Status of technological development on LGAD and Future plans

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Work done in the framework of the RD50 CERN collaboration

Summary

- **LGAD Radiation hardness strategy**
- **Batch in process**
- **Gallium Diodes**
- **LGAD with Gallium multiplication layer & Carbon PSpray**
- **Boron removal study on different resistivity wafers and carbon doped wafers**
- **First LGAD on 6’’ FZ Silicon Wafers**
- ***50 µm thick LGAD: HGTD structure***
- **Causes of early Breakdown**
- **Future Plans: HGTD yield improvement**
- **Future Plans: 4’’ p-type epitaxial multiplication layer**
- **Conclusions**

LGAD Radiation hardness strategy

- **Previous studies demonstrated LGAD has a gain decrease while fluence increases [1]. There is almost no gain for fluences higher than $2 \cdot 10^{15}$ n_{eq} /cm^2, due to Boron removal. B_s is displaced to an interstitial position and B_i forms the complex B_i - O_i which is more energetically favourable.**

- **First challenge was the fabrication of Gallium and Boron PiN diodes in order to study the Gallium diffusion and the response to different neutron fluences. Boron diodes were also fabricated for comparison. Some references stands that carrier removal is drastically reduced in Gallium doped wafers [2] meanwhile others affirm that the reduction is not that much [3]. Furthermore Gallium introduces the electron trap level (Ec-0.11 eV) [4]**

- **Second challenge is the introduction of C_s in order to reduce the concentration of O_i. As a consequence, the amount of $B_i – O_i$ complexes will be reduced. However $C_i – O_i$ complex will increase, introducing the level E_v+0.36 eV that acts like a trap of holes [4]**

[1] G. Kramberger et al., *Radiation effects in LGAD after hadron irradiations*, 2015 JINST 10 P07006 [doi:10.1088/1748-0221/10/07/P07006].
[2] A. Khan et al., *Role of the impurities in production rates of radiation-induced defects in silicon materials and solar cells*, Journal of Applied Physics, 90 , 1170, (2001)[doi:10.1063/1.1384855]
[3] H. Matsuura et al., *Si Substrate Suitable for Radiation-Resistant Space Solar Cells*, Japanese Journal of Applied Physics , Vol. 45, No. 4A, 2006, pp 2648, [doi:10.1143/JJAP.45.2648].
[4] M. Yamaguchi et al., *Radiation-resistant properties of Ga-doped Si*, Physica B 340-342 (2003) 596-600 [doi:10.1016/j.physb.2003.09.127]

Batch in process

Run	Name	Status	Next step	Measurements
9089	Gallium & Boron PiNs	Irradiation	Comparison of irradiated and non-irradiated PiNs.	Sheet Resistance, IV & CV
9889	LGAD with Ga multiplication layer	Pstop (**April 2017)**	IV, CV, MIP, TCT, Neutron irradiation.	IV, CV, MIP & TCT
	Carbon Spray	Pstop (**March 2017)**	IV, CV, MIP, TCT, Neutron irradiation.	IV, CV, MIP & TCT
9435 + 10029	Carbon doping (DCE oxidation) + Bare wafers (different resistivity)	Finished. Wafers are being diced	Neutron irradiation & comparison of irradiated & non-irradiated wafers.	Sheet Resistance
9974	LGAD on 6'' SOI wafers	Pstop (**March 2017)**	IV, CV, MIP, TCT, Neutron irradiation.	IV, CV, MIP & TCT
9254	HGTD on Epitaxial wafers	Metallization **(January 2017)**	IV, CV, MIP, TCT, Neutron irradiation.	IV, CV, MIP & TCT

Run 9089: Gallium Diodes Run

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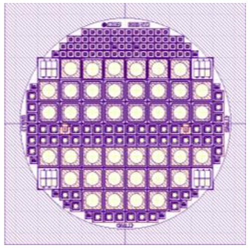
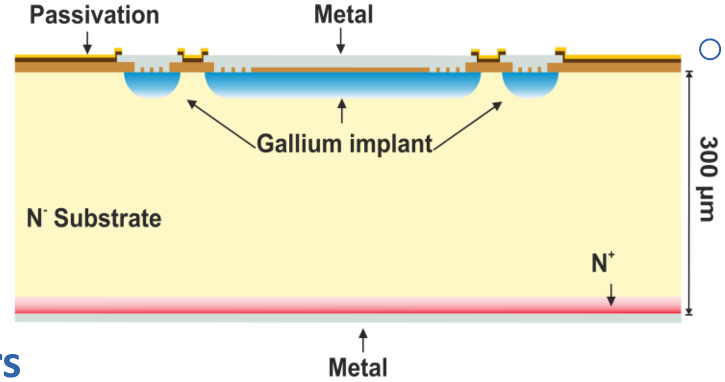
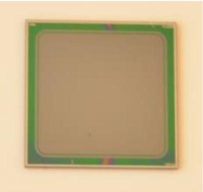
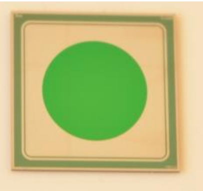




- 156 PiNs P-on-N
  - ✓ 40 (8.2x8.2 mm² area) → x10
  - ✓ 54 (3.2x3.2 mm² area)
  - ✓ 62 (1.2x1.2 mm² area) → x10

