Electrical characterization and optimization of silicon carbide p^+/n junctions for particle detectors

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IMM Bologna

Motivations

- Final goal: realization and characterization of a particle detector based on SiC
- Use of a planar technology (no Mesa) $\Rightarrow$ ion implanted p/n junctions

The research team

- **University of Perugia (Italy)**
  - **Device design and simulation**
  - **Electrical measurements**
- *Partner (SiC technology)*
  - *CNR-IMM Bologna (Italy)*
- *Collaborations*
  - *INFN-Italy (SiCPOS project)*
  - *Cegely Lyon (France)*

Outline

- Introduction on SiC properties
- Test diode p^+/n (and n^+/p):
  - Technological process
  - I / V and C / V measurements
- Preliminary modeling of SiC detectors
  - Motivations and simulation tool
  - Test diode and calibration
  - Preliminary results
- Conclusions

Silicon Carbide

- large E_g (3-3.3 eV) → very low leakage current
- MIP (Minimum Ionizing Particle) generates 51 e/h pairs per μm
- radiation hardness (?) (high atomic binding within the material)
- high quality crystals now available
- Schottky barrier detectors have been studied as α-particle detectors (100% of charge collection efficiency (CCE))*

* Nava, Cavallini, Bruzzi, Bertuccio 2000-2002

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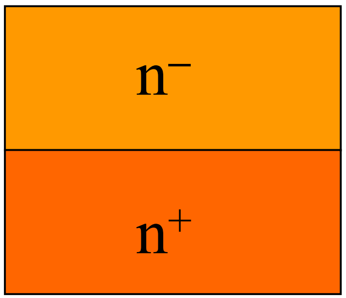
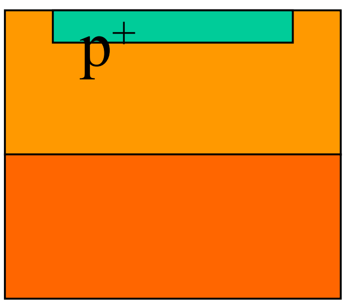
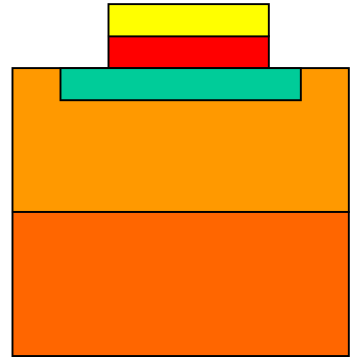
SiC Process: p^+/n



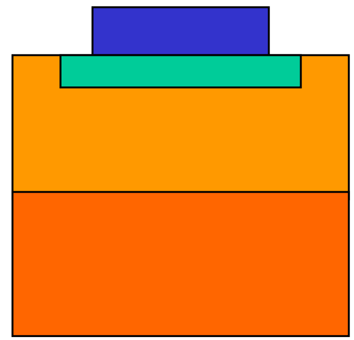
Epi (40 µm) doping:
1×10^{15} cm^{-3}



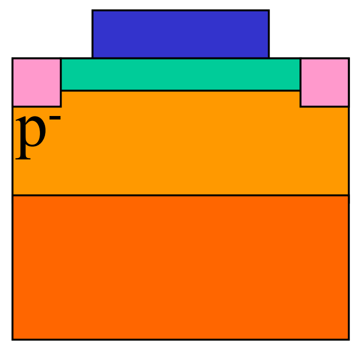
Ion implantation
Al^+ @ 300°C
Annealing 1650°C 30 min
p^+ doping (0.4 µm)
= 4×10^{19} cm^{-3}



