Irradiation study with passive CMOS pixel detector structures on RD50-MPW2 chips

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RD50 CMOS common project

RD50 CMOS project participants:
IFIC (CSIC-UV), Valencia, CPPM, Marseille , U. Liverpool, HEPHY, Vienna, U. Barcelona, IFAE, Barcelona, FBK, Trento, U. Birmingham, U. Lancaster, U. Sevilla, JSI, Ljubljana, IFCA (CSIC), Santander

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RD50

Introduction

- **RD50 collaboration common project**
- RD50-MPW2 is a CMOS pixel detector prototype chip in 150 nm LFoundry process
- successor of RD50-MPW1 → MPW2 lower leakage current, higher breakdown voltage
- delivered in February 2020
- more info on slides presented at June 2020 RD50 workshop:

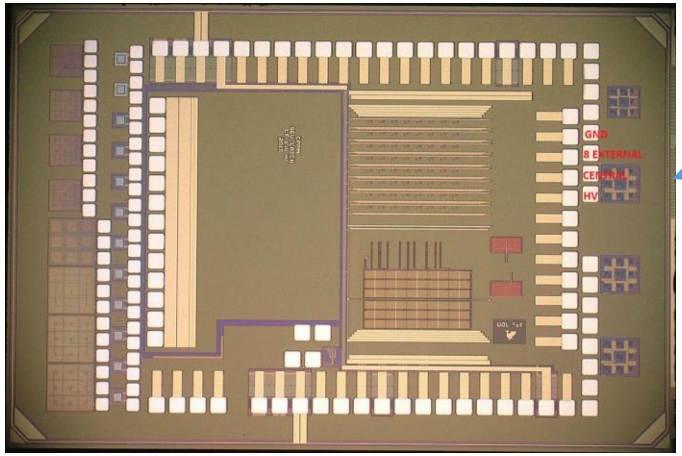
R. Marco https://indico.cern.ch/event/918298/contributions/3880520
M. Franks https://indico.cern.ch/event/918298/contributions/3880578/

- chips produced on p-type wafers, 4 resistivities: 10 Ωcm (standard), 0.5-1.1 kΩcm , 1.9 kΩcm , >2 kΩ·cm

- Chips irradiated in reactor in Ljubljana to fluences from 1e13 n/cm² to 2e15 n/cm²

- E-TCT and I-V with passive pixel arrays

RD50-MPW2 CMOS chip



2 mm

3 mm

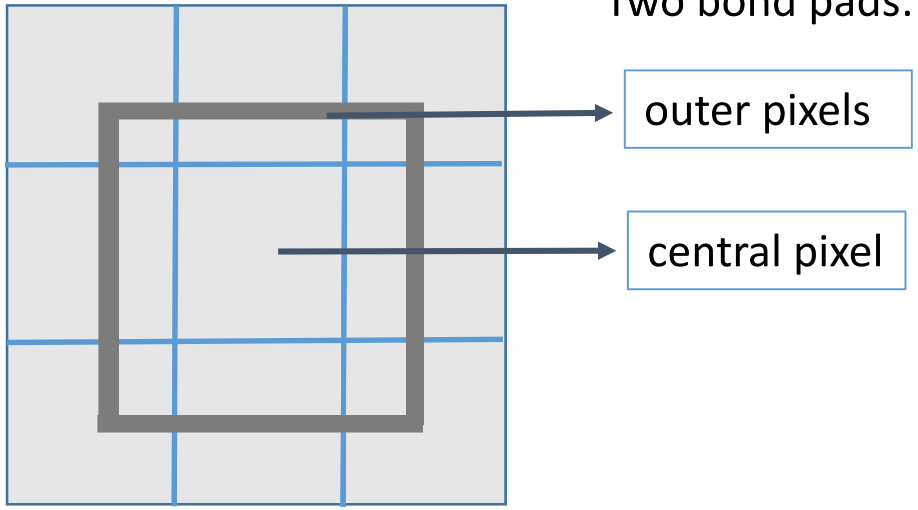
Passive test structure:

- 3x3 pixel matrix
- 60 µm x 60 µm pixels
- round corners
- 8 µm p-n spacing

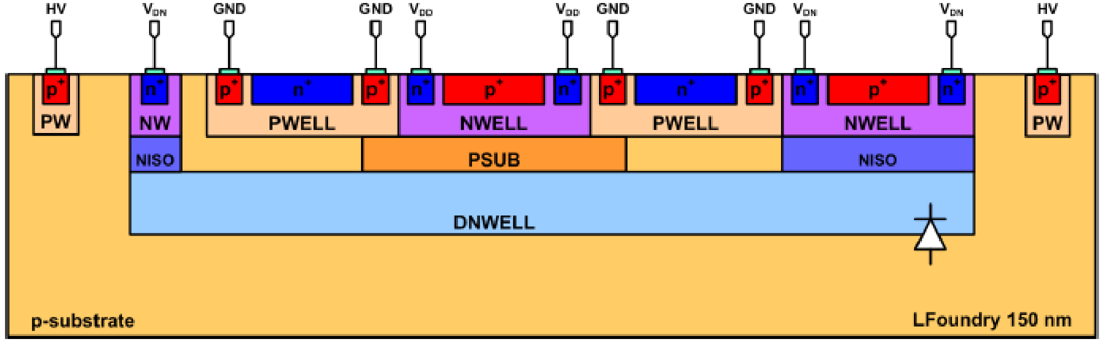
- central pixel to read out
- outer pixels connected together

3x3 pixel matrix

Two bond pads:



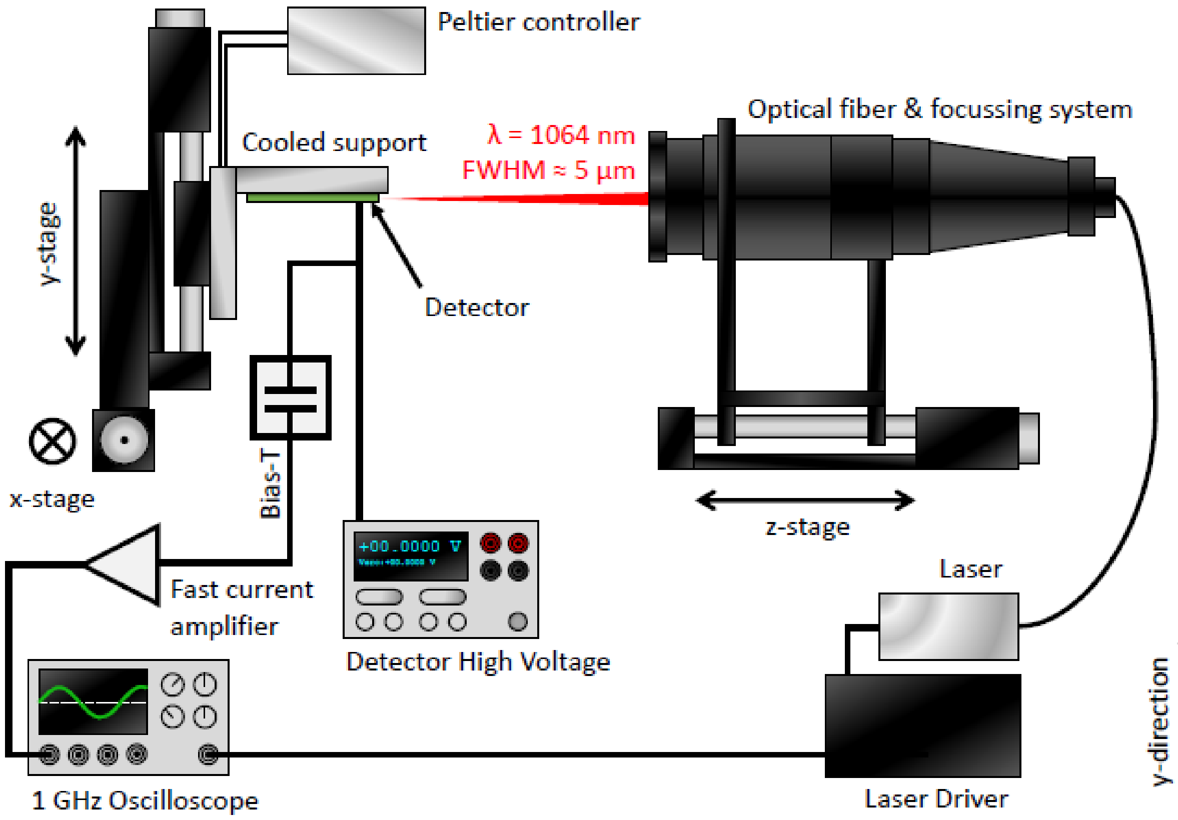
- passive pixel (no transistors in the wells)
- DNWELL connected to HV and to amplifier via bias-T
- P-substrate connected to ground
- chips 270 um thick, back plane not processed



