Status of TCT measurements with different HV-CMOS test structures in Ljubljana

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TCT measurements with HVCMOS structures from 3 different foundries made on different substrate resistivities:

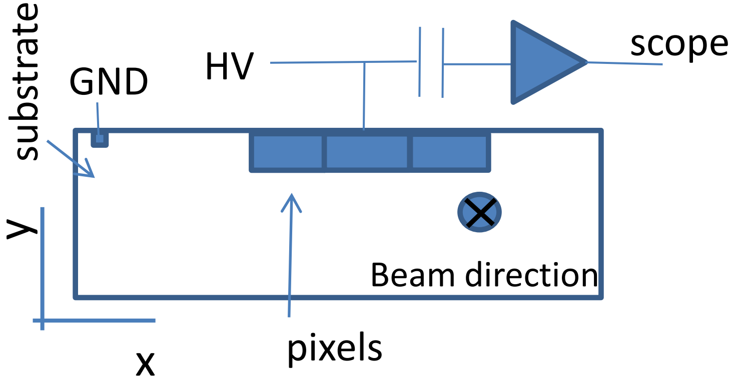
1. **AMS**: 10 Ohm-cm and 20 Ohm-cm
2. **X-FAB** :100 Ohm-cm
3. **LFoundry**: 2000 Ohm-cm

All devices are made on **p-type** substrates

These materials are being investigated as candidates for HV-CMOS detectors for trackers at HL-LHC

- TCT measurements with passive pixels (no amplifier on detector)
  ➔ collecting electrode connected to amplifier

Detector connection scheme:

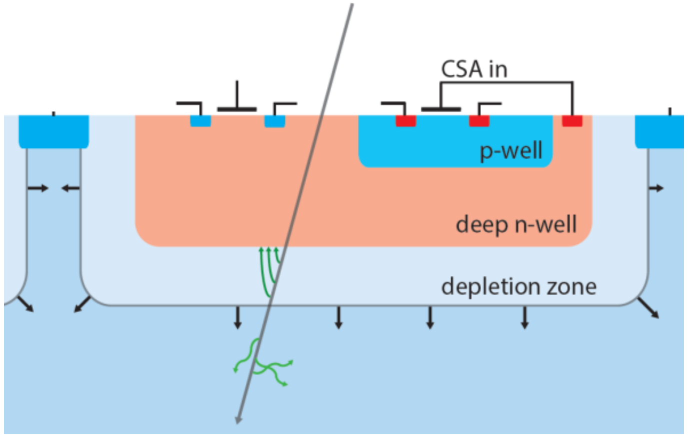


AMS: 10 Ωcm, 20 Ωcm

Two different chips produced by AMS investigated

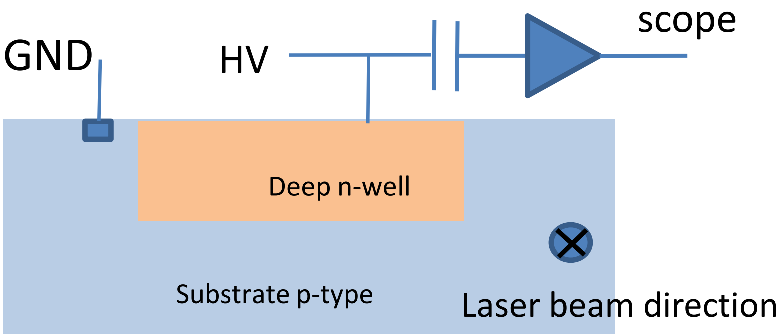
(most measurements already shown at earlier RD50 workshops):

- CHESS1 chip
  - AMS-0.35 μm process
  - substrate resistivity 20 Ωcm
  - max bias **120 V**
- CCPDv2 (HV2FEI4)
  - AMS-0.18 μm process
  - substrate resistivity 10 Ωcm
  - max bias **60 V**
- back plane of the devices were not processed
  → bias connected from the top of the chip



From: S. Fenandez-Perez, TWEPP 2015

Passive pixel: no electronic in the n-well



LFoundry: 2000 Ωcm

- 150nm CMOS
- 2kΩcm p-type bulk
- Deep N-well available
- HV process, max bias > 100 V
- Thinning and back side metallization possible

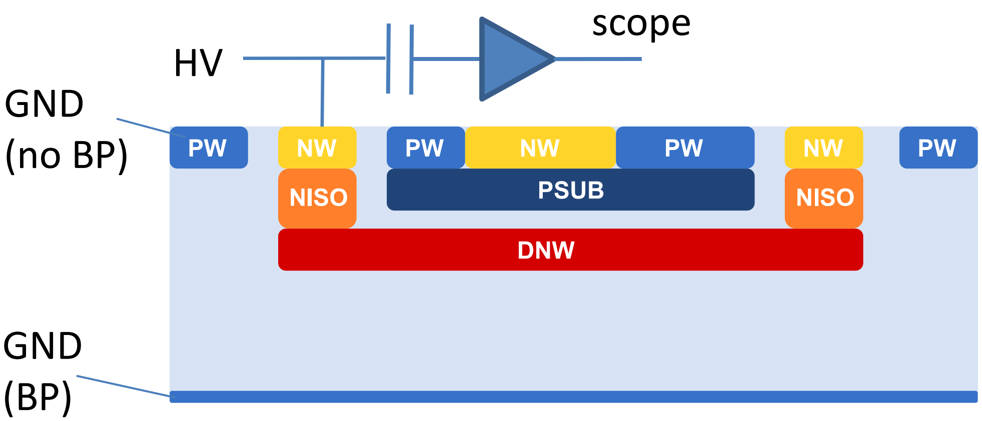
More detail about LFoundry:

- Piotr RYMASZEWSKI et al., *Prototype active silicon sensor in LFoundry 150nm HV/HR-CMOS technology for ATLAS Inner Detector Upgrade* (TWEPP 2015)

https://indico.cern.ch/event/357738/session/9/contribution/200

Two versions:

- without back side (BP) metallization
  → substrate bias from top
- with BP
  → substrate bias from back plane

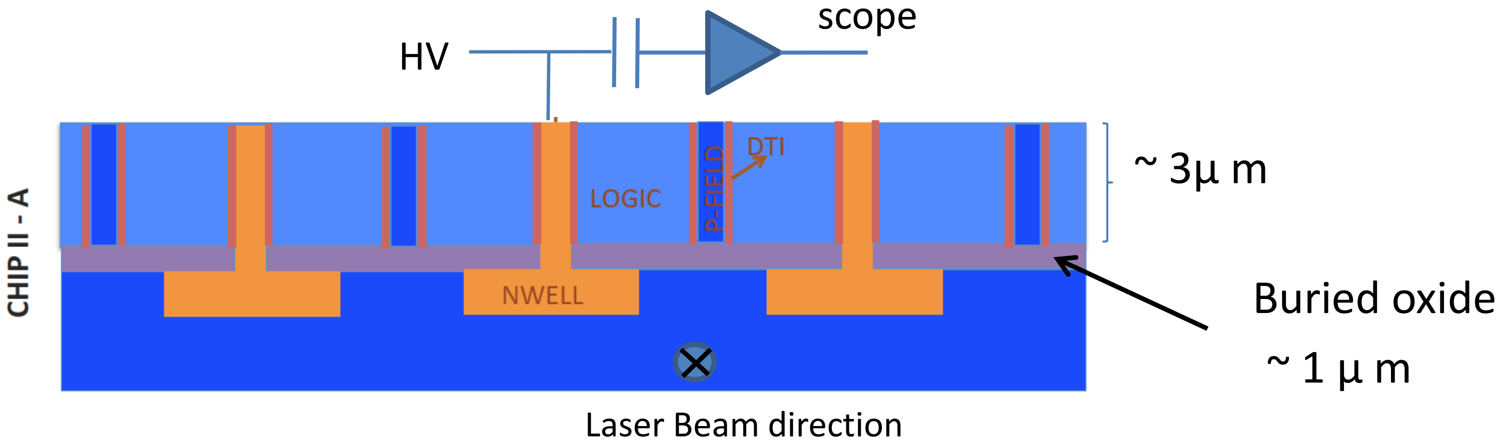


X-FAB: 100 Ωcm

- X-FAB Trench **SOI** 0.18 um
- p-type bulk, 100 Ohm-cm
- back side not processed (bias from TOP)
- max bias 300 V

More detail about X-FAB process:

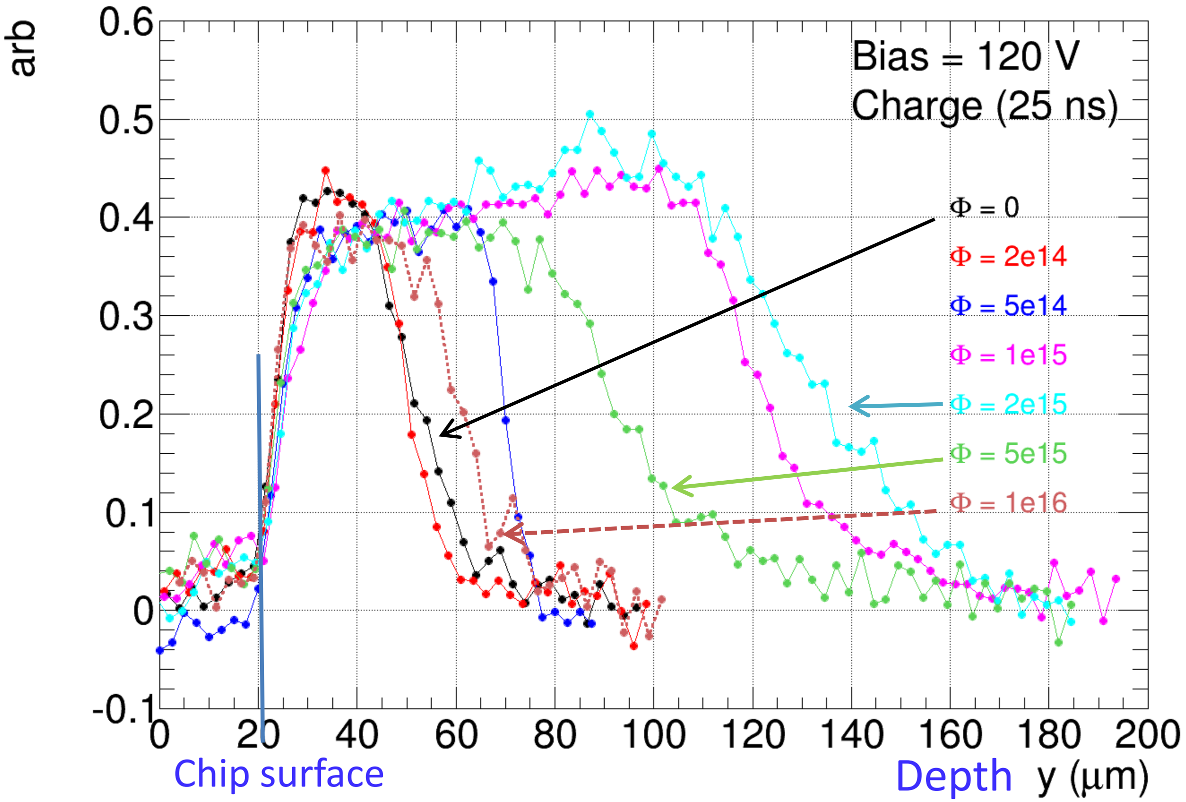
- S. Fernandez et al., *Charge Collection Properties of a Depleted Monolithic Active Pixel Sensor using a HV-SOI process* (TWEPP 2015) https://indico.cern.ch/event/357738/session/9/contribution/3
- T. Hemperek et al, *A Monolithic Active Pixel Sensor for ionizing radiation using a 180 nm HV-SOI process,* NIMA 796(2015)8-12

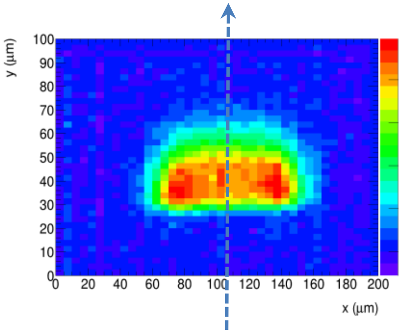


AMS (20 Ωcm)

Chess1, irradiated with neutrons up to 1e16 n/cm2

Fluence steps: 2e14, 5e14, 1e15, 2e15, 5e15, 1e16





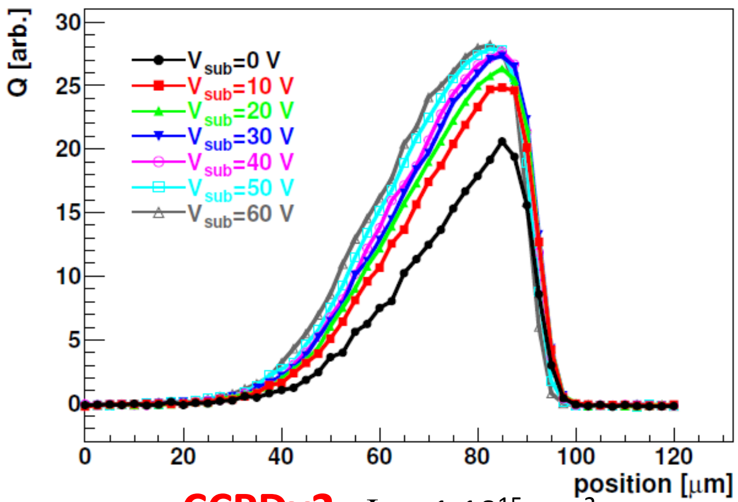
Scan direction

- charge collection width (depleted depth) increases with fluence up to ~ 2e15
  - ➔ concentration of initial acceptors falls with irradiation faster than new acceptors are created
- collection depth gets smaller with larger fluence
  - ➔ initial acceptor removal finished, space charge concentration increases with irradiation
- **at 1e16 charge collection region still larger than before irradiation**

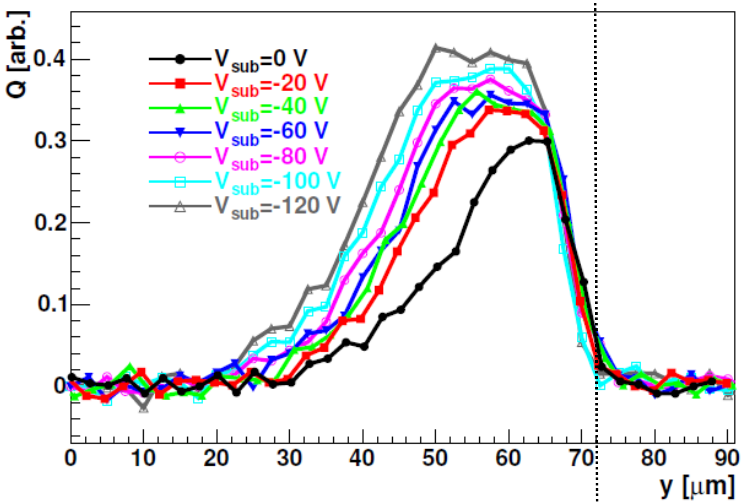
See also presentation from Santander: https://indico.cern.ch/event/381195/session/6/contribution/6

AMS (10 Ωcm and 20 Ωcm)