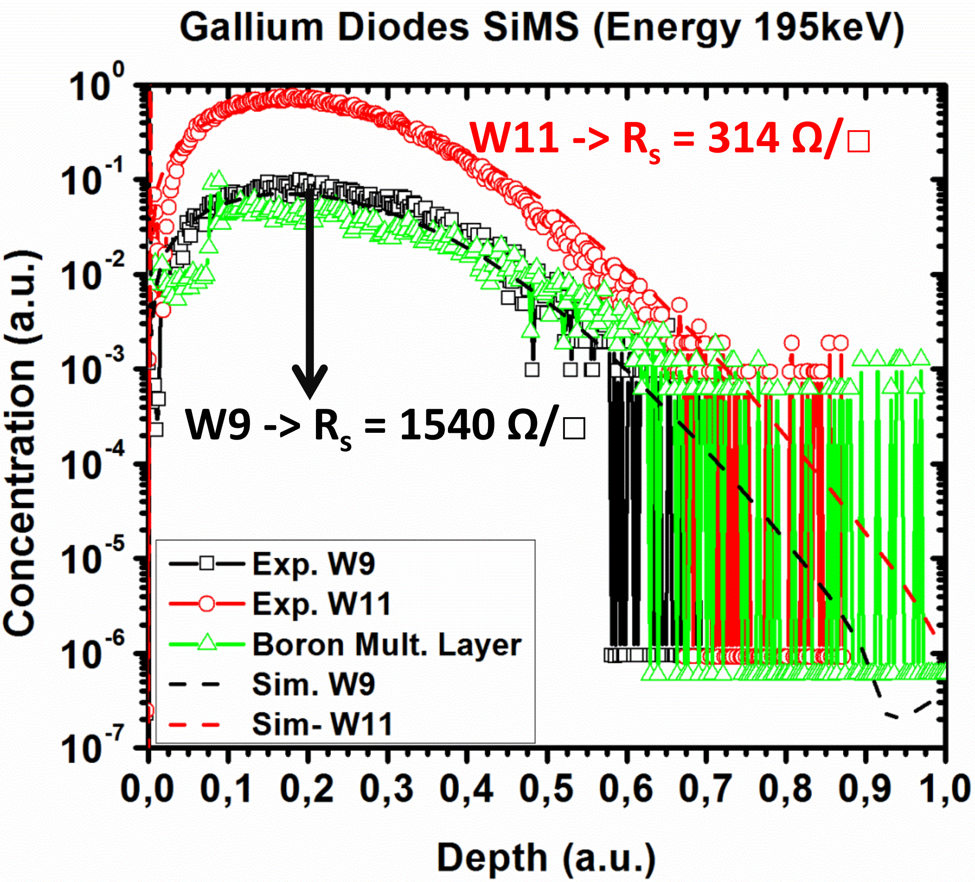




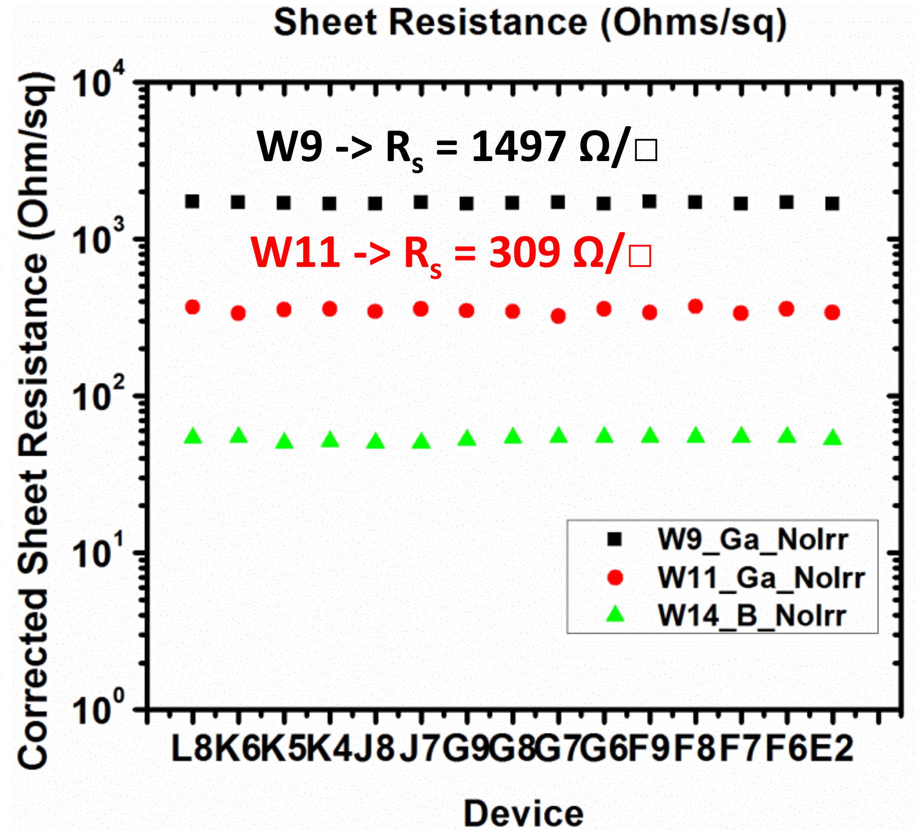
- 15 Wafers
  - ✓ 3 Wafers (W13, W14, & W15) with Boron diodes (3 different implanters)
  - ✓ 12 Wafers with Gallium diodes (3 Imp. Energies, 2 Imp. Doses, 2 Drive-in)
  - ✓ SIMS of W9, W10, W11, W12 were done in order to study the diffusion of Gallium
  - ✓ Passivation and Metallization removal of 10 diodes from W9, W11 and W14
  - ✓ Measurement of Sheet Resistance on Non-irradiated samples
  - ✓ Measurement of IV and CV curves on Non-irradiated devices
  - ✓ Irradiation of 20 samples from each wafer to fluences ($1\cdot10^{12}$ n_{eq}/cm^2, $1\cdot10^{13}$ n_{eq}/cm^2, $1\cdot10^{14}$ n_{eq}/cm^2, $1\cdot10^{15}$ n_{eq}/cm^2, $5\cdot10^{15}$ n_{eq}/cm^2). Total : 60 samples.