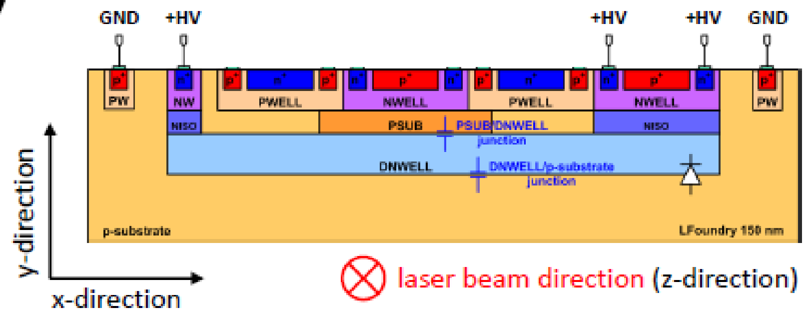
Slide from M. Franks from 36th RD50 workshop: https://indico.cern.ch/event/918298/contributions/3880578/

www.particulars.si

RD50-MPW2 e-TCT experimental setup

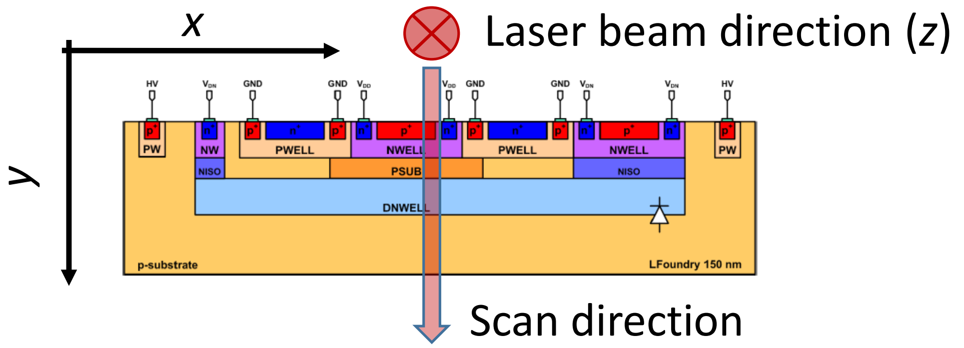


- E-TCT measurements
  - Beam diameter in the silicon FWHM ≈ 5 µm
  - Width of light pulses ≈ 300 ps, repetition rate 500 Hz
- Connection scheme:
  - INNER = +HV
  - sub! = GND

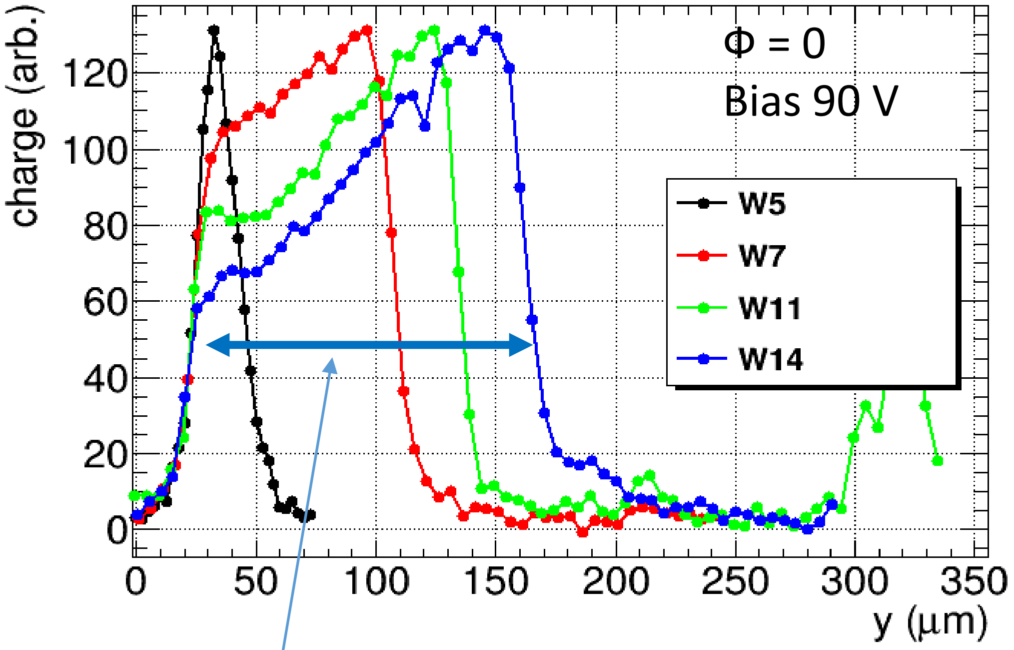


E-TCT

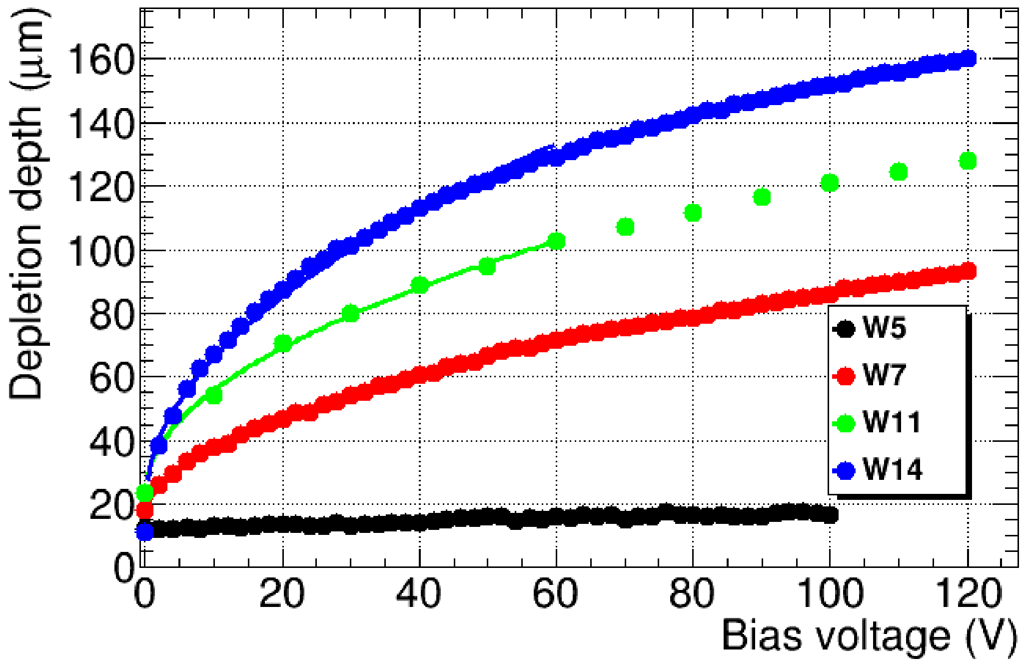
- scan across the centre of central pixel of the array
- central pixel read out
- all measurements done at 20 C



