Understanding the frequency dependence of CV measurements of irradiated silicon detectors

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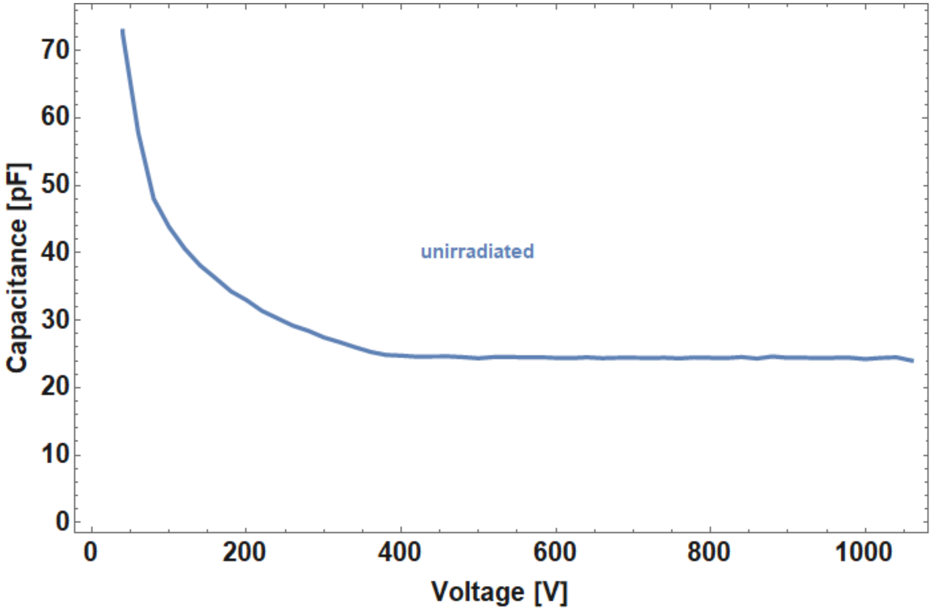
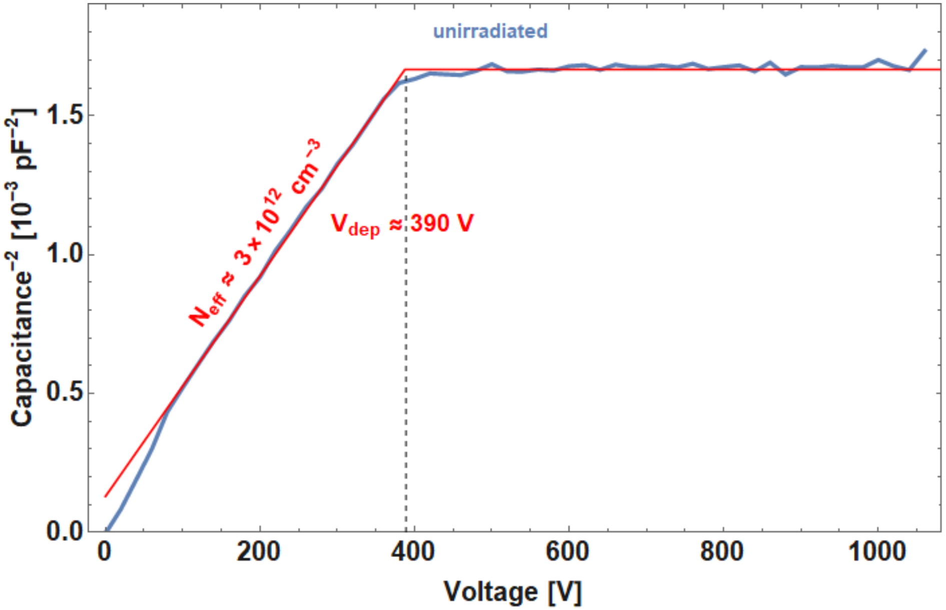
41st RD50 Workshop, Sevilla

Motivation

- Capacitance vs. Voltage measurements well established for sensor characterisation

- Capacitance decreases due to increasing depletion
- When fully depleted, capacitance remains constant
- Provide doping level and depletion voltage
- Independent of measurement frequency