Al (350 nm) /
Ti (80 nm)
deposition

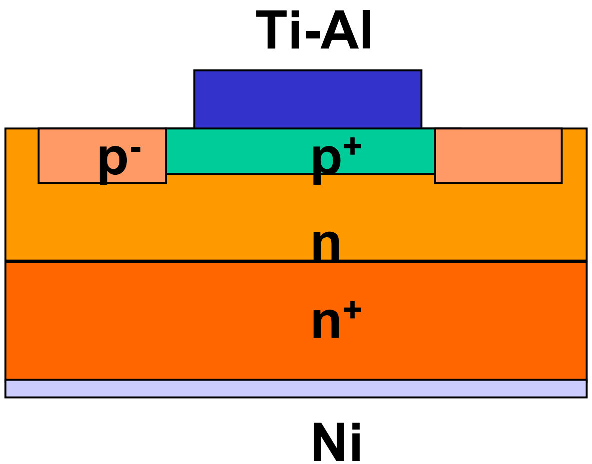


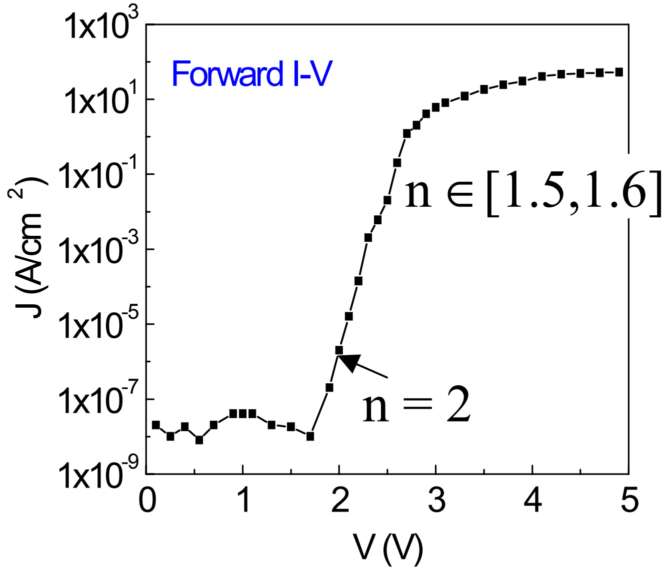
Annealing 1000°C
in vacuum 2 min

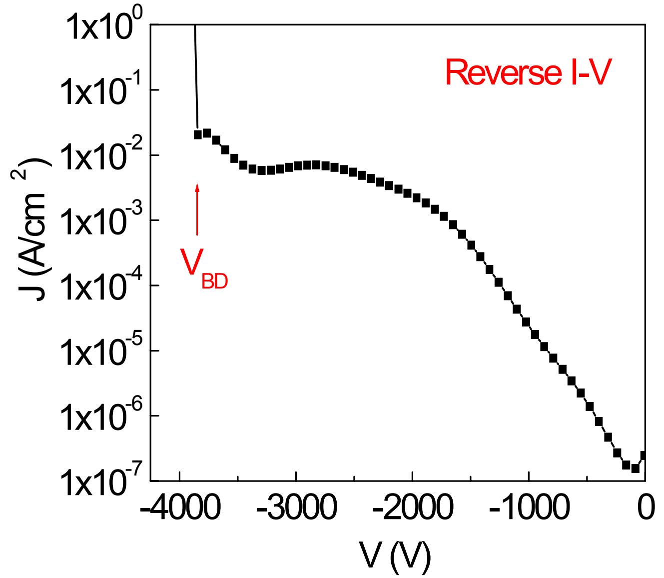


Optional
p^- extensions

I-V measurements on p^+/n diodes





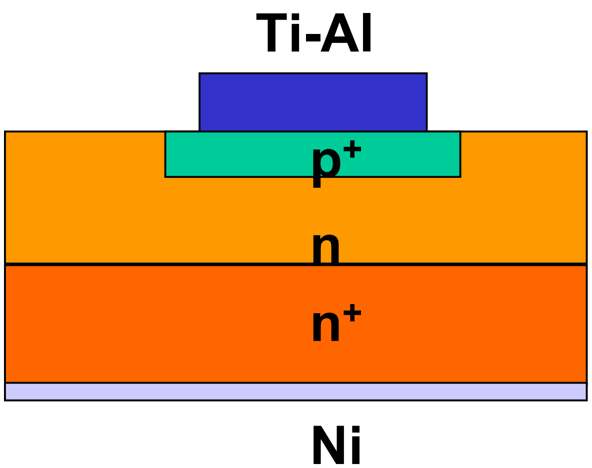


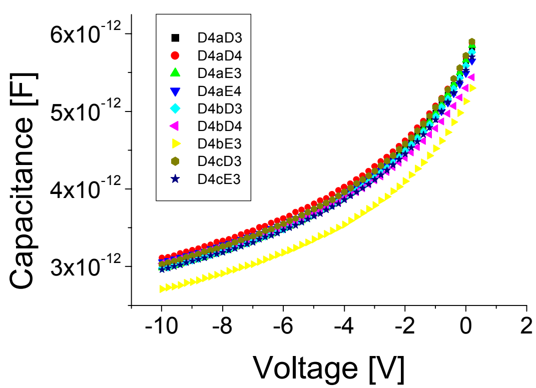
- 75% of diodes have good I-V curves
- V_{BD} is about 4 kV
- Theoretical limit for this device: 5 kV
- A few diodes now available for testing as particle detectors

