Systematic investigation of 24 GeV/c proton-irradiated Micron pad detectors made of different silicon materials

Hannes Neugebauer[1 2]*, Marcos Fernandez Garcia[3],
Christian Gallrapp[1], Michael Moll[1]

[1] CERN / [2] University of Hamburg / [3] IFCA-Santander

* hannes.neugebauer@cern.ch

23rd RD50 workshop
CERN, November 13-15, 2013

Outline

- Introduction
- Studied sensors and irradiation details
- IV/CV review
- TCT & CCE
    - Setup and sample preparation
    - Results
- Conclusion & outlook

Introduction

Motivation:

- due to luminosity upgrade for LHC

→ integrated radiation doses on the inner detector layers up to 2e16 n/cm^2

→ radiation hardness limits of present silicon detector systems not sufficient

Problems caused by radiation damage in the bulk:

- modification of basic electrical properties in silicon sensors

→ **I_{leak} increase, V_{fd} change, CCE decrease**

→ charge trapping, modification of internal electric field distribution

- main source of SNR degradation

Main objectives of this work (within RD50):

→ proper **characterisation of wide range of silicon sensor types** in terms of operating ability beyond higher irradiation levels (i.e. long-term impacts):

  - pad+strip sensors of FZ and MCz n- and p-type
  - irradiated with 24GeV/c protons at CERN PS

→ deeper insight into underlying physics mechanisms (e.g. E-field distribution)
Techniques: **IV/CV, red&IR TCT, Alibava (CCE) and eTCT including annealing**

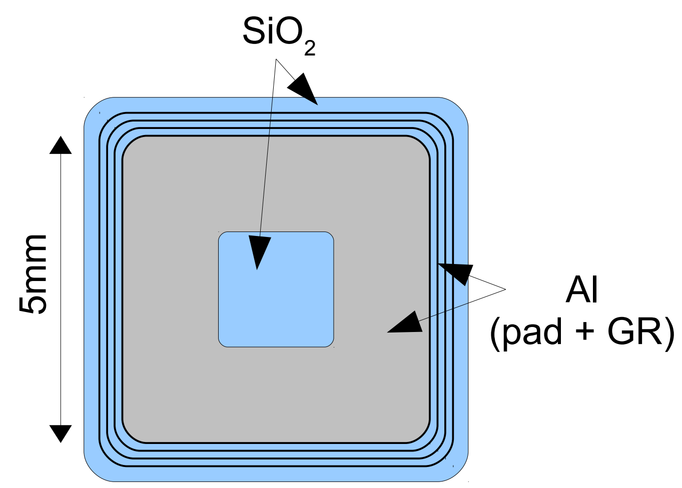
→ **simulation with TCAD** to compare to measurements and predict performance/properties

Investigated materials

Common RD50 4” wafer production (2010) of MICRON Semiconductor Ltd. (UK)

- pad and strip detectors
- p- and n-type FZ and MCz
- thickness ~ 300µm
- resistivity $\rho = 1 - 30$ kΩcm
- orientation <100>
- no full processing information (implant depths, masks etc.)

  → simulation



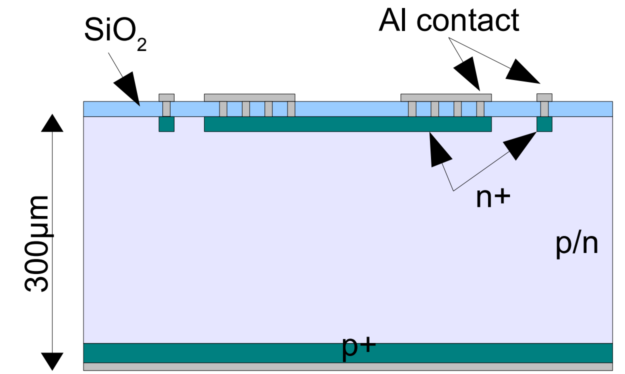
Irradiation facts:

- 24 GeV/c Protons at CERN PS
- Flux: 1e13 – 3e13 p/cm² h
- annealing during irradiation (~ 27°C)
- stored in freezer after irradiation

→ fluences received [p/cm²]:

5.85e13, 1.03e14, 5.31e14, 9.84e14, 1.95e15, 4.42e16

(Φ_{eq} = 3.63e13, 6.39e13, 3.29e14, 6.10e14, 1.21e15, 2.74e16 n/cm2)



! n-in-n samples (single-sided processed) without GR structure on backside → don't work before irradiation !

IV/CV measurements

Measurement of leakage current & capacitance as function of reverse detector bias V and dependent on T, f, Φ, material

Deep defects proportional to non ionizing energy loss (NIEL) generated by radiation:

$$I_{leak} = \alpha \Phi_{eq} V$$

N_{eff} is related to depletion voltage and thickness of detector

→ information about N_{eff}: $$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_o}\frac{V_{fd}}{d^2}$$

Parameters:

- GR to ground
- T = 20, 10, 0, -10, -20°C (dry air)
- f = 1 kHz, 455 Hz
- annealing 80min@60°C

properties of non-irradiated samples

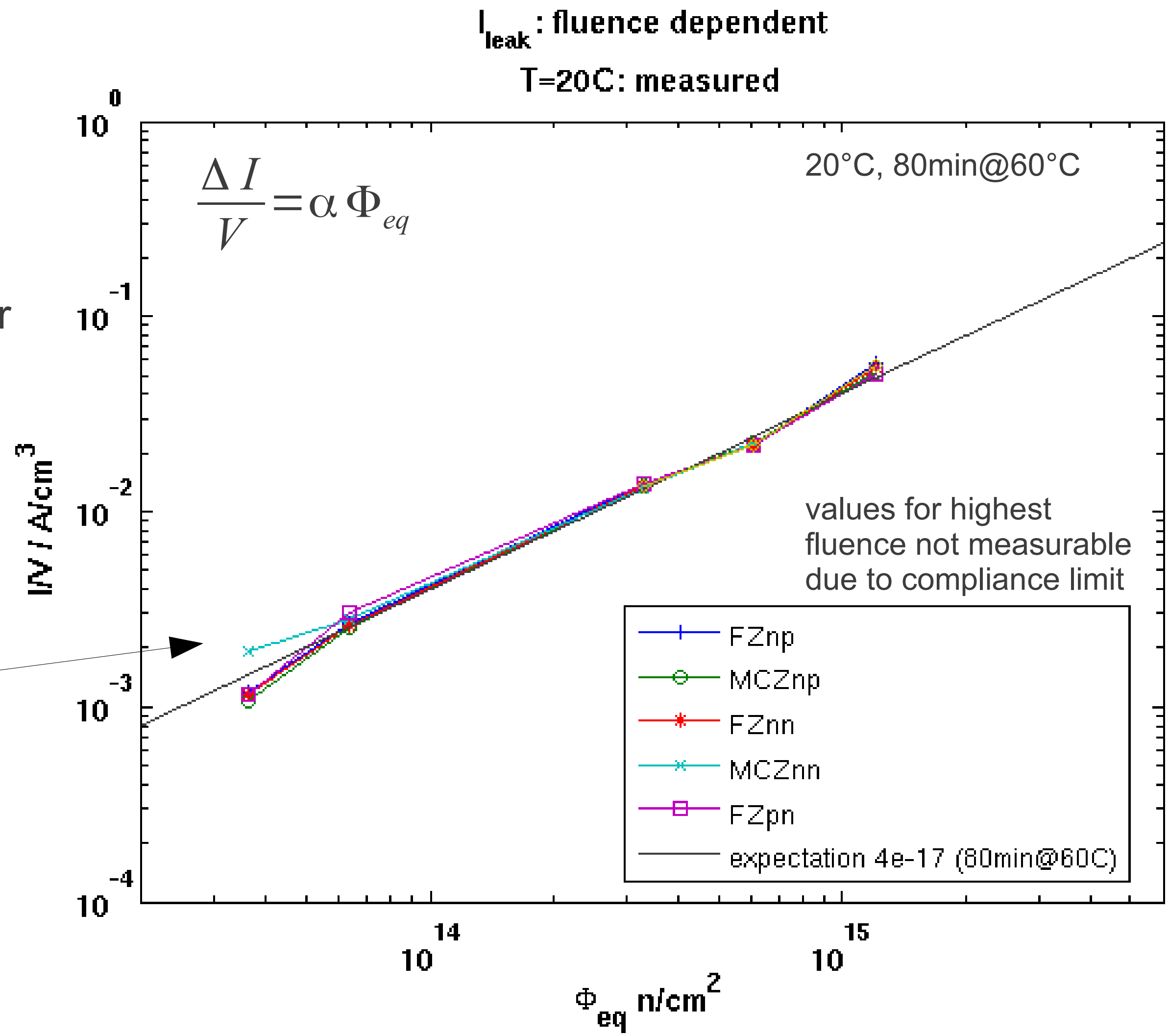
Material	V_{fd} [V]	I_{leak} [A]	N_{eff} [cm^{-3}]	SIMS (O_2-conc. [cm^{-3}])	ρ [kΩcm]
FZ n-in-p	13.6	9.3e-10	1.96e11	2.2e16	20
MCz n-in-p	12.7	1.6e-10	1.78e11	4.4e17	13
FZ n-in-n	18.6	2.7e-6	-2.67e11	2.2e16	8
MCz n-in-n	34.4	2.2e-5	-4.52e11	4.0e17	0.6
FZ p-in-n	21.2	9.1e-11	-2.78e11	4.0e16	9
"MCz p-in-n"	62.2	1.9e-5	-11.15e11	4.7e17	0.6

messed up processing ← (last row, "MCz p-in-n")

I_{leak} scales linear with fluence:

α = 4.38e-17 A/cm²

Damage parameter is nearly independent of leakage current per volume and material type. Almost linear increase between 1e13 cm⁻² up to 2e15 cm⁻².