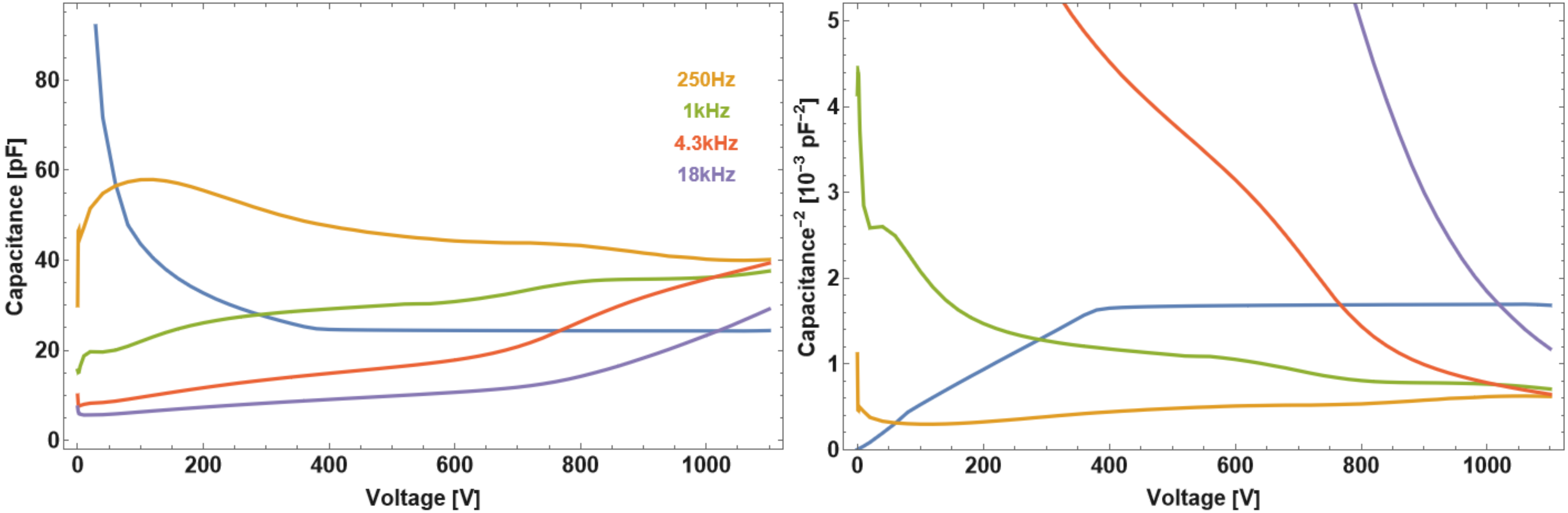




Motivation

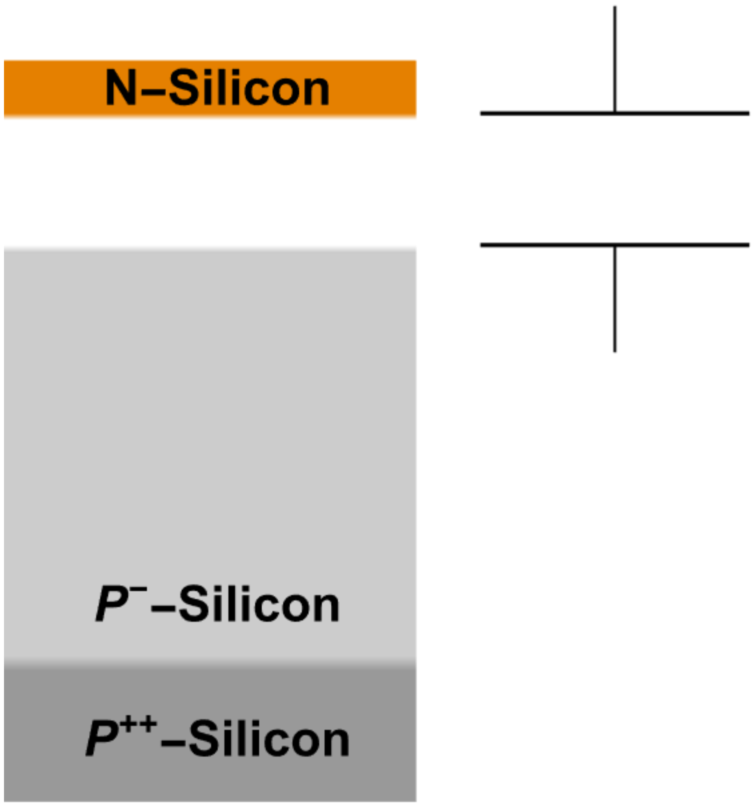
- Capacitance vs. Voltage measurements well established for sensor characterisation
- When measuring irradiated devices:
  - Frequency dependence
  - Not fittable anymore

Goal: Understand behaviour and maybe rescue technique



Depletion of planar detectors

- Assumptions for resistivity:
  - Infinite for depleted zone
  - Zero for all others



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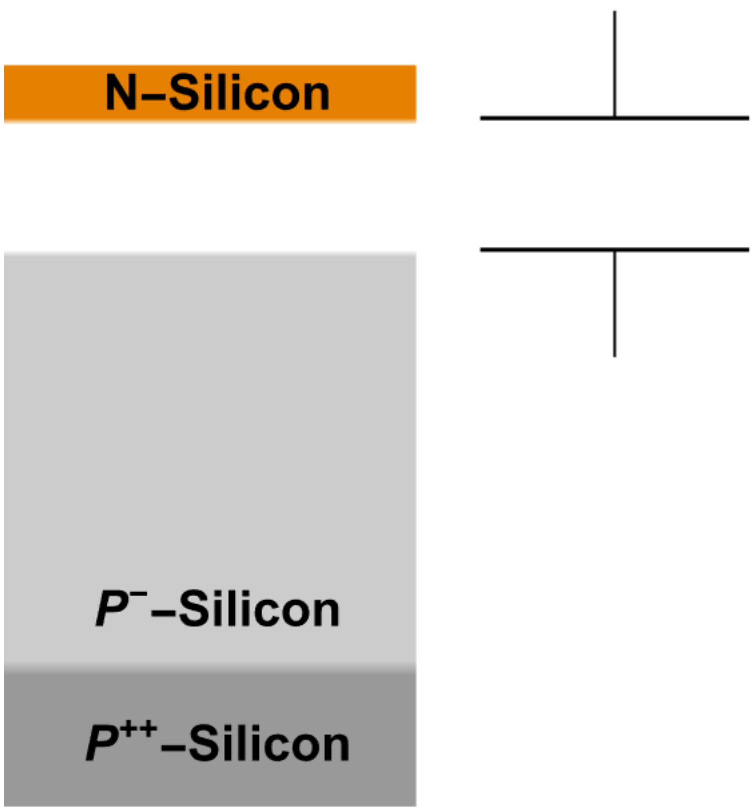
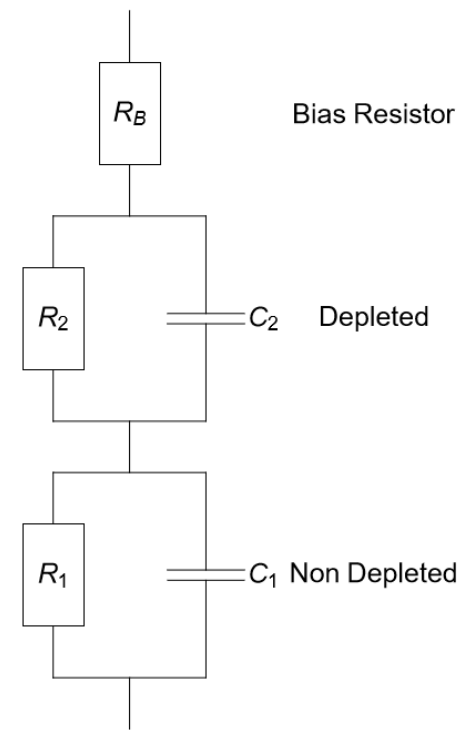
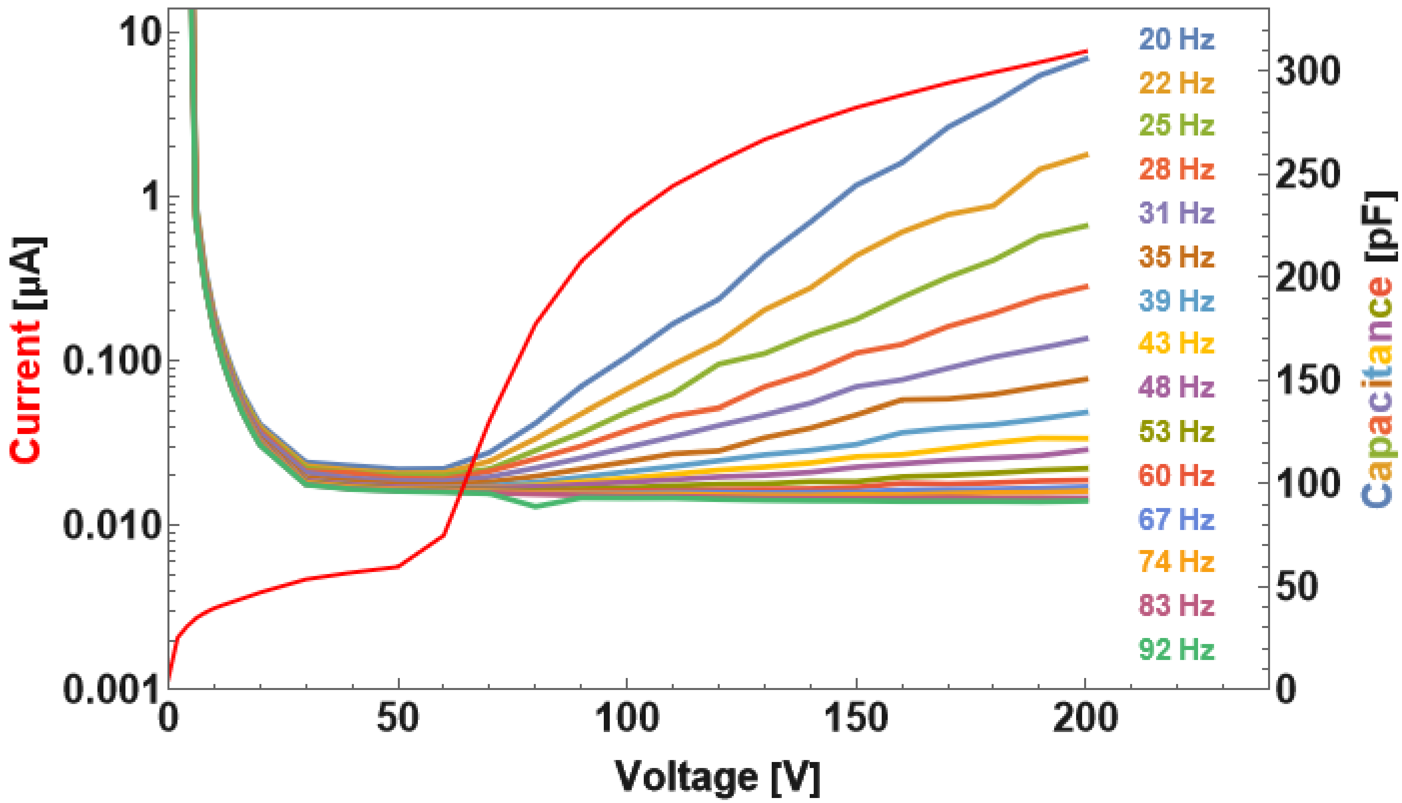


