HPK EIC production sensors: C-V and laser measurements

Jennifer Ott, Casey Bishop, Ayan Das, Simone Mazza & the SCIPP team

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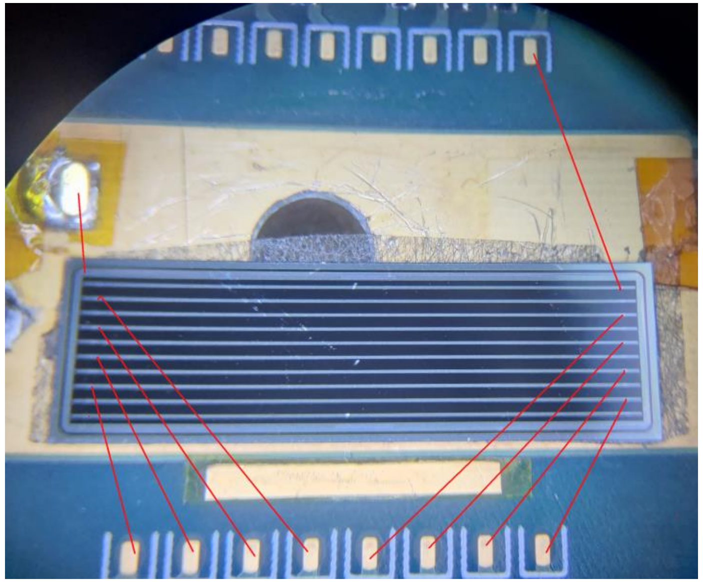
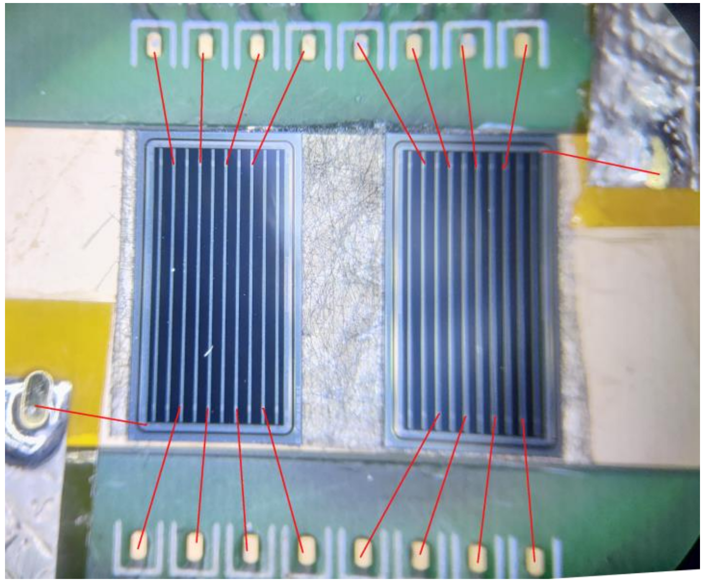
jeott@ucsc.edu

HPK sensors

- Strips and 4x4 pad arrays with uniform, 500 µm pitch
- Splits according to:
  - n+ doping: C and E type (C: lower resistivity)
  - Dielectric: 240 and 600
  - Bulk thickness: 50 µm, 20 µm (only for dielectric 600)

  - Strip length
    - 0.5, 1, 2 cm
  - Strip metal width
    - 50, 100 µm
  - Pad size
    - 150, 300, 450 µm





Irradiations at LANL and pre-testing

J. Ott et al, AC-LGAD capacitances

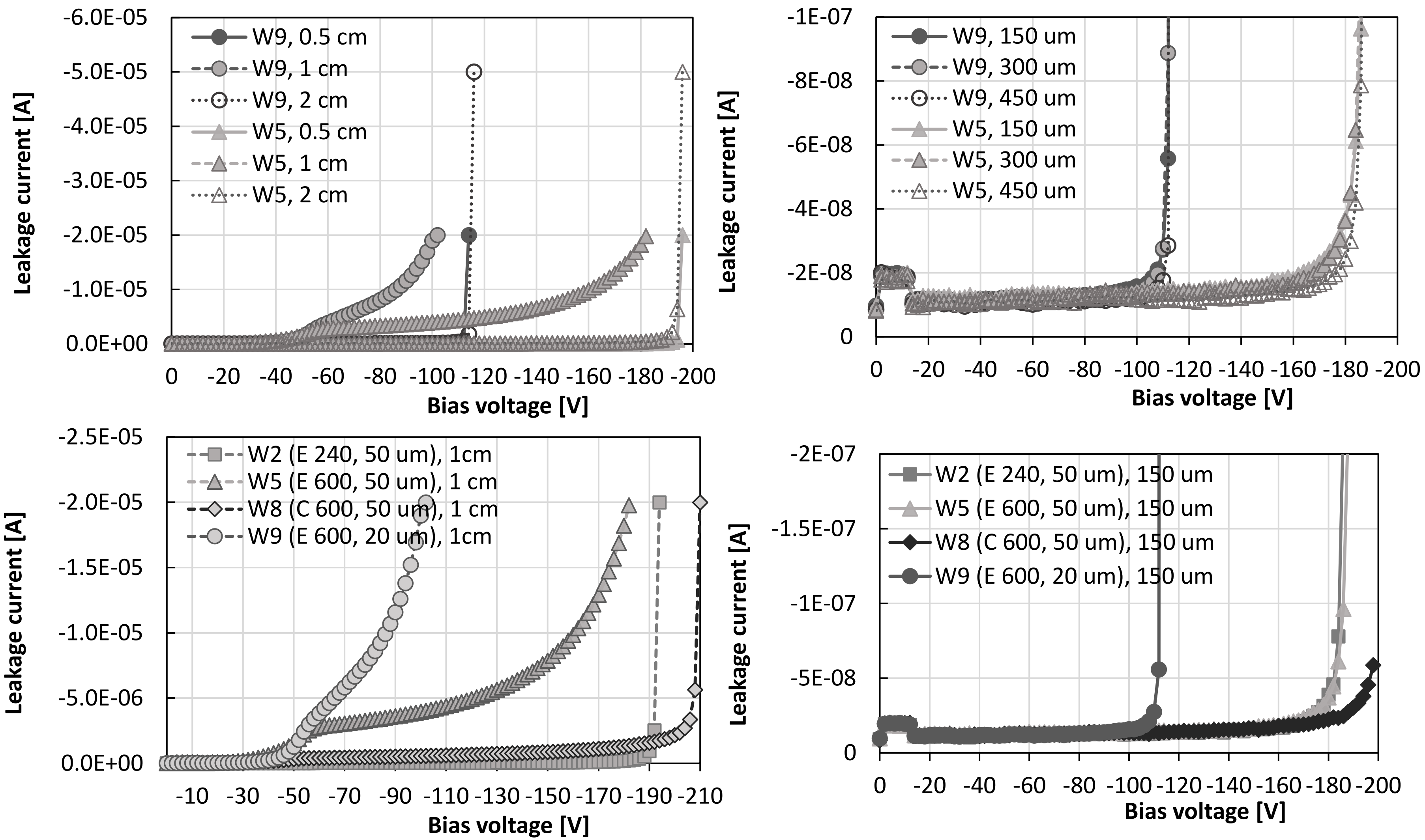
- Based on experience with laser and test beam, focus on the most relevant sensors: E-600, benchmark size (1 cm) and a chosen strip width (100 µm)
- C vs E and 240 vs 600 comparisons for 1 cm strips and 150 µm pads

1	SCIPP HPK ID	Geometry	wafer	positi	size	HPK n+ layer doping	Nominal dielectric C (pF/mm2)	thickness	lenght (mm)	pitch (um)	width (um)	Breakdown (V)		Irradiation	Card #
2															
3	HPK19	strip	W02			E	240	50	10	500	100	195		1.00E+13	1
4	HPK21	strip	W05			E	600	50	10	500	100			1.00E+13	1
5	HPK22	strip	W08			C	600	50	10	500	100			1.00E+13	1
6	HPK23	strip	W09			E	600	20	10	500	100	110		1.00E+13	1
7															
8	HPK15	strip	W05			E	600	50	10	500	50	190		1.00E+13	2
9	HPK17	strip	W09			E	600	20	10	500	50	95		1.00E+13	2
10															
11	HPK33	strip	W05			E	600	50	20	500	100	185		graded 5e13-1e14 if possible	
12	HPK35	strip	W09			E	600	20	20	500	100	110		graded 5e13-1e14 if possible	
13															
14	HPK9	strip	W05			E	600	50	5	500	100	190		1.00E+14	3
15	HPK11	strip	W09			E	600	20	5	500	100	110		1.00E+14	3
16															
17	HPK37	pixel array	W02		4x4	E	240	50	150	500		185		2.00E+14	5
18	HPK39	pixel array	W05		4x4	E	600	50	150	500		185		2.00E+14	5
19	HPK40	pixel array	W08		4x4	C	600	50	150	500		200		2.00E+14	5
20	HPK41	pixel array	W09		4x4	E	600	20	150	500		110		broken?	
21															
22	HPK45	pixel array	W05		4x4	E	600	50	300	500		185		2.00E+14	6
23	HPK47	pixel array	W09		4x4	E	600	20	300	500		110		2.00E+14	6
24															

IV

- Consistency along metal size (expected), except for some individual samples

- Slightly higher breakdown voltage for C-type n+ layer

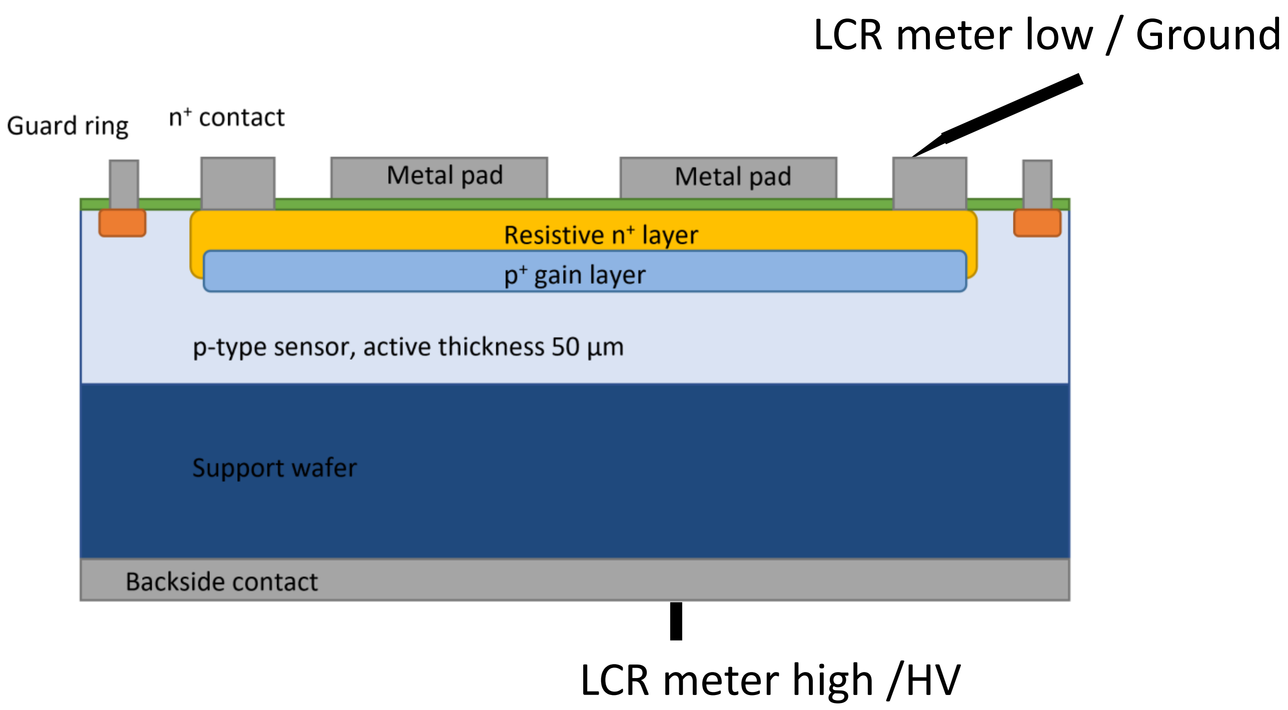


Standard C-V measurement

"Conventional" C-V measurement configuration: sensor backplane to front side electrode

- In AC-LGADs, there is one shared n⁺ layer with the DC contact – capacitance measured over the full sensor area

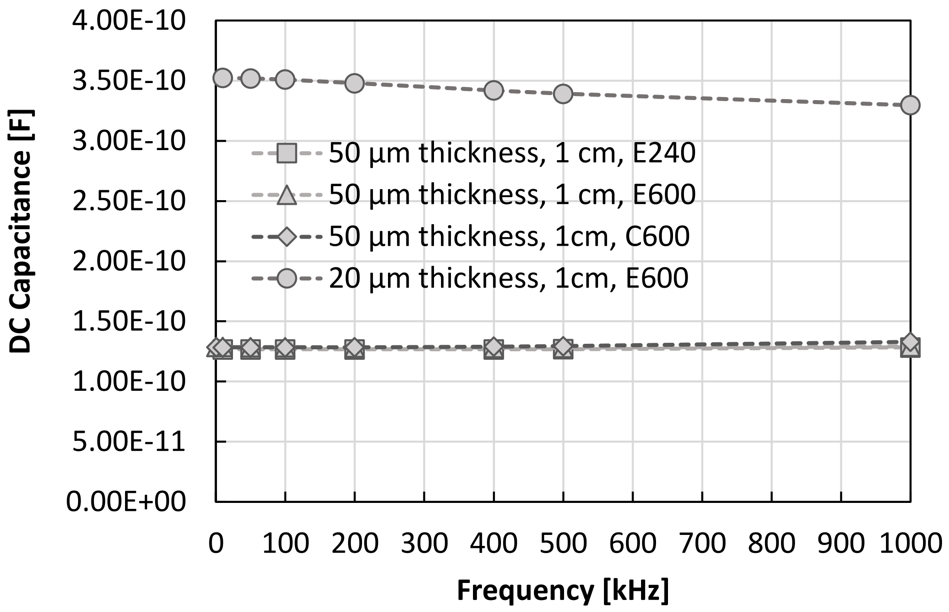
- In these sensors, no contact openings on guard ring – left floating

