36th RD50 Workshop
Wednesday, 3rd June 2020

Initial I-V and e-TCT measurements of a depleted CMOS sensor within the CERN-RD50 collaboration

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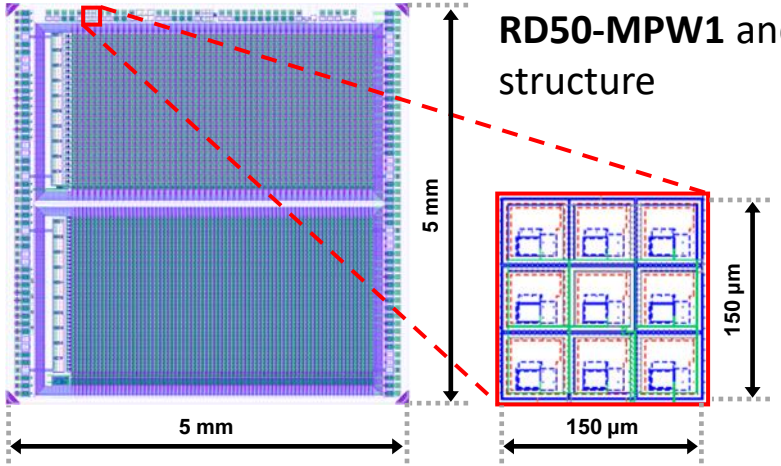
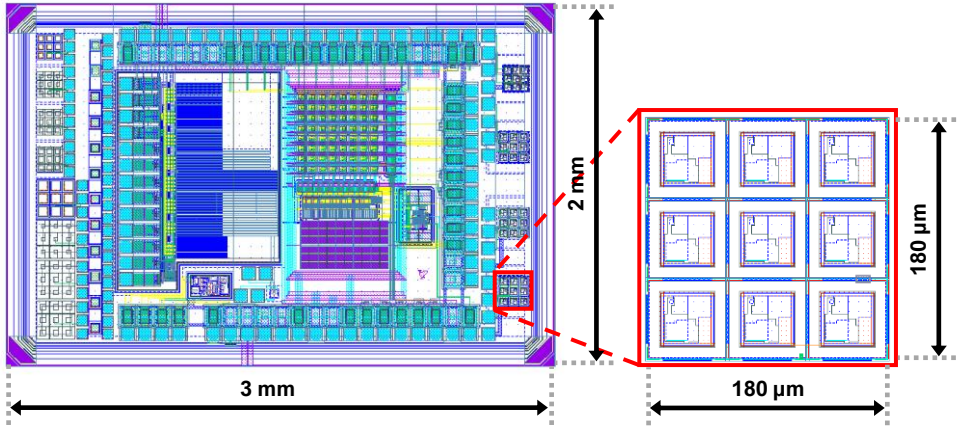
Outline

- Introduction
  - RD50-MPW1 (Motivations)
  - RD50-MPW2
- I-V measurements
  - Breakdown voltage V_{BD}
  - Leakage current I_{leak}
- E-TCT measurements
  - Experimental setup
  - Calculation of substrate resistivity
- Irradiation campaign
  - Irradiated I-Vs
  - Irradiated e-TCT
- Summary and future work



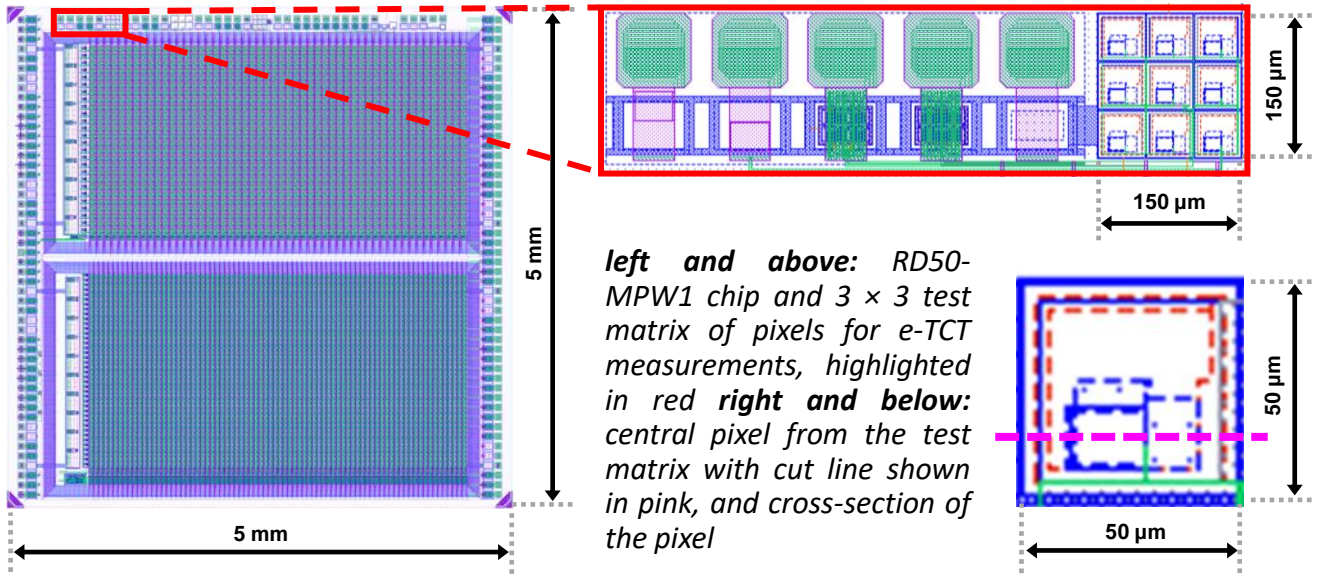
RD50-MPW1 and test structure

RD50-MPW2 and test structure

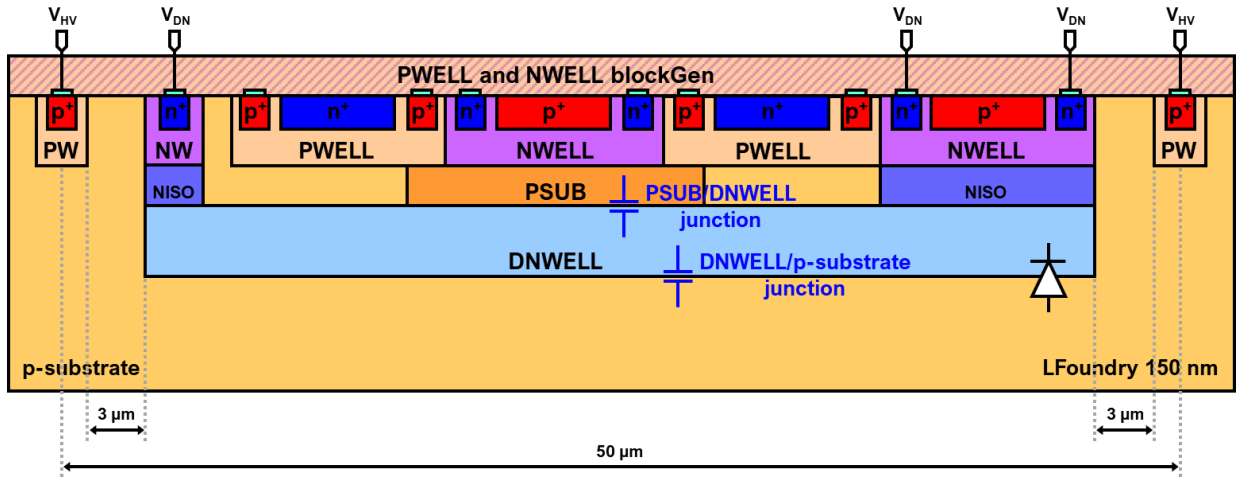


RD50-MPW1 and motivations for the new submission

- General design features
  - MPW in the 150 nm HV-CMOS process from LFoundry
  - Submitted Nov '17, received Apr '18
  - Fabricated using 2 different substrate resistivities: 500-1100 Ω·m (600 measured) and 1900 Ω·cm (1100 measured)
- Chip details
  - Large matrix of DMAPS pixels for particle physics applications
  - Test structures for e-TCT
- Measurements
  - Sensors work well but devices exhibit high leakage current I_{leak} and low breakdown voltage V_{BD}

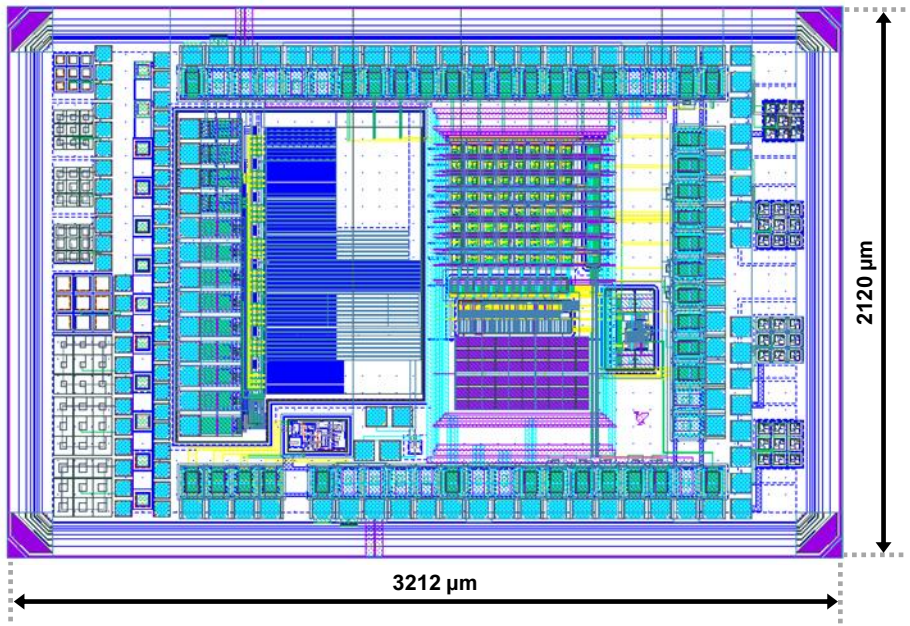


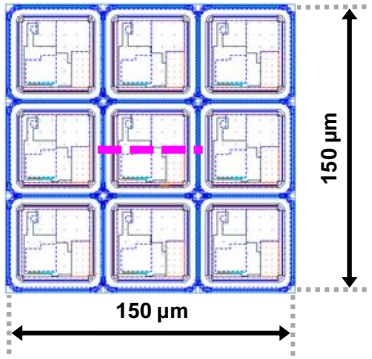
left and above: *RD50-MPW1 chip and 3 × 3 test matrix of pixels for e-TCT measurements, highlighted in red* ***right and below:*** *central pixel from the test matrix with cut line shown in pink, and cross-section of the pixel*



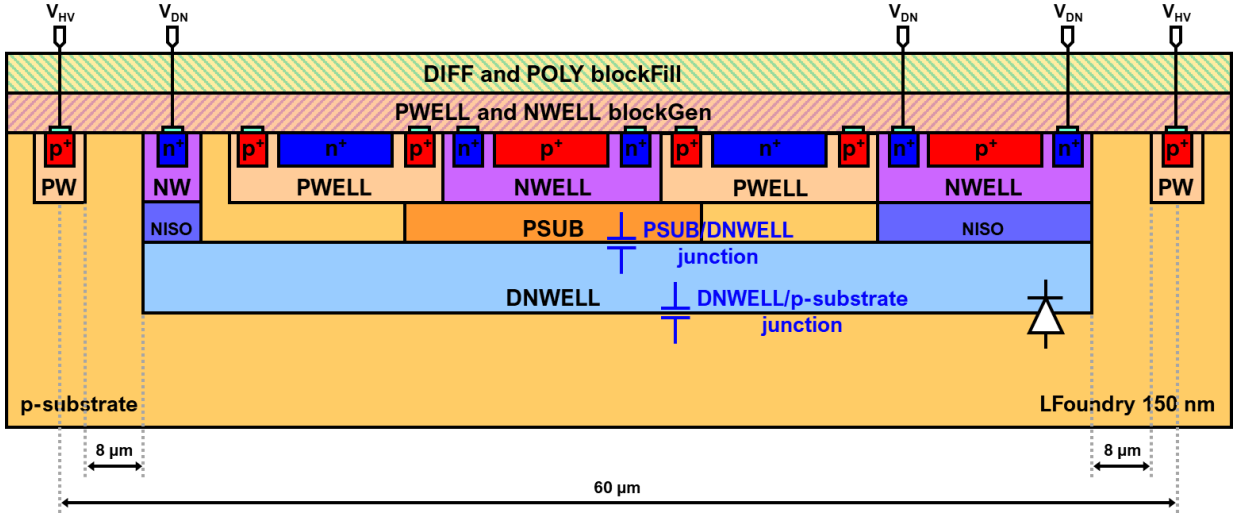
RD50-MPW2

- General design features
  - MPW in the 150 nm HV-CMOS process from LFoundry
  - Submitted February 2019, received February 2020
  - Fabricated in substrate resistivities 10 (standard), 500-1100, 1900, >2000 Ω·cm (nominal)
- **RD50-MPW2 Aim:** Optimise parameters I_{leak} and V_{BD}
  - Both parameters were improved
  - Measurements and further studies are currently underway