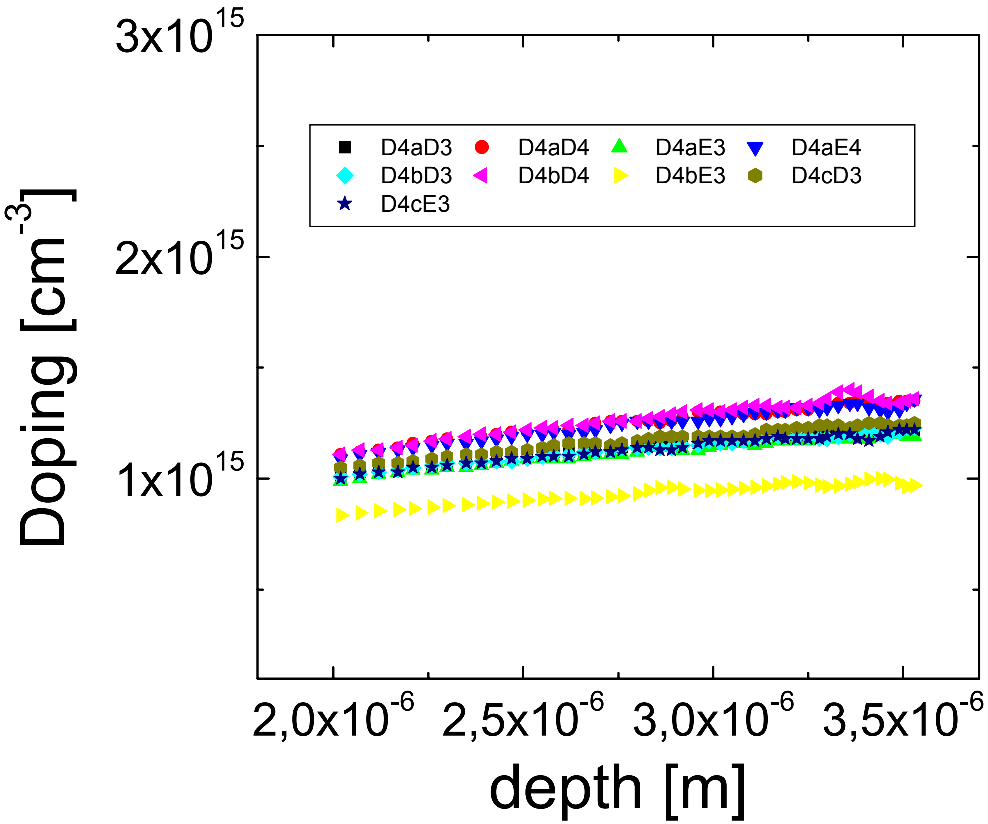
Diode diameter: [0.3,1] mm

Power diode layout design by INSA-CEGELY, Lyon France

CV measurements

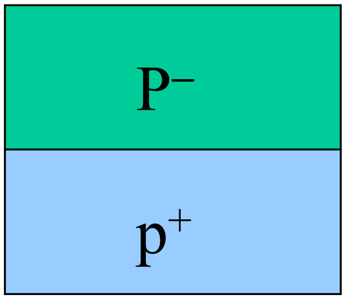






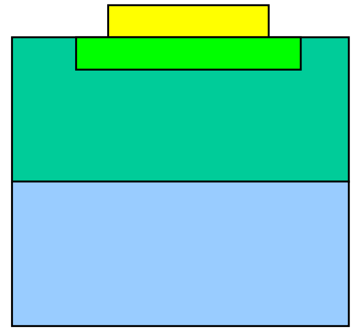
- Epi doping confirmed

SiC Process: n^+/p



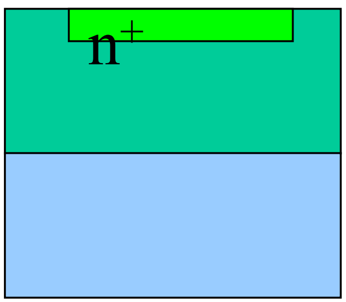
Epi doping:

8.5×10^{15} cm^{-3}



Ni deposition

(50 nm)



Ion implantation

P^+, 10-170 keV @ 300°C

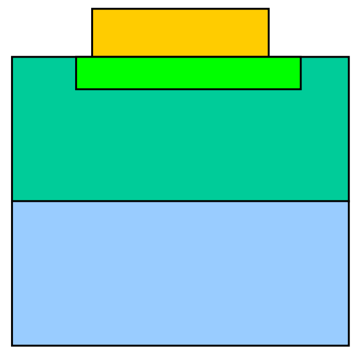
Total dose: 2×10^{15} cm^{-2}

a)annealing 1300°C 20 min

b)annealing 1500°C 20 min

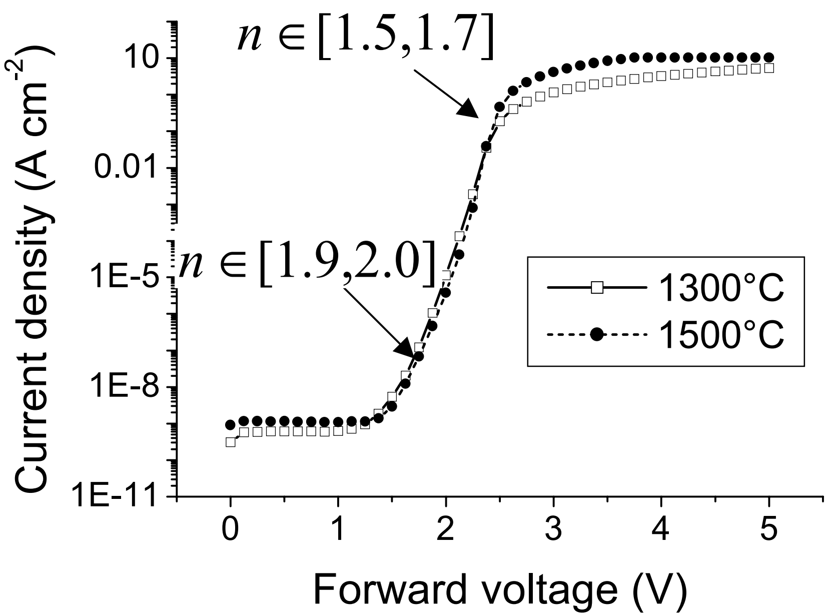
c)annealing 1650°C 20 min

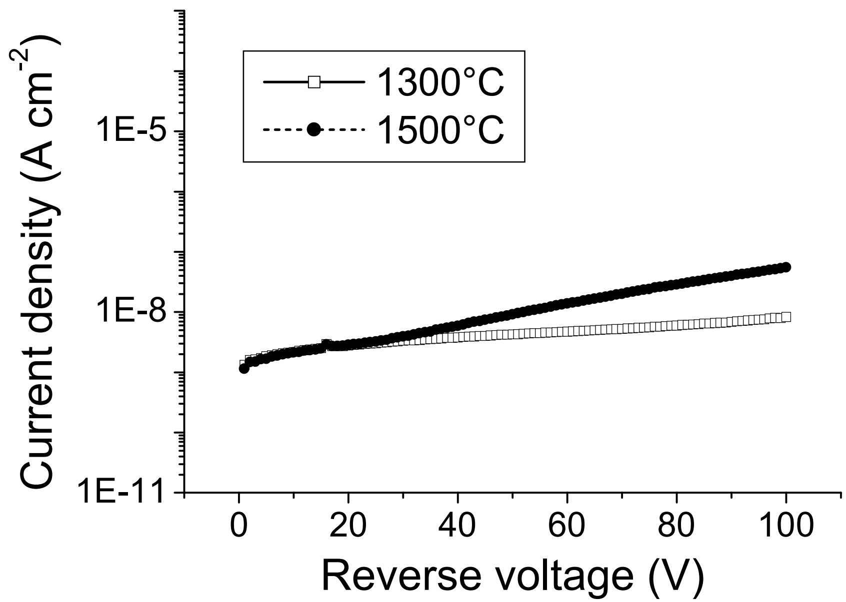
n^+ doping (0.2 μm) = 1×10^{20} cm^{-3}



Next step to do:
silicidation by
annealing at 950°C
in N_2 2 min

Preliminary I-V measurements on n^+/p diodes





80% of diodes have good I-V curves (both direct and reverse)