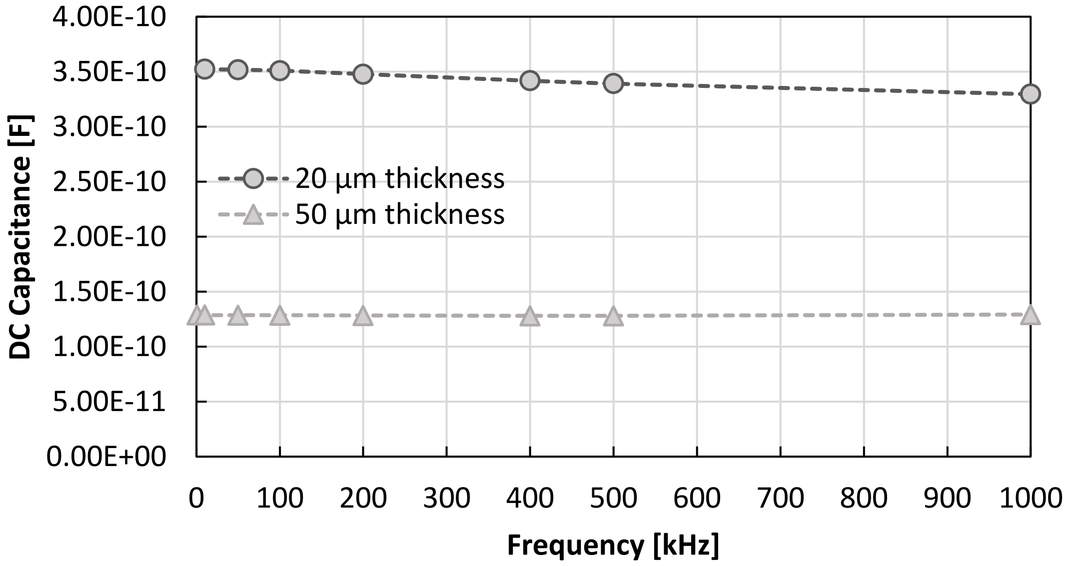


DC capacitance

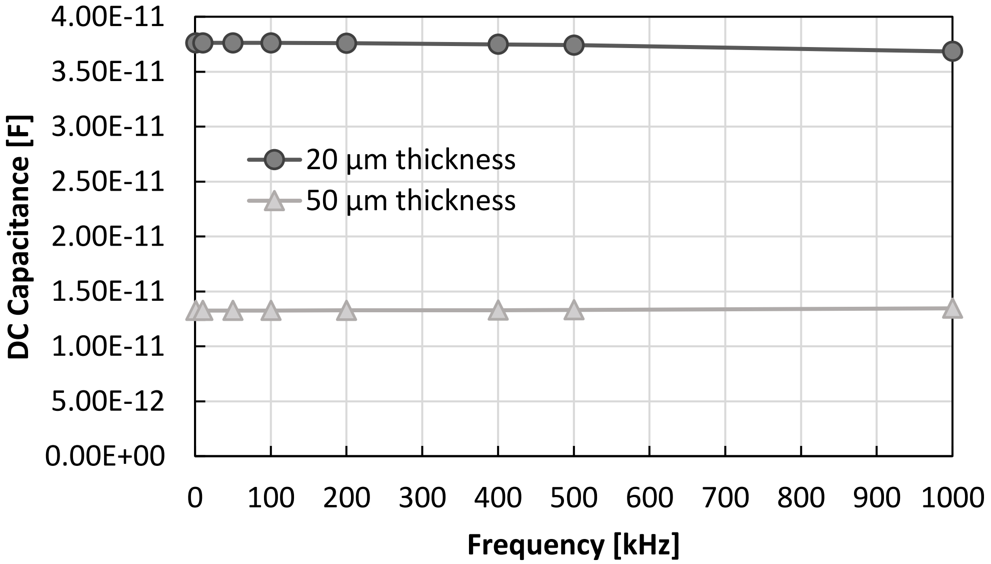
As expected

- Inversely proportional to bulk thickness
- No difference with dielectric or n+ layer





1 cm strip, 100 µm width



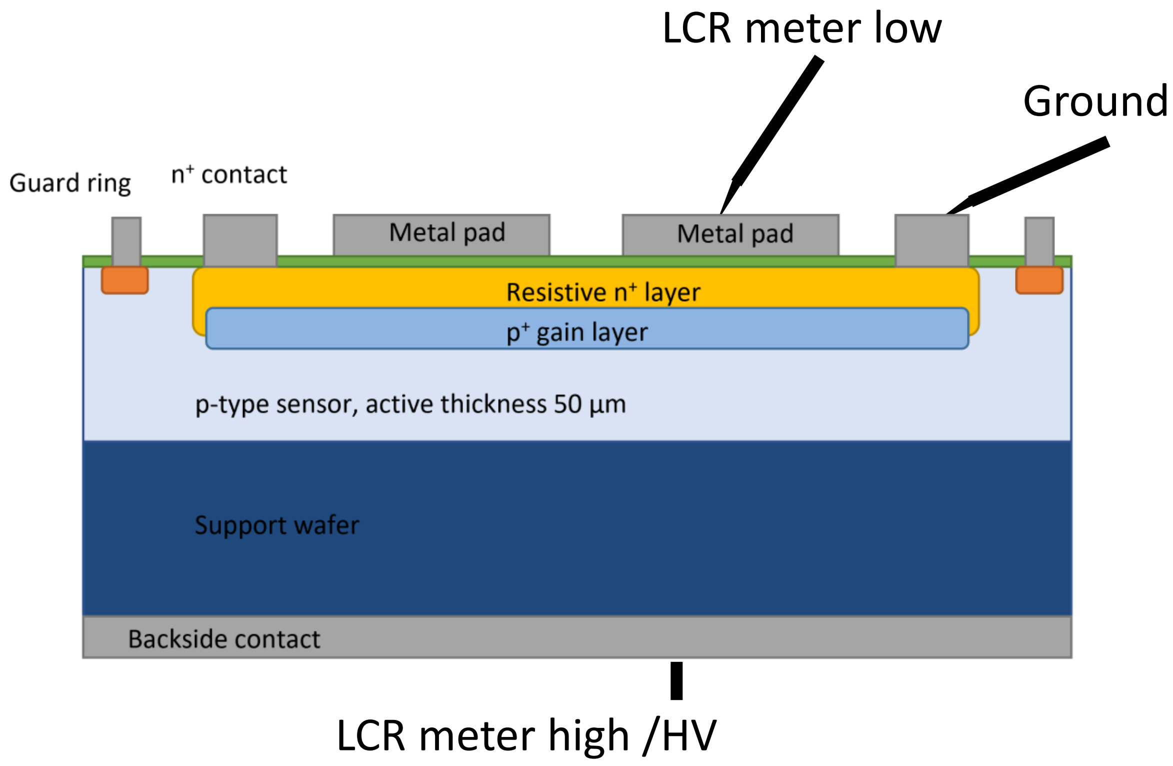
150 µm pad size

AC capacitance

Specific to AC-LGADs: measurement from backplane to individual AC metal pad

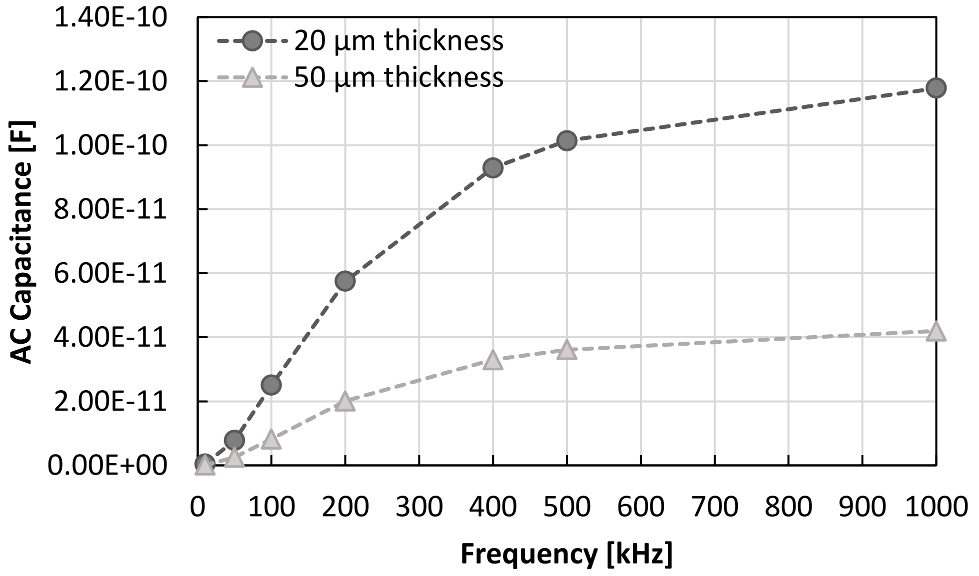
- Depletion visible, frequency dependence before depletion – capacitance component through the bulk
- Pad size affects the final capacitance values, since capacitance is directly proportional to the area

- Here: other pads/strips left floating

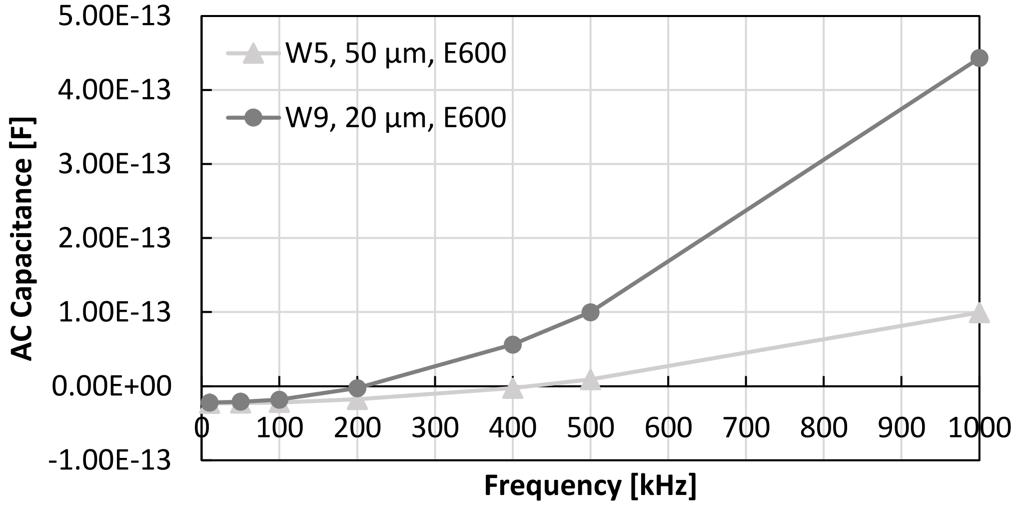


AC capacitance

- Frequency dependency is visible, behavior with frequency different for strips and pads
- AC capacitance also scales with bulk thickness