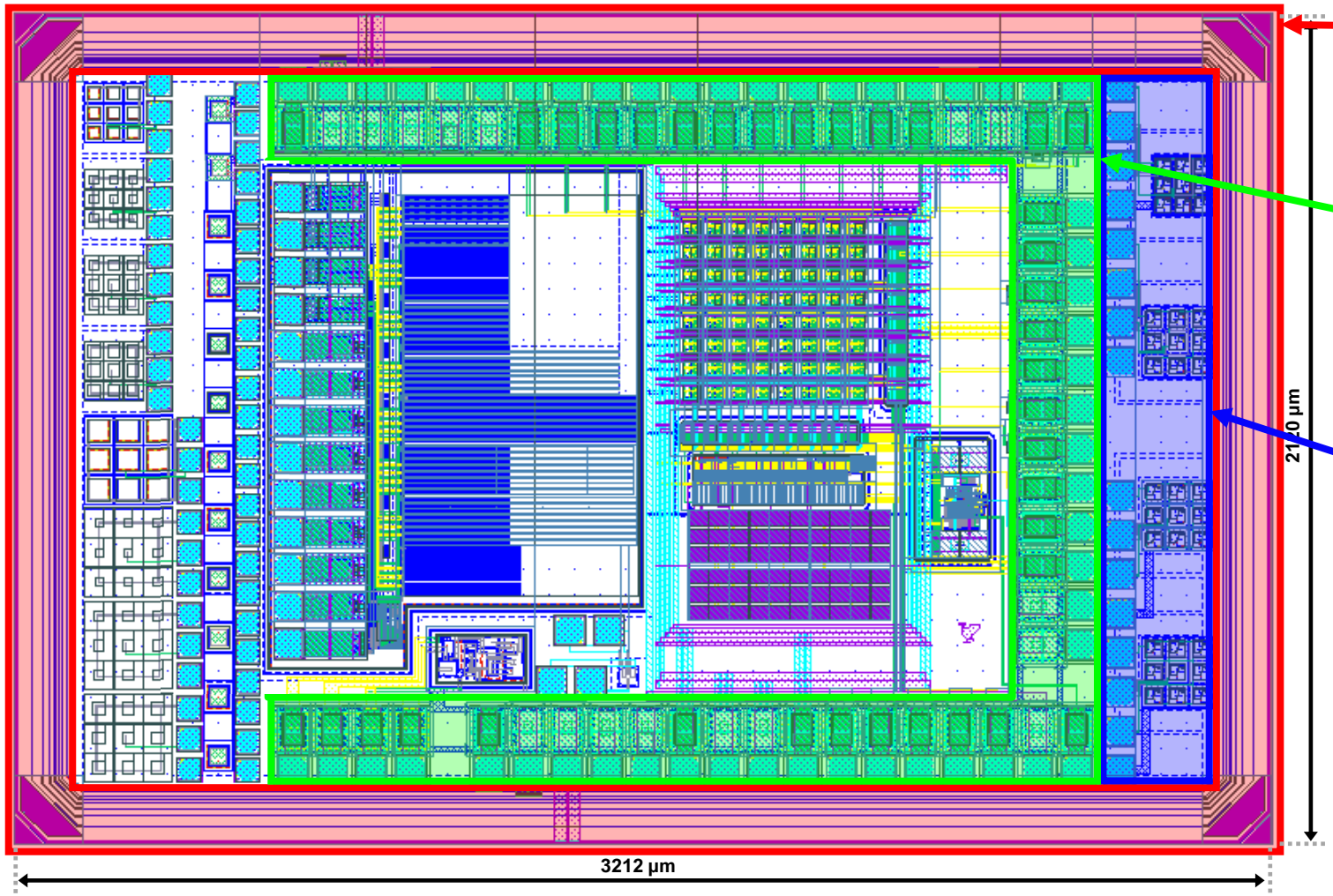




left *RD50-MPW2 chip* ***above:*** *3 × 3 test matrix of 50 µm × 50 µm pixels for e-TCT measurements. Cut line is shown in pink* ***below:*** *Cross-section of pixel from RD50-MPW2*

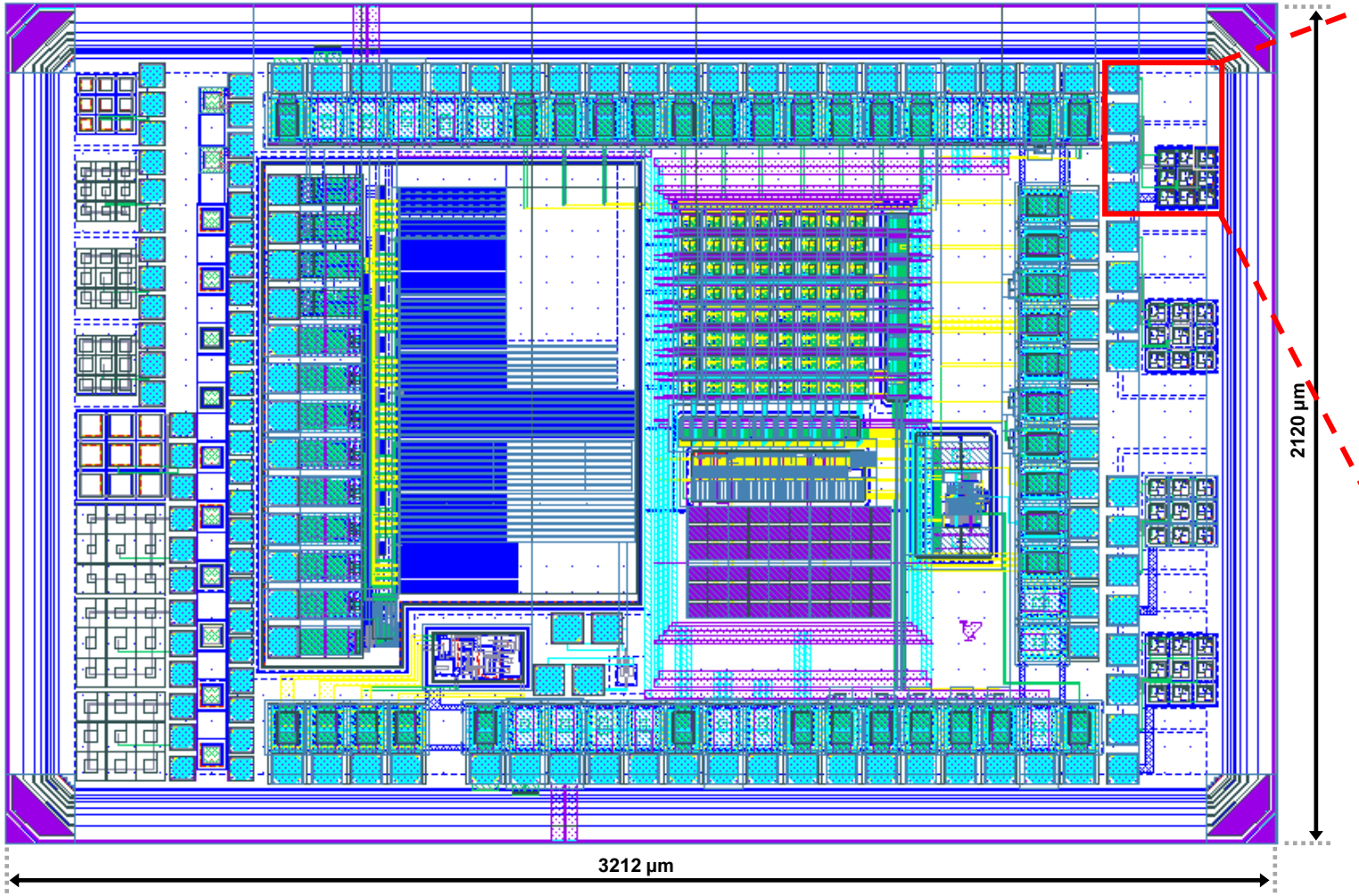


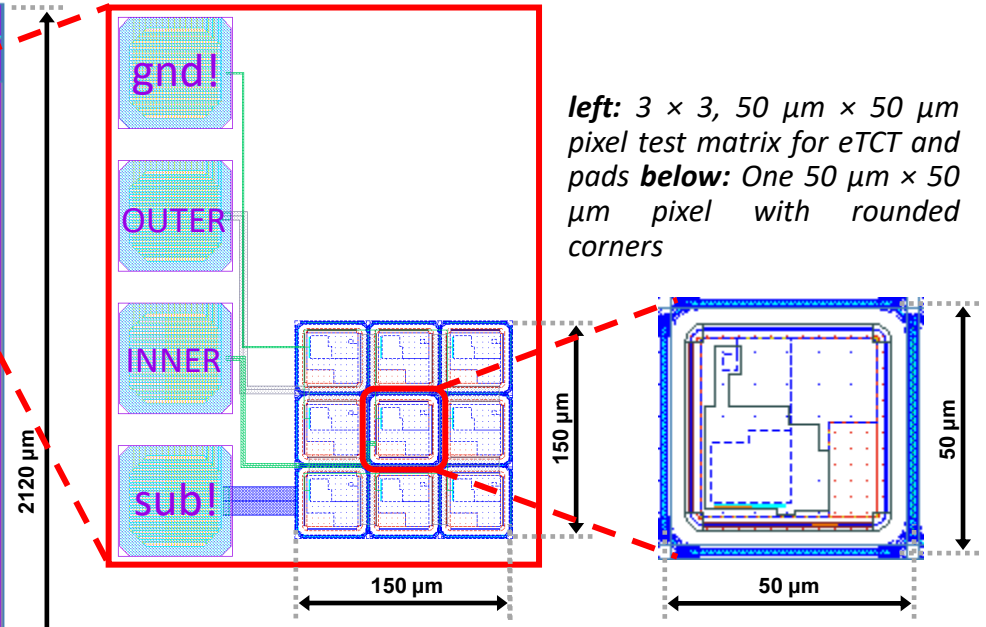
RD50-MPW2: summary of changes from RD50-MPW1



- Included guard rings at the edge of the device
  - Improve I_{leak}
- Modified pad diodes and analog buffers
  - Chamfered corners to improve V_{BD}
- Four test matrices for I-V and e-TCT measurements
  - 50 µm × 50 µm pixels
  - 60 µm × 60 µm pixels to improve V_{BD}
- Careful placement of “blocking layers” to improve I_{leak}

RD50-MPW2 I-V measurements, Test matrix 1: 50 µm × 50 µm pixels

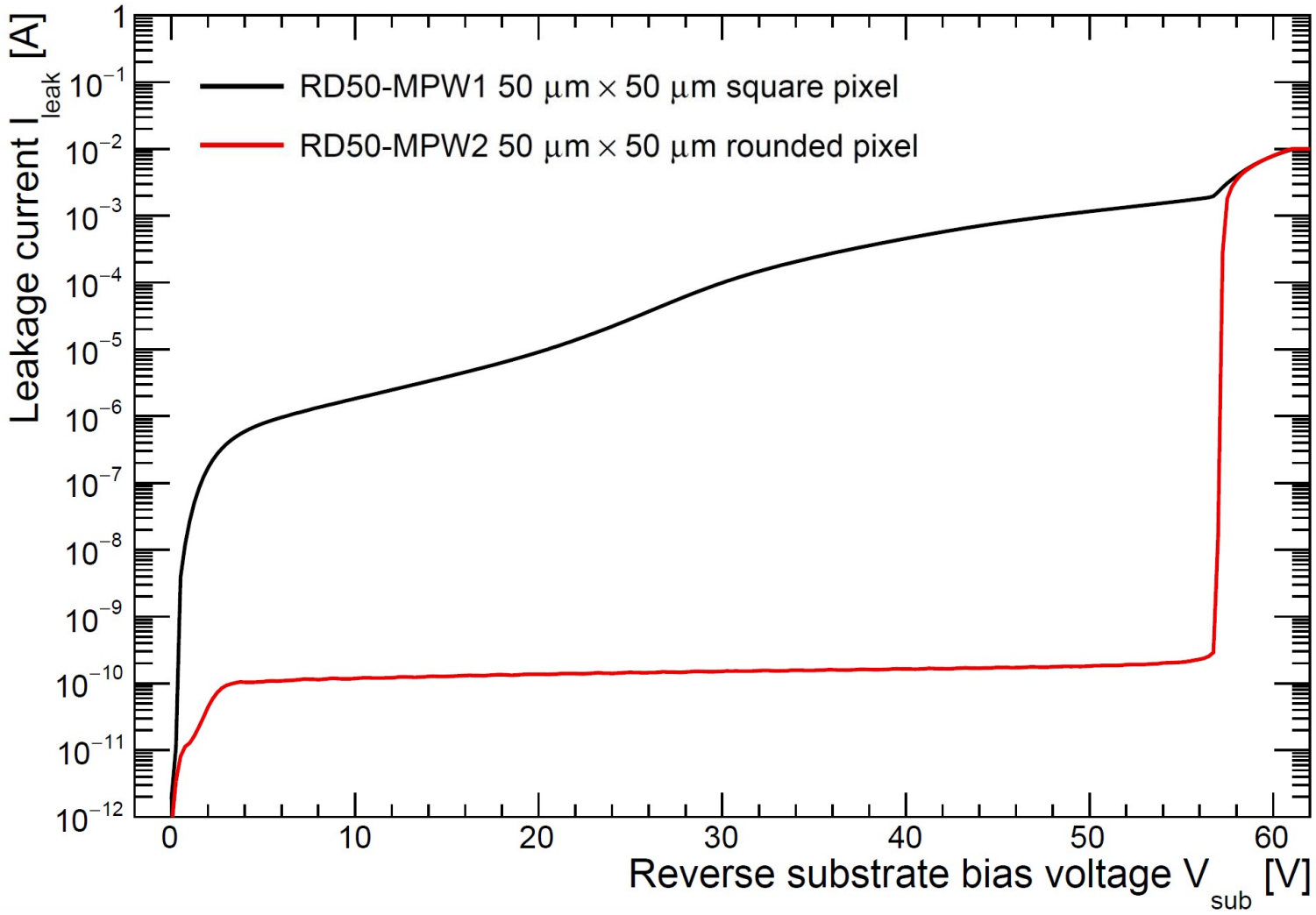




left: *3 × 3, 50 µm × 50 µm pixel test matrix for eTCT and pads* ***below:*** *One 50 µm × 50 µm pixel with rounded corners*

