Radiation damage investigation of epitaxial p-type silicon using Schottky and pn-junction diodes

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Last RD50 Workshop, 28 Nov – 1 Dec 2023

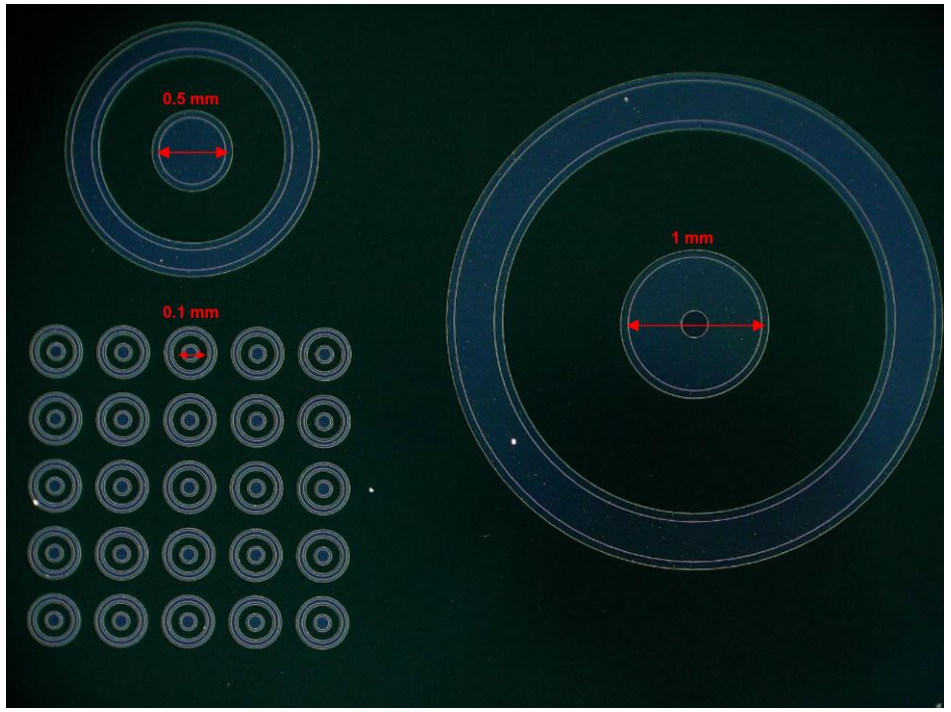
Schottky Project description and goals

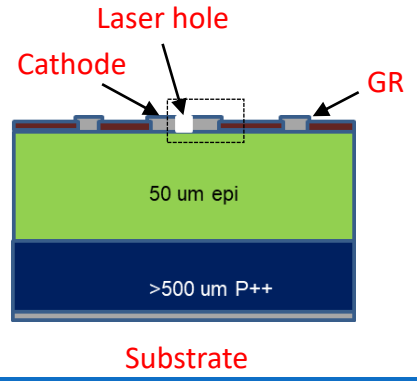
- **What:**
  - fabricate Schottky and n^+p diodes on p-type epitaxial (50µm thick) silicon wafers
  - doping concentrations as they are normally found in CMOS MAPS devices
- **Why:**
  - investigate and gain a deeper understanding of radiation bulk damage in CMOS sensors
  - develop reliable damage models that can be implemented in TCAD device simulators
- **How:**
  - 6-inch wafers at five B-doped epitaxial levels (10^{13} to 10^{17} cm^{-3}) 25x each, total **125 wafers**
  - fabrication process at ITAC (RAL) and Carleton University Microfabrication Facility (CUMFF)
  - measurements will be carried out at RAL, Carleton, Birmingham, JSI, IHEP

Design and layout of devices

5 type of devices proposed:

- #1: 2 mm Ø cathode with 0.4 mm Ø central hole, 10 x 10 mm^2 area
- #2: 1 mm Ø cathode, 0.2 mm Ø central hole, 5 x 5 mm^2
- #3: 0.5 mm Ø cathode, no central hole, 2.5 x 2.5 mm^2
- #4: 0.1 mm Ø cathode, no central hole, 0.5 x 0.5 mm^2
- ‘cell’ with the previous 3 flavors (2,3,4) grouped together, to exploit wafer uniformity on small area
- #5: 6 TLM points for contact and epi resistance
- 2 masks only (metal and oxide)
- detailed description during the 35th RD50 workshop





Fabrication details & comparison

RAL-ITAC

- Schottky fabrication process only, optimised on test wafers
- oxide deposition @150°C
- Al sputtering immediately after etching (no thin SiO2 layer)
- Al lift-off in Acetone ultrasonic tank

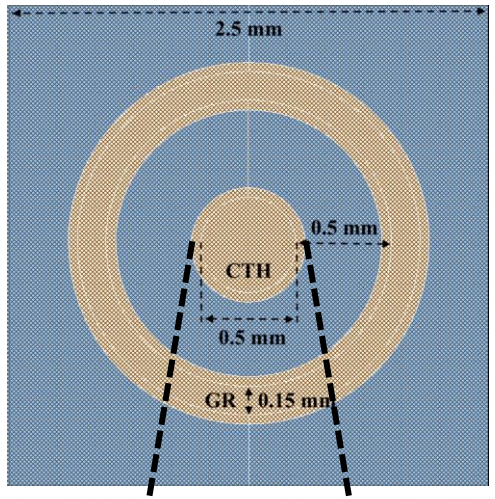
CUMFF

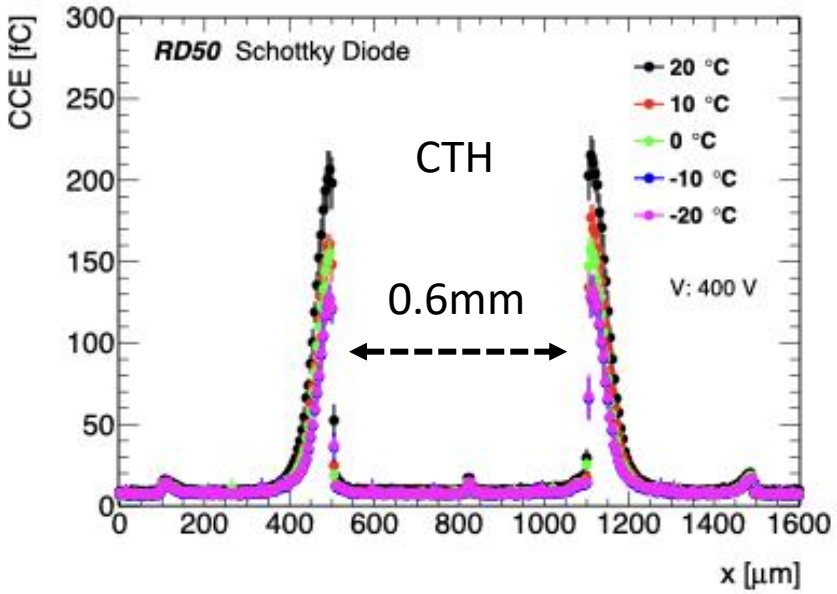
- pn-junction and Schottky processes, optimised on test wafers
- 6” substrate wafers laser cut into 4” or 6” wafer pieces
- high temperature thermal oxidation
- Al front metal thermal deposition, back Al via e-beam evaporation
- front metal patterning + etching

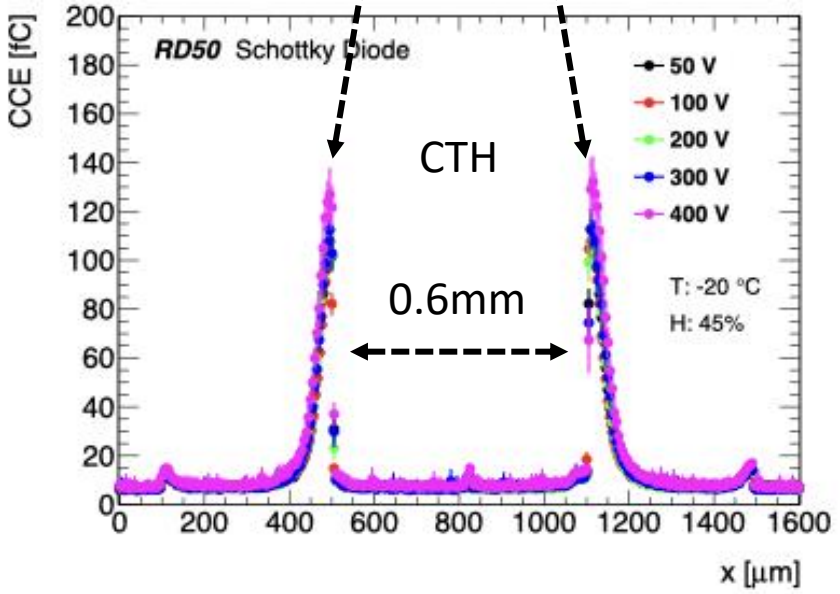
full details of fabrication processes in E.G. Villani’s talk from the 36th RD50 Workshop

Charge Collection Efficiency: RAL Schottky (unirrad.)