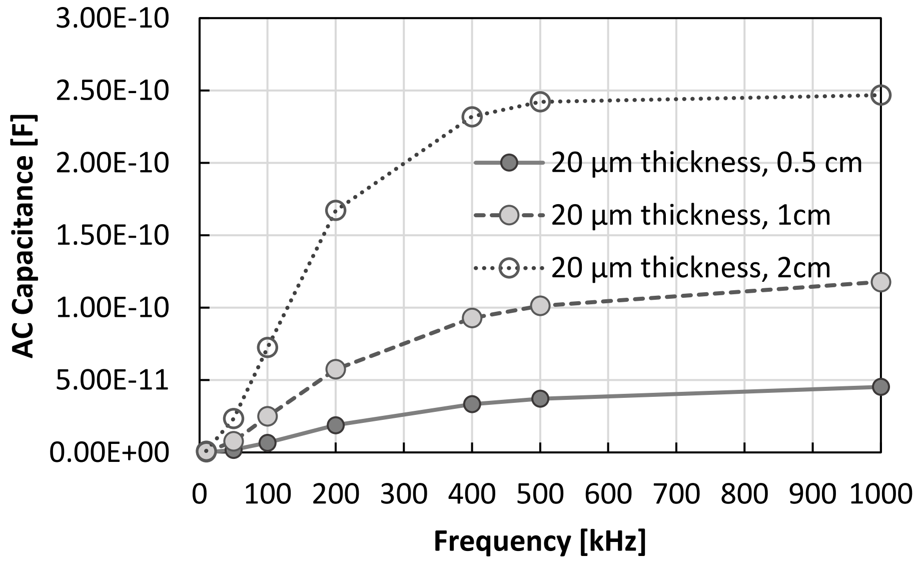
1 cm strip, 100 µm width

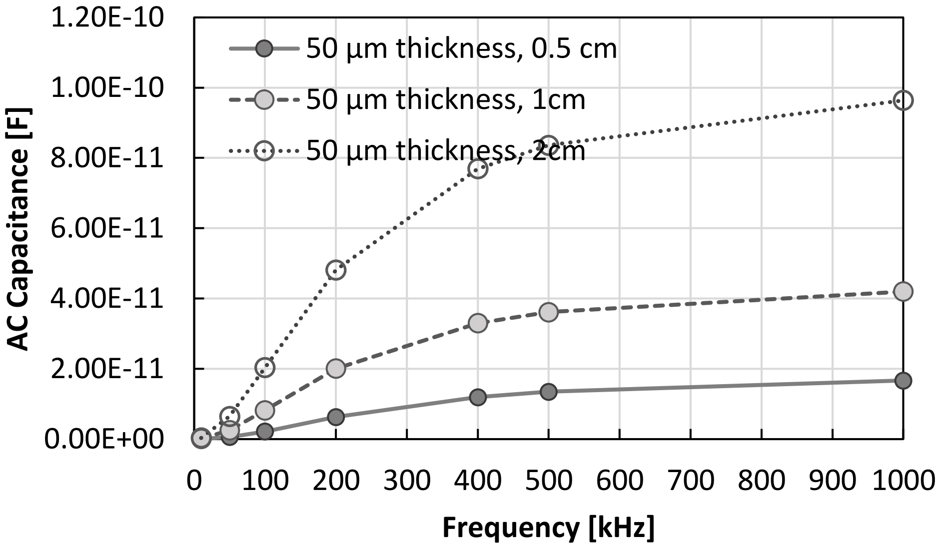


150 µm pad size

AC capacitances: metal size

- AC capacitance depends on strip length

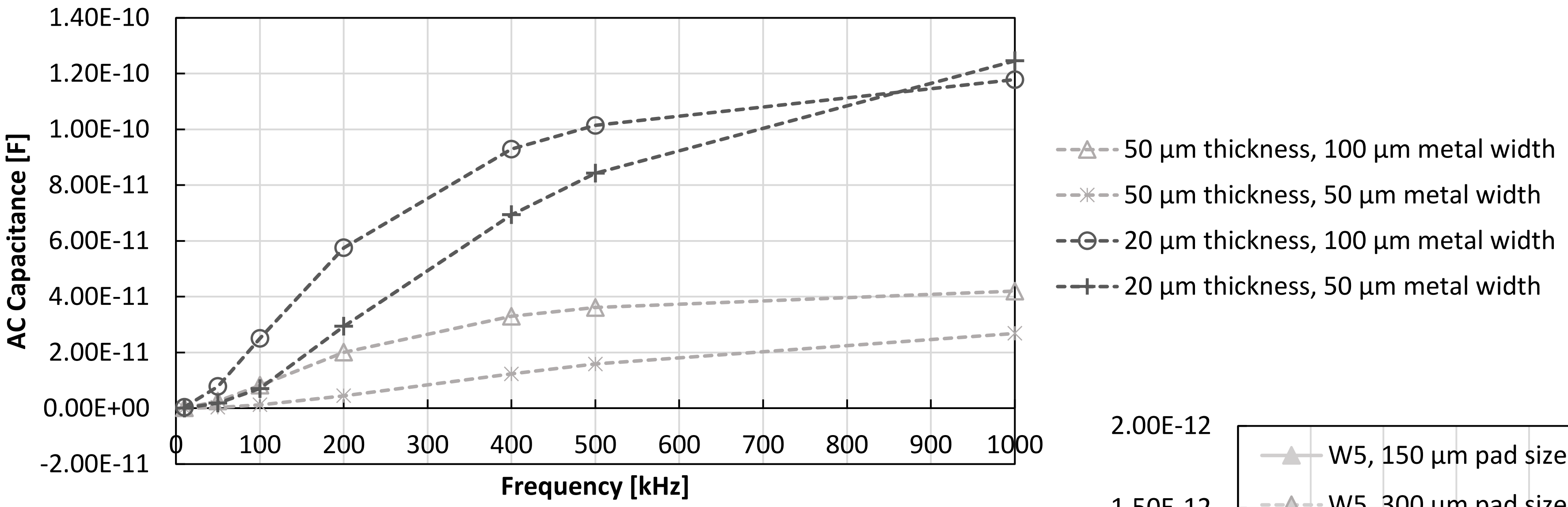


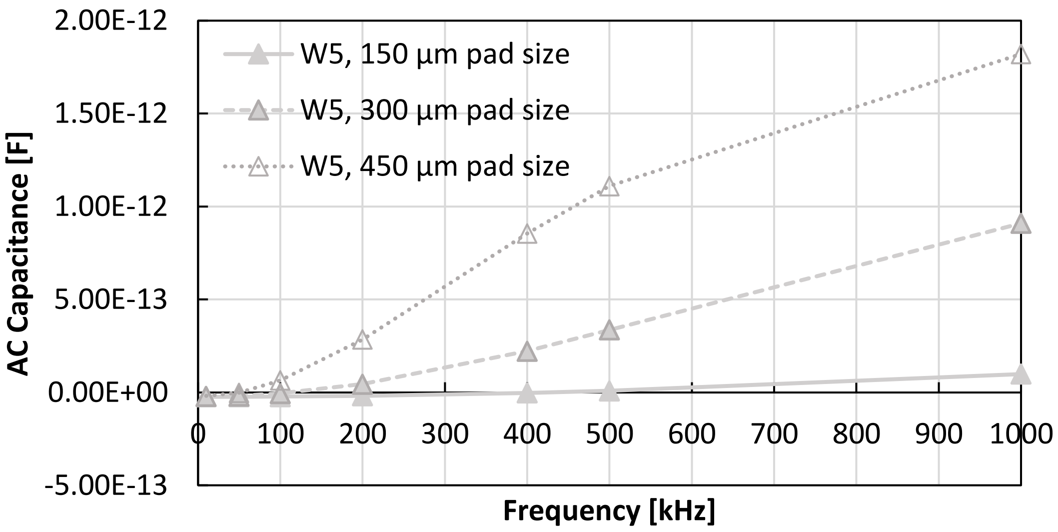


J. Ott et al, AC-LGAD capacitances

AC capacitances: metal size

- AC capacitance also scales with metal size





50 µm thickness

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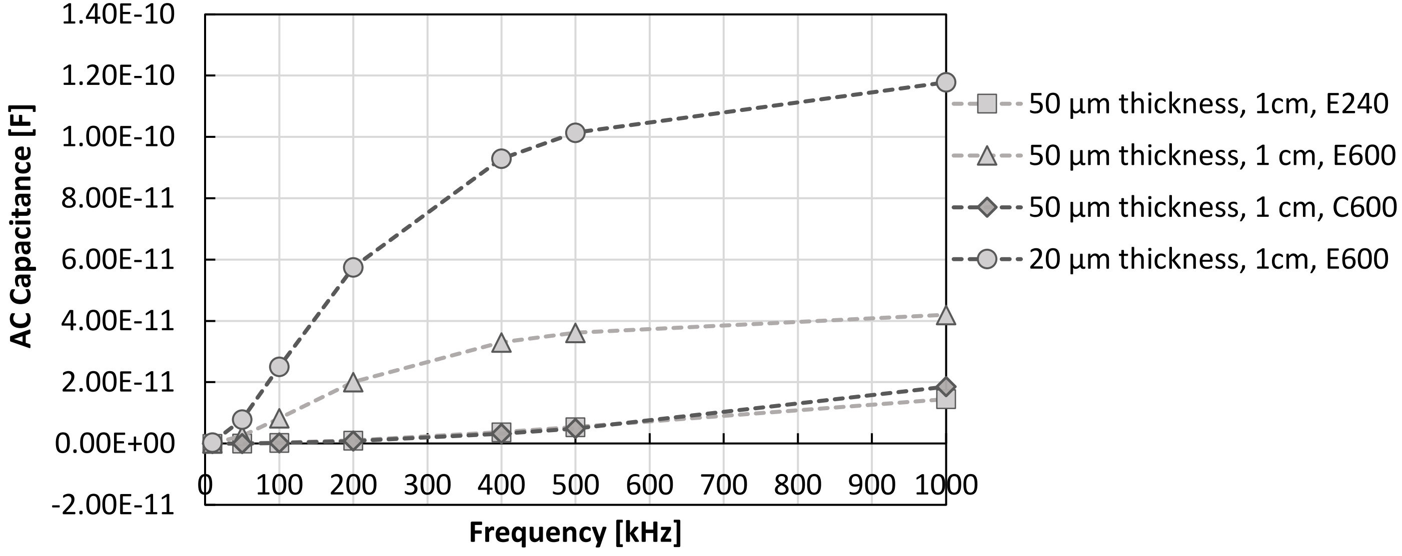
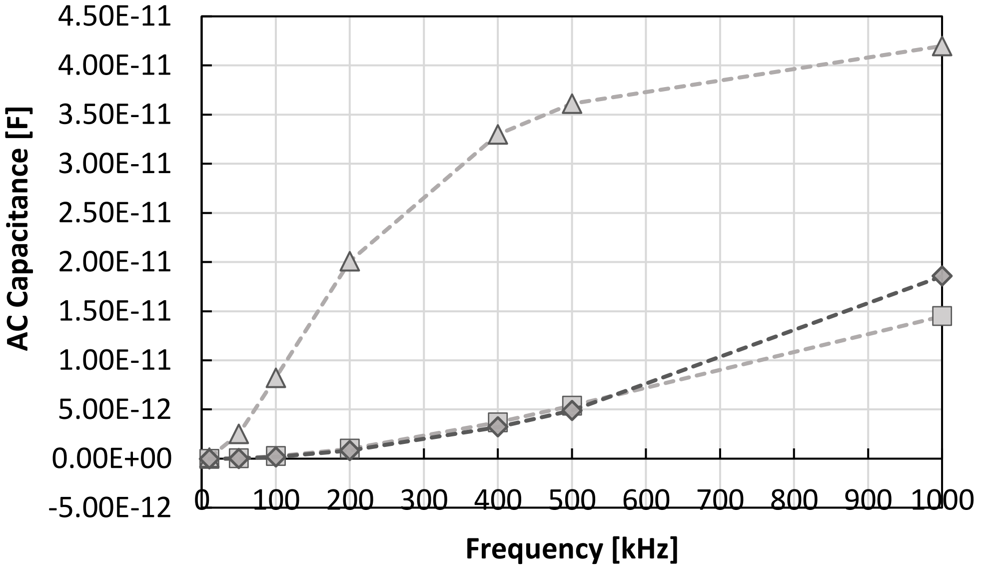
AC capacitance

- Lower AC capacitances for E240 and C600!

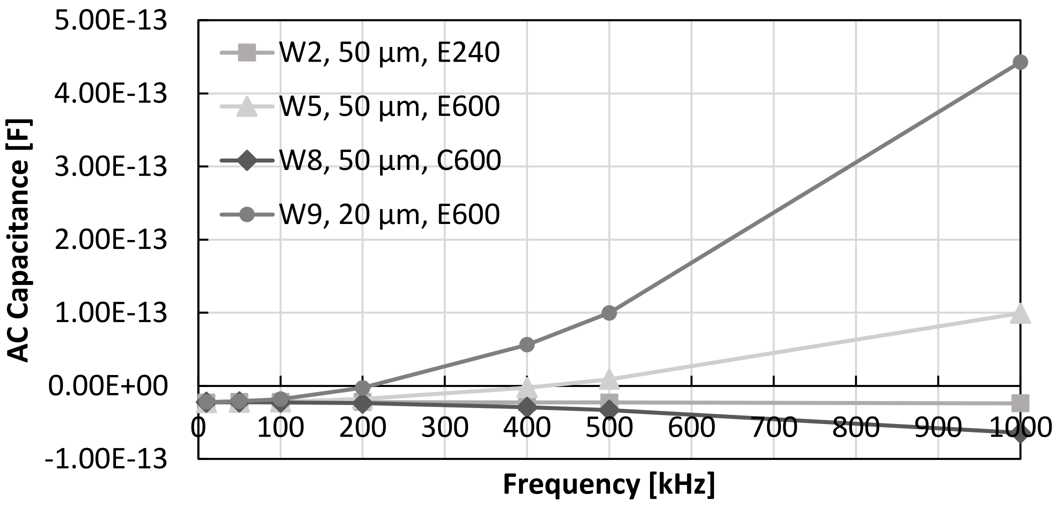


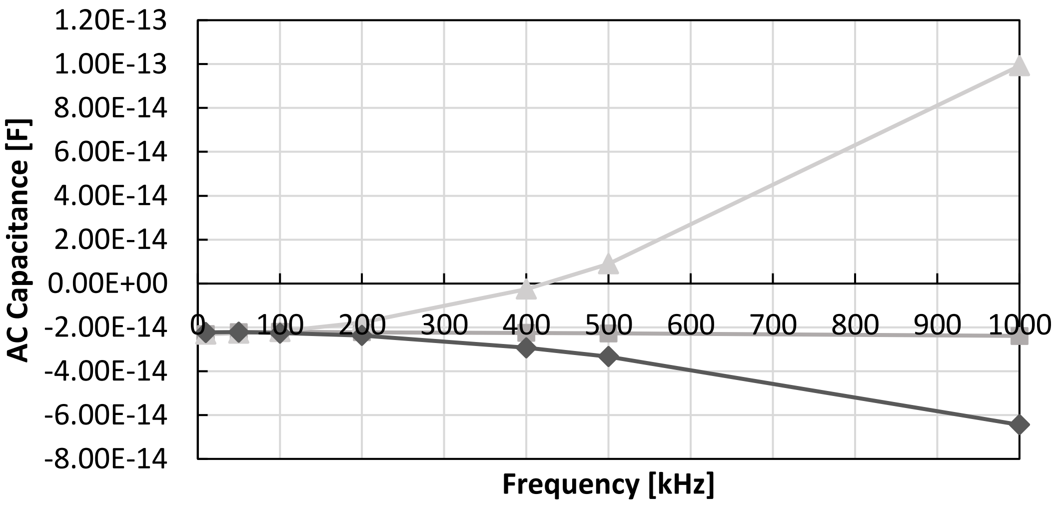


1 cm strip, 100 µm width

AC capacitance

- Lower AC capacitances for E240 and C600!