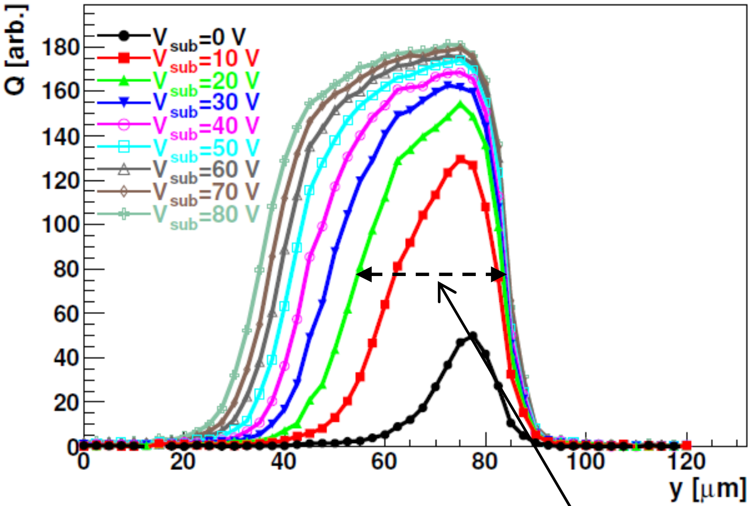
CCPDv2 , non-irradiated



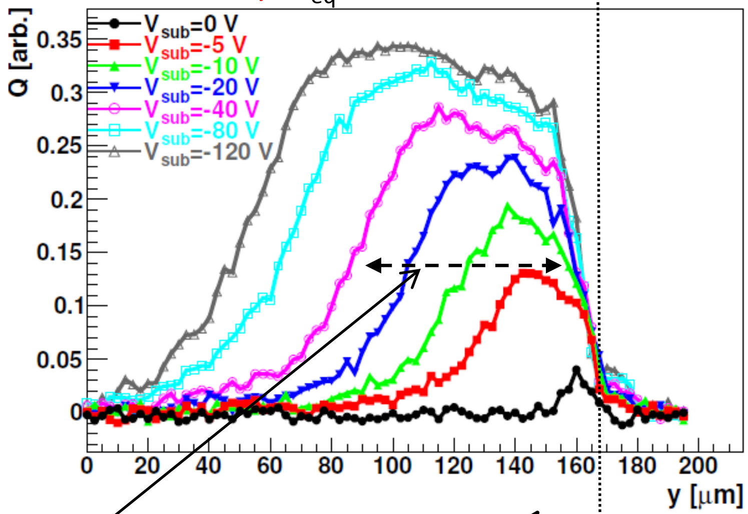
CHESS1, non-irradiated



CCPDv2, $\Phi_{eq}=1\cdot10^{15}$ cm^{-2}



CHESS1, $\Phi_{eq}=2\cdot10^{15}$ cm^{-2}

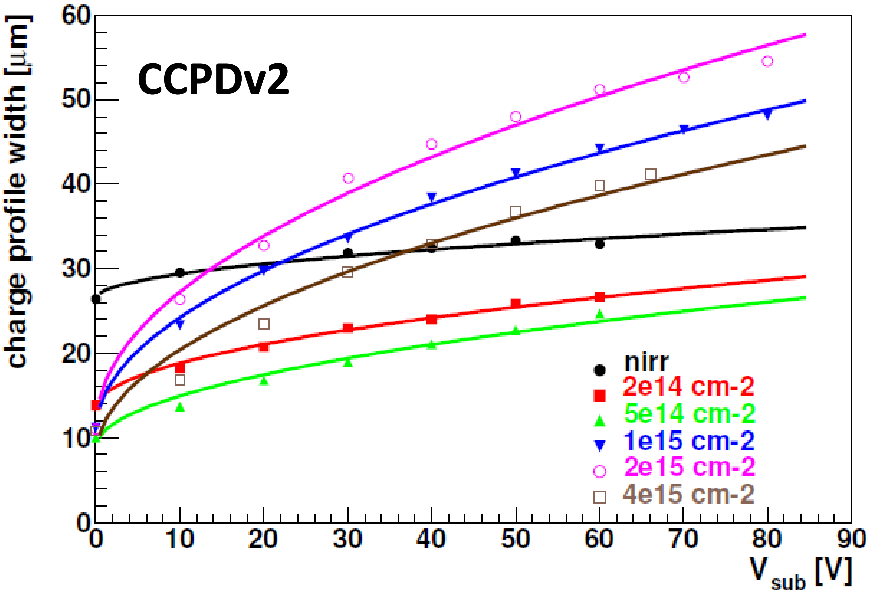


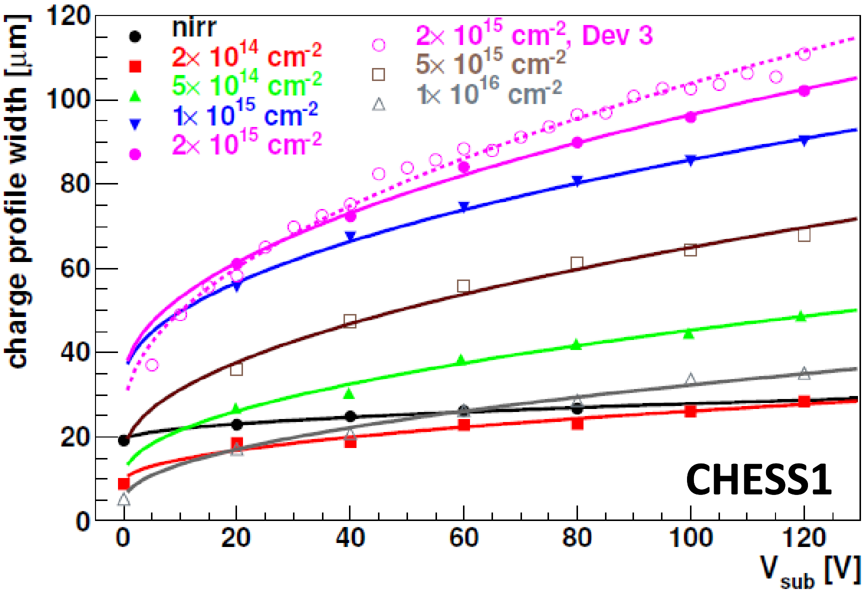
Charge collection width: FWHM of profile

← depth

Chip surface

AMS (10 Ωcm and 20 Ωcm)





Dependence of depleted region on substrate bias for constant space charge

At $V_{sub}=0$ V it is assumed that charge is collected by diffusion (note the FWHM of the beam)

Any additional bias depletes the certain width of the substrate which adds to the diffusion contribution:

$$d = d_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} \cdot V_{sub}}$$

Effective dopant concentration is extracted from the fit for each fluence!

➔ Effective acceptor removal clearly observed

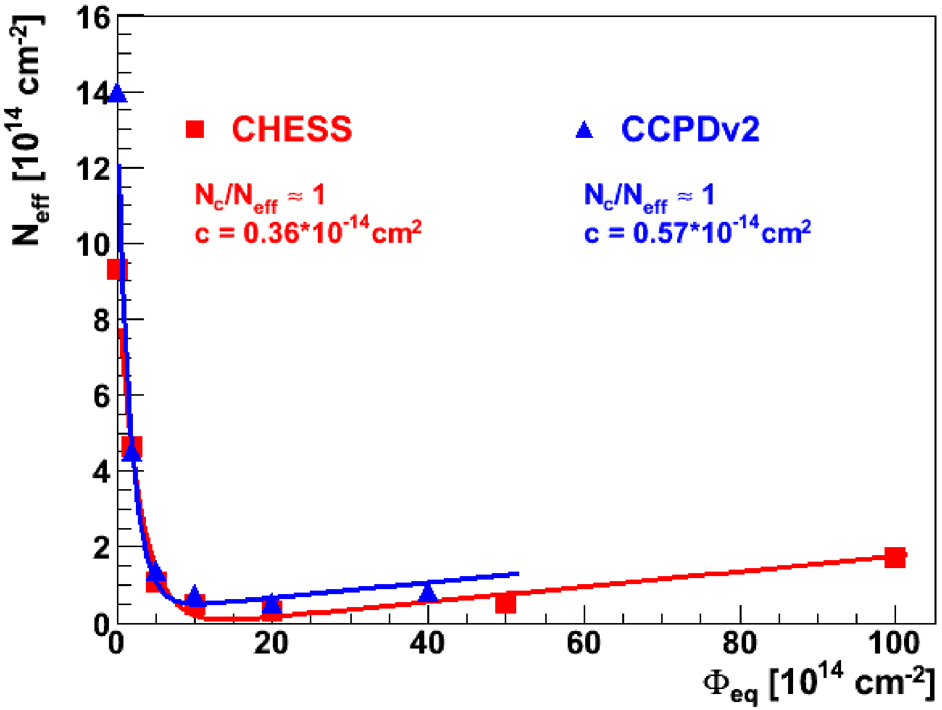
(G. Kramberger, presented at: IEEE NSS-MIC 2015)

AMS (10 Ωcm and 20 Ωcm)

$$N_{eff} = N_{eff\,0} - \underbrace{N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))}_{\text{acceptor removal}} + g \cdot \Phi_{eq}$$

Radiation introduced deep acceptors: $g \sim 0.02\ \mathrm{cm}^{-1}$

Fit to measurements, N_c/N_{eff} and c free parameters

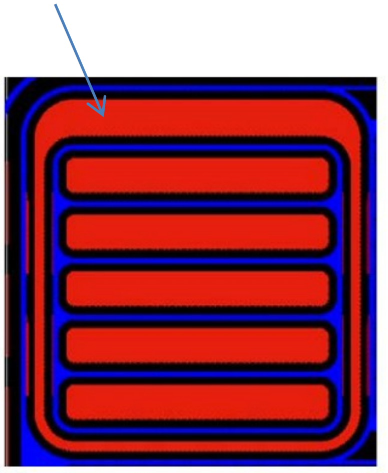


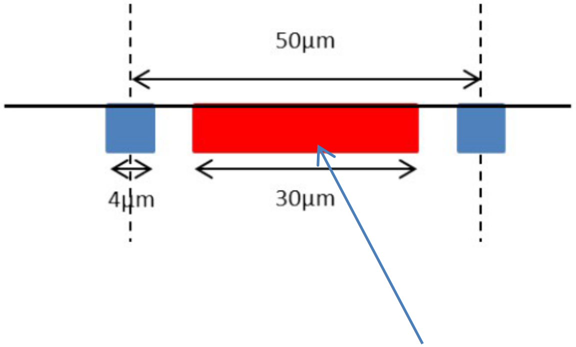
LFoundry (2 kΩcm)

