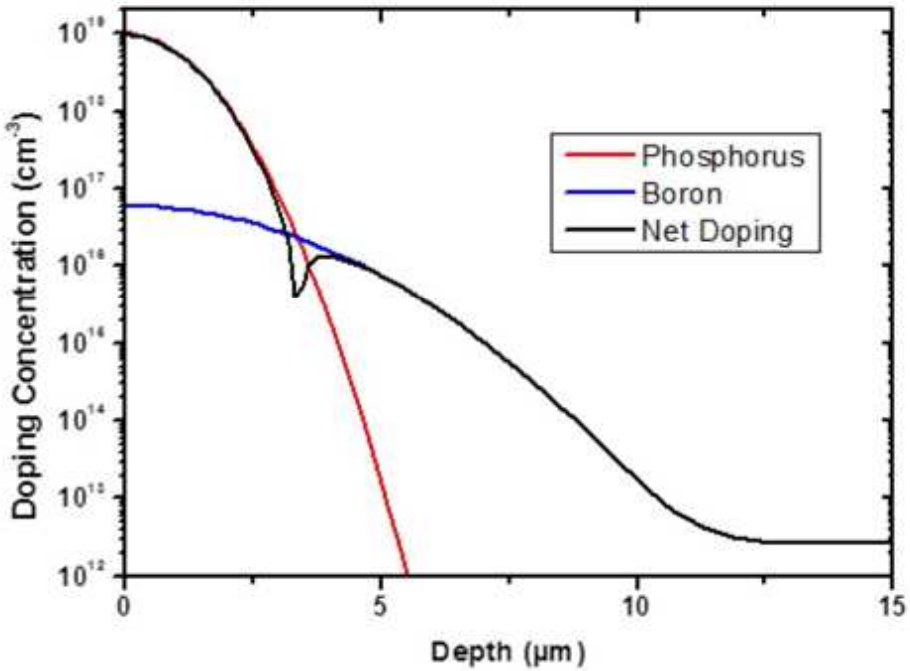
- low-energy Boron implantation
- medium-energy Boron implantation
- high-energy Gallium implantation



- p+ multiplication region is the main technological Parameter
- Critical impact on gain, noise factor and breakdown voltage
- **Goal** : Adjustment of the gain layer doping profile to yield desired device performance.

Boron and Gallium doping profiles

Net doping profiles



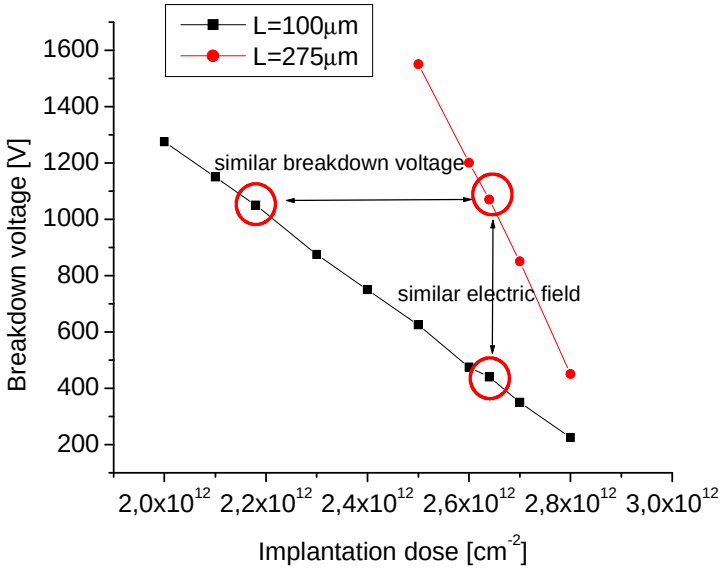
CNM-Barcelona[3]

- Deep boron implantation ~10^{13}cm^{-2}
- High resistivity, 300 μm p-type substrate

