TCAD simulations of High-Voltage CMOS pixel structures for the CLIC vertex detector

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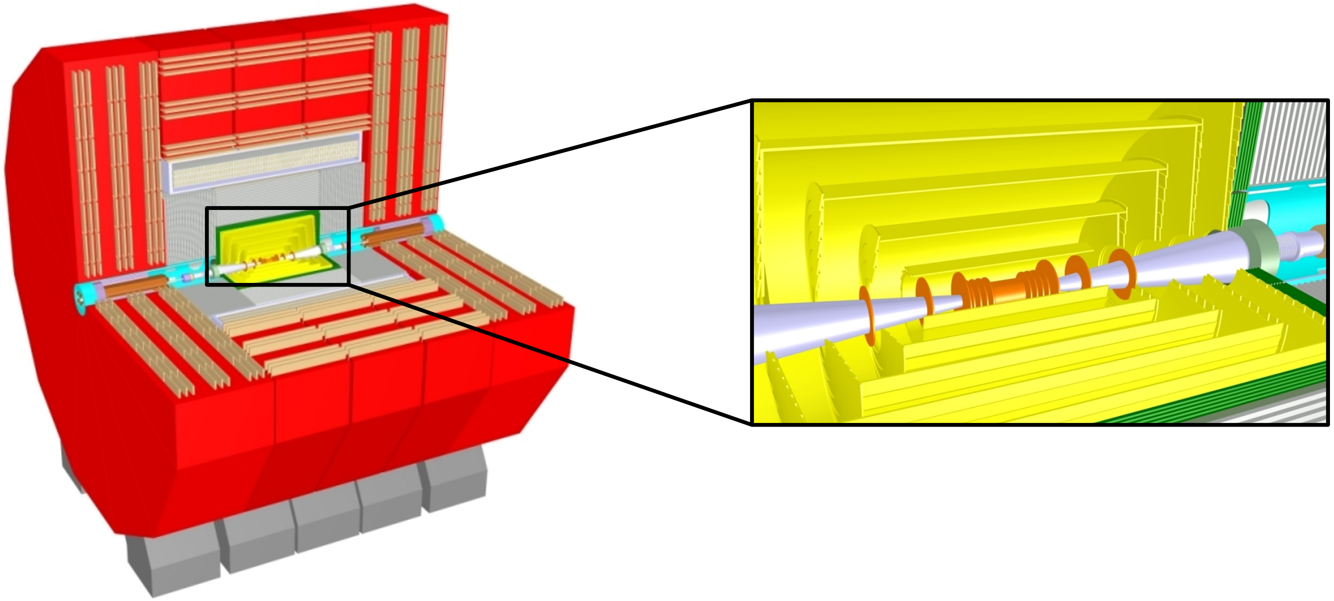
On behalf of CLICdp collaboration

Outline

- CLIC vertex detector
- Capacitively coupled pixel detector
- TCAD simulations
  - Goals
  - 2D 3D comparison
  - 3 pixel structure
- Summary

CLIC vertex detector

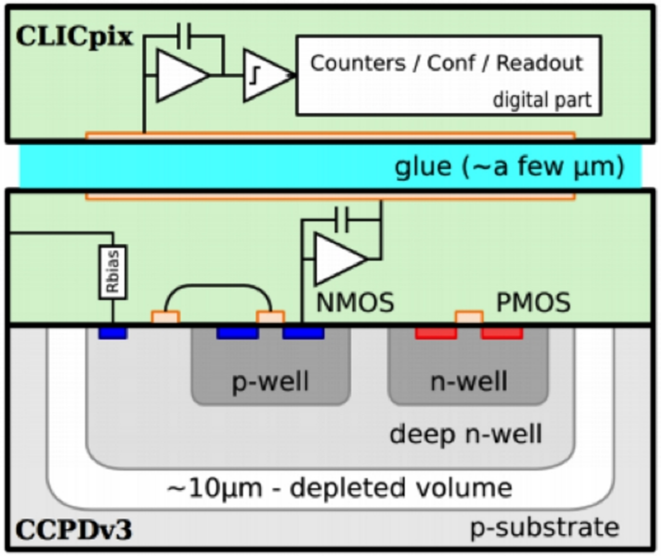
- Compact linear collider (CLIC) is a proposed e^+e^- collider with $\sqrt{s}$ 3 TeV at the final stage
- Precision physics and experimental conditions impose stringent conditions on the vertex detector:
  - 3 µm point resolution
  - Low material budget, ~0.2% X_0 per layer => air cooling
  - Fast signal, ~10 ns time stamping
  - Low power consumption, power pulse operation

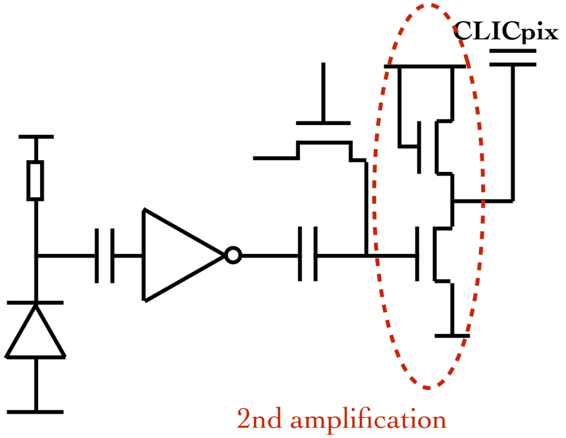


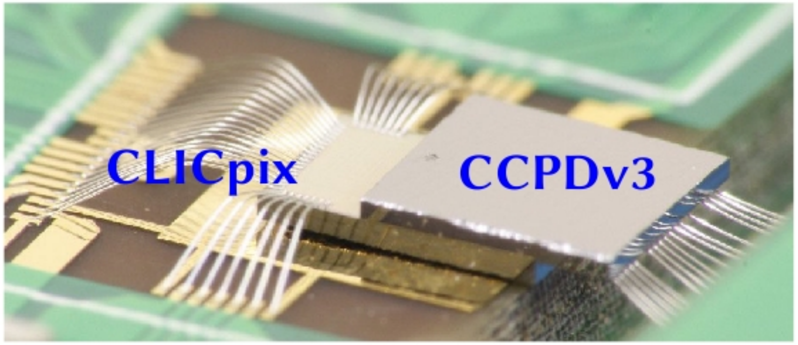
CLIC_SiD

HV-CMOS sensor

- Capacitively couple pixel detector (CCPD):
  - HV-CMOS sensor
  - Operated at high voltage to maximise the depletion region
  - Improves performance due to decreased detector capacitance and larger signal amplitude
  - Sensor is capacitively coupled to readout chip via glue
  - Hence low cost and low mass, compared to bump bonding
- CCPDv3:
  - Fabricated in 180 nm AMS technology
  - 2 stage amplification, peaking time ~ 120 ns
  - 25 µm x 25 µm pixels, 64 x 64 matrix







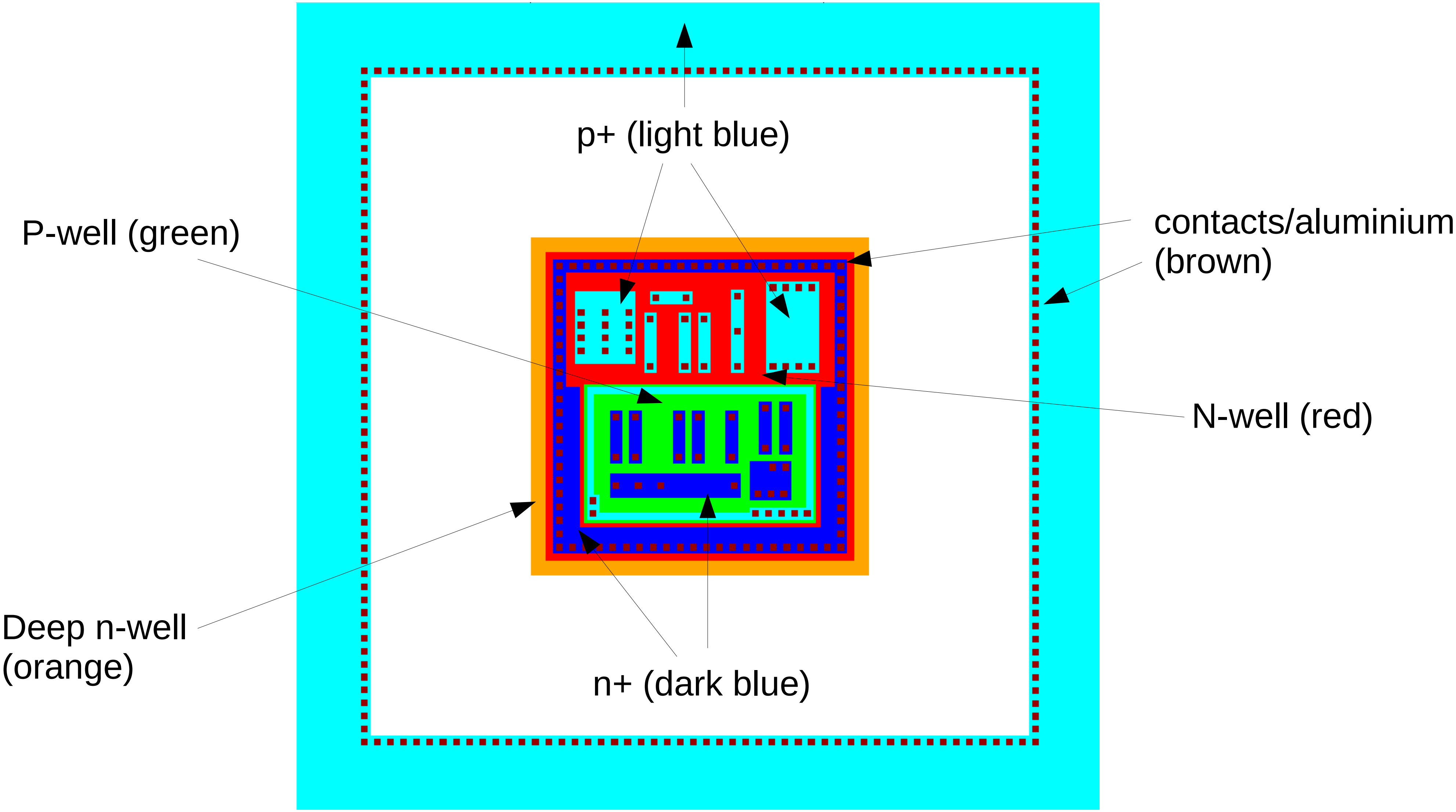
Goals of HV-CMOS TCAD studies

- Understand features of the measurements better e.g. transient signal development
- An accurate model will improve the comparison between simulation and measurements
- Use as input for simulation chain of sensor and readout chip
- Want to check the validity of the 2D simulations by comparing to 3D ones

- Limitations of 3D simulations:
  - Very memory intensive, using large amount of RAM (~16GB), long run times (+30hrs)
  - Has a trade off between mesh size (convergence) and memory
  - Reduced the model with less implants to reduce memory
- Hence 2D is much quicker but is it realistic?