Outline

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- Test diode p^+/n (and n^+/p):
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- Preliminary modeling of SiC detectors
  - Motivations and simulation tool
  - Test diode and calibration
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Motivations for simulation

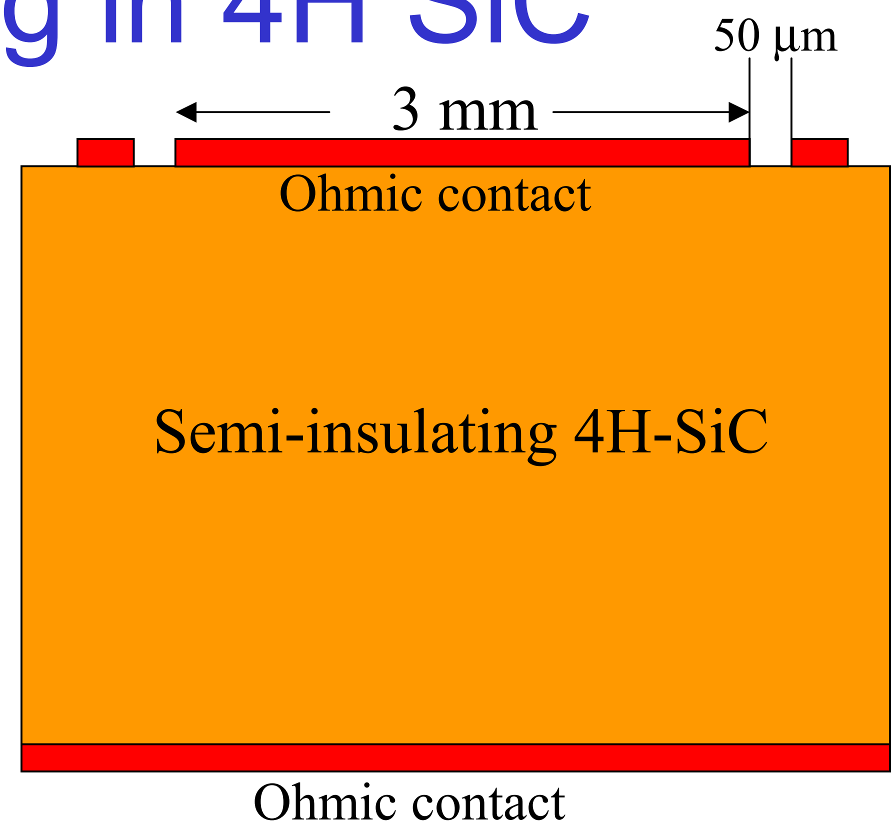
- Very high cost of SiC wafers
- Suitability of device simulation for design optimization
- Trade off between SiC wafer quality and available budget

Simulation Tool

- DESSIS ISE-TCAD
  - Discrete time and spatial solution to the fundamental semiconductor equations
  - **6H-SiC model available**

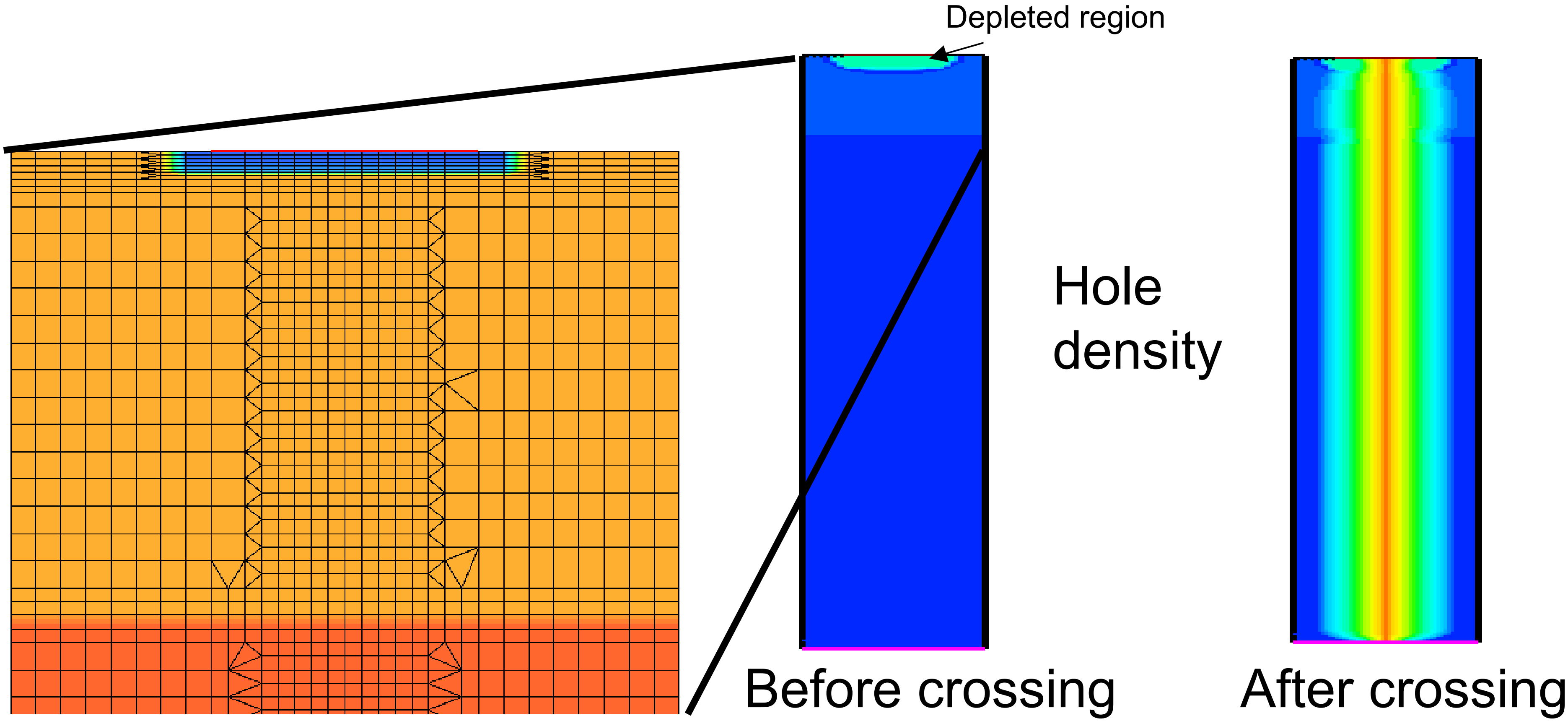
Known experimental results: MIP crossing in 4H SiC*