CCPDLF_VB chip

Structure A

- 250 µm x 50 µm pixels
- 5 pixels connected together
- n-well-ring around structure - can be connected separately



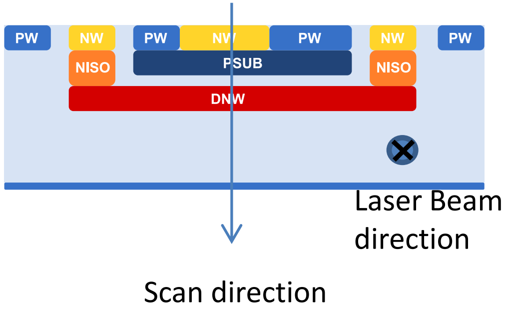


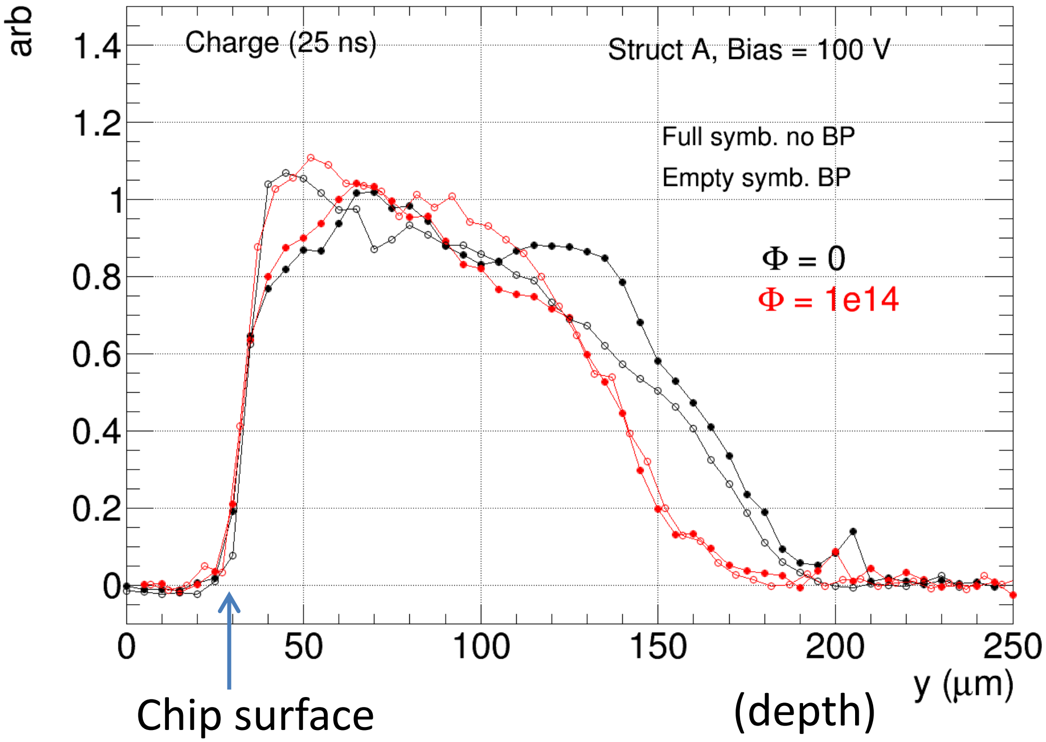
n-well

- measure with device with BP and without processed BP
- device with BP: 300 µm thick

LFoundry (2 kΩcm)

Before and after irradiation with neutrons to 1e14 n/cm^2

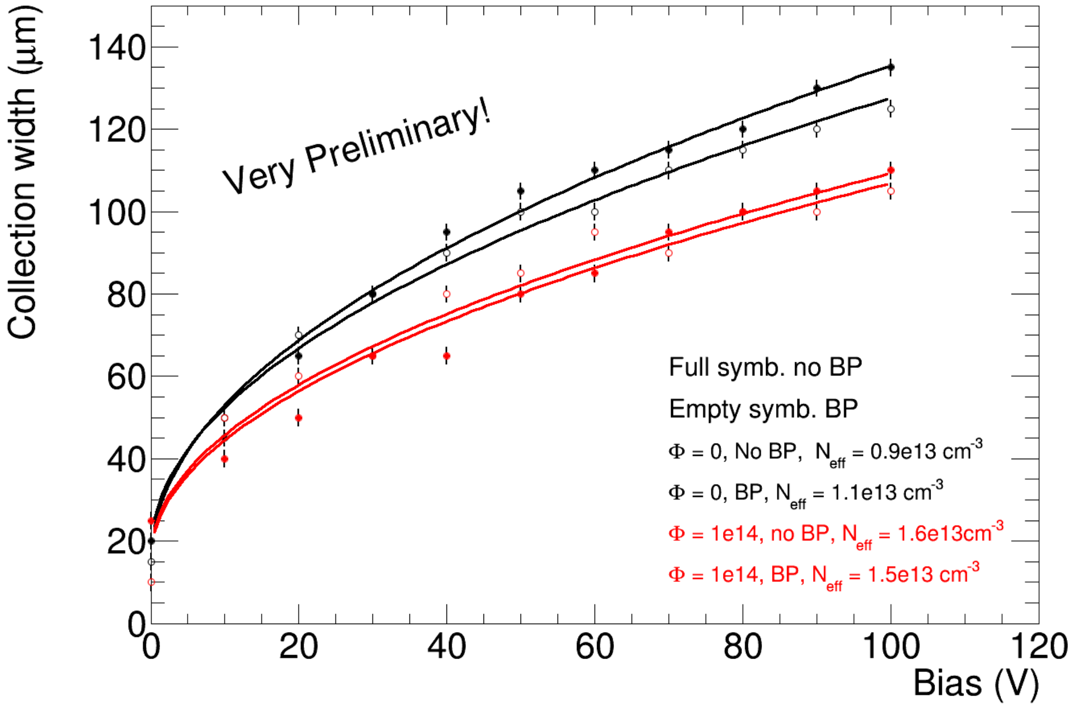




- after irradiation charge collection width smaller → N_{eff} increases → smaller depleted depth
- no significant difference between BP and no BP sample
- if n-well ring connected profile more flat → charge collection region under electrode better defined

LFoundry (2 kΩcm)

- collection width (FWHM of charge profile) vs. Bias voltage



Fit with: $Width(V_{bias}) = d_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$

N_{eff} : effective space charge concentration - free parameter

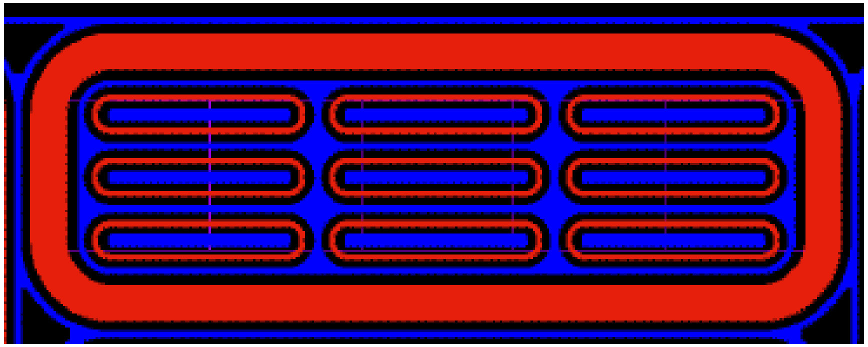
d_0: free parameter

- before irradiation: acceptor concentration 1e13 cm^{-3} corresponds to 1.3 kΩcm (somewhat too low)
- *N_{eff}* increased by 5e12 cm^{-3} after irradiation → to much if g ~ 0.02 cm^{-1}
  - → method not very precise
- no increase of collection width due to acceptor removal seen in this measurement