- charge collection profiles



Depletion depth

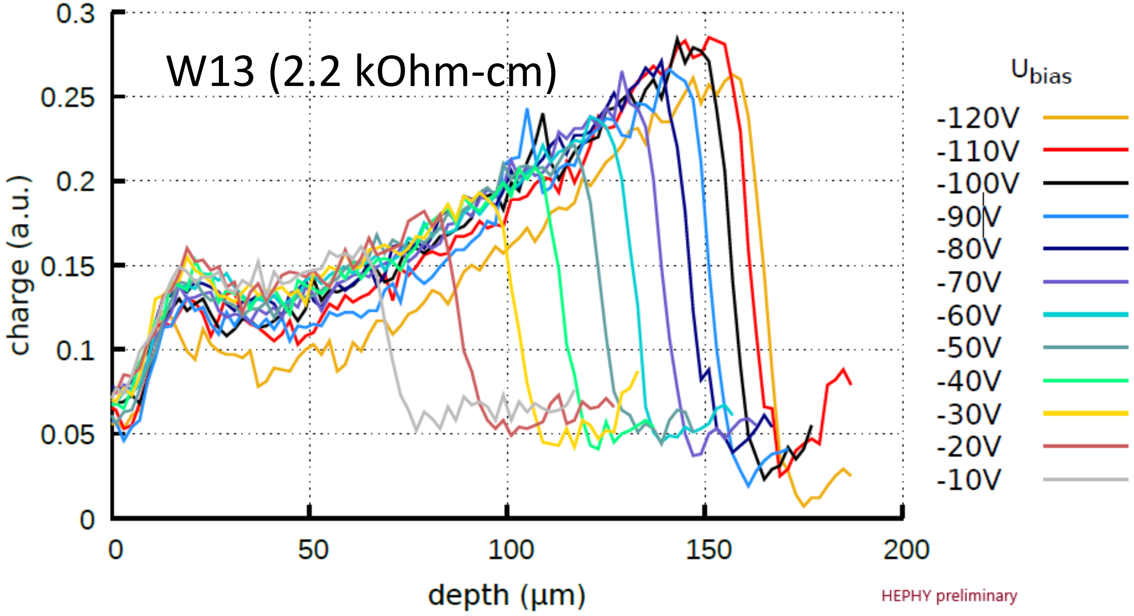


Fit: $$d = d_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} \cdot V_{sub}}$$ → extract N_{eff}

E-TCT

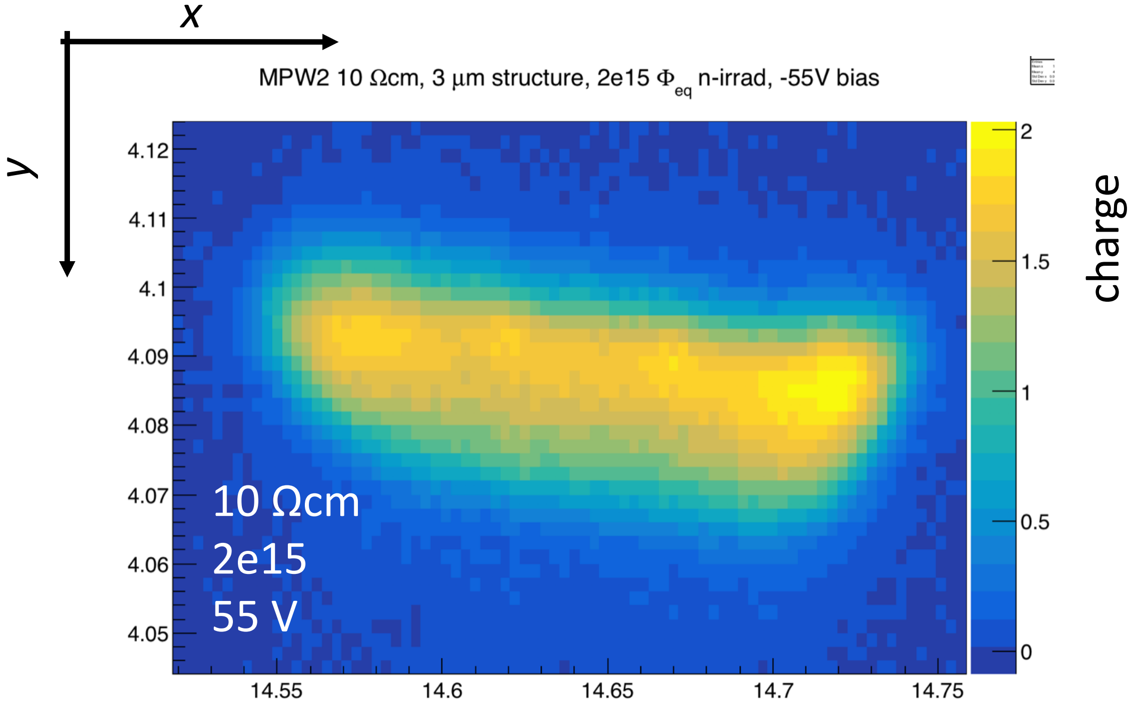
E-TCT studies with RD50 MPW chips ongoing at other institutes within RD50 CMOS project
➔ results at next RD50 workshops

HEPHY, Vienna, Austria



- Preliminary results:
  - optics: single focusing lens (3 mm focus)
    ➔ preparing to use Particulars optics
  - cividec amplifier

Lancaster University

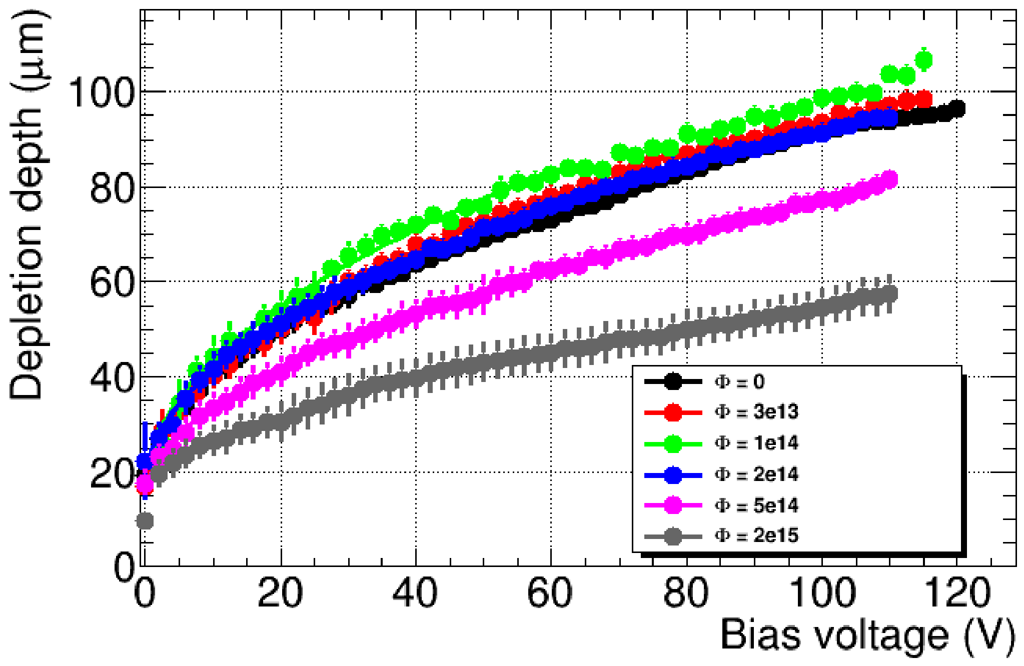


- systematic studies with samples from standard resistivity wafer (~ 10 Ωcm) going on in Lancaster
  ➔ large increase of depletion depth observed due to acceptor removal
- Particulars setup