[3] Hartmut F.-W. Sadrozinski, thin LGAD, 25th RD50, Nov 2014

Simulation Results: Breakdown voltage versus dose factor

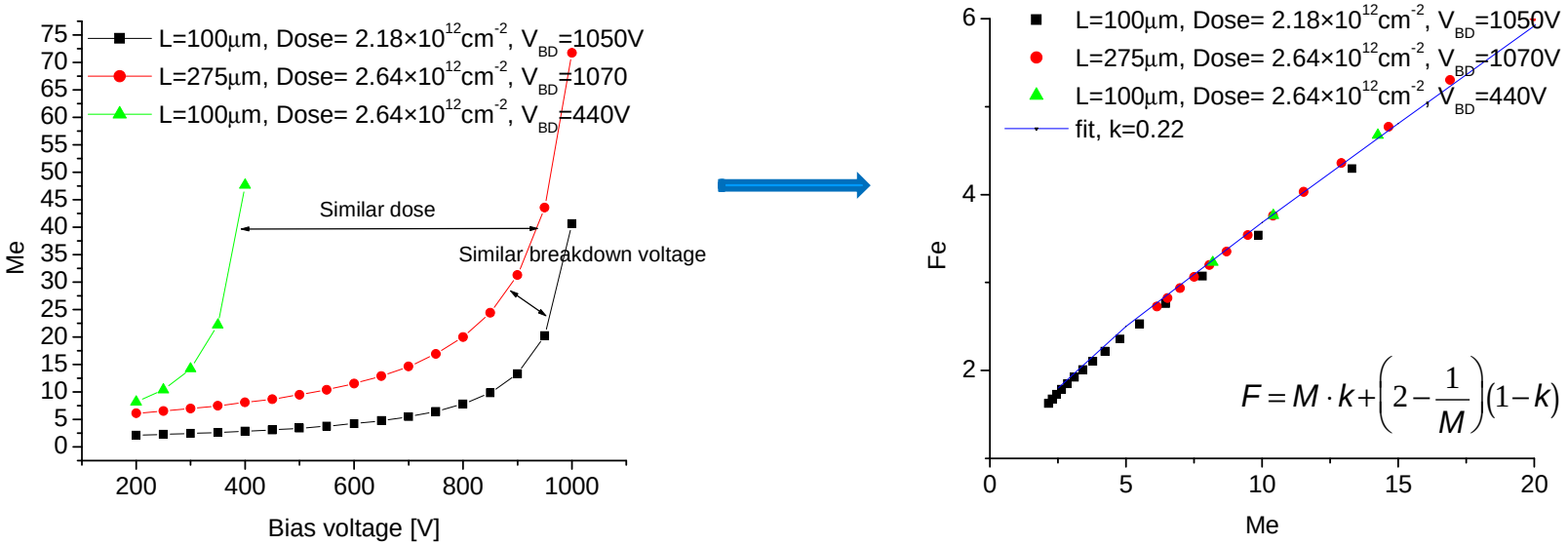
Low-energy Boron implantation



- Small modification in the Boron implant dose ~0.1 $10^{12}cm^{-2}$ can induce huge change in the breakdown value
- High dose dependence of the breakdown voltage for thick structure.

