LGAD Development at Teledyne e2v for the LHC's High-Luminosity (HL) Upgrade

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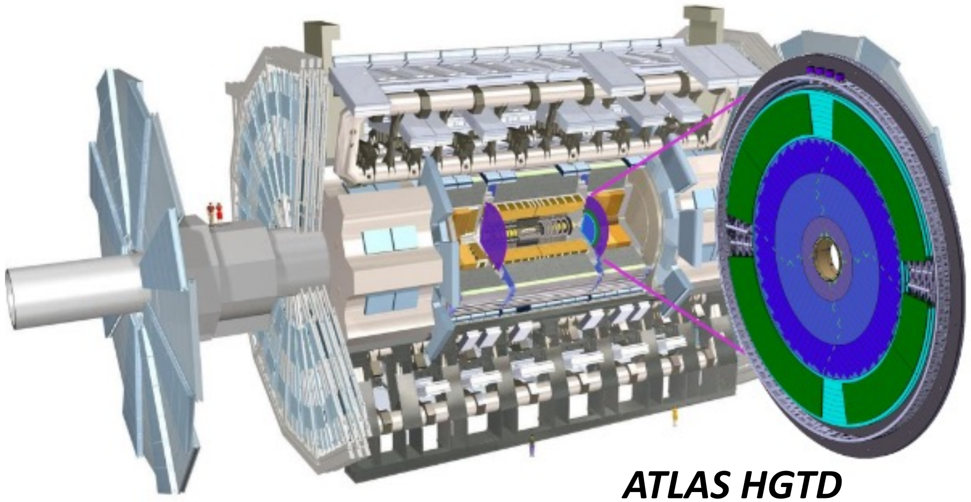
TELEDYNE e2v Everywhereyoulook™

Outline

- Introduction: Ultra Fast Silicon Detectors
- Project overview: LGADs manufactured by Teledyne e2v
- LGAD Simulation
- Wafer characterization: IV and CV
- Inferred doping density
- Dicing and post-dicing treatment
- Summary

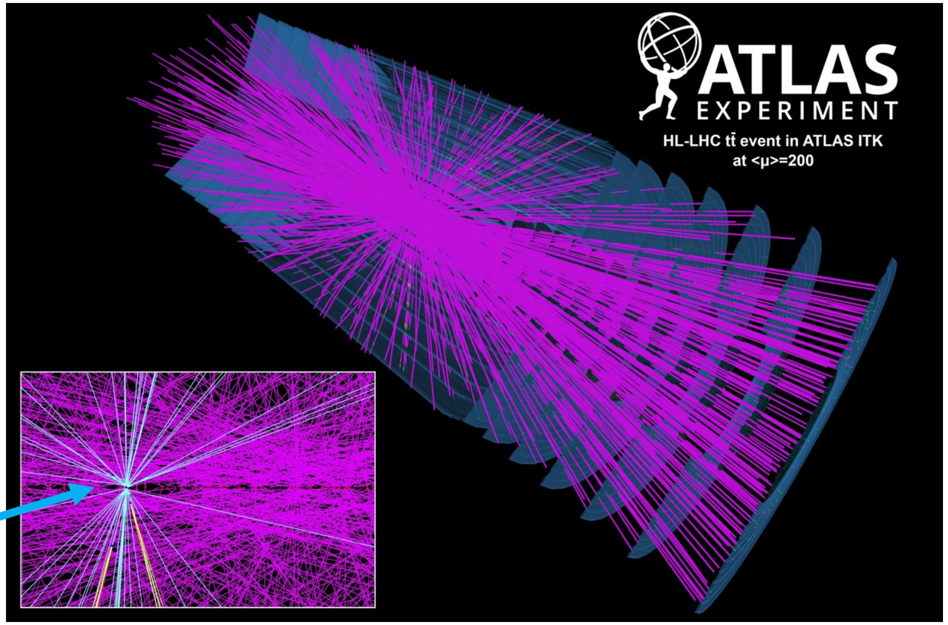
The need for Ultra Fast Silicon Detectors

- HL-LHC: Pile-up is one of the major challenges for tracking
- Detectors with high granularity for spatial measurement with added high resolution time measurement (4D tracking)
- Timing information used to disentangle overlapping events
- ATLAS High-Granularity Timing Detector placed outside the ITk



ATLAS HGTD

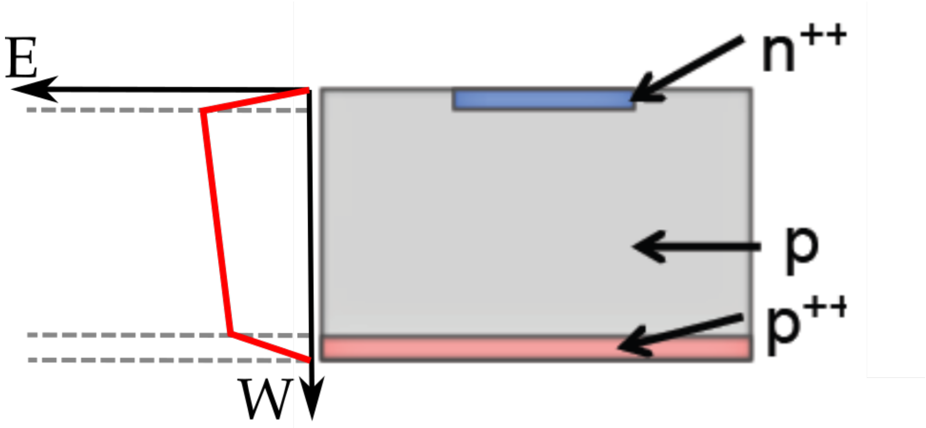
1 pp interaction amongst 200



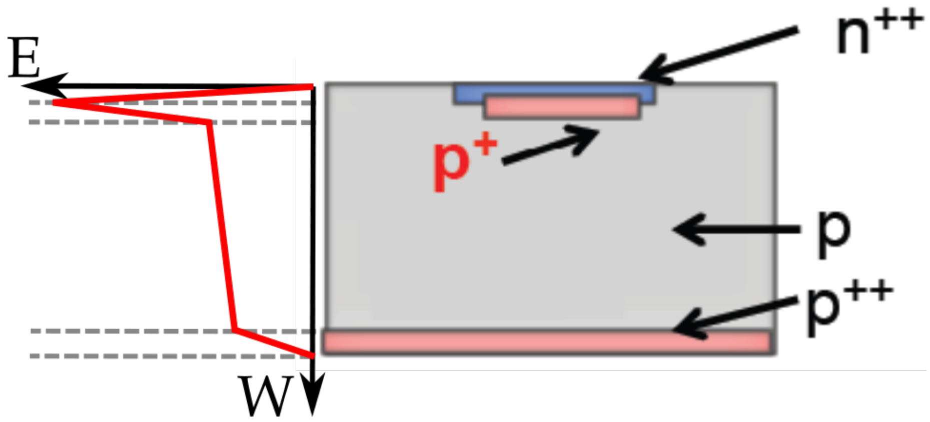
Low Gain Avalanche Detectors (LGAD)

- Aim: Track timing resolution of ≈30-50 ps over detector lifetime
- Boron implantation forms gain layer (p^+) -> impact ionization
- Time resolution of LGAD benefits from high slew rate, which is increased by introducing internal gain G