- Bias voltage 500 V
- Induced collected charge: 2000 e^-
- Noise charge 300 e^-
- Drawbacks:
  - High number of defects
  - high operating voltage



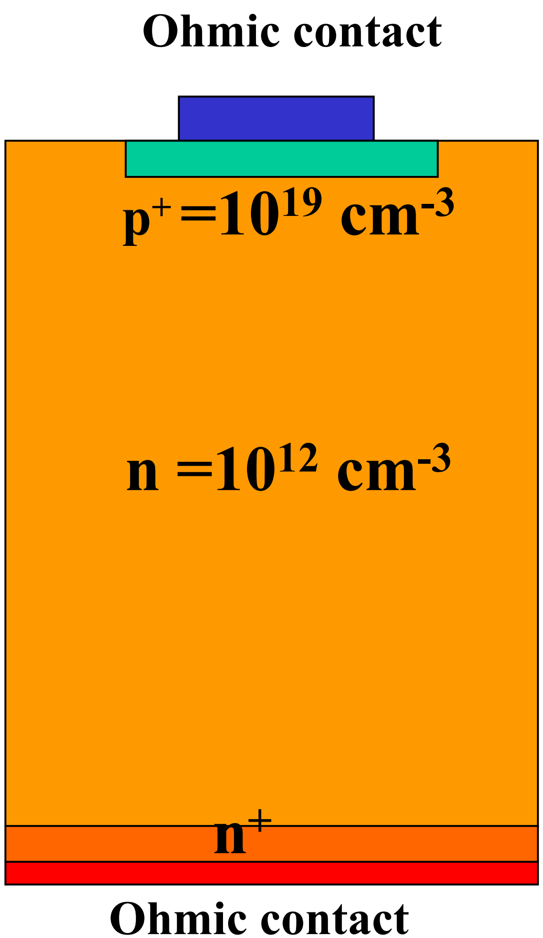
* M. Rugalla, K. Runge, A. Soldner-Rembold "Particle detectors based on semi-insulating Silicon carbide," *Nuclear Physics B*, vol. 78 (**1999**) 516-520

Grid and Heavy Ion crossing



Heavy Ion crossing modeling available in DESSIS ISE-TCAD

Model Calibration

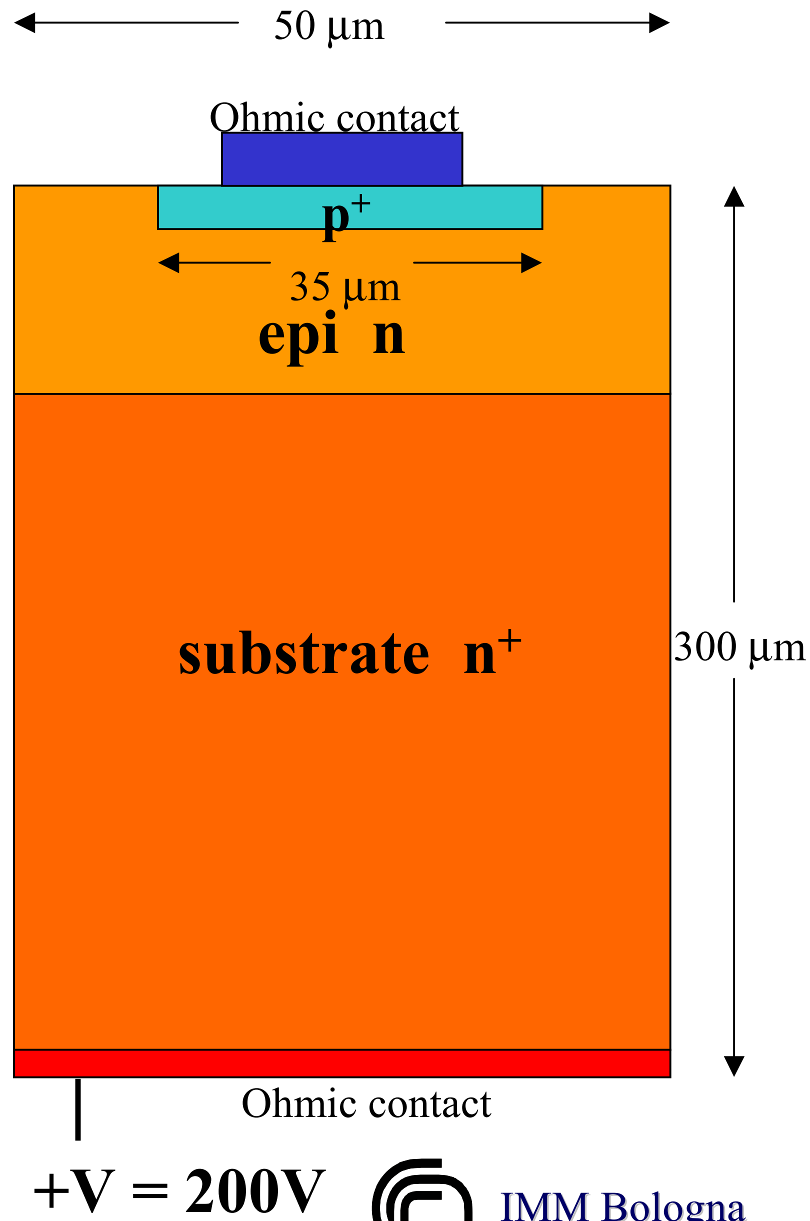


- Signal: 3 completely depleted diodes:
  - 10 μm → 500 e/h pairs ,
  - 20 μm → 1000 e/h pairs ,
  - 300 μm → 15000 e/h pairs
- Noise: agreement between measured and simulated leakage current densities
- Calibration with experimental CCE from a MIP still to be done (data are not yet published)