LFoundry

Structure F, 3x3 pixels, 125 um x 33 um

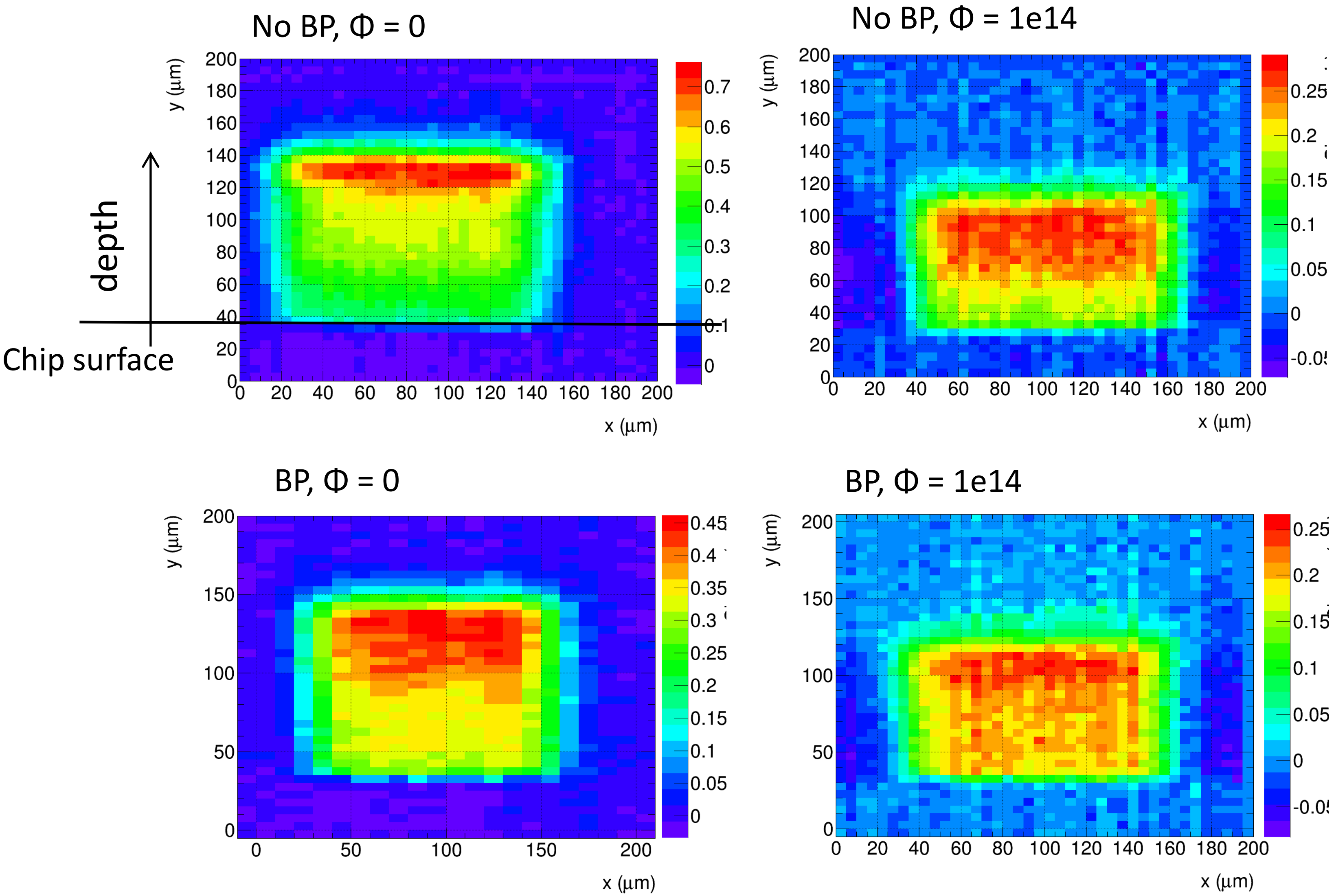
Top view (only nw and pw shown, resp. in red and blue):



Cross section of one pixel along the short side:

- local n-well ring connected
- read out central pixel or all pixels
- all pixels at same bias

LFoundry, structure F, 40 V, central pixel read out



No BP, Φ = 0

No BP, Φ = 1e14

BP, Φ = 0

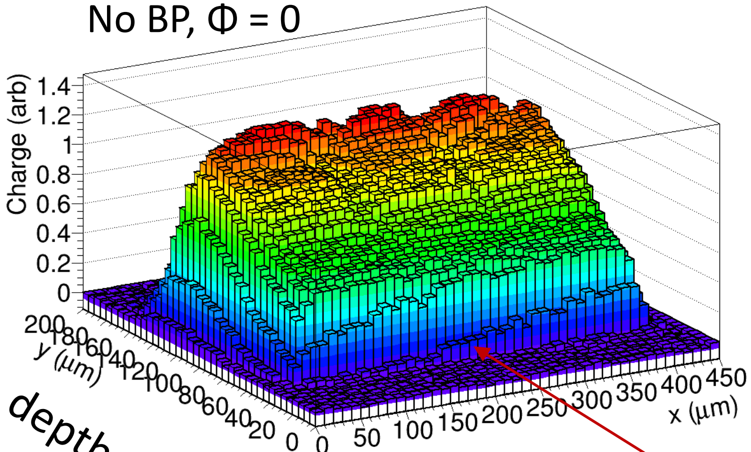
BP, Φ = 1e14

- somewhat more charge measured at larger depths

LFoundry, structure F, 40 V, all pixels read out,

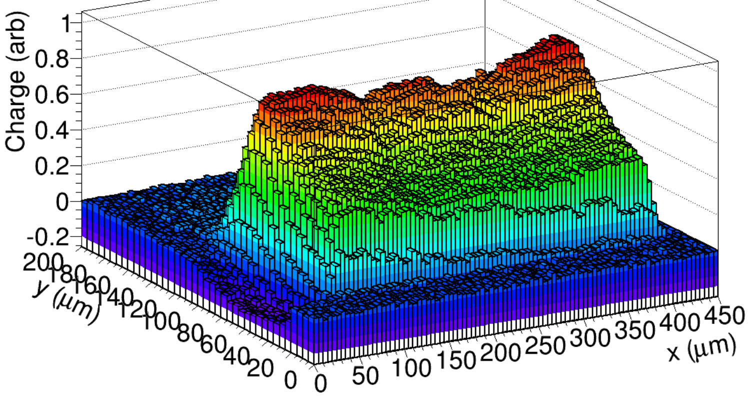
- no significant charge collection gaps between pixels
- somewhat more charge from larger depth, more inclined in no BP case