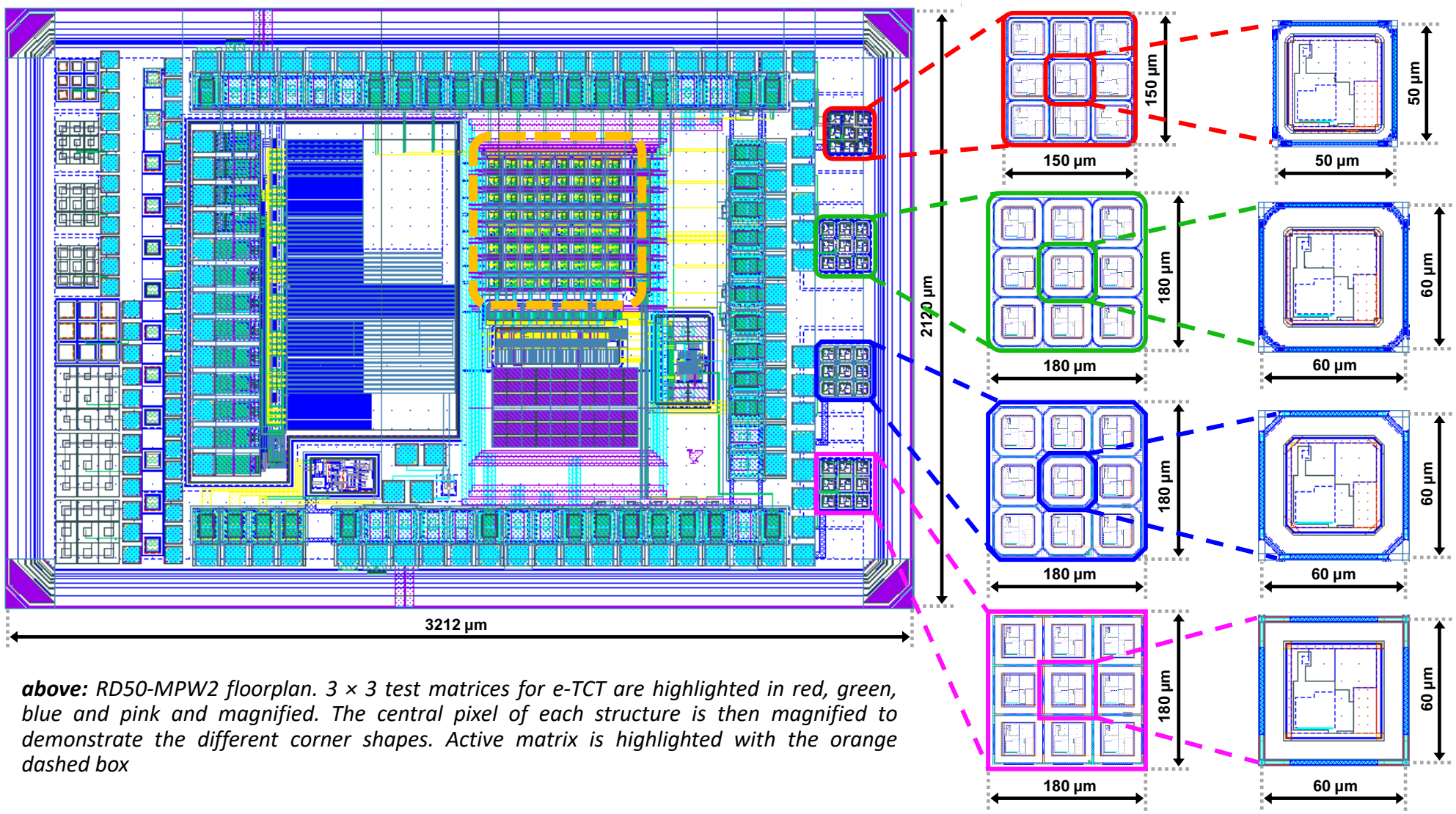
- Connections:
  - gnd! = 0 V
  - OUTER = (floating)
  - INNER = +1.8 V
  - sub! = -HV

RD50-MPW2 comparison with RD50-MPW1



- I-V measurements
  - ρ = 1100 Ω·cm
  - 50 μm × 50 μm pixel
  - 10 mA compliance
- Pad connections
  - gnd! = 0 V
  - OUTER = floating
  - INNER = +1.8 V
  - sub! = -HV
- RD50-MPW2 I_{leak}
  - Reduced by many orders of magnitude with respect to MPW1

RD50-MPW2 I-V measurements: Test matrices



above: *RD50-MPW2 floorplan. 3 × 3 test matrices for e-TCT are highlighted in red, green, blue and pink and magnified. The central pixel of each structure is then magnified to demonstrate the different corner shapes. Active matrix is highlighted with the orange dashed box*

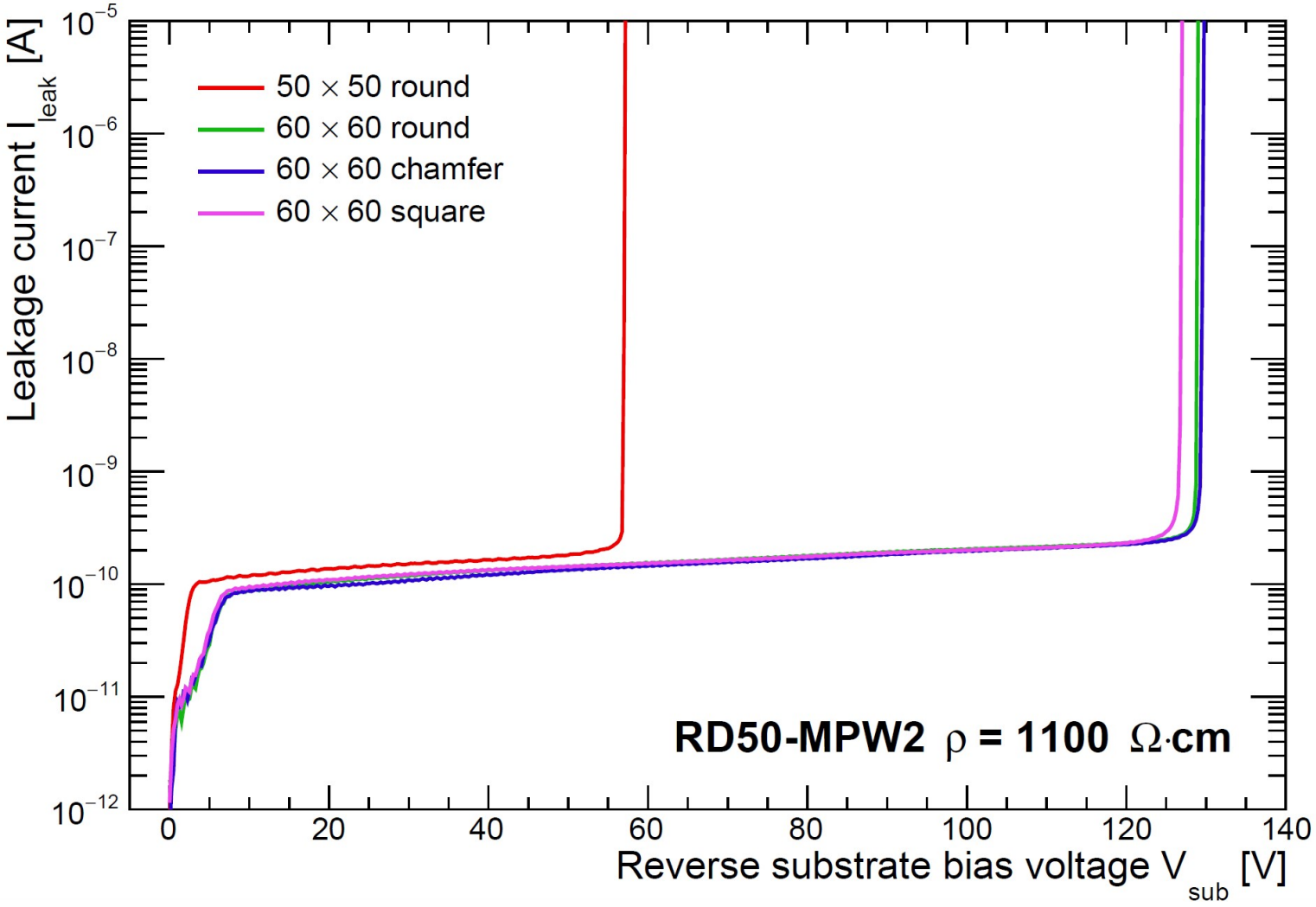
Test matrix 1 for e-TCT
- **50 µm × 50 µm** pixel
- 3 µm electrode spacing
- **Rounded** corners
- (Similar to RD50-MPW1)

Test matrix 2 for e-TCT
- **60 µm × 60 µm** pixel
- 8 µm electrode spacing
- **Rounded** corners
- (Geometry shared with the pixels in the active matrix)

Test matrix 3 for e-TCT
- **60 µm × 60 µm** pixel
- 8 µm electrode spacing
- **Chamfered** corners

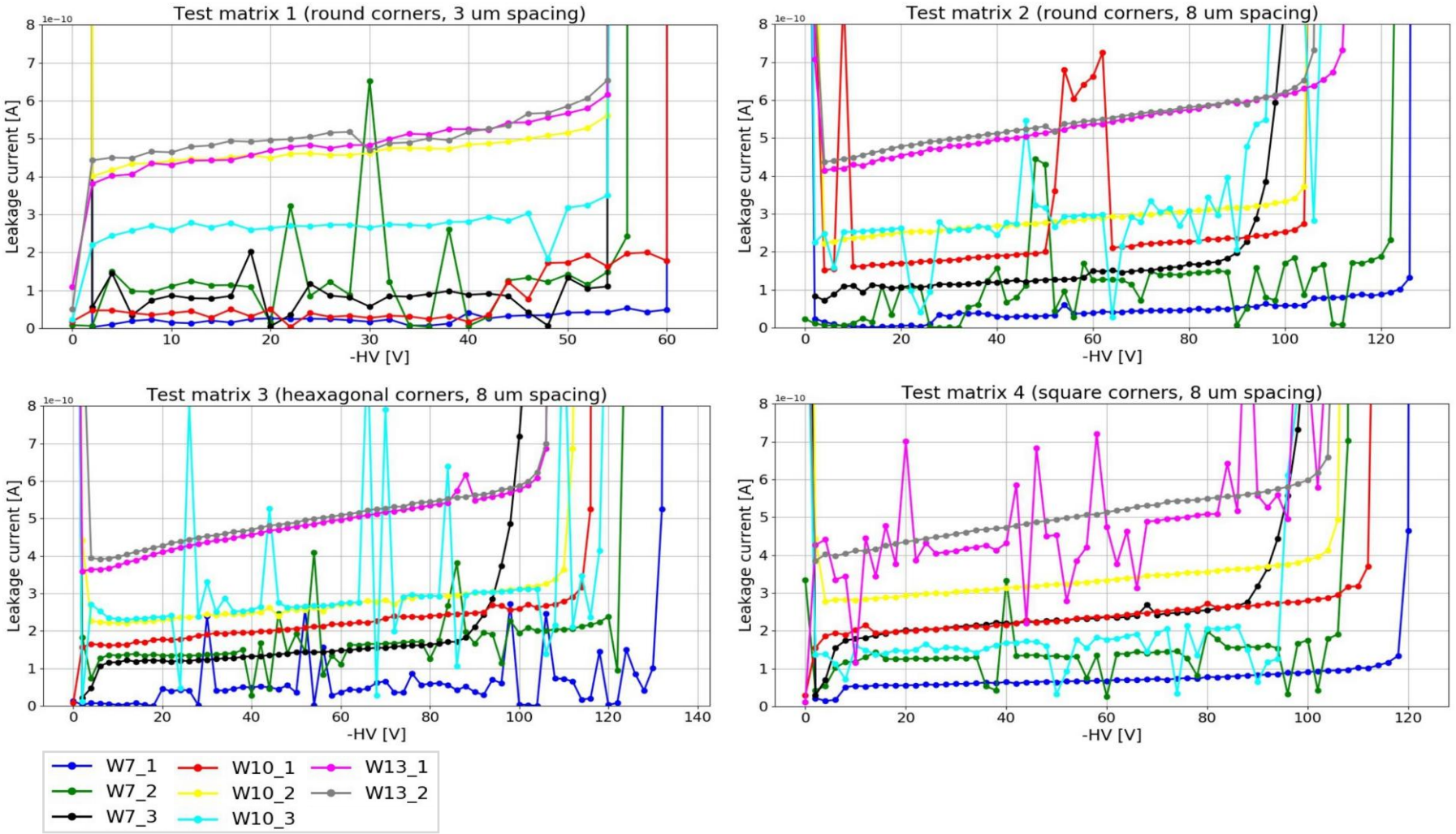
Test matrix 4 for e-TCT
- **60 µm × 60 µm** pixel
- 8 µm electrode spacing
- **Squared** corners