PiN diode

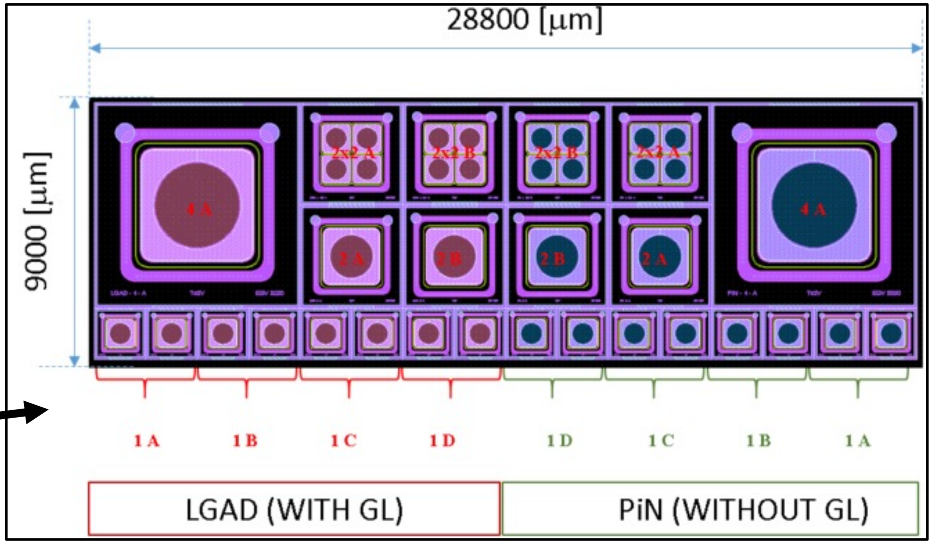


LGAD

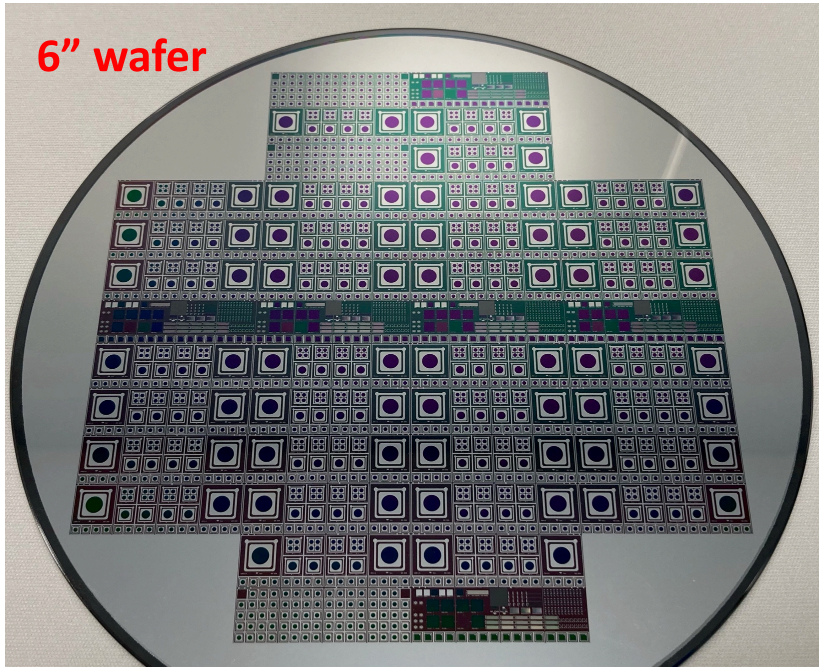


Teledyne e2v LGAD project

- Epitaxial layer: 50 um, high resistivity
- Boron as the gain layer dopant
  - 8 different combinations of manufacturing parameters
- Each field contains LGADs and PiN diodes of the same layout (4 mm, 2 mm, 1 mm)

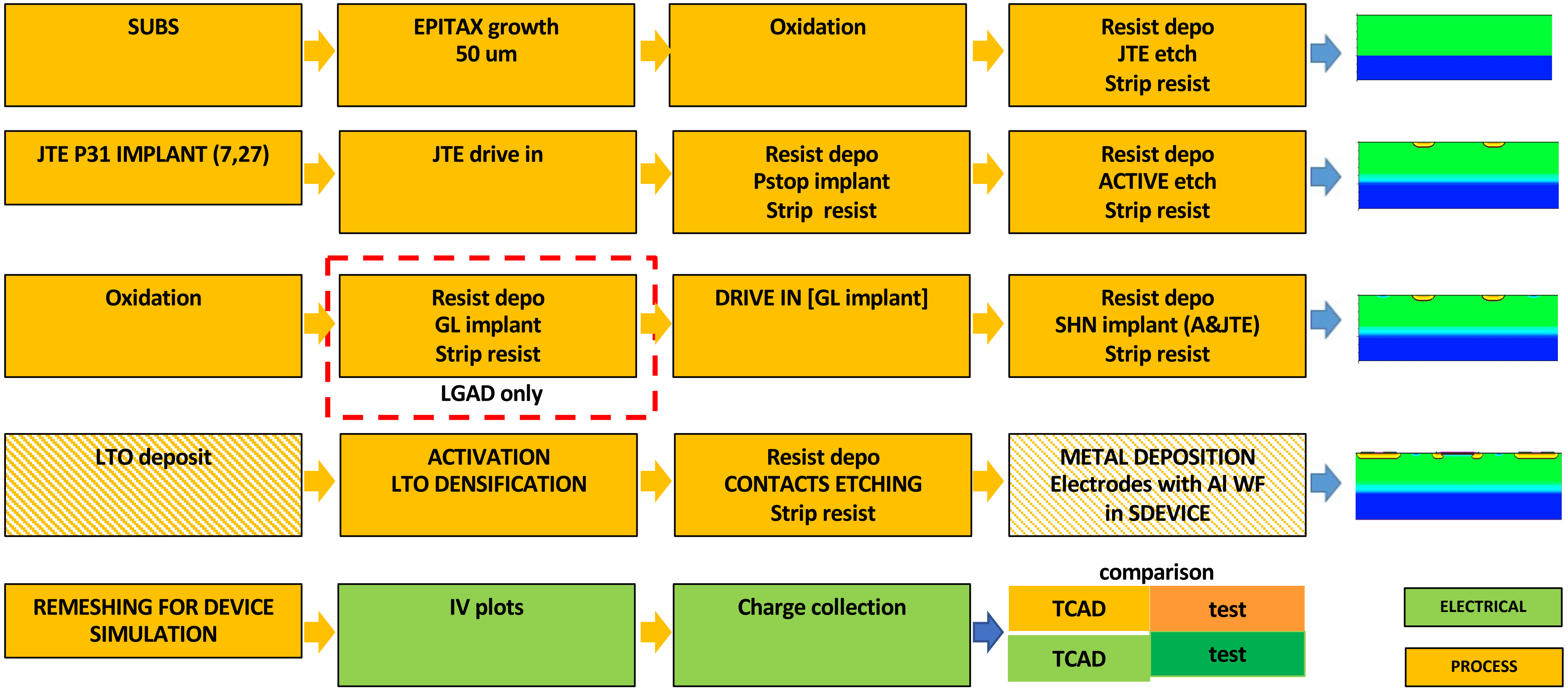


Wafer code	Implant dose (normalised)	Implant energy (normalised)
A	1.07	1.11
B	1.07	1.05
C	1.07	1.00
D	0.92	1.05
E	1.15	1.05
F	1.00	1.00
G	1.00	1.05
H	1.00	1.11



LGAD Simulation I

- Fabrication steps of the devices simulated using TCAD tool from Synopsis



PROCESS flowchart

SUBS → EPITAX growth 50 um → Oxidation → Resist depo JTE etch Strip resist

JTE P31 IMPLANT (7,27) → JTE drive in → Resist depo Pstop implant Strip resist → Resist depo ACTIVE etch Strip resist

Oxidation → Resist depo GL implant Strip resist (LGAD only) → DRIVE IN [GL implant] → Resist depo SHN implant (A&JTE) Strip resist

LTO deposit → ACTIVATION LTO DENSIFICATION → Resist depo CONTACTS ETCHING Strip resist → METAL DEPOSITION Electrodes with Al WF in SDEVICE