Model parameters

Electron mobility (cm^2/Vs)	380
Hole mobility (cm^2/Vs)	70
Relative dielectric constant	9.66
Intrinsic concentration n_i @300K (cm^{-3})	1.6×10^{-6}
Saturation velocity (cm/s)	2×10^{7}
Electron lifetime (ns)	100
Hole lifetime (ns)	20

Test diode



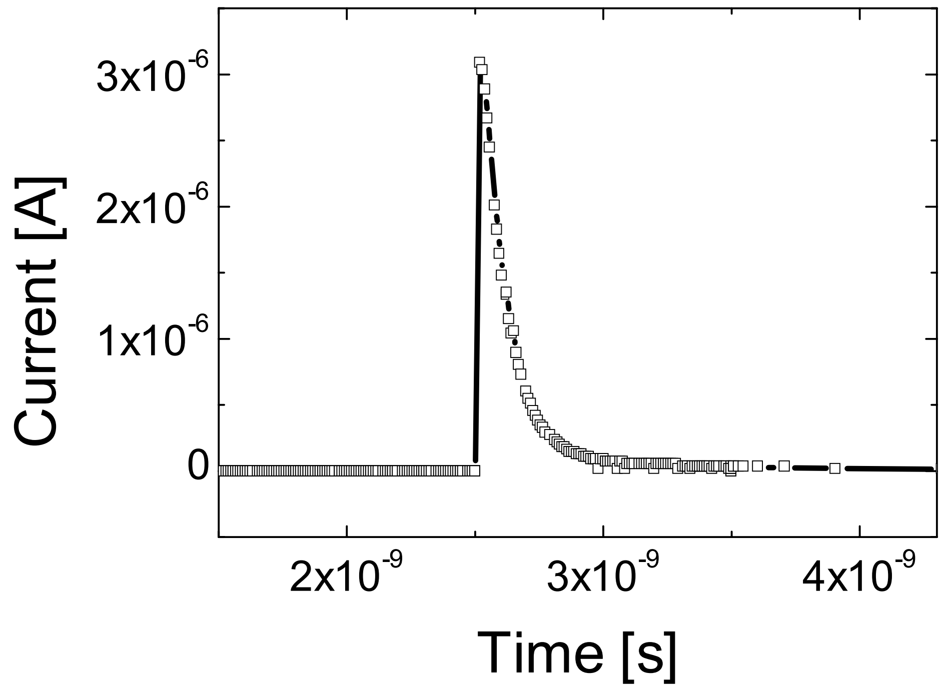
- p+/n diode
- 4 technological parameters:
  - p+ depth between **0.45** and **3** µm
  - p+ doping between **10^{18}** and **10^{20}** cm^{-3}
  - epi doping between **10^{14}** and **10^{15}** cm^{-3}
  - n epi thickness between **10** and **40** µm