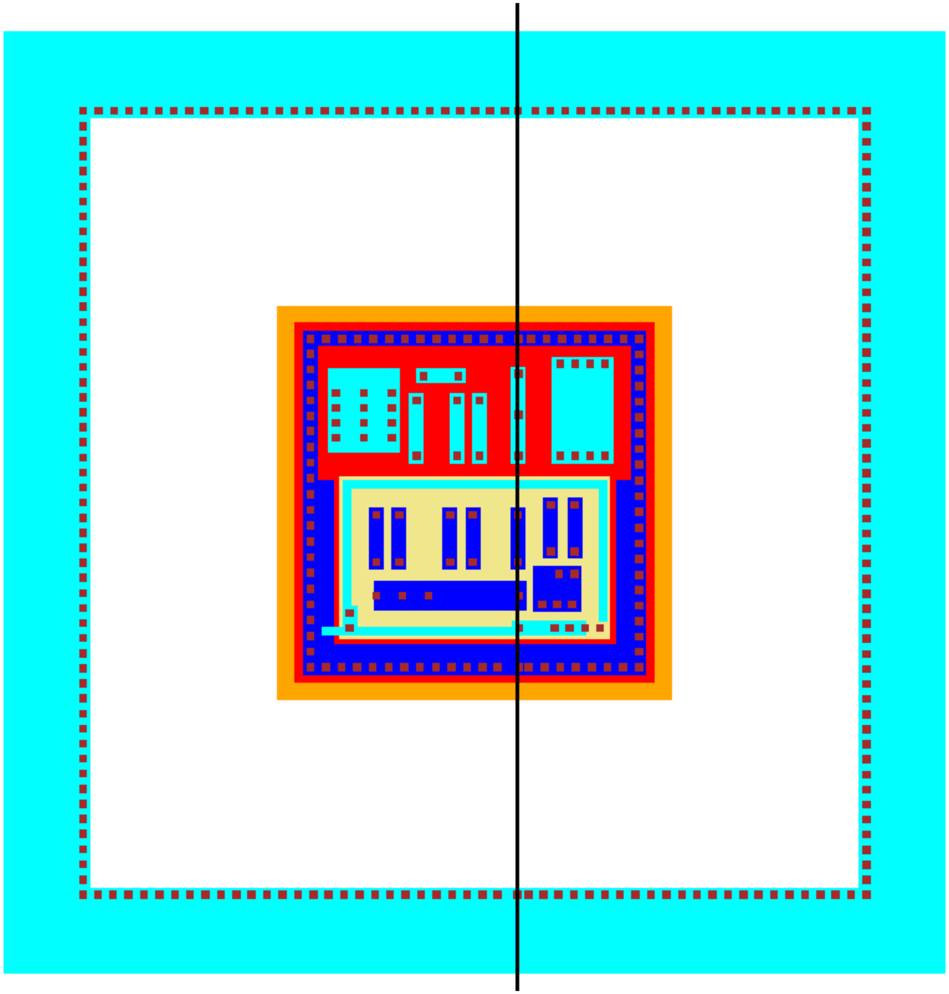
CCPDv3 layers to be simulated

- Layers obtained from the design file (gds layout file), imported to ligament layout
- Full implant structure, no metal lines shown



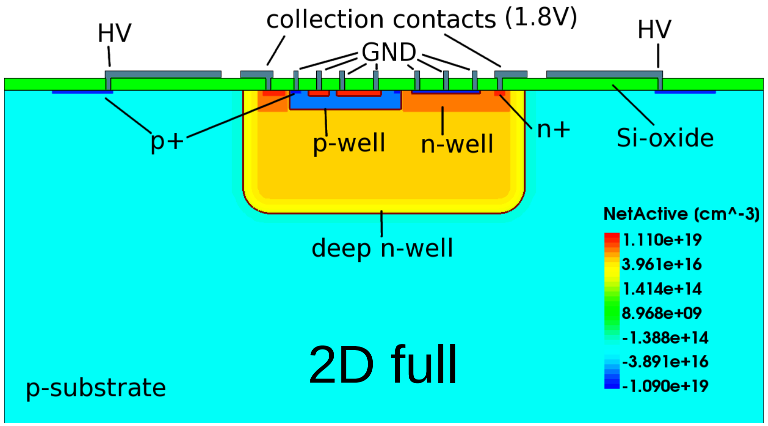
2D Cut

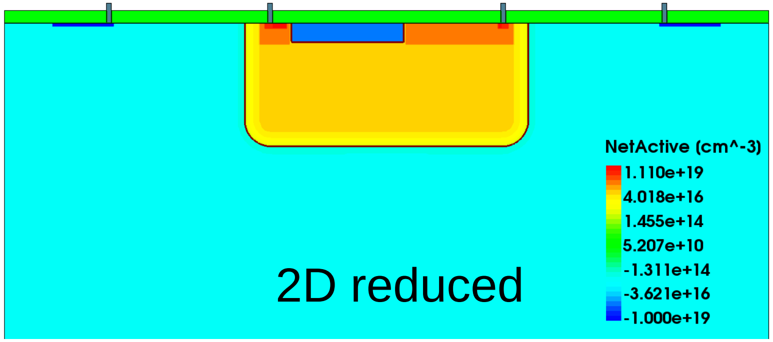
- There is no ideal cut as it is not symmetric
- Adjusted some layers so that contacts could be made
- => not an exact cut of CCPDv3

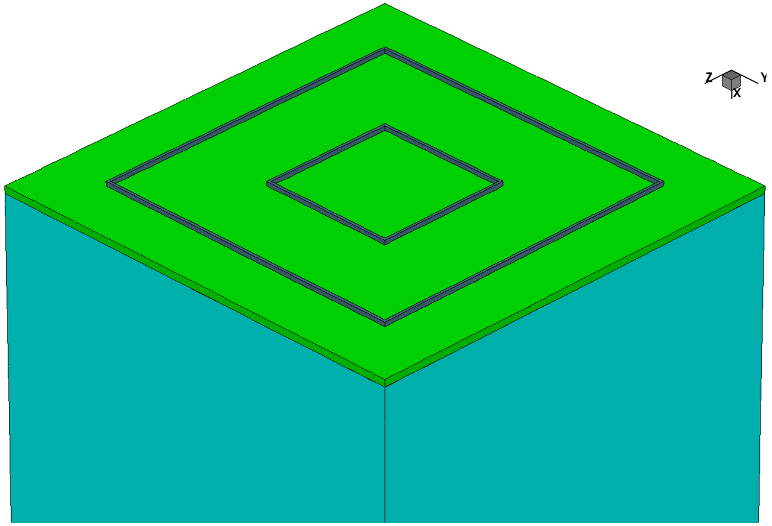


Simulated TCAD structures

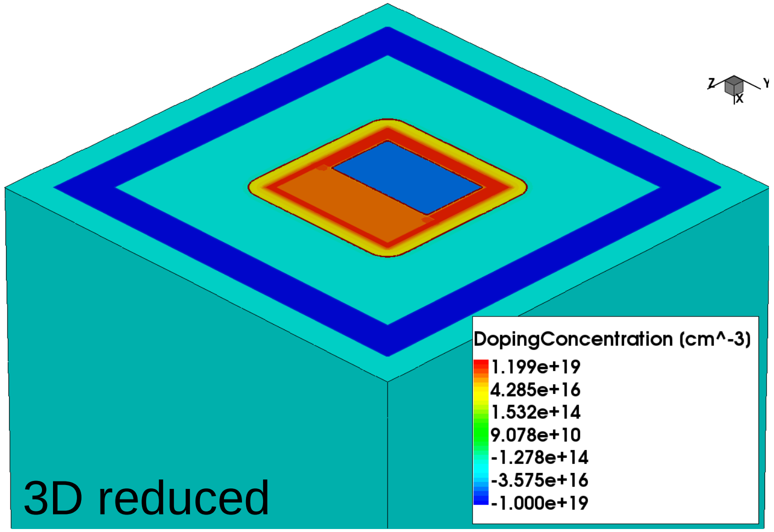
- 3 structures simulated: 2D full, 2D reduced and 3D reduced
- 2D full has all the implants and contacts
- The 2D reduced and 3D reduced structures both have the same implant structure
- 100 µm thick 31.5 µm wide, 10Ωcm
- Created in Sentaurus structure editor
- “Net active” is the doping concentration





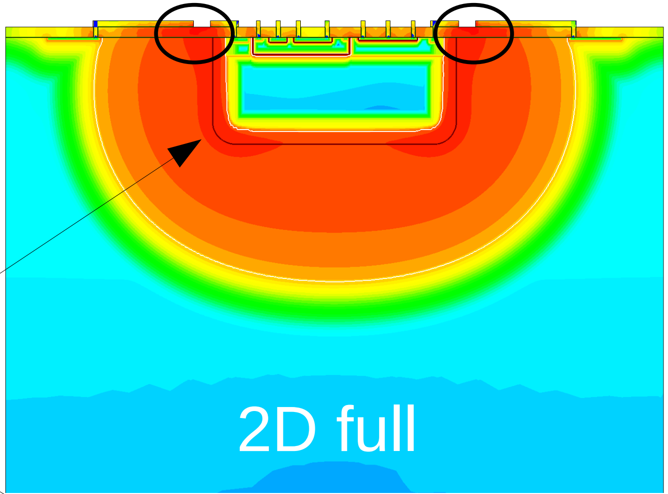


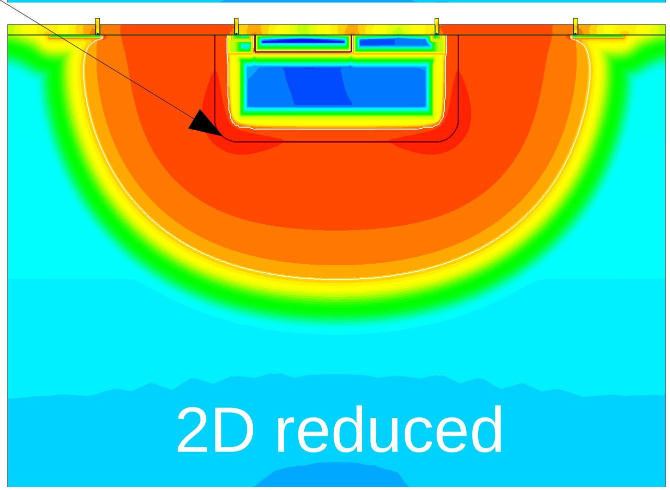
3D reduced with oxide and aluminium

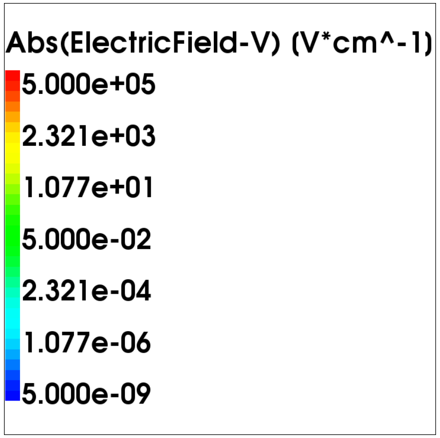


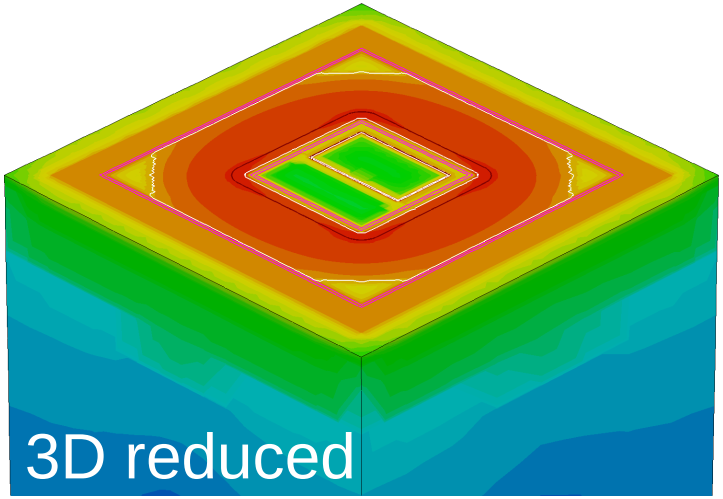
E-field comparison

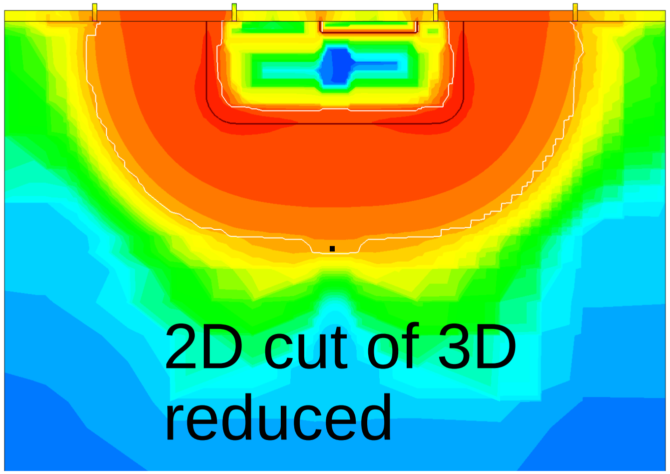
- Biased to -60V, operating voltage of device
- All electric fields are roughly the same:
  - higher value at edges of the deep n-well
  - Lower value in deep n-well and outside depletion
- One difference: 2D full model has a higher electric field value in the oxide because of the metal layer