REMESHING FOR DEVICE SIMULATION → IV plots → Charge collection → comparison

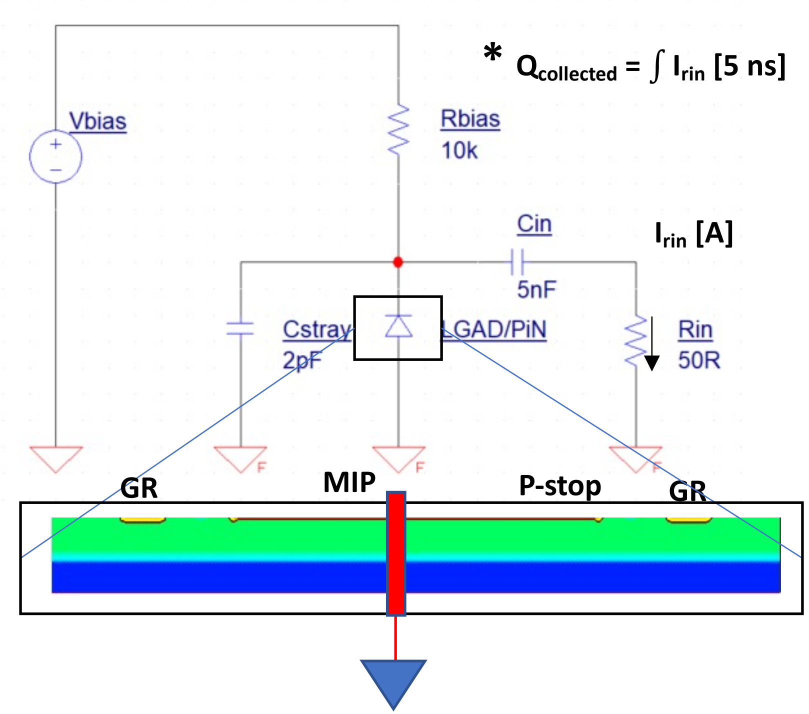
TCAD	test
TCAD	test

ELECTRICAL

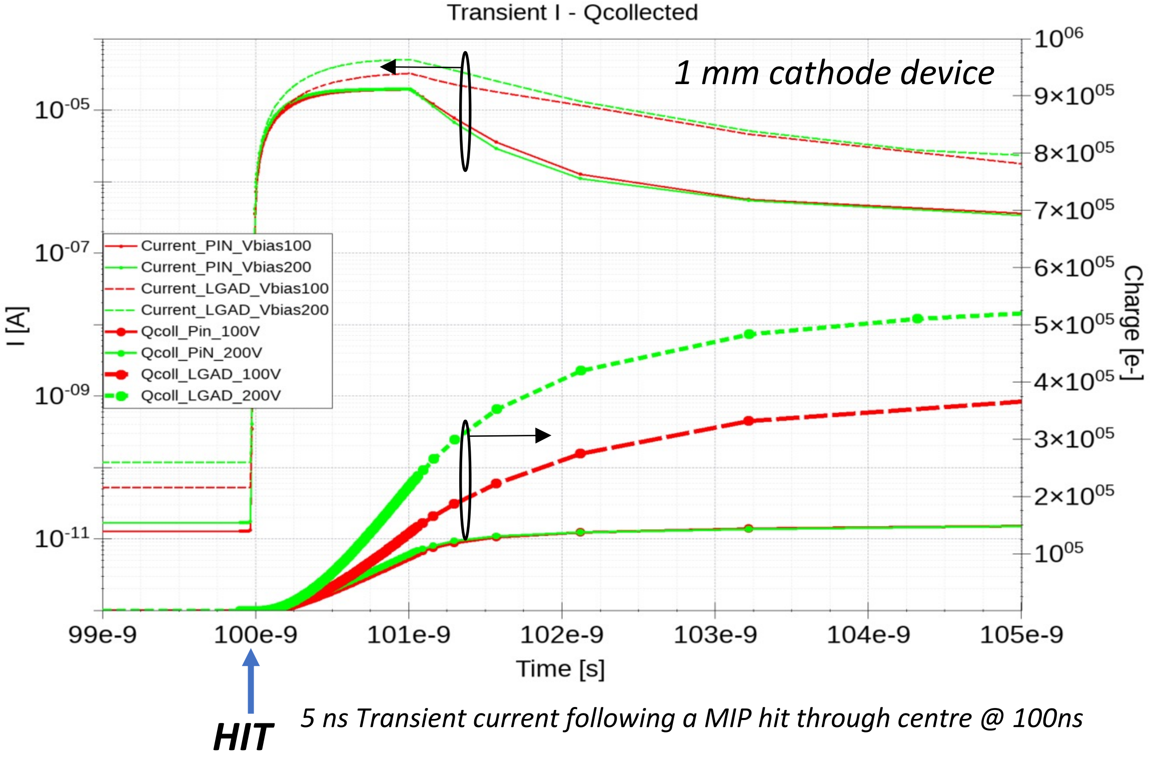
PROCESS

LGAD Simulation II

- Electrical simulation setup, common to PiN and LGAD, with RC network



* $Q_{collected} = \int I_{rin}$ [5 ns]



1 mm cathode device

5 ns Transient current following a MIP hit through centre @ 100ns

- Bulk radiation damage not included in this iteration, but effects of Si-SiO_2 surface states have been modelled

Wafers of interest

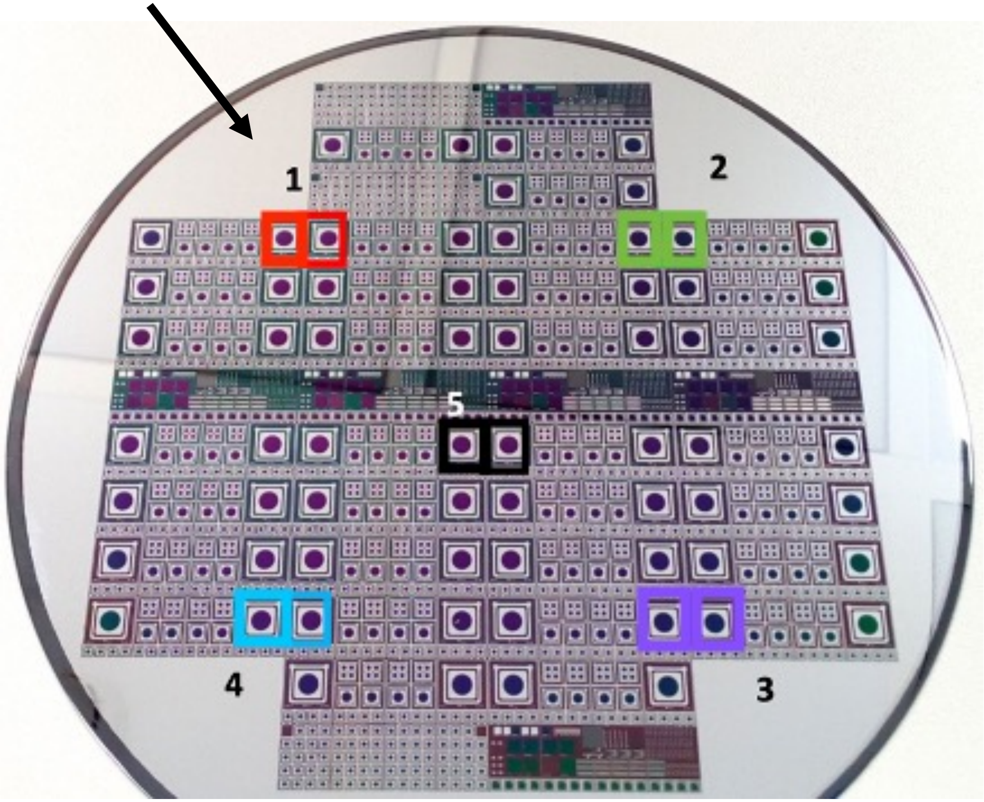
- Variation of behaviour with implant energy (dose constant)

Wafer code	Implant dose (normalised)	Implant energy (normalised)
A	1.07	1.11
B	1.07	1.05

Parameters normalised to a reference dose and energy of the implant

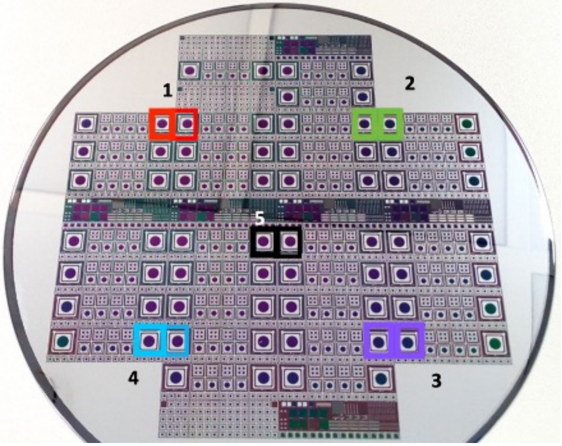
Measured 5 LGADs and 5 PiNs

(consistent colour coding used throughout)