Gallium Diodes

SIMS Measurements & Simulation



Experimental Measurements



- **Implantation Dose, Implantation Energy and Drive-in of W9 looks the best candidate to reproduce de p-type multiplication layer.**

LGAD with Gallium multiplication layer & Carbon PSpray

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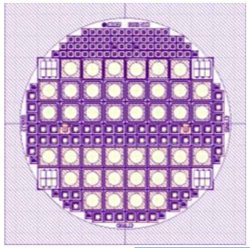


- 16 Wafers
  - ✓ 1 Wafer from Carbon Doping Run (9435, High Resistivity p-type FZ)
  - ✓ 15 Wafers (High Resistivity p-type FZ)

W1 LGAD Carbon Dop:

* PWell Implantation Dose $1.9 \cdot 10^{13}$ at/cm^2
* Run 9435

Co-diffusion of Boron, Phosphorous and Carbon will introduce some difference in the final doping profile. Carbon can reduce the Boron and Phosphorus diffusion. Because that variation, 5 Pwell imp. doses are proposed.

W2-6 LGAD Carbon PSpray:

* D_0 = 1.9 cm^2/s , E_a=3.1 eV
  Carbon Depth = 26 µm [5]
* PWell Implantation Dose :
  - W2 -> $1.5 \cdot 10^{13}$ at/cm^2
  - W3 -> $1.7 \cdot 10^{13}$ at/cm^2
  - W4 -> $1.8 \cdot 10^{13}$ at/cm^2
  - W5 -> $1.9 \cdot 10^{13}$ at/cm^2
  - W6 -> $2.0 \cdot 10^{13}$ at/cm^2

W7-11 Control LGAD:

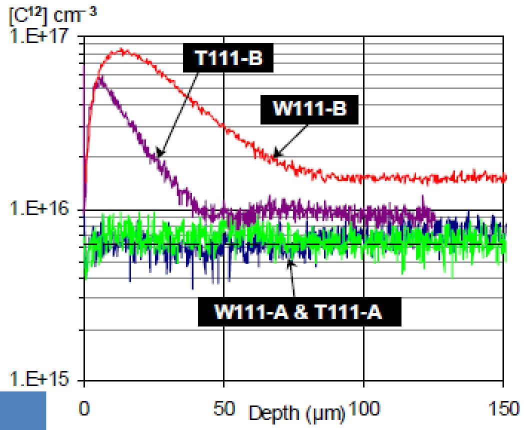
* Without Carbon Spray
* PWell Implantation Dose :
  - W7 -> $1.5 \cdot 10^{13}$ at/cm^2
  - W8 -> $1.7 \cdot 10^{13}$ at/cm^2
  - W9 -> $1.8 \cdot 10^{13}$ at/cm^2
  - W10 -> $1.9 \cdot 10^{13}$ at/cm^2
  - W11 -> $2.0 \cdot 10^{13}$ at/cm^2

W12-16 LGAD Ga PWell:

* Ga-PWell Implantation Dose :
  - W12 -> $7 \cdot 10^{13}$ at/cm^2
  - W13 -> $8 \cdot 10^{13}$ at/cm^2
  - W14 -> $9 \cdot 10^{13}$ at/cm^2
  - W15 -> $1 \cdot 10^{14}$ at/cm^2
  - W16 -> $1.2 \cdot 10^{14}$ at/cm^2
* Drive-in W9 (Run 9089)

[5] R.C. Newman and J. Wakefield, *Diffusion and precipitation of Carbon in Silicon*, Metallurgy of Semiconductor Materials, V.15, ed. By J.B. Schroeder, (Interscience Publishers, New York, 1962), pp. 201-208.

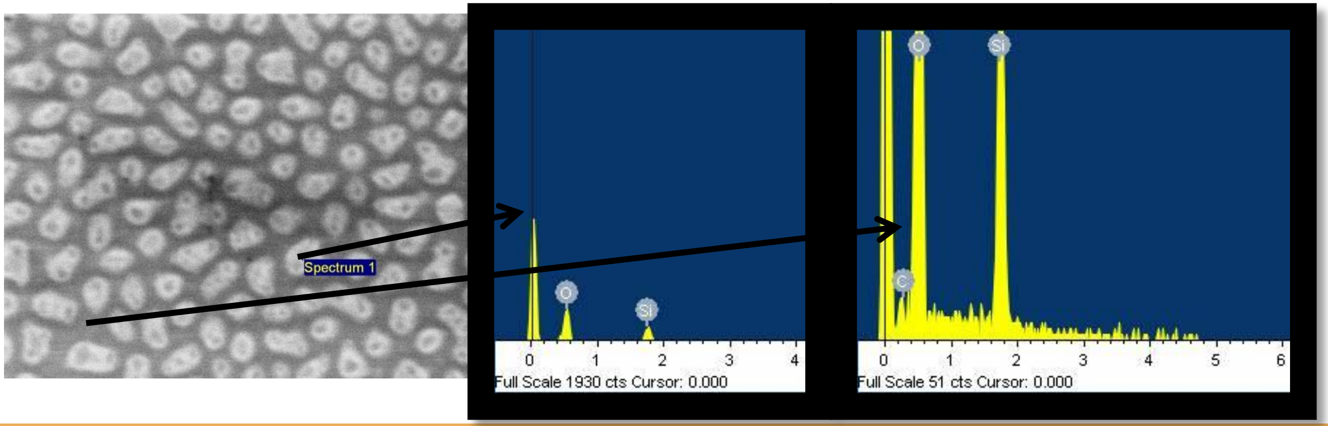
Boron Removal Study on different resistivity wafers and carbon doped wafers