Simulation Results: Multiplication gain and noise factor

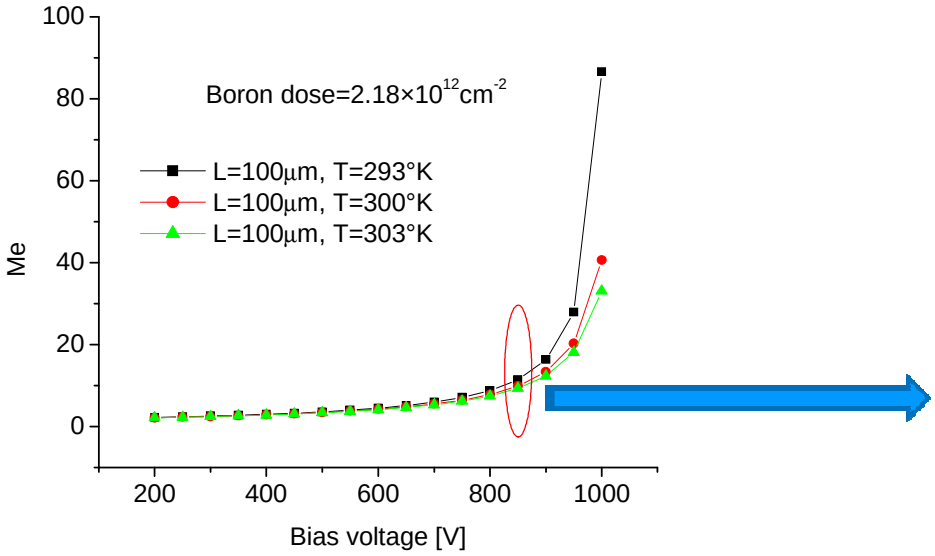
Low-energy Boron implantation

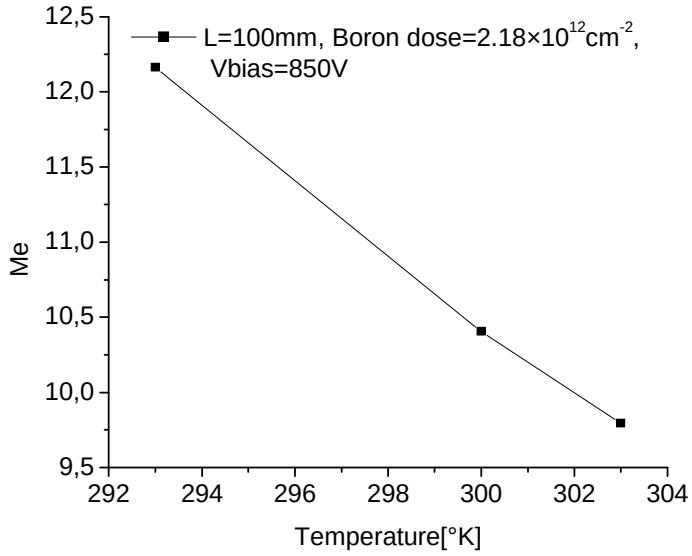


- Small Interval of bias voltage for thin detectors
- Gain of 10-15 at low bias voltage for low-dose thin detectors
- Similar noise factor for all detectors, k=0.22

Simulation Results: Multiplication gain Vs Temperature

Low-energy Boron implantation

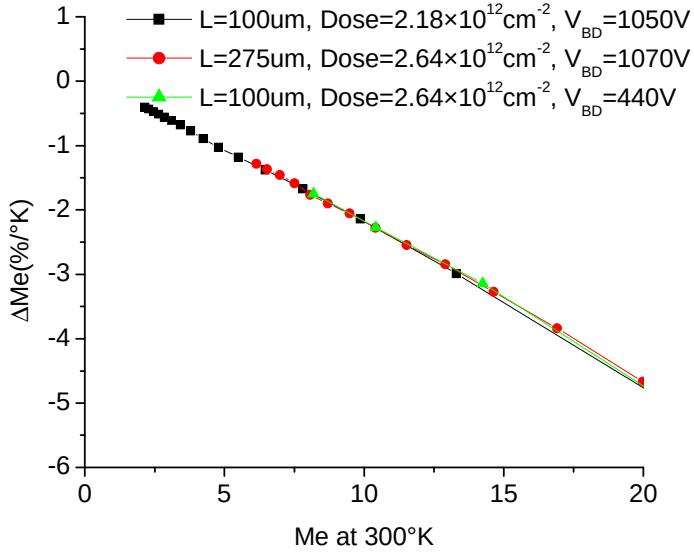




- Variation of gain over temperature is estimated at a fixed bias voltage of 850V → M =10 .
- High gain at low temperature