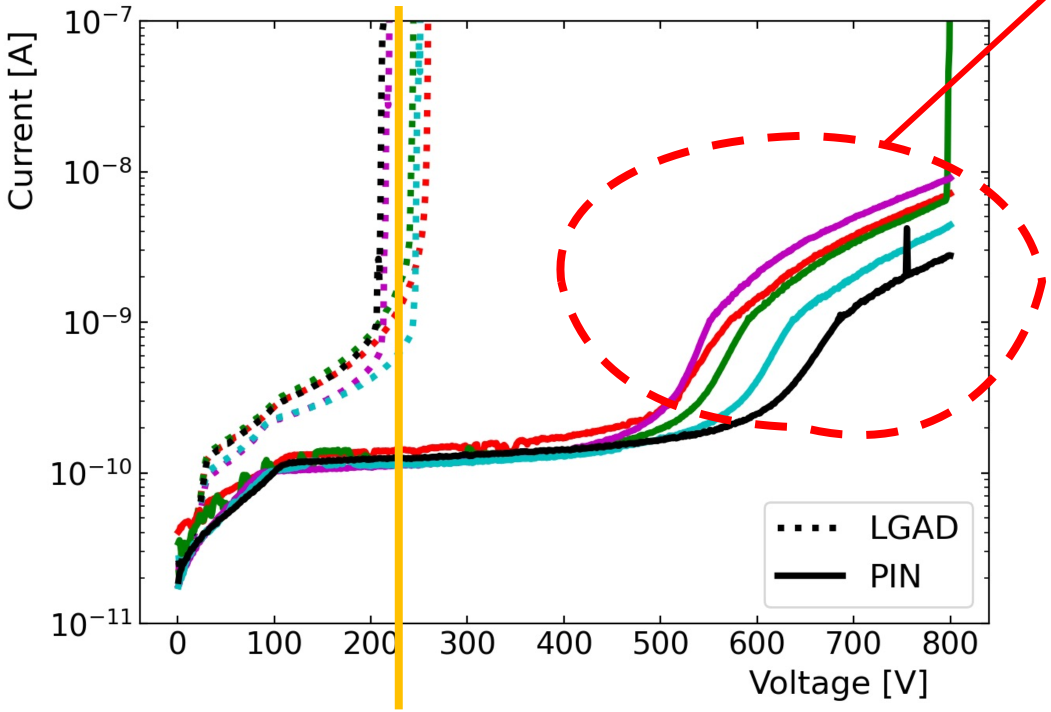


Characterization of wafers – IV data

4 mm devices

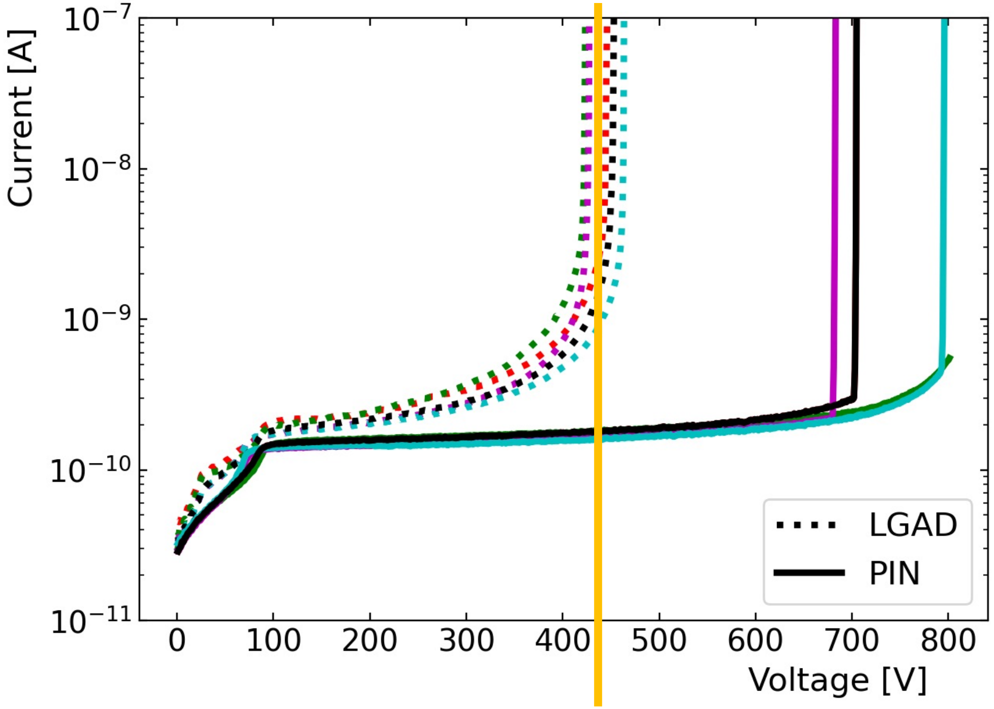


Wafer A (higher implant energy)



"soft-breakdown"

Wafer B

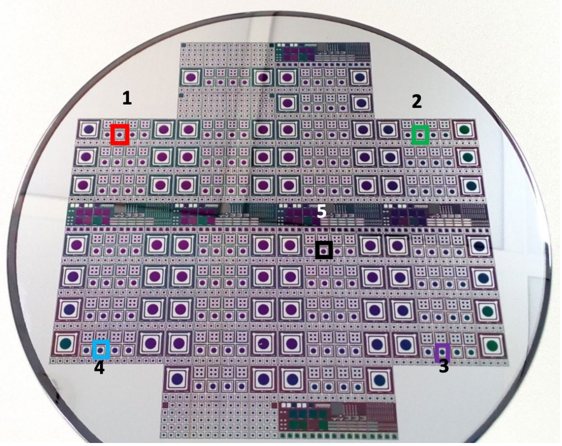


T = 21°C

LGAD breakdown voltage ≈250 V

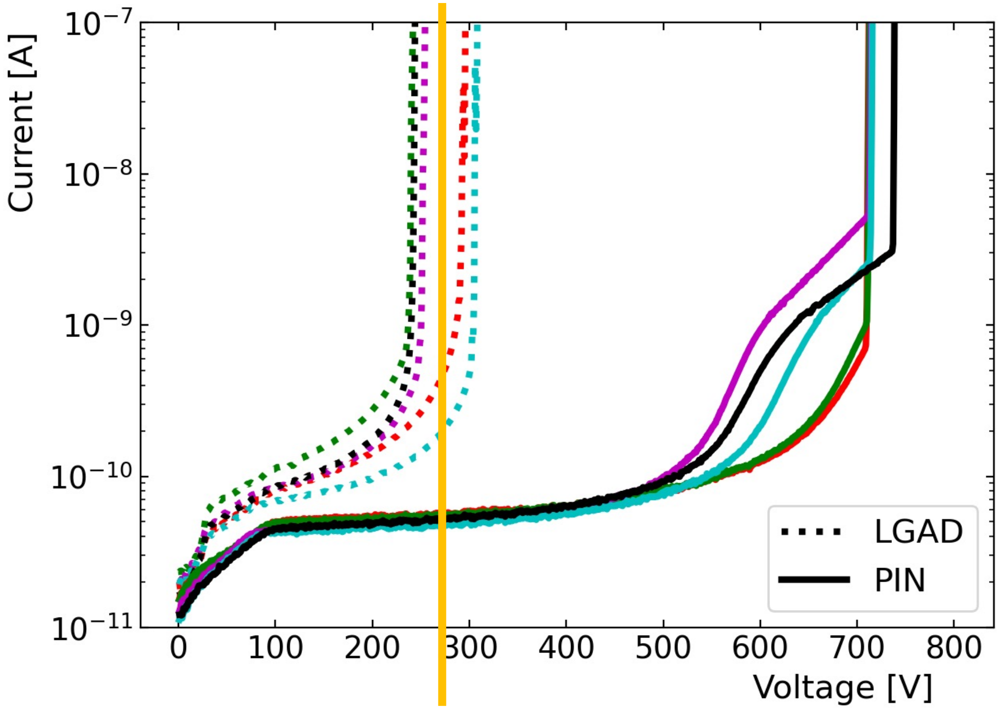
LGAD breakdown voltage ≈450 V

Characterization of wafers – IV data



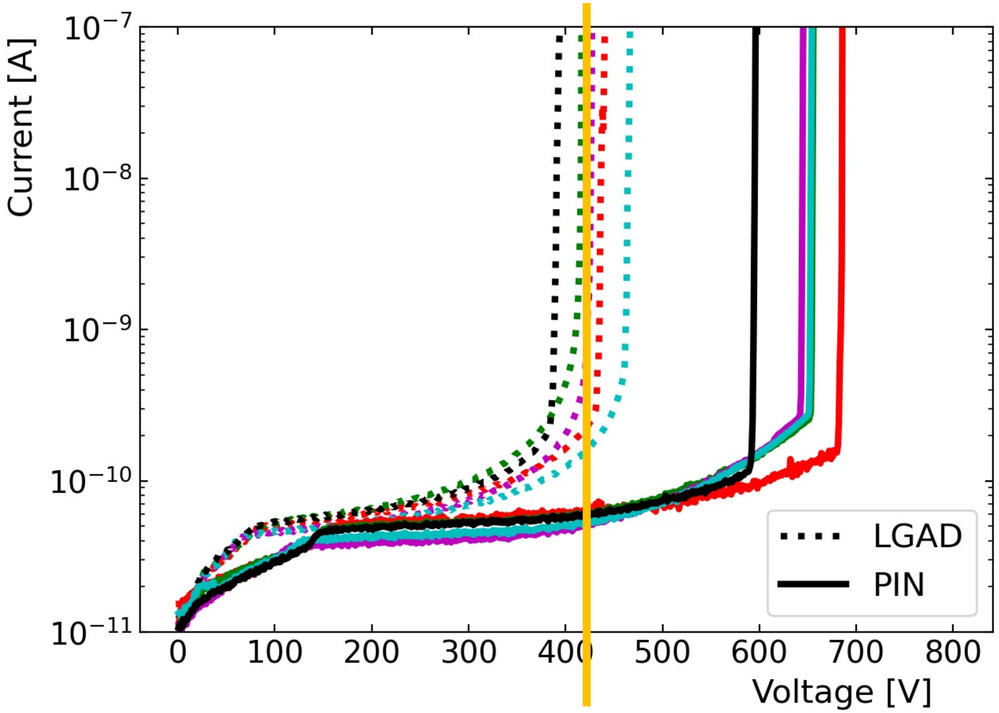
2 mm devices

Wafer A (higher implant energy)