- Schottky diode with no central laser hole
- Bias Voltages: 50, 100, 200, 300, 400 V
- Temperatures: 20, 10, 0, -10, -20°C

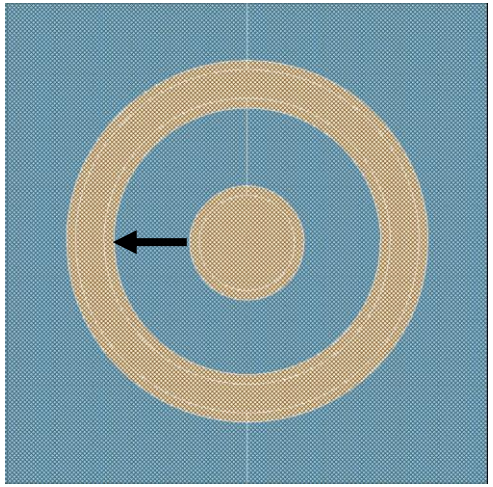


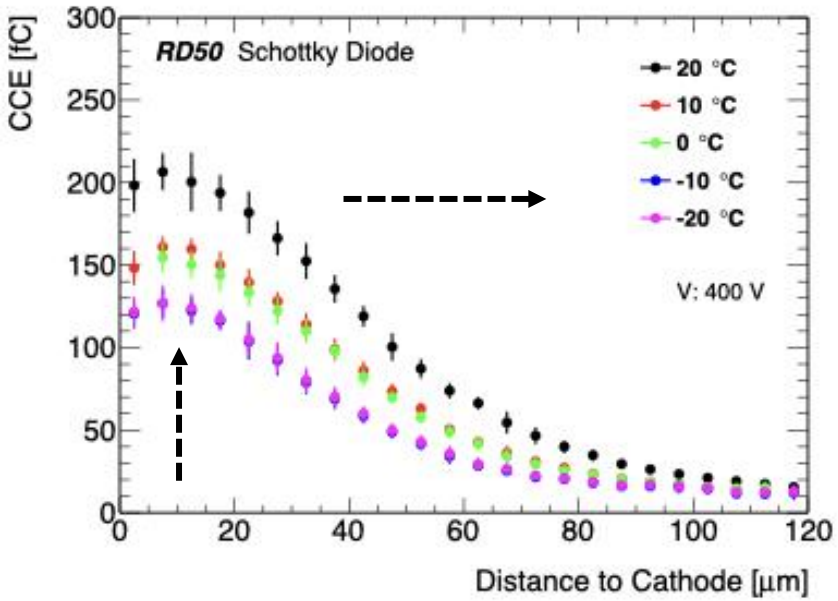


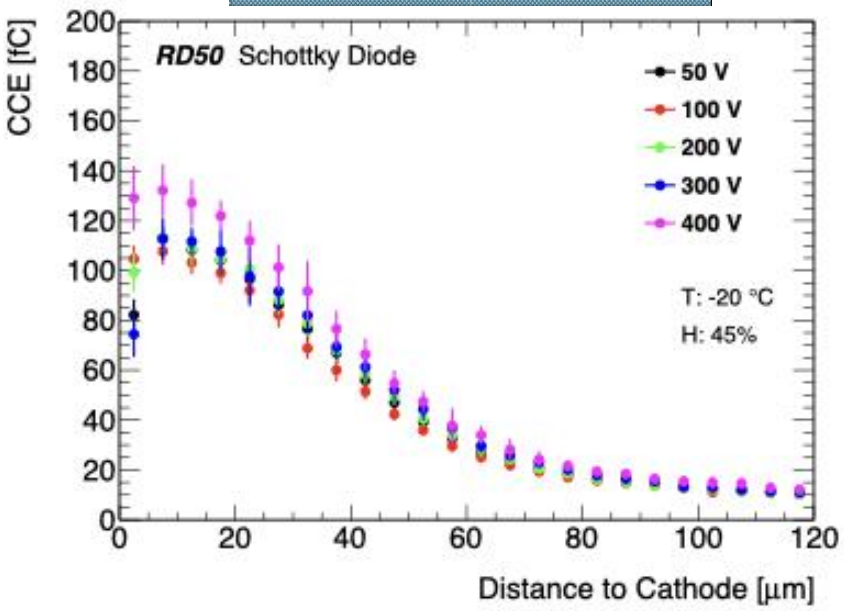


Charge Collection Efficiency: RAL Schottky (unirrad.)

- depleted thickness decreases with increased distance from the cathode edge
- at fixed bias voltage, the higher the temperature, the larger the CCE; due decrease in light absorption
- at low temperature, no significant improvement on CCE for various bias voltages

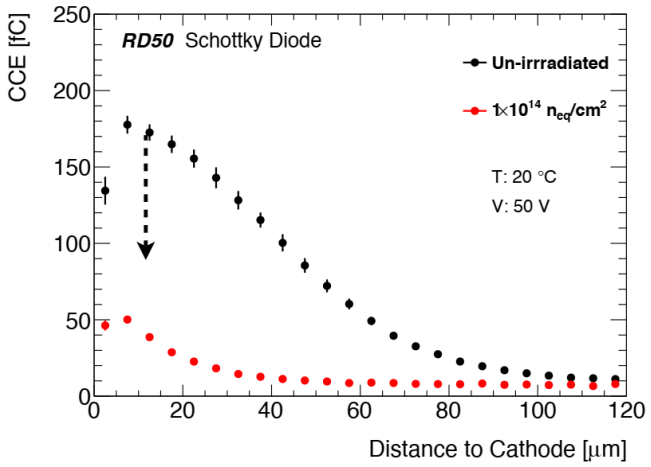


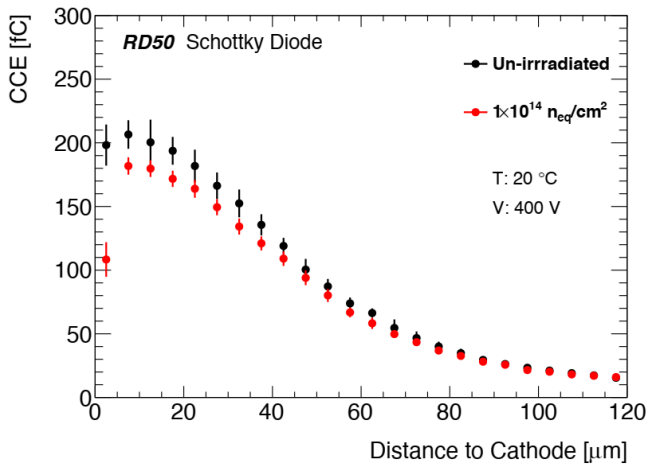




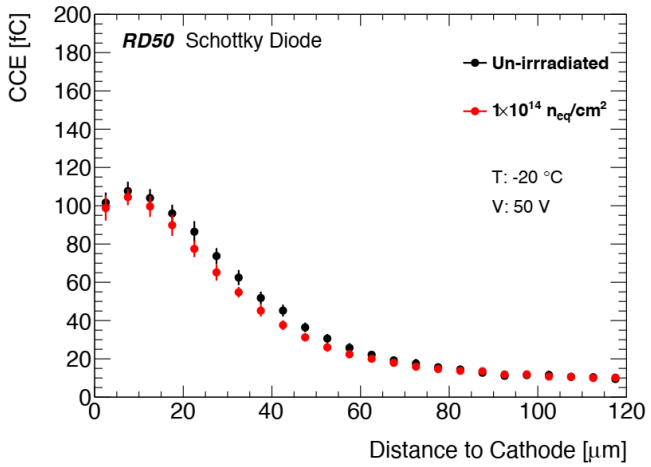
Charge Collection Efficiency: irrad. RAL Schottky

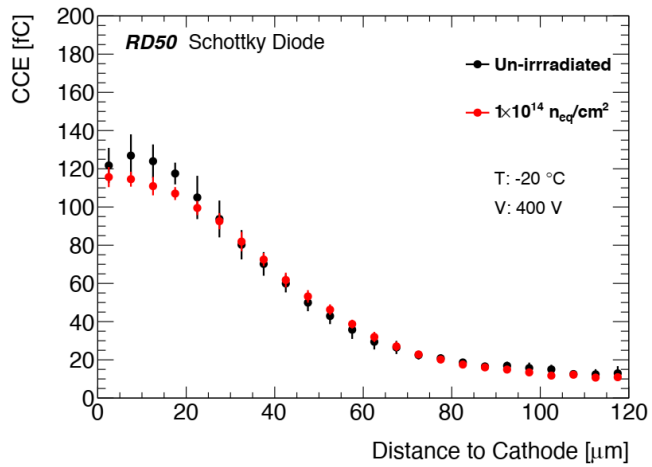
- CCEs of Schottky diodes before/after neutron irradiation ($1x10^{14}$ n_{eq}/cm^2)
- charge trapping effects reduced at higher bias voltage or low temperature