- 3rd RD48 Status report (1999)
  - ✓ <111> FZ wafers oxidation with TCA
- Carbon Diffusion: 11 Wafers
  - ✓ Different Resistivity

Wafer	W1-2	W3-4	W5-6	W7-8	W9-10	W11
Type	FZ	CZ	CZ	CZ	FZ	FZ
Resistivity (Ohms·cm)	> 5000	> 150	> 10	> 0.1	> 0.01	> 1000

  - ✓ Oxidation with DCE during 36h at 1100ºC (7 oxidation of 5h 10min)



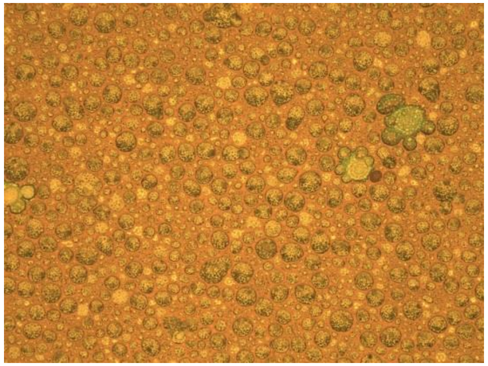
<u>After first oxidation :</u>

* SEM+EDX (Test Wafer)

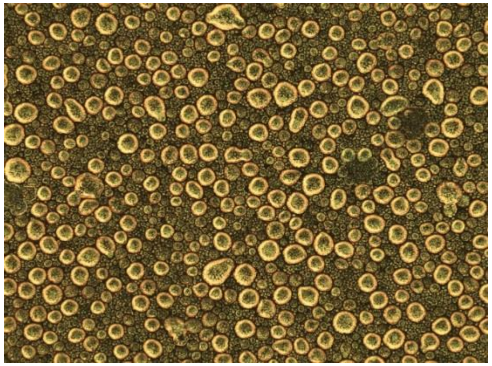
At 5 keV there is some Carbon.

* There is no presence of Nitrogen

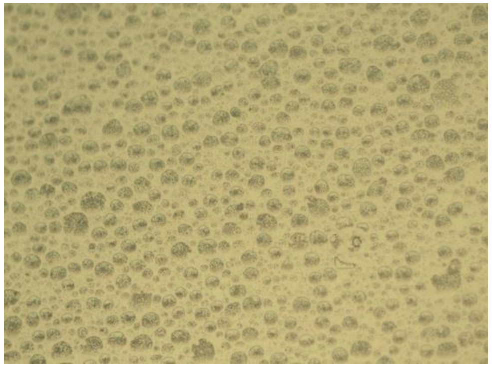
Boron Removal Study on different resistivity wafers and carbon doped wafers



a) Oxide on Wafer1(x20 Bright Field)



b) Oxide on Wafer1 (x20 Dark Field)



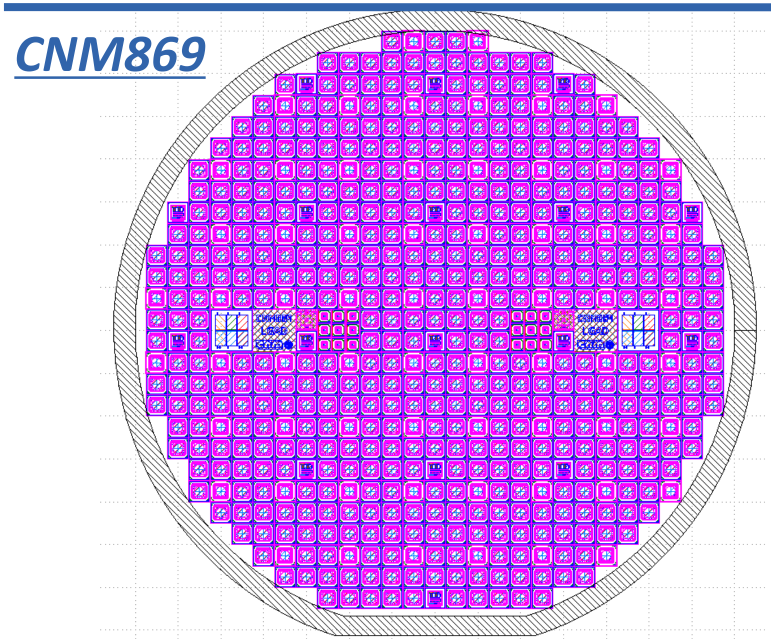
c) Wafer1 after oxide etching (x20 BF)

- **Run 10029: 11 Wafers**
  - ✓ **W1, W3, W5, W7, W9, & W11 from Run 9435 + 5 Wafers (1 wafer of each resistivity)**