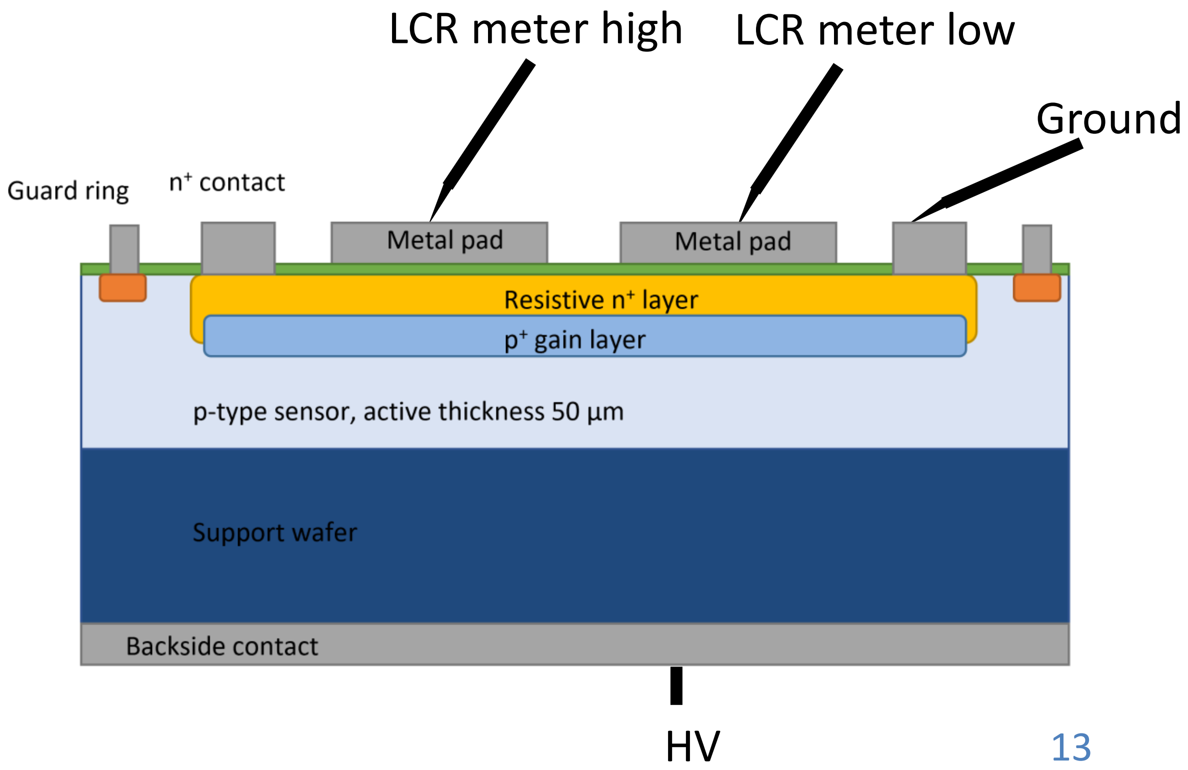


150 µm pad size

Interpad capacitance

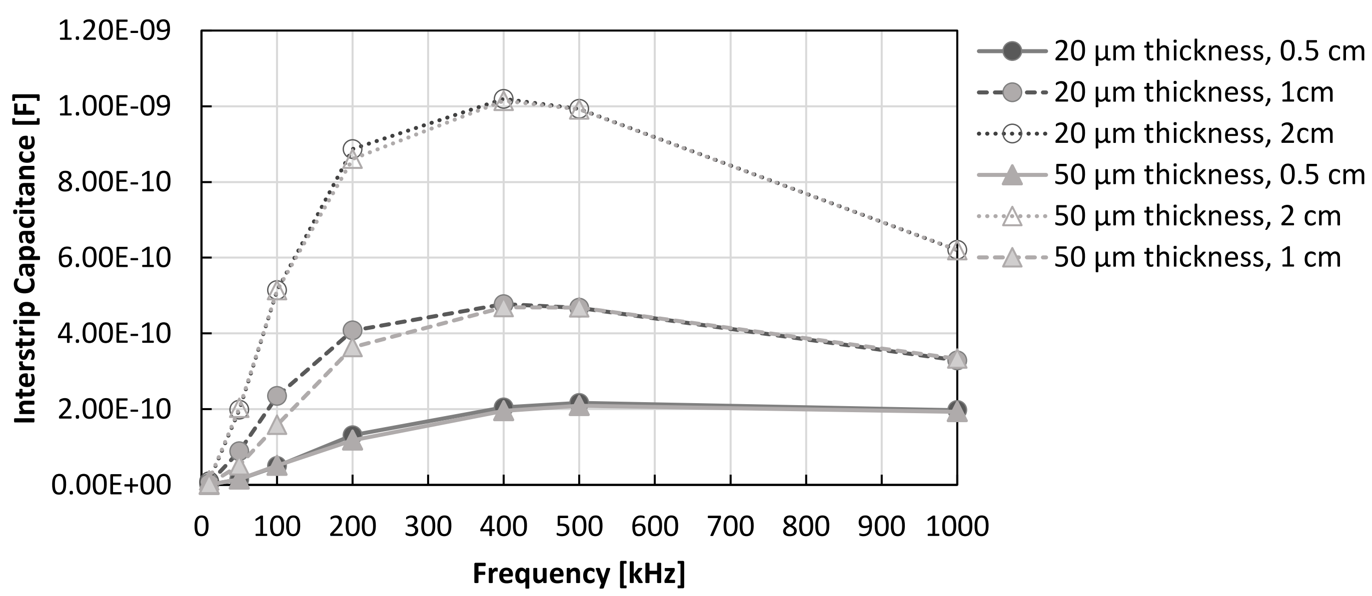
Interpad capacitance: between two AC metal pads, sensor biasing from backplane as usual, grounding to the n$^+$ DC contact

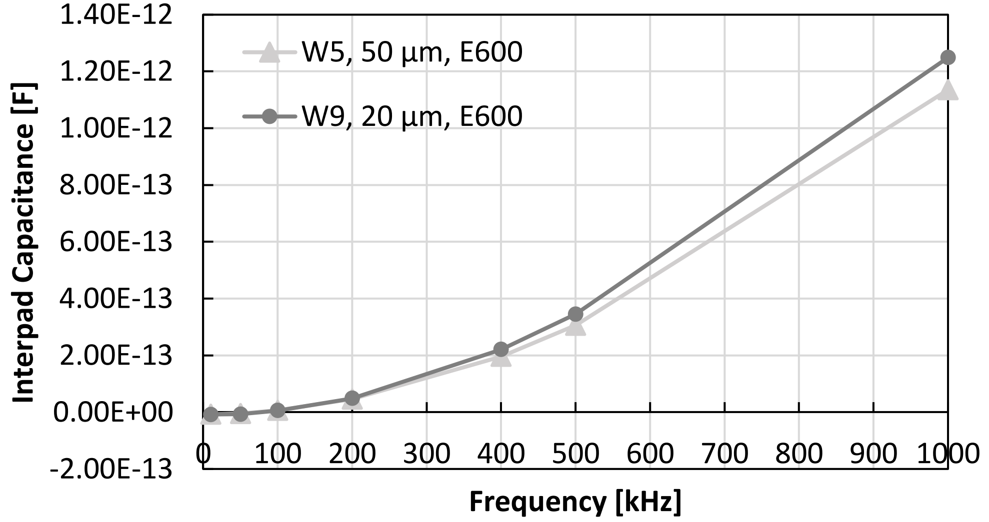
- Depletion visible, frequency dependence before depletion – capacitance component through the bulk?



Interstrip capacitance: thickness

- Interstrip capacitance is ~independent of bulk thickness
  - Supported by measurements on other sensors with same metal size but varying pitch/distance, or by measuring non-neighboring strips – interpad capacitance essentially unchanged
  - Series of dielectric capacitance --- n+ resistance --- dielectric capacitance?

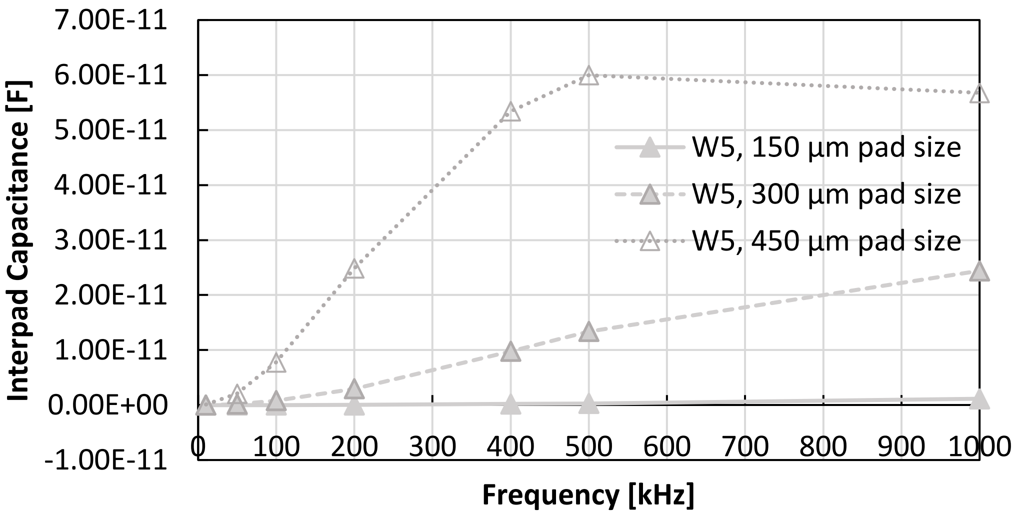




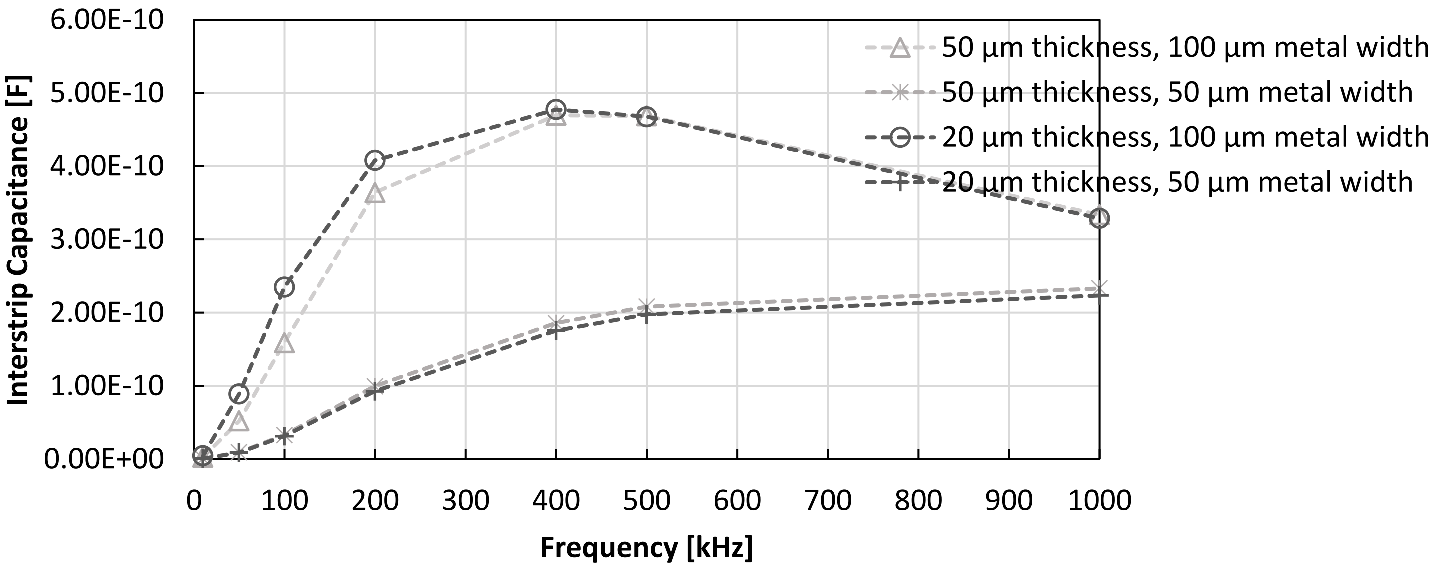
150 μm pad size

Interstrip capacitance: metal

- Interstrip capacitance scales with strip length and metal size



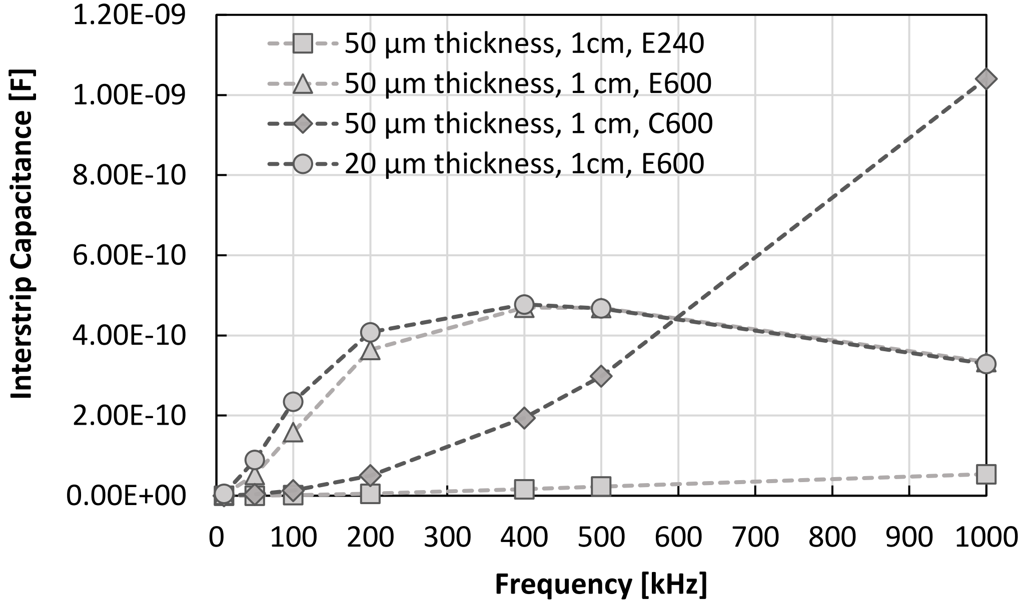
150 µm pad size



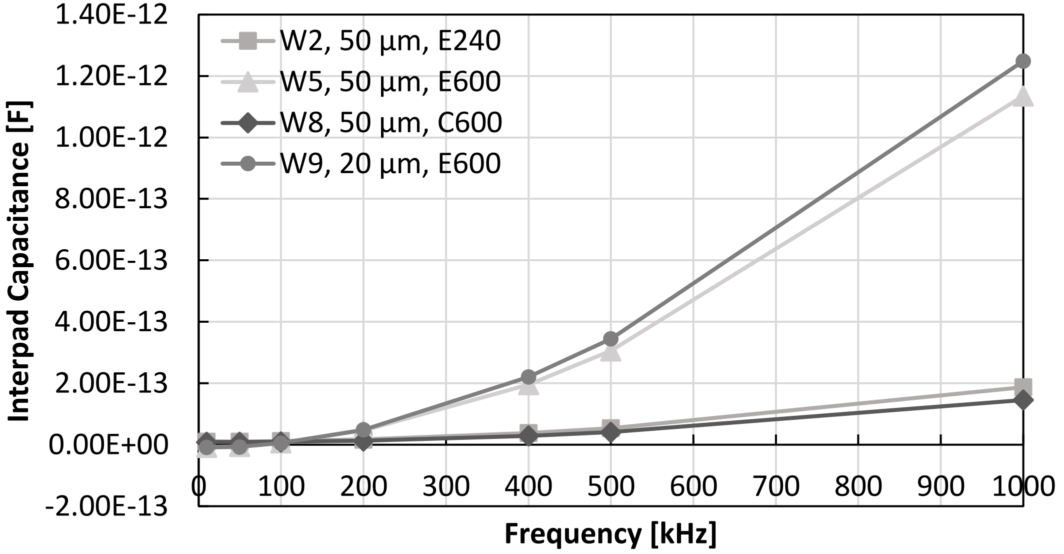
1 cm strip

Interstrip capacitance

- E240 has significantly lower interstrip (and AC) capacitance
- Pads: C600 also with lower capacitance
- Strips: C600 in between others, but increases with frequency