- Modifications for irradiation:
  - Decrease for depleted zone
  - Increase for all others
- Modification for strip detectors:
  - Introduce bias resistor



Additional capacitance contribution

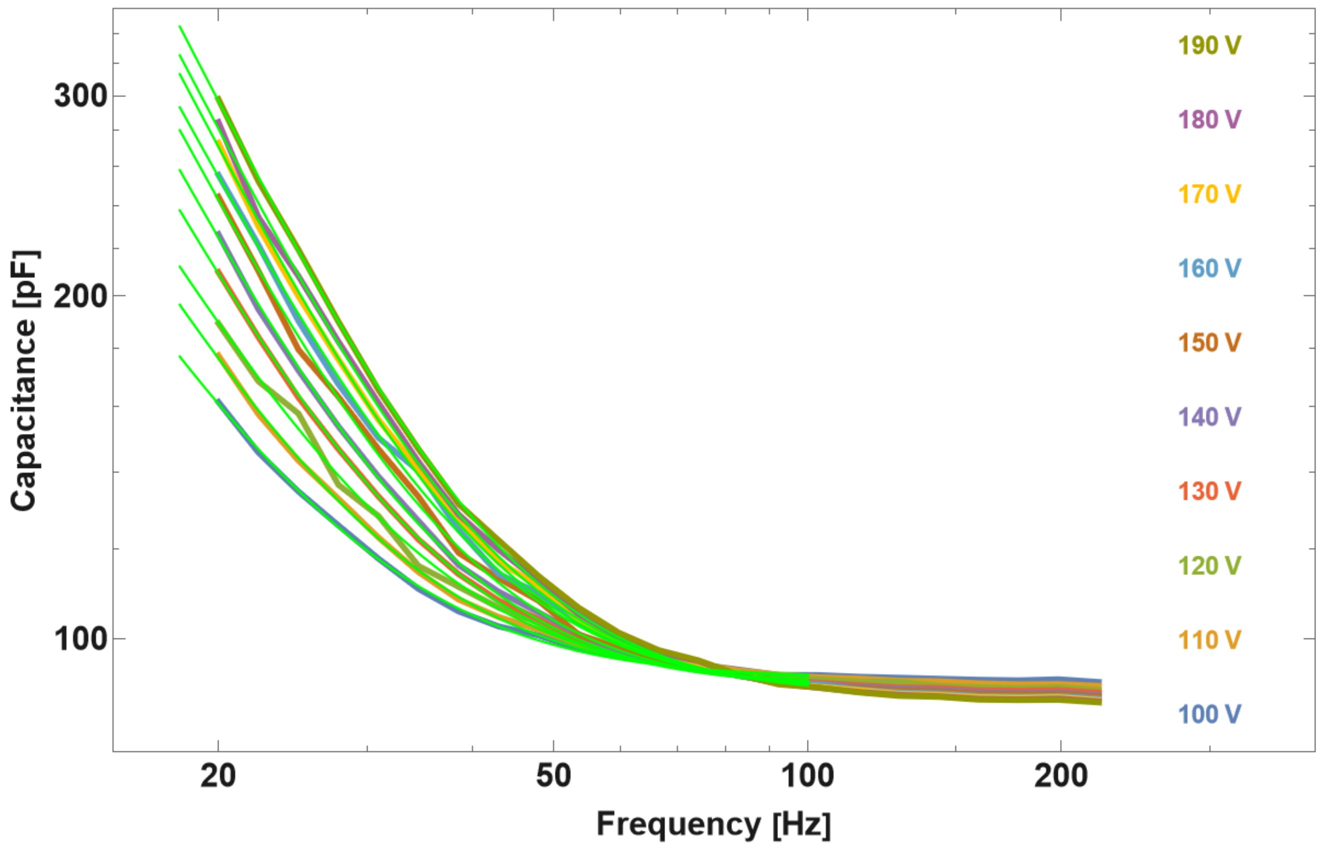
- For unirradiated sensors:
  - Capacitance increases when current increases
  - Only for low frequencies with clear dependency (LF increase)



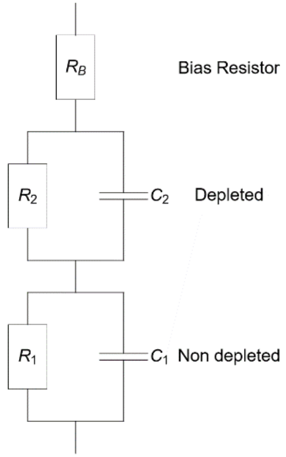
Additional capacitance contribution

- Frequency dependence perfectly described with: $e^{-\sqrt{f}}$
- Important: Not representable by any lumped element model