+20°C





-20°C

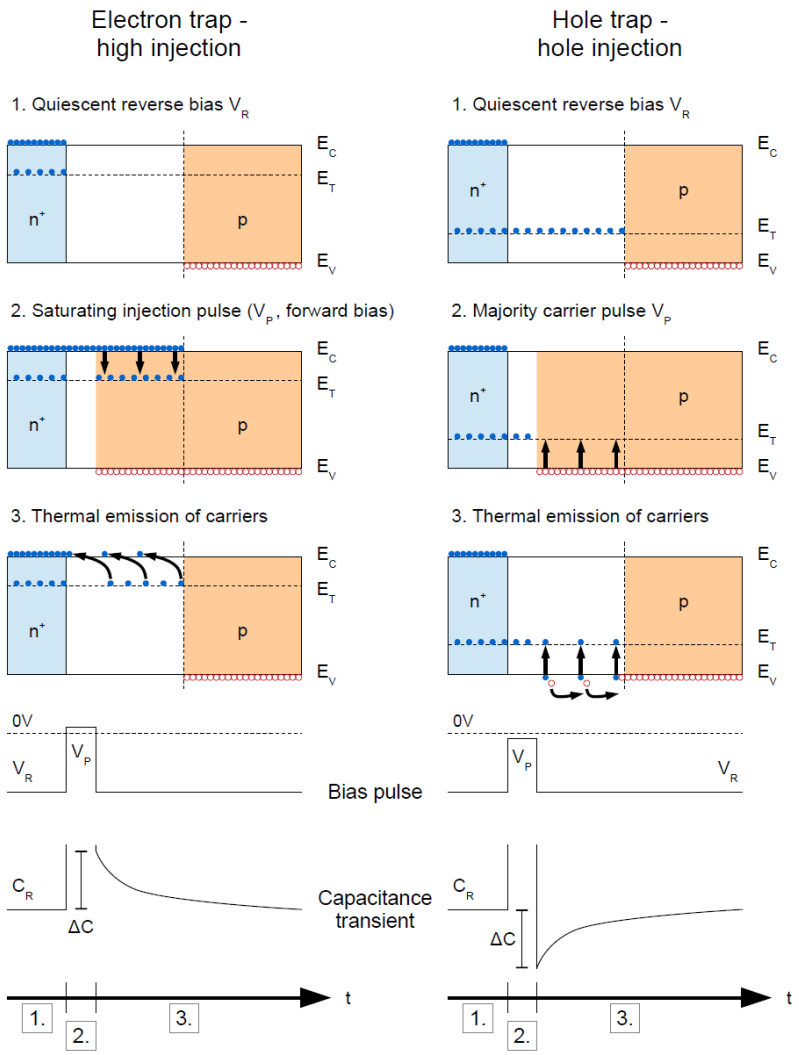
50V

400V

Measurement methods: DLTS/I-DLTS

1. DUT is under constant reverse bias
2. filling pulse with specific voltage V_P and duration is applied, adjusted to trap states of interest
   - V_P as reduced reverse bias → majority carrier traps (holes)
   - V_P slight forward bias → minority carrier traps (electrons), if capture rate much larger than competing majority traps
3. bias back to prior level, measure transients
   - capacitance or current transients, depending on sample

- usually average O(100) transients per temperature point
- plot ΔC or ΔI vs. temperature for fixed rate window corresponding to emission rate
- analysing spectrum for varying rate window $[t_1; t_2]$ yields Arrhenius plot of trap levels



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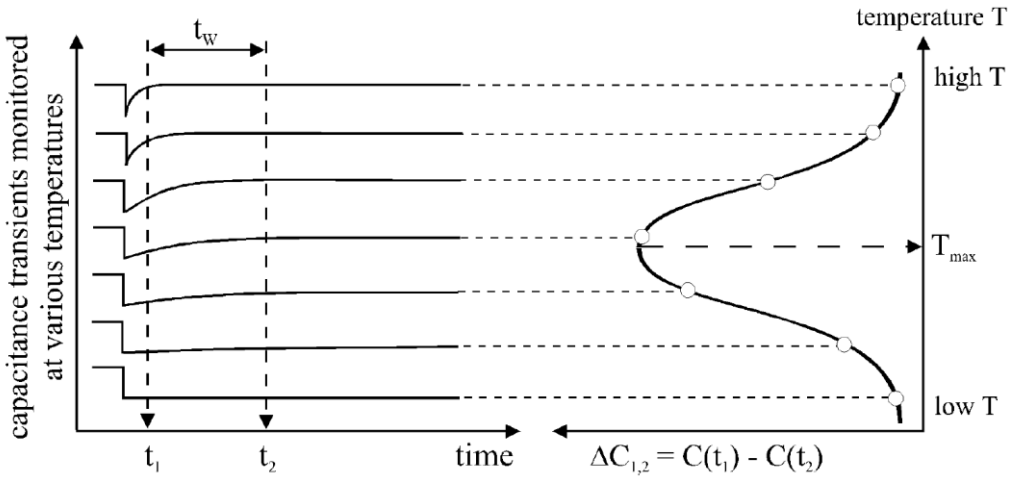
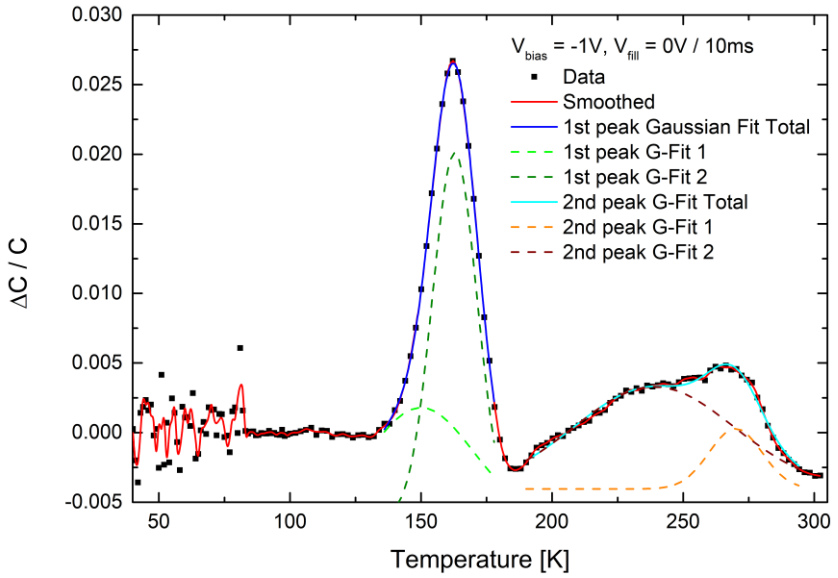




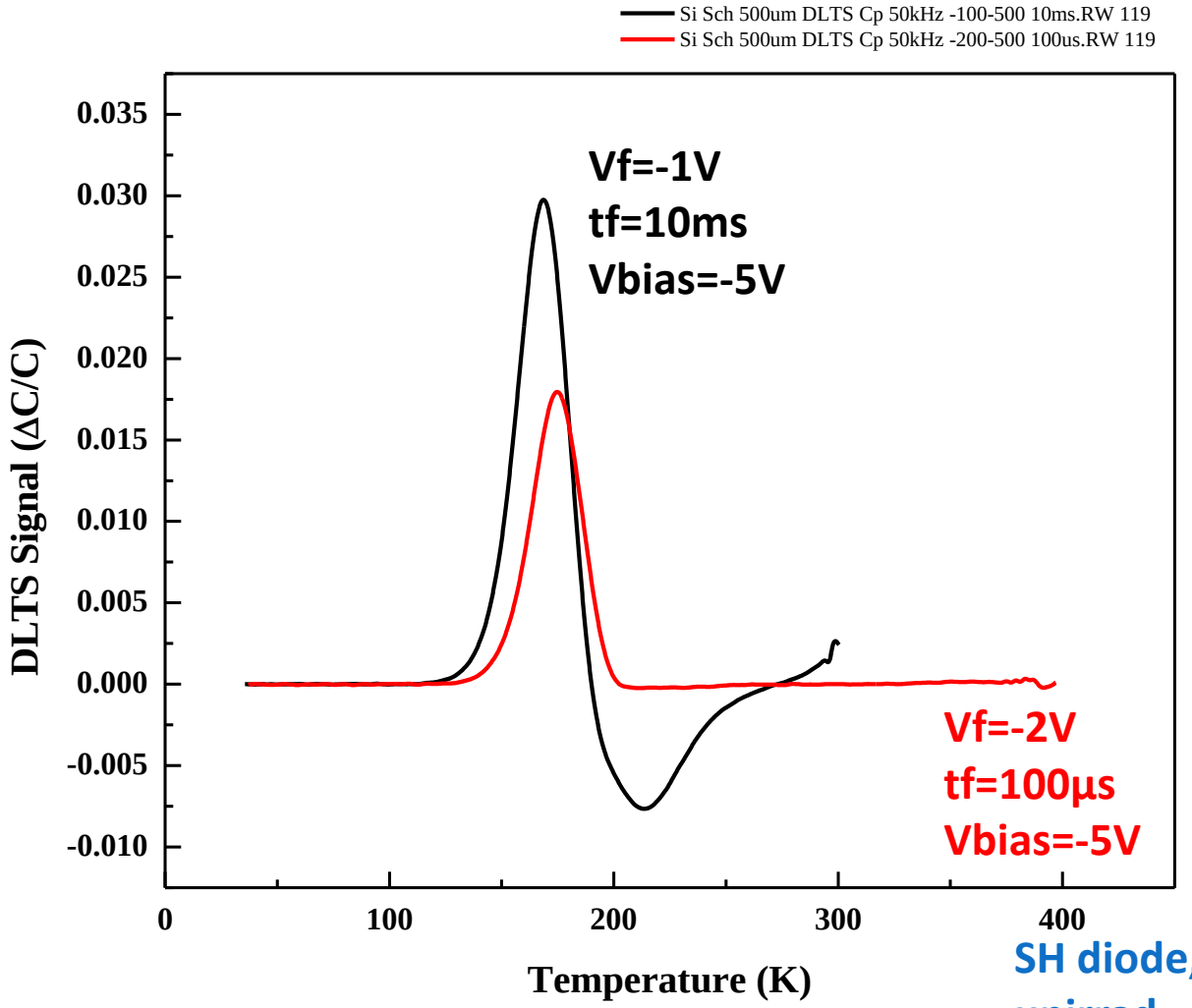
D. V. Lang, Deep-level transient spectroscopy

DLTS: RAL Schottky diode (unirrad.)