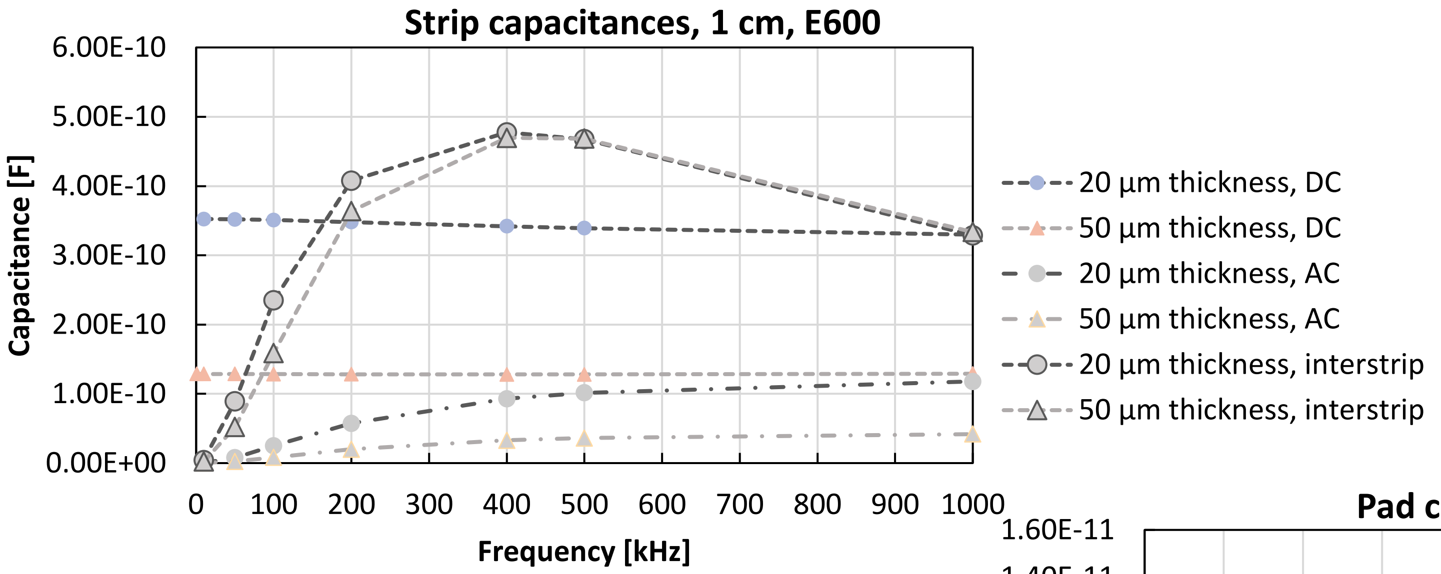


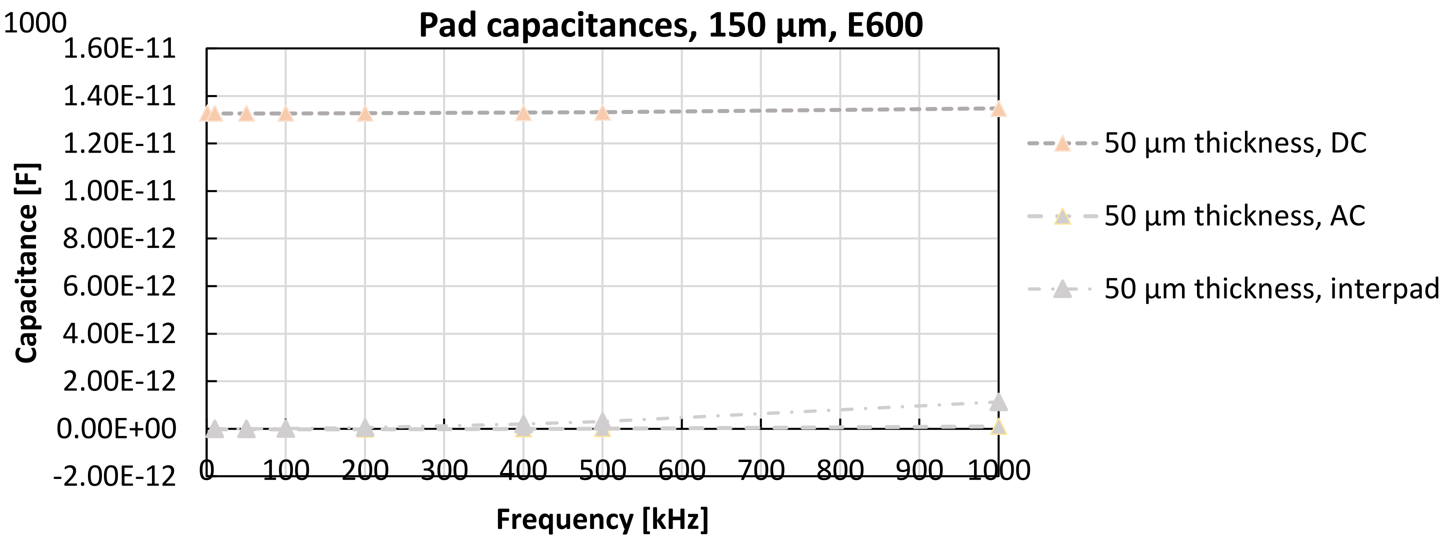
1 cm strip, 100 µm width



150 µm pad size

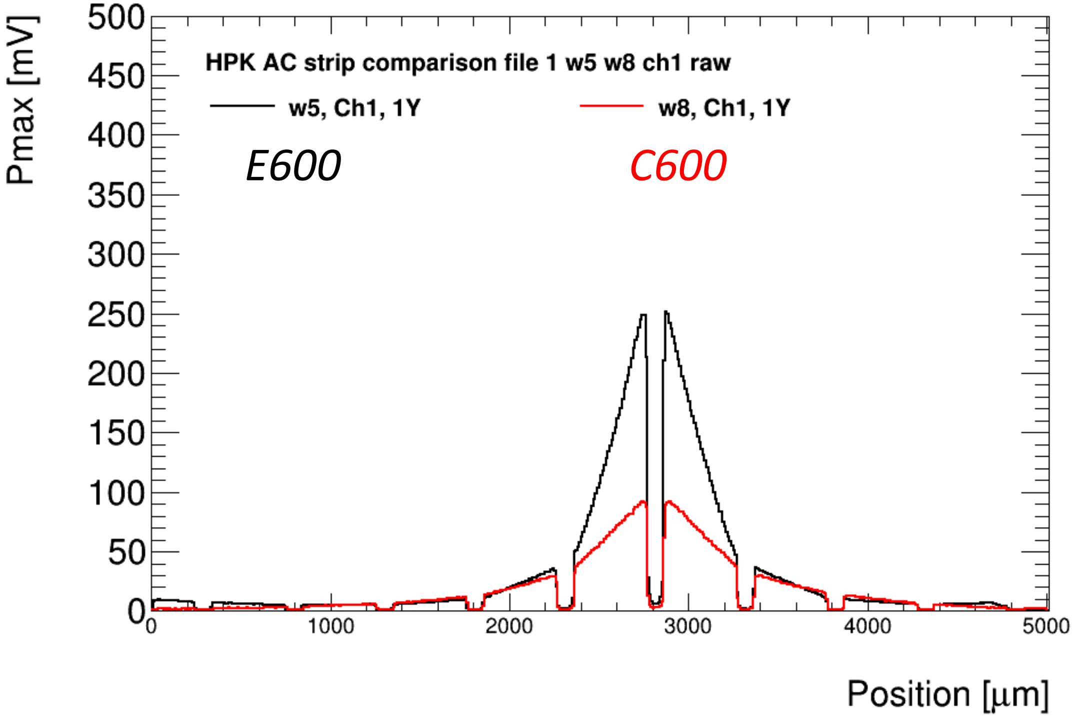
Capacitances, summary

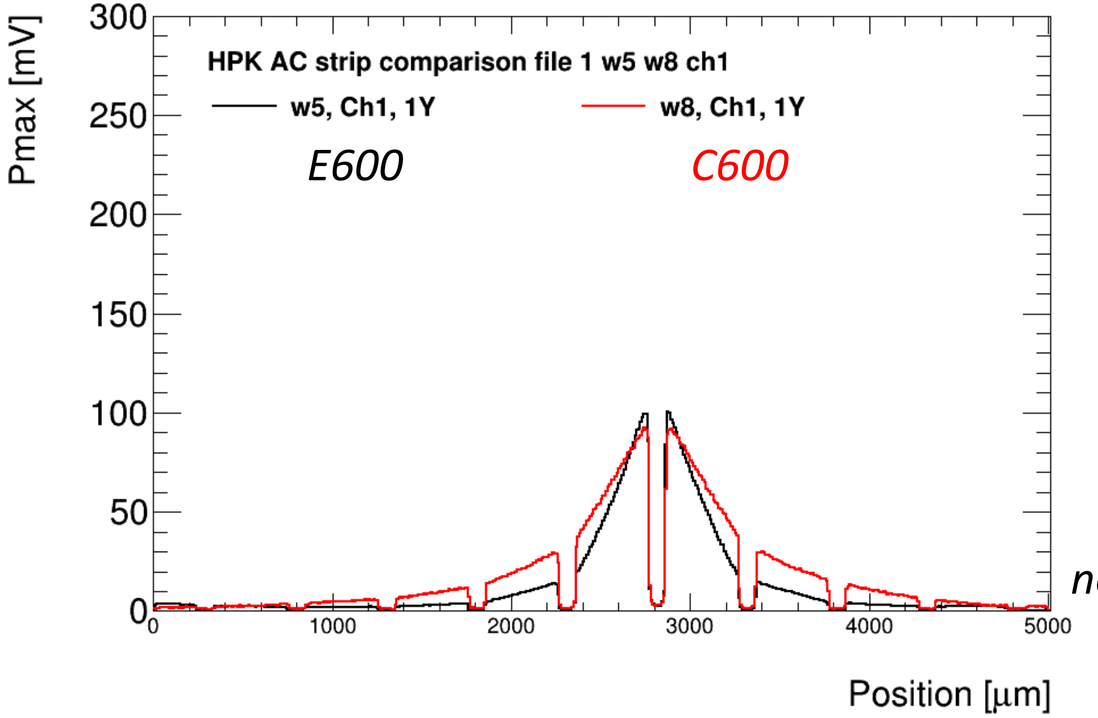




Laser testing: E600 vs C600

- 1 cm strips, 100 μm width, 50 μm
- Smaller signal at main hit: relatively, more sharing to neighboring strips in C600

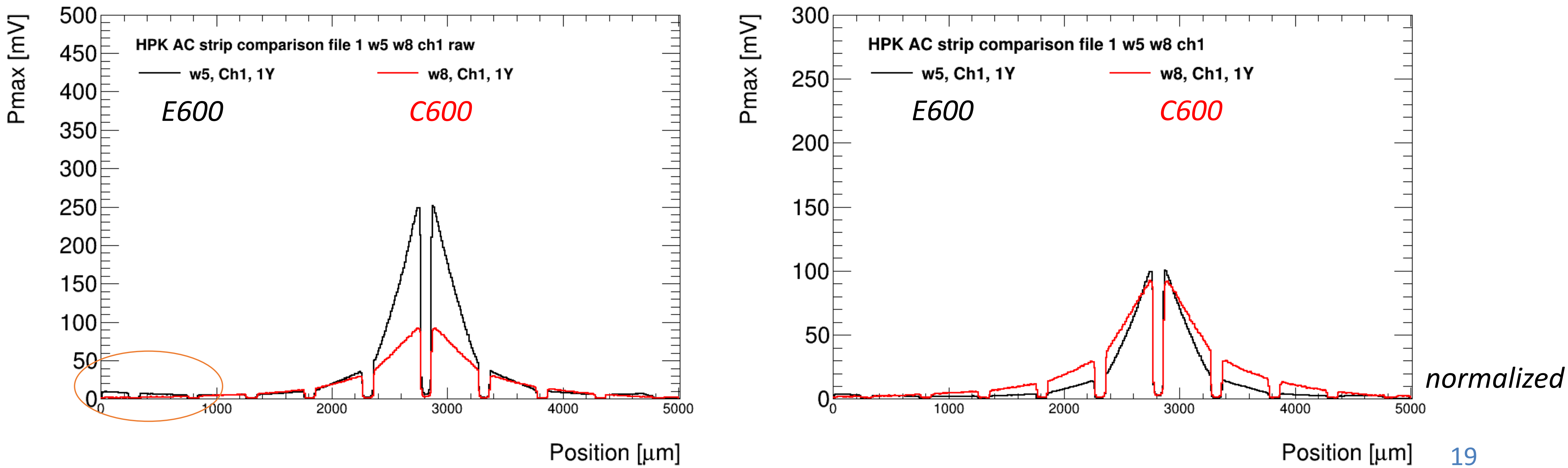




normalized

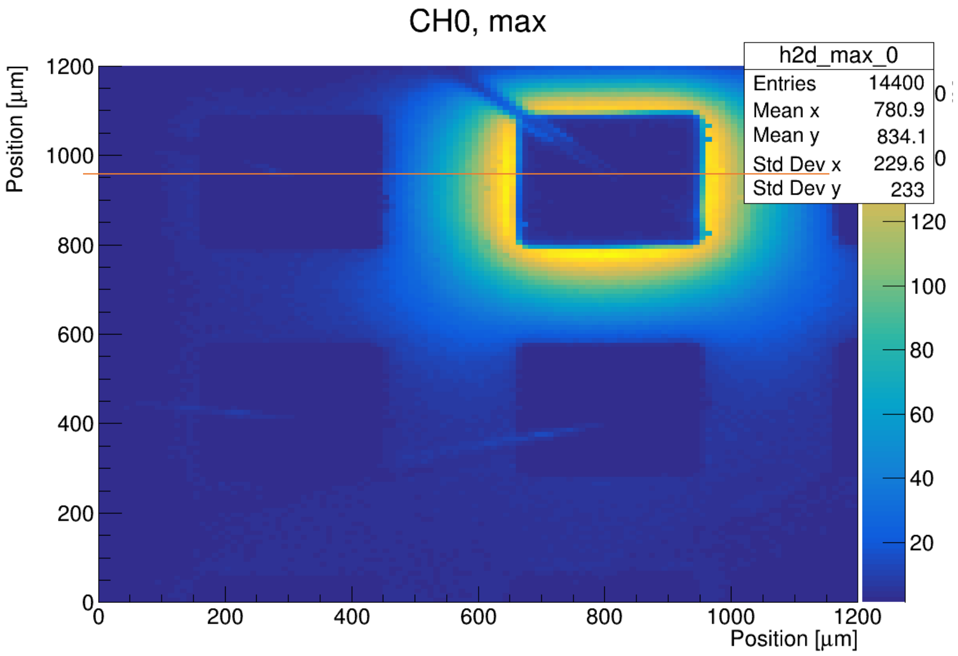
Laser testing: E600 vs C600

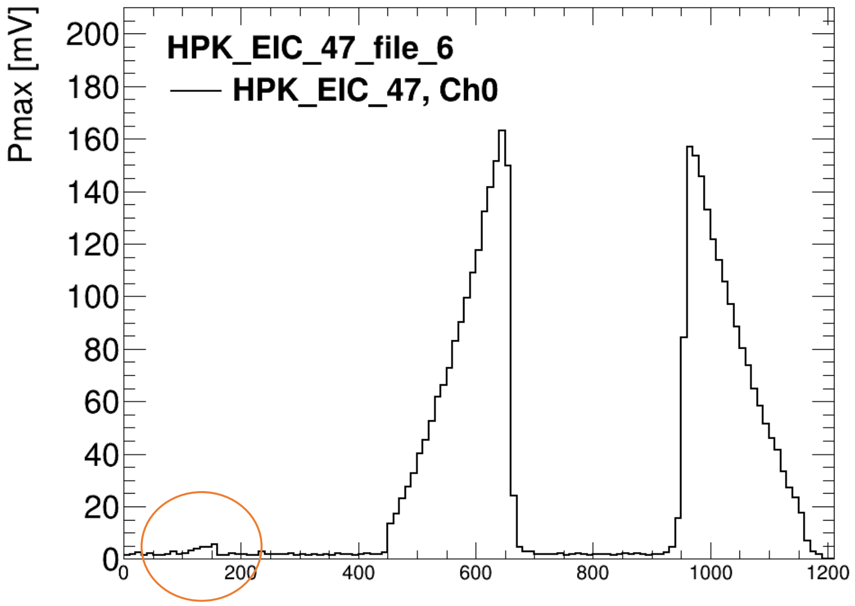
- 1 cm strips, 100 µm width, 50 µm
- Smaller signal at main hit and more sharing to neighboring strips in C600
- Increase at longer distances for E-type: resistivity of the n+ starts to affect sharing