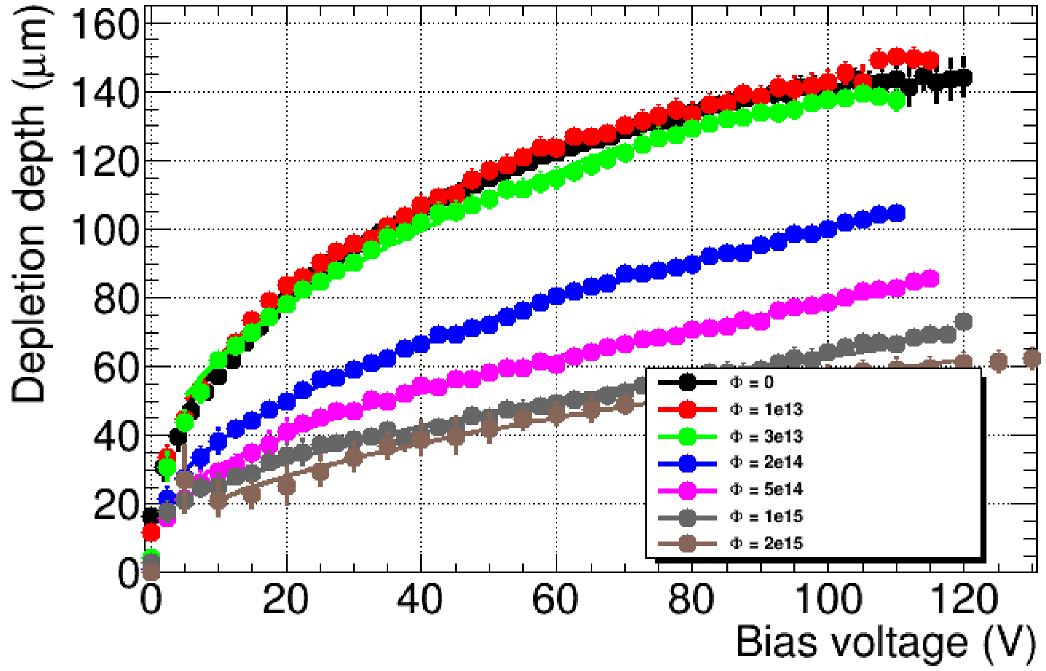
E-TCT with irradiated chips

- annealed at 60°C for 80 minutes
- measured at 20°C

MPW2 W8 (0.5 kΩcm)



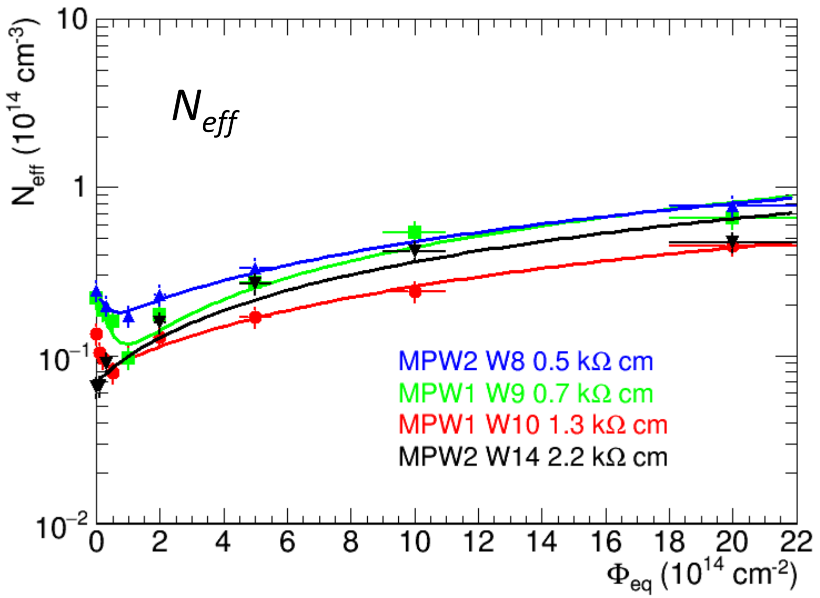
MPW2 W14 (2.2 kΩcm)

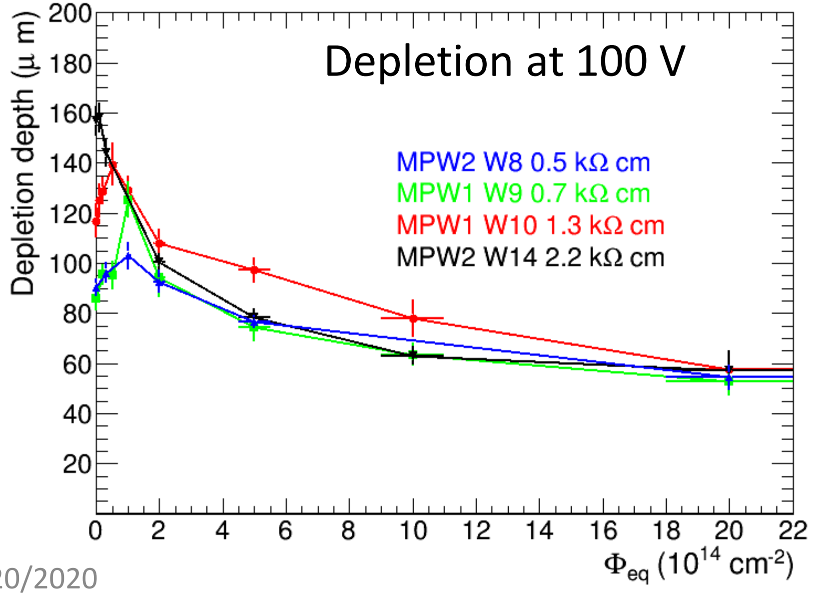


Depletion depth d: $d = d_0 + \sqrt{\frac{2\varepsilon\varepsilon_0}{e_0 N_{eff}} \cdot V_{sub}}$ → extract N_{eff}

Acceptor removal

Fit: $N_{eff} = N_{eff0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq})) + g_C \cdot \Phi_{eq}$





Fit parameters

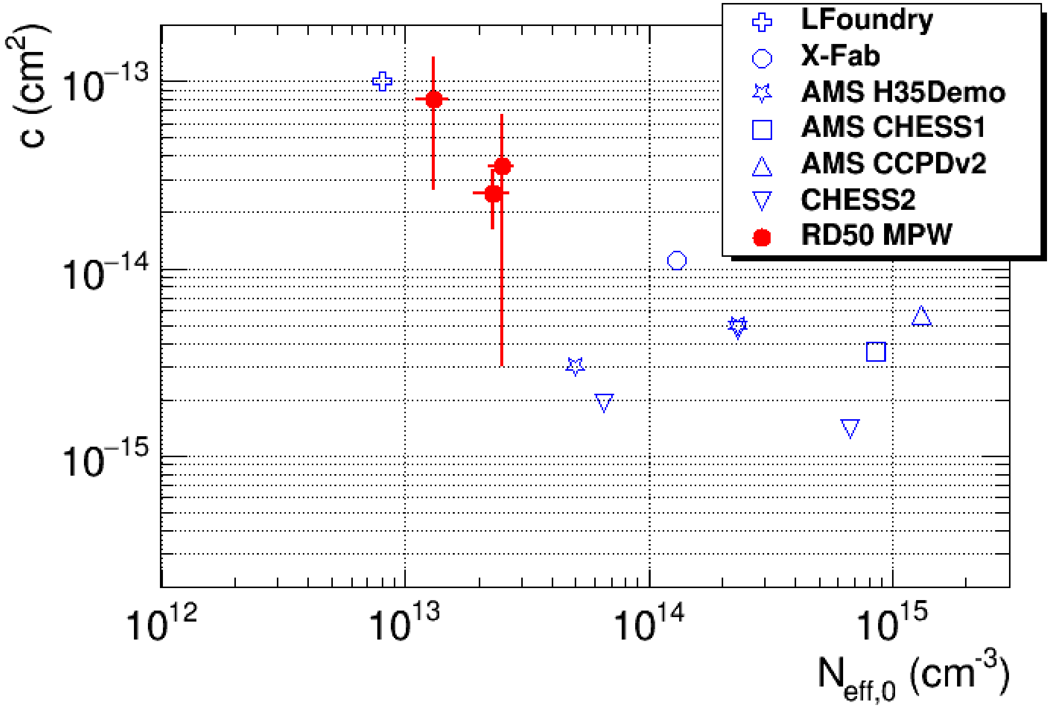
Wafer	Nominal initial resistivity [kΩcm]	Measured N_{eff0} [10^{14}cm^{-3}]	[N_c/N_{eff0}]	c [10^{-14} cm^2]	g_c [10^{-2} cm^{-1}]
w8	0.5	0.25±0.04	0.39 ± 0.14	3.5 ± 3.2	3.3 ± 0.6
w9	0.7	0.23±0.03	0.72 ± 0.10	2.5 ± 0.9	3.9 ± 0.6
w10	1.3	0.13±0.02	0.43 ± 0.10	8.1 ± 5.4	1.8 ± 0.3
w14	2.2	0.07±0.01	/	/	2.9 ±0.4