LGAD breakdown voltage ≈280 V

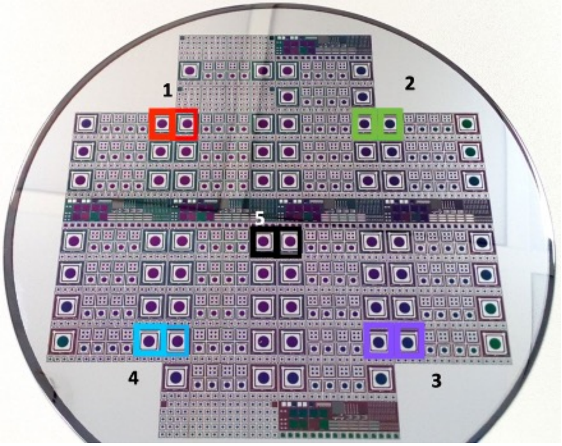
Wafer B



LGAD breakdown voltage ≈420 V

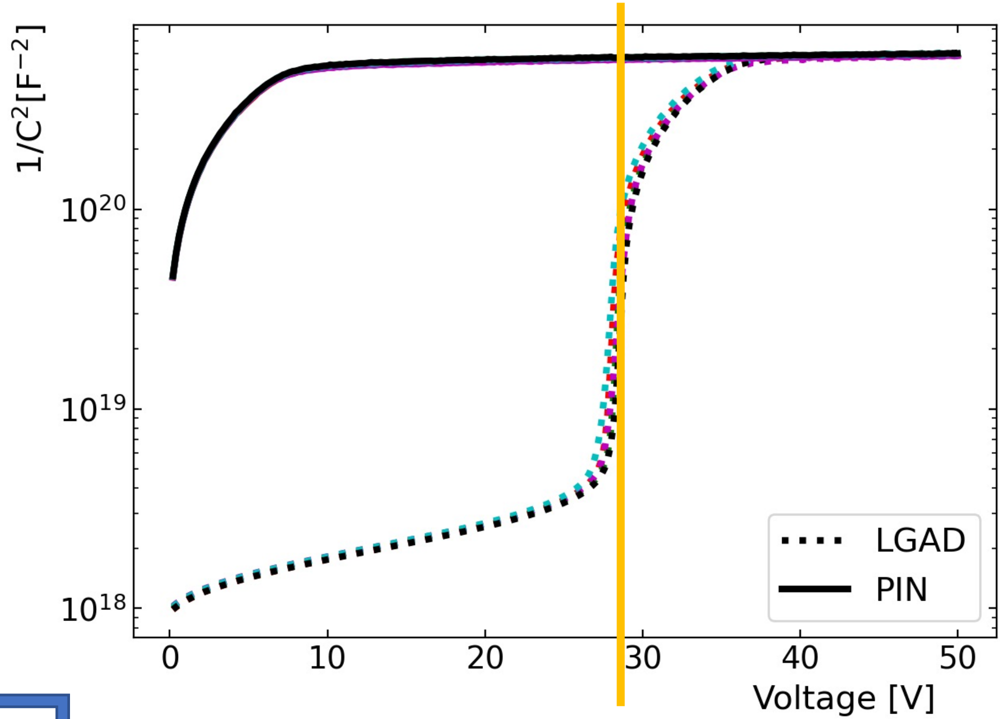
T = 21°C

Characterization of wafers – CV data



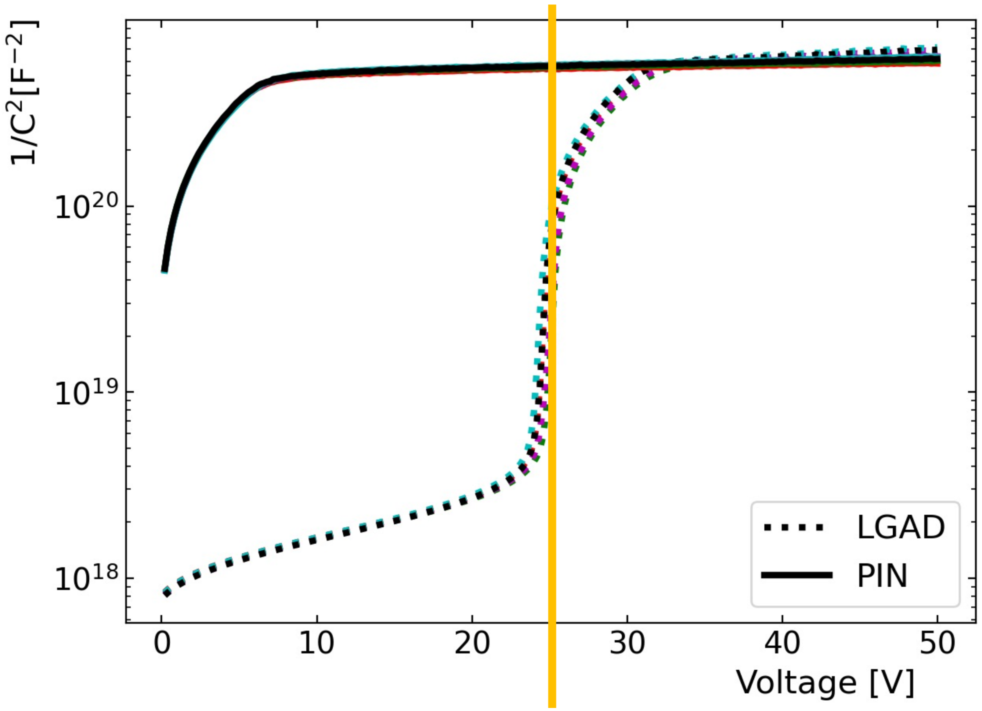
4 mm devices

Wafer A (higher implant energy)