Laser testing: pad

- 300 µm pads, E600, 20 µm (150 µm sample started exhibiting high currents and was not usable)
- Sharing just above background but <5 % beyond next neighbor





Laser testing: pad

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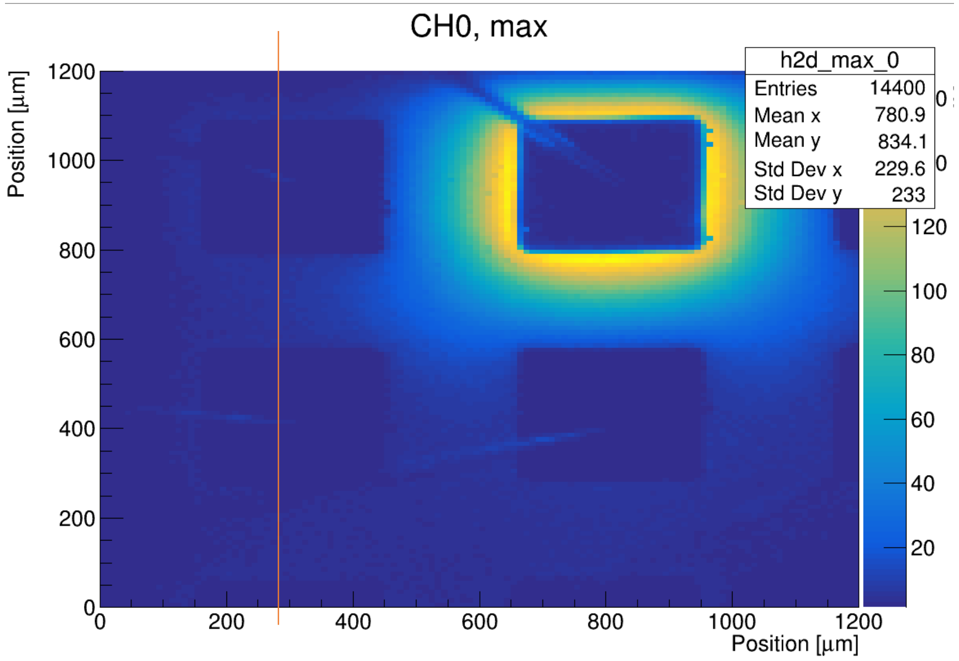

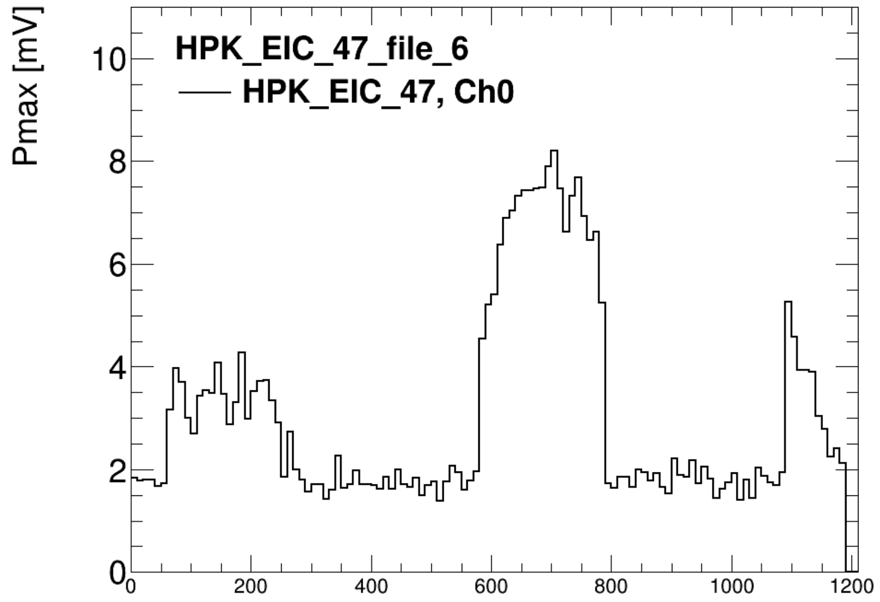

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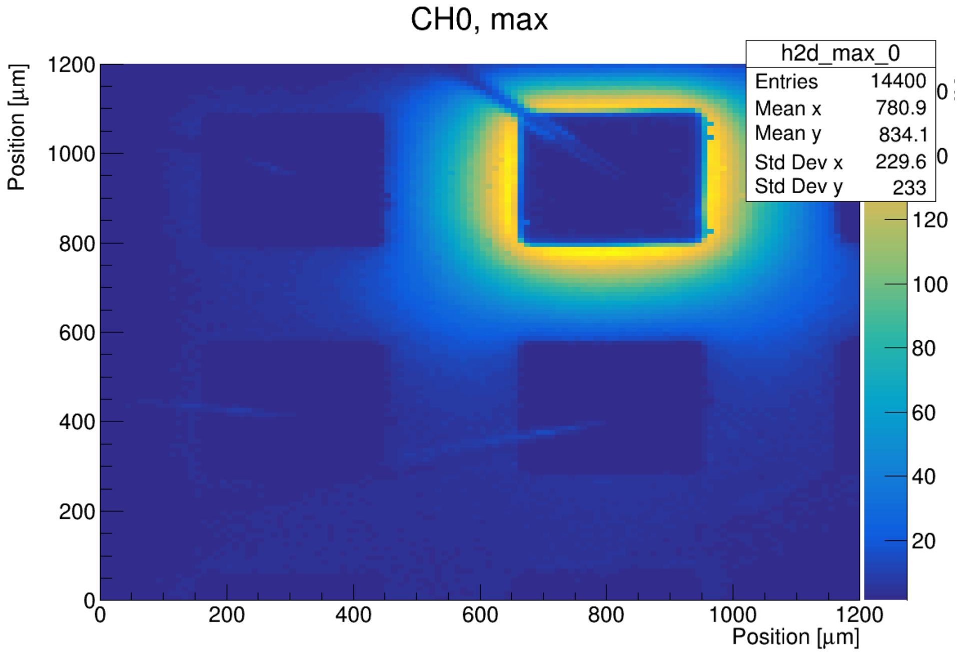
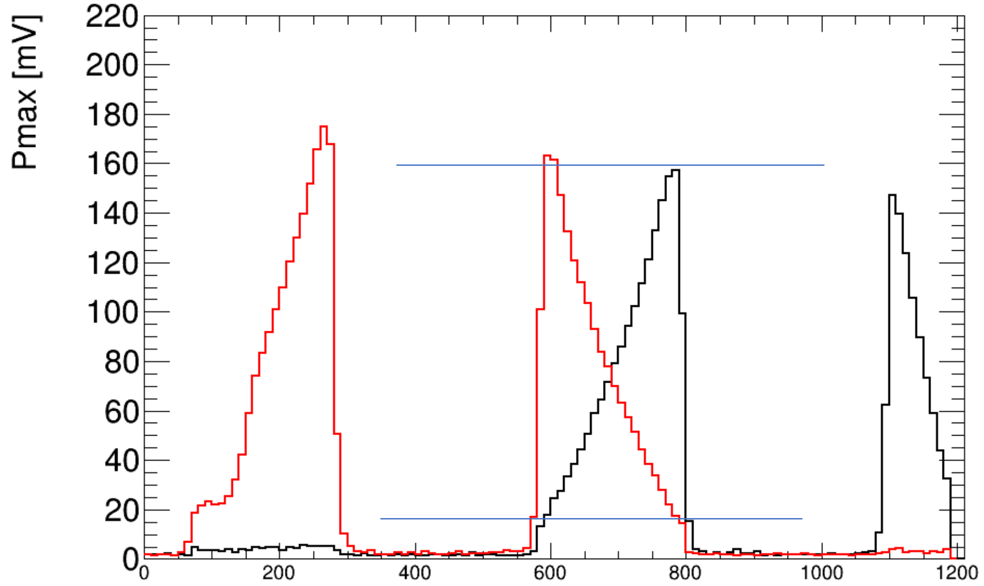
Laser testing: pad

- 300 µm pads, E600, 20 µm (150 µm sample started exhibiting high currents and was not usable)
- Sharing down to ca. 10 % at the metal edge of the next neighbor
  - Good performance for position reconstruction if the pad capacitance is acceptable – if it is reduced to 150 µm, E-type n+ layer may indeed have too little signal sharing for reconstruction





Conclusions

- Pad and strip capacitances are vastly different – impact on chip design / choice!
- Interstrip/interpad capacitance: independent of bulk, depend on metal size
- N+ and dielectric impact interstrip and AC capacitances
- Frequency dependence: perhaps less than BNL sensors, but still difficult to determine what the final value (to be used in electronics design) would be

- Smaller signal near main hit for C600 and same (relatively, more) sharing to neighbors – for strips, E600 more promising
  - Far away: signal increases again for E600 = more resistive n layer –> this will be more pronounced for very large sensors when n+ contact may be cm's away!
  - ➢ important to fabricate close-to-full size sensor prototype!
- Pads: 500-300 good in E600, for smaller pads sharing might be too small

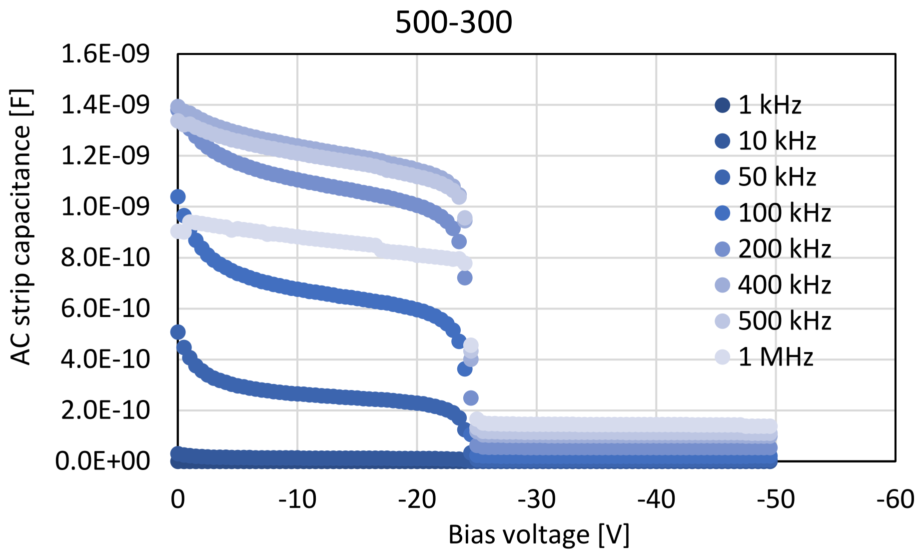
Next steps

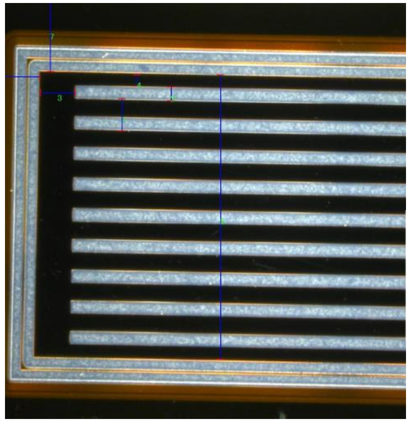
- Dielectric capacitance cross-checks
- Interstrip/interpad resistances
- Grounding of neighbors: different effect depending on n+ resistivity?
- Interstrip measurement between central strip and left+right neighbor (instead of just between two adjacent strips)
- Full comparison (using 50 µm wide strips) of length, 20/50µm, C/E and 240/600 in C-V and laser
- Direct comparison of sensors before/after LANL irradiation: ~Q4/23 – Q1/24, depending on release of samples