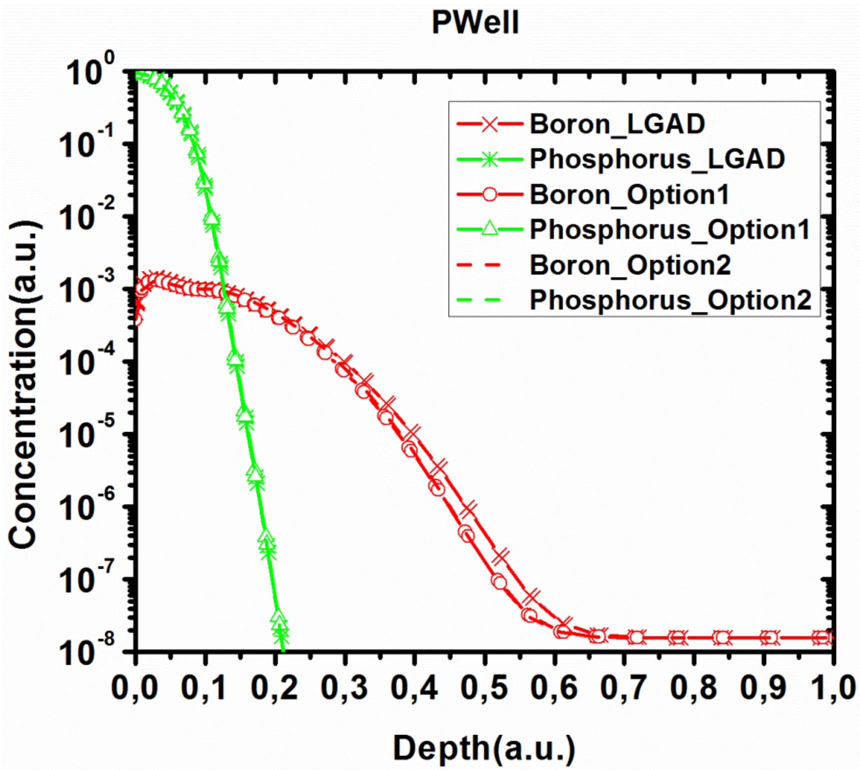
Wafer Specifications			Bare Wafer			After DCE Oxidation		
Wafer	Thickness	Resistivity	Sheet Resistance		Resistivity	Sheet Resistance		Resistivity
#	Type	Ohms·cm	Ohms/□	StDev (%)	Ohms·cm	Ohms/□	StDev (%)	Ohms·cm
W1-2	FZ	> 5000	$1.01\cdot10^{6}$	31	$2.89\cdot10^{4}$	$1.14\cdot10^{4}$	72	$3.24\cdot10^{4}$
W3-4	CZ	> 150	$1.05\cdot10^{4}$	26	$3.16\cdot10^{2}$	$8.39\cdot10^{3}$	39	$2.52\cdot10^{2}$
W5-6	CZ	> 10	$6.41\cdot10^{2}$	50	$3.21\cdot10^{1}$	$2.41\cdot10^{6}$	19	$1.21\cdot10^{1}$
W7-8	CZ	> 0.1	7.40	1.9	0.39	7.70	6,4	0.40
W9-10	FZ	> 0.01	0.30	1.4	0.02	0.30	1,2	0.02
W11	FZ	> 1000	$1.47\cdot10^{5}$	31	$4.40\cdot10^{3}$	$2.68\cdot10^{5}$	5	$8.03\cdot10^{3}$

- ✓ **10 samples of each wafer will be selected, measured and sent for neutron irradiation**

First LGAD fabrication on 6'' wafer



- 6'' wafers have to be processed in new implanter and new furnace
  - ✓ Re-calibrated Drive-in
  - ✓ Re-calibrated Implantation Energy and Dose



- 554 Diodes (LGAD + PiN)
  - ✓ 472 LGAD (3.2x3.2 mm^2 area)
  - ✓ 64 PiN (3.2x3.2 mm^2 area)
  - ✓ 16 LGAD (1.2x1.2 mm^2 area)
  - ✓ 2 PiN (1.2x1.2 mm^2 area)
  - ✓ 21 test structures, sheet resistance, SiMS