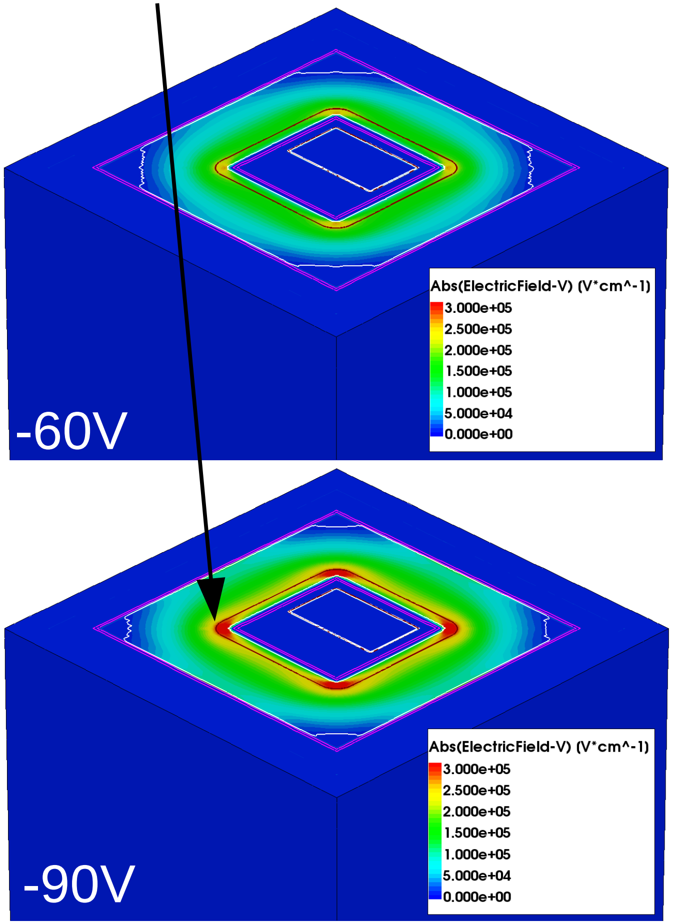


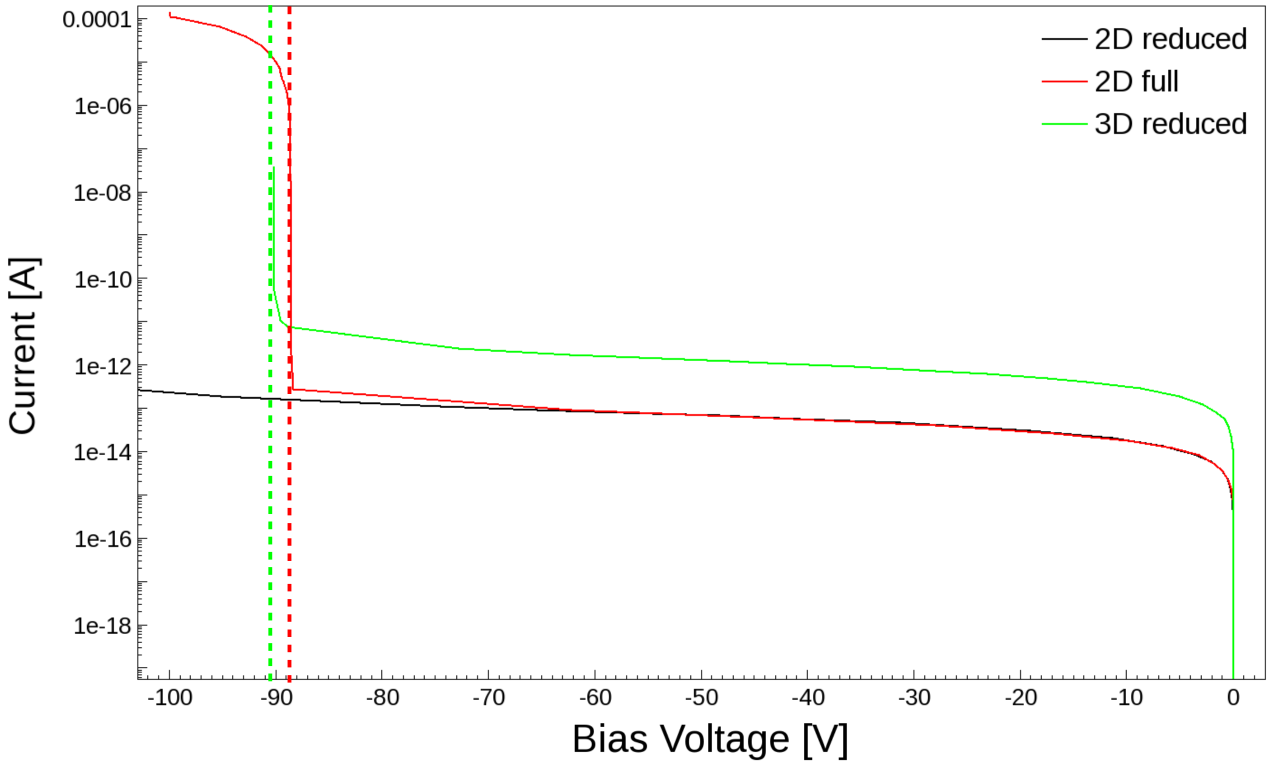




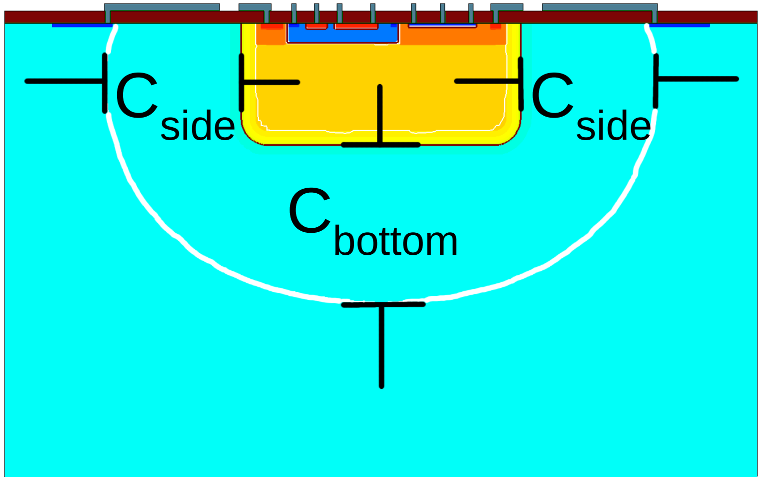
Leakage current comparison

- Breakdown of real device was measured to be -93V
- See breakdown in 2D full at ≈ -88V and for 3D reduced ≈ -90V
- Breakdown in 2D reduced greater than -100V due to no metal layer
- Breakdown field of silicon ≈ 3x10^5 V/cm





Capacitance comparison



- Deep n-well to bulk
- Test bench measurements: ~10 fF
- Parallel plate estimate:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

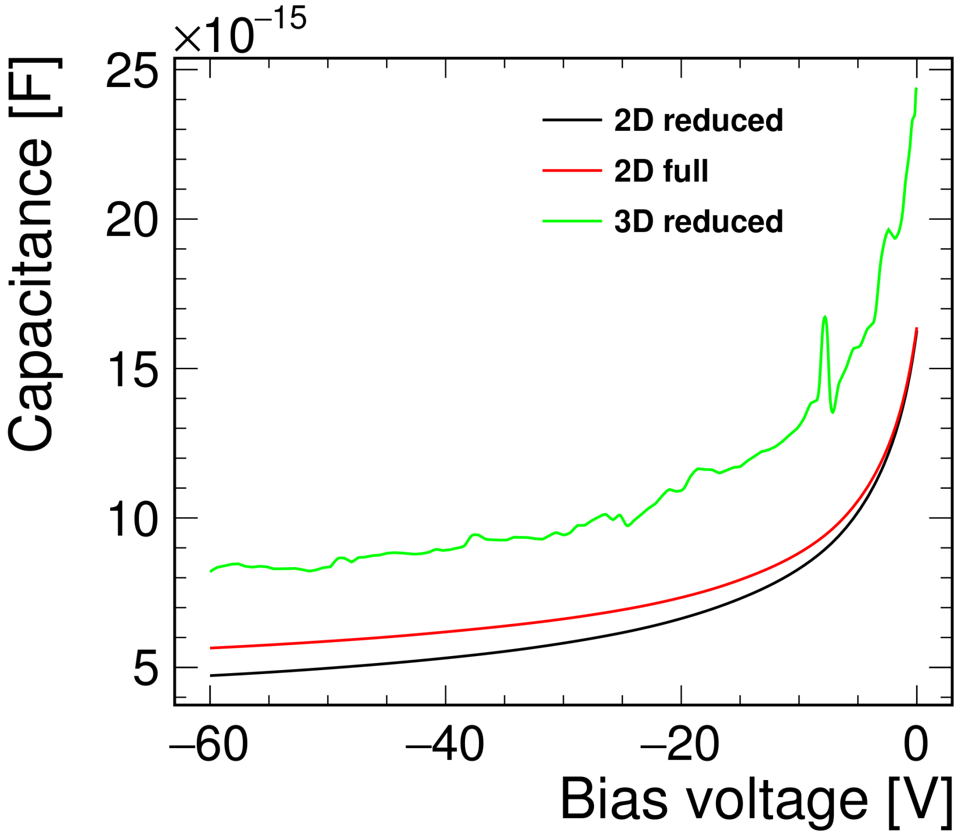
- Where A = area of deep n-well and

  d = depletion width

- At -60V:

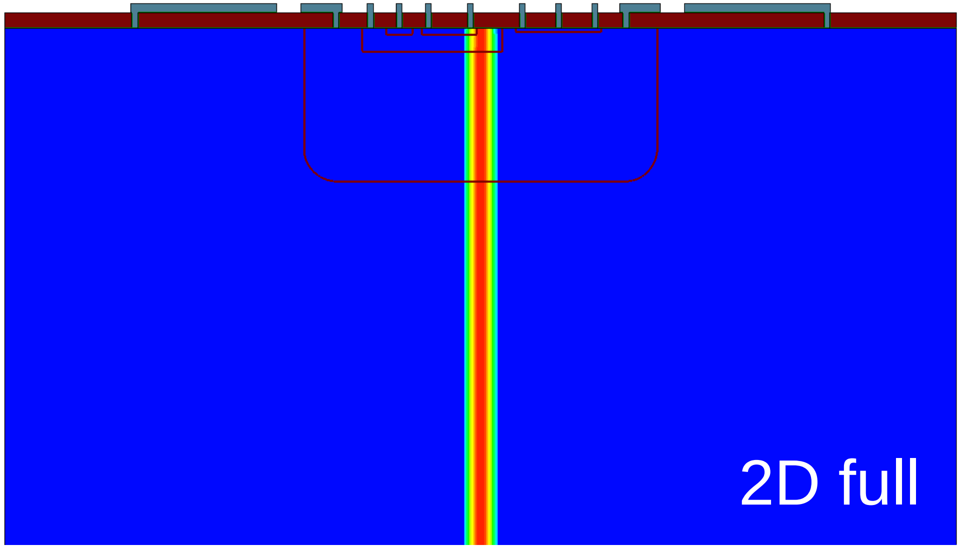
$$C_{total} \approx C_{bottom} + 4C_{side} \approx 6 \text{ fF}$$

- Simulations are consistent with measurements
- 2D simulation results are given in F/µm, then multiplied by deep n-well length hence only estimates