RD50-MPW2 I-V measurements: Test matrices



- I-V measurements
  - ρ = 1100 Ω·cm
  - All pixel types
  - 10 µA compliance
- Pad connections
  - Same as before
- RD50-MPW2 V_{BD}
  - Increasing electrode spacing increases V_{BD}
  - Modifying corner shape can further increase V_{BD}

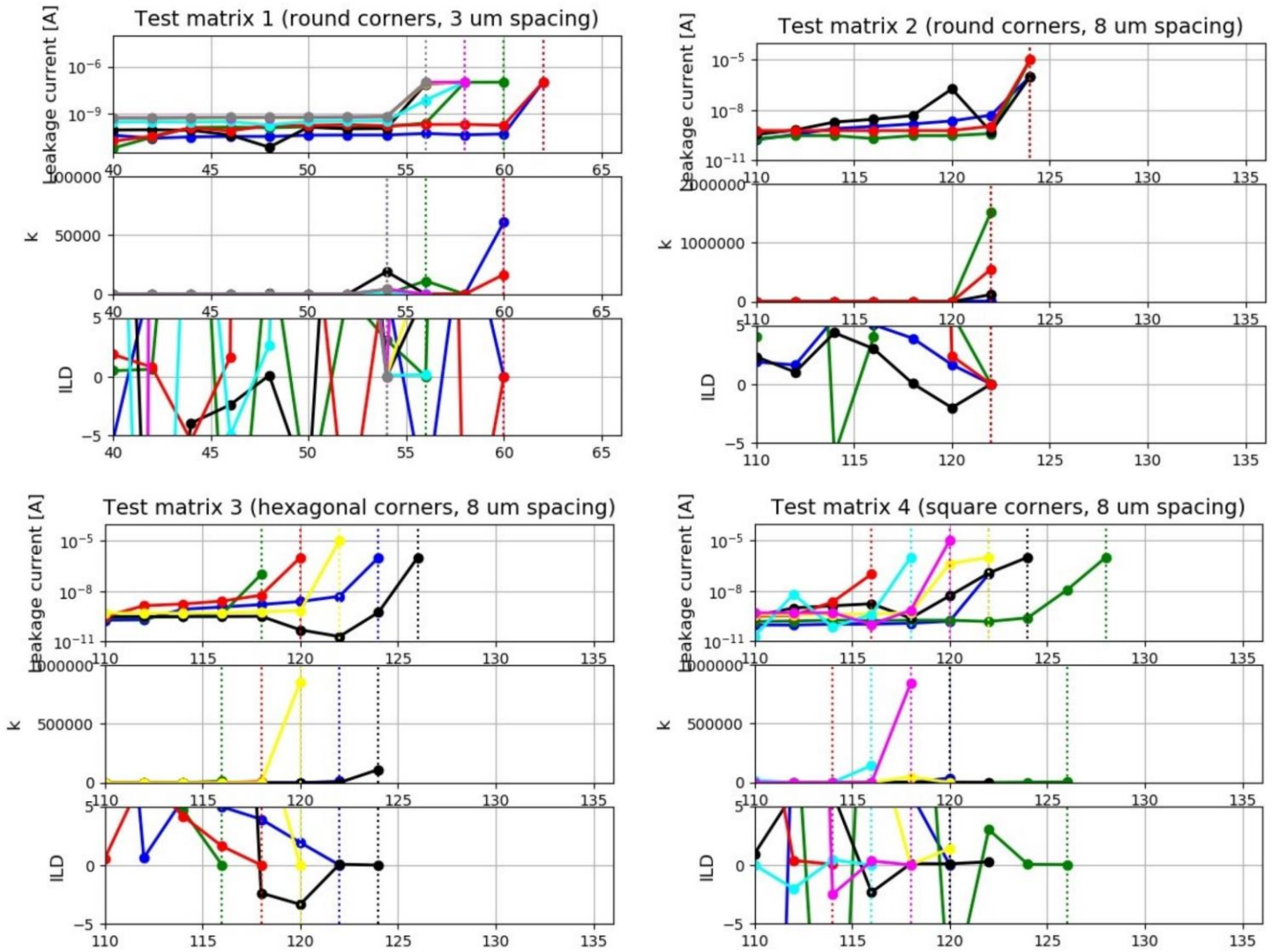
RD50-MPW2 Test matrices: Breakdown voltage V_{BD}



- I-V measurements
  - ρ = 500-1100 (W7), 1900 (W10), >2000 Ω·cm (W13)
  - All four test matrices
  - V_{step} = 2 V
- Pad connections
  - Same as before
- Leakage current I_{leak}
  - Generally increases with ρ

Measurements done at IFIC

RD50-MPW2 Test matrices: Breakdown voltage V_{BD}



Measurements done at IFIC

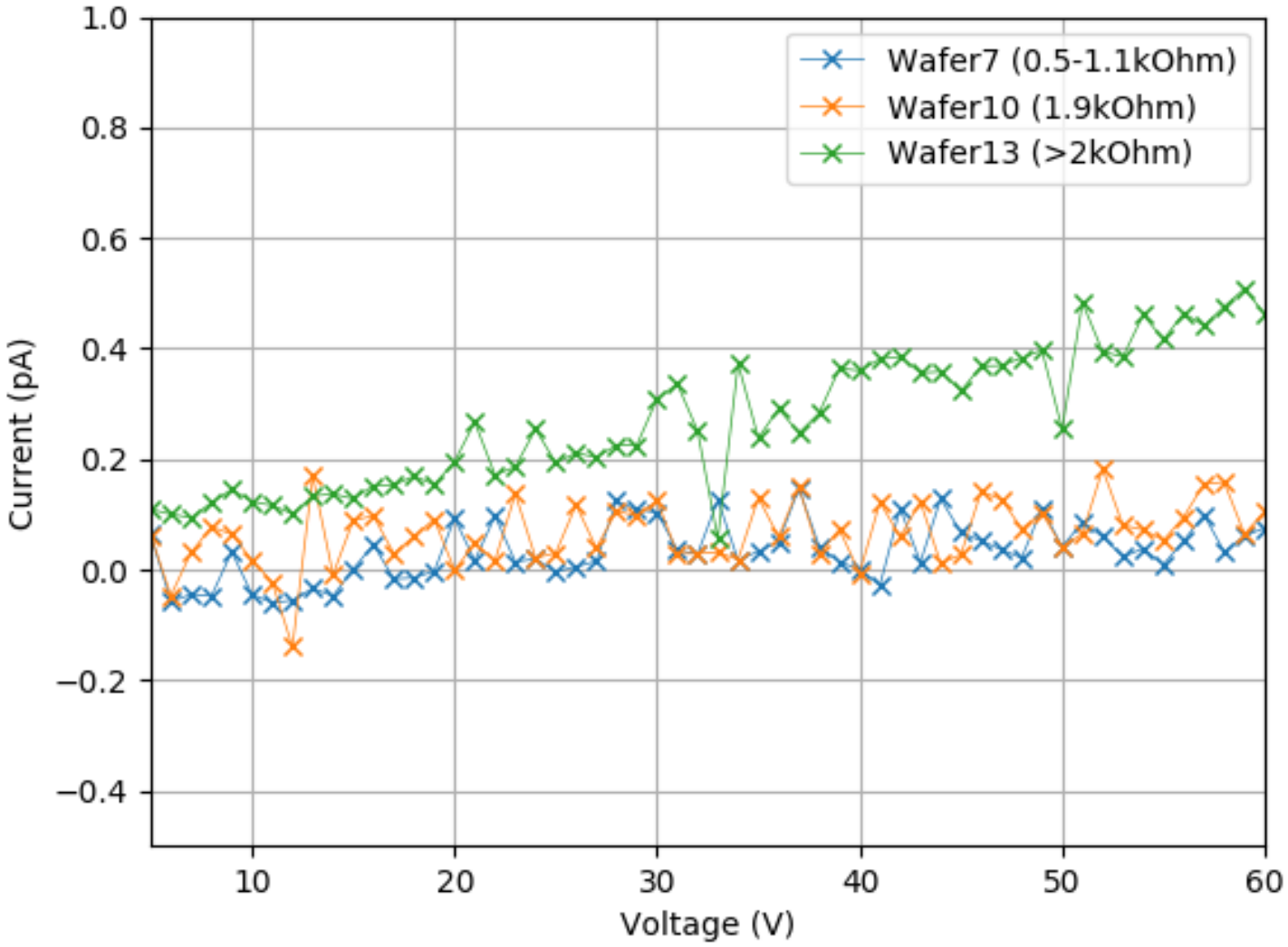
- Different current compliances I_{comp} used to measure V_{BD}
  - 100 nA, 1 µA, and 10 µA
- Two parameters calculated in order to determine breakdown voltage
  - $k = \frac{(dI/dV)}{(I/V)}$
  - $\mathrm{ILD} = \left(\frac{d\ln[I(V)]}{dV}\right)^{-1} \equiv \left[\frac{1}{I} \cdot \frac{dI(V)}{dV}\right]^{-1}$
- V_{BD} criteria
  - V where I_{comp} is reached (computed for comparison)
  - V for maximum k
  - V for minimum $\mathrm{ILD} > 0$

RD50-MPW2 Test matrices: Breakdown voltage V_{BD}

	1st matrix (round 3 µm)			2nd matrix (round 8 µm)			3rd matrix (hexagonal 8 µm)			4th matrix (square 8 µm)		
	Vbd (Icomp)	Vbd (k)	Vbd (ILD)	Vbd (Icomp)	Vbd (k)	Vbd (ILD)	Vbd (Icomp)	Vbd (k)	Vbd (ILD)	Vbd (Icomp)	Vbd (k)	Vbd (ILD)
0.5-1.1 kΩ·cm	W7_1 (Icomp = 100nA)									W7_1 (Icomp = 100nA)		
	62 V	60 V	60 V							122 V	120 V	120 V
	W7_2 (Icomp = 100nA)									W7_2 (Icomp = 1µA)		
	60 V	56 V	56 V							128 V	126 V	126 V
	W7_3 (Icomp = 100nA)			W7_3 (Icomp = 1µA)			W7_3 (Icomp = 1µA)			W7_3 (Icomp = 1µA)		
	58 V	54 V	54 V	124 V	122 V	122 V	124 V	122 V	122 V	124 V	120 V	120 V
1.9 kΩ·cm	W10_1 (Icomp = 100nA)						W10_1 (Icomp = 100nA)			W10_1 (Icomp = 100nA)		
	62 V	60 V	60 V				118 V	116 V	116 V	116 V	114 V	114 V
	W10_2 (Icomp = 100nA)			W10_2 (Icomp = 10µA)			W10_2 (Icomp = 1µA)			W10_2 (Icomp = 1µA)		
	58 V	54 V	54 V	124 V	122 V	122 V	126 V	124 V	124 V	122 V	118 V	118 V
	W10_3 (Icomp = 100nA)			W10_3 (Icomp = 1µA)			W10_3 (Icomp = 1µA)			W10_3 (Icomp = 1µA)		
	58 V	54 V	54 V	124 V	122 V	122 V	120 V	118 V	118 V	118 V	116 V	116 V
>2 kΩ·cm	W13_1 (Icomp = 100nA)											
	58 V	54 V	54 V									
	W13_2 (Icomp = 100nA)			W13_2 (Icomp = 10µA)			W13_2 (Icomp = 10µA)			W13_2 (Icomp = 10µA)		
	56 V	54 V	54 V	124 V	122 V	122 V	122 V	120 V	120 V	120 V	118 V	118 V