No BP, Φ = 0



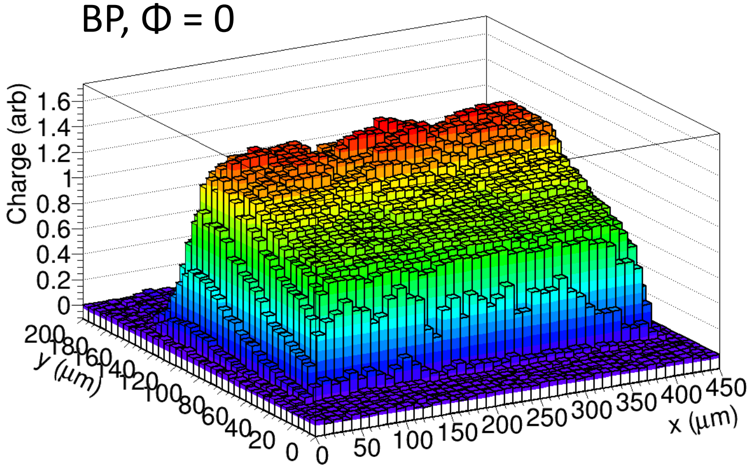
depth

No BP, Φ = 1e14

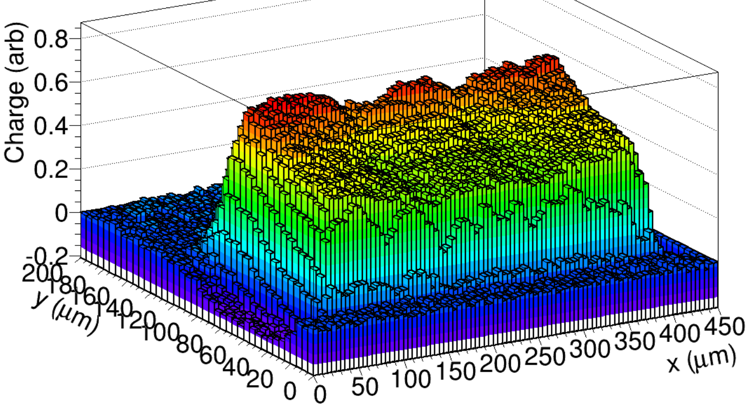


Chip surface

BP, Φ = 0



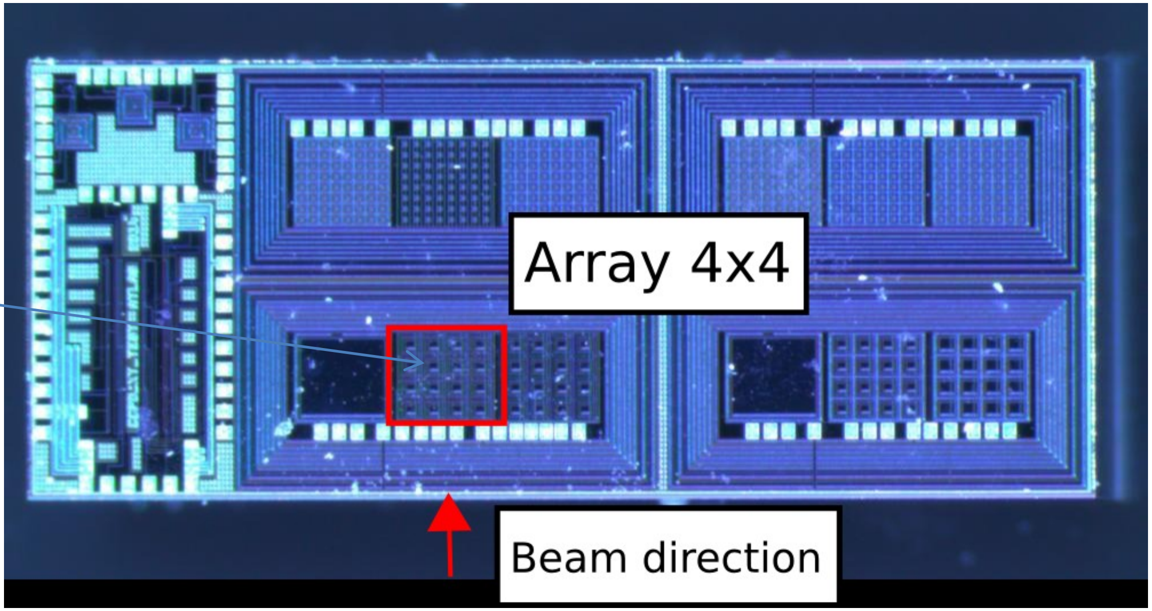
BP, Φ = 1e14



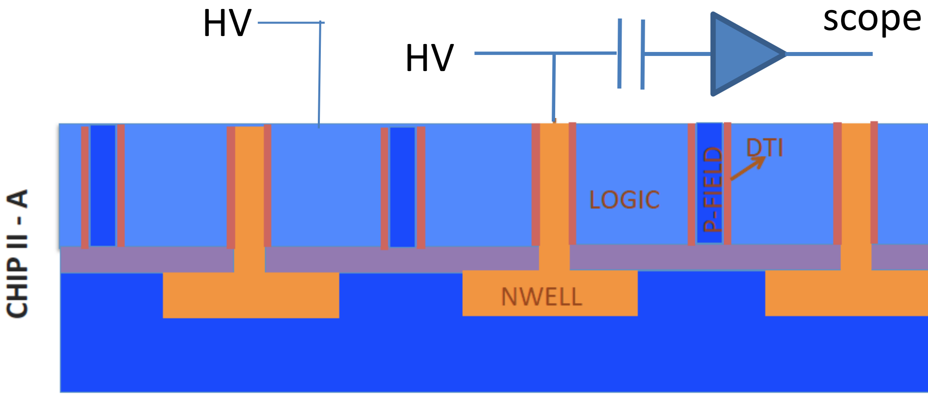
X-FAB: 100 Ωcm

XTB02 chip

Structure A2



- pitch 100 µm
- n-well: 40 µm x 50 µm
- bias from the top
- max bias 300 V

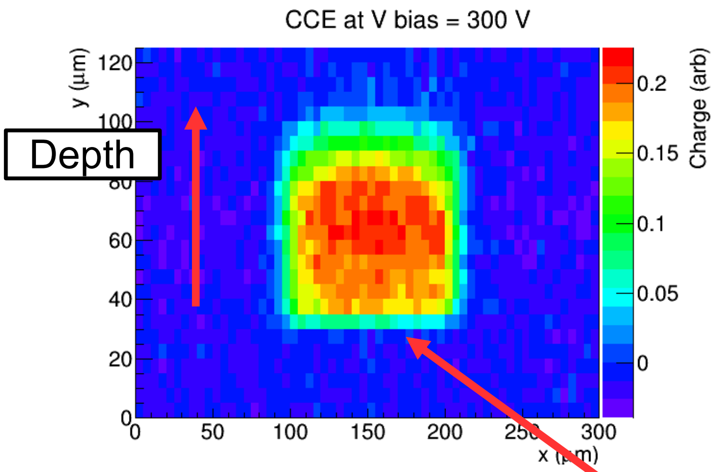


➔ “logic” (space for CMOS circuits for active device) and n-well at same potential

X-FAB: 100 Ωcm

- 2-d edge TCT scan, before irradiation

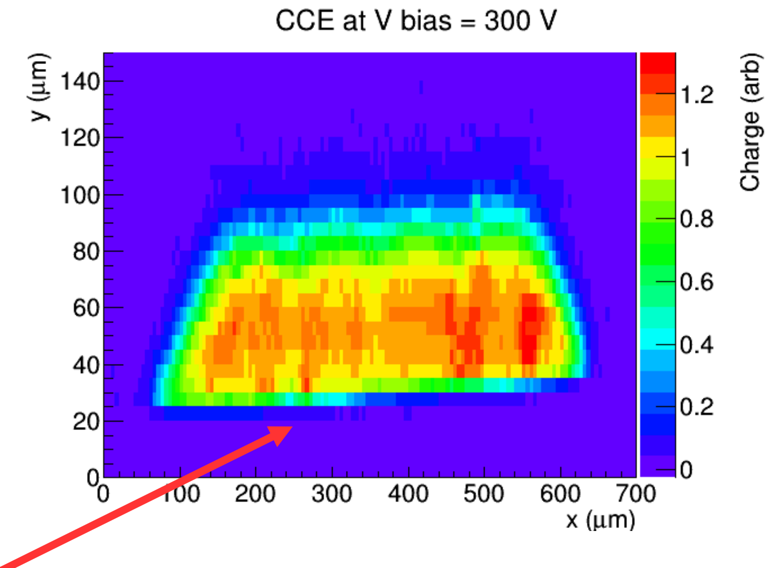
Single pixel:



- pixel size 100 μm

Chip surface

- 4x4 pixel array, all pixels read out:

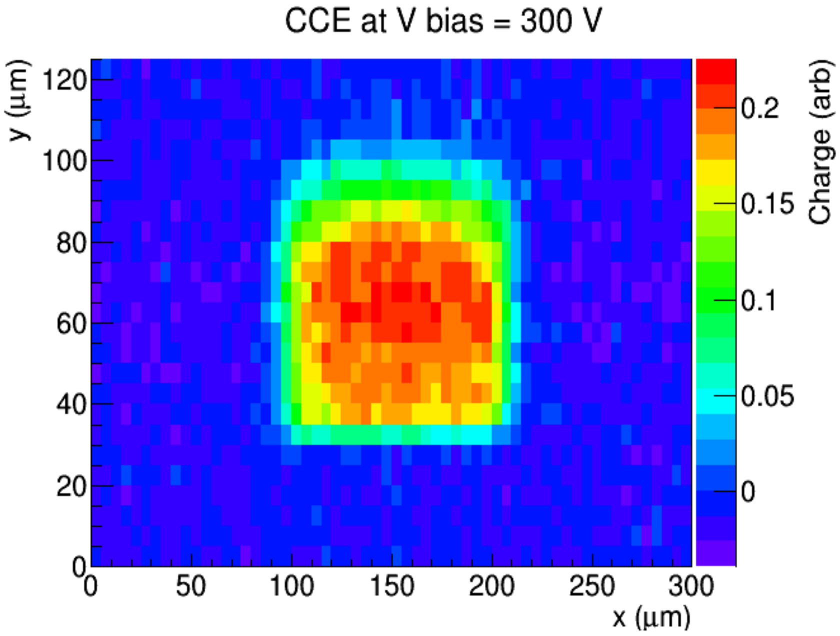


- no CCE gaps between pixels
- charge collection region in X direction larger than array width because n-well ring surrounding it not connected