DLTS spectrum:

- 1 peak with 2 majority carrier traps
- ‘minority’ carrier trap
  ⇒ vanishes for reduced + shorter filling pulse
  ⇒ surface/interface states likely
- large majority carrier trap for larger filling pulses at room temperature

T_{median} [K]	E_{trap} [eV]	σ [cm²]
170	0.312	5.5E-15
180	0.294	3.3E-16

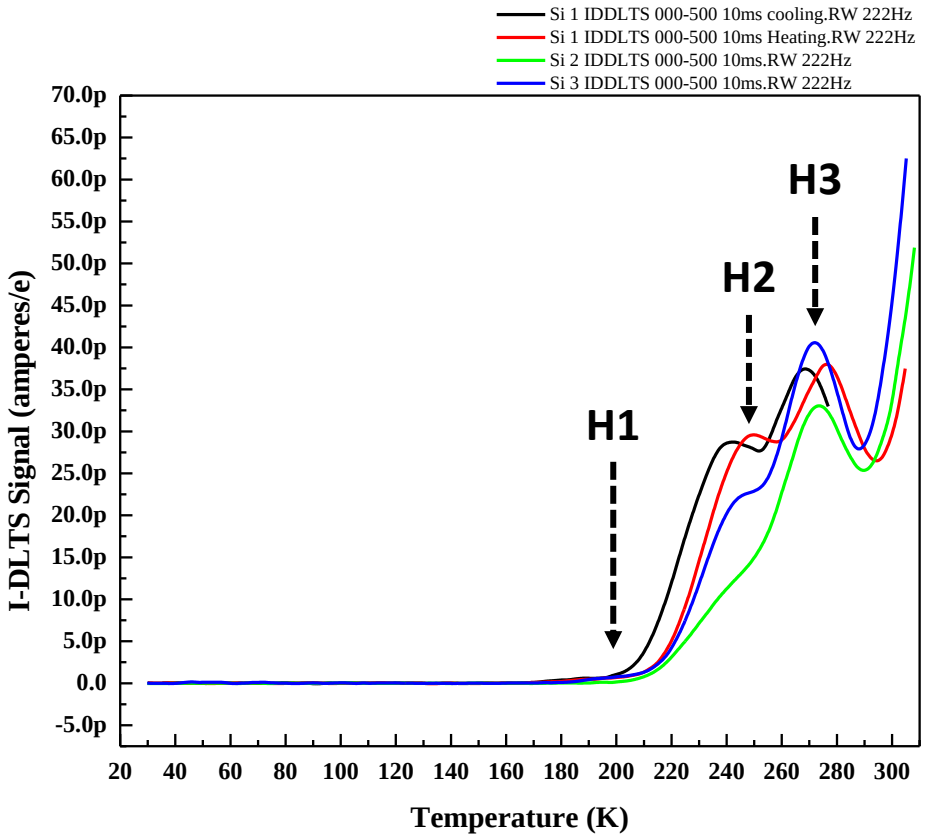


SH diode, unirrad.

I-DLTS: irrad. RAL Schottky (Semetrol setup)

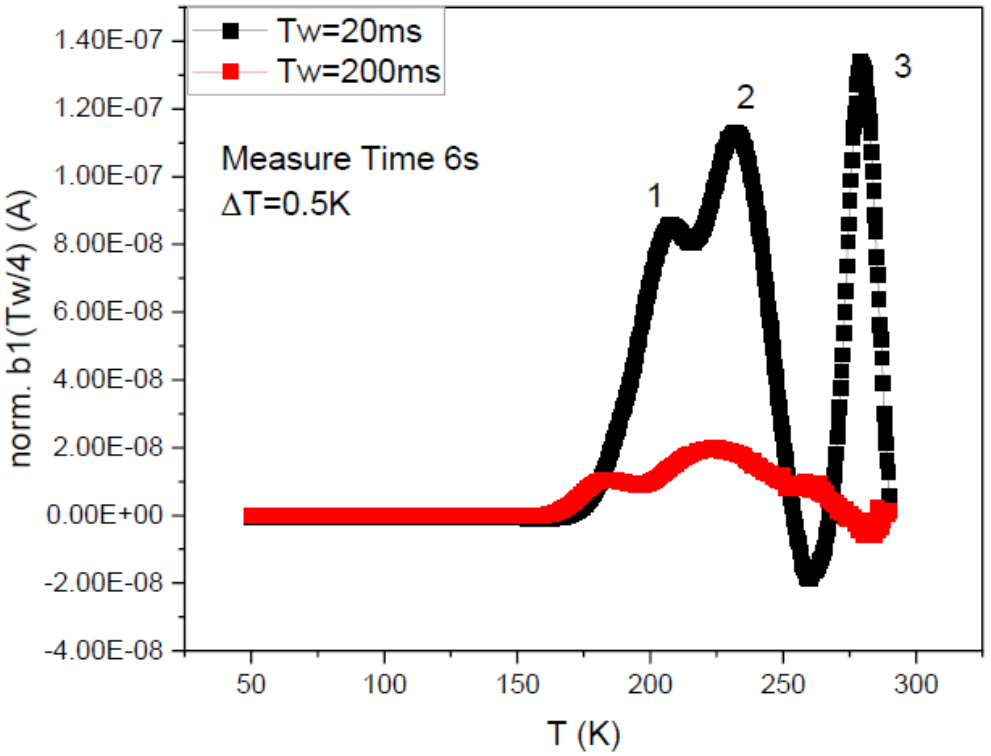
- regular DLTS difficult due to high leakage current
- similar to capacitance DLTS, but no AC test signal, measures current transients
  - double-pulse variant for increased sensitivity
- filling pulse 0V/10ms at -5V
- trap signals at 200K, 240K, 270K, and possibly >300K
  - signal at > 300K may be due to increasing current

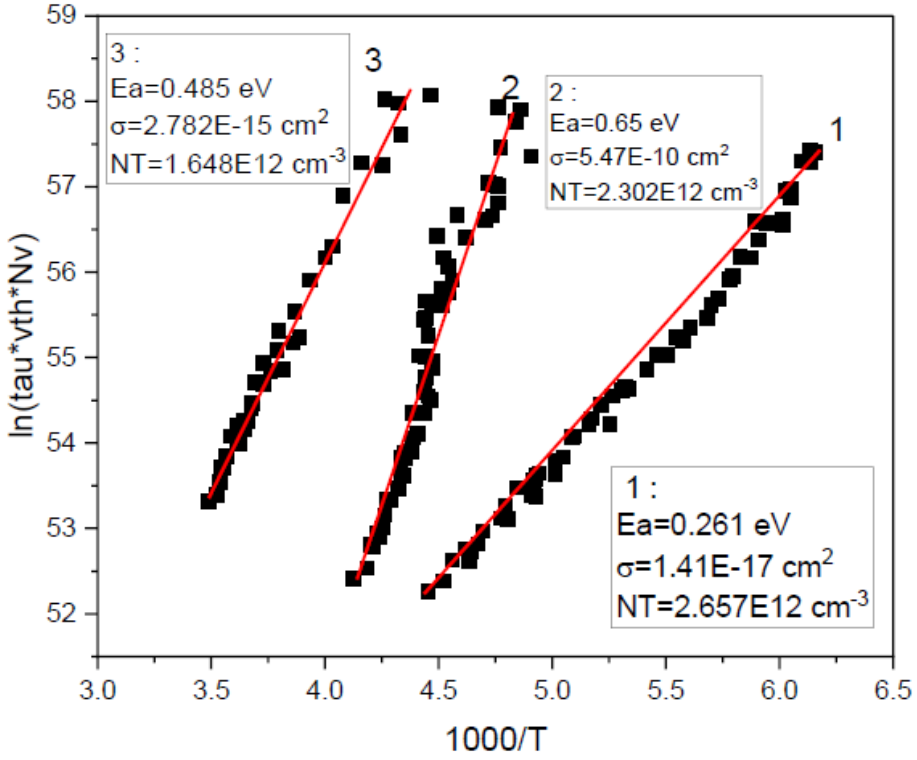
	T_{median} [K]	E_{trap} [eV]	σ [cm²]
H1	200		
H2	250	0.46 ± 0.009	2.4E-15 ± 1.5X
H3	275	0.58 ± 0.014	4.5E-14 ± 1.8X



SH diode, 1x10^{15} irrad.