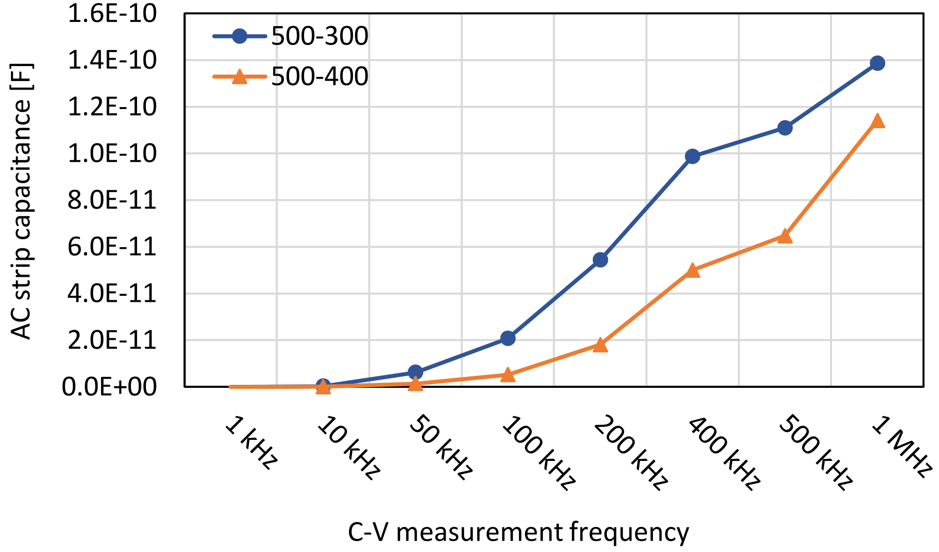
Earlier: Results on BNL strip AC-LGADs

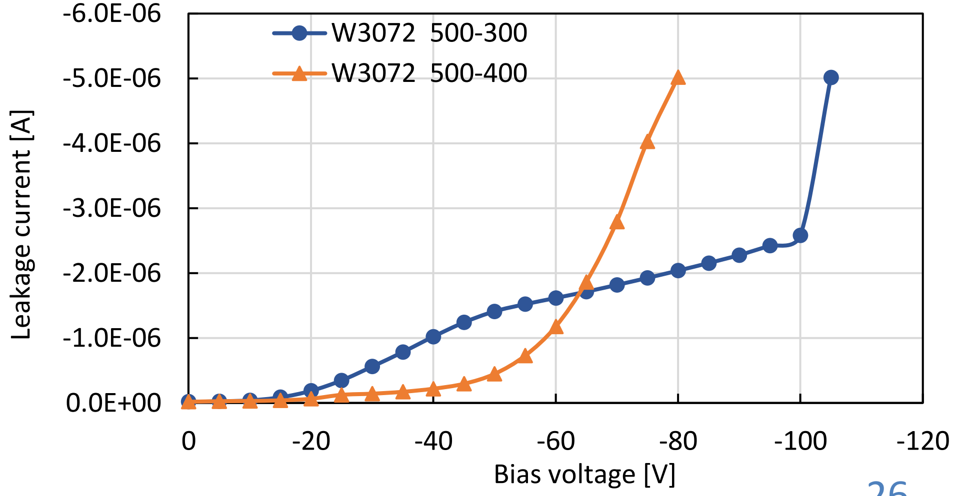
- **Measured at room temperature**
- **Other strips and guard ring floating**
- **In AC and interpad capacitance measurements, n^+ layer goes to ground**

Newer BNL strips: 1 cm, 500 µm pitch, 300 or 400 µm gap









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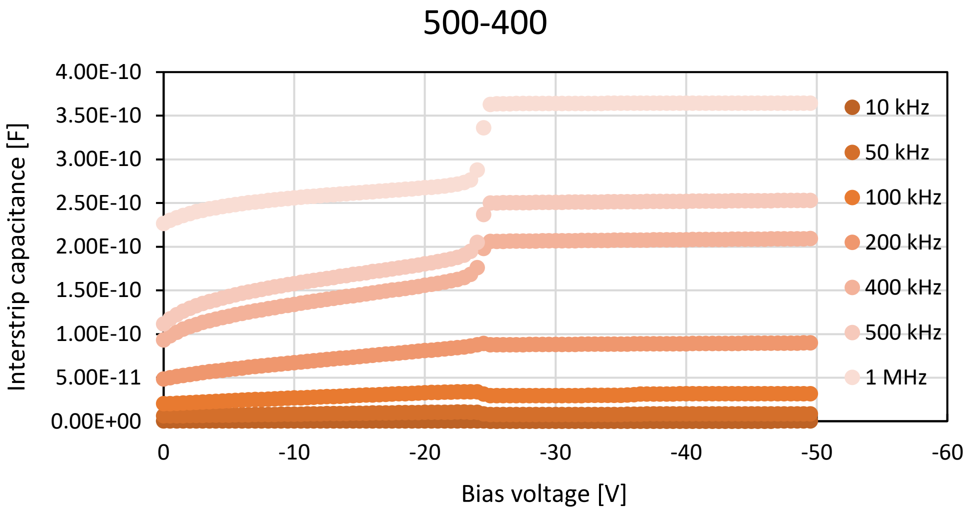

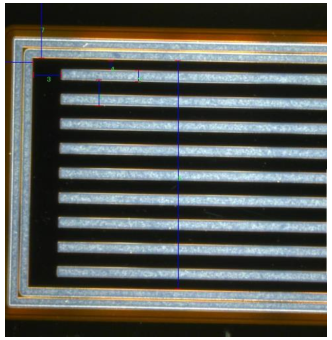

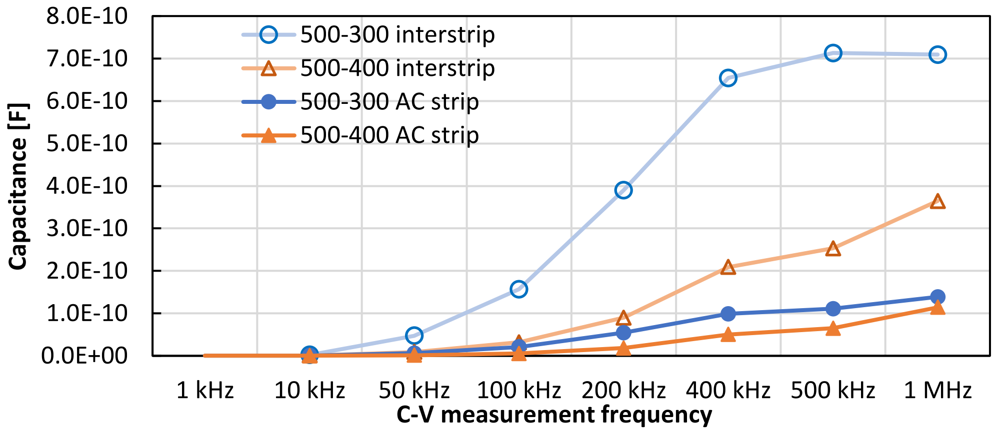

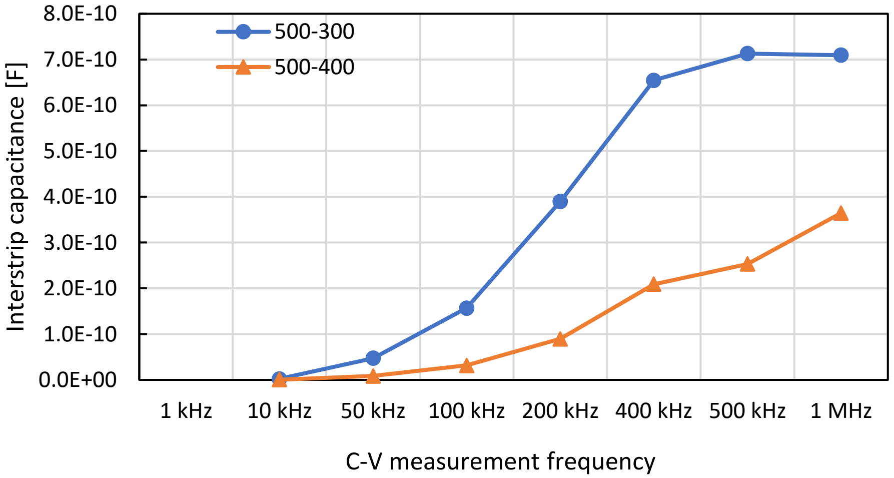

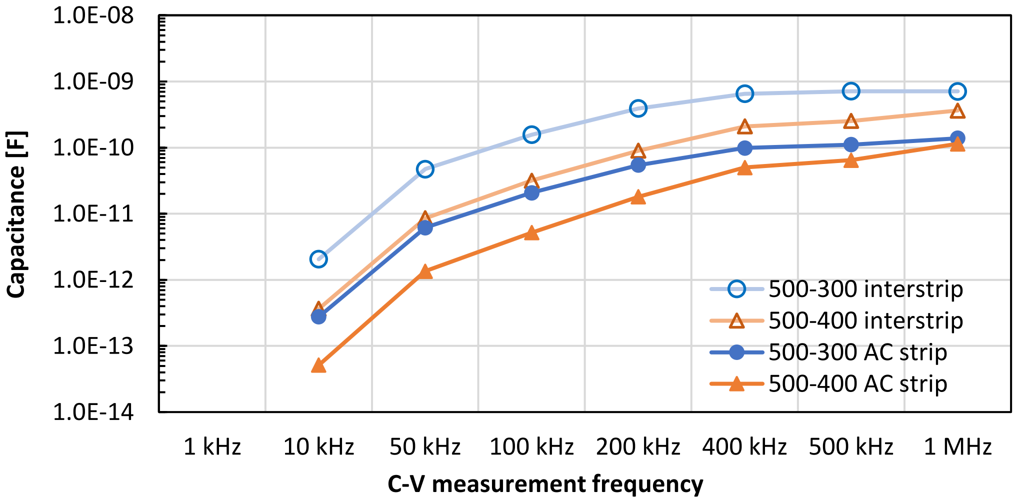

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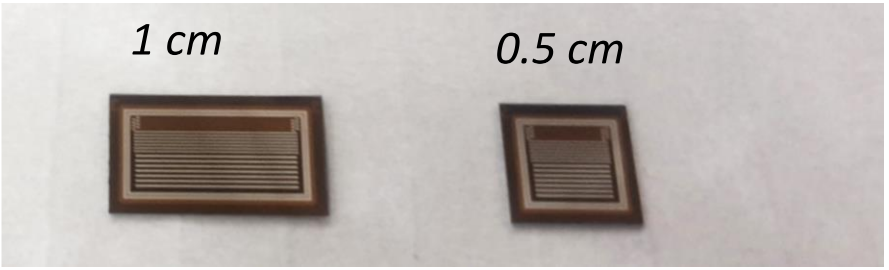
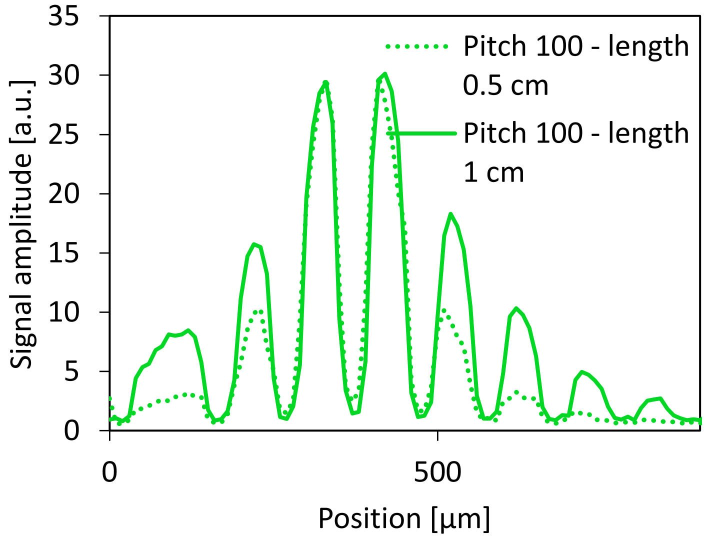
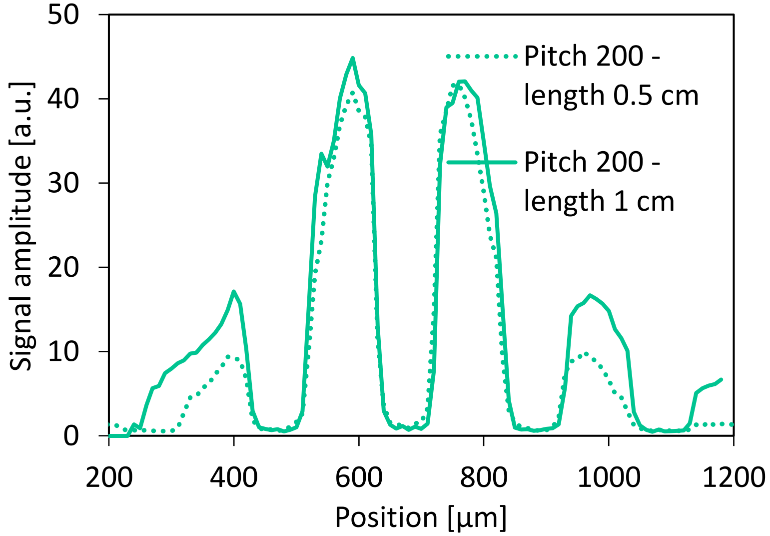
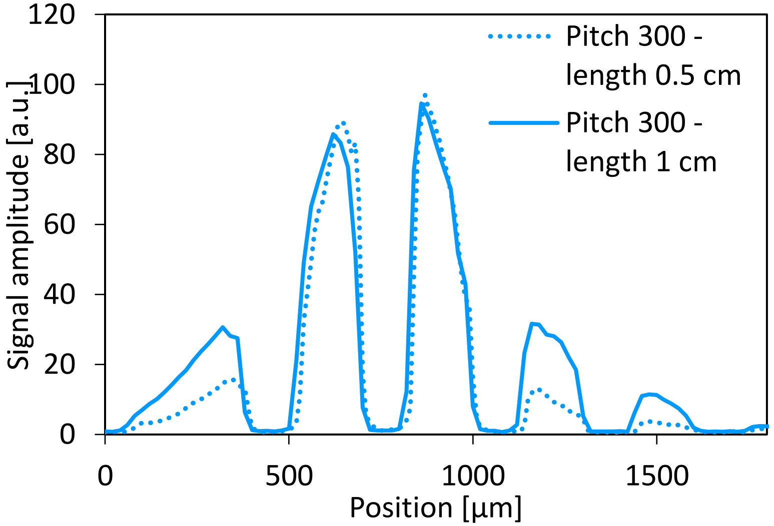
BNL multipitch strips

- More charge sharing in longer strips observed in laser (laser data from BNL earlier production W1)