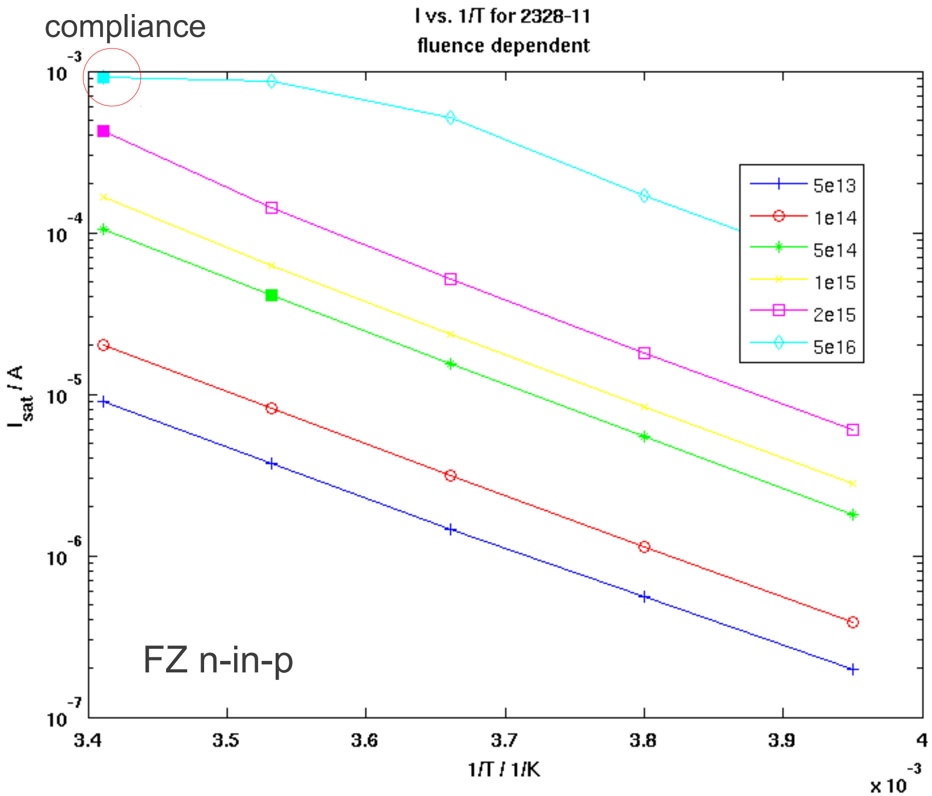


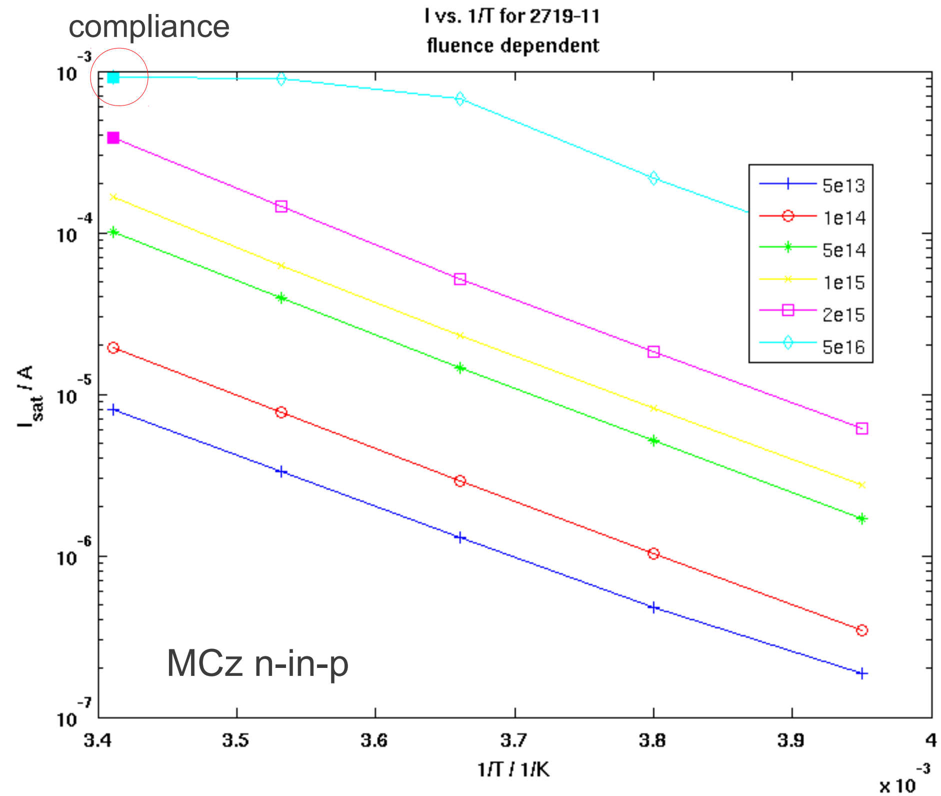
Remarks:

- high leakage current of MCz (n-in-n) for non-irradiated and for lower irradiated samples
- non-irrad. “wrong_p-in-n MCz” behaves like n-in-p (stated by SR&SIMS)

→ becomes issue in TCT

IV/CV facts - I vs. 1/T





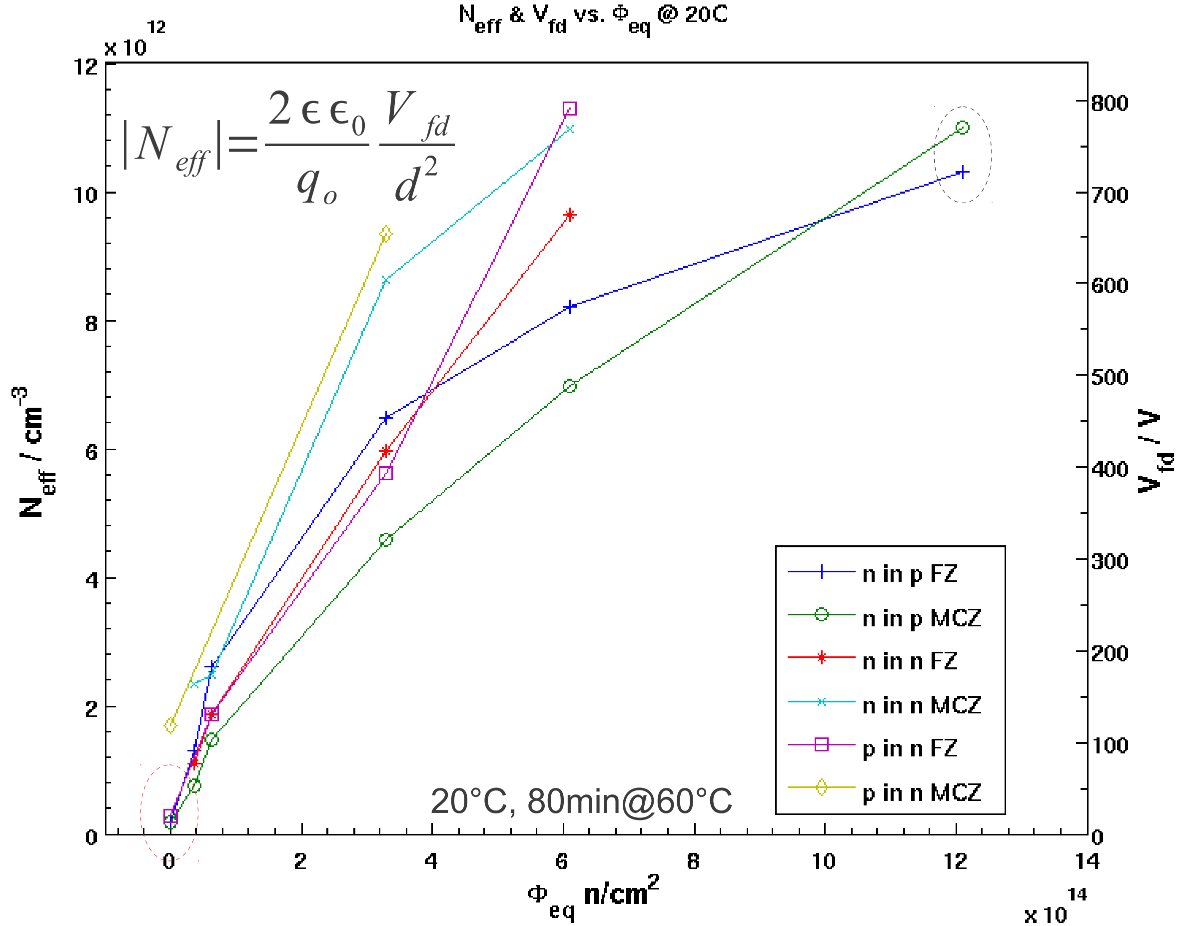
→ ln I_{leak} scales linear with 1/T

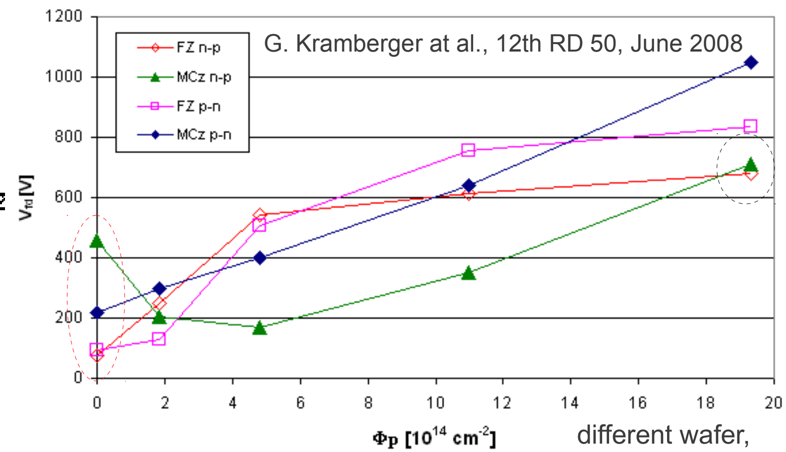
E_{eff} = (1.209 ± 0.009)eV
(compare A. Chilingarov E_{eff} = 1.214eV)

table shows averaged values over all fluences → check dependency on fluence later!
(slopes differ slightly with fluence: steeper slope with higher Φ)

Material	E_{eff} [eV]
FZ n-in-p	1.202
MCz n-in-p	1.219
FZ n-in-n	1.209
MCz n-in-n	1.206
FZ p-in-n	1.198
MCz p-in-n	1.221

average values over all fluences



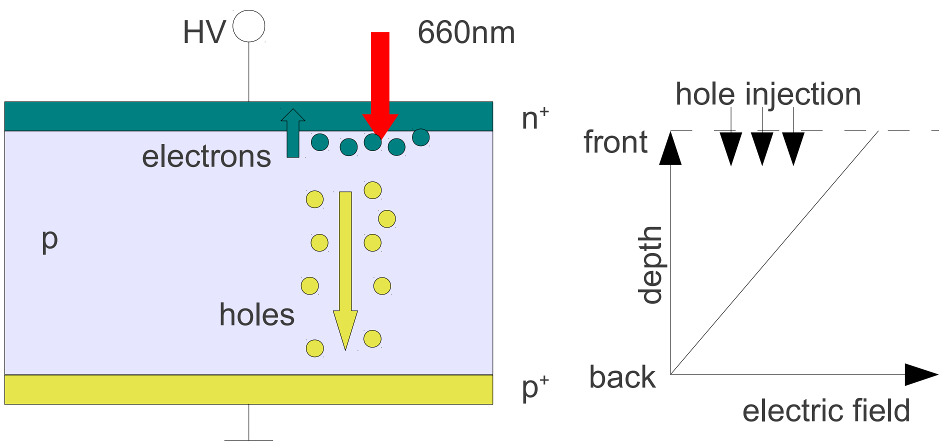


different wafer,
20C, 80min@60C

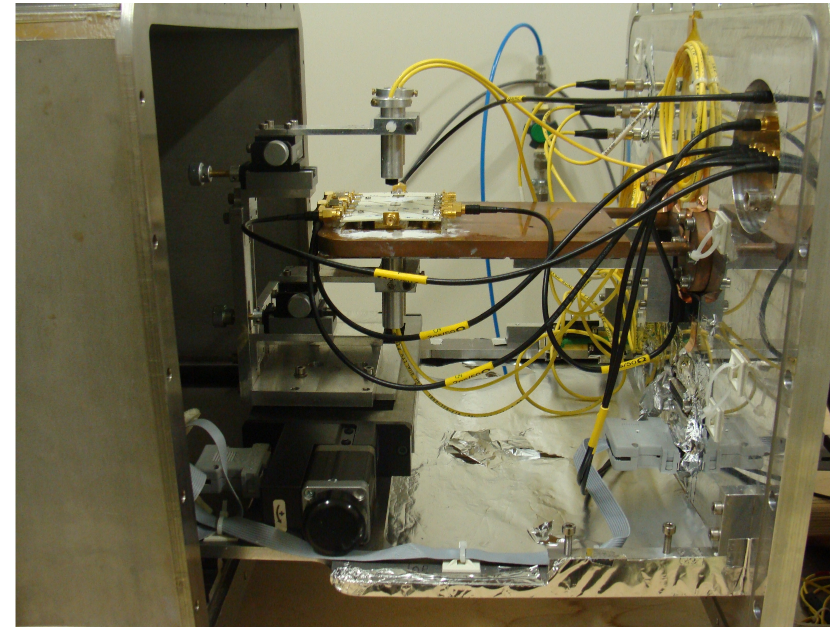
at 2e15 p/cm^2 FZ and MCz p-type in different works (different wafer productions) show same V_{fd} even if initial resistivity is different and hence V_{fd} of non-irradiated samples

- pulsed ps red/infrared laser illumination (front or back)
- generating e-h-pairs in the detector
  → drift in externally applied electric field
  → record transient of induced current pulse
- all measurements performed at -20°C, GR floating

Red TCT:



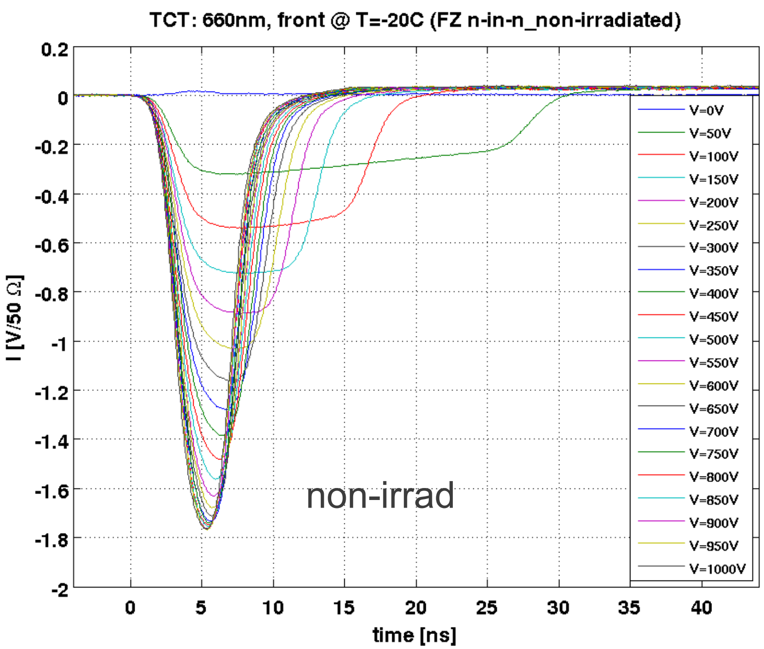
TCT-signal (induced current pulse from red Laser) is generated by only one kind of charge carriers



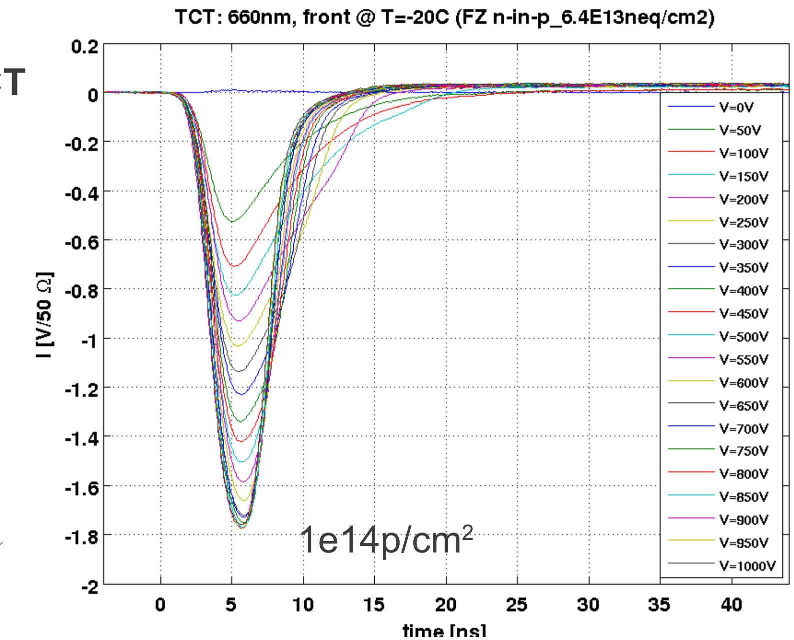
- cooling to -20°C
- Red (660 nm) and IR (1060 nm) laser illumation
- FWHM pulse width 80 ps
- Miteq 1.3 GHz 58 dB low noise amplifier
- Agilent 2.5 GHz oscilloscope
- detector bonded on thermally conductive PCB
- front biasing, decoupling with 12 GHz Bias-Tee
- Laser system with 4 focusers (front/back, red/IR) incl. beamsplitter used for reference diode to scale measurements
- humidity controlled: dry air atmosphere with dew point < -50°C
- in-situ annealing of PCB with diodes possible

→ possible to disentangle the separate contributions from electrons and holes
→ study of trapping time for e^- and h depending on fluence Φ_{eq}

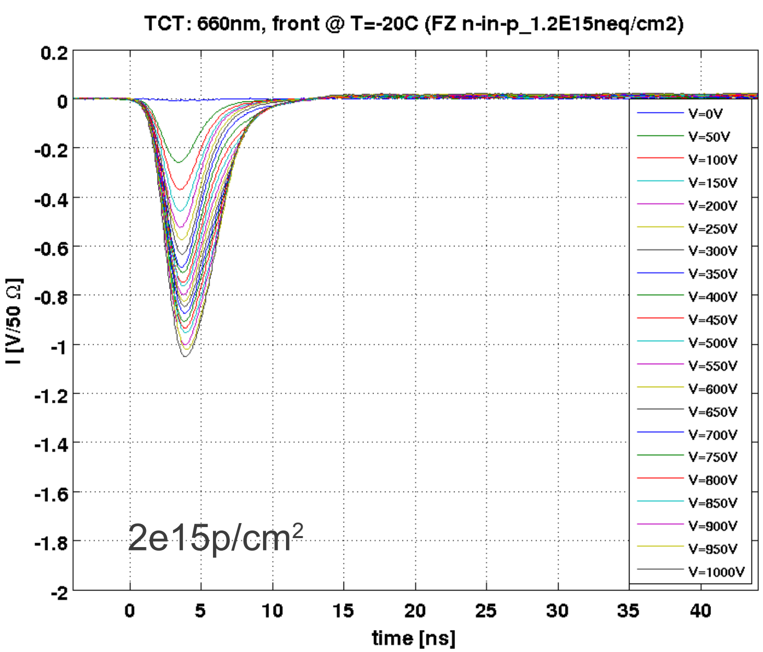
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



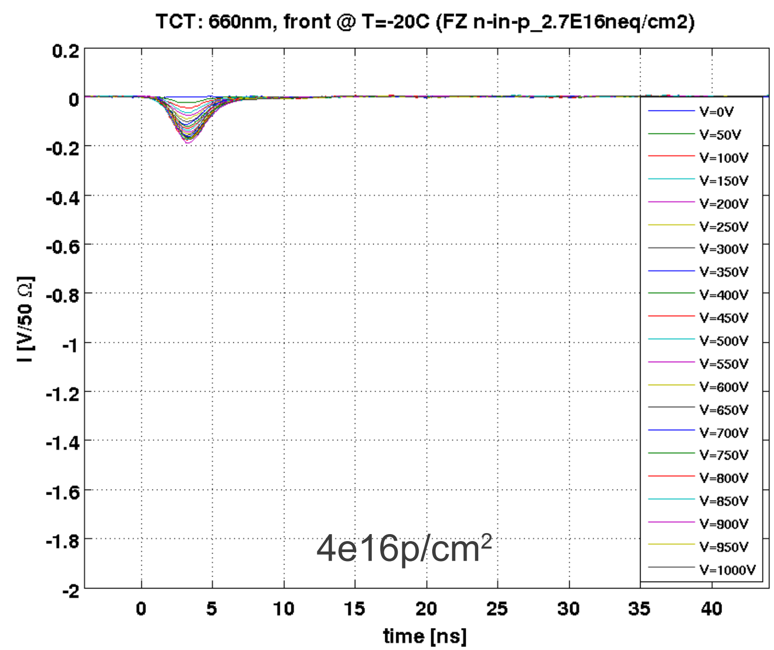
FZ n-in-p: red TCT from front side



reduced pulse width

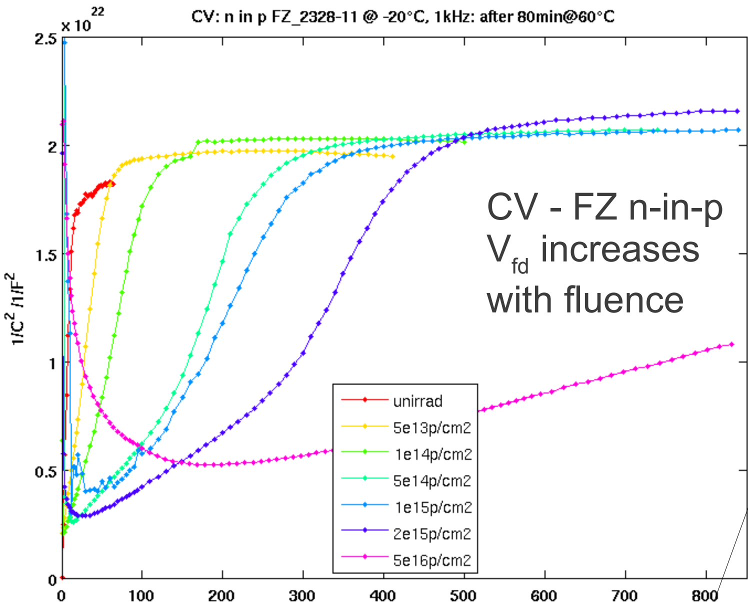


decrease of signal amplitude with fluence

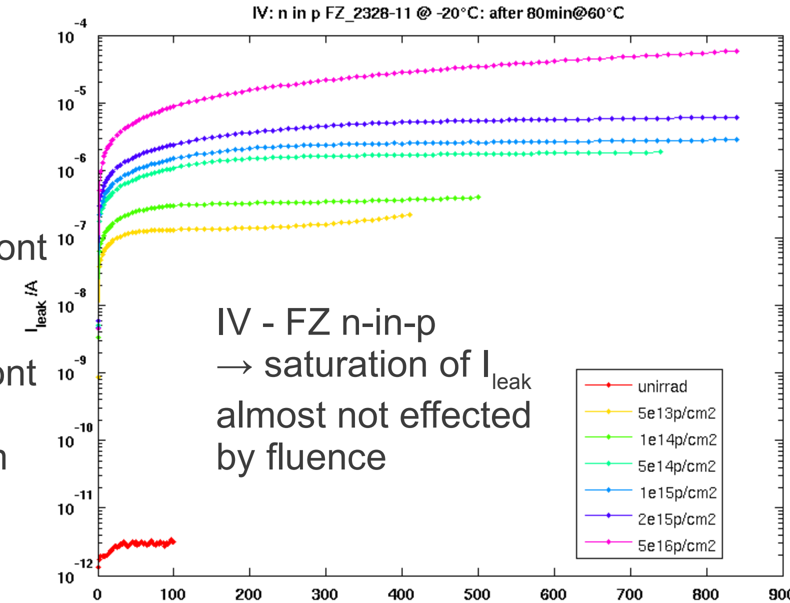


→ Collected charge by integration over pulses (25ns)

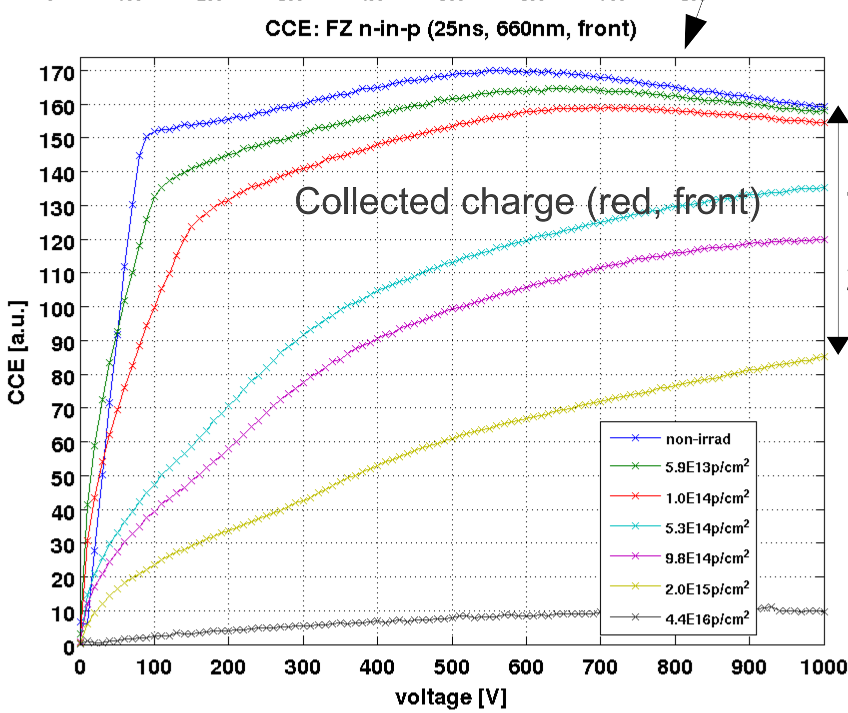
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