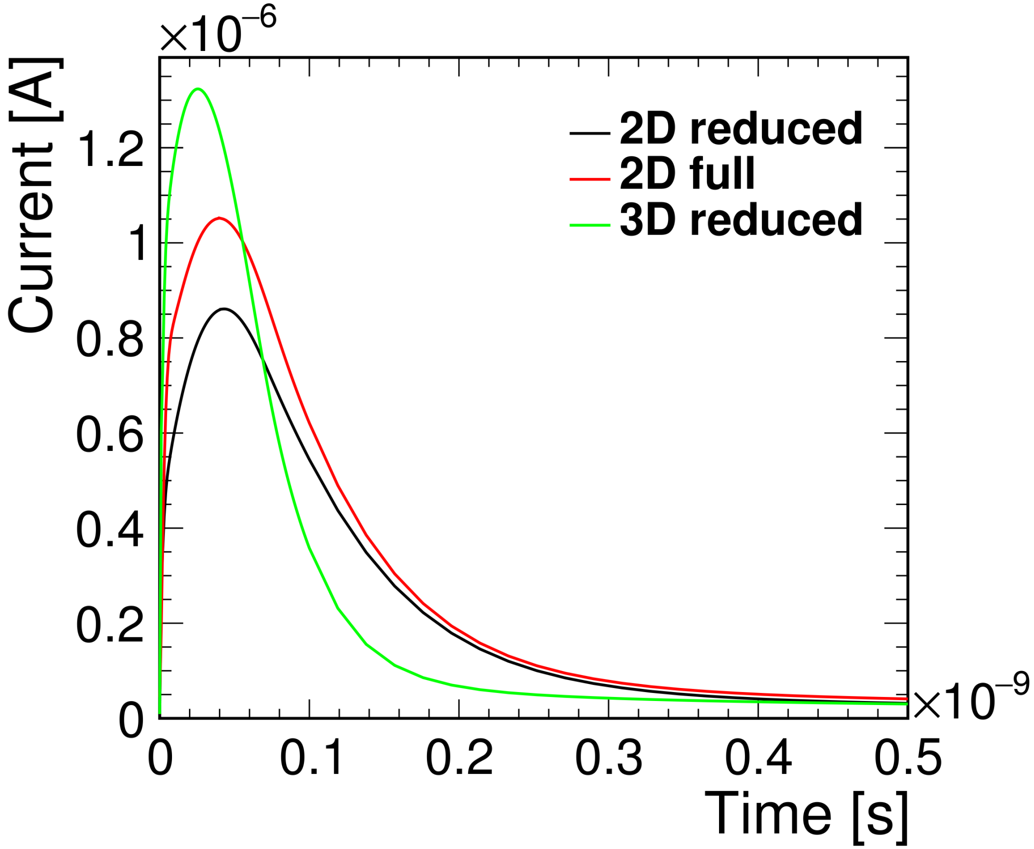
MIP simulation

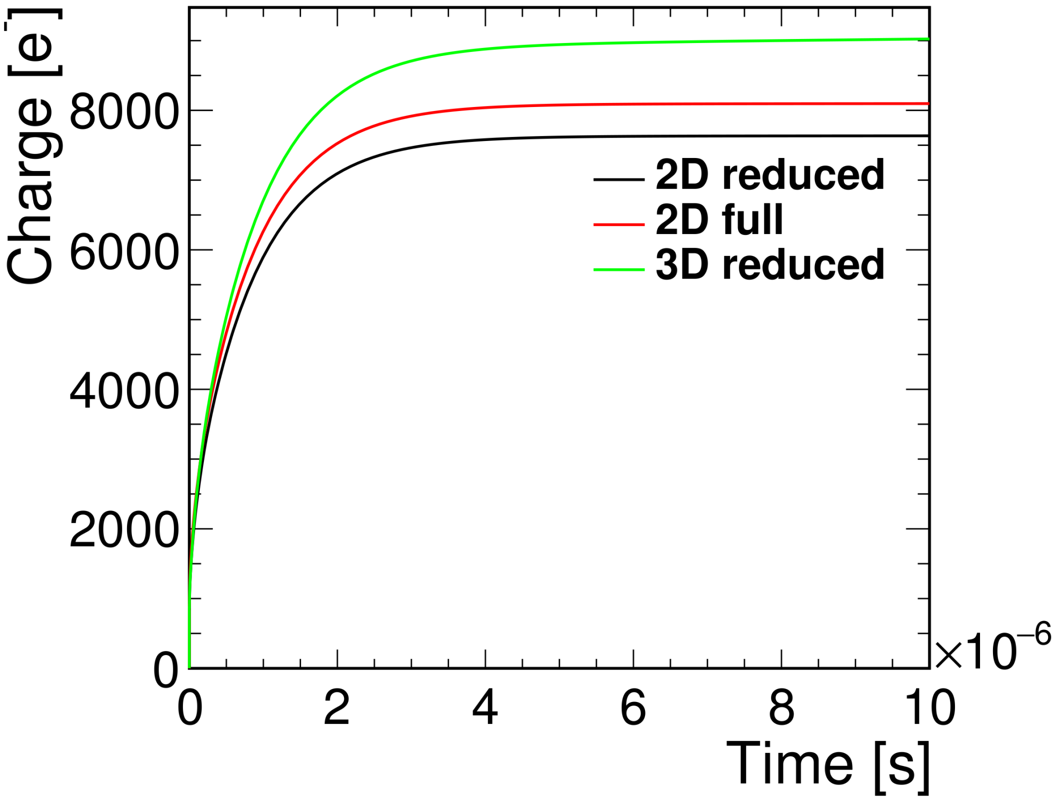
- In TCAD specify time, direction, position and charge deposition of the particle
- Charge is then instantaneously placed
- The MIP passes the centre of all three structures
- Deposits 80 electron-hole pairs per micron, no landau fluctuations
- Transient simulation from 0-10µs is performed at bias voltage -60V
- Real sensor is 250µm thick but found only 100µm contribute to signal over an appropriate time scale



MIP signal

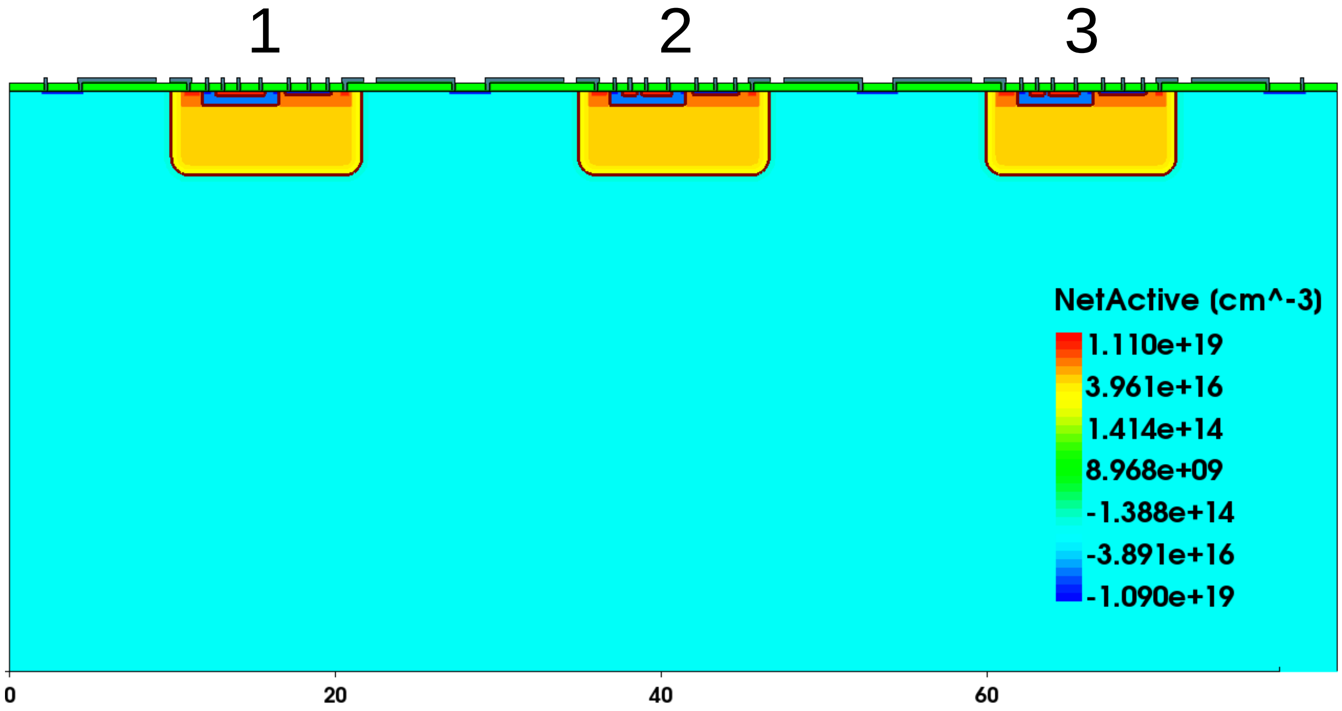
- 3D reduced model has the largest peak but quickly drops to the lowest value
- The 2D full model has larger current value than the 2D reduced model
- After 10μs 3D reduced collects the most charge: around 900e$^-$ more than 2D full and 1400e$^-$ more than 2D reduced
- May be due to coarser mesh





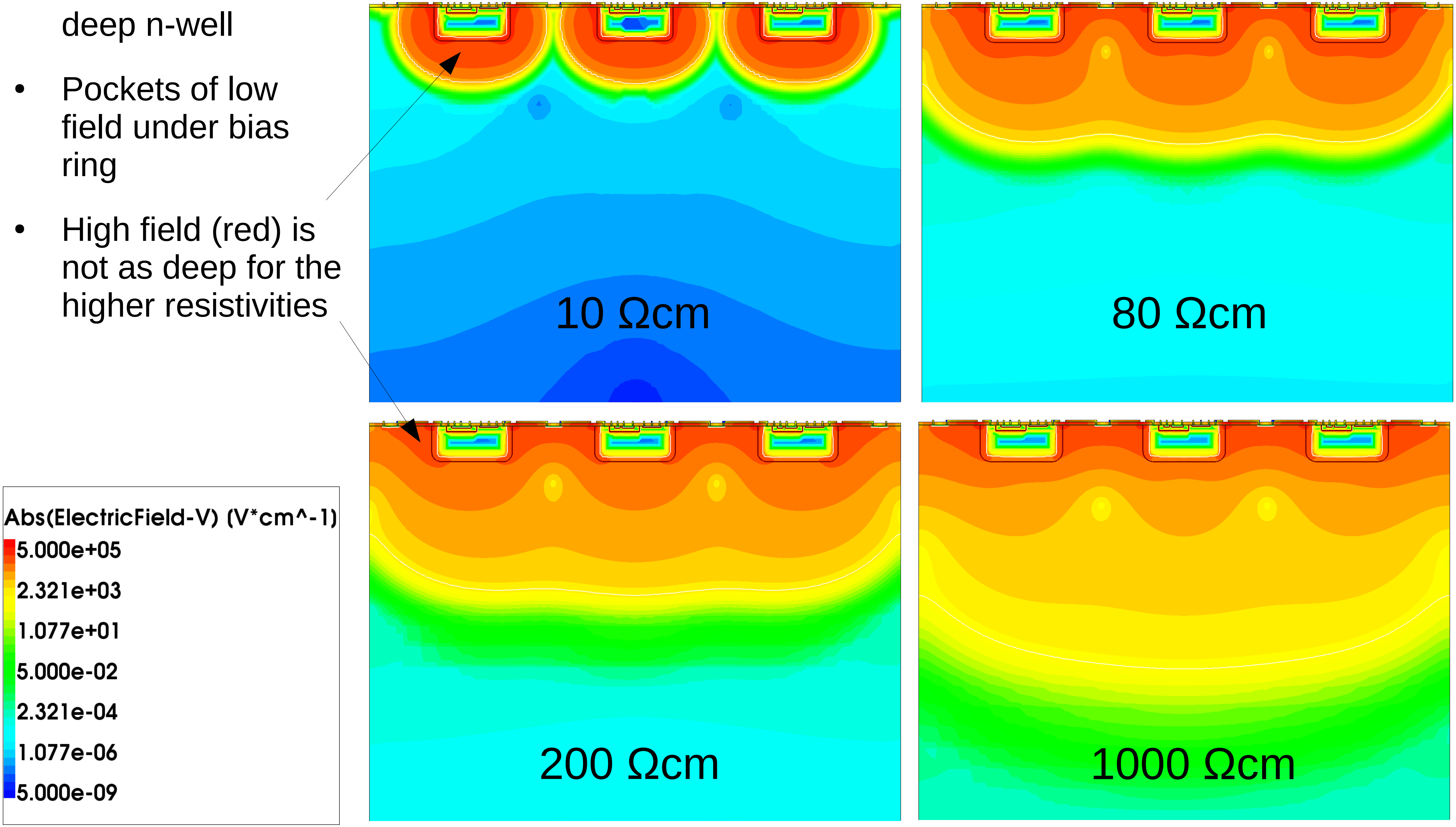
2D full 3 pixel structure

- 3 pixel structure with a pixel pitch of 25µm
- Width 81.5µm, thickness 100µm
- Labelled pixel 1, 2 and 3 from left to right
- Look at different resistivities 10 Ωcm, 80 Ωcm, 200 Ωcm and 1000 Ωcm