Gain layer depletion voltage ≈30 V

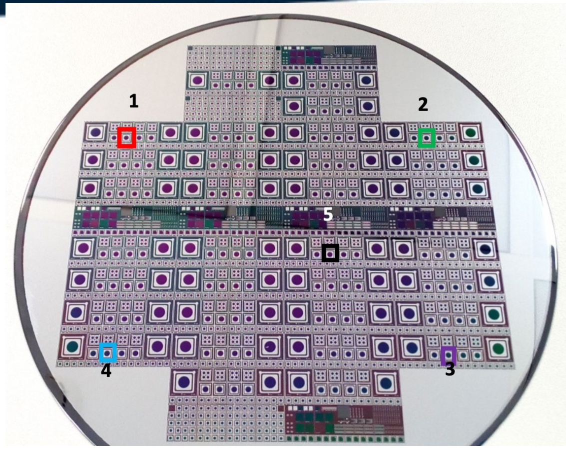
Wafer B



Gain layer depletion voltage ≈25 V

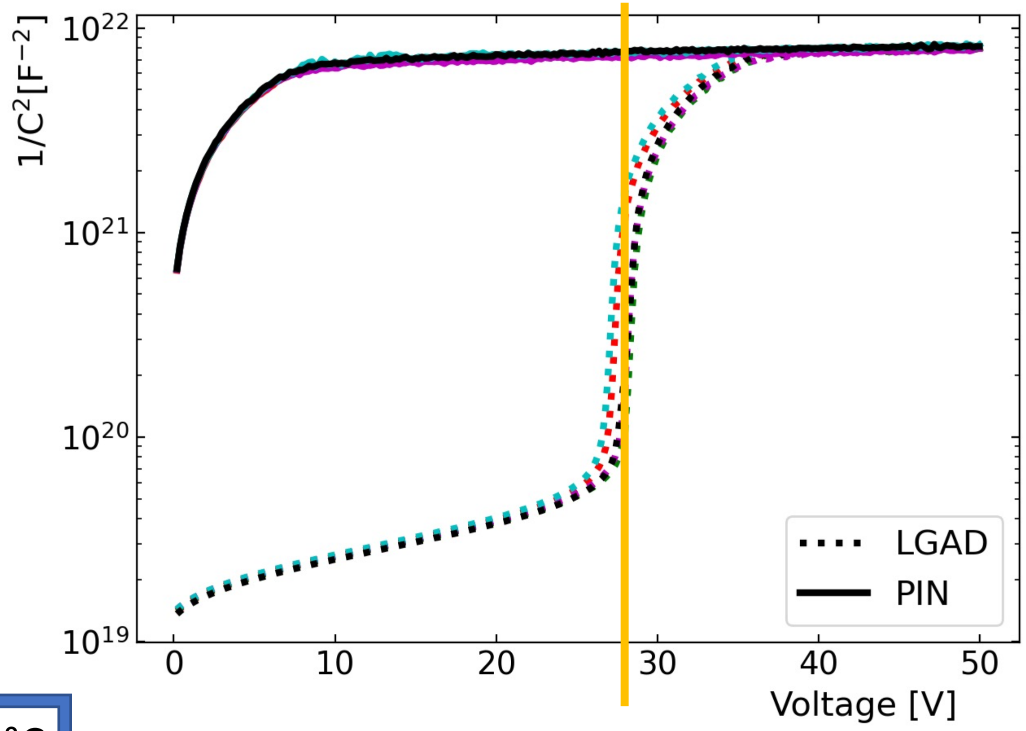
T = 21°C

Characterization of wafers – CV data



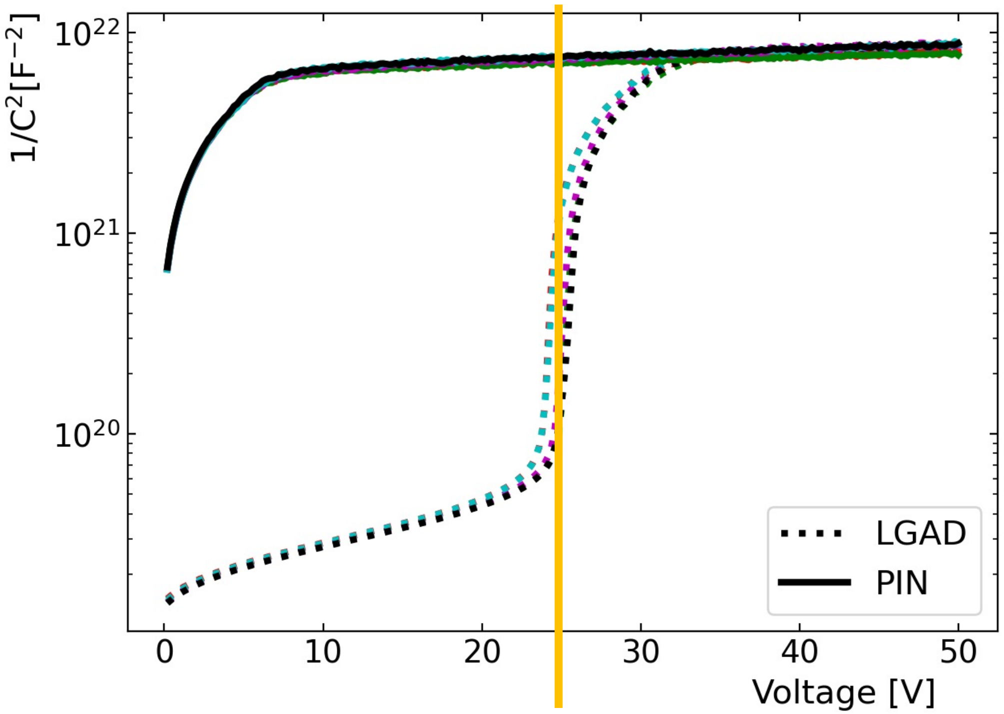
2 mm devices

Wafer A (higher implant energy)



Gain layer depletion voltage ≈30 V

Wafer B



Gain layer depletion voltage ≈25 V

T = 21°C

Concentration inference

- Inferred from capacitance measurement using Profiler’s Equation

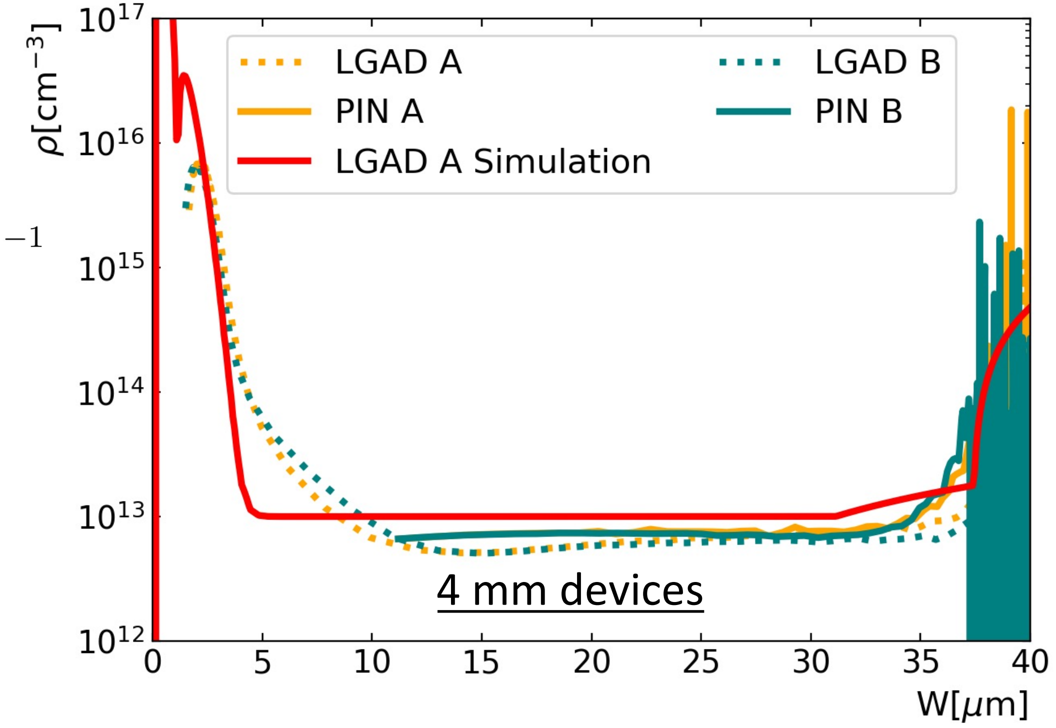
Relates to majority carrier density rather than doping

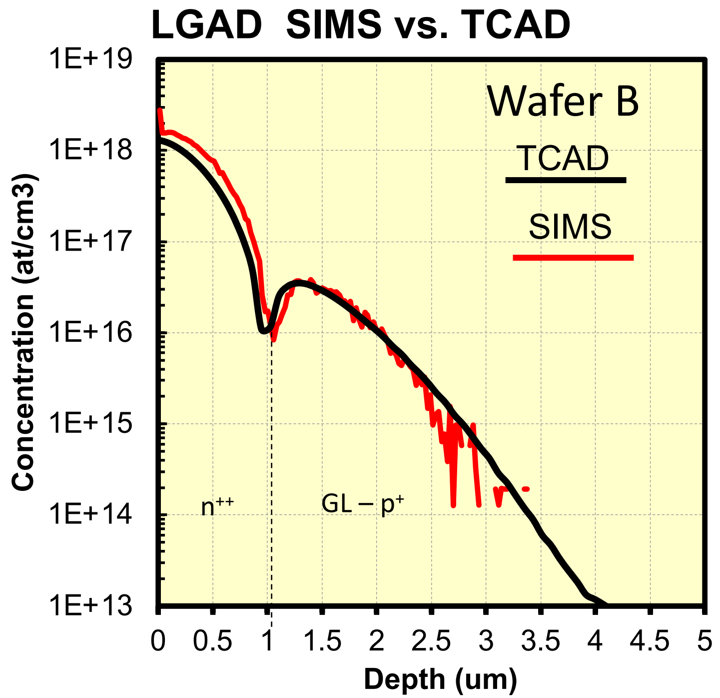
Doping density:

$$\rho = \frac{2}{A^2 e\epsilon\epsilon_0}\left(\frac{d(1/C^2)}{dV}\right)^{-1}$$

at depth (from n^{++} layer):

$$W = \frac{\epsilon\epsilon_0 A}{C}$$



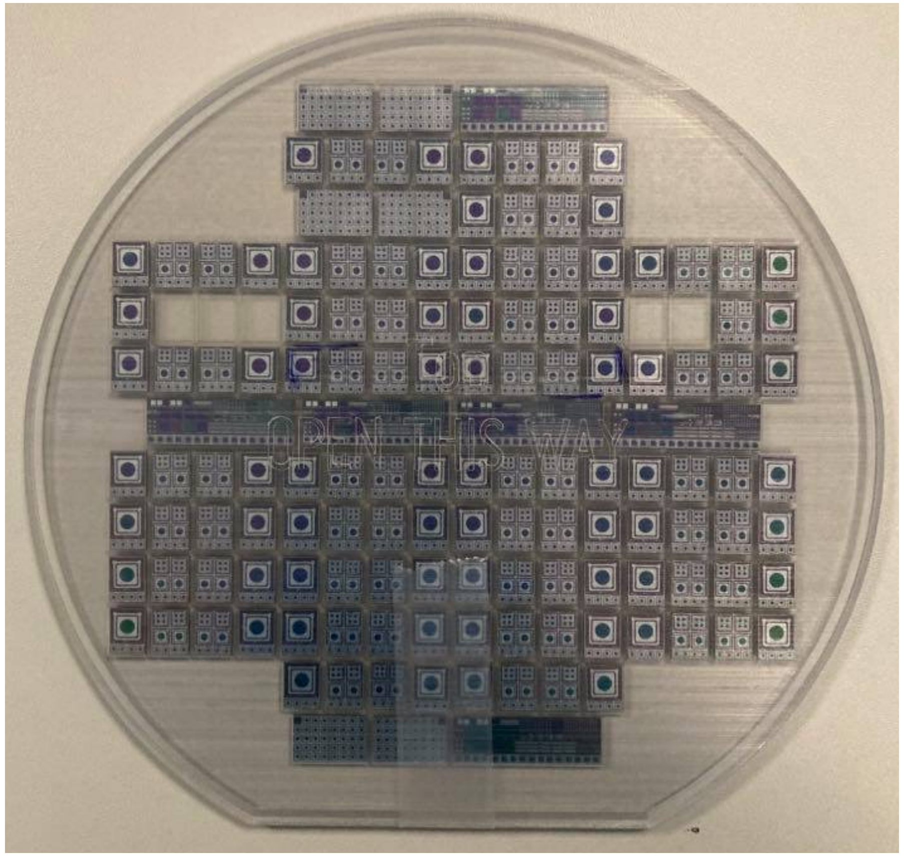


Comparison of simulation data and Secondary-ion mass spectrometry (SIMS)