Simulation Results: Temperature Gain coefficient

Low-energy Boron implantation



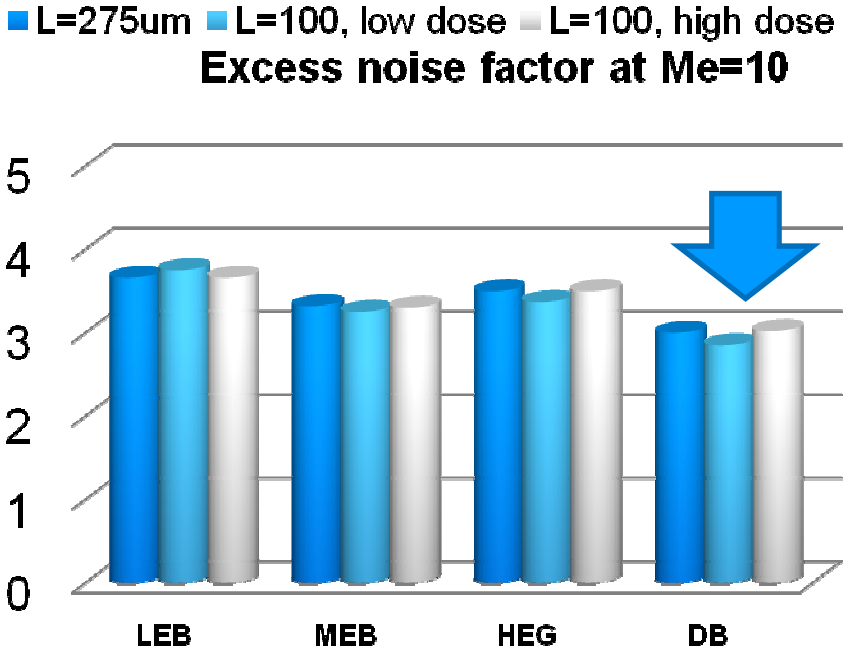
❑ Similar gain temperature sensitivity of all structures.

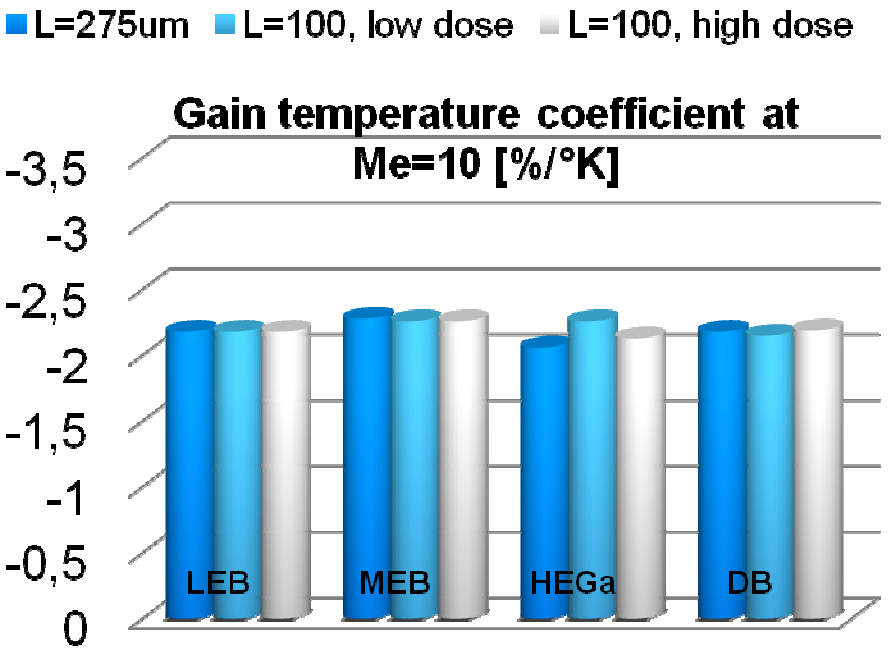
All the gain temperature coefficients are calculated in the range of 293-303°K using the following equation:

$$\Delta Me(\%/^\circ K) = \frac{1}{Me\big|_{T0}} * \frac{(Me\big|_{T0} - Me\big|_{T})}{T - T_0} \times 100$$