Measurements done at IFIC

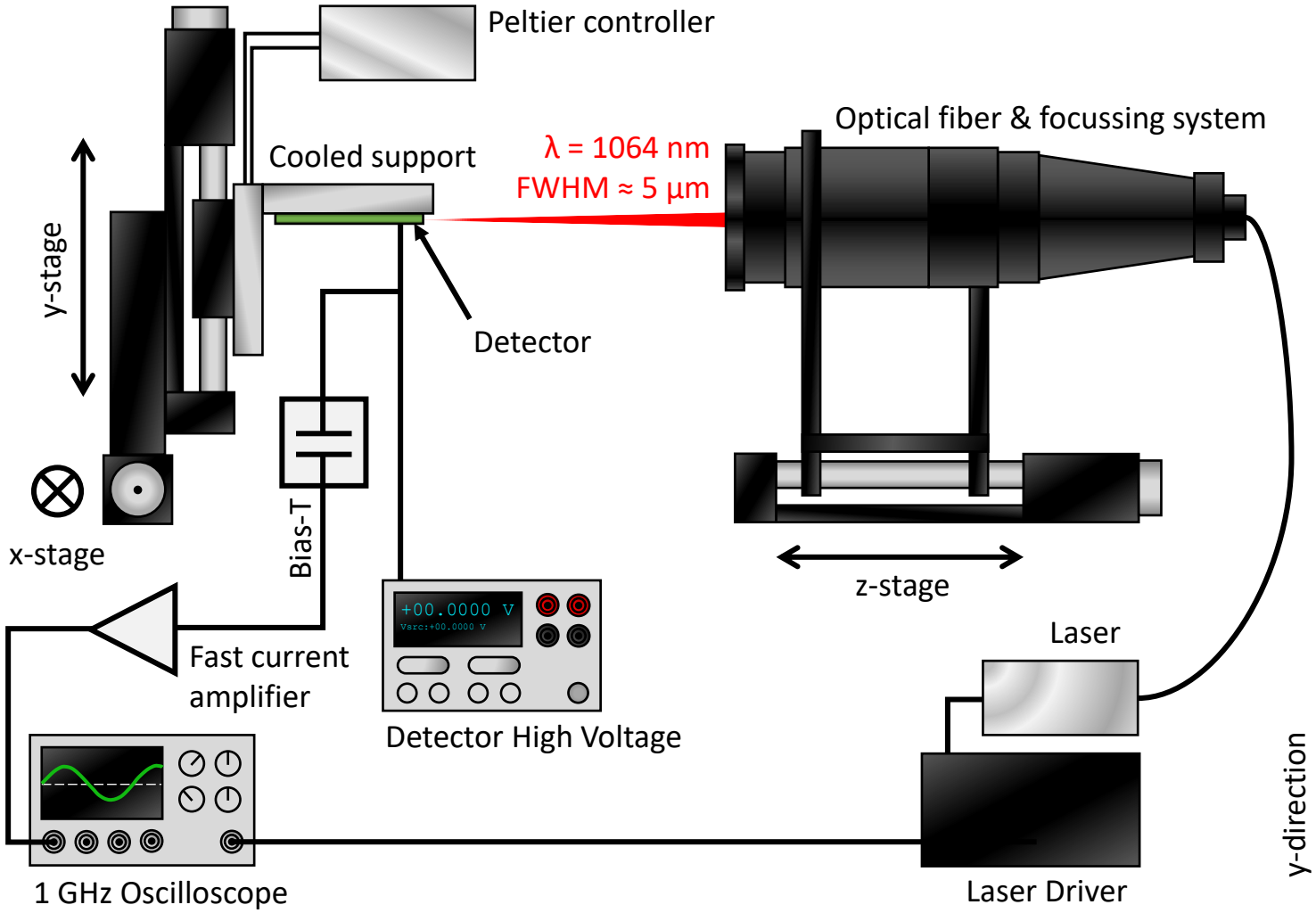
RD50-MPW2 Test matrix 2: Leakage current I_{leak}



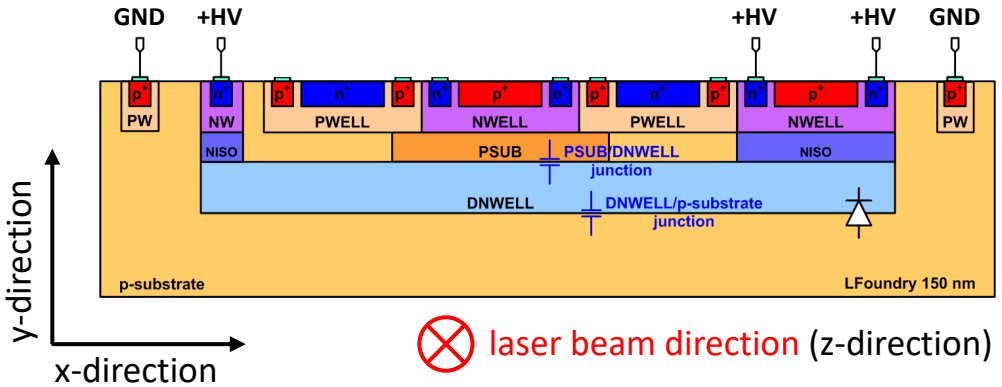
- I-V measurements
  - ρ = 500-1100 (W7), 1900 (W10), >2000 Ω·cm (W13)
  - Only test matrix 2
- Pad connections
  - gnd! = GND
  - OUTER = GND ("guard-ring")
  - INNER = GND (through ammeter)
  - sub! = -HV
- Leakage current I_{leak}
  - Current of central DNWELL/p-substrate junction is measured using the additional ammeter
  - Below 1 pA (≈ 0.1 pA)

Measurements done at HEPHY

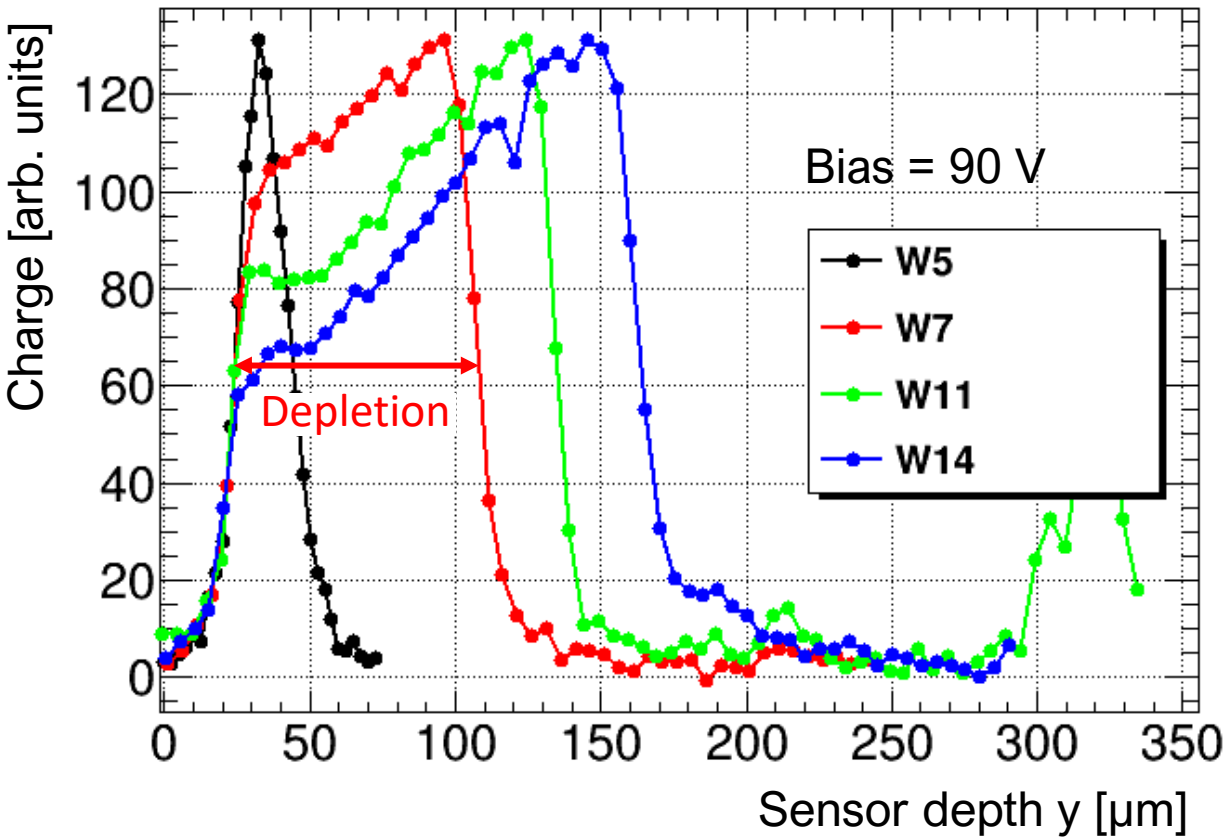
RD50-MPW2 e-TCT experimental setup



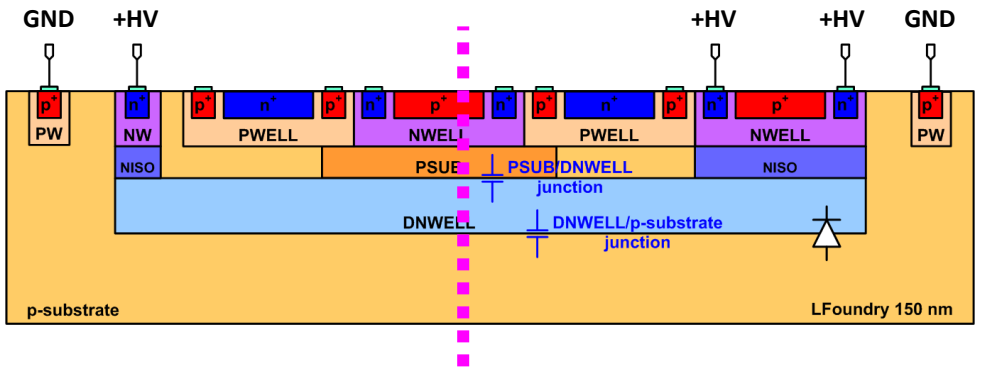
- E-TCT measurements
  - Beam diameter in the silicon FWHM ≈ 5 µm
  - Width of light pulses ≈ 300 ps, repetition rate 500 Hz
- Connection scheme:
  - INNER = +HV
  - sub! = GND