  Only broken rational functions possible



Complete frequency model

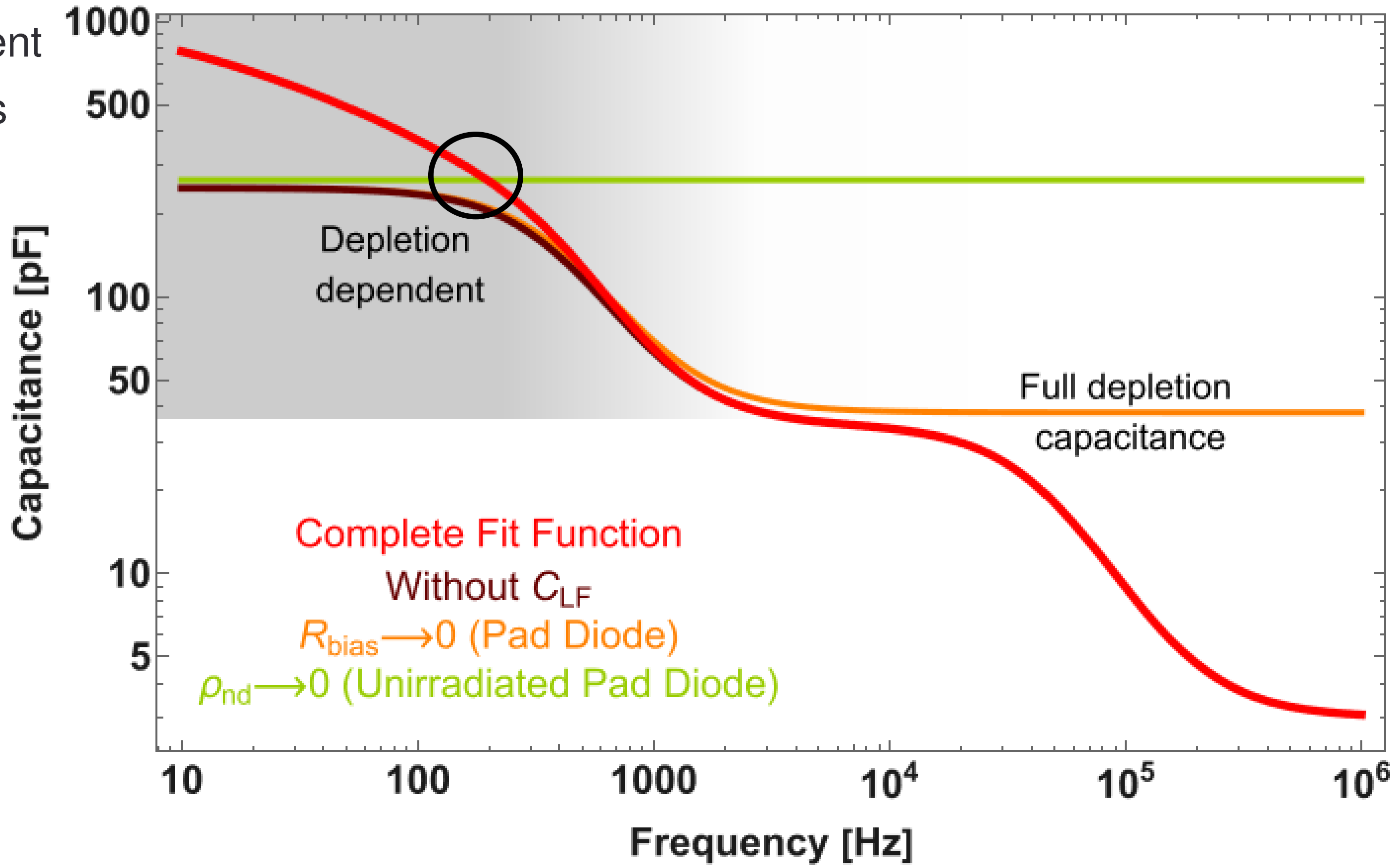
- Capacitance() + $c_1 e^{-c_2\sqrt{f}}$ + C_{HF}

- Dependent on sensor parameters:
  - Active area
  - Thickness
  - Depletion width
  - Resistivities of depleted and non depleted zone
- Same model without HF term works for resistivity

Complete frequency model

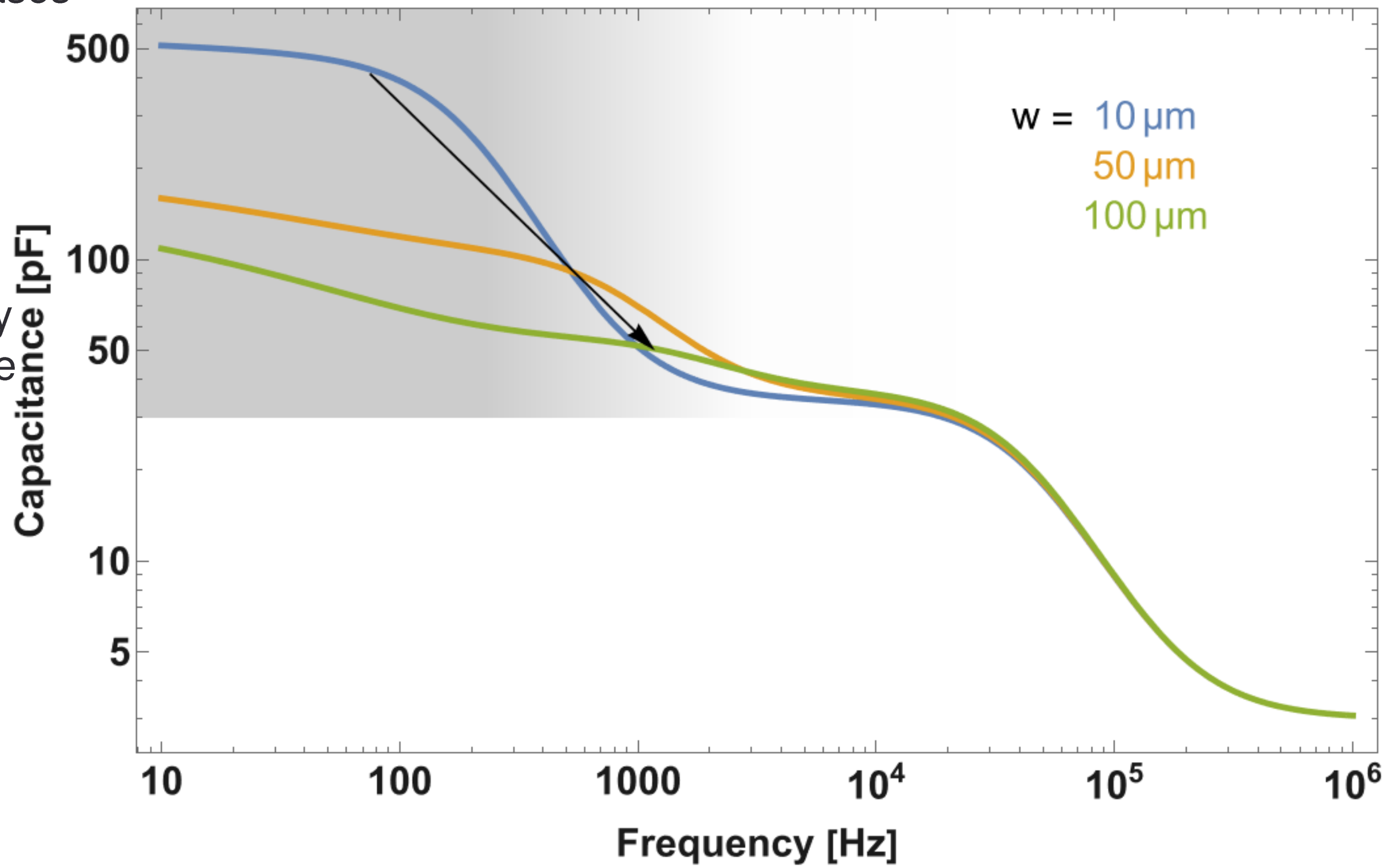
- Capacitance:
  - Depletion dependent for low frequencies
  - Intersection of red and green line gives true value

  Problem solved?