p^+/n diode output signal

- Collected Charge

$$CC = \int_0^t I \cdot dt$$

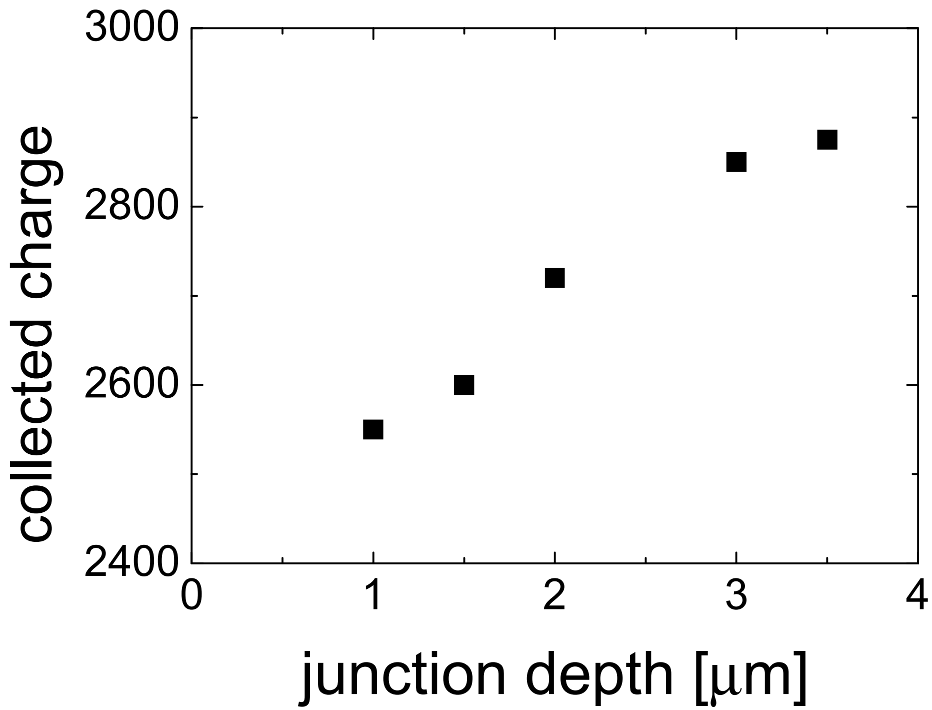
- Particle crossing at 2.5 ns



epi doping (40 μm) = 10^{15} cm^{-3}
p^+ doping (0.45 μm) = 4×10^{19} cm^{-3}

Collected Charge vs. junction depth

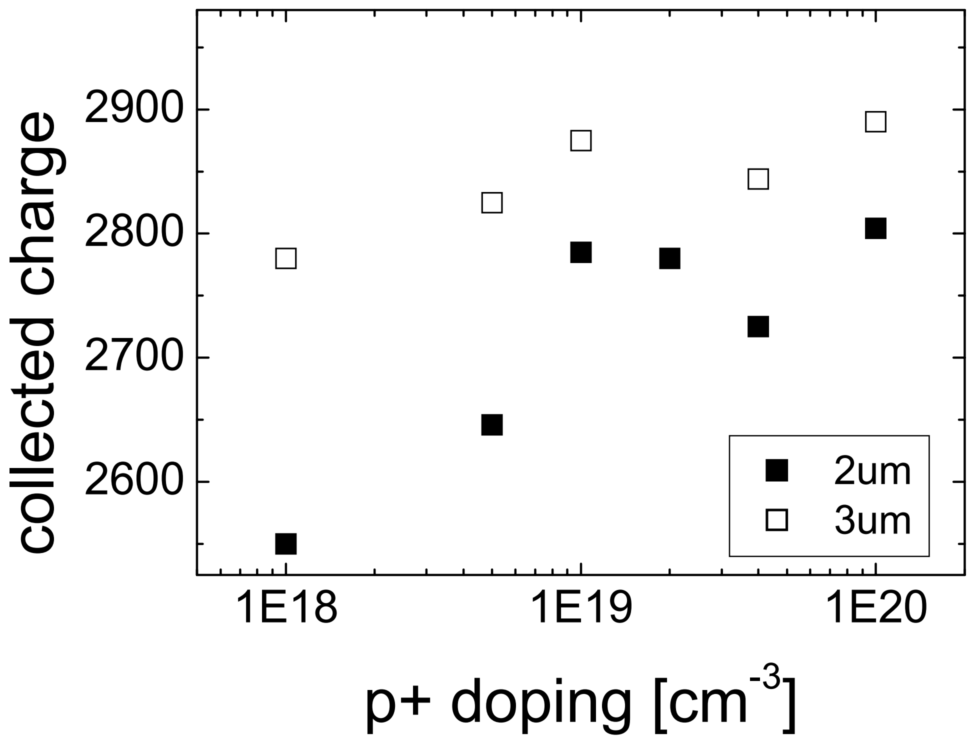
- Epitaxial layer:
  - thickness = 40 μm
  - doping = 10^{15} cm^{-3}
- p^+ doping = 4×10^{19} cm^{-3}
- CC increase due to:
  - 51 e/h pairs per μm
  - minority carrier diffusion length ≥ than junction depth



- Note: the charge generated in the epi layer is about 2000 e/h ⇒ charge collection from the substrate! Calibration problem still to be solved (also present in next slides)

Collected Charge vs. p^+ doping

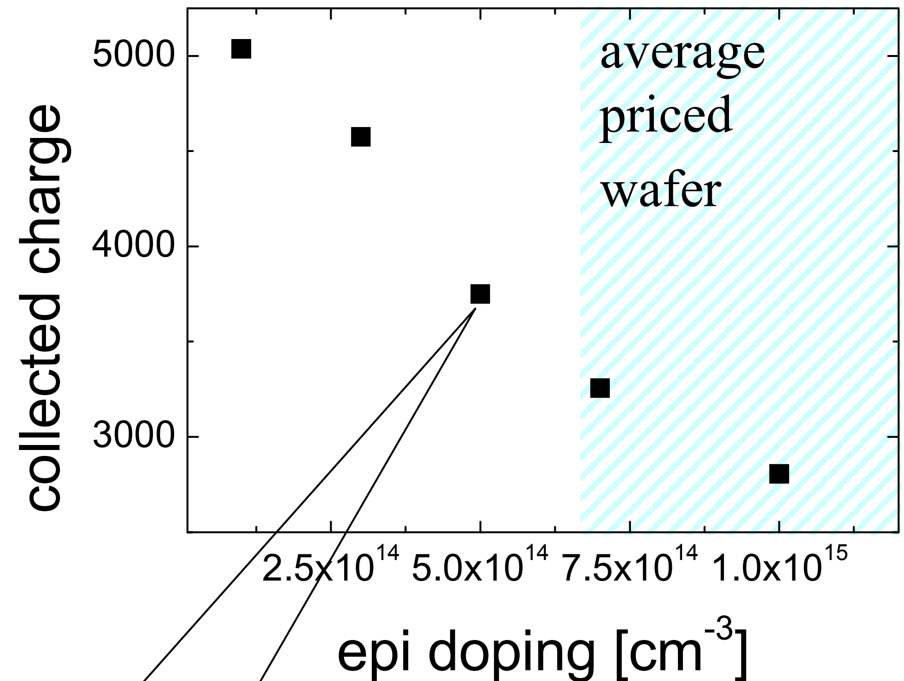
- Epitaxial layer:
  - Thickness = 40 μm
  - doping = 10^{15} cm^{-3}
- junction depth:
  - 2 μm and 3 μm
- Reasons for increase at small junction depth not well understood so far