RD50-MPW2 e-TCT: Charge collection profiles



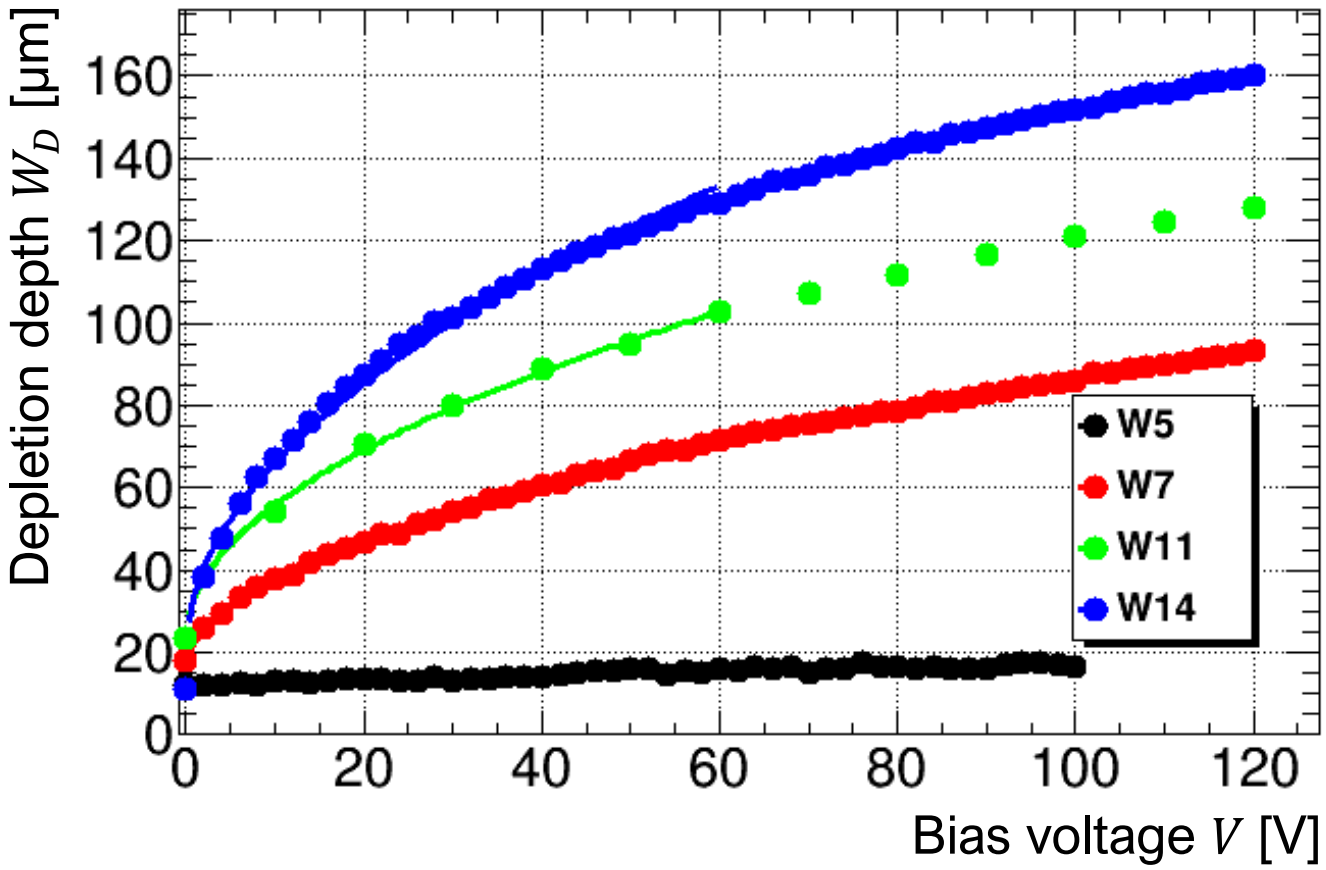
- E-TCT measurements
  - Wafers 5, 7, 11, 14 (10, 500-1100, 1900, >2000 Ω·cm nominal ρ, respectively)
  - Bias up to 120 V
  - (W5 up to 100 V, breakdown at ≈ 105 V)
- Charge collection profiles
  - Scan across centre of central pixel
  - Profiles normalised to same maximum



Scan line

Measurements done at JSI

RD50-MPW2 e-TCT



Fit:

$$W_D = W_{D_0} + \sqrt{\frac{2\varepsilon_{\mathrm{Si}}\varepsilon_0}{e_0 N_{\mathrm{eff}}} \cdot V}$$

Free parameters:

W_{D_0} = width of charge collection profile at 0 V bias voltage

N_{eff} = effective doping concentration

Constants:

ε_0 = permittivity of free space

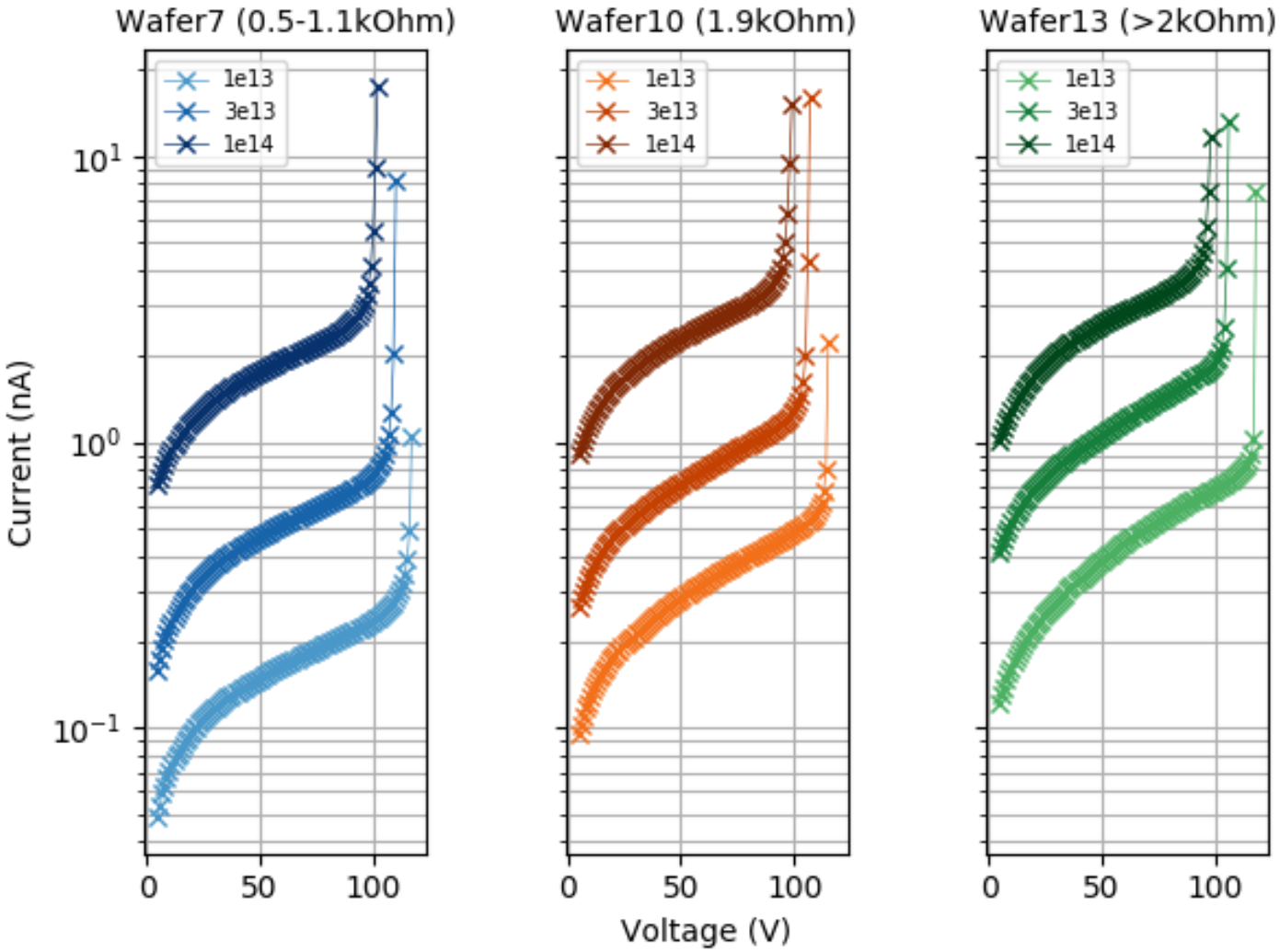
$\varepsilon_{\mathrm{Si}}$ = relative permittivity of silicon

e_0 = elementary charge

Wafer	N_{eff} [cm^{-3}] ($0 < V < 60$)	ρ [Ω·cm]	Nominal ρ [Ω·cm]
W5	$3.2 \cdot 10^{15}$	4	10
W7	$2.4 \cdot 10^{13}$	500	500-1100
W11	$1.2 \cdot 10^{13}$	1100	1900
W14	$5.9 \cdot 10^{12}$	2200	>2000

Measurements done at JSI

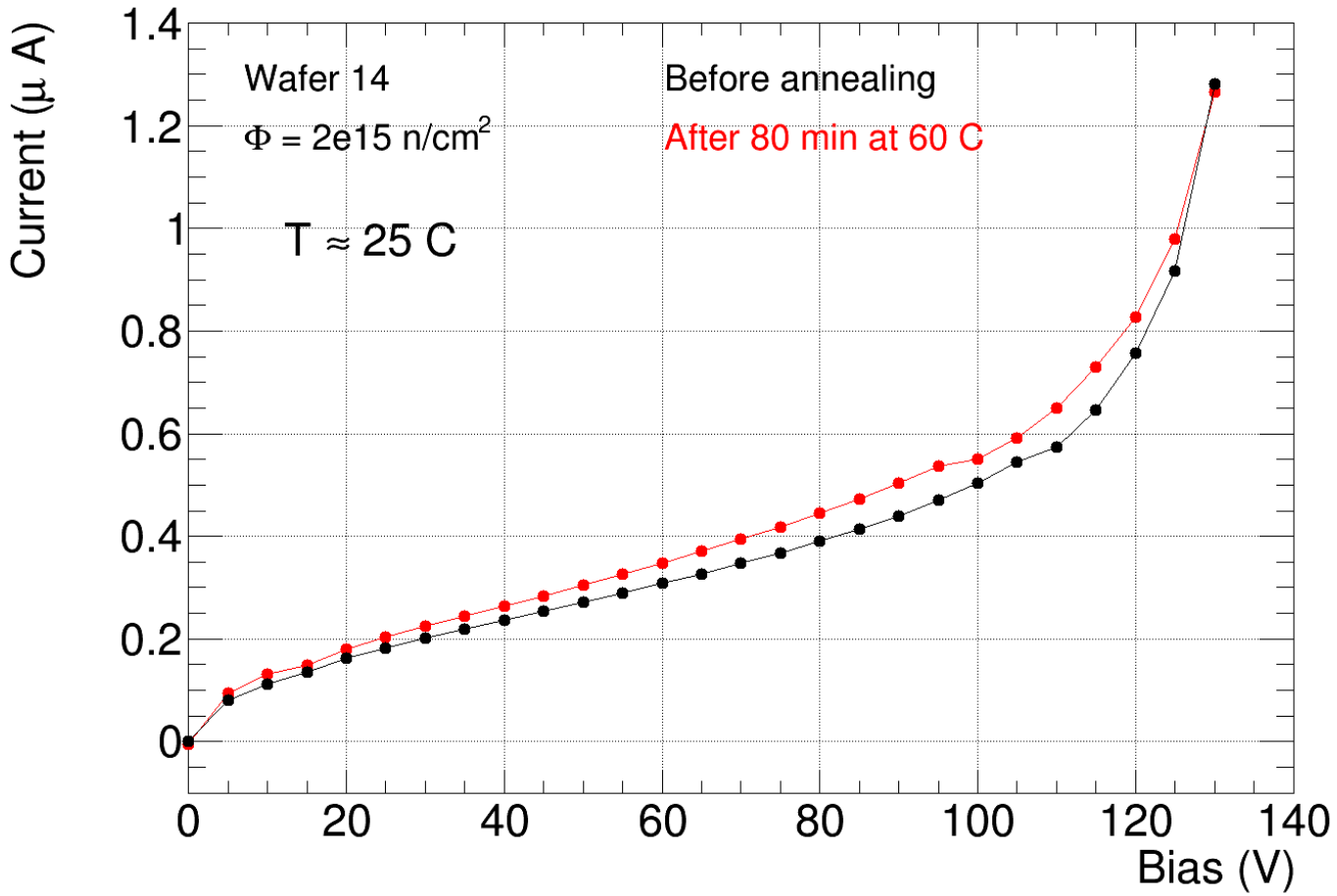
RD50-MPW2 irradiated I-V



- Irradiation to a range of neutron equivalent fluences Φ_{eq} up to $1 \cdot 10^{14}$ 1 MeV $n_{eq} \cdot cm^{-2}$
  - No annealing
- I-V measurements
  - ρ = 500-1100 (W7), 1900 (W10), >2000 Ω·cm (W13) nominal values
  - Only test matrix 2
- V_{BD} and I_{leak}
  - I_{leak} increases with Φ_{eq}
  - V_{BD} decreases with Φ_{eq} and similar for all ρ