Complete frequency model

- Cut-off frequency shifts to higher frequencies as capacitance decreases
- Also dependent on sensor parameters
- No single frequency sufficient for reliable CV measurement
- But there is an optimum frequency (dependent on the sensor)

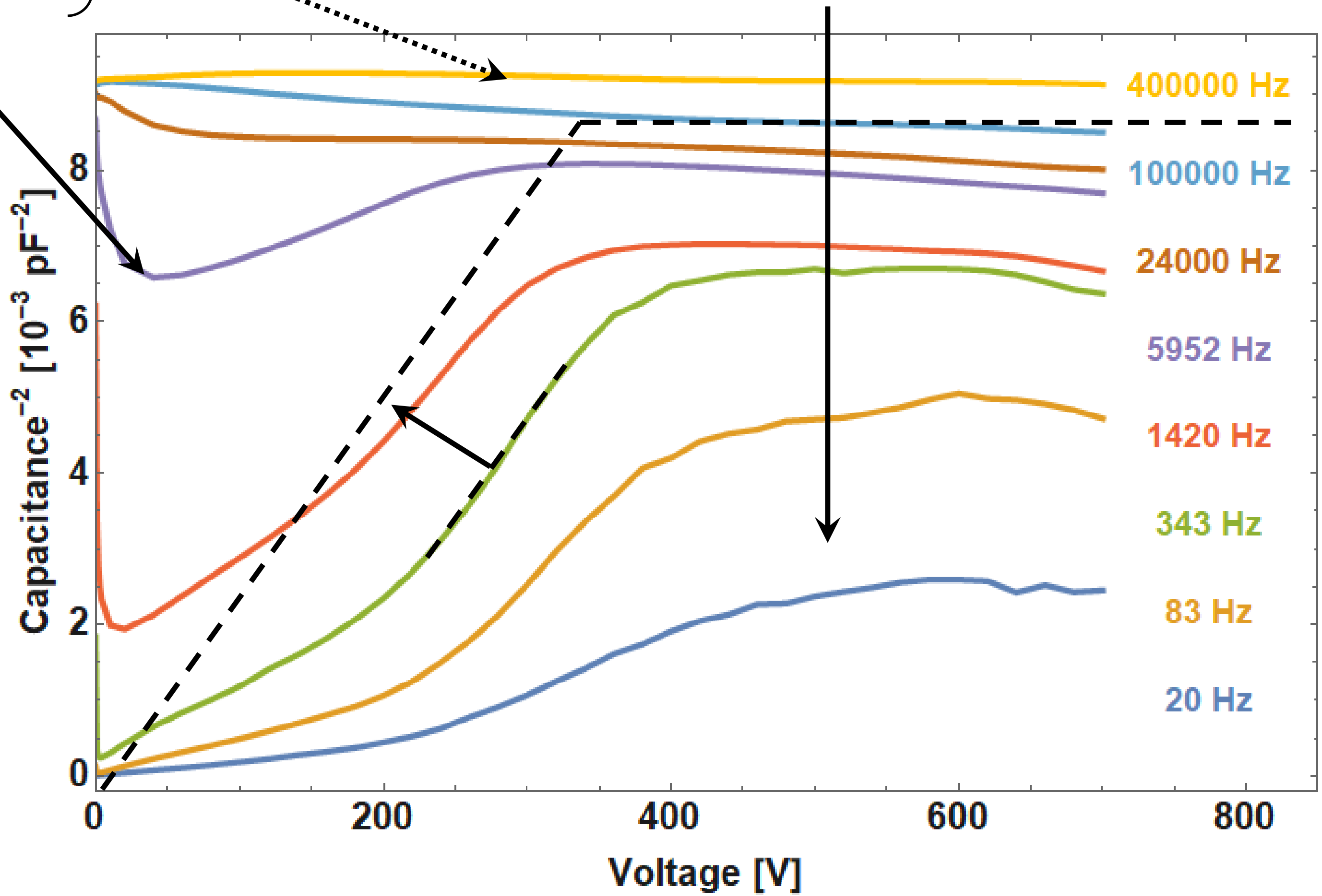


Best possible CV result (Diode)

- Strip effect would cause further increase from saturation
- Shift of cut-off frequency causes offset from zero at low voltages
- Find steepest increase and let it begin at the origin. Intersection with plateau is the best estimate for V_{FD}:

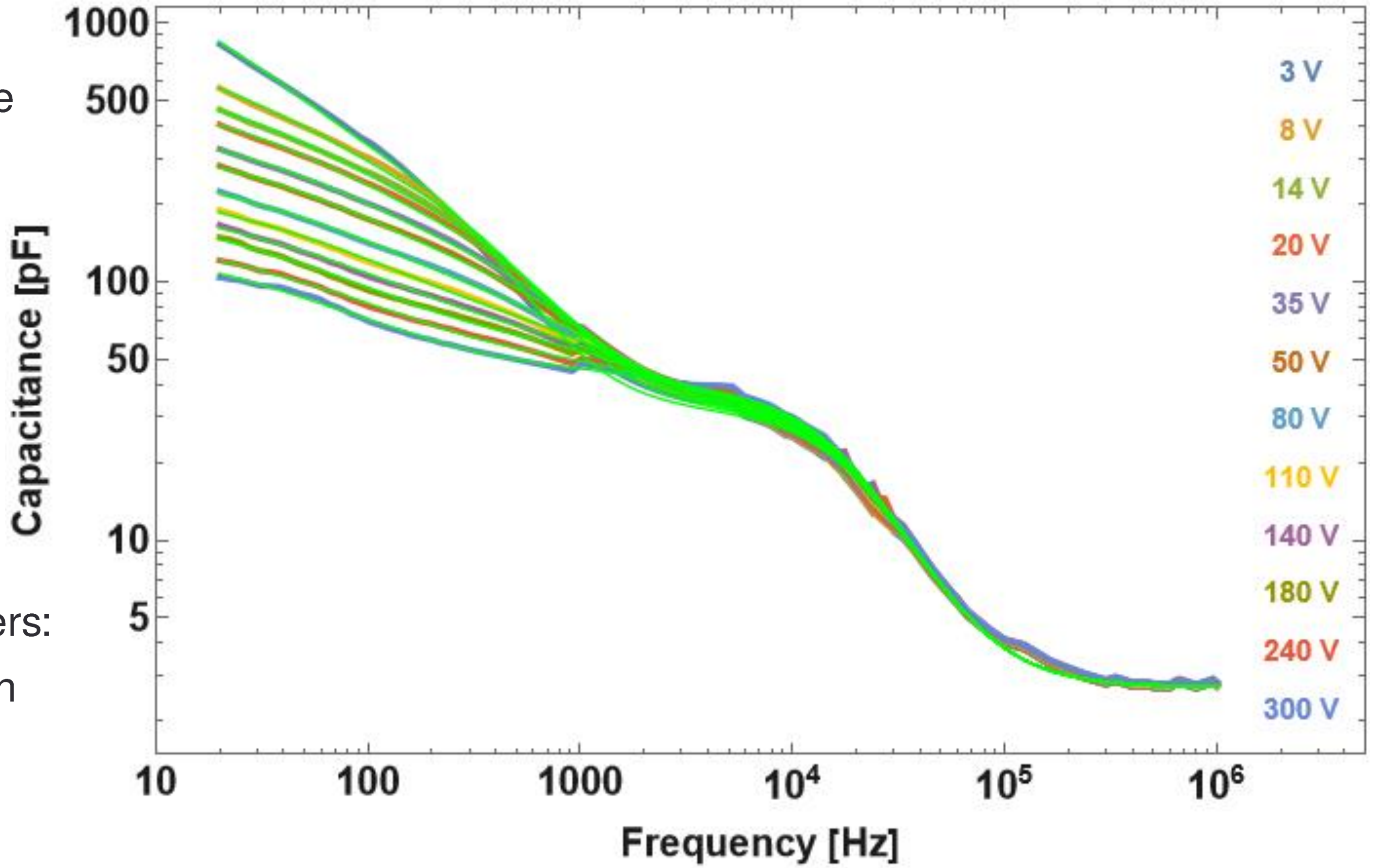
  (330 ± 15) V

- LF increase causes lower saturation level



Complete fits

- Use of complete model to fit frequency dependent measurements give sensor parameter that can be used for verification:
  - Active area
  - Bias resistance



- And new parameters:
  - Depletion width
  - Bulk resistivity

Verification results

- Active Area

	CMOS	ATLAS R5
Fitted [cm^2]	0.59 ± 0.04	84 ± 3
Reference [cm^2]	0.63* ± 0.05	90** ± 1

* Calculated from optical inspection

** Calculated from coordinate specs

- Bias resistance

	CMOS	ATLAS R5
Fitted [MΩ]	8.2 ± 0.2	1.42 ± 0.12
Reference [MΩ]	8.7* ± 0.2	1.5** ± 0.5