I-DLTS: irrad. RAL Schottky (Bucharest setup)





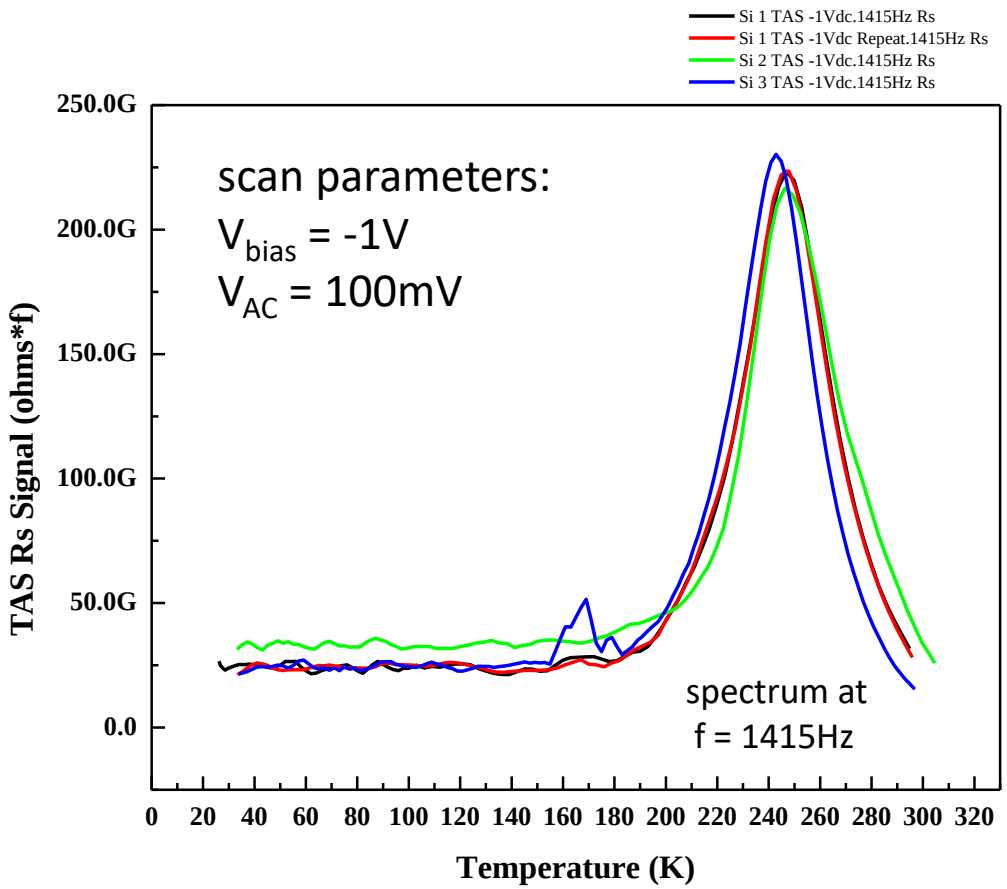
- double-pulse I-DLTS
  - $-5V_{bias}$; $V_{fill,1}$ = -5V / 10ms ; $V_{fill,2}$ = 0V / 10ms
- three deep defects identified

SH diode, $1x10^{15}$ irrad.

TAS: irrad. RAL Schottky

- measure capacitance, resistance, and conductance as function of frequency and temperature
  - steps/peaks in temperature dependence indicate thresholds for new traps contributing
- applicable for low-doped or high-resistivity materials
  - complements DLTS
  - useful for irradiated devices with high fluences
- trap energy is 0.4-0.5 eV above the valence band
  - consistent with I-DLTS results

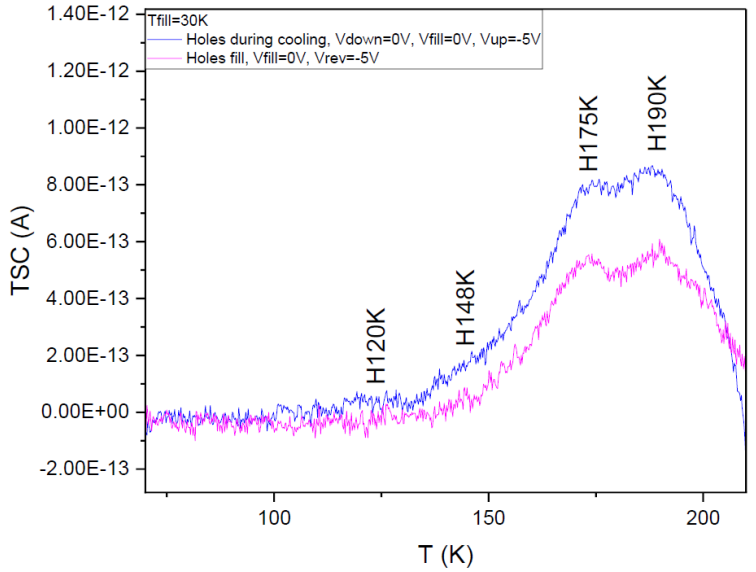
sample	E_{trap} [eV]	σ [cm^2]
Si 1	0.433 ± 0.006	$3.6x10^{-14}$ ± 1.3X
Si 1 (repeat)	0.422 ± 0.008	$2.2x10^{-14}$ ± 1.5X
Si 2	0.486 ± 0.008	$4.0x10^{-13}$ ± 1.5X
Si 3	0.445 ± 0.009	$9.3x10^{-14}$ ± 1.5X



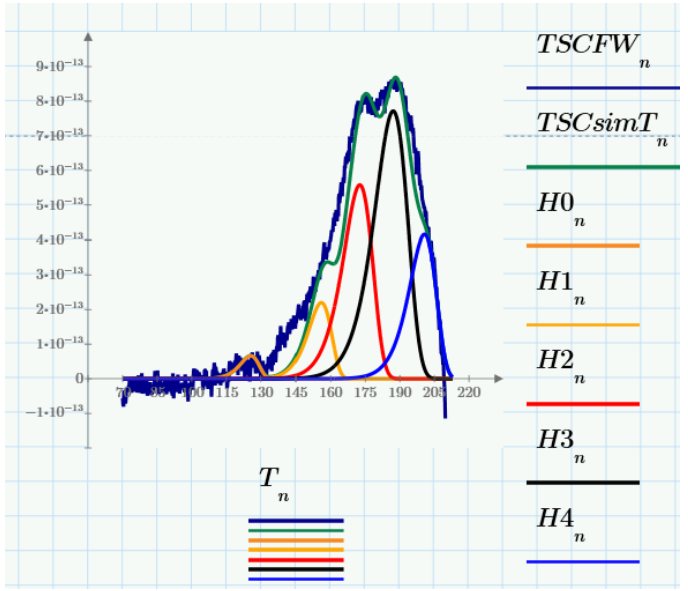
SH diode, $1x10^{15}$ irrad.

TSC: irrad RAL Schottky

- two measurements with cooling under different conditions:
  - 0V during cooling, deep defects filled with holes
  - reverse bias -5V during cooling, 0V filling pulse at 30K
- heating 11K/min with -5V_{bias}
- TSC spectrum results simulated:



	$E_t(eV)$	$\sigma(cm^2)$	$N_T(cm^{-3})$
H0 (known as H116K, hole trap with electric field enhanced emission)	0.3	$7 * 10^{-16}$	$1.05 * 10^{11}$
H1 ((known as H140K, hole trap with electric field enhanced emission)	0.375	$4 * 10^{-16}$	$4.3 * 10^{11}$
H2 (known as H152K, hole trap with electric field enhanced emission)	0.354	$4 * 10^{-18}$	$13.85 * 10^{11}$
H3	0.368	$1.1 * 10^{-18}$	$21.5 * 10^{11}$
H4	0.538	$4.5 * 10^{-15}$	$9.5 * 10^{11}$



SH diode, 1x10^{15} irrad.