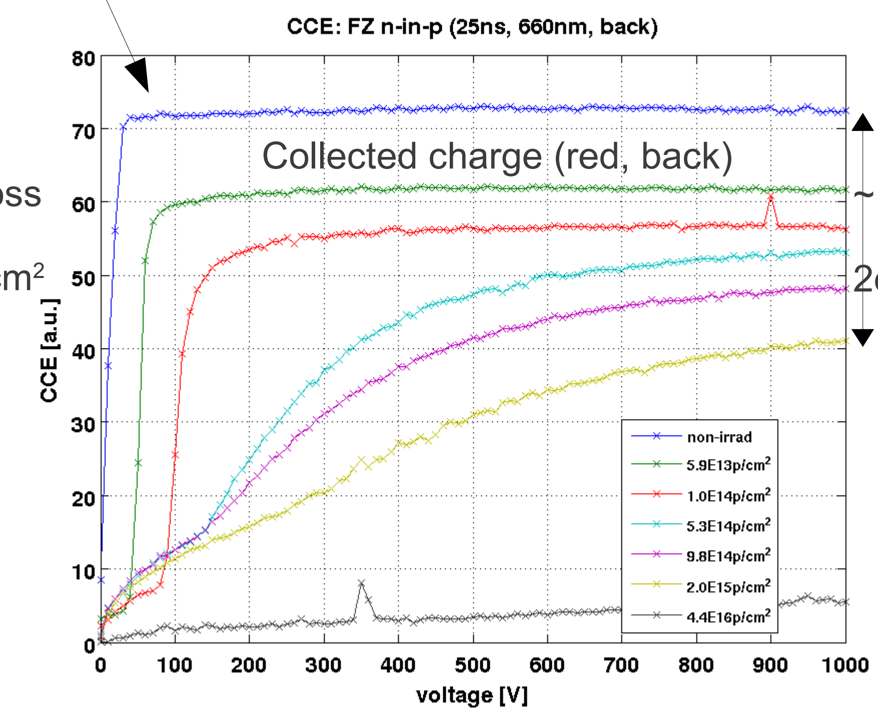
FZ n-in-p: red TCT from front vs. back



Collected charge for front and back illumination agree well with CV
→ higher signal from front side illumination
→ slightly lower V_{fd} from back CCE

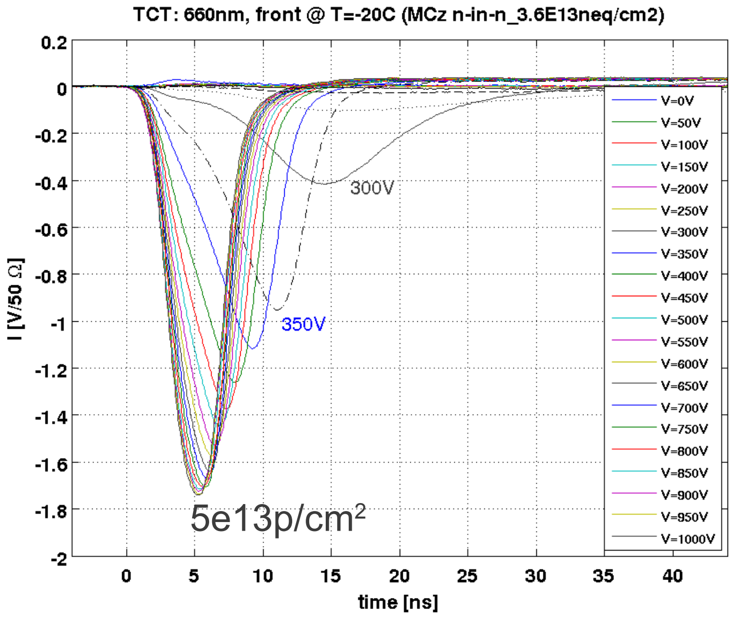


~50% loss for $2e15p/cm^2$

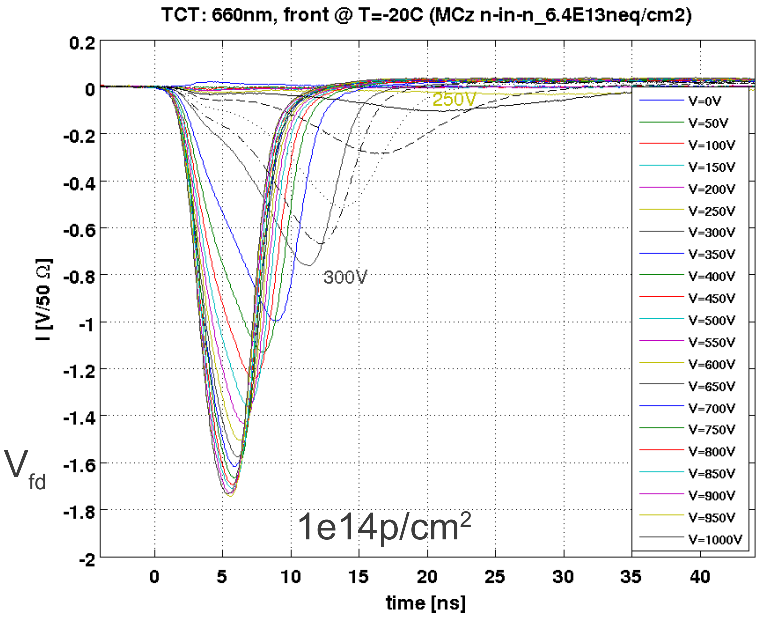


~ 48% loss for $2e15p/cm^2$

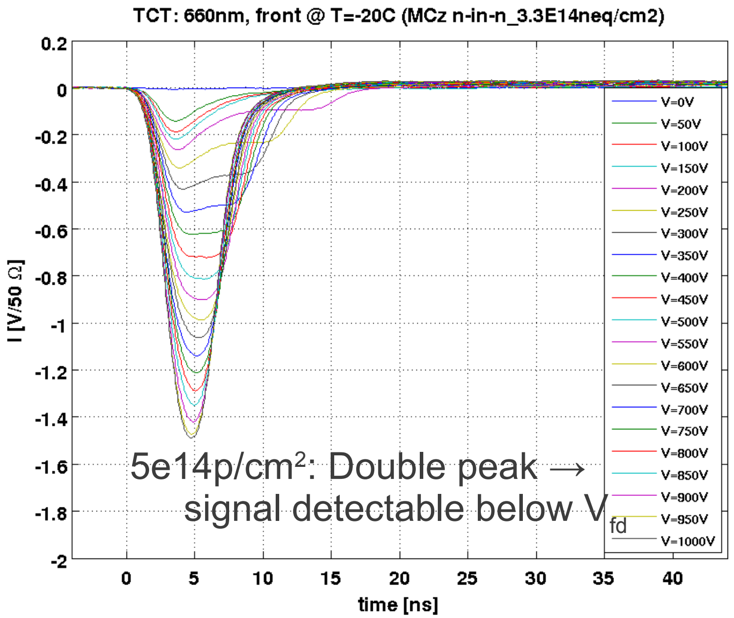
Red TCT results – signals in n-type



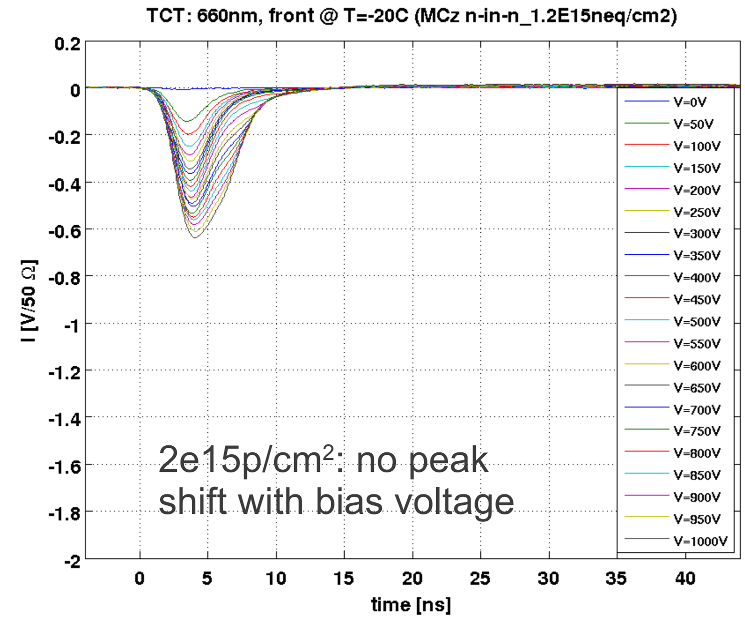
MCz n-in-n: red TCT from front side



5e13 and 1e14p/cm²:
no signal until bias 250V > V_{fd}
peak shifts in time with higher bias

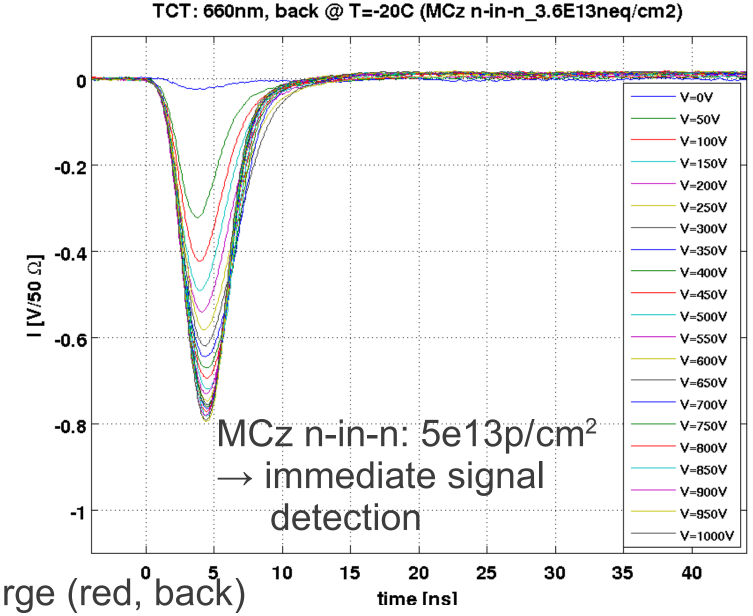


Decrease of signal amplitude with fluence



MCz n-in-n: red TCT from front vs. back

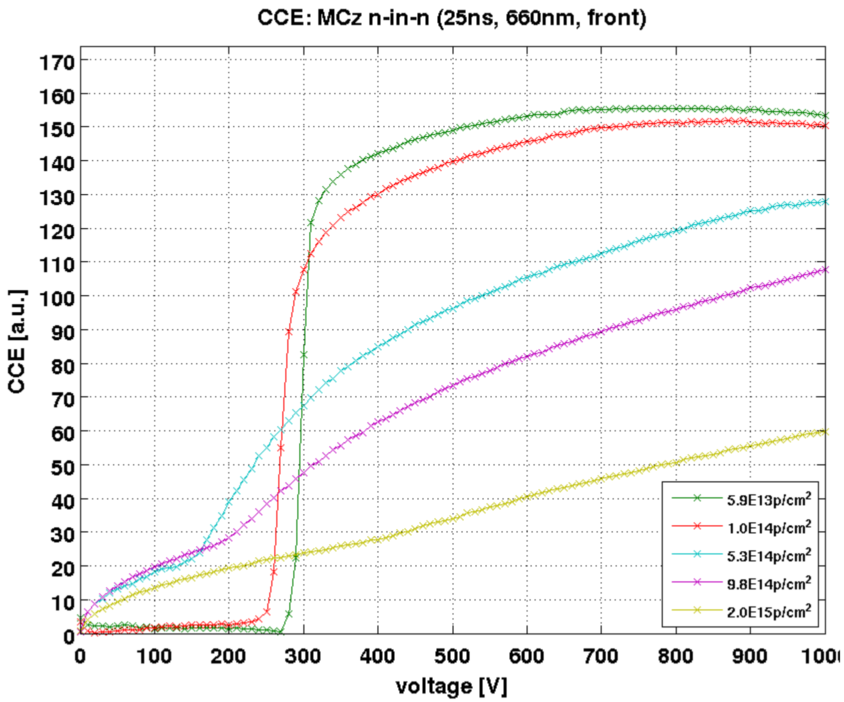
→ compare to backside illumination at lowest fluence:



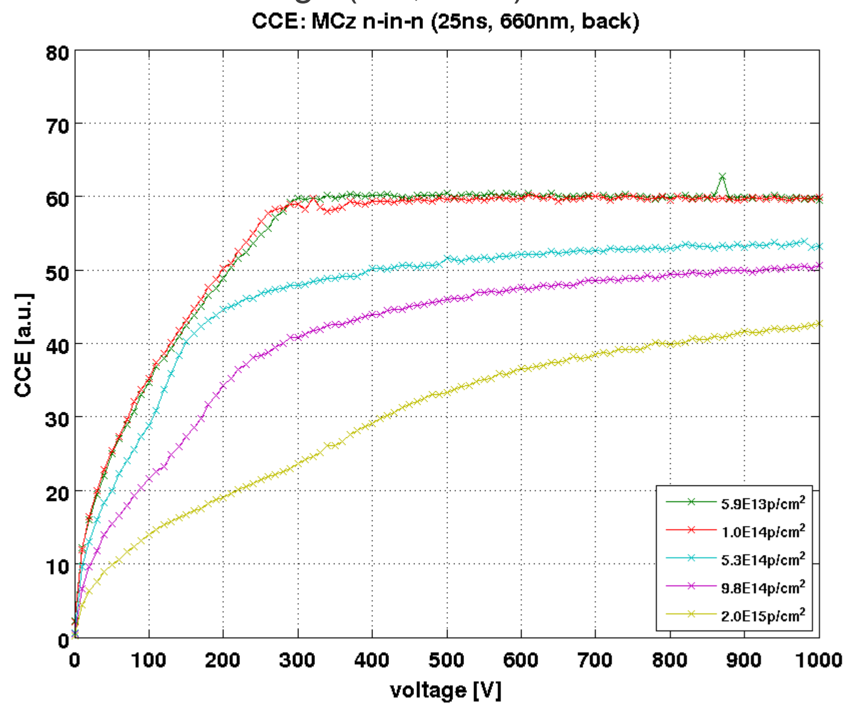
→ Collected charge of backside illumination to extract V_{fd} of lower fluence irradiated sensor

- decrease of collected charge with fluence
- shift of V_{fd} with fluence: V_{fd} for lower Φ seem to high

Collected charge (red, front)

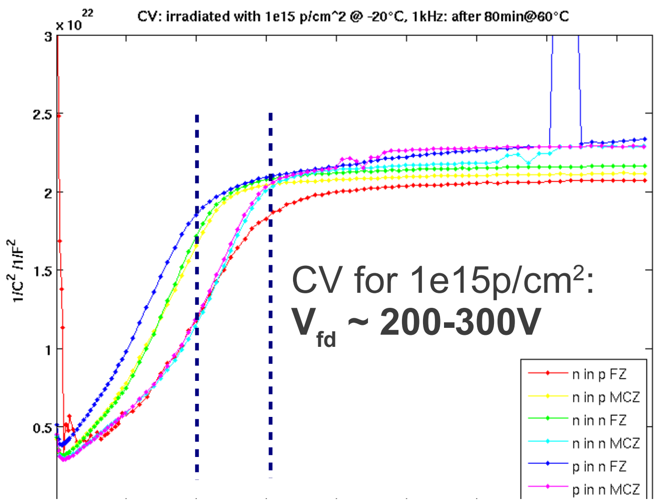


Collected charge (red, back)



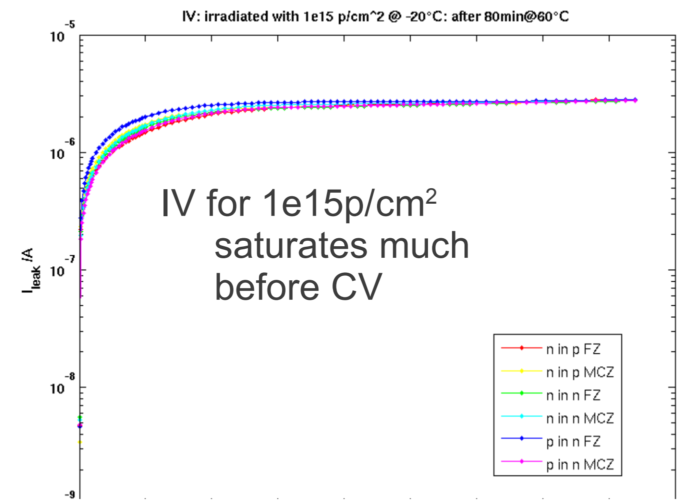
Red TCT results

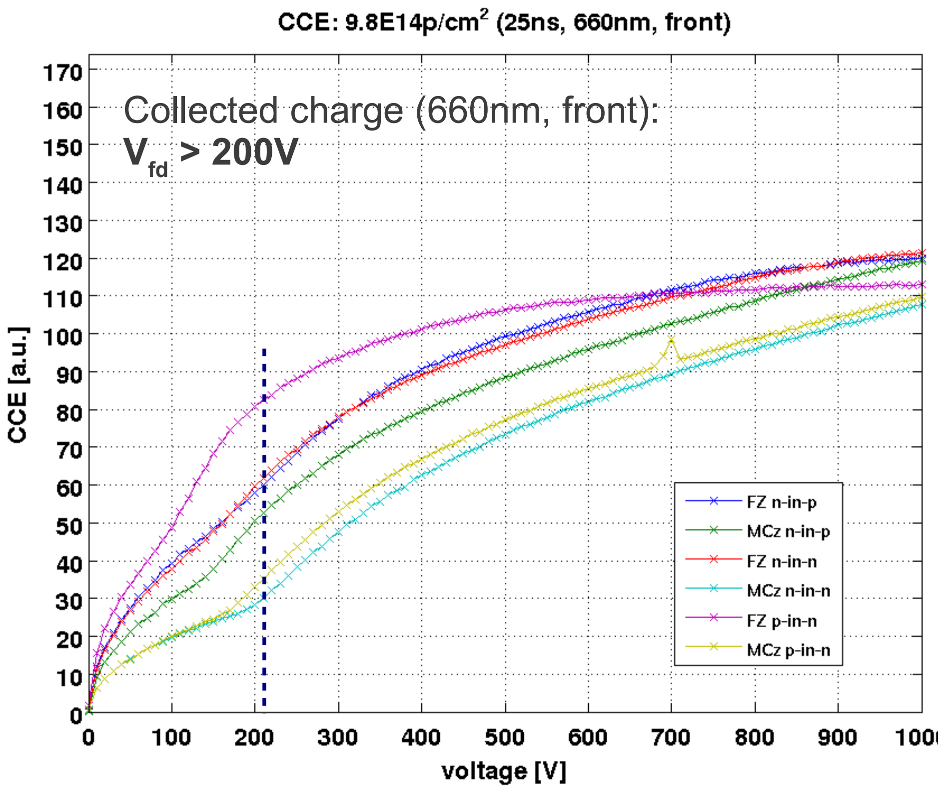
Φ = 1E15p/cm²: comparison of CV/IV with collected charge by red TCT:

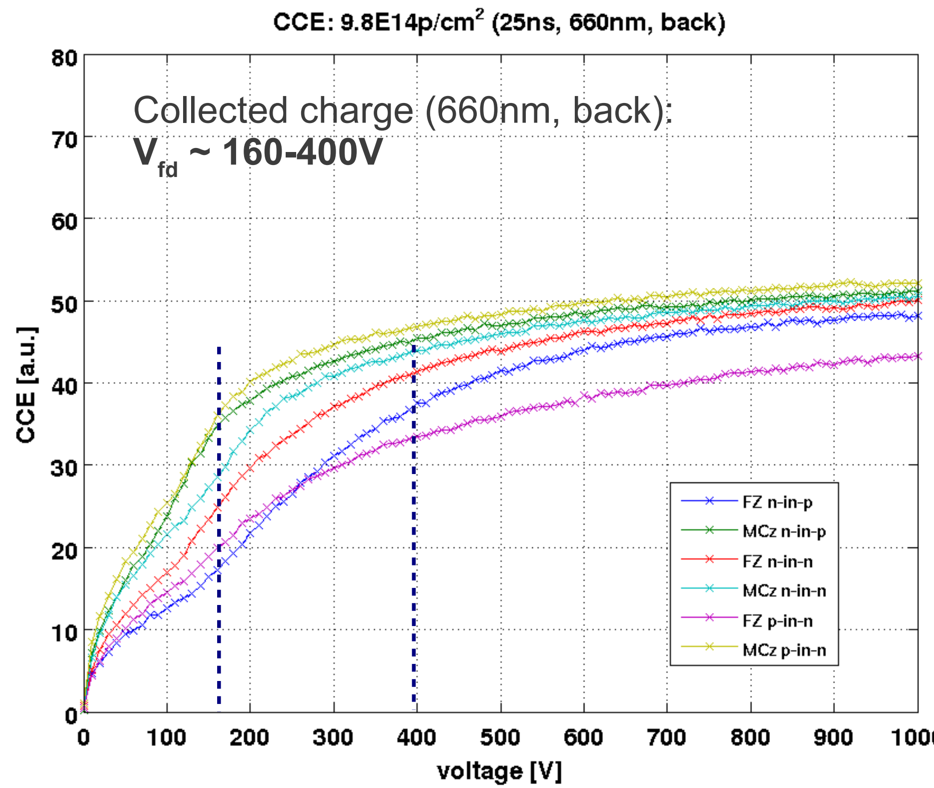


→ extracted V_{fd} values in the same range for CV and TCT front+back

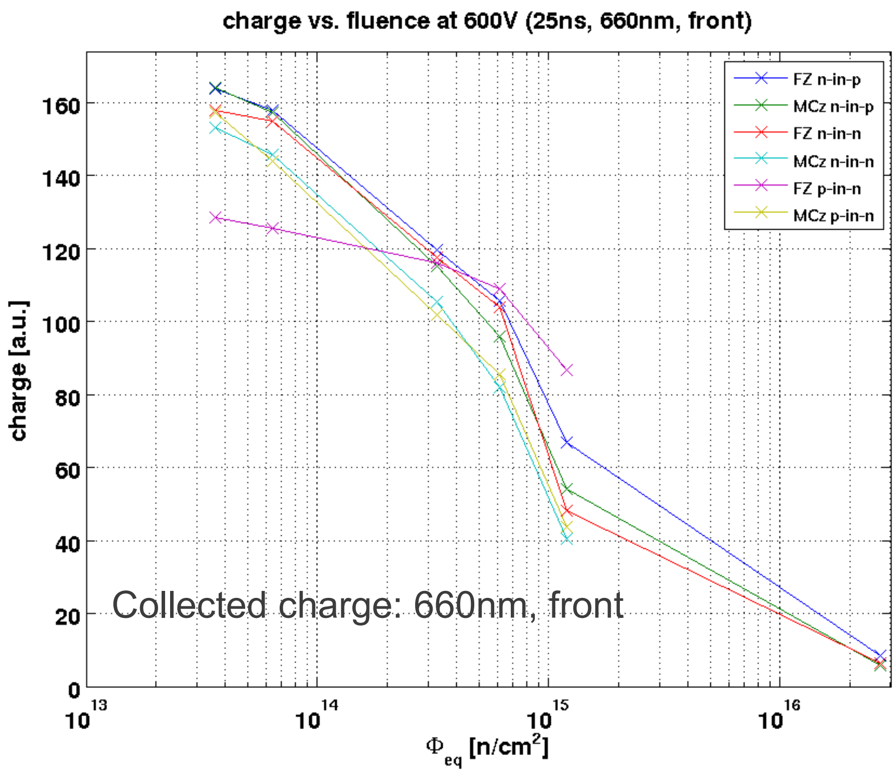
→ clearer from TCT back than front

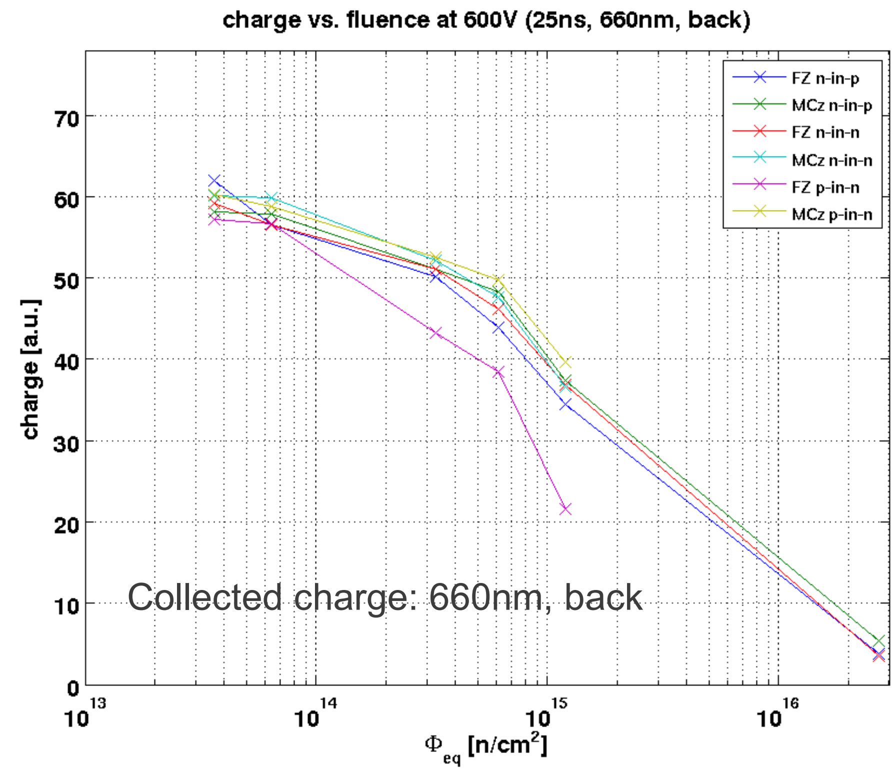






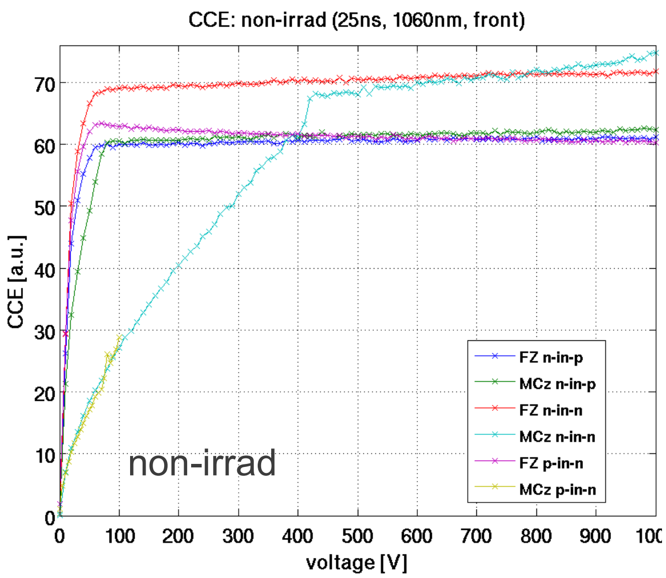
Collected charge at 600V vs. fluence

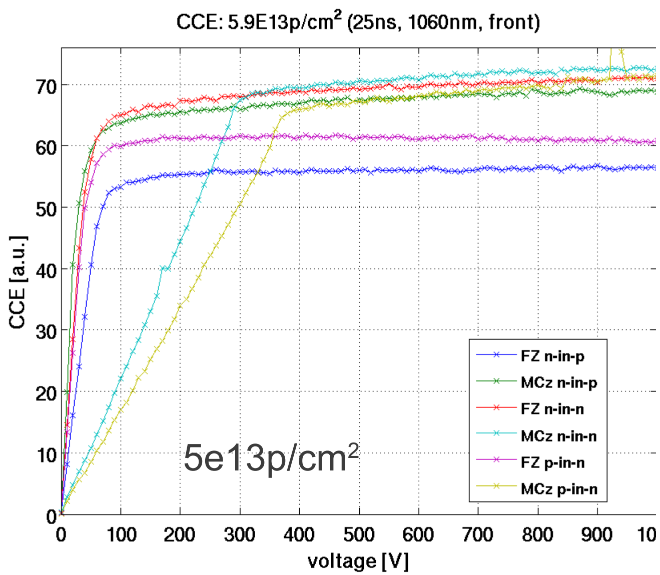


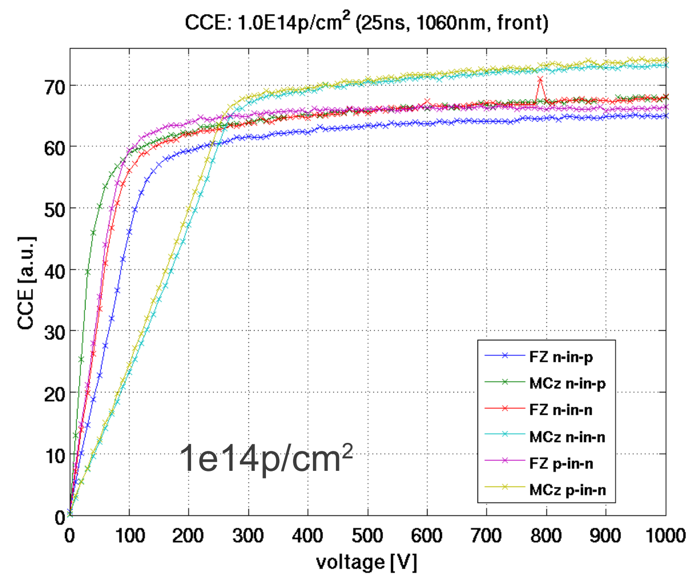


→ after irradiation with 7e14n/cm^2 all types show similar behaviour
except FZ p-in-n degrades (faster) with fluence

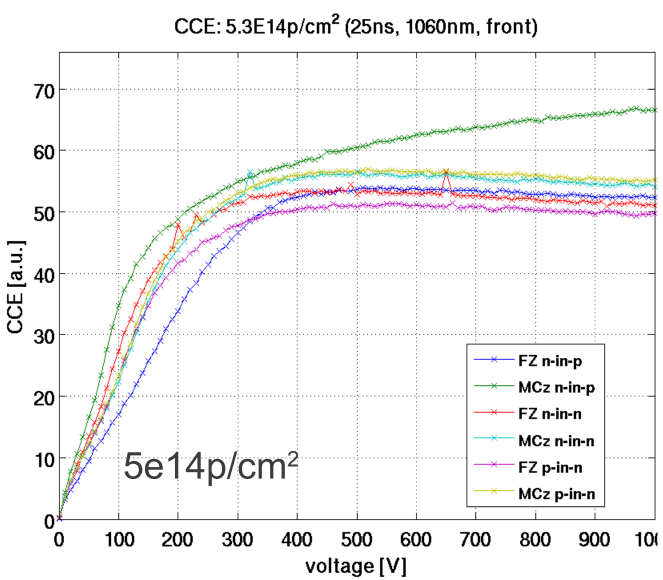
CCE with Laser-TCT

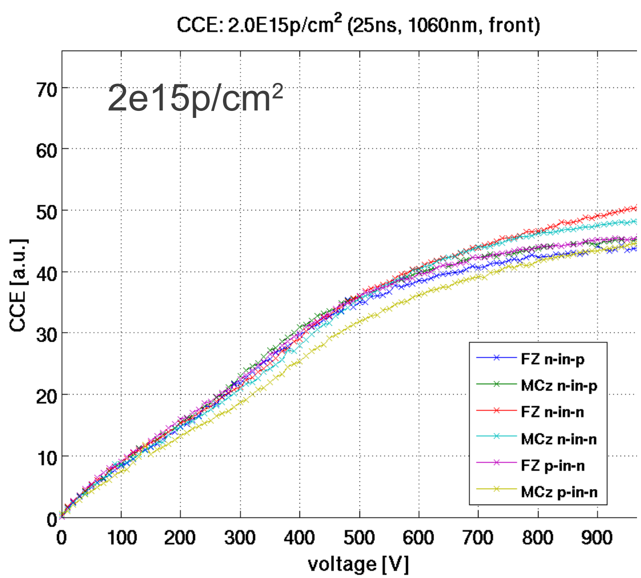


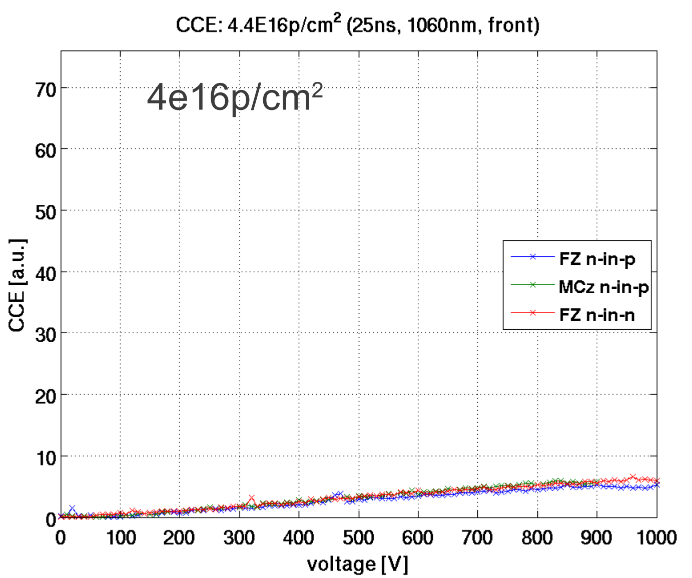




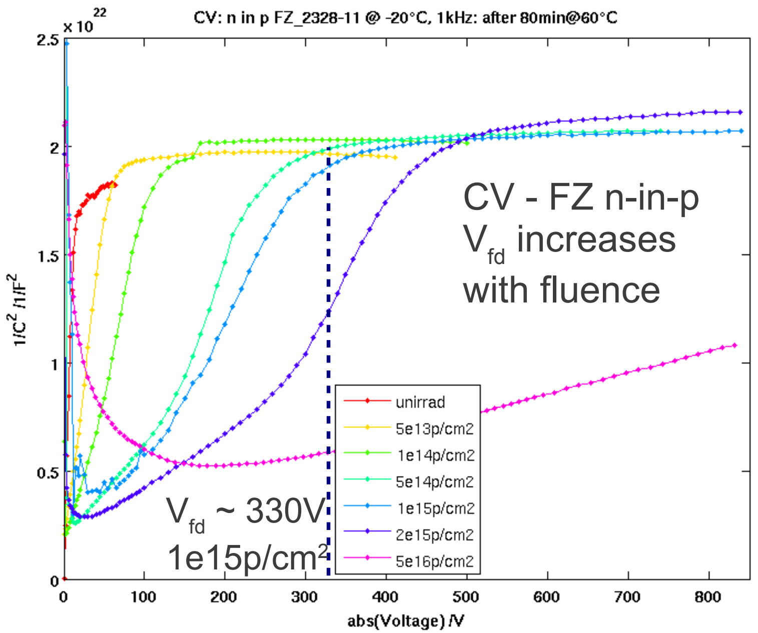
- Charge collection efficiency (CCE) measured using IR-TCT pulses → integration over 25ns
- Charge scaled with reference diode after beam is split → **scaling problem**?! → need to recheck!