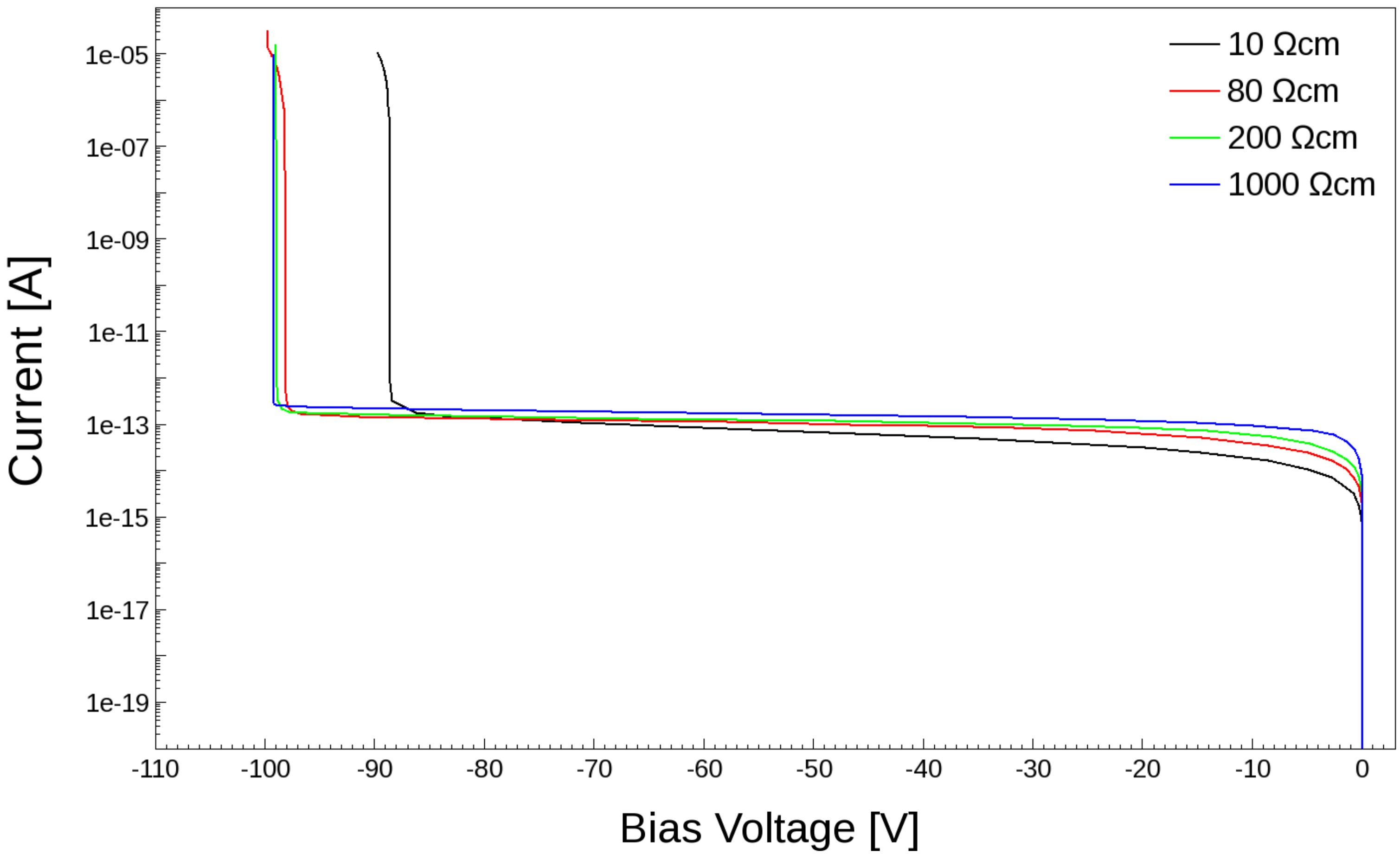
Electric field for different resistivities, -60V

- Field extends the most under the deep n-well
- Pockets of low field under bias ring
- High field (red) is not as deep for the higher resistivities



Breakdown for different resistivities

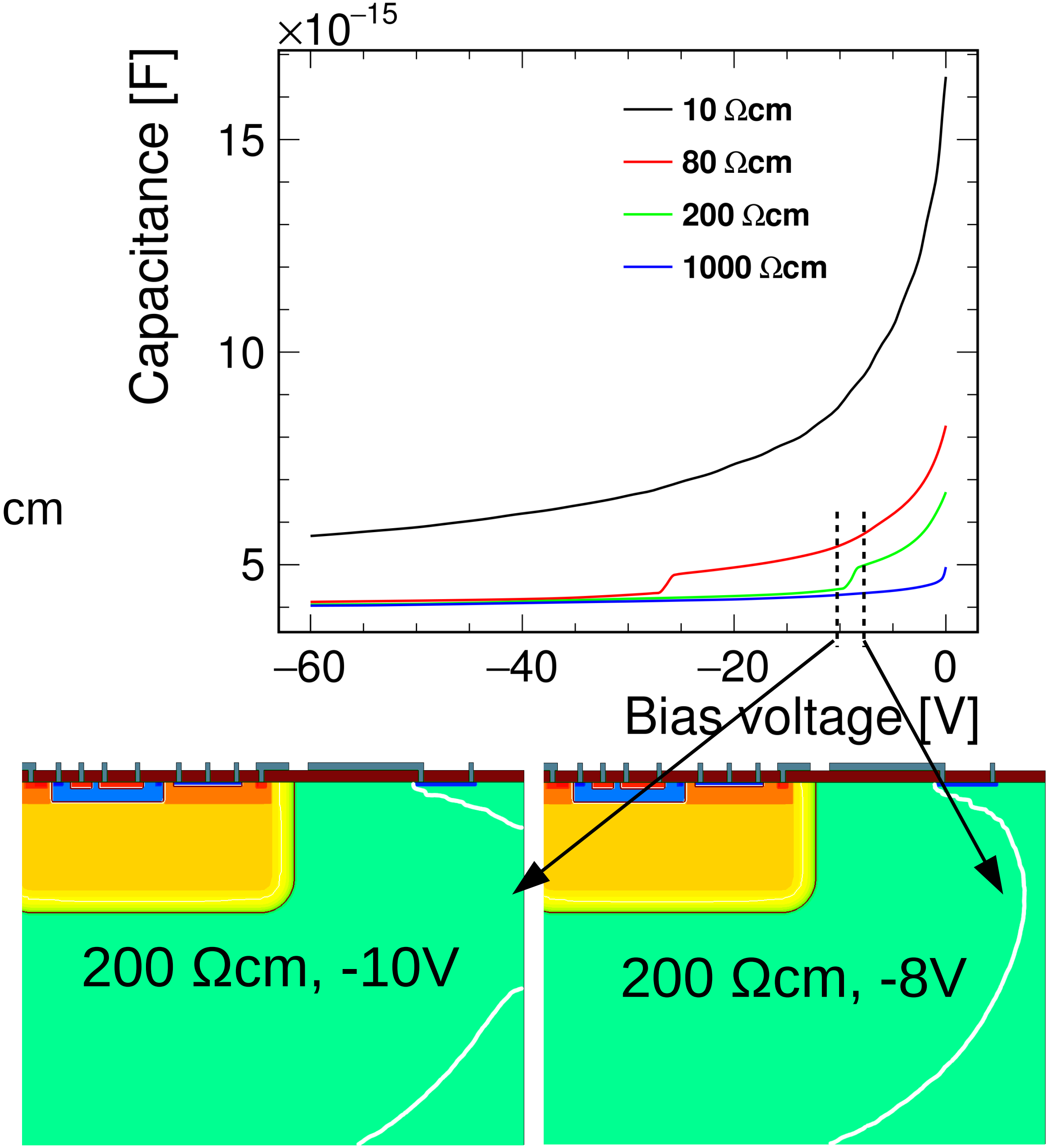
- The breakdown increases with resistivity
- The higher resistivities all breakdown ≈ -100V suggesting the implant structure is the limiting factor



Capacitance comparison

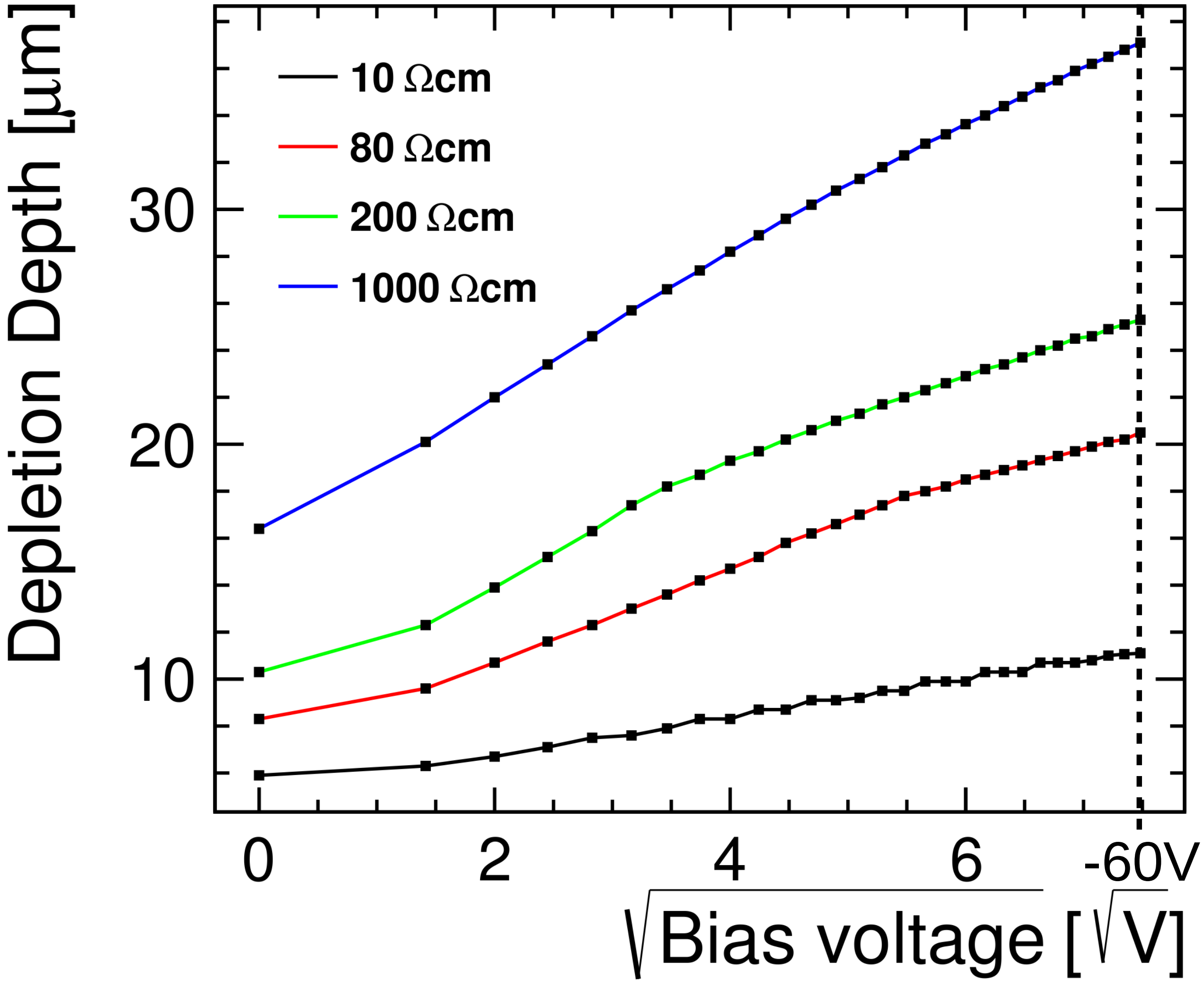
- Deep n-well to bulk
- Kink in curve due to depletion region reaching edge
- Capacitance reduces with resistivity
- Small difference between

  80 Ωcm, 200 Ωcm and 1000 Ωcm



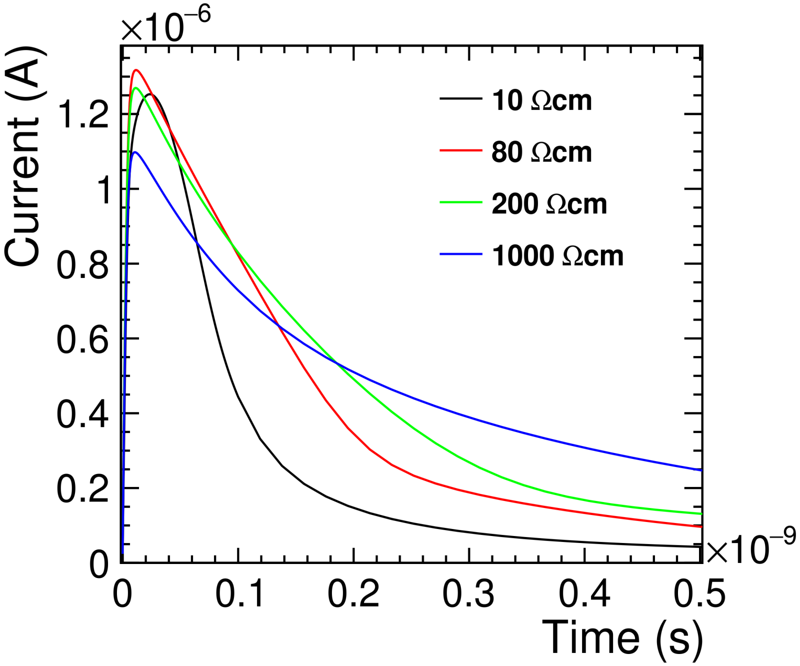
Depletion depth for different resistivities

- As expected the larger the bias voltage and resistivity the larger the depletion depth