LGAD characteristic for L=100um and 275um

LGAD characteristics

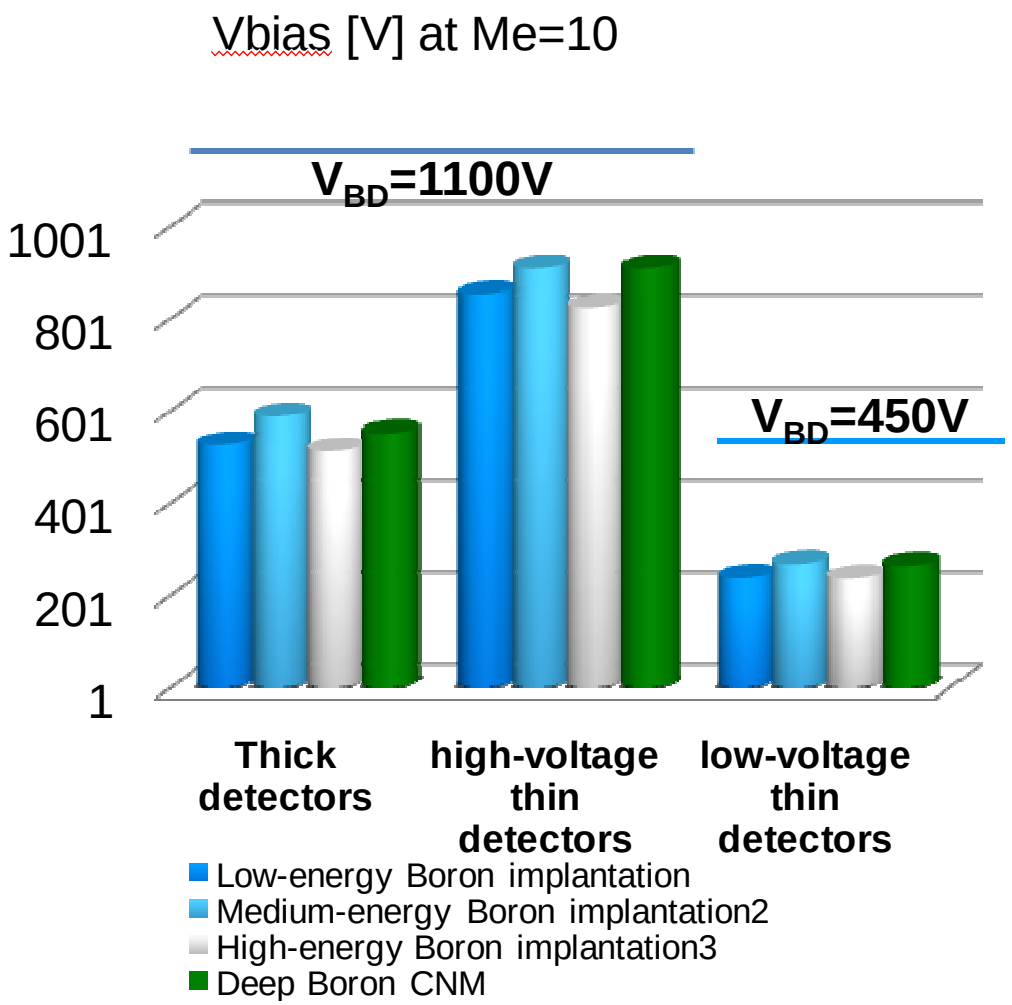




LEB: Low-energy Boron implantation.
MEB: Medium-energy Boron implantation.
HEGa: High-enegry Gallium implantation
DB: Deep Boron (CNM)

LGAD characteristic for L=100um and 275um

LGAD characteristics



Ratio $V_{bias}(M=10)/V_{BD}$ is between:

- 80% and 84% for high-voltage thin detectors
- 54% and 60% for low-voltage thin detectors.
- 48% and 56% for the thick detectors.