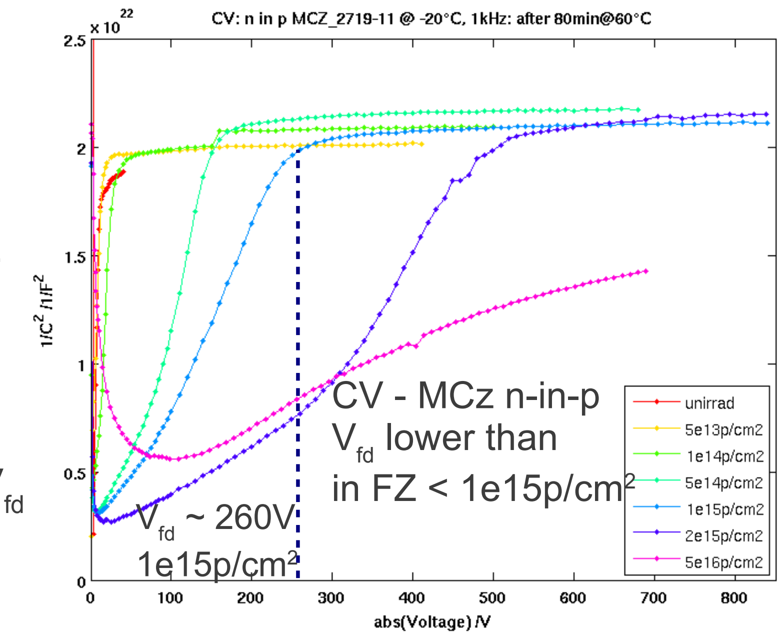
IR TCT results

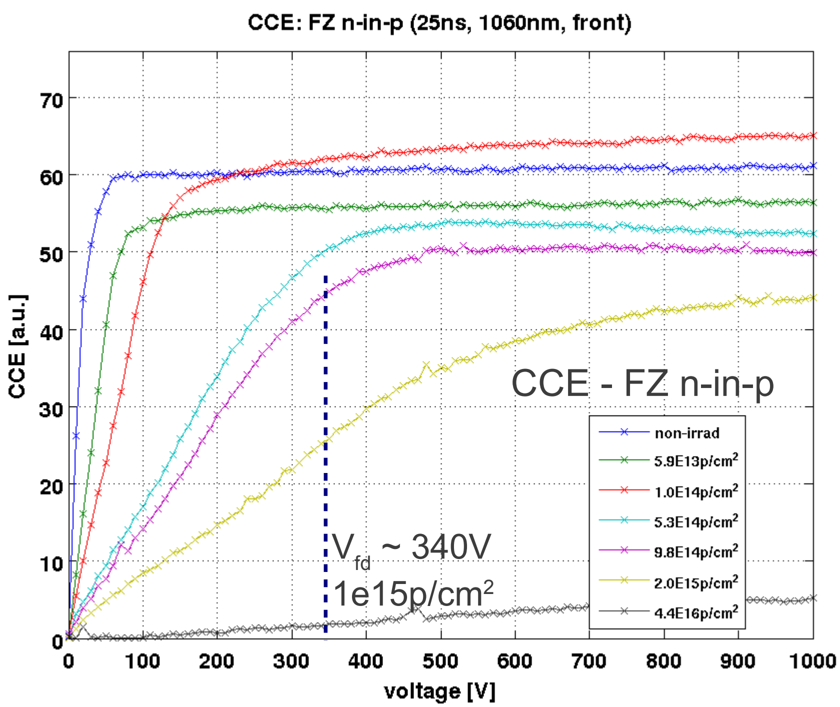


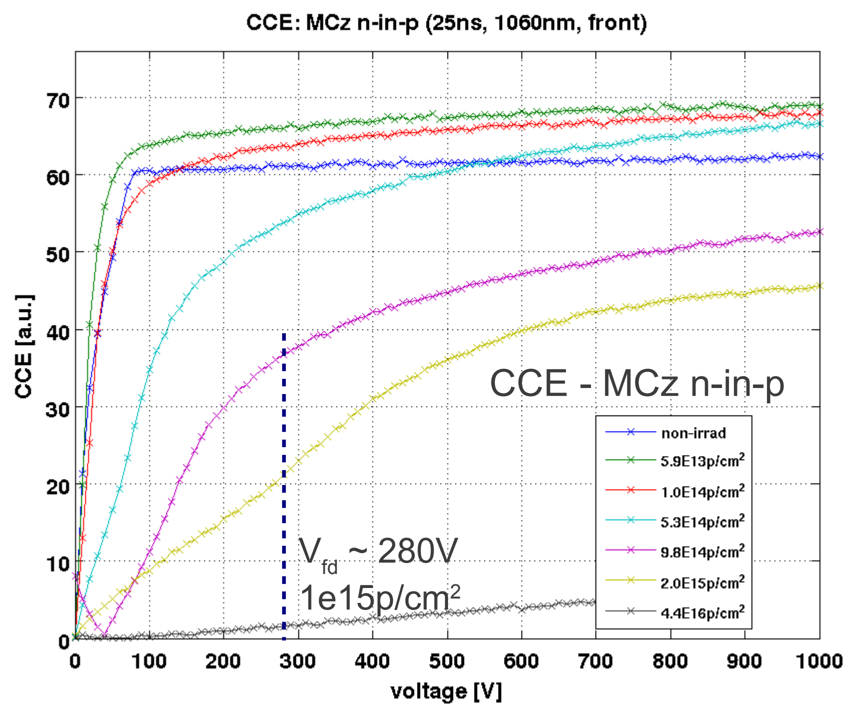
Comparison of CV and CCE between n-in-p FZ and MCz for various fluences

→ decrease of charge collection with fluence

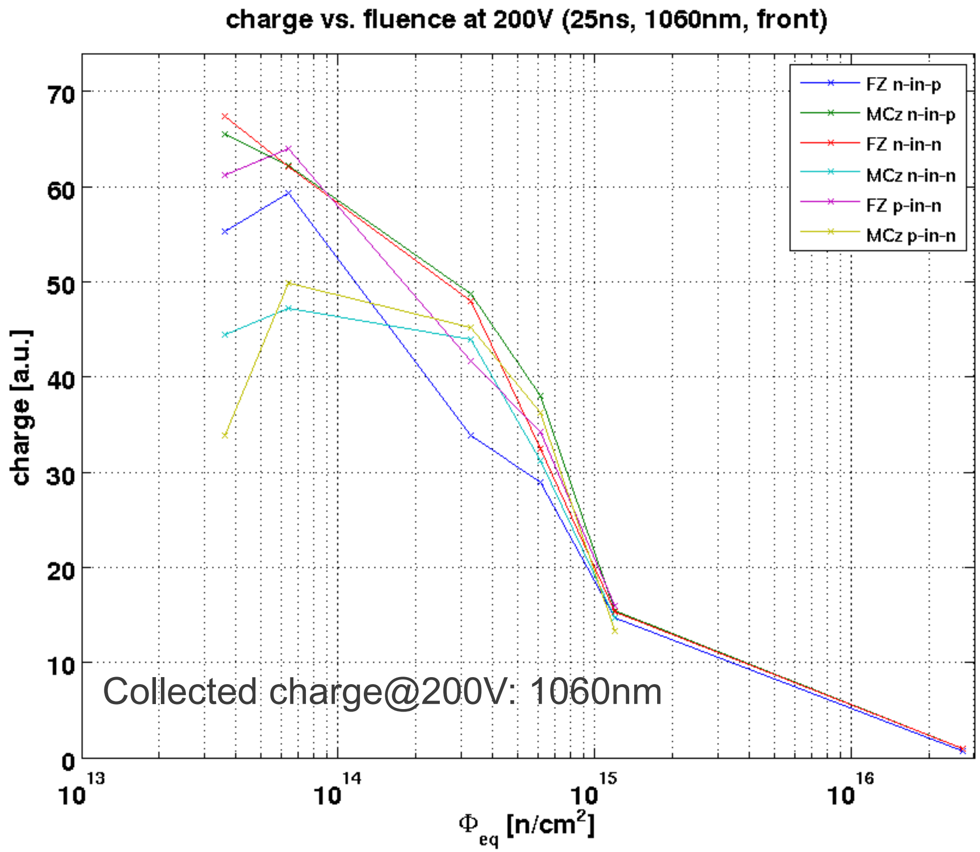
→ good agreement in V_{fd} at 1e15p/cm² (marked values as doted line)