50 µm thick LGAD: HGTD structures

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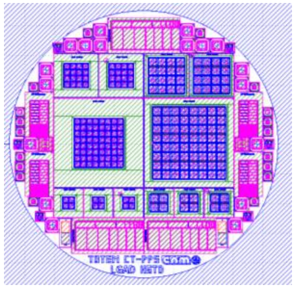
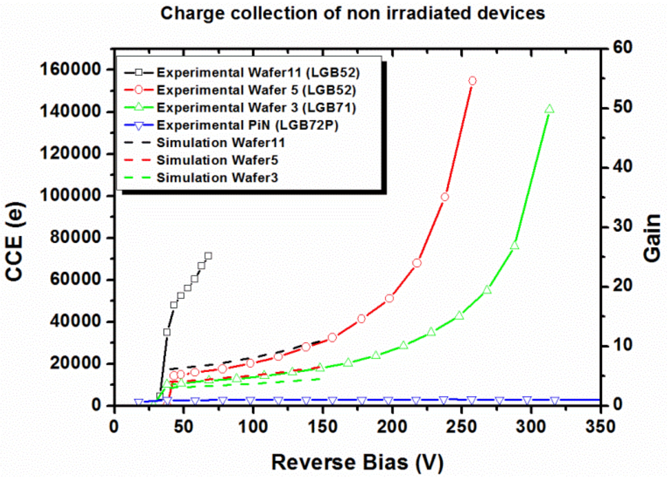
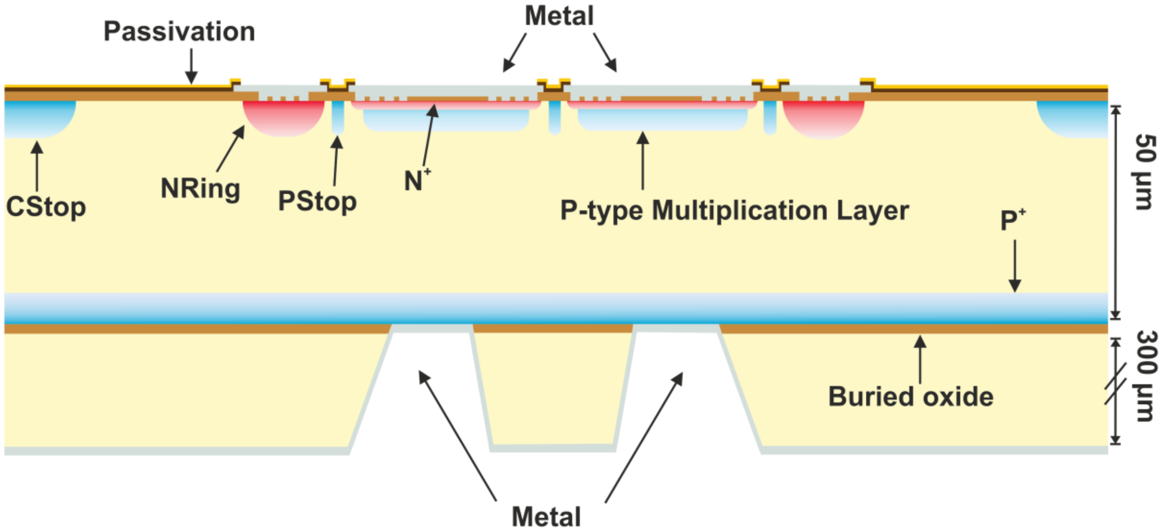


- First 50 µm thick LGAD on SOI Wafers was fabricated at CNM facilities
  - ✓ After irradiation, the probability of trapping decreases for thin devices.
  - ✓ Thin LGAD has boron removal too
- ✓ First design has a good electrical and timing performance
- ✓ Low yield