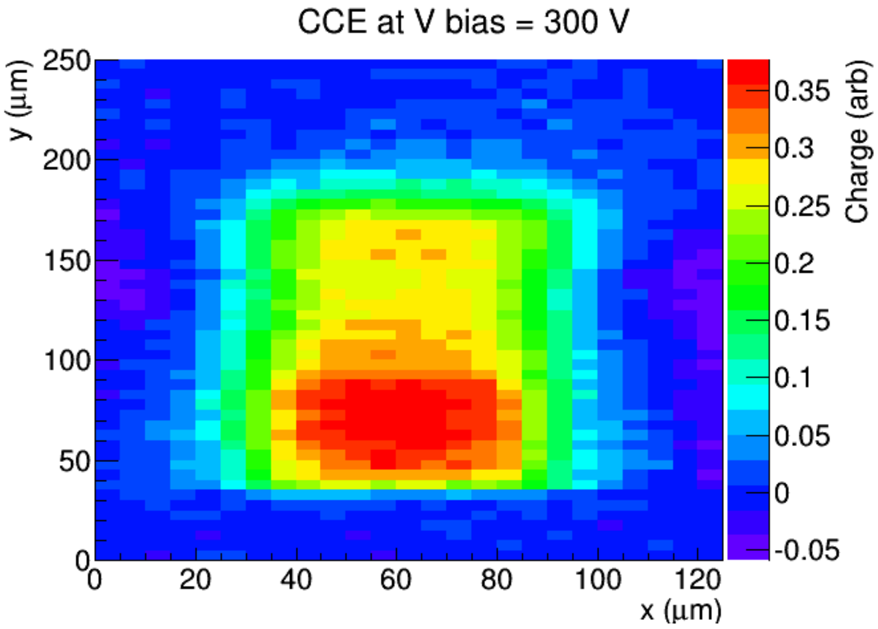
X-FAB: 100 Ωcm

Single pixel read out

Before irradiation



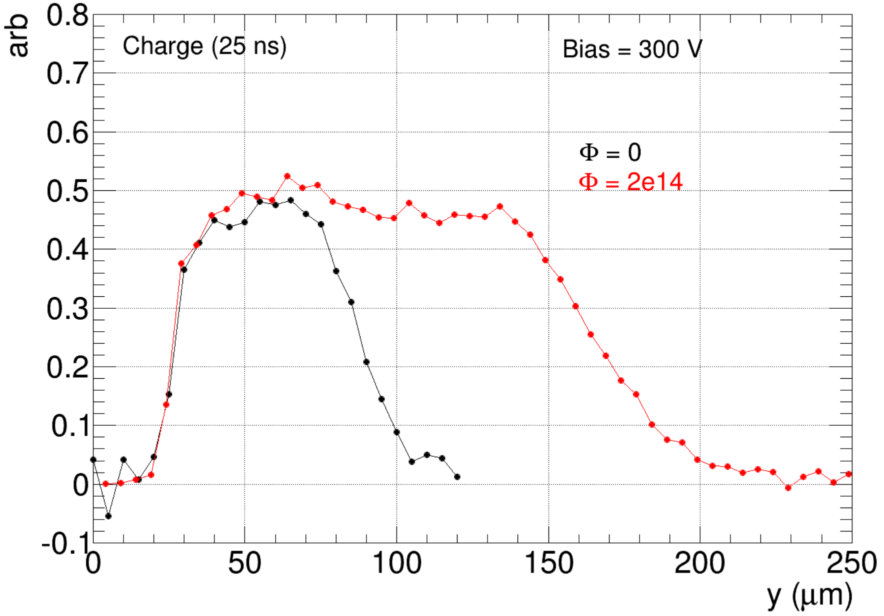
After 2e14 n/cm2

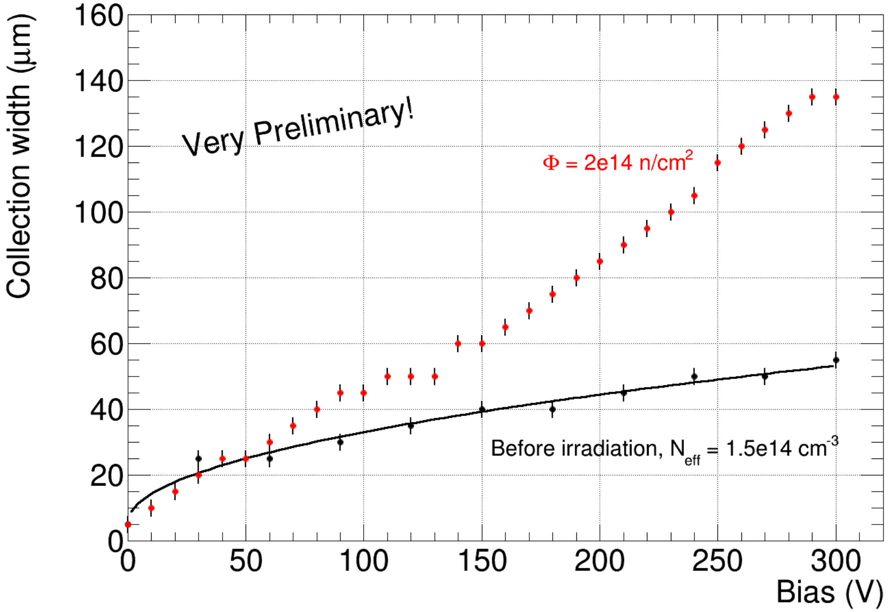


- large increase of charge collection width after irradiation
- after irradiation charge collection range under the n-well deeper but narrower
  → behavior after irradiation not fully understood, investigation ongoing

X-FAB: 100 Ωcm

Charge profile across pixel centre before and after irradiation with neutrons to 2e14 n/cm^2



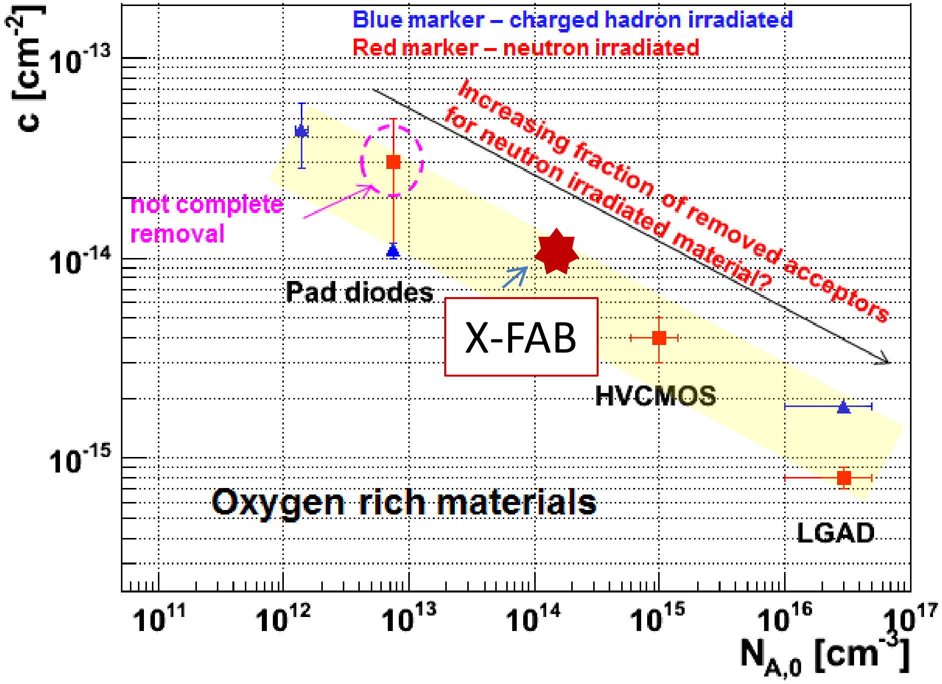


- before irradiation, fit with $d_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$ N_{eff} = 1.5e14 → resistivity 87 Ohm-cm
- after irradiation: can't fit with sqrt(V)
- if we anyway use: $Width = \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} V_{bias}}$ ➔ N_{eff} (300 V) ~ 2e13 cm^{-3}
- if we assume complete acceptor removal then this is consistent with: **c ~ 1e-14 cm^{-2}**

in: $N_{eff} = N_{eff\,0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g \cdot \Phi_{eq}$ (g = 0.02 cm^{-1})

Acceptor removal

G. Kramberger et al, 10th Trento Meeting, Feb. 17-19, 2015



- acceptor removal constant **c ~ 1e-14 cm^{-2} for X-FAB** fits well into the plot

- **LFoundry:** $N_{A,0}$ = 6.4e12 cm^{-3} : we see increase of N_{eff} at 1e14 n/cm^2
  → if donors and acceptors in the material (compensated material)
  increase of N_{eff} at low fluence could also be the consequence of faster donor removal?