- W14: acceptor removal parameters could not be extracted, fit: $N_{eff} = N_{eff0} + g_c \cdot \Phi$
- large variations of $\boldsymbol{N_c/N_{eff0}}$
- large uncertainties of **c**
- $\boldsymbol{g_c}$ larger than typical for p-type silicon (~ 0.017 cm^{-1})

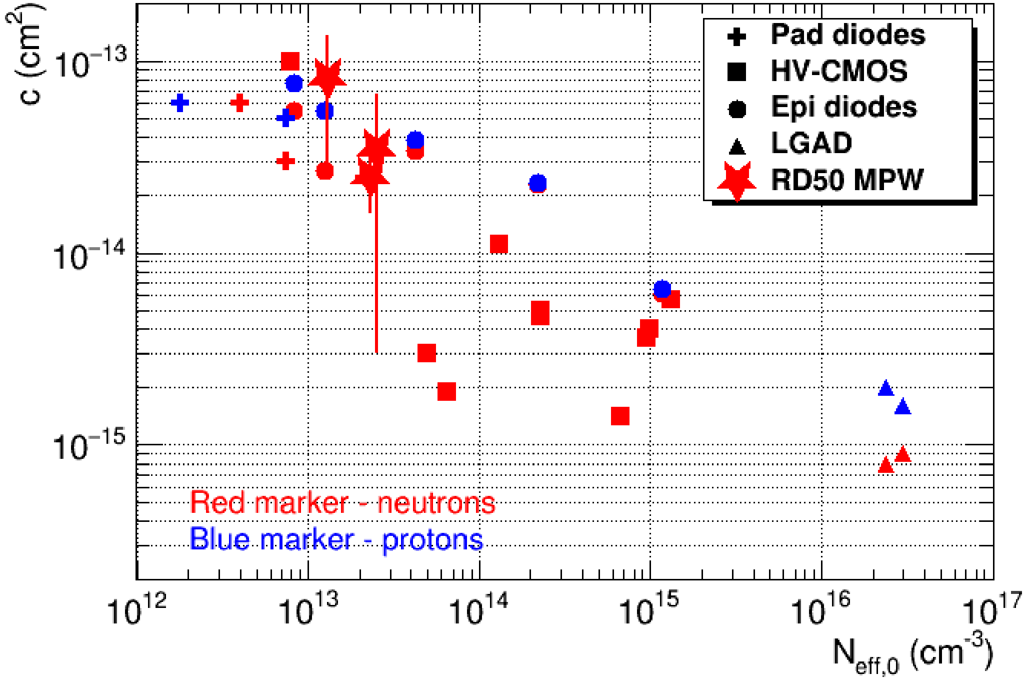
Acceptor removal

- value of acceptor removal parameter ***c*** consistent with other measurements

CMOS



CMOS, LGAD, FZ diodes, Epi diodes

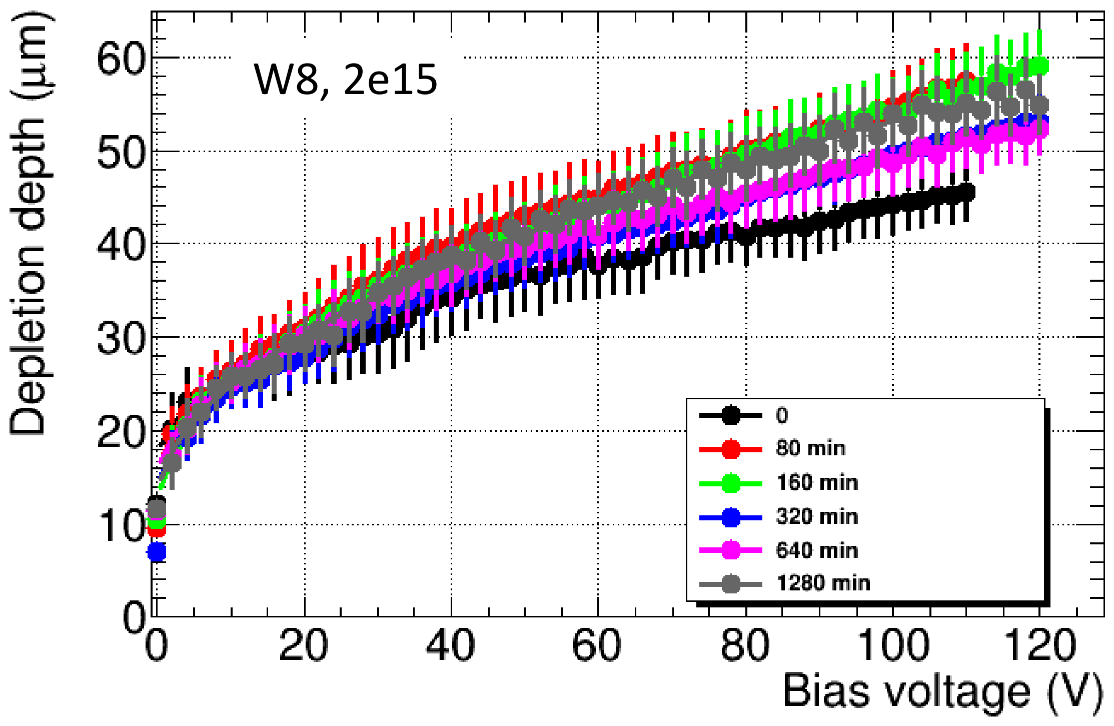


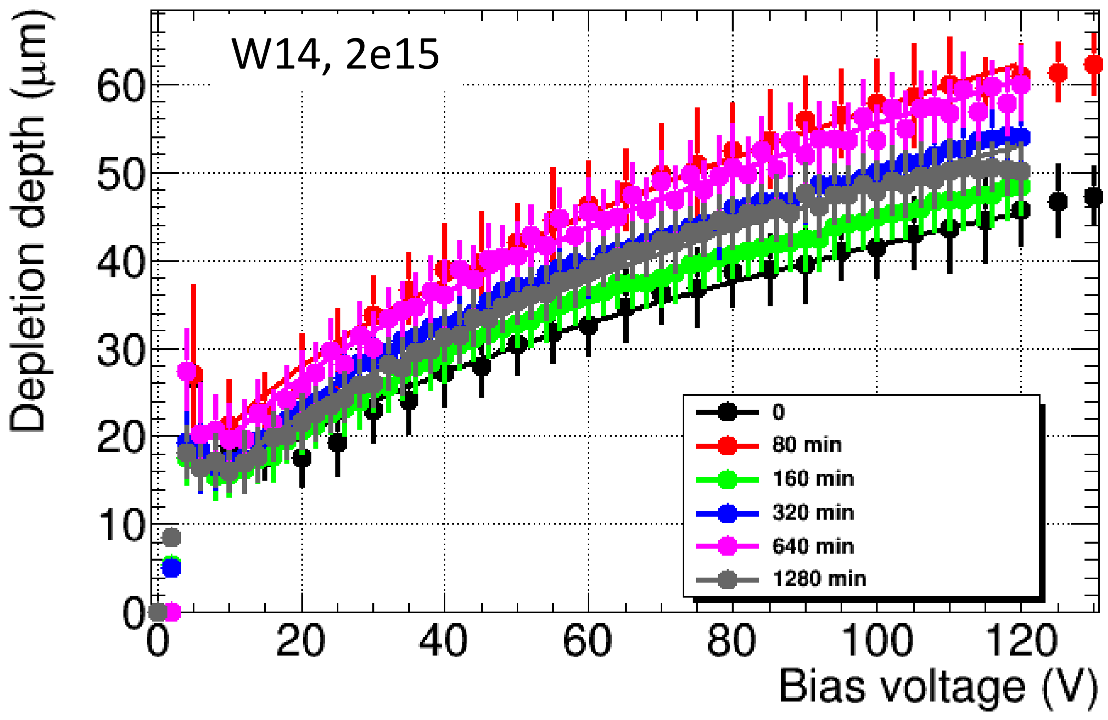
- references for other measurements of ***c*** in the above plot:
  - slides at 33rd RD50 workshop (2018): https://indico.cern.ch/event/754063/contributions/3222815/
  - M. Moll, Vertex 2019 proceedings, https://doi.org/10.22323/1.373.0027