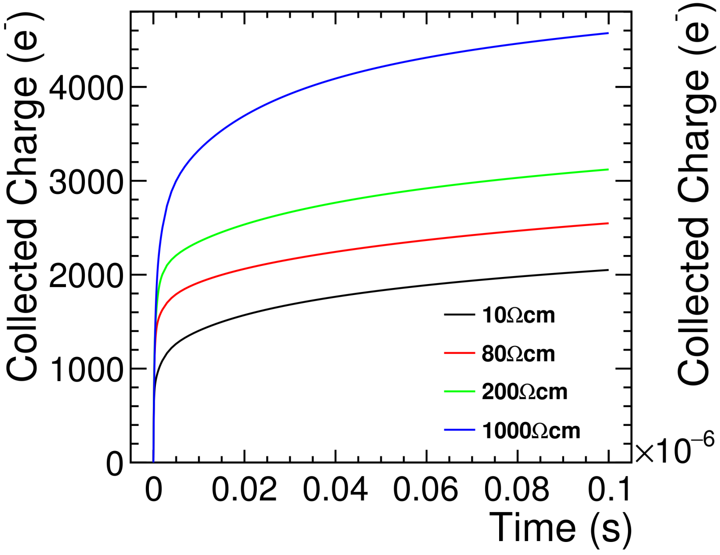


MIP signal for different resistivities, -60V

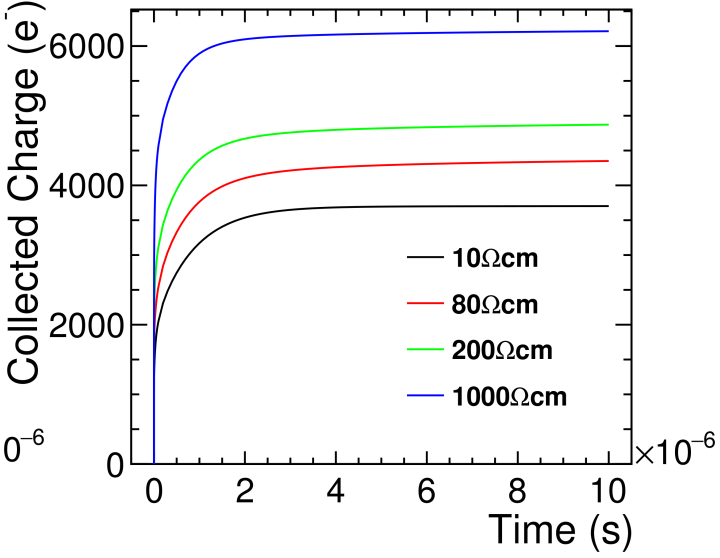
- Send a MIP through the centre
- Similar current peak height and time for all resistivities
- After 10 µs 1000 Ωcm collects the most charge by ≈ 1000 e^-
- 10 Ωcm is significantly slower at collecting charge
- Difference in signal collection speed increases with higher thresholds

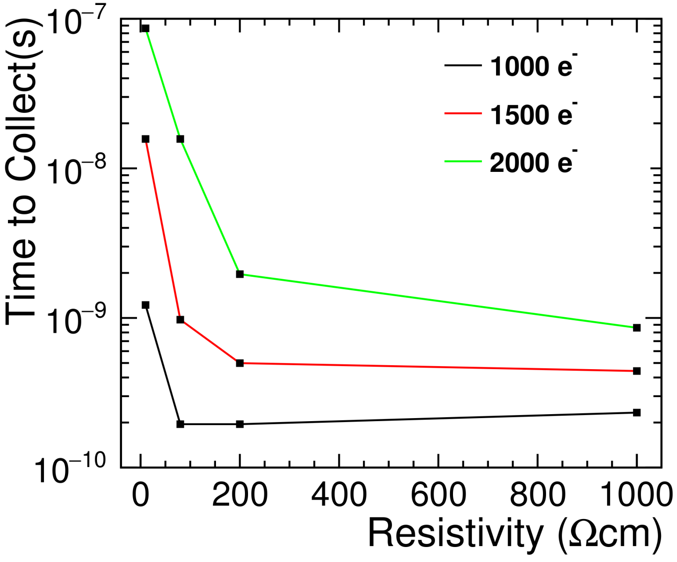


100ns



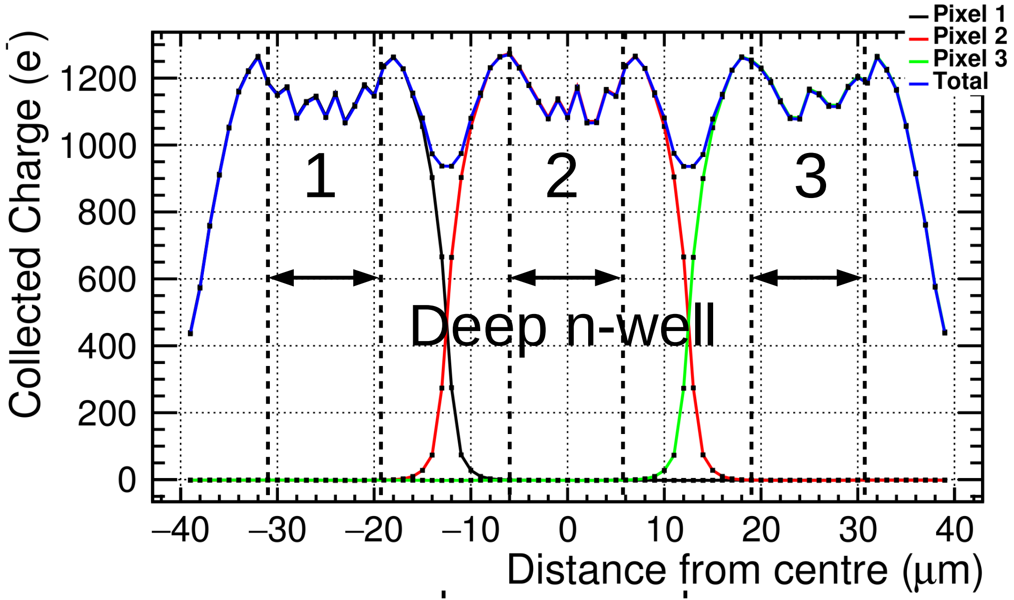
10µs

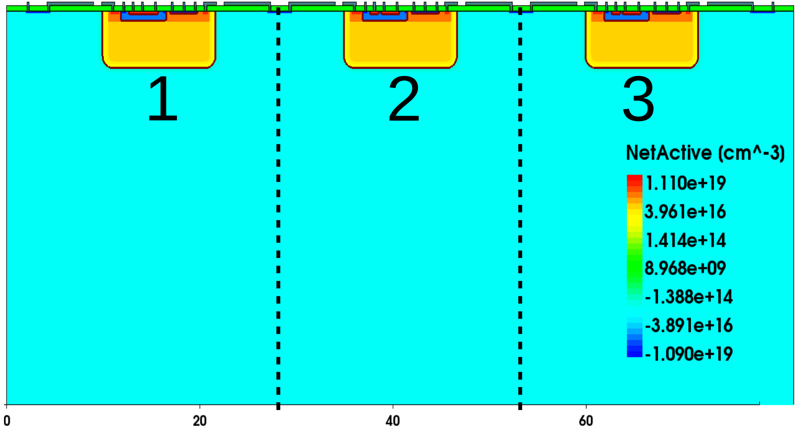


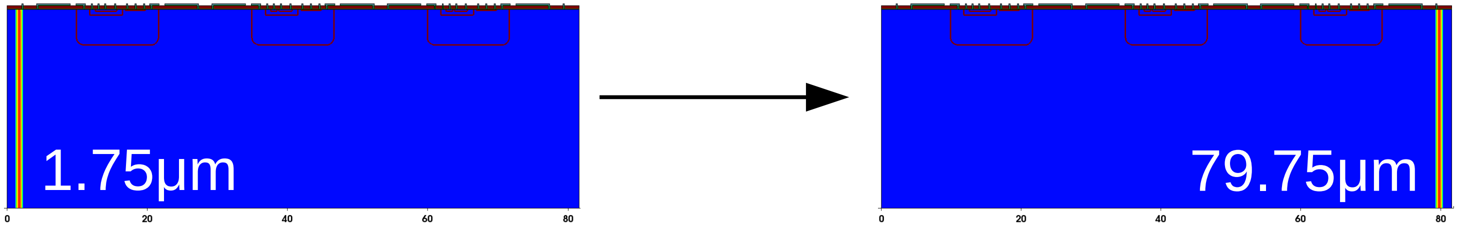


MIP scan collected charge 2ns

- 10 Ωcm, -60V
- MIP scan across the structure, perpendicular to surface
- From 1.75µm (-39µm) to 79.75µm (+39µm) in 1µm steps
- Centre of device is 40.75µm (0µm)
- After 2ns not as much charge is collected when mip passes through deep n-well
- Pixels collect 0 charge when the mip is far enough away
- No diffusion from these regions yet
- Lowest collected charge at edges

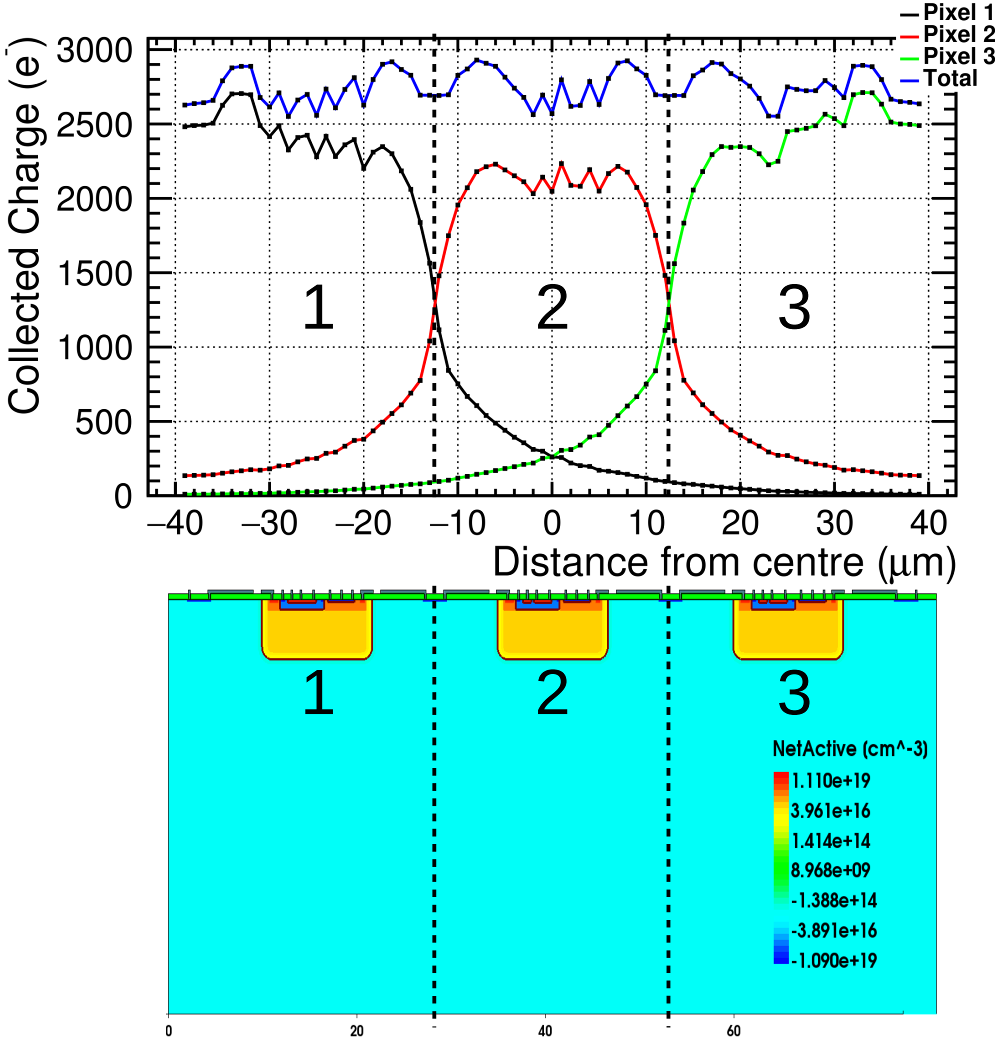






MIP scan collected charge 100ns

- 10 Ωcm, -60V
- After 100ns two side pixels collect more charge (edge effect)
- Did not occur after 2ns, hence this is due to diffusion
- Start to see diffusion to neighbouring pixels, charge sharing
- Total charge is uniform across whole device, agrees within 10%