* Measured prior to irradiation

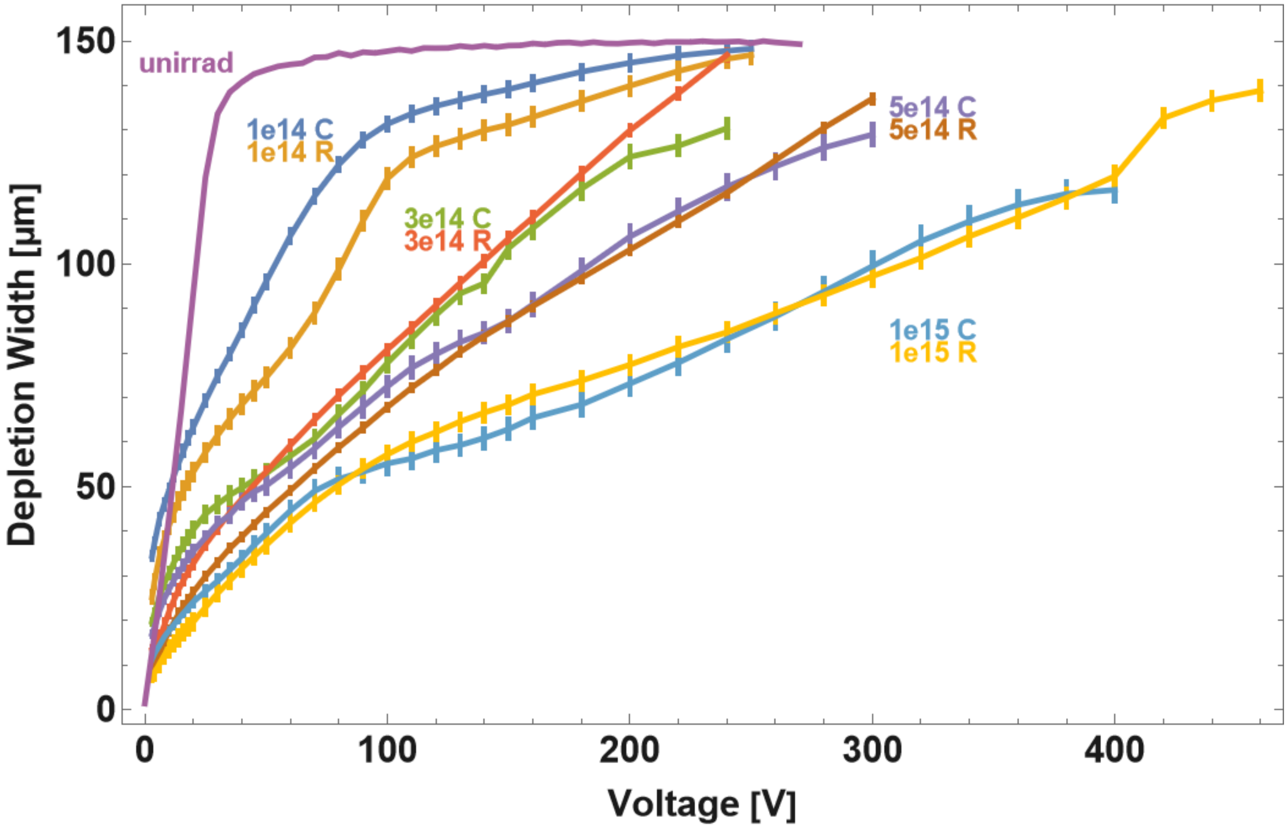
** From Hamamatsu specs

- Slightly underestimated

Overall: consistent agreement

Results: Depletion Width

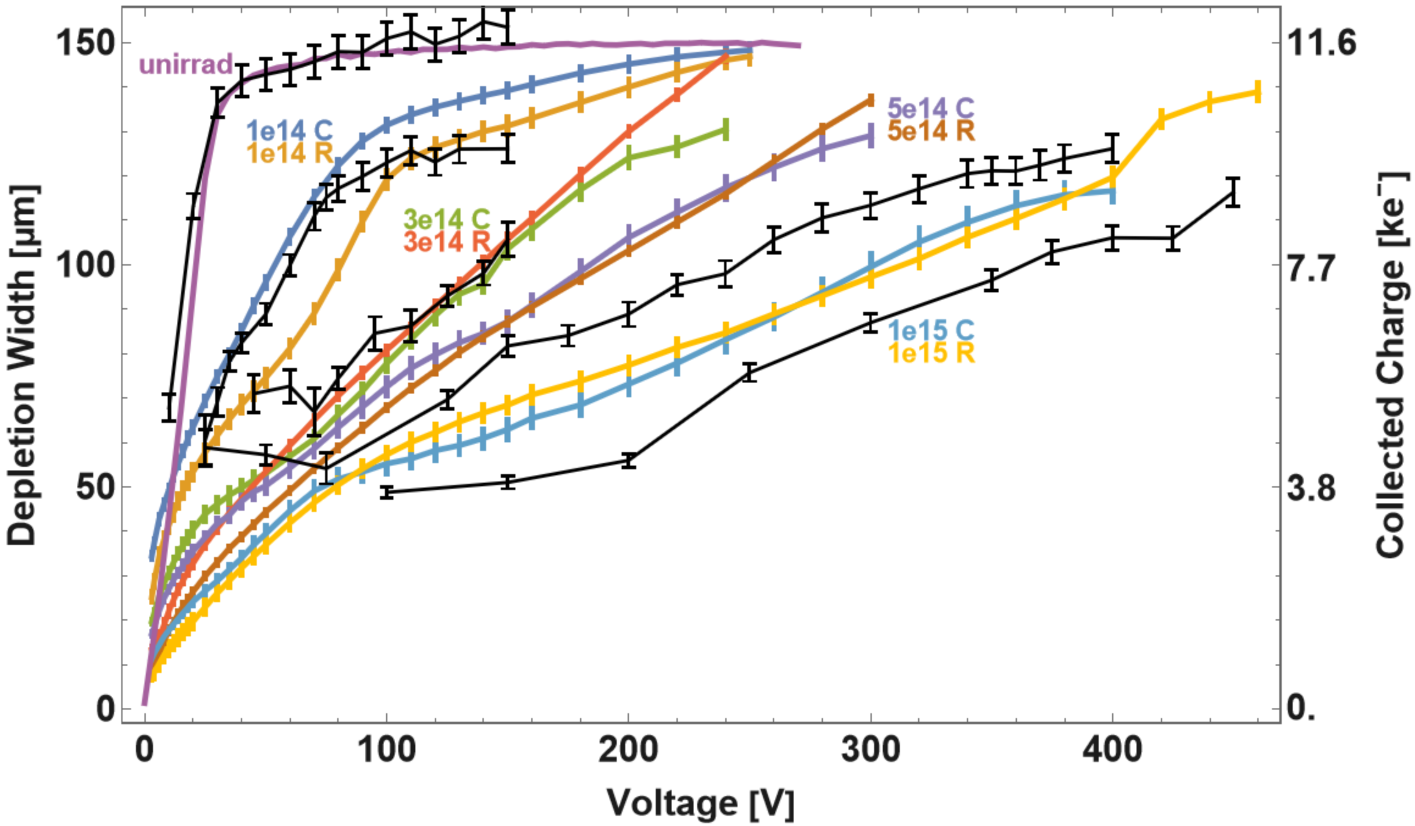
- For CMOS sensors of multiple fluence levels derived from capacitance and resistance measurements



Results: Depletion Width

- For CMOS sensors of multiple fluence levels derived from capacitance and resistance measurements
- Comparison with charge measurements (AliBaVa):

  Disagreement for higher fluences expected due to additional effects (trapping)

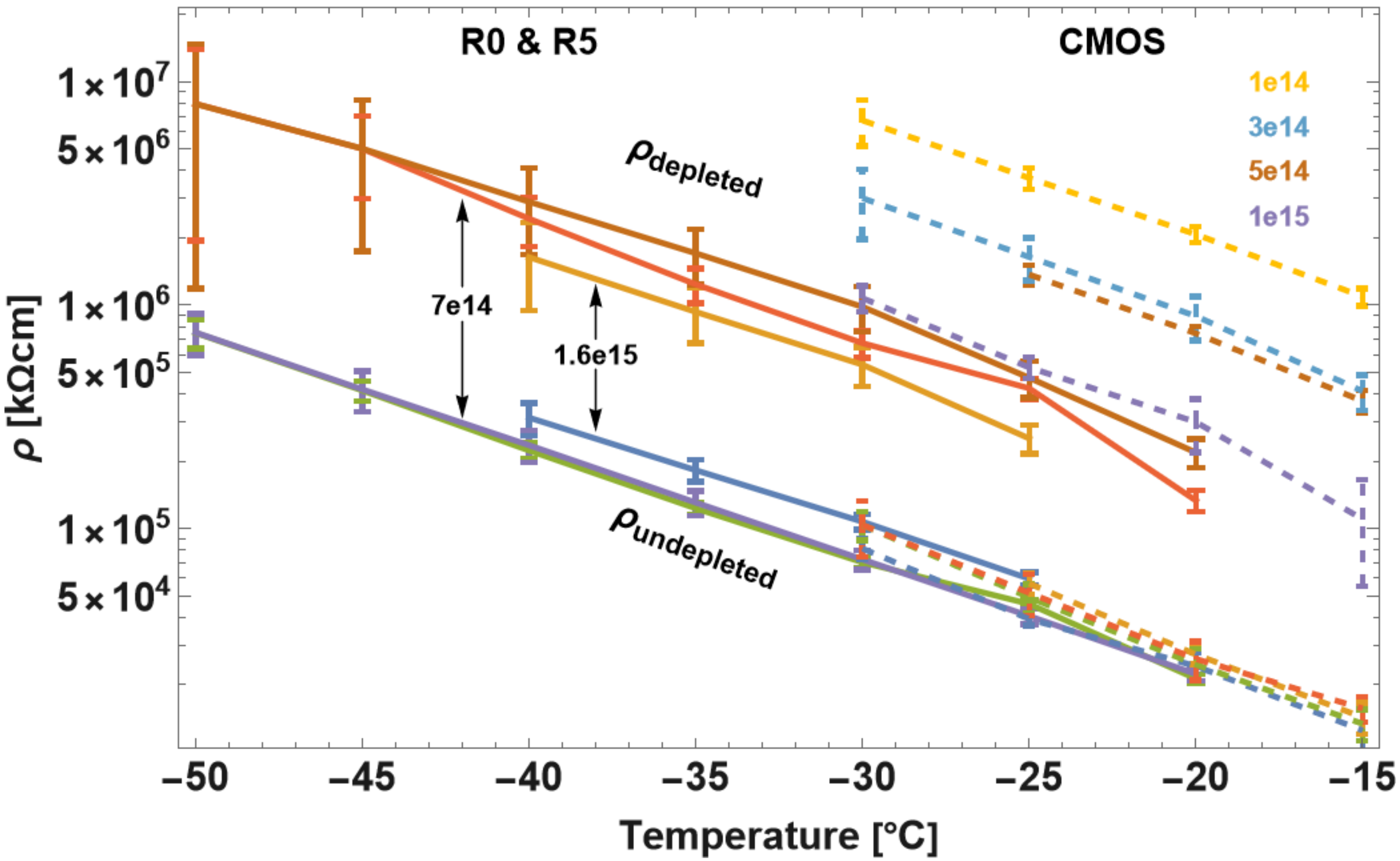


Results: Bulk resistivity

- For depleted and non depleted silicon:
- Clear temperature signature implies activation energy of (0.60 ± 0.02) eV
- Fluence dependence only for depleted bulk

- Annealing also only visible for depleted bulk

- Magnitudes higher than resistivities according to full depletion voltage: 3.3 – 0.4 kΩcm



Summary

- New frequency model for CV measurements
  - Based on complete equivalent circuit
  - Extended by exponential low frequency term

- Explanation for frequency dependence of CV measurements
- Good consistency within verification parameters

- Realistic orders for depletion width resp. voltage
- Much larger bulk resistivity than expected from depletion voltage