Annealing studies

- W8 and W14 irradiated to 2e15 n/cm^2

➔ anneal at 60°C , steps: 0, 80, 160, 320, 640 and 1280 minutes
➔ measure N_{eff} after every annealing step



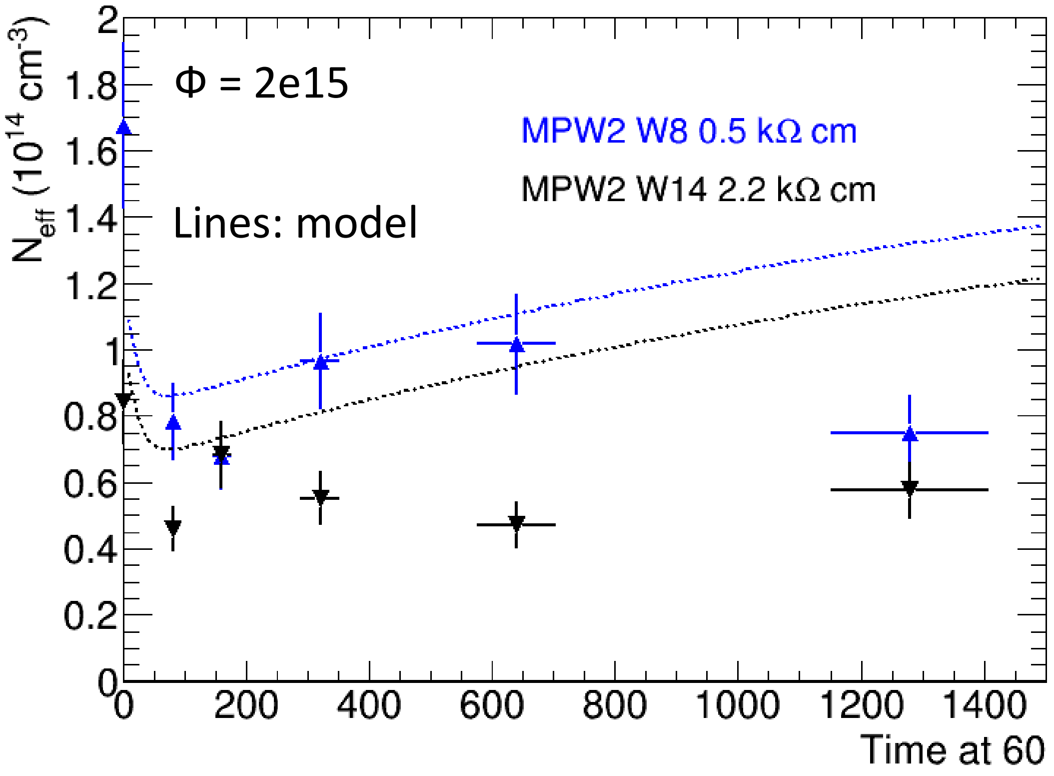


N_{eff} vs. annealing time

- compare measurements with Hamburg model (RD48 (Rose) collaboration NIM A466 (2001) p.308):

$$N_{eff} = N_{eff0} - N_c(\Phi) + \Phi \cdot [g_A \cdot e^{-\frac{t}{\tau A}} + g_C + g_Y \cdot (1 - e^{-\frac{t}{\tau Y}})]$$

- not enough measured points to fit all parameters:
  - ***N_{eff} – N_c*** and ***g_c*** as measured with **E-TCT**
  - **RD48** parameter values: **g_A = 0.02 cm^{-1}, τ_A = 20 min, g_y = 0 0.05 cm^{-1}, t_Y = 1800 min**



➔ it seems reverse annealing effect smaller than predicted by RD48 parameters

➔ more measurements needed to estimate annealing parameters

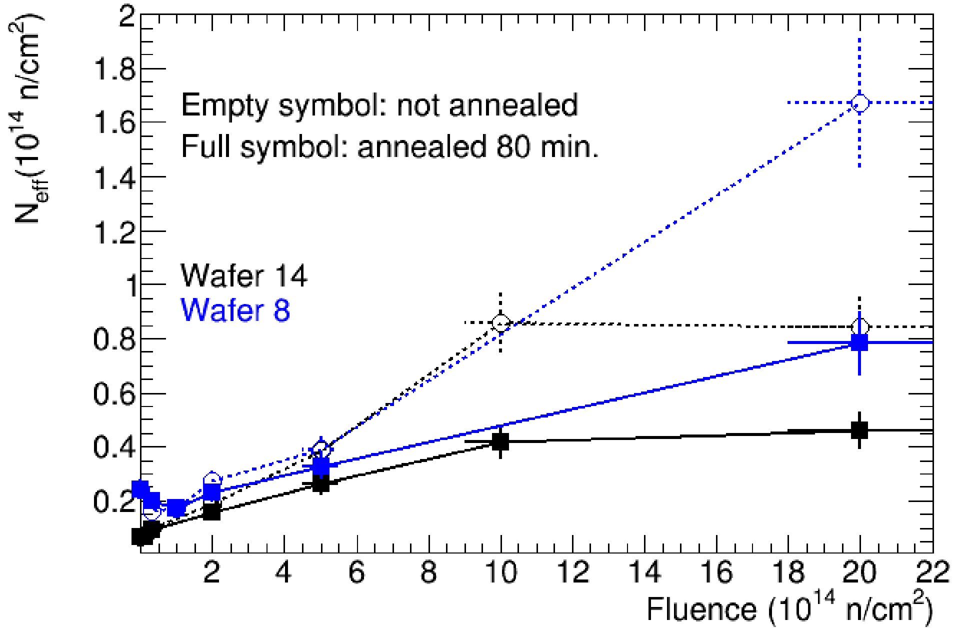
Short term annealing effect

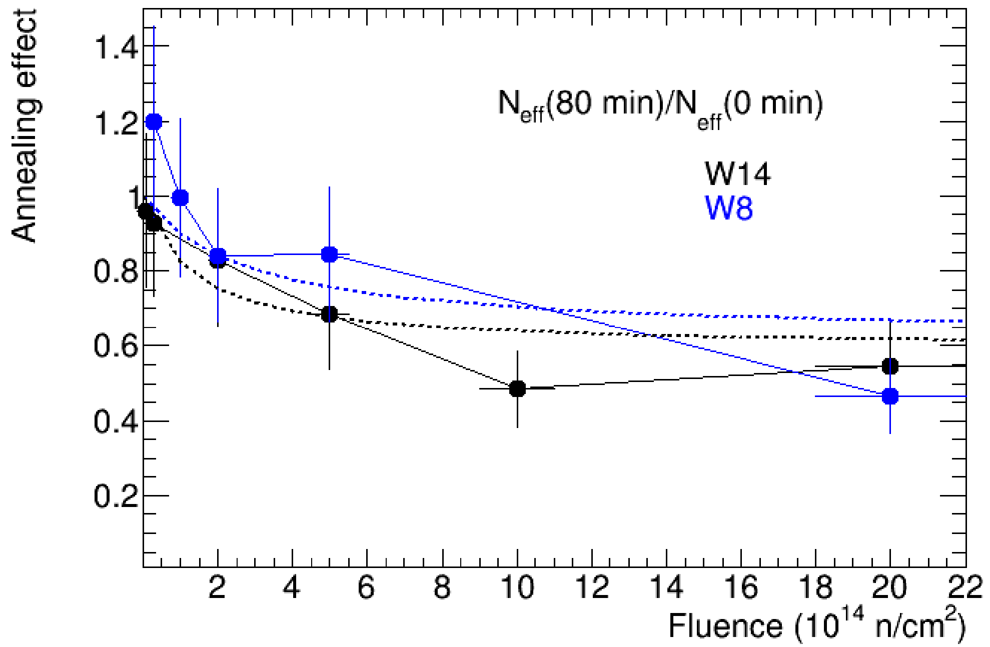
- effect of beneficial annealing (80 minutes at 60°C) measured for all fluences