Summary

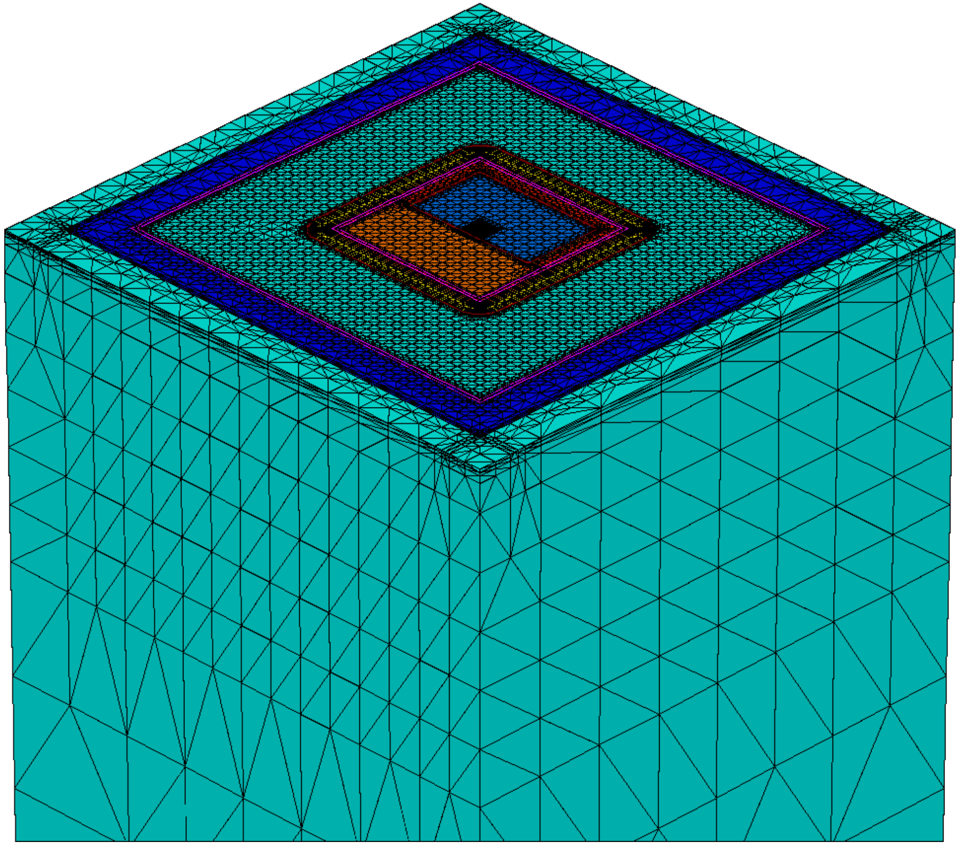
- 2D 3D comparison:
  - Agreement between the models in electric field
  - IV and CV curves are similar for 2D full and 3D reduced
  - Difference is less than 10% for charge collection after 10μs
  - Reasonable to use the 2D full model

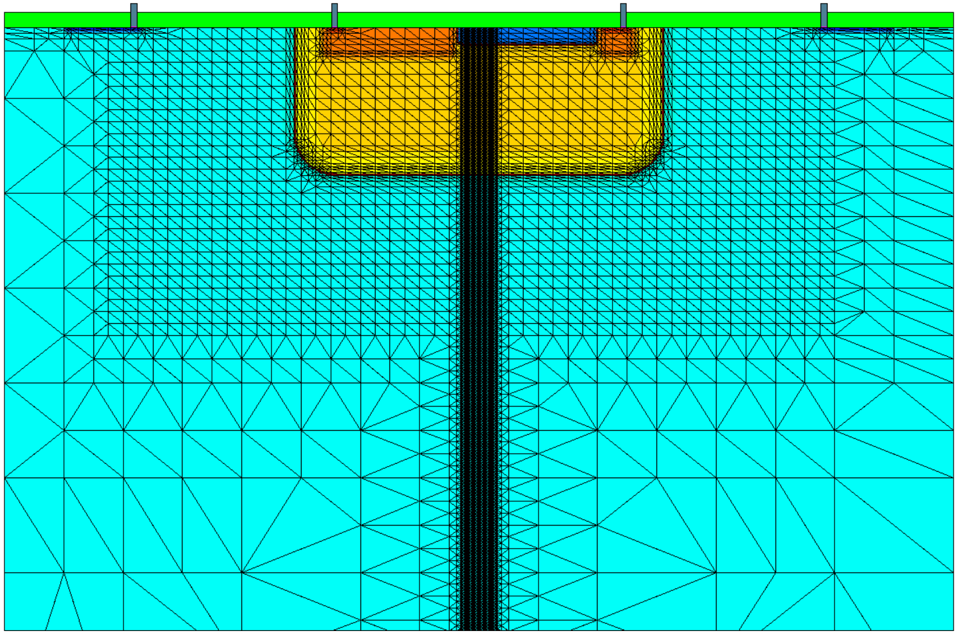
- 3 pixel structure
  - Breakdown and depletion depth increase with resistivity, capacitance decreases
  - Larger resistivities collect more charge, 1k Ωcm 50% larger than 10 Ωcm after 100ns
  - 10 Ωcm has slower charge collection, ≈ 5 times slower to collect 1000 e^-
  - After 100ns charge collection across the device is approximately uniform
  - In all simulations there is a substantial improvement for higher resistivites compared to 10 Ωcm

Backup

Meshing

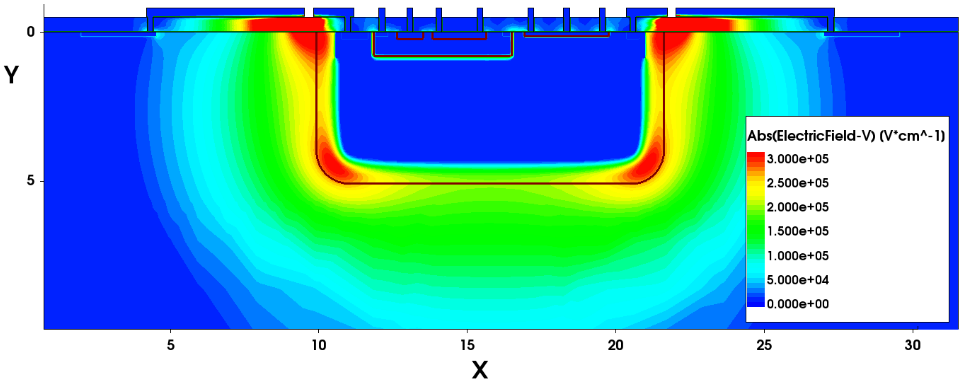
- Global mesh refines around doping concentration and extra refinement around depletion region and mip track



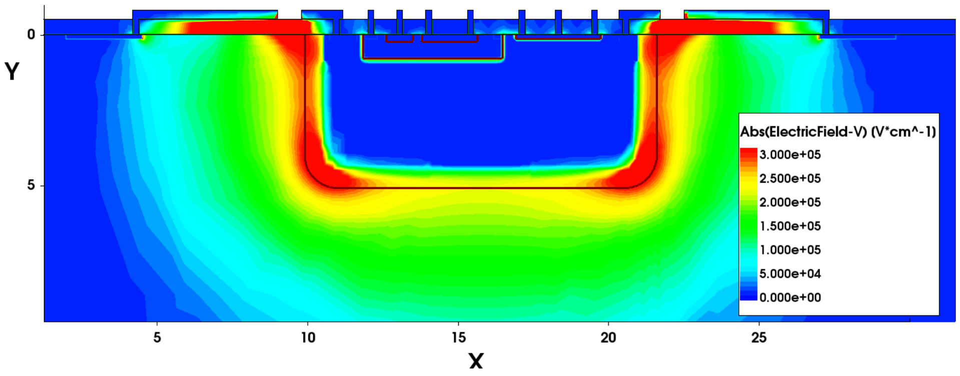


2D cut of 3D reduced

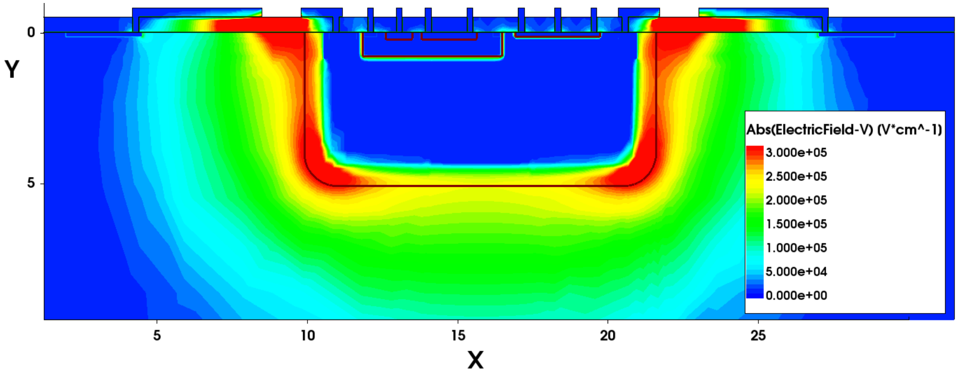
E-field for different metal widths, -100V, 2D full



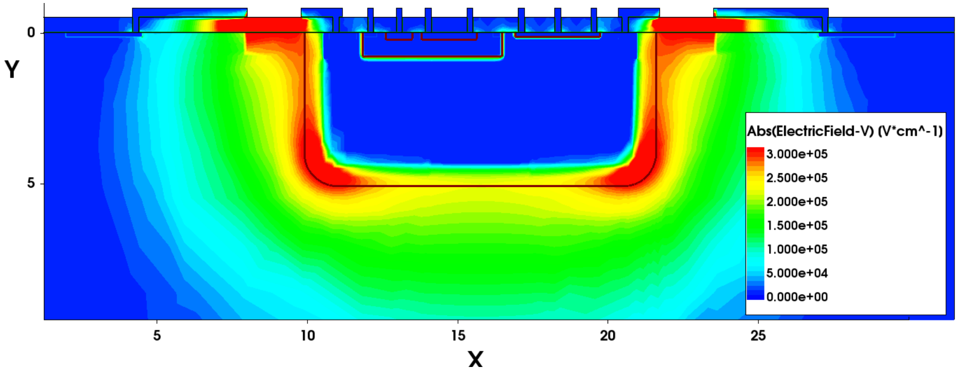
M1+0.5 (-79V)