Measurements done at HEPHY

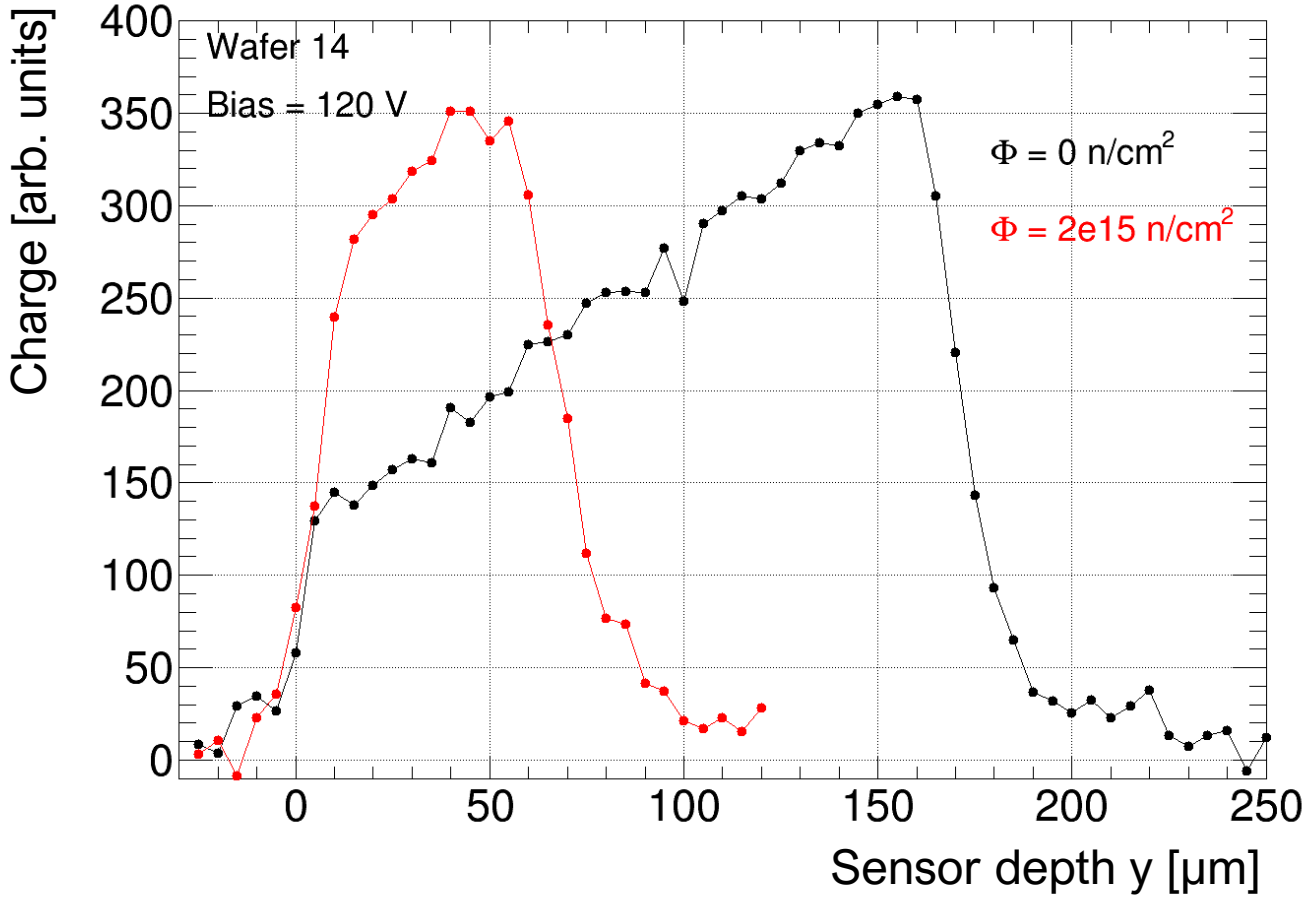
RD50-MPW2 irradiated I-V



- Irradiation to neutron equivalent fluence $\Phi_{eq} = 2 \cdot 10^{15}$ 1 MeV $n_{eq} \cdot cm^{-2}$
  - No annealing
  - 80 minutes annealing at 60 °C
- I-V measurements
  - W14 (ρ = 2200 Ω·cm measured)
  - Only test matrix 2
- V_{BD} and I_{leak}
  - I_{leak} increases with Φ_{eq}
  - V_{BD} similar to before irradiation

Measurements done at JSI

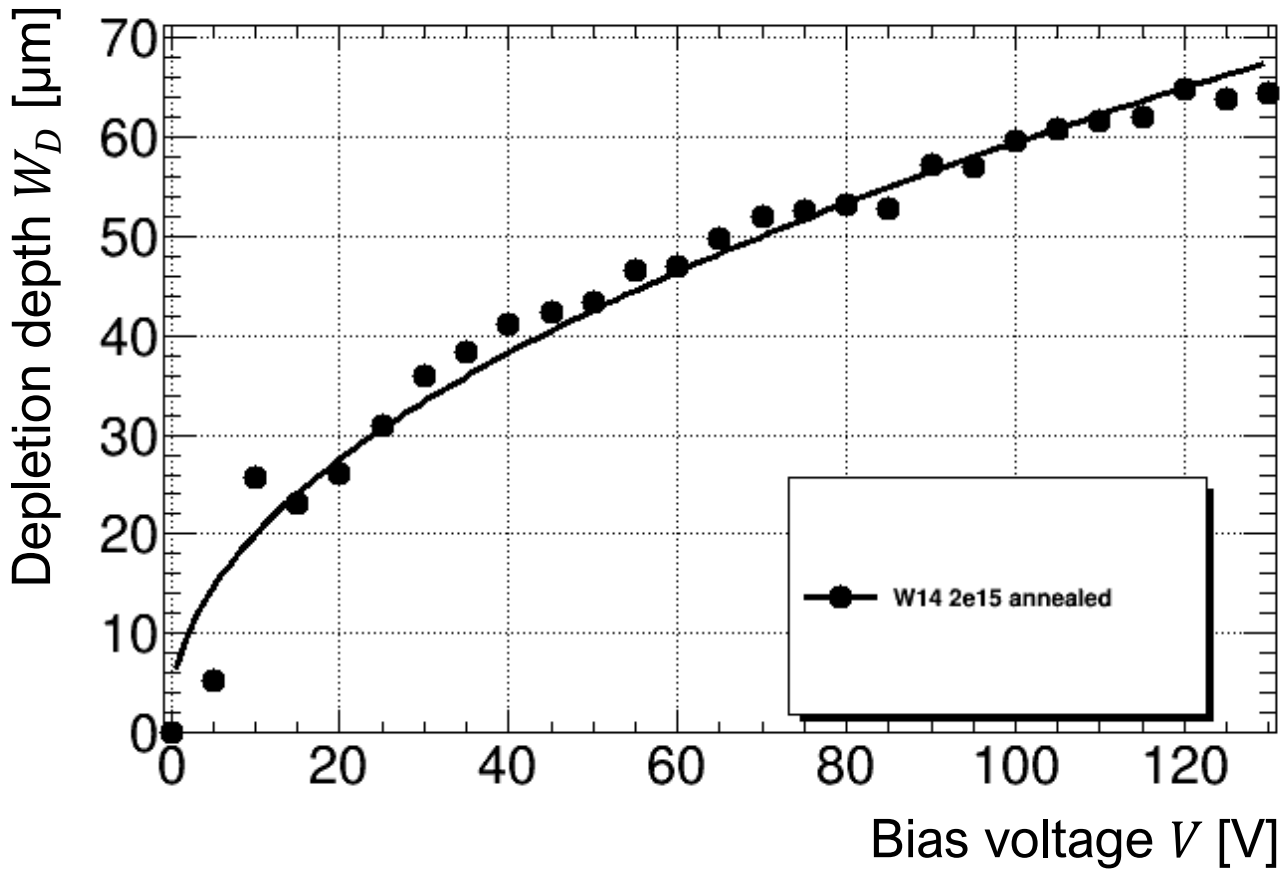
RD50-MPW2 irradiated e-TCT: Charge collection profiles



- E-TCT measurements
  - Only irradiated Wafer 14
  - W14 (ρ = 2200 Ω·cm measured)
  - Irradiated to $\Phi_{eq} = 2 \cdot 10^{15}$ 1 MeV $n_{eq} \cdot cm^{-2}$
- Charge collection profiles
  - Depletion depth shrinks due to irradiation
  - But ≈ 70 µm depleted at 120 V

Measurements done at JSI

RD50-MPW2 irradiated e-TCT



Fit:

$$W_D = W_{D_0} + \sqrt{\frac{2\varepsilon_{\mathrm{Si}}\varepsilon_0}{e_0 N_{\mathrm{eff}}} \cdot V}$$

- Similar V_{BD} as before irradiation
- Effective doping concentration N_{eff}
  - Extracted from fit $0 < V < 130$
  - $N_{\mathrm{eff}} = 4 \cdot 10^{13}$ cm^{-3}
  - Increase with respect to non-irradiated device

Measurements done at JSI

Summary

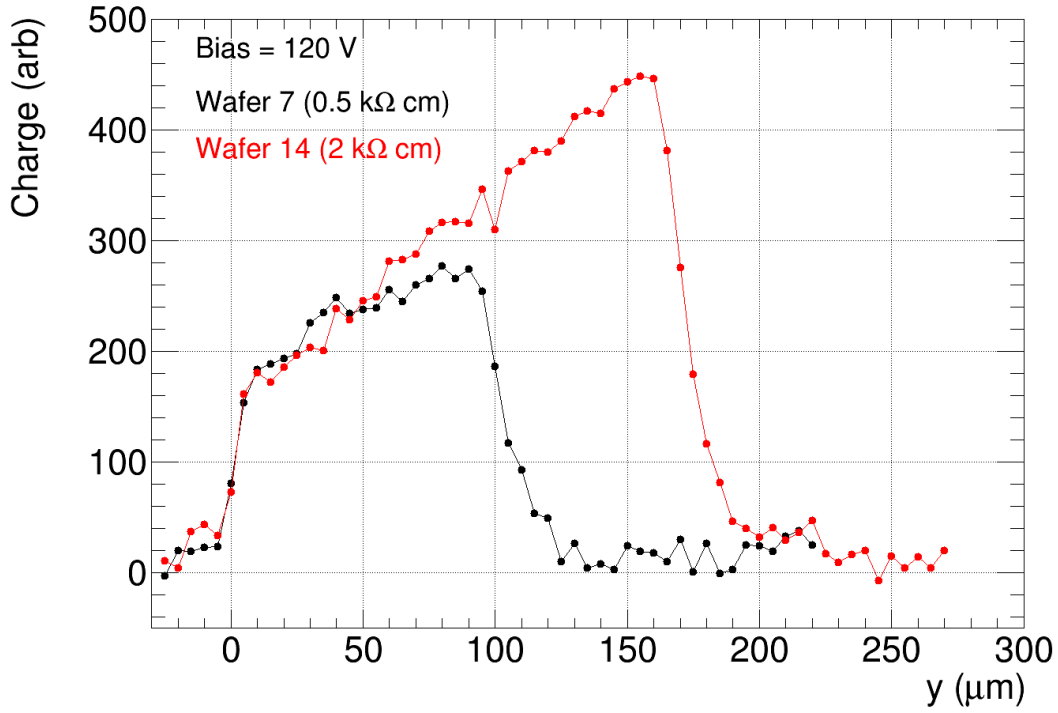
- RD50-MPW2 I_{leak} and V_{BD}
  - I_{leak} was reduced by many orders of magnitude with respect to RD50-MPW1
  - V_{BD} was increased with respect to RD50-MPW1
  - Methods developed for RD50-MPW2 will be incorporated in future RD50 submissions

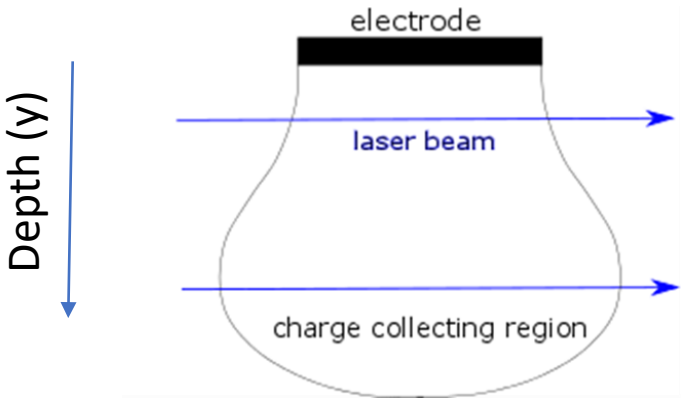
Ongoing and future work

- I_{leak} and V_{BD}
  - Complete I_{leak} measurements for other test matrices, more samples and resistivities
  - Extract V_{BD} for more samples and resistivities
- C-V measurements
- Irradiation campaign
  - Annealing studies
  - E-TCT of other fluences