Conclusion

In this work:

- 1D Numerical solver for LGAD implemented in Matlab.
- A good agreement was found with TCAD simulations.
- We have studied the impact of Boron and Gallium doping profiles on LGAD performance.
- Electrical characteristics of LGAD with L=100um and 275um
- Breakdown voltage of thinner structures is less variable with implantation dose.
- Noise factor and gain temperature coefficient are similar in all cases.

Future work:

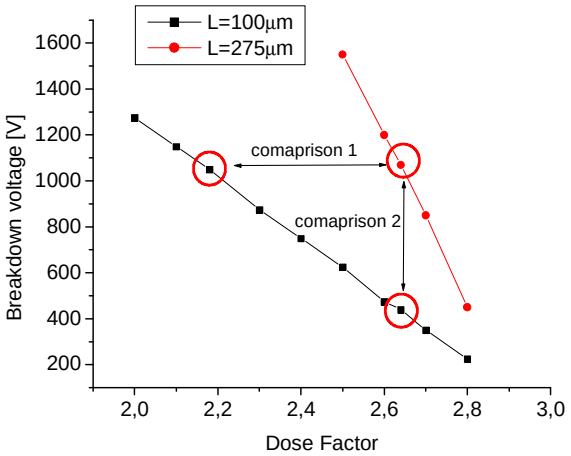
- Implementation of optimization methods.
- Study of different impact ionization models.

Acknowledgement

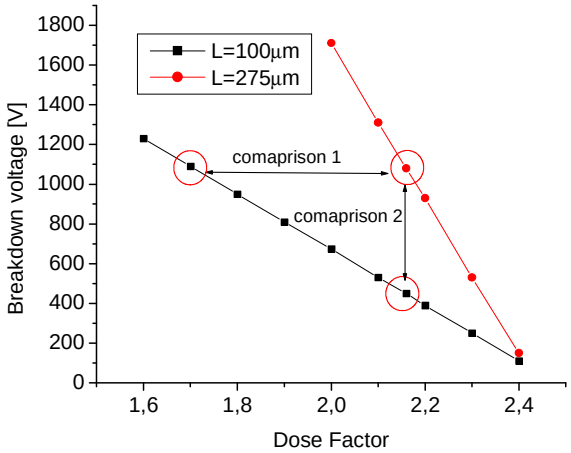
We thank M. Boscardin, G. Paternoster from FBK for giving us the doping profiles and INFN group from Torino for further discussion.