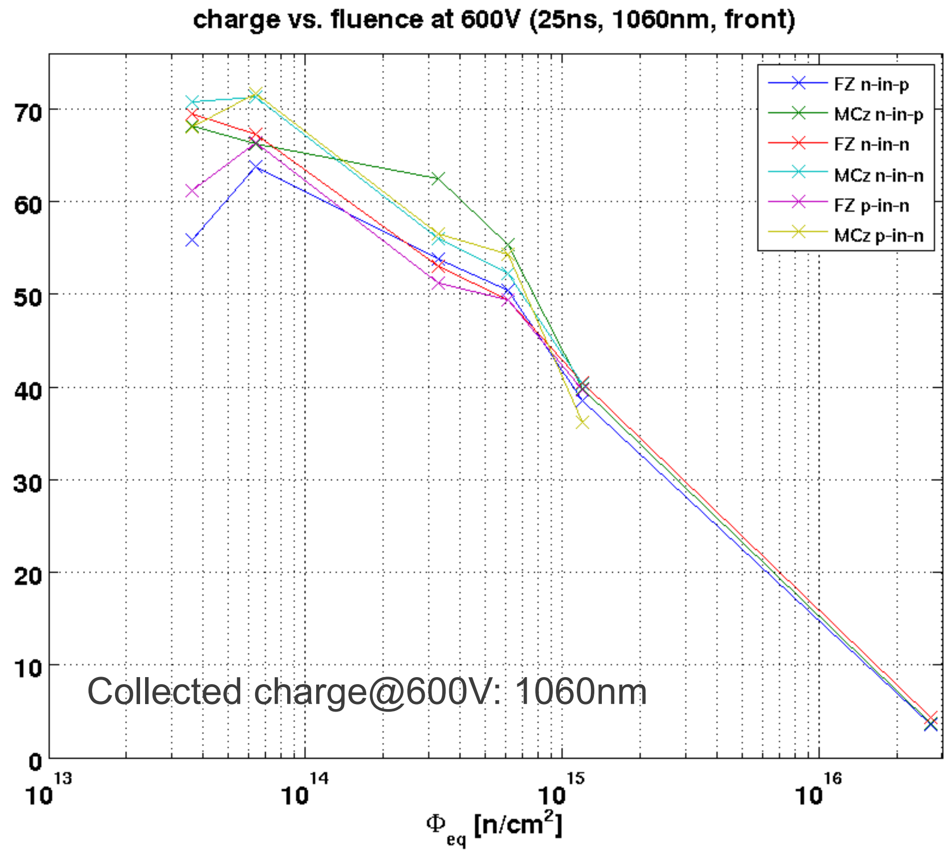






CCE with Laser-TCT – collected charge





CCE (IR) vs. fluence @ 200V and 600V

→ performance degrades with higher fluence

→ at higher fluences > 1e15n/cm² similar CCE for all different materials

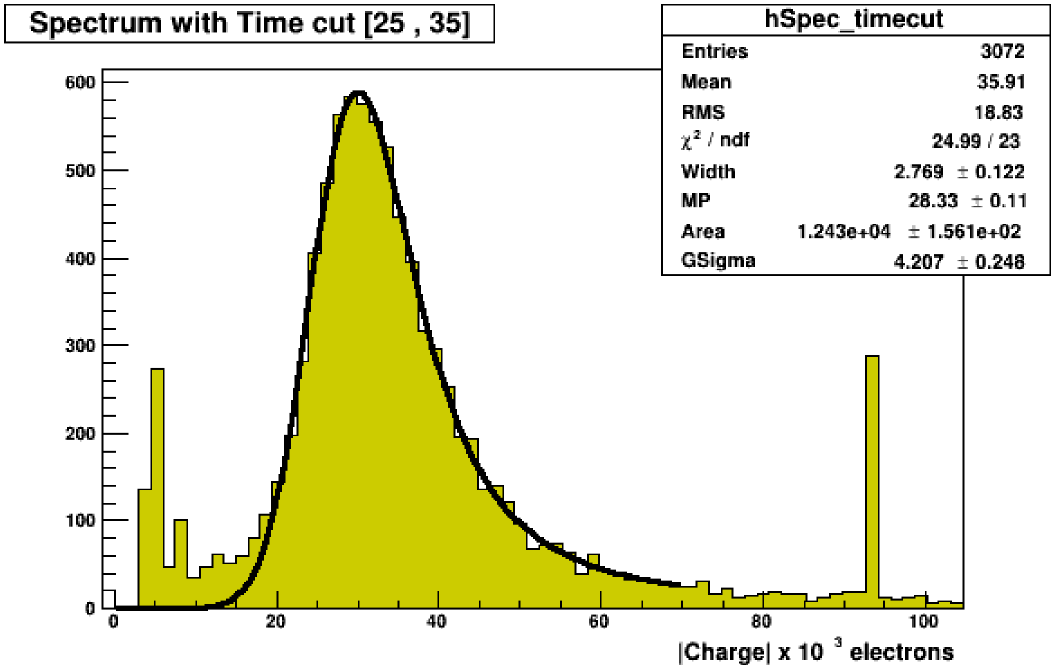
Conclusion

- systematic measurements were performed of a set of Micron pad detectors
  - made of different types (n-in-p, n-in-n, p-in-n) of FZ and MCz
  - irradiated with Protons to fluences from 5e13p/cm^2 to 4e16p/cm^2
- IV/CV study of irradiated Micron diodes:
  → leakage current independent of material type, with:
  MCz n-in-n show high current as expected from single sided processing
  → $\ln(I_{leak})$ scales linear with 1/T over all fluences
  activation energy E_{eff}= (1.209 ± 0.009)eV
  → MCz n-in-p shows lower V_{fd} compared with FZ n-in-p for Φ<1e15p/cm^2
- TCT measurements with red/IR front&back illumination
  - extracted CCE properties
  - problems with calibration → unclear scaling – recheck!
  - compared V_{fd} from CV and collected charge
  - for Φ>1e15p/cm^2 all materials show same behaviour
- suitable systematic set of data for different materials and fluences to compare with simulations and predict performances

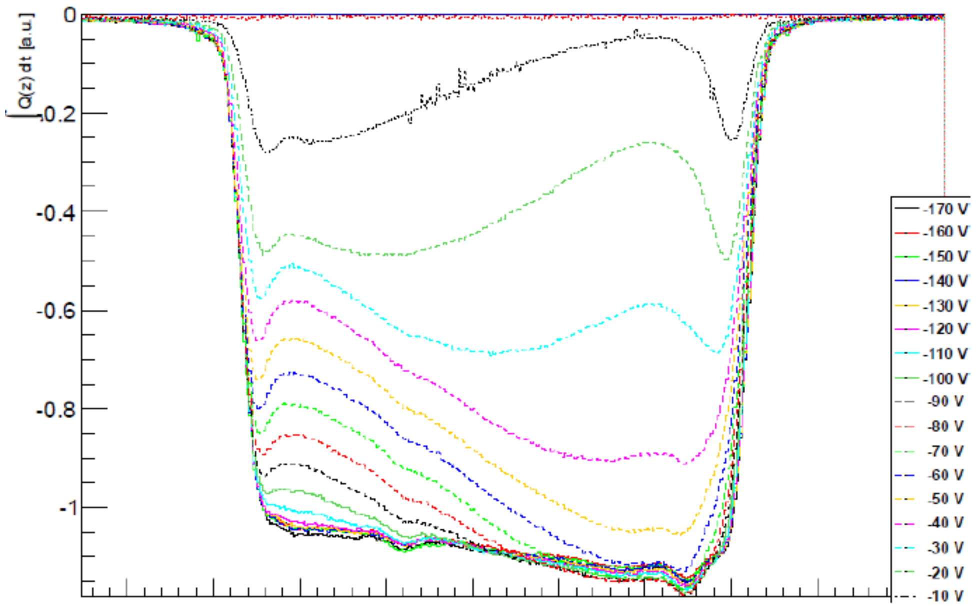
Outlook

- comparison with simulation
- T- dependence of TCT-signal
- study of trapping time for e^- and h depending on Φ with red TCT
- further annealing studies on V_{fd} and N_{eff} with diodes/strip sensor
- Alibava and e-TCT measurements on strip sensors

Charge spectrum with ^{90}Sr Alibava setup on non-irradiated FZ n-in-p strip sensor



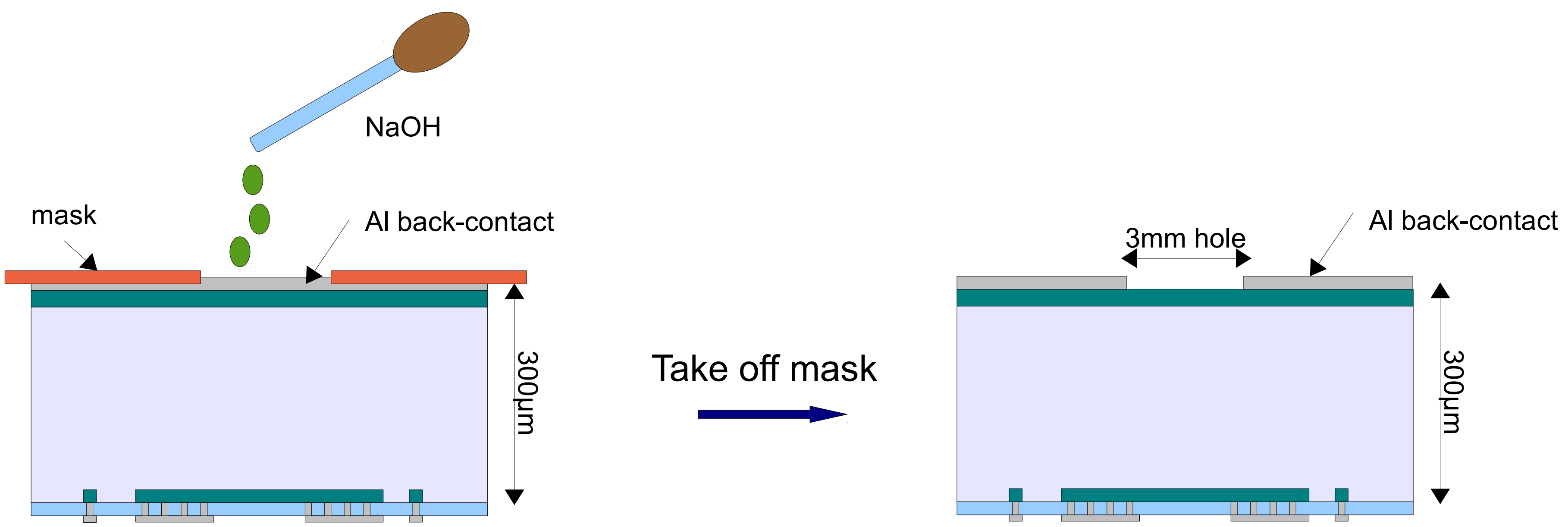
eTCT on non-irradiated FZ n-in-p strip sensor



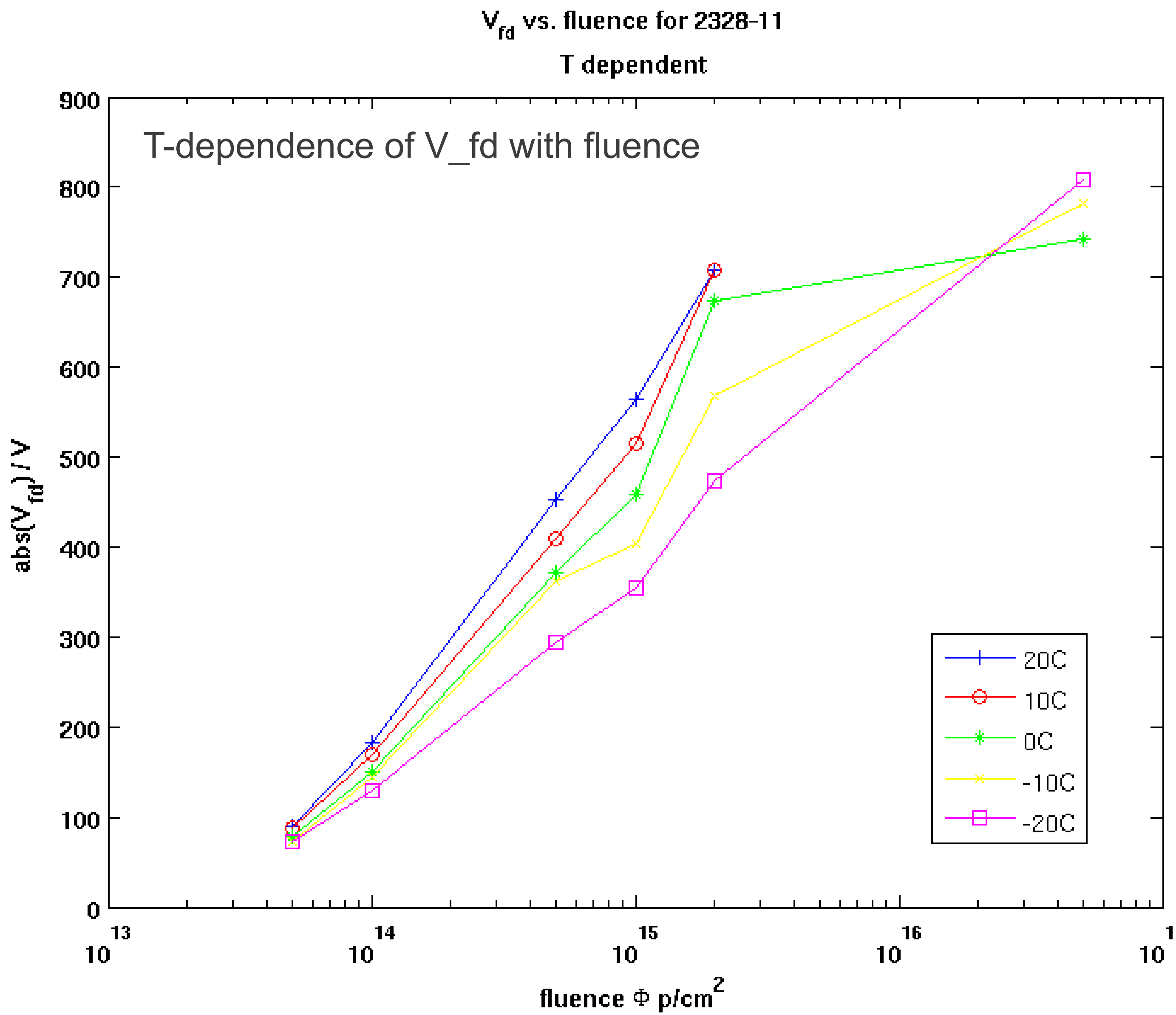
Thank you for listening! Questions?!

• IR laser light for proper CCE measurement
→ homogeneous introduction of charge carriers represents MIP

• windows needed in both electrodes to avoid reflections
• etching of full metallized Al-backside:
  → mask of Kapton: holes of d = 3mm
  → sodium hydroxide solution (NaOH)



→ no effects or changes in IV/CV after Al-etching!



V_{fd} vs. fluence for 2328-11
T dependent
T-dependence of V_fd with fluence
abs(V_{fd}) / V
fluence Φ p/cm^2
0
100
200
300
400
500
600
700
800
900
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
20C
10C
0C
-10C
-20C