Summary & outlook

- RAL Schottky diodes underwent neutron irradiation at Ljubljana
  - post-irradiation results from DLTS and CCE measurements

Outlook:

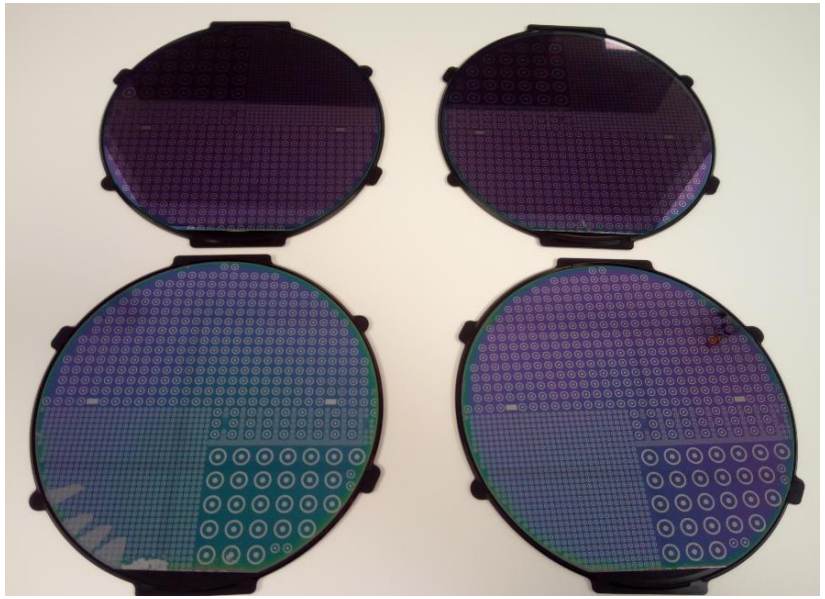
- CUMFF pn-junction diodes sent out for irradiation
- TCAD simulations of Schottky diodes ongoing
- ongoing charge collection measurements at RAL and DLTS + TAS at Carleton
  - comparison of pre/post-irradiation, input for TCAD simulation

Backup

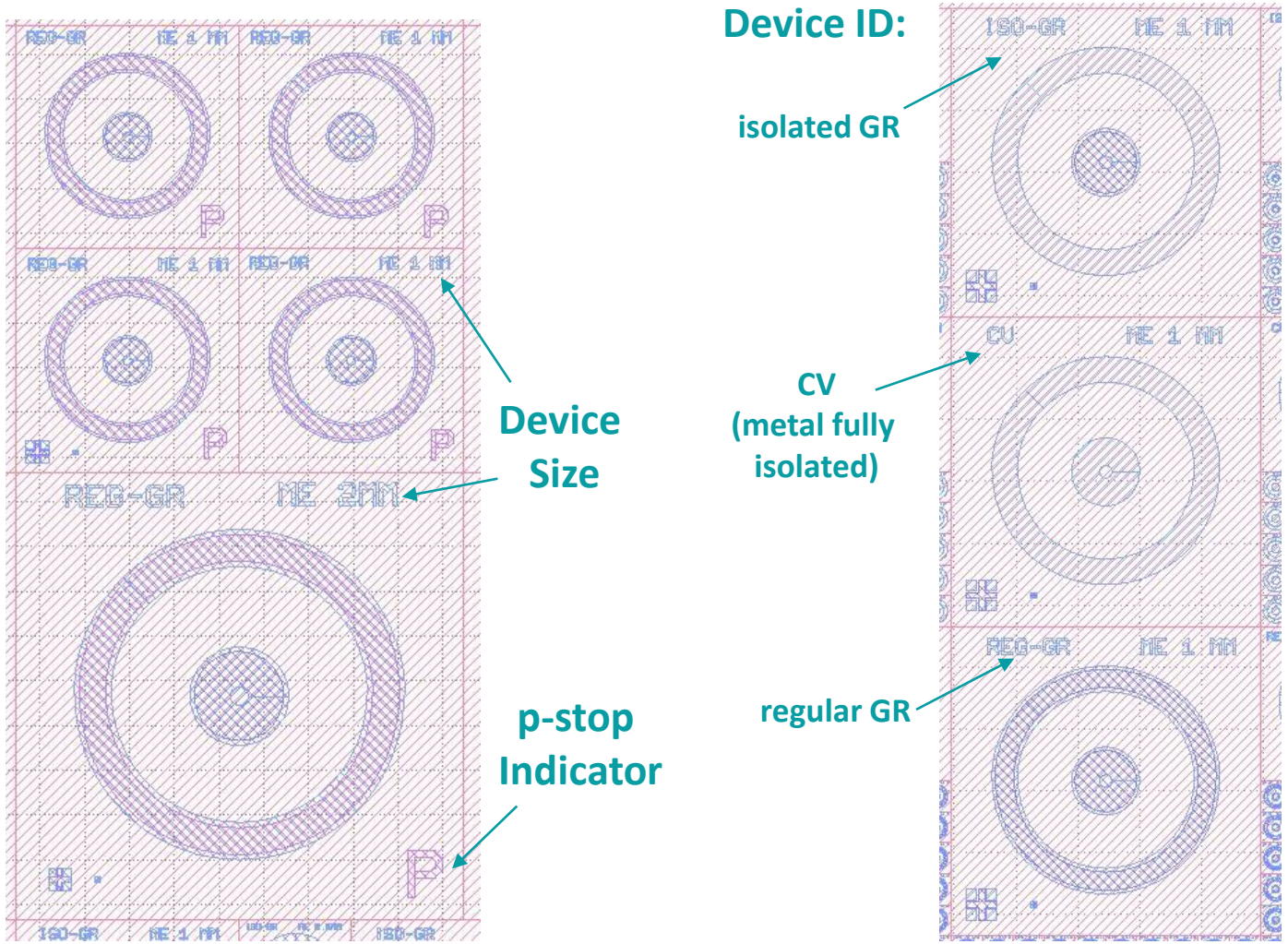
Fabrication details

CUMFF

- new masks made, including isolated MOS gate GR variation for all device types + optional p-stop

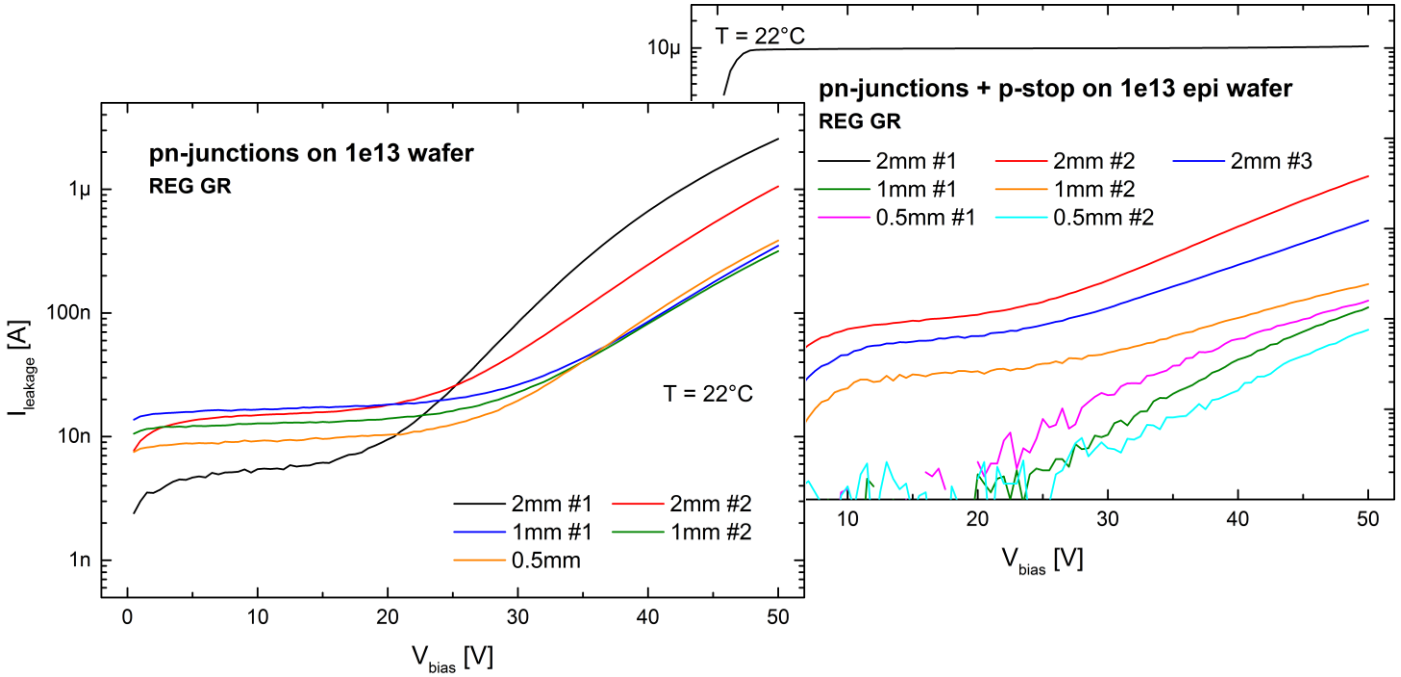


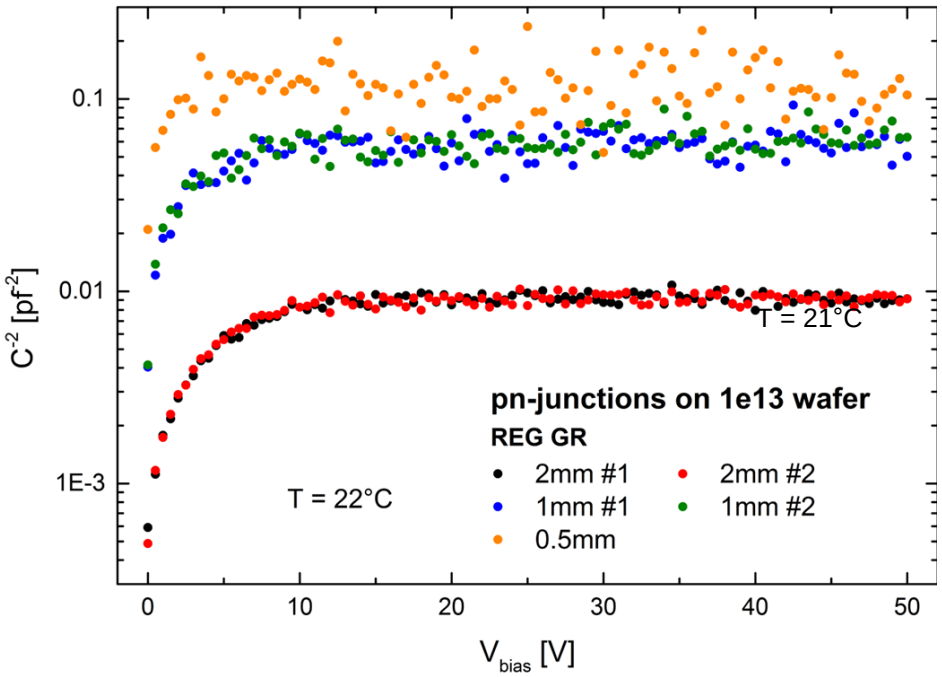
full 6” Schottky wafers @RAL



new masks with different structure flavours @CUMFF

IV + CV measurements: CUMFF pn-junctions (1e13 vs. 1e16)