Laser dicing of wafers

- Laser dicing
  - λ = 1028 nm
  - Power: 10 W
  - Beam size: 25 x 25 um^2

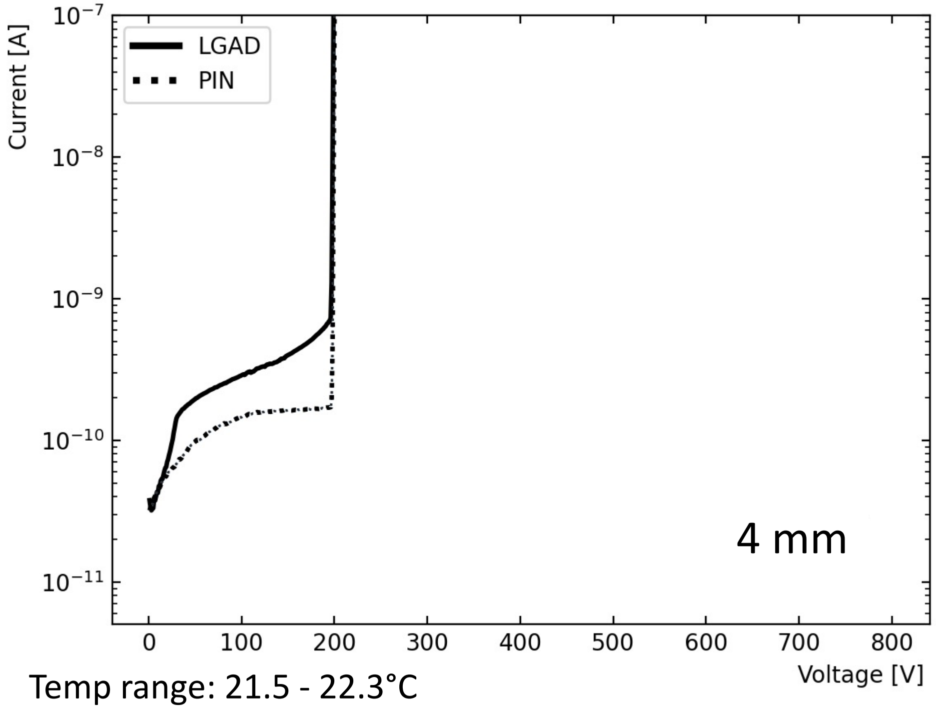
Custom-made 3D printed frame to keep sensors in place and allow for direct comparison pre- and post-dicing



Post-dicing treatment - thermal annealing

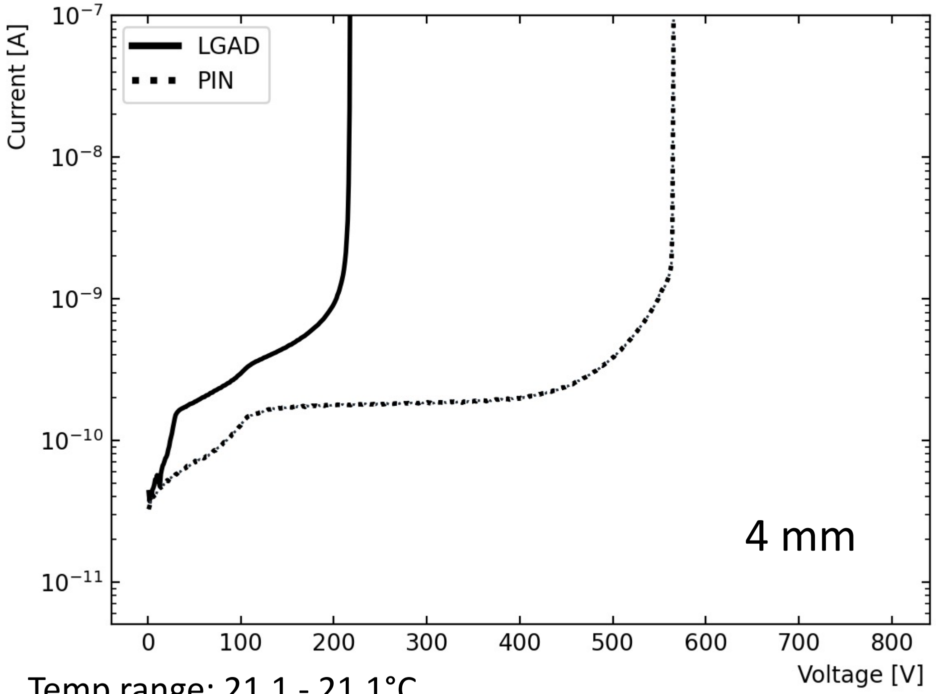
- Suspected surface states formed after wafer dicing
  - Detrimental effects: lower breakdown voltage, soft-breakdown behaviour
- Previous behaviour recovered by thermal annealing (conditions: 2 hours at 150°C)

Before annealing



Temp range: 21.5 - 22.3°C
Humidity range: 35.9 - 40.8%

After annealing



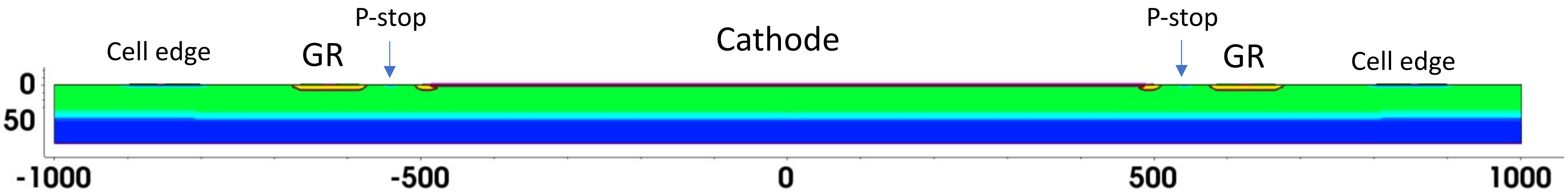
Temp range: 21.1 - 21.1°C
Humidity range: 44.5 - 46.8%

Summary

- Ultra-fast silicon detectors required for 4D tracking and disentanglement of overlapping interactions
- First batch of LGAD devices designed, simulated and produced in collaboration with Teledyne e2v
  - Devices being tested at Oxford, Birmingham and Rutherford Appleton Laboratory
- Observed that higher gain layer implant energy leads to lower breakdown voltage and higher gain layer depletion voltage
- Post-dicing treatment required (thermal annealing)

More on irradiation and gain measurements can be found in the presentation by Jonathan Mulvey @14:45 (CERN time)

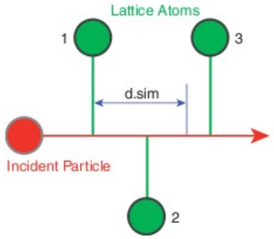
Backup – Simulated cross-section



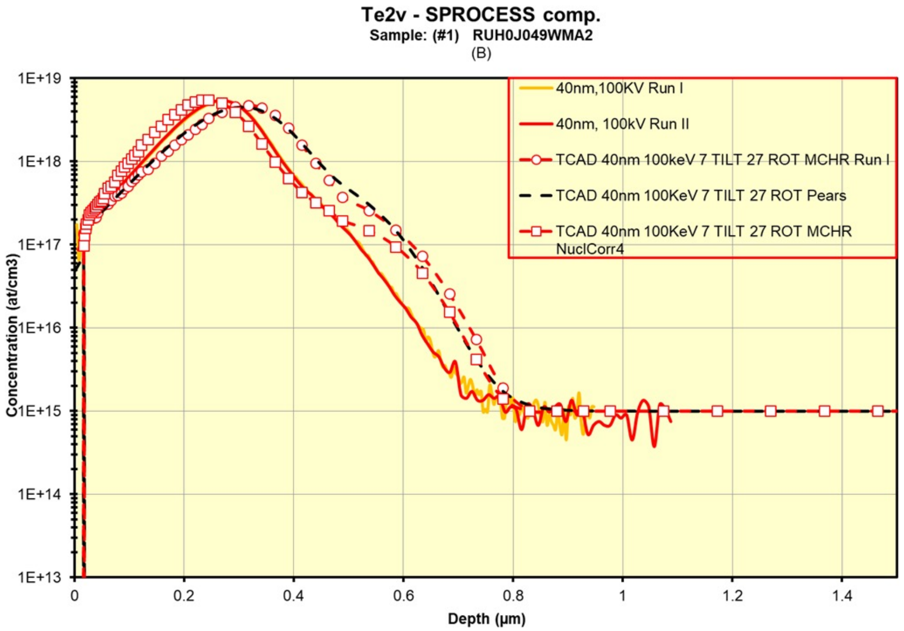
- **2 implantation models implemented:**
  - **MC (1e5 runs) using BCT with modified parameters**
  - **Pearson IV (analytical)**

$$\frac{\Delta E_n}{E_0} = \frac{4M_1M_2}{(M_1+M_2)^2}\cos^2(bI) \quad \mathrm{x}\alpha$$