Hamburg model: $N_{eff}(t) = \underbrace{N_{eff0} - N_c(\Phi)} + \Phi \cdot g_A e^{-\frac{t}{\tau A}}$ (reverse annealing term neglected)

N_s (Φ), measured with E-TCT after 80 min. annealing

Lines: $\frac{N_{eff}(t=80)}{N_{eff}(t=0)} \sim \frac{N_S(\Phi)}{N_S(\Phi) + g_A \cdot \Phi}$, for $g_A = 0.02$ /cm



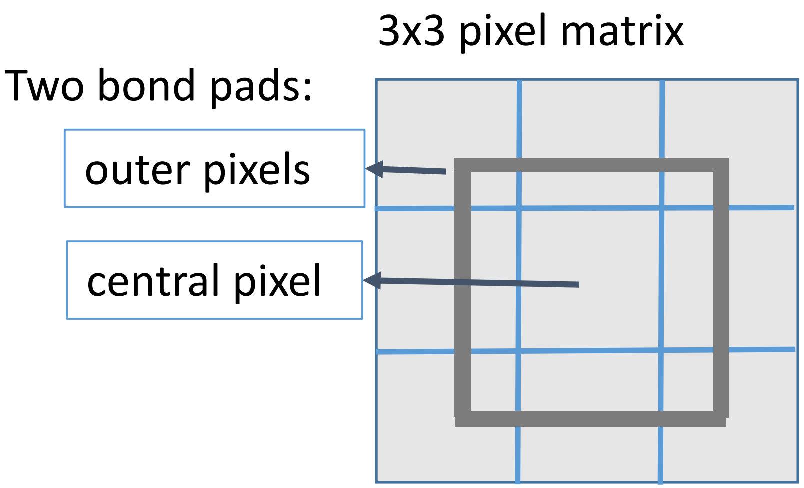


Current

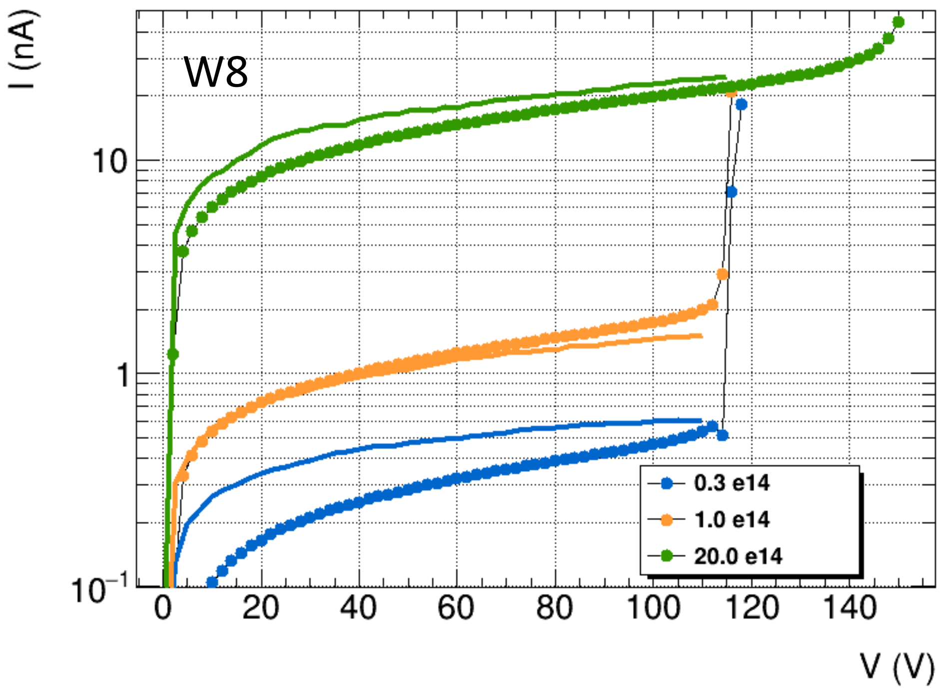
- current measured with **Keithley 6517A**
- measured at 20°C, samples annealed for 80 min. at 60°C
- current on central pixel, outer pixels used as guard-ring

- compare with calculation: ***I = α· Φ ·S·d*, α = 4E-17 Acm^{-1}, *d*** from E-TCT

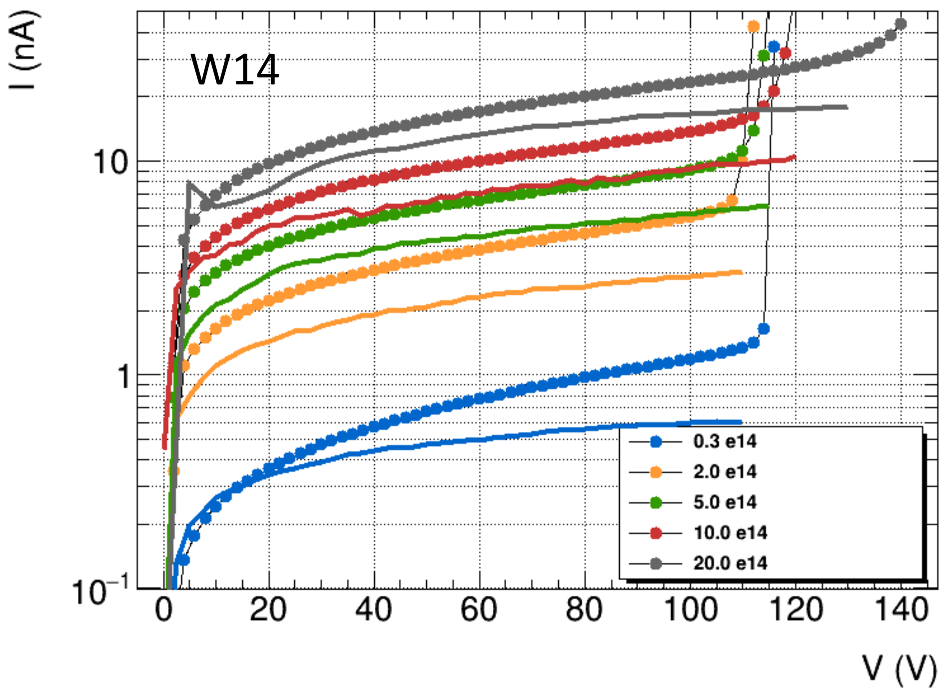
➔ agreement not perfect but ***I = α· Φ ·V*** can be used to roughly estimate current



lines: calculation



lines: calculation



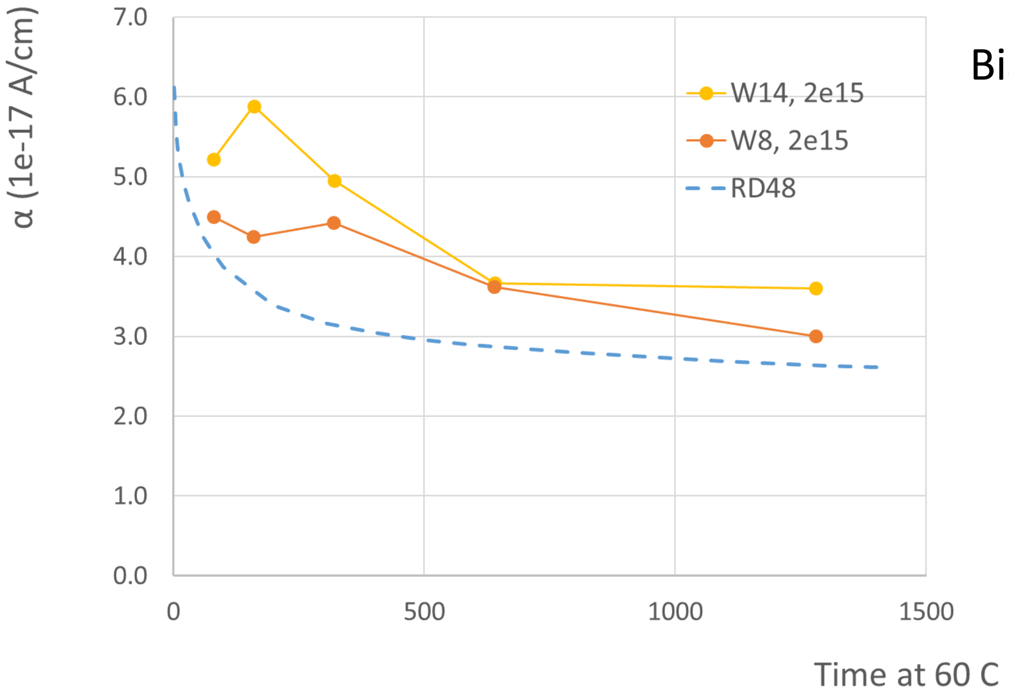
Annealing of current

- W8 and W14 samples irradiated to 2e15 n/cm^2
- current measured at 20 C
- **α = *I/V*,** volume: V = 60 x 60 um^2 x depletion, depletion depth from E-TCT