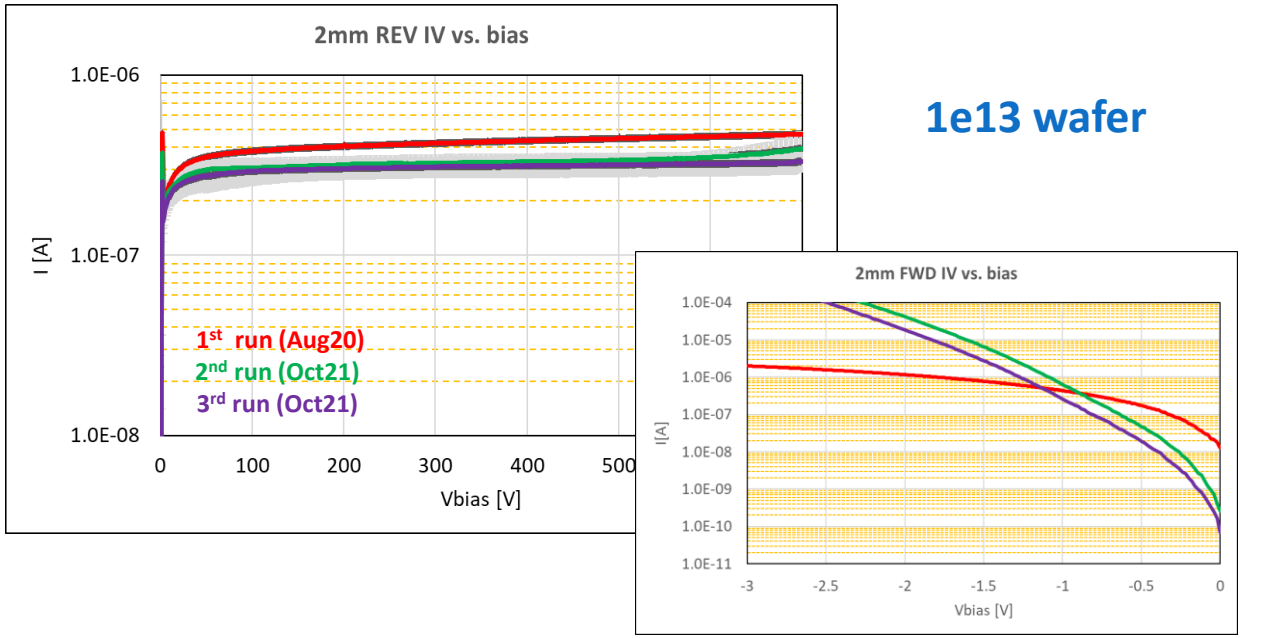
- current can vary by large margin on same wafer
- very low initial current often seen
- no hard breakdowns observed; gradual increase in current
- ➢ leakage current at much lower levels compared to first fabrication iterations

- depletion of epi layer at low voltages
  - small differences for different structure flavours
  - agrees with back-of-the-envelope calculation for high-resistivity 50um epi layer
- capacitance scales nicely with structure size

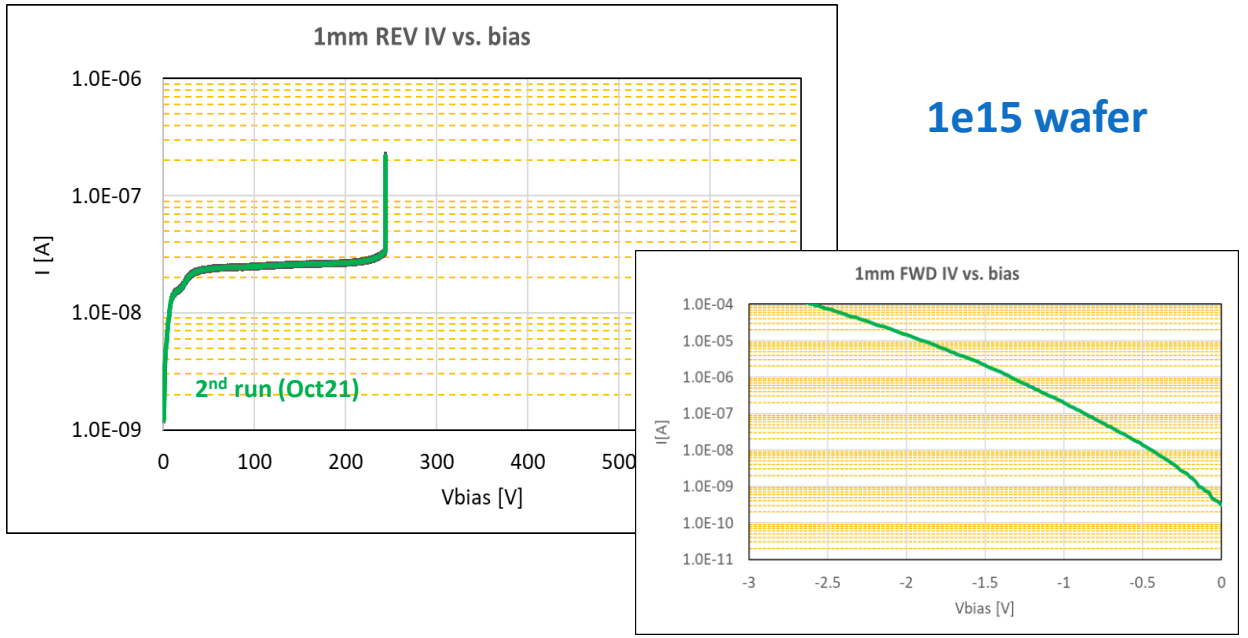
more basic electrical measurements in backup

T = 21°C

IV measurements: RAL Schottky (1e13 vs. 1e15)



1e13 wafer



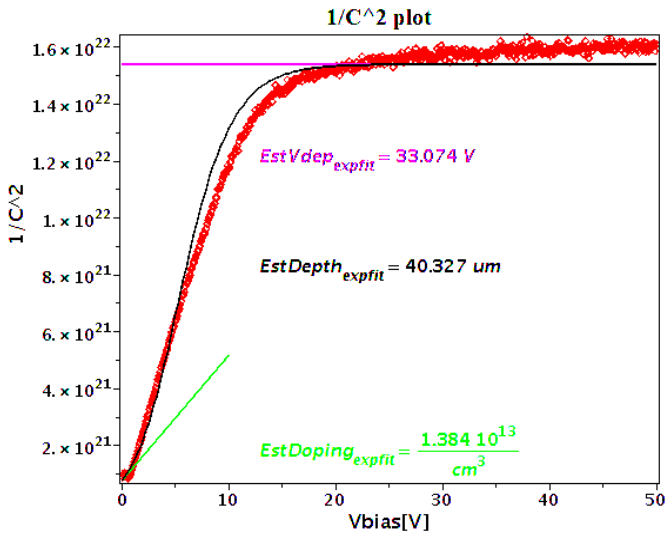
1e15 wafer

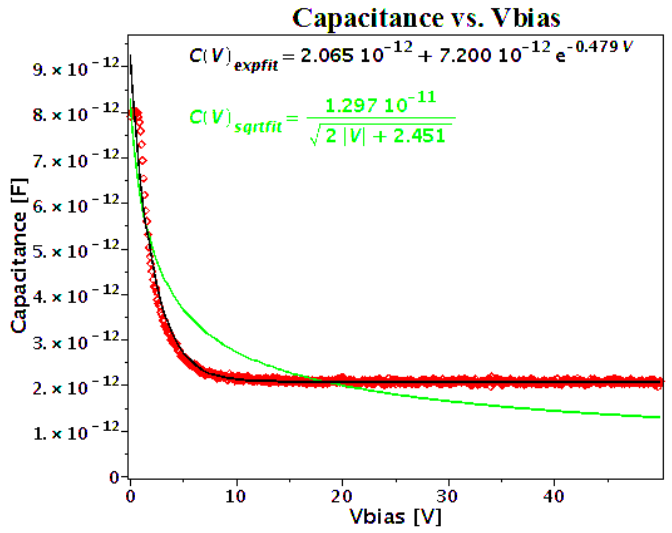
- reverse bias IV similar in all runs, slightly lower leakage in the two latest runs
  - breakdown voltage > 700V
- forward bias shows very different characteristics