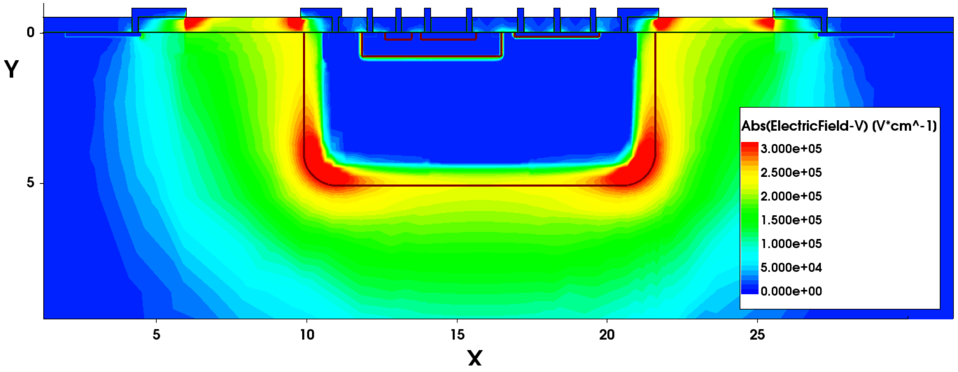
M1



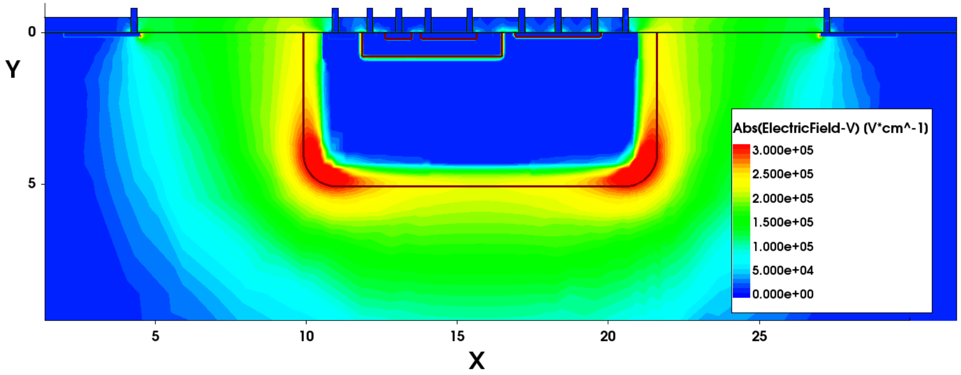
M1-0.5



M1-1



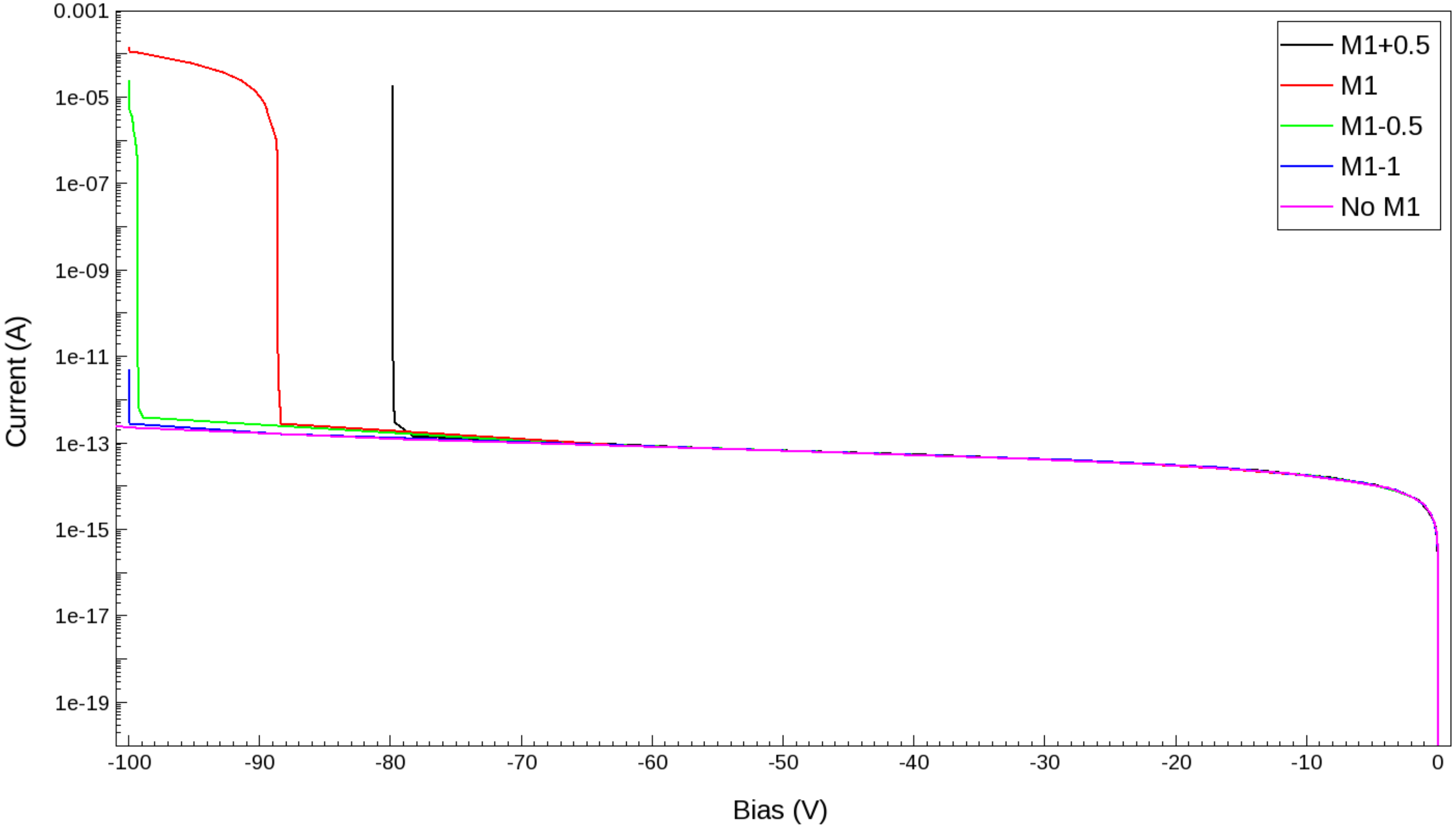
M1-3



No M1

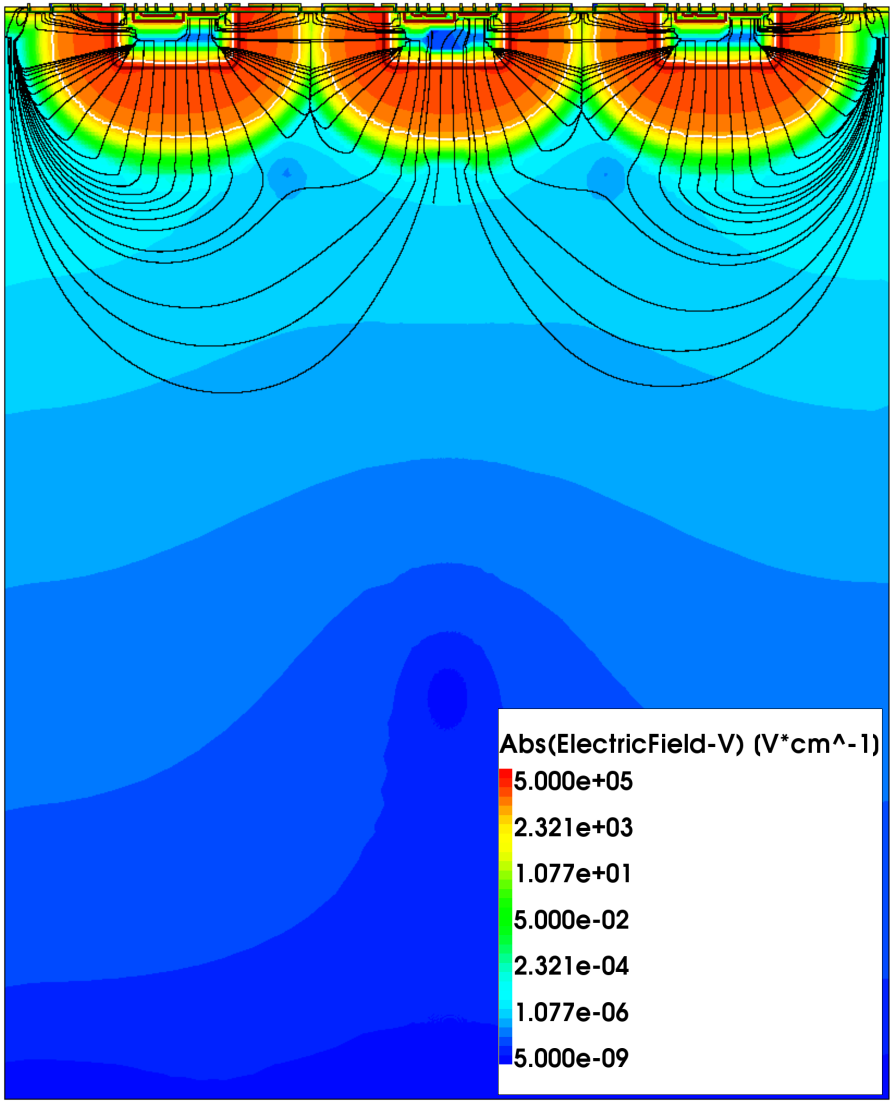
IV Curve M1 comp, 2D full

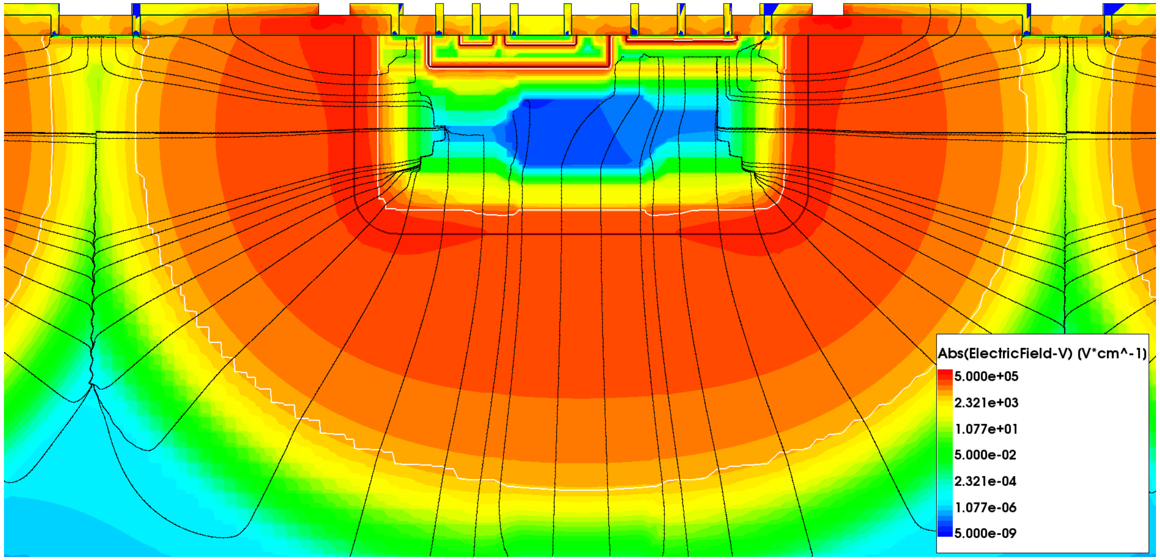
- The closer the M1 lines are the lower voltage at which breakdown will occur
- Around -88V for the correct M1 lines



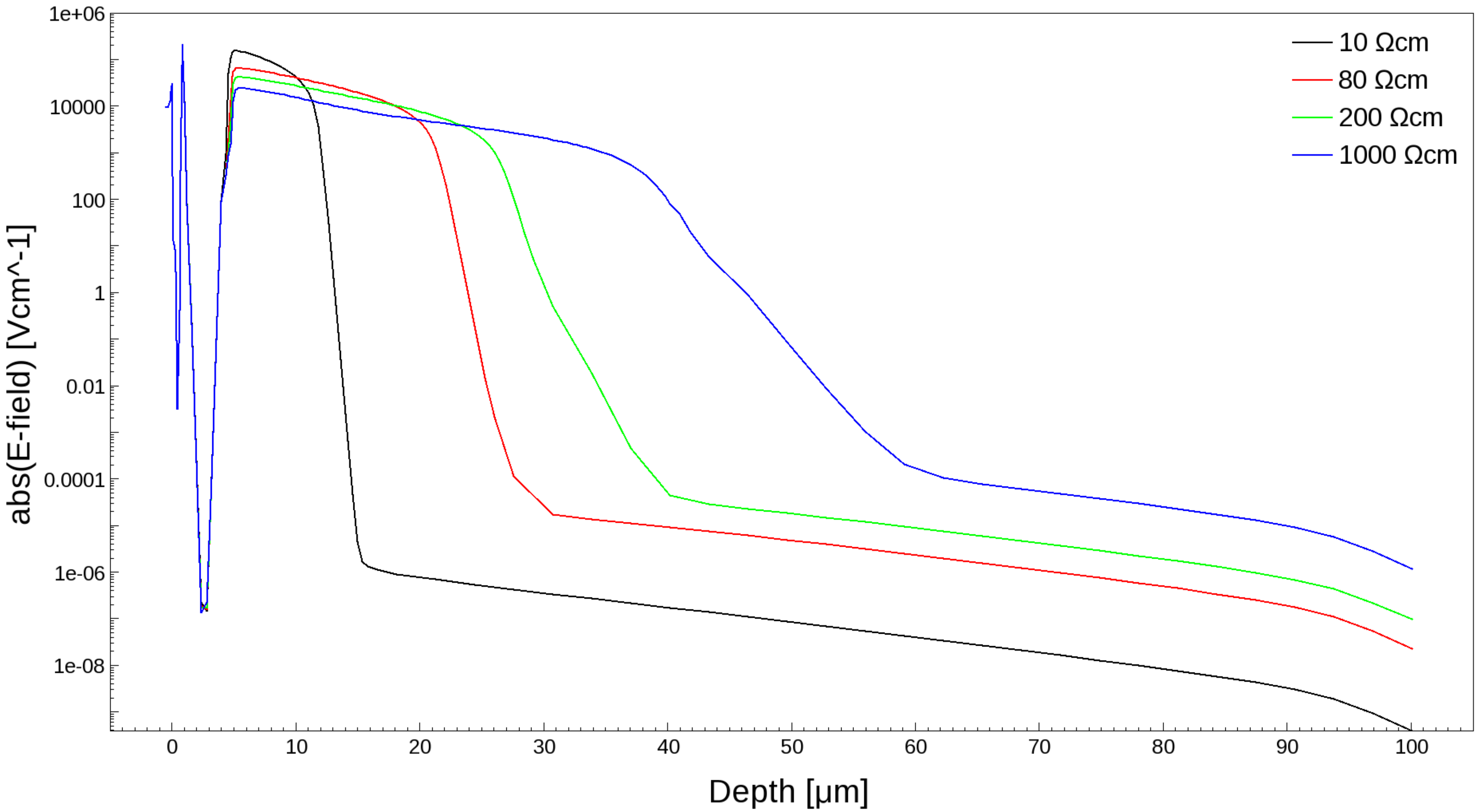
Electric field, -60V, 10 Ωcm

- Very low outside depletion
- Highest around edges of deep n-well
- See low field inside deep n-well
- Field curves round to edges due to geometry of the structure
- Not true field lines, streamlines





E-field depth, 3 pixel structure



Side mip, 10Ωcm, -60V

- Simulate mip passing through side at different depths, look at pixel 2
- Slight decrease when mip passes through deep n-well
- Largest CC for depths of 6-8μm
- No diffusion from 90μm after 100ns