Back-up slides

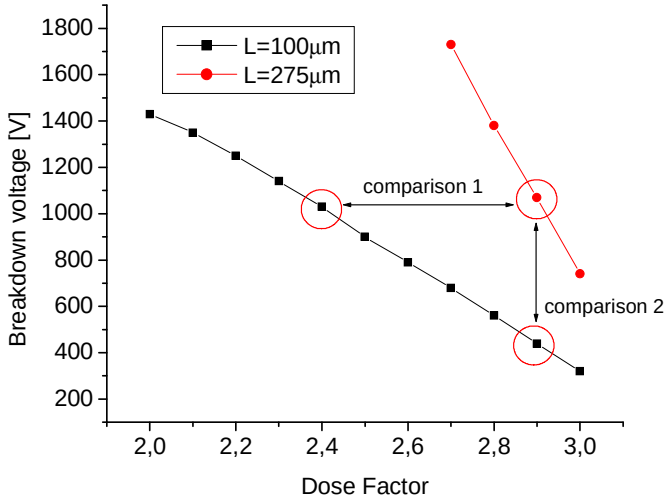
low-energy Boron implantation



Medium-energy Boron implantation



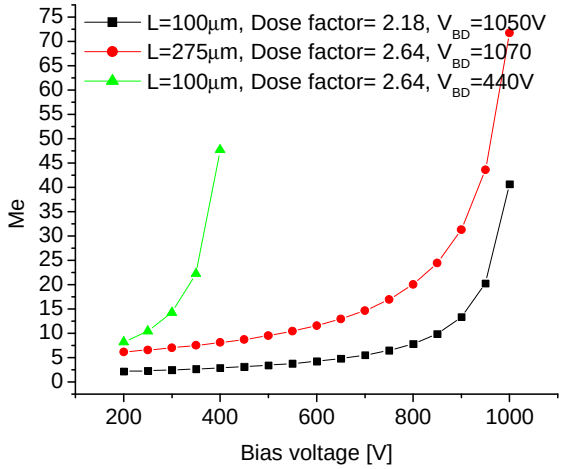
High-energy Gallium implantation

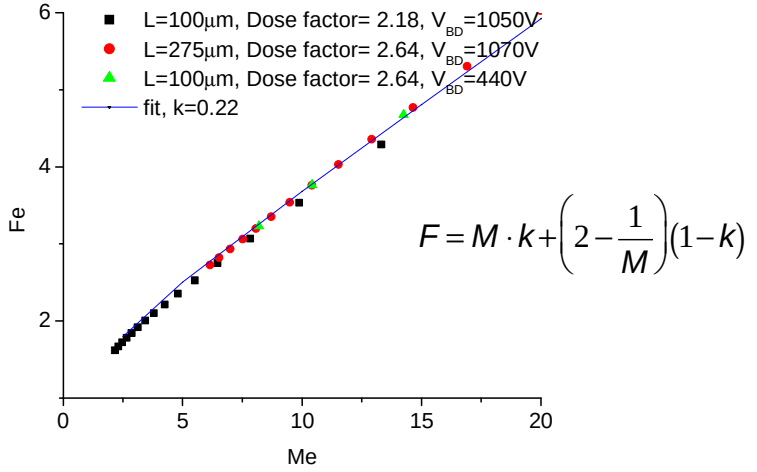


Breakdown voltage Vs Implantation dose

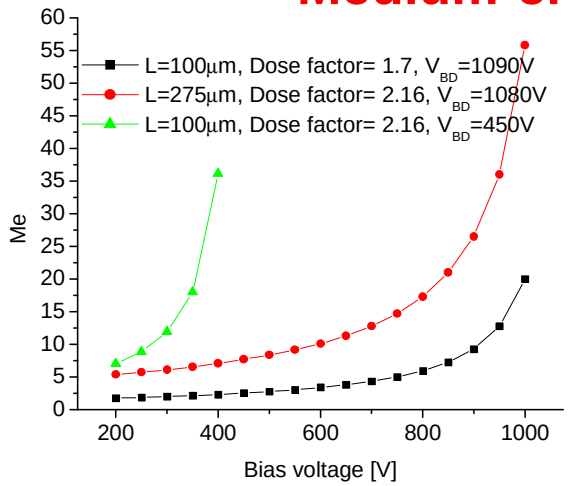
Multiplication gain and noise factor

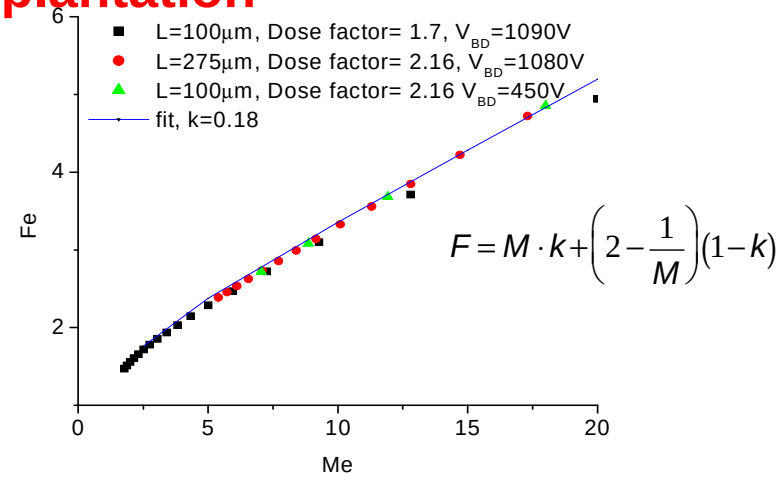
Low-energy Boron implantation





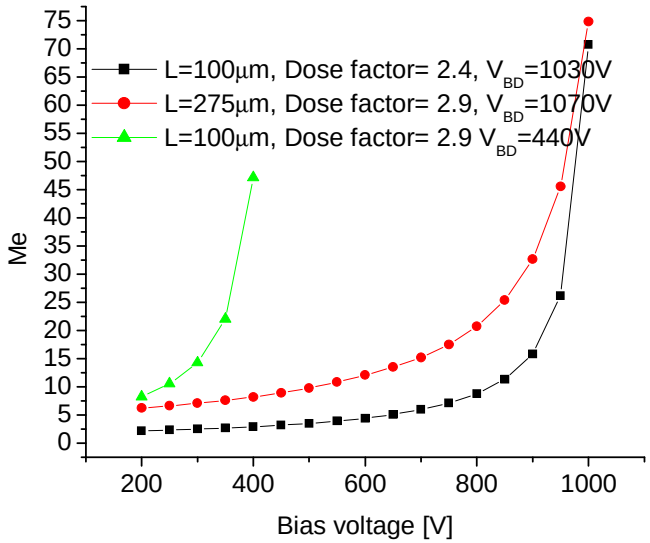
Medium-energy Boron implantation

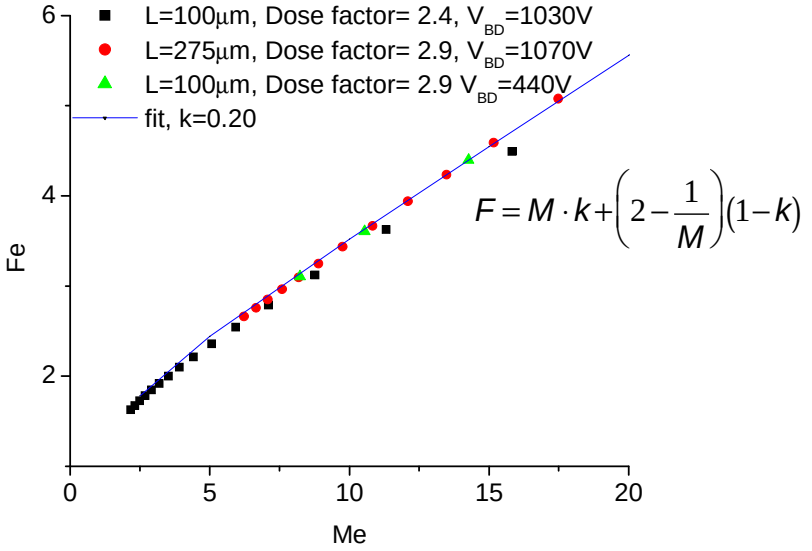




Multiplication gain and noise factor

High-energy Gallium implantation





LGAD characteristics

LGAD characteristics

L=275um

Implant	Implanted dose [cm^{-2}]	V_{BD} [V]	Bias voltage for M=10	Noise factor F for M=10	Gain Temperature coefficient at M=10 [%/K]
B, low-energ	2.64×10^{12}	1070	529	3.66	-2,18
B,medium-energ	2.16×10^{12}	1080	598	3.32	-2.28
Ga,High-energ	2.90×10^{12}	1070	515	3.5	-2.06

L=100um

Implant	Implanted dose [cm^{-2}]	V_{BD} [V]	Bias voltage for M=10	Noise factor F for M=10	Gain Temperature coefficient at M=10 [%/K]
B, low-energ	2.18×10^{12}	1050	854	3,75	-2,18
	2.64×10^{12}	440	241	3.66	-2.18
B,medium-energ	1.70×10^{12}	1090	912	3.25	-2.26
	2.16×10^{12}	450	270	3.30	-2.26
Ga,High-energ	2.40×10^{12}	1030	826	3.37	-2.26
	2.90×10^{12}	440	240	3.50	-2.13

Ratio $V_{bias}(M=10)/V_{BD}$ is between:

- 80% and 84% for high-voltage thin detectors
- 54% and 60% for low-voltage thin detectors.
- 48% and 56% for the thick detectors.