Summary

- Edge-TCT measurements with passive test structures with devices made on 3 different substrate resistivities:
  - AMS : 10 and 20 Ohm-cm
  - X-FAB: 100 Ohm-cm
  - LFoundry: 2000 Ohm-cm

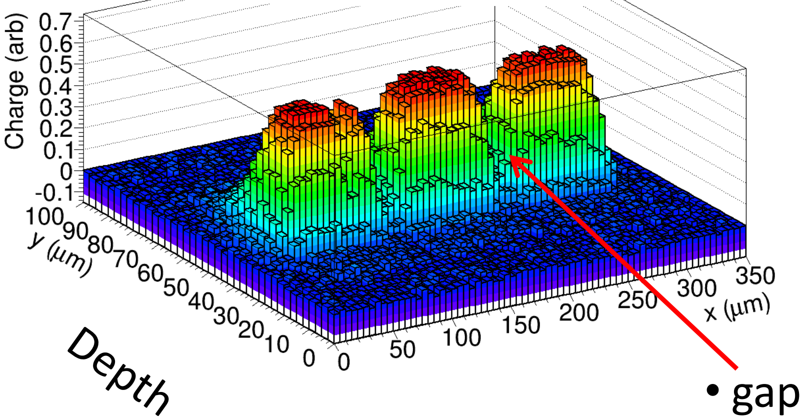
- large increase of charge collected depth after irradiation with neutrons observed in AMS and X-FAB samples
  - dependence of charge collection width with fluence in AMS can be explained with acceptor removal
  - first measurements with X-FAB after 2e14 n/cm^2 also point to acceptor removal

- in LFoundry samples charge collection depth decreased after 1e14 n/cm^2
  - no or incomplete acceptor removal or effects of compensated material (combination of donor and acceptor removal)
  - samples with and without processed back plane tested → not much difference seen at this fluence step
  - no significant charge collection gaps between pixels

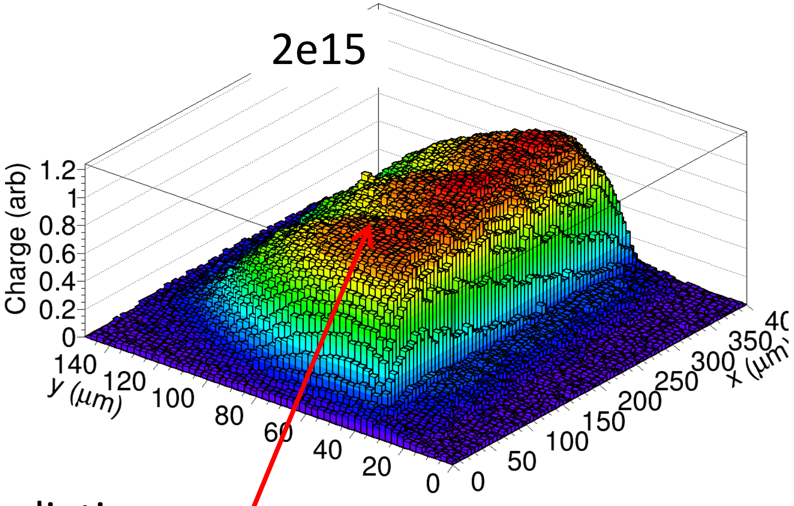
AMS (20 Ωcm)

Bias = 120 V, all 9 pixels connected to readout

Not irradiated

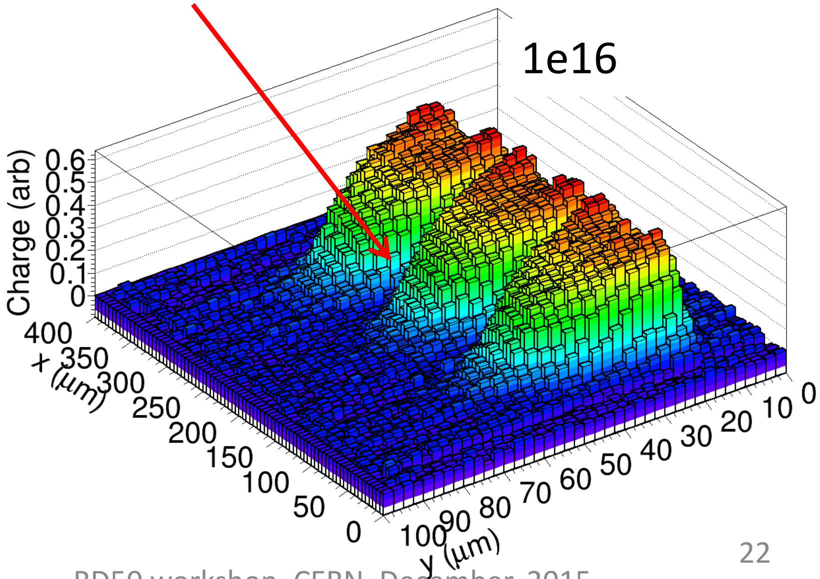


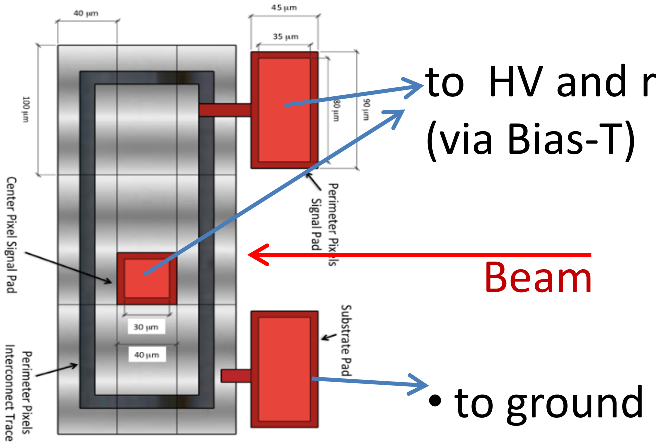
2e15



- gaps before irradiation
- guard ring gaps smaller after 2e15
- gaps better seen again after 1e16

1e16





to HV and readout (via Bias-T)

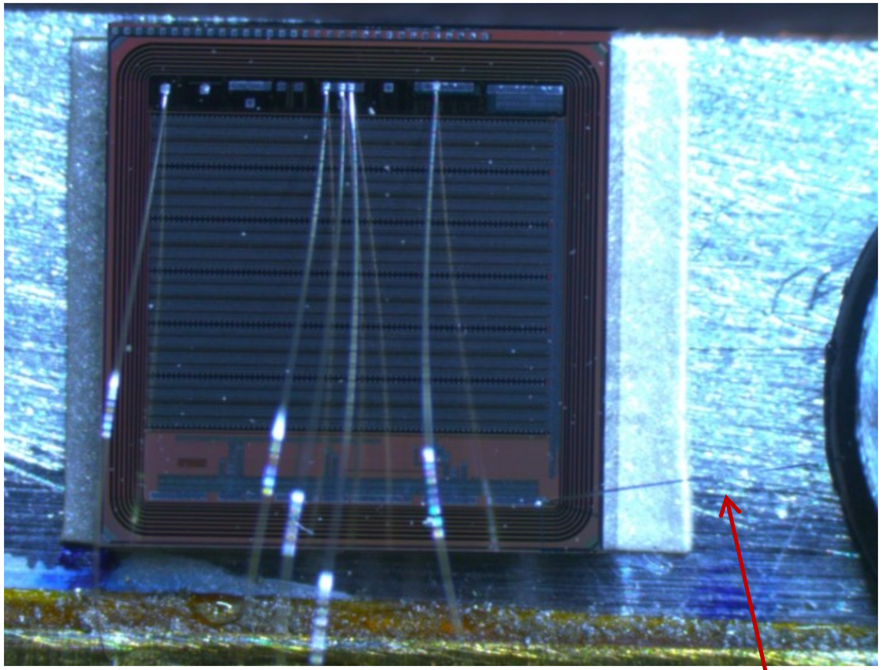
Beam

- to ground

LFoundry bonding

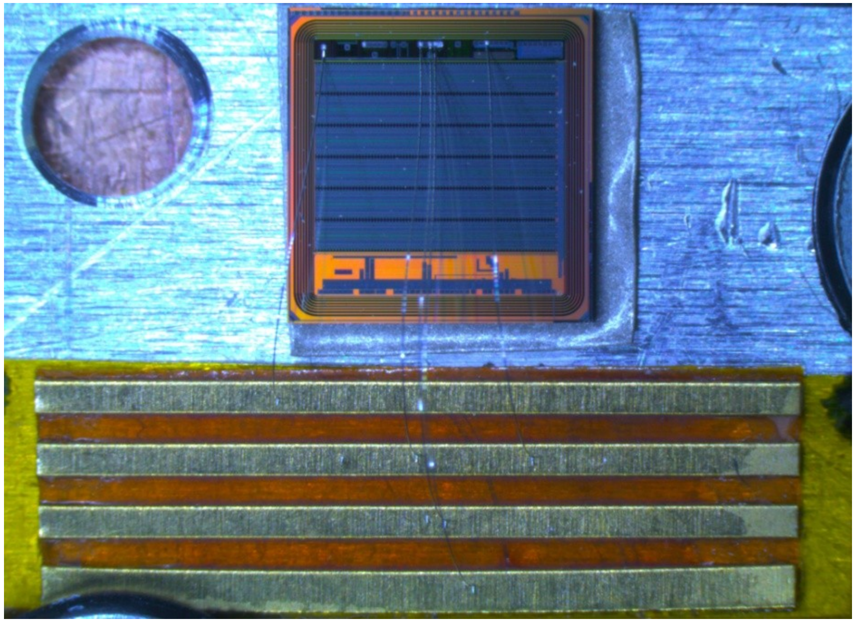
No back plane

Laser beam direction



Back plane

Conductive glue
(staystik)



Bond wire for substrate connection