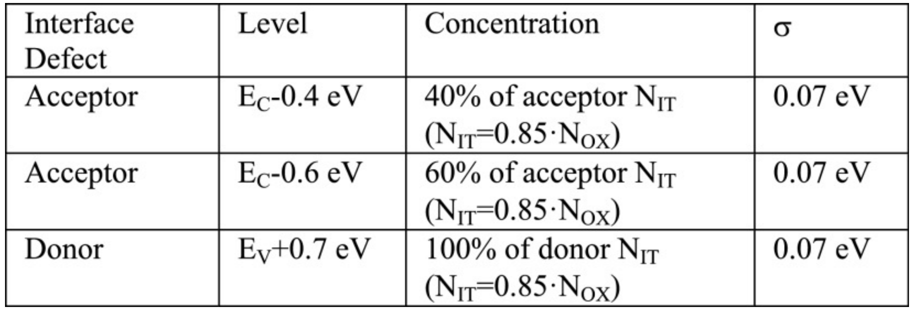
E lost by BC by Nucl. Scattering custom factor α (=1 default)



Multi-body collisions for crystal [0.25,1] lattice constant assume d=1

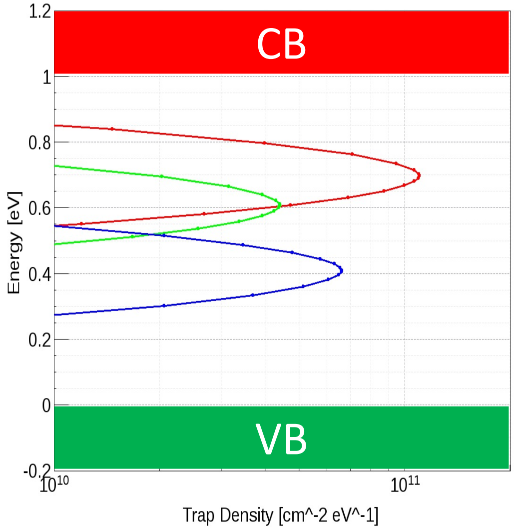


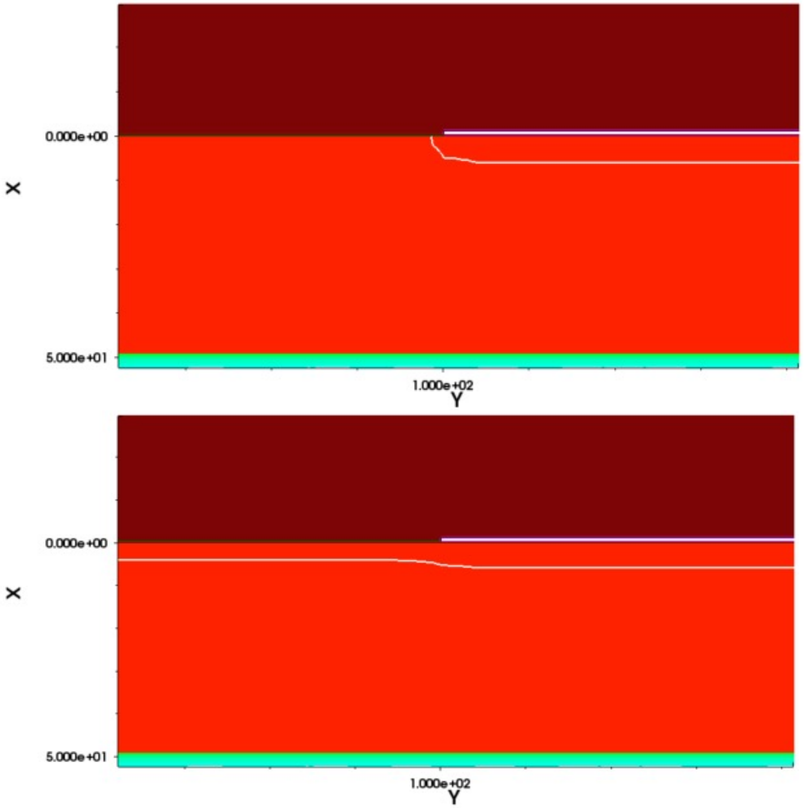
Backup – Traps inclusion



Interface Defect	Level	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV

* ***Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC**, DOI:* 10.1109/TNS.2017.2709815

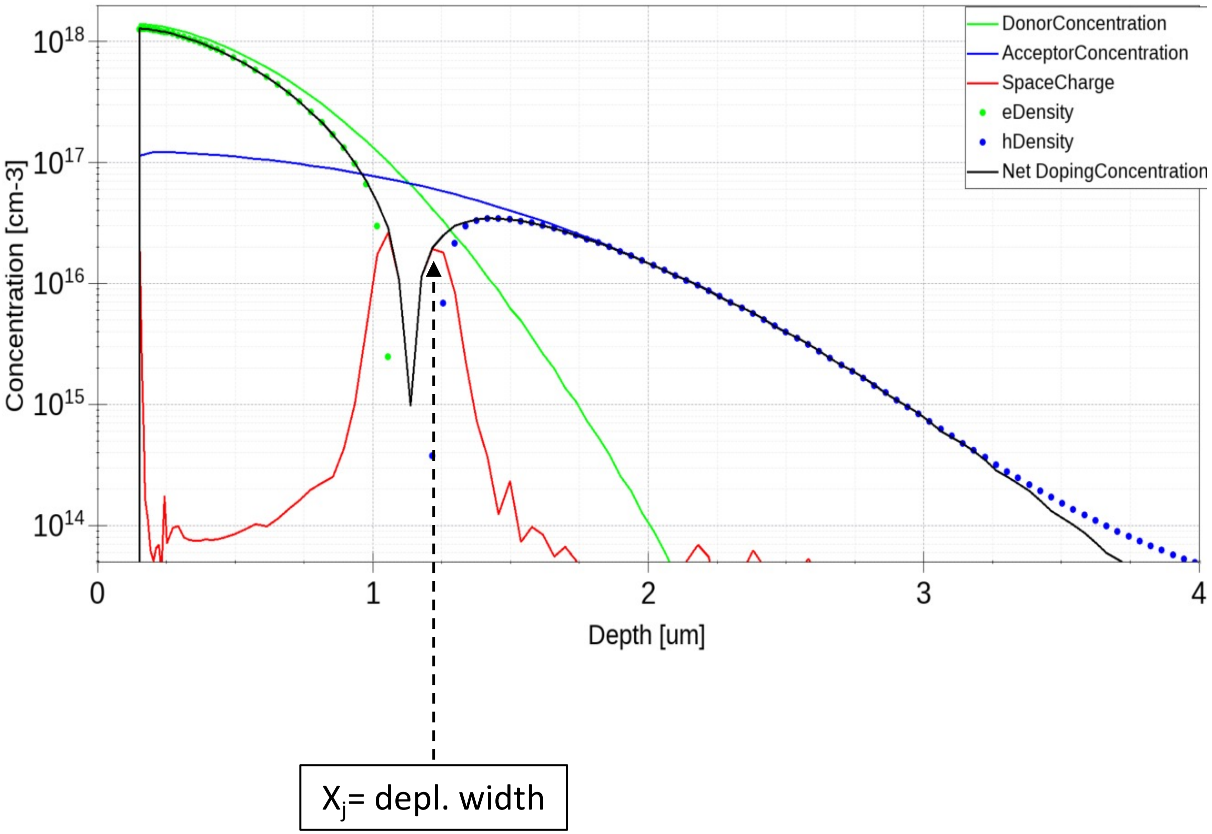




Fixed oxide-charge density and interface traps included
Interface traps distributed among 3 energy levels,
Gaussian , σ = 70 meV
Ratio Oxint/Oxch ~ 0.9

Backup – CV profiling and doping I

- Plots of doping and carriers concentration for WF2 at V_{bias}= 0 V
- HP: x_j:=depletion width
- For $x>x_j$ p concentration differs from doping concentration N_a, due to diffusion
- For $x< x_j$ assume depletion



X_j= depl. width

Backup – CV profiling and doping II

Assume:

$$x < x_j : \varrho = -N_A$$

$$x \geq x_j : \varrho = -N_A + p(x)$$

Surface charge and Potential (L = length of the device)

$$Q_s := e\int_0^{x_j} \left(-N_A\right) \mathrm{d}x + \int_{x_j}^{L} \left(-N_A + p(x)\right) \mathrm{d}x \quad [1]$$

$$\Phi_s := \frac{e}{\varepsilon_s}\left\{\int_0^{x_j} x\left(-N_A\right) \mathrm{d}x + \int_{x_j}^{L} x\left(-N_A + p(x)\right) \mathrm{d}x\right\} \quad [2]$$

Take differentials from [1] and [2] w.r.t. x_j:

$$dQ_s = e\,p\left(x_j\right)dx_j$$

$$d\Phi_s = \frac{e}{\varepsilon_s}\,x_j p\left(x_j\right)dx_j$$

$$C_s = \frac{dQ_s}{d\Phi_s} = \varepsilon_s \frac{e\,p\left(x_j\right)dx_j}{e\,x_j p\left(x_j\right)dx_j} = \frac{\varepsilon_s}{x_j} \qquad [3]$$

Assume $\Phi_s \approx V_s$, take derivative of C_s and solve for p in [3]:

$$\boxed{p\left(x_j\right) = \frac{C_s^3}{e\,\varepsilon_s}\left(\frac{dC_s}{d\Phi_s}\right)^{-1}}$$

i.e. the usual ‘profile equation’ showing that what is sampled is p, not N_a