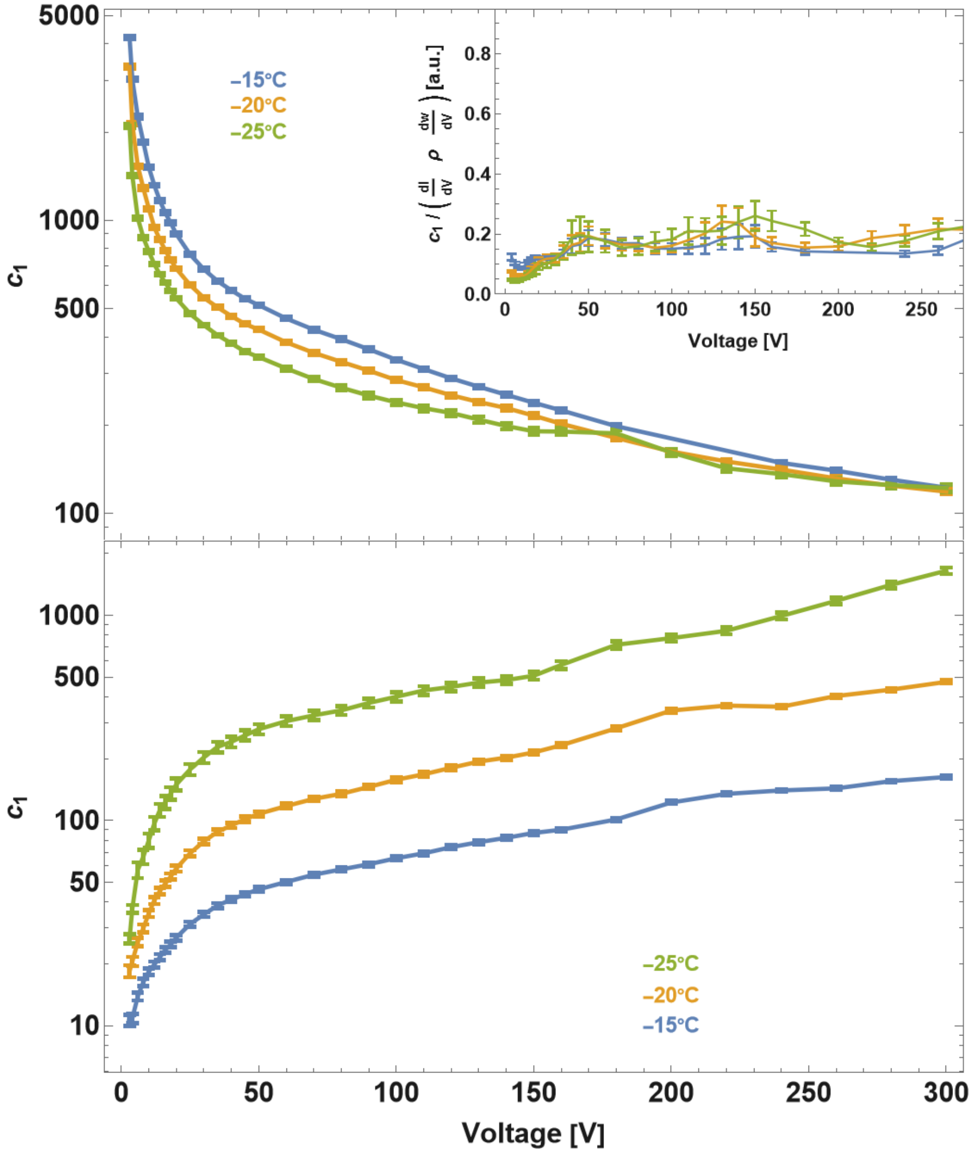
- Next step:
  - Understand the origin of the LF increase

Backup

LF parameters: c_1

- For capacitance:

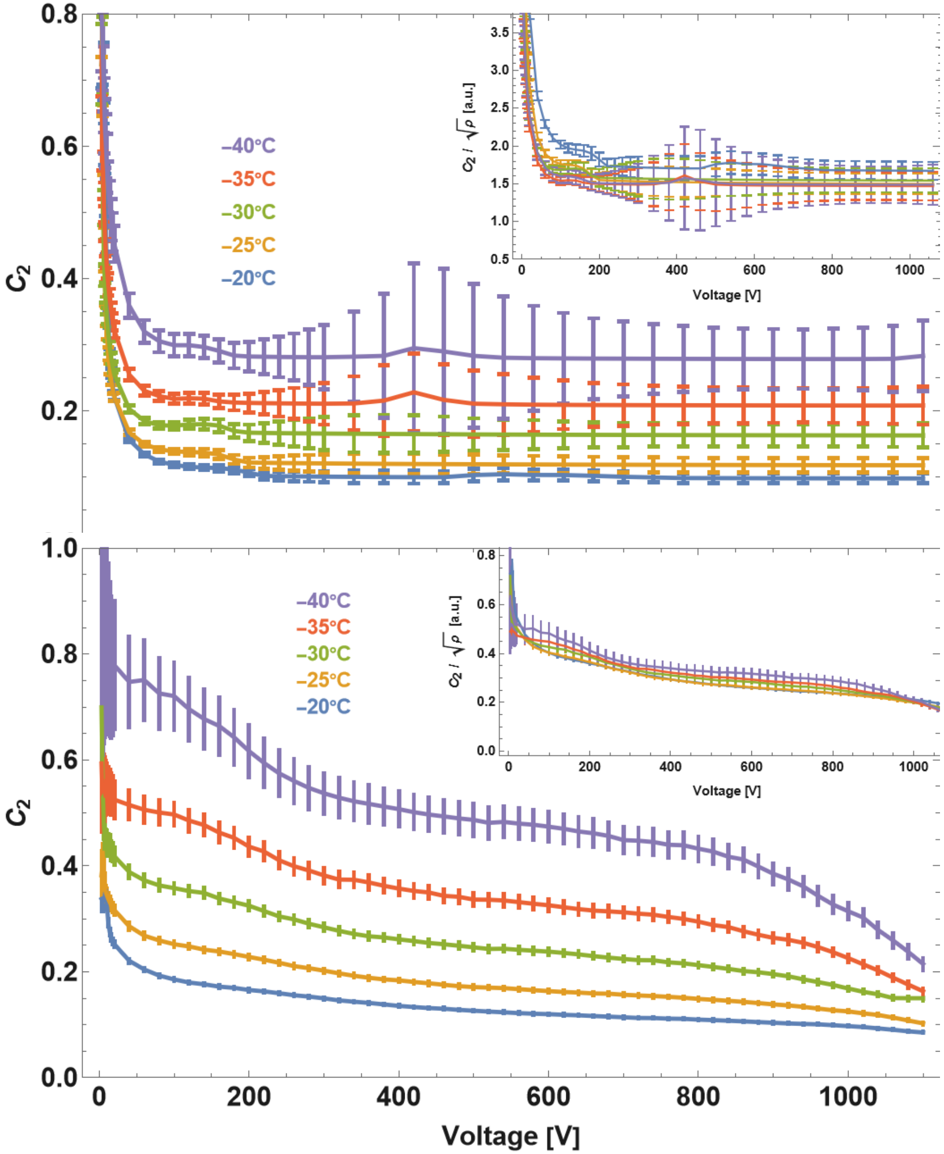
- For resistance:



LF parameters: c_2

- For capacitance:

- For resistance:



Annealing effect on depletion width

- Depletion width of ATLAS R5 sensor prior and after annealing