Thanks to Gregor for the measurements

Causes of low yield

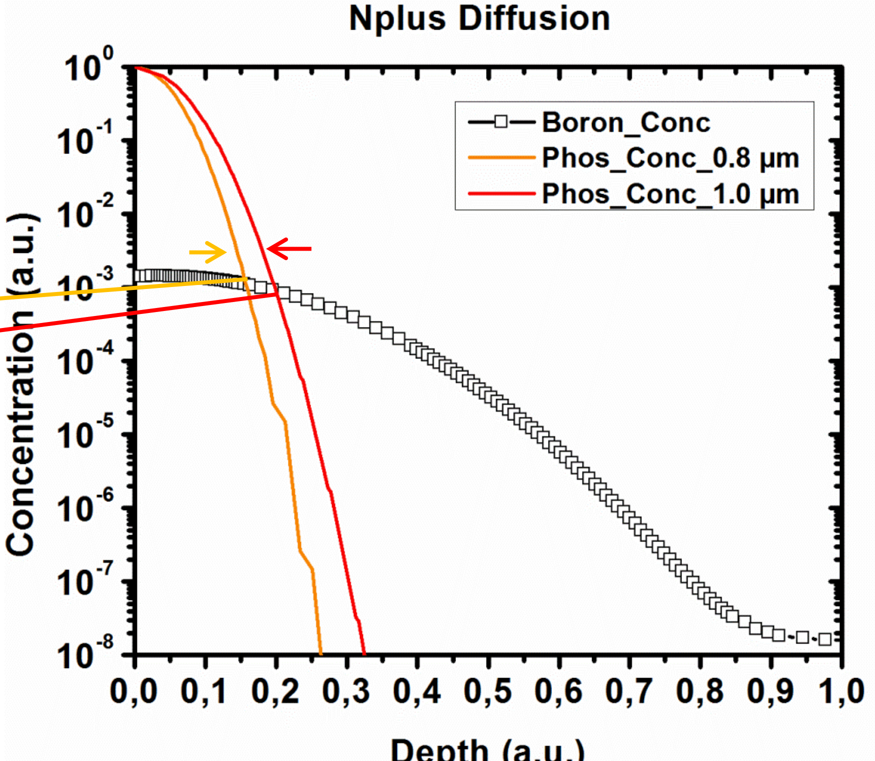
Nplus Diffusion

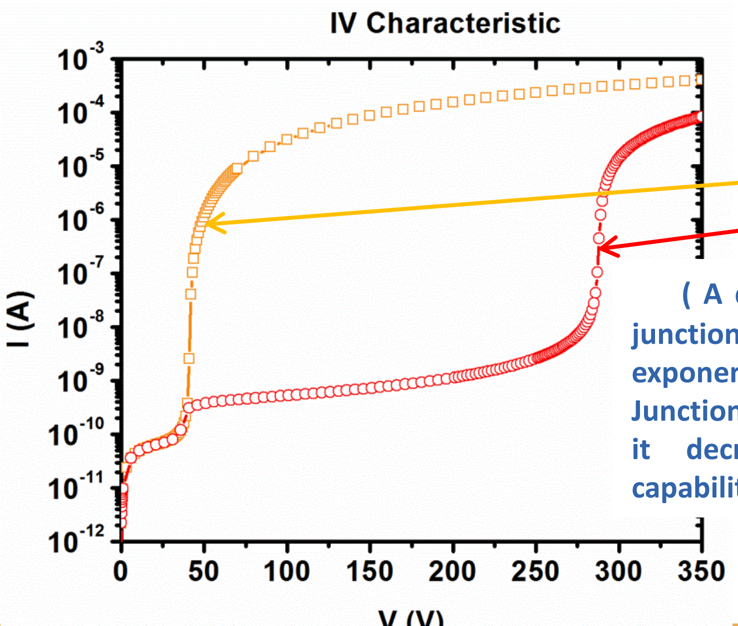
✓ **Electrical simulations of the core region with a different Nplus diffusion depths show a drastic decrease of voltage capability.**

Absence of JTE

✓ **LGAD structures (with JTE) shows better yield than HGTD structures (without JTE)**

Maximum Electric Field at the Junction Flat Area





(A decrease of 20 nm in junction depth means a exponential increase of Junction concentration and it decreases the voltage capability 240V)

Future Plans: HGTD yield improvement

○ **Proposed options to improve the yield of HGTD**

New 4'' HGTD Fabrication Process

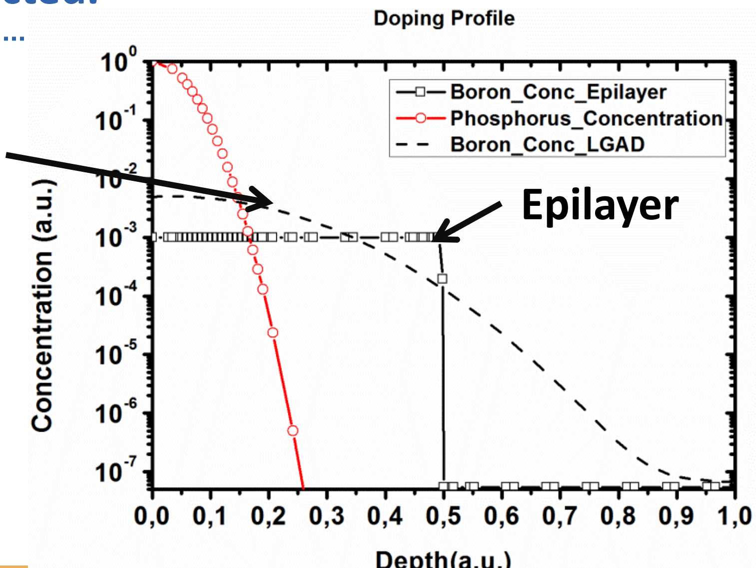
New mask with JTE in all structures and test structures to control the double diffusion process:

✓ Sheet resistance measurement of Multiplication layer diffusion.

New 4'' p-type epitaxial multiplication layer

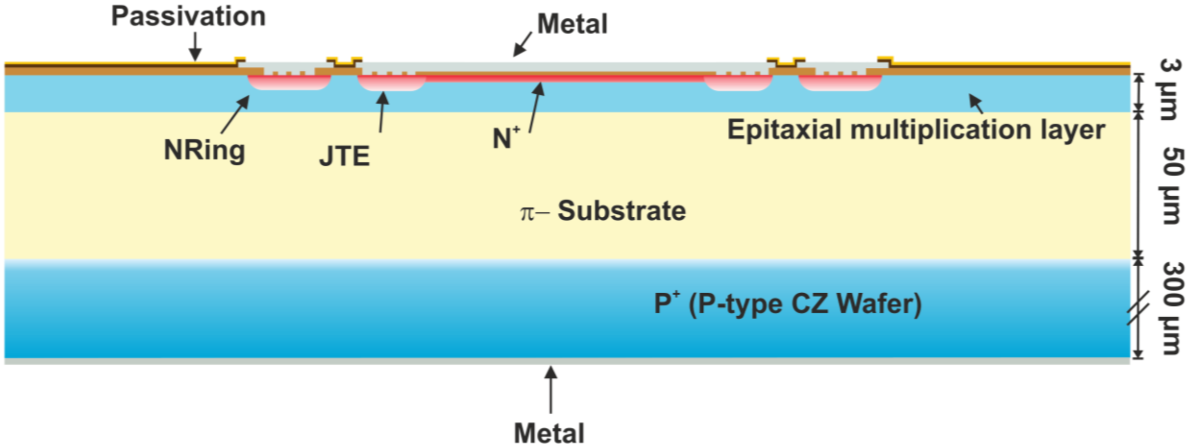
A constant epilayer doping concentration will reduce the sensitivity to Nplus diffusion depth. Better stability of voltage capability is expected.