Collected Charge vs. epi n doping

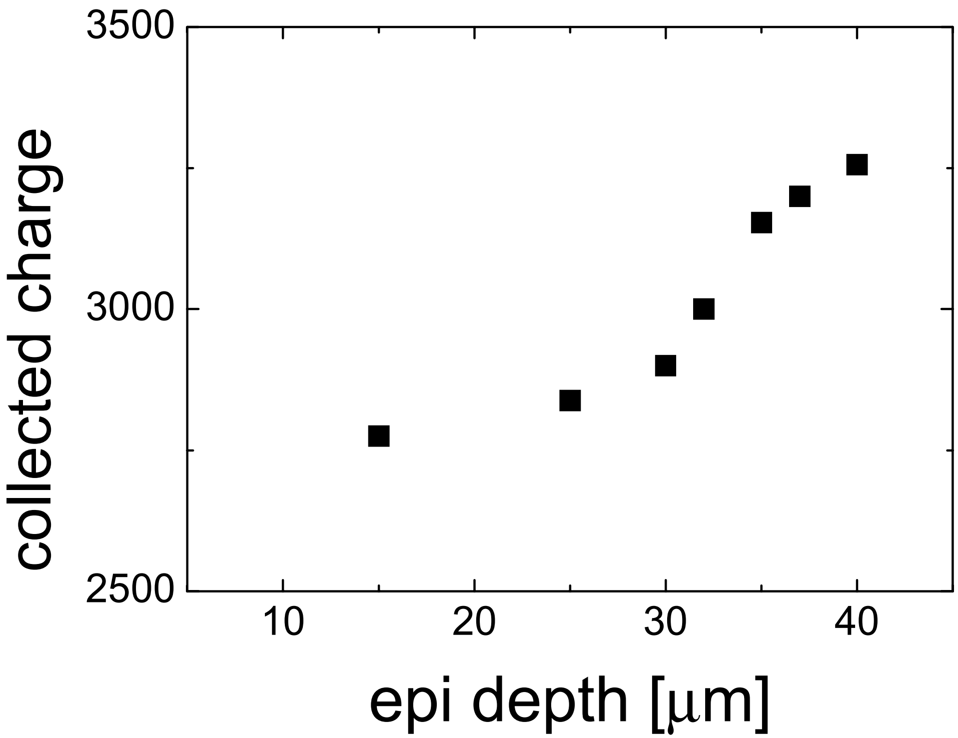
- epi thickness = 40 μm
- junction depth = 2 μm

  p^+ doping = 4×10^{19} cm^{-3}
- CC decrease to:
  – decrease of depleted region for constant V_R
  – transient behavior of the CC due to displacement current $\varepsilon_0 \cdot dE/dt$



Depleted region: 15 μm

Collected Charge vs. epi n depth



- Epi doping = 7×10^{14} cm^{-3} (depletion depth 12 μm)
- Junction depth = 2 μm
  p^+ doping = 4×10^{19} cm^{-3}
- CC increase might be due to:
  - smaller recombination likelihood
  - transient behavior of the CC due to displacement current $\varepsilon_0 \cdot dE/dt$

Conclusions

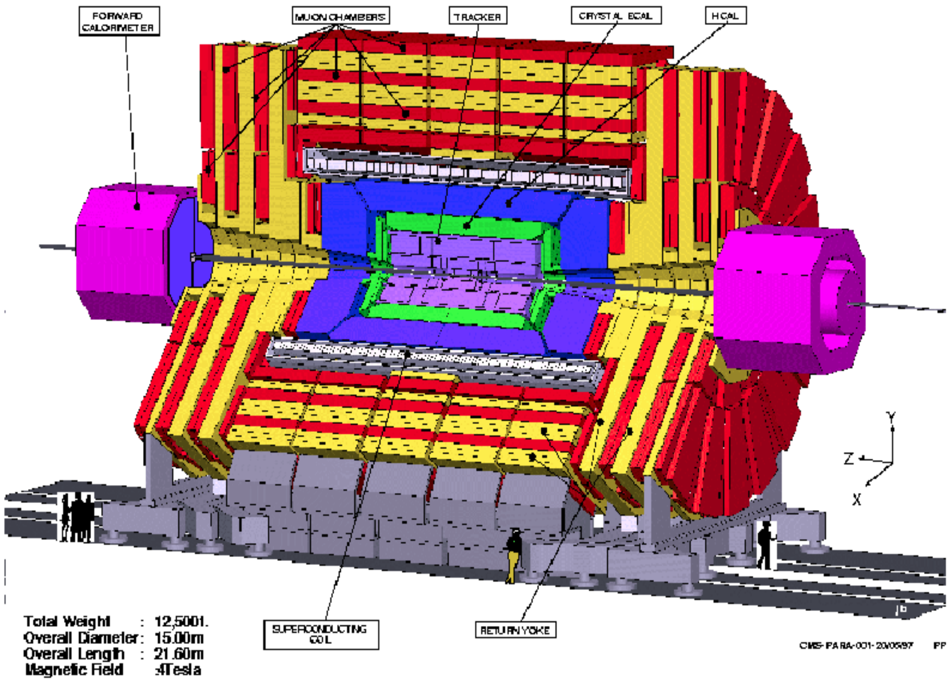
- p^+/n junctions have been realized and electrically characterized. Good forward and reverse characteristics have been obtained
- SiC detectors have been analyzed and simulated:
  - charge collection from the substrate. Calibration problem still to be solved;
  - technological parameters have been studied. The epi doping and the epi depth are the most important parameters. junction depth is also an important parameter;
  - an average price wafer seems to be suitable for the realization of a SiC detector.

Future developments

- Analysis of the lateral crossing of a MIP
- DLTS and CCE analysis will be carried out on the realized diodes and results will be compared with the simulations
- Radiation hardness will be verified
- New SiC detectors will be realized taking into account the simulation results

Appendix

Experiments at CERN



- Large Hadron Collider (LHC) experiment (upgrade)
- Fast hadron fluences above 10^{16} cm^{-2} (after 10 years)
- Current silicon technology is unable to cope with such an environment
  - Unreachable full depletion voltage
  - Very high leakage current
  - Poor charge collection efficiency

Silicon Detectors

- Minimum Ionizing Particle (MIP) generates in Si 80÷90 e/h pairs per micron