Backup Slides

E-TCT charge collection profiles



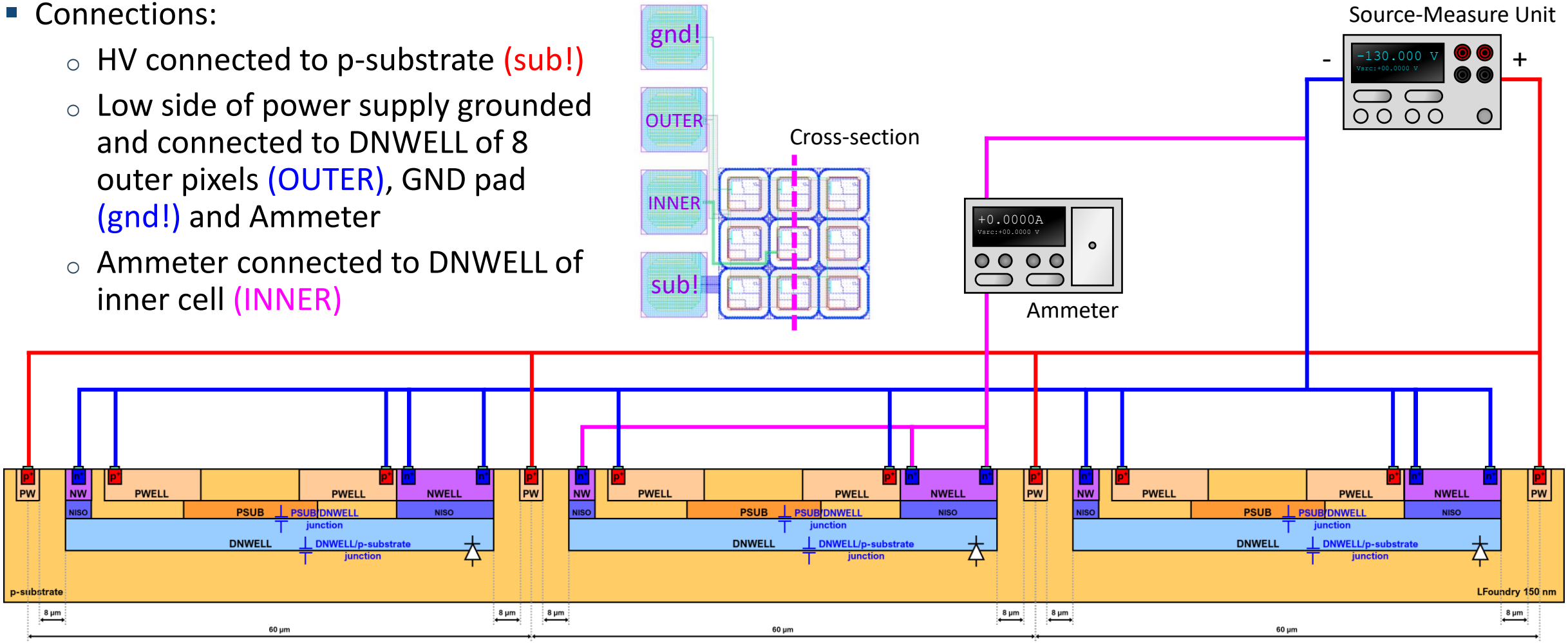


- More charge collected at larger y (depth)
  - length of laser beam inside charge collection region increases
  - shape of the region
- Not expected in larger pixel array
  - Depletion much smaller than dimensions of the structure

[1]Plot and diagram courtesy of I. Mandić (JSI) - I. Mandić et al., 2017 JINST 12 P02021, doi.org:10.1088/1748-0221/12/02/P02021

Diagram of I_{leak} measurements setup

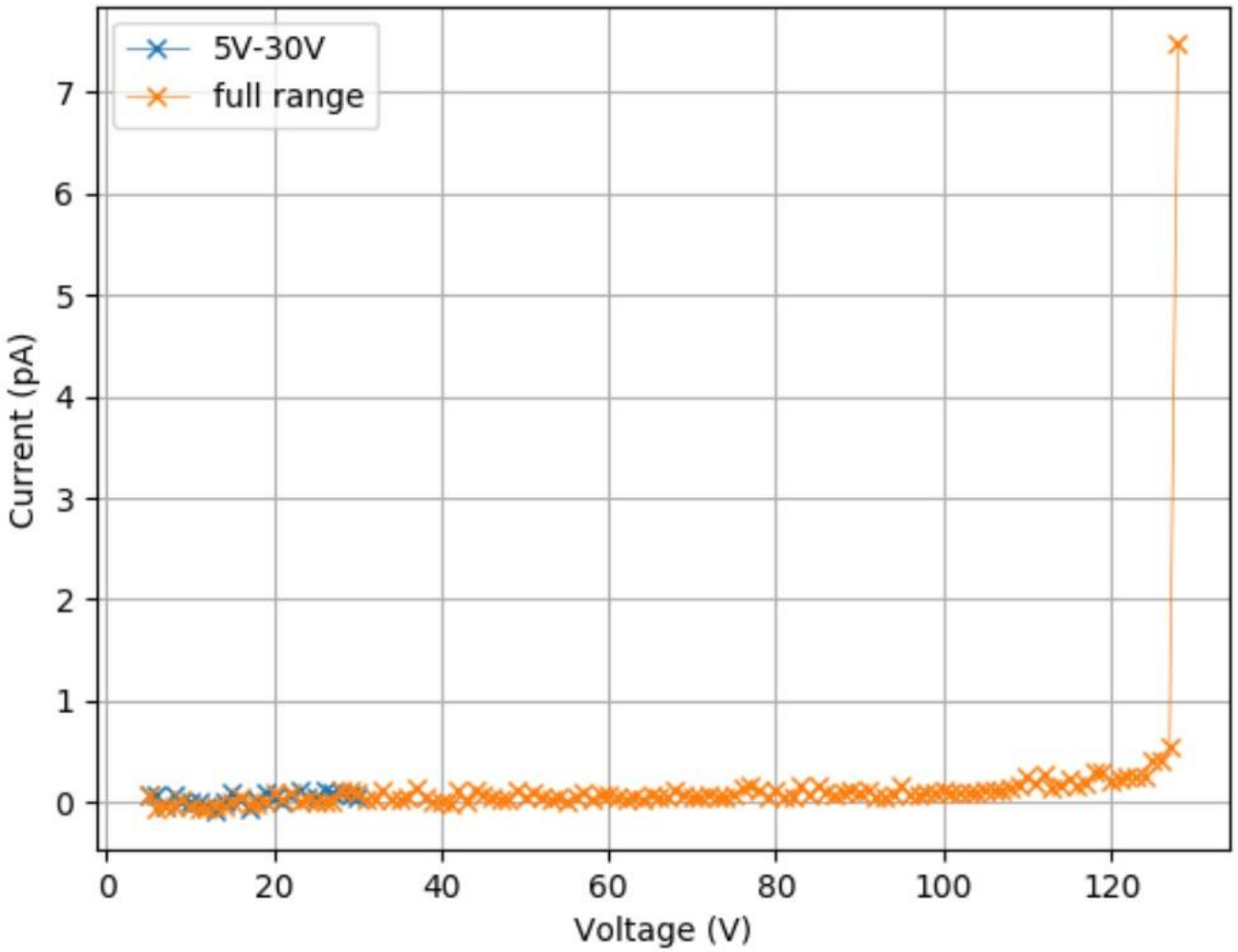
- Connections:
  - HV connected to p-substrate (sub!)
  - Low side of power supply grounded and connected to DNWELL of 8 outer pixels (OUTER), GND pad (gnd!) and Ammeter
  - Ammeter connected to DNWELL of inner cell (INNER)



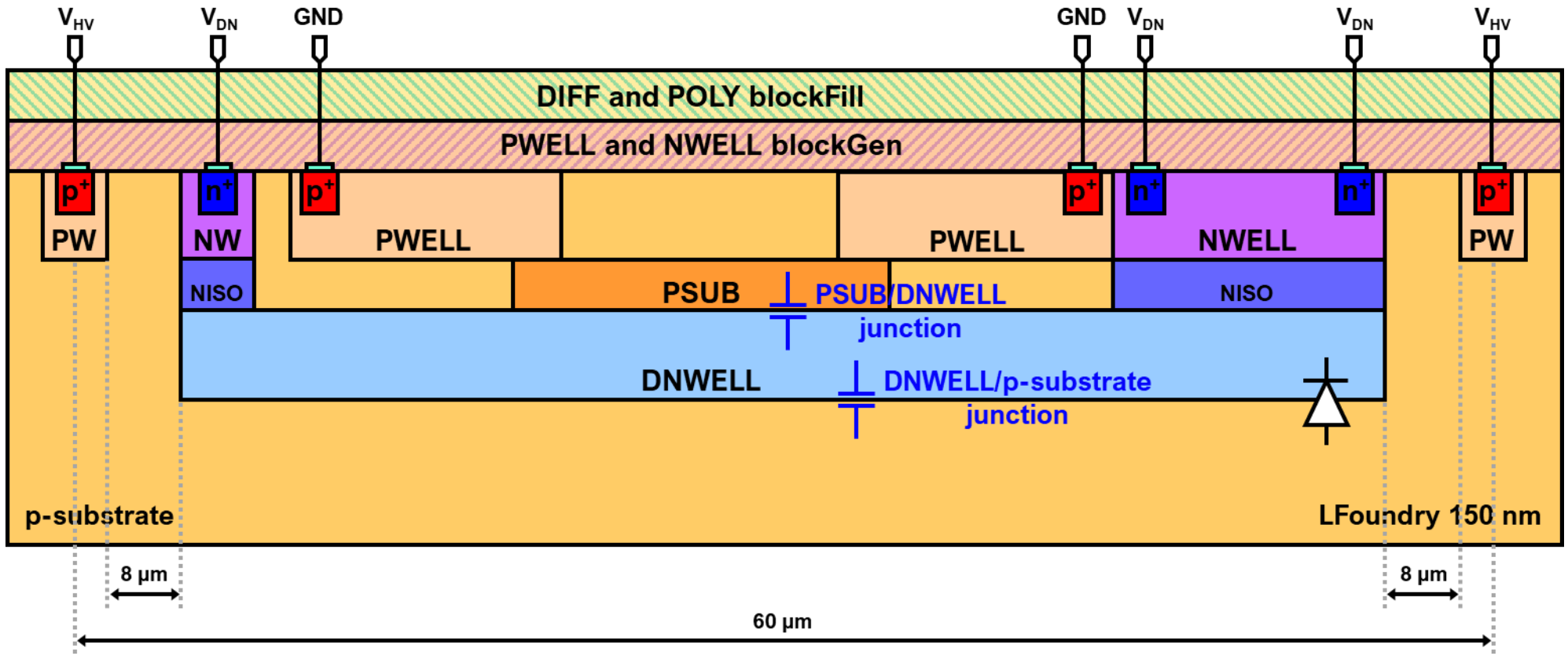
I_{leak} measurements full range test

- Contact test
  - 5 – 130 V bias voltage
  - 10 µA compliance
  - Second test structure used (same as active matrix pixels)

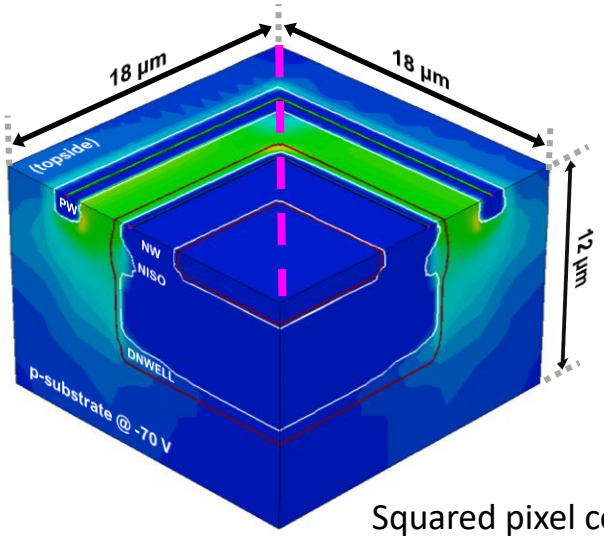
  - Full range tested to see breakdown
  - 5 V – 60 V (not 30 V) range used for leakage studies



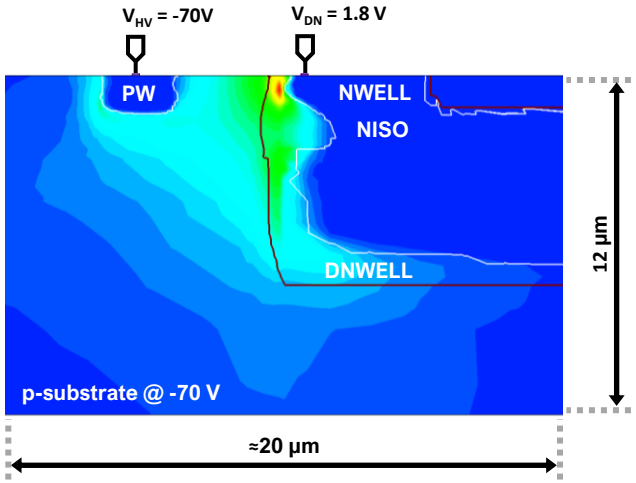
2D cross-section of test structure pixels in RD50-MPW2

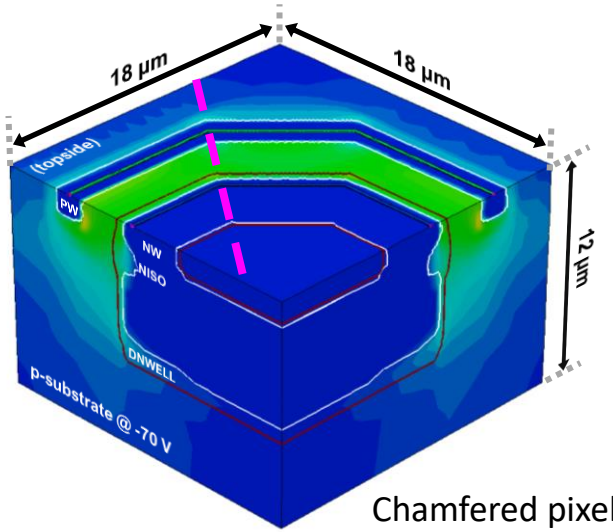


TCAD simulations of 3D pixel corners



Squared pixel corner





Chamfered pixel corner