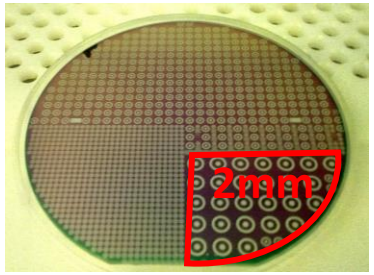
- expected lower leakage in reverse bias, with lower BV
- measured BV is high for this doping
- forward bias ~linear

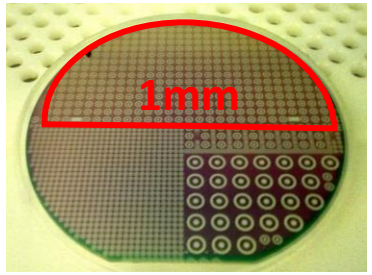
CV measurements: RAL 1e13 Schottky

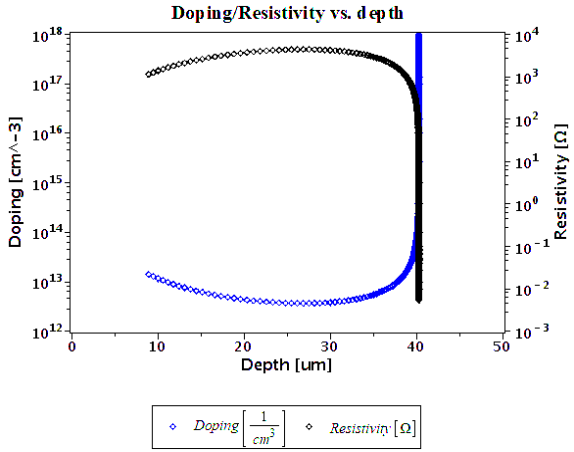
T = 21°C
f = 100kHz
V_{AC} = 30mV











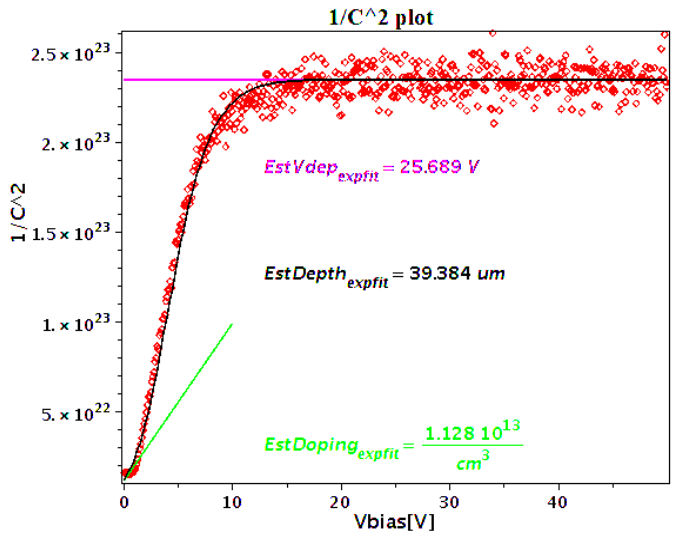
V_d	1.716
φ_b	2.134

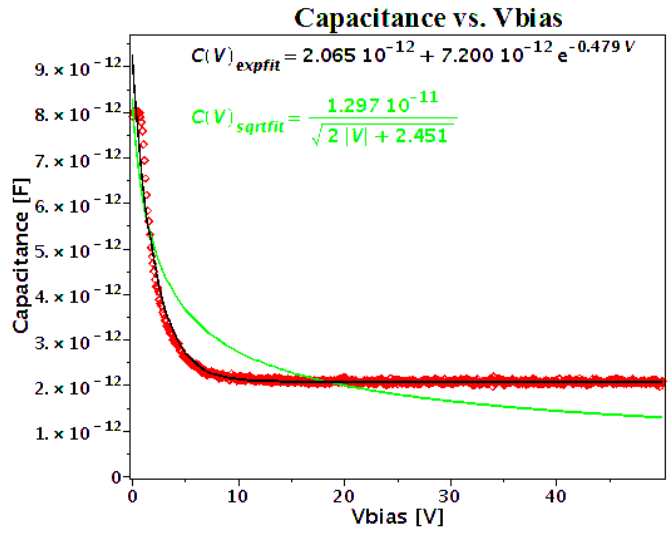
V_d	1.343
φ_b	1.739

Φ(Al) = 4.1 [eV]
χ(Si) = 4.05 [eV]

φ_b = 1.16 - (4.1 - 4.05)
= 1.11 (ideal case)

φ_b from CV too high – needs further investigation (TCAD)

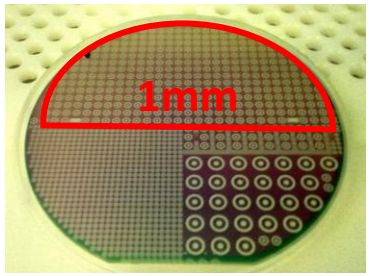


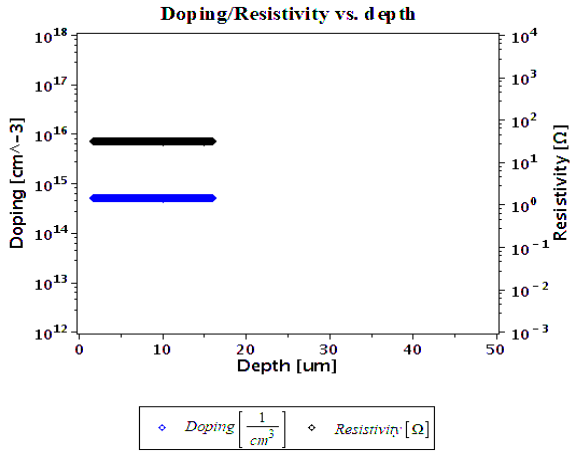


CV measurements: RAL 1e15 Schottky

T = 21°C
f = 100kHz
V_{AC} = 30mV

- 2 HR wafers show doping as expected
  - CV plot not really well described by 1/√V fit
  - barrier height estimate from CV too high
  - estimate from IV in progress
- devices on 1e15 wafer so far show very good 1/√V Cap dependence
  - doping as expected
  - barrier height clearly too high





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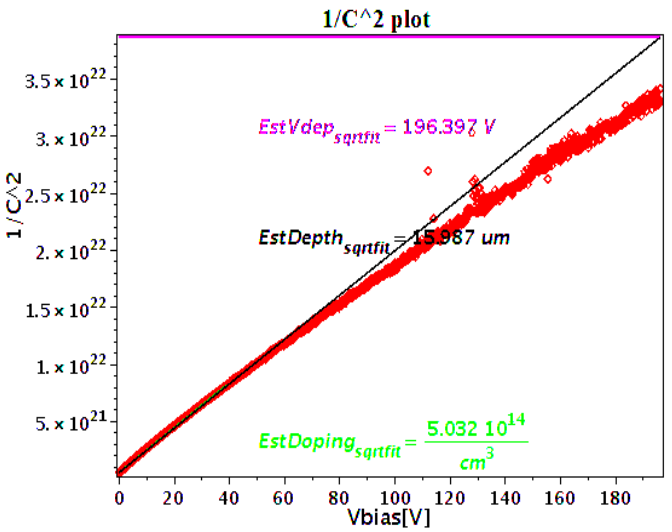
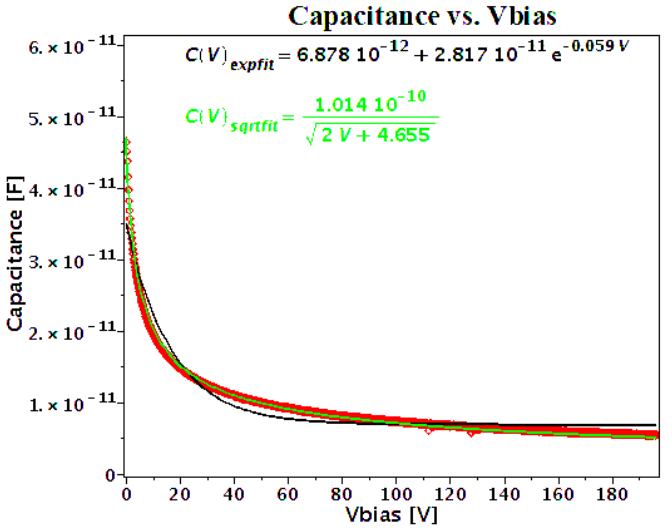


V_d	2.328
φ_b	2.646



Charge Collection Efficiency: Setup

- Laser: IR(1064 nm), 5µm x 50µm, 23.44 ± 0.2 pJ
- Stage: move step of 5µm
- Temperature: -20℃ … +20 ℃