Boron conc. after Drive-in



Future Plans: New 4’’ p-type epitaxial multiplication layer

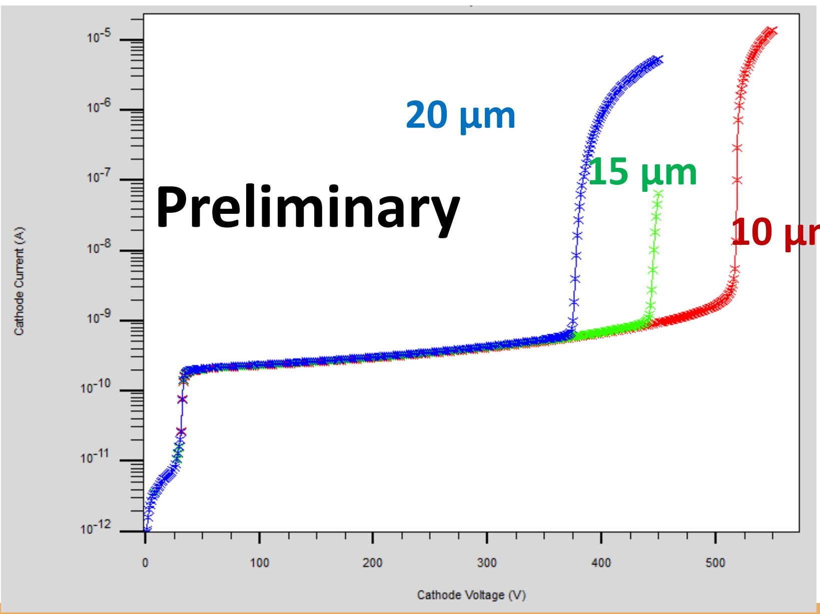
Si-Si Wafer Bonding: 3 µm **Epi** + 50 µm **FZ** + 300 µm **CZ**

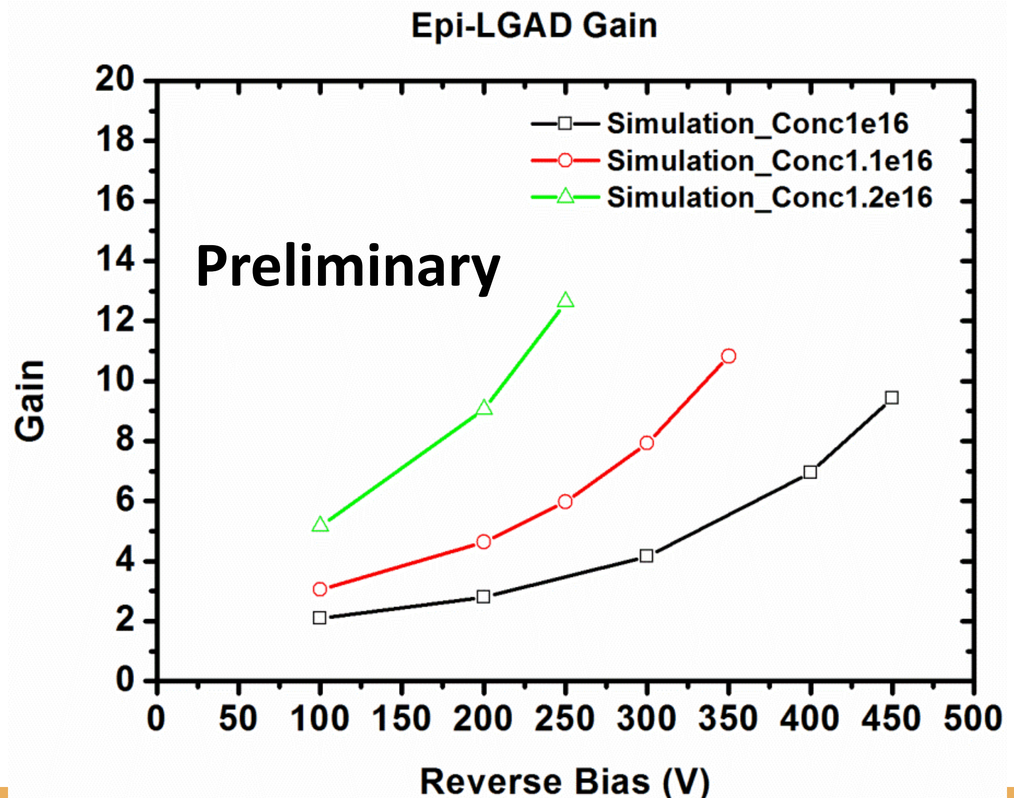


- **Advantages:**
  - ✓ **Control of the doping concentration at the N^+/P junction**
  - ✓ **Simplification of the fabrication process. There will be 2 photolithography steps less and 2 implantation steps less (No PStop, No PWell)**
  - ✓ **Epitaxial wafers have a lower carbon and oxygen concentration than FZ and CZ wafers. Maybe the Boron Removal effect will be less.**
- **Drawbacks:**
  - ✓ **JTE is required**
  - ✓ **New mask design**

Future Plans: New 4'' p-type epitaxial multiplication layer

- The voltage capability of the structure depends on the inter-cell distance. Simulation shows an increase of voltage capability to 500V when the inter-cell distance is decreased to 10 µm.
- MIP Simulation shows gain. The gain depends on the epilayer doping concentration as well as the epilayer thickness. A better study of the best epilayer option is required.





Conclusions

- **The best option for Gallium multiplication layer LGAD was obtained from SIMS data. Furthermore, LGADs with Gallium multiplication layer are under fabrication.**
- **Control steps during fabrication processes, such as sheet resistance measurement of the multiplication layer, are been implemented in new 6’’ and 4’’ batches.**
- **The lack of JTE and variations in Nplus diffusion depth can be the causes of low yield in HGTD batch.**
- **The introduction of JTE in all structures is one option to improve the HGTD yield.**
- **Another option is the Epitaxial multiplication layer. Furthermore It could reduce the boron removal after neutron irradiation.**

Thank you for your attention !