- compare with RD48 (M. Moll et al., NIM A 426 (1999) 87-93):

$$\boldsymbol{\alpha(t) = \alpha_1 e^{-\frac{t}{\tau_1}} + \alpha_0 - \beta \ln(t)}\,;\quad \alpha_1 = 1.01\text{e-17 A/cm},\ \alpha_0 = 5.03\text{e-17 A/cm},\ \tau_1 = 93\text{ min}, \beta = 3.34\text{e}{-18}\text{ A/cm}$$

- measured somewhat larger than calculated
  → depleted volume not accurate, other sources of current
  ➔ RD48 parametrization can be used to roughly estimate annealing of current



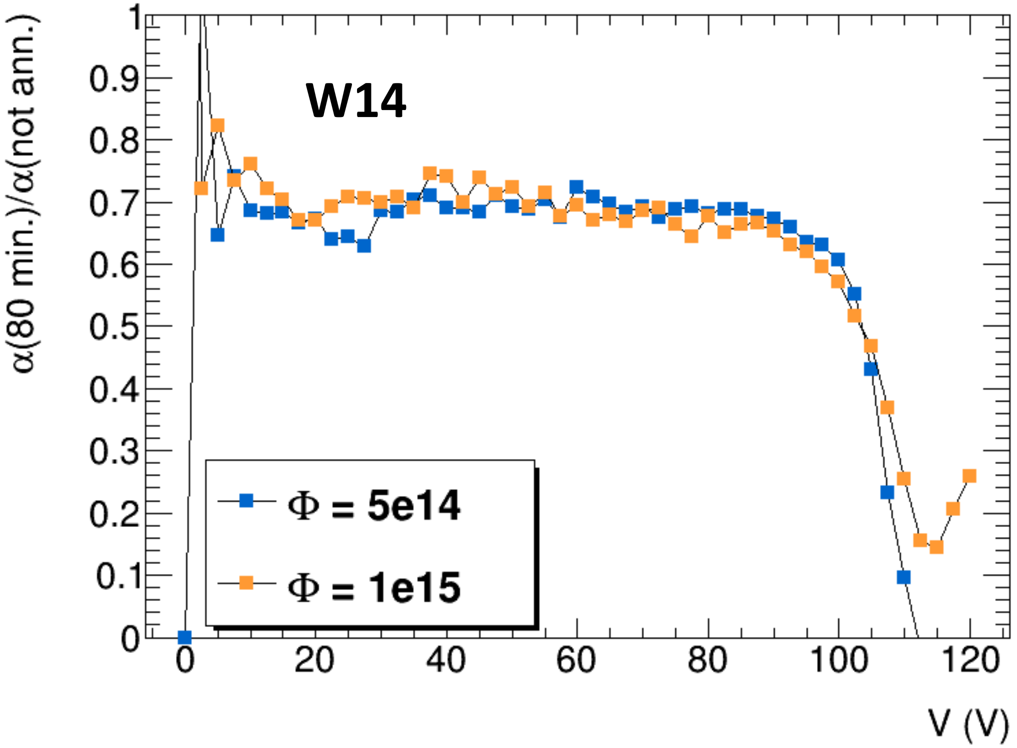
Bias = 60 V, Φ_{eq} = 2e15 n/cm^2

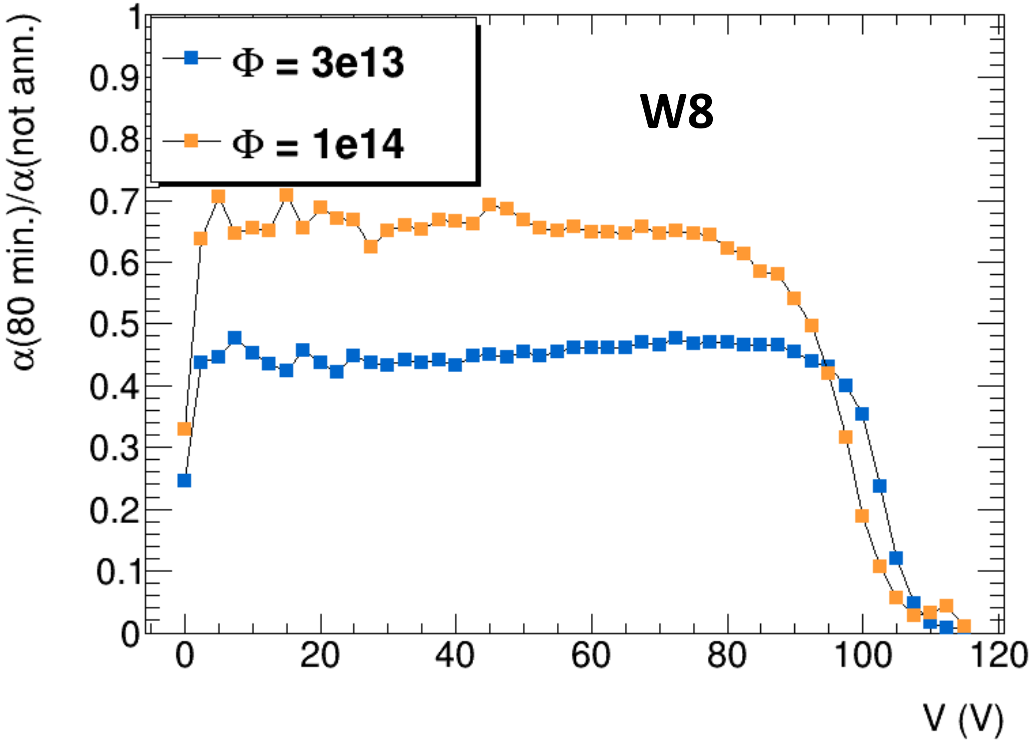
Annealing of current in first 80 min

$$\boldsymbol{\alpha(t) = \alpha_1 e^{-\frac{t}{\tau_1}} + \alpha_0 - \beta \ln(t)};\quad \alpha_1 = 1.01\text{e-17 A/cm},\ \alpha_0 = 5.03\text{e-17 A/cm},\ \tau_1 = 93 \text{ min}, \beta = 3.34\text{e}{-18} \text{ A/cm}$$

$$\frac{\alpha(80 \text{ min.})}{\alpha(1 \text{ min.})} = \frac{1.01 \cdot e^{-\frac{80}{93}} + 5.03 + 0.334 \cdot \ln(80)}{1.01 + 5.03} = \mathbf{0.66}$$

➔ measurements agree with calculated value (somewhat less for W8 irradiated to 3e13)





Conclusions

- E-TCT and I-V measurements with irradiated RD50 MPW2 CMOS pixel test structures presented
- E-TCT used to measure depletion depth
- N_{eff} estimated from depletion depth
- measurements made up to neutron fluences **2e15 n/cm²**

  ➔ parameters describing $N_{eff}(\Phi)$ estimated, compatible with other measurements, significant uncertainties

  ➔ leakage current scales with fluence and bias voltage as expected

- annealing at 60°C up to 1280 minutes

  ➔ reverse annealing of N_{eff} somewhat smaller than predicted by RD48 parameters

  ➔ current as expected