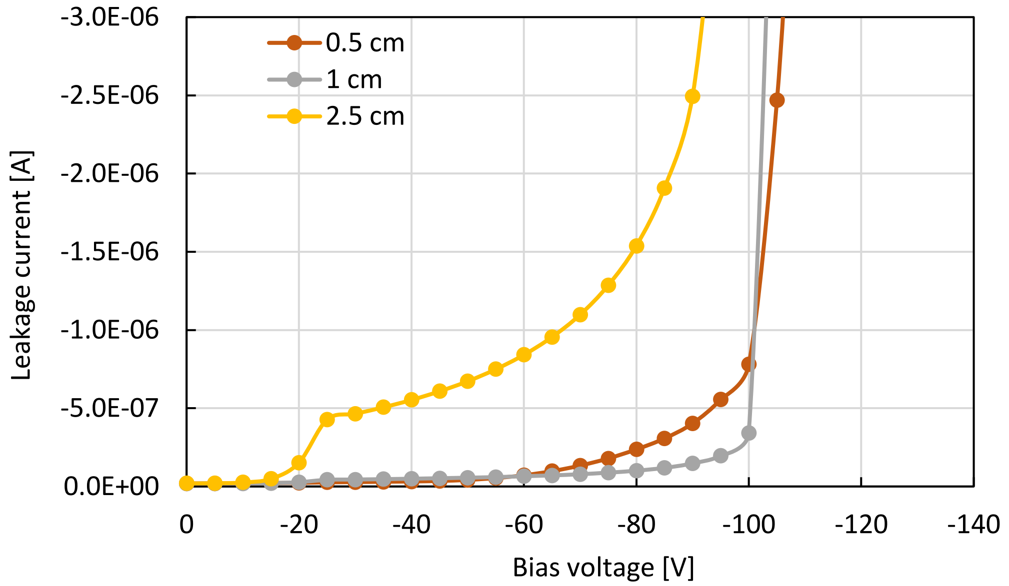


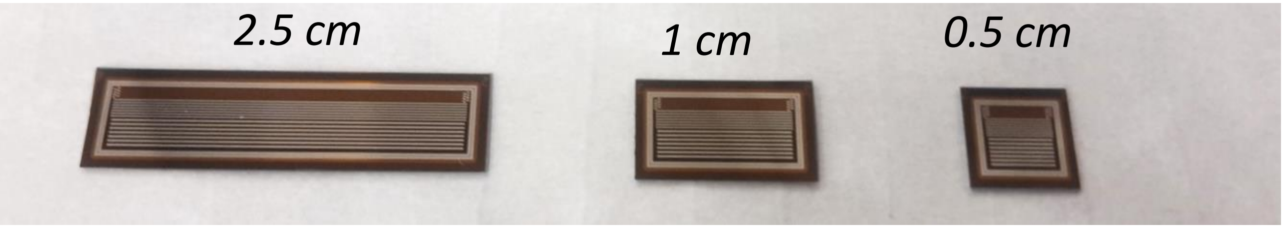


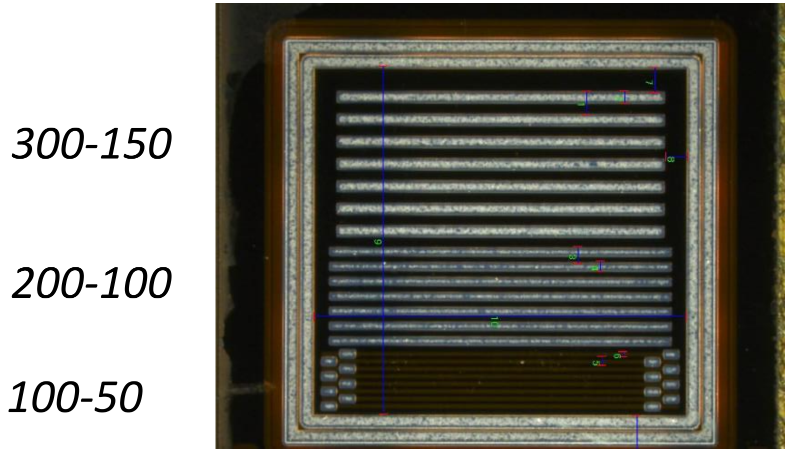


Newer BNL multipitch strips

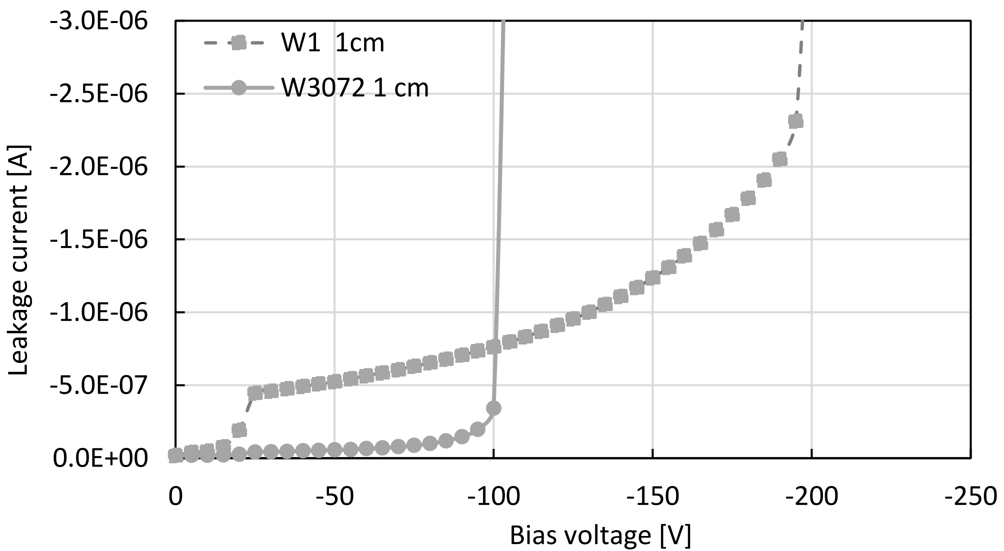
- I-V for different strip lengths







- I-V for newest and older multipitch sensor



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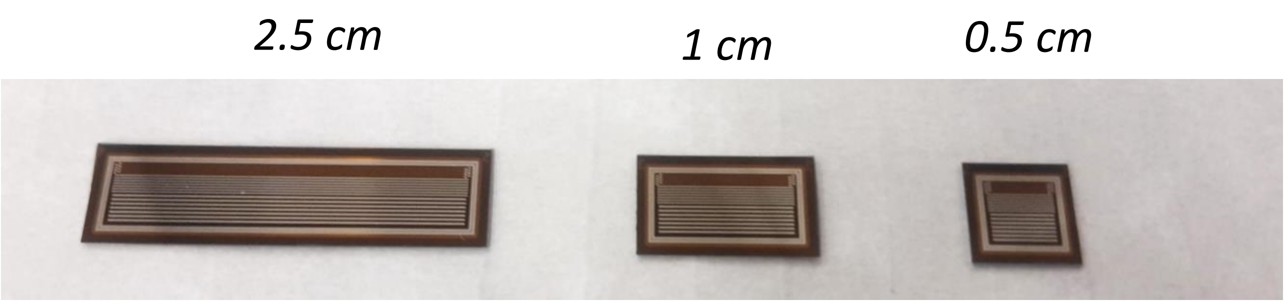
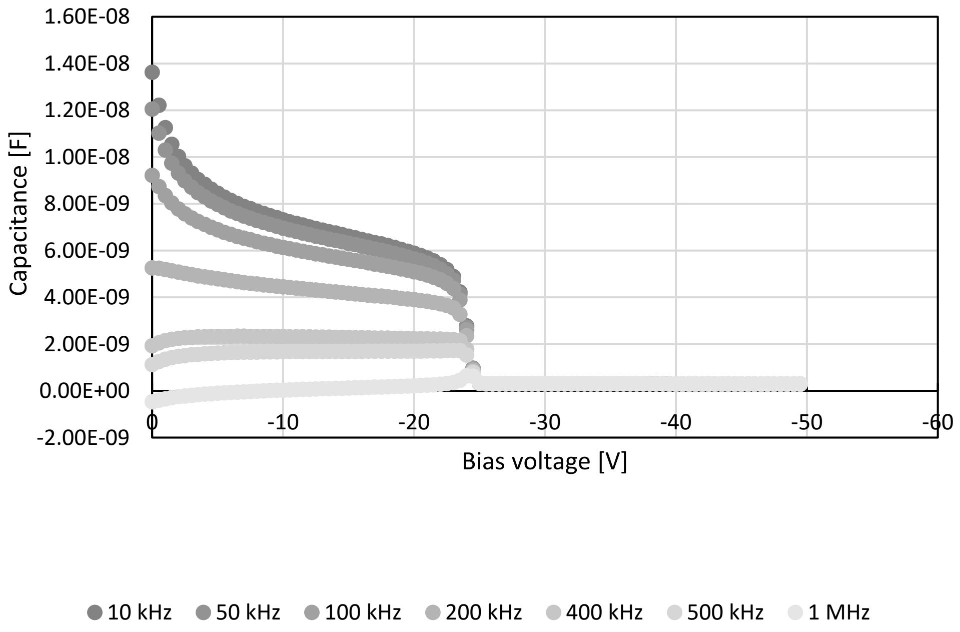
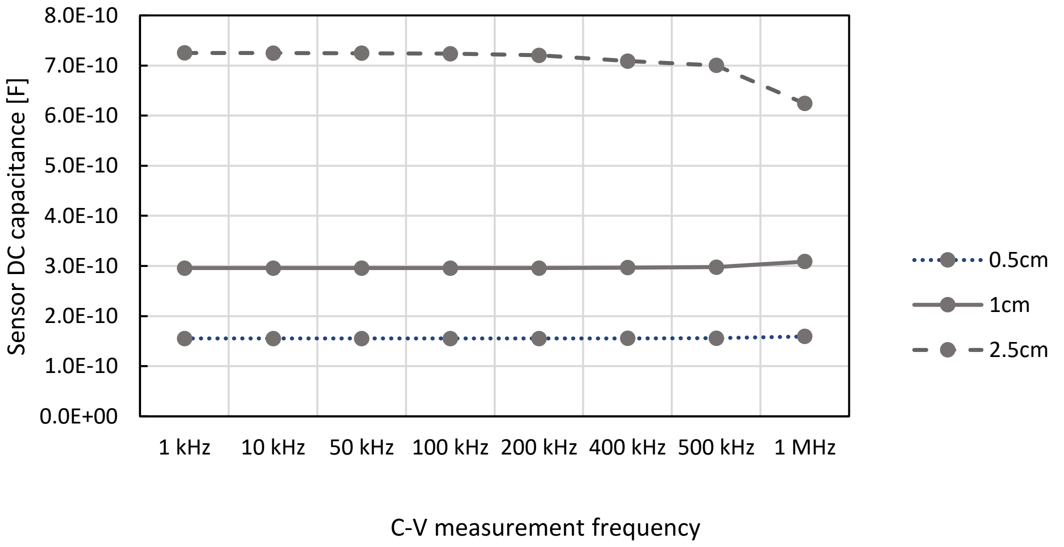
Newer BNL multipitch strips: sensor capacitance



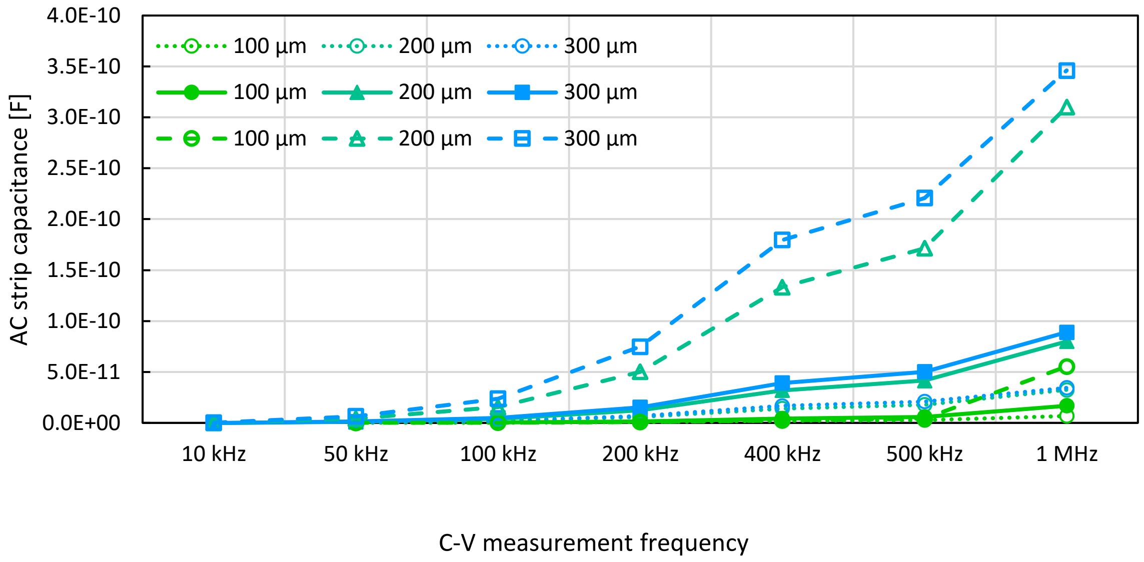


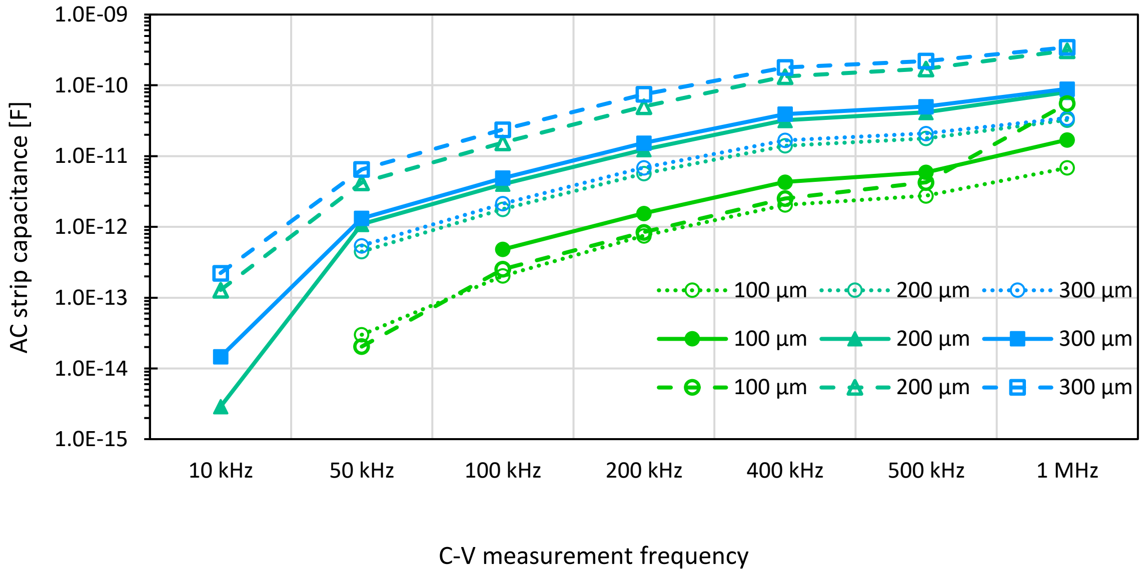


BNL multipitch strip capacitance

Dotted line: 0.5 cm
Solid line: 1 cm
Dashed line: 2.5 cm

- Higher strip capacitance for:
  - Wider metal
  - Longer strips
- Higher capacitance at high frequency: unusual
  - Compared to DC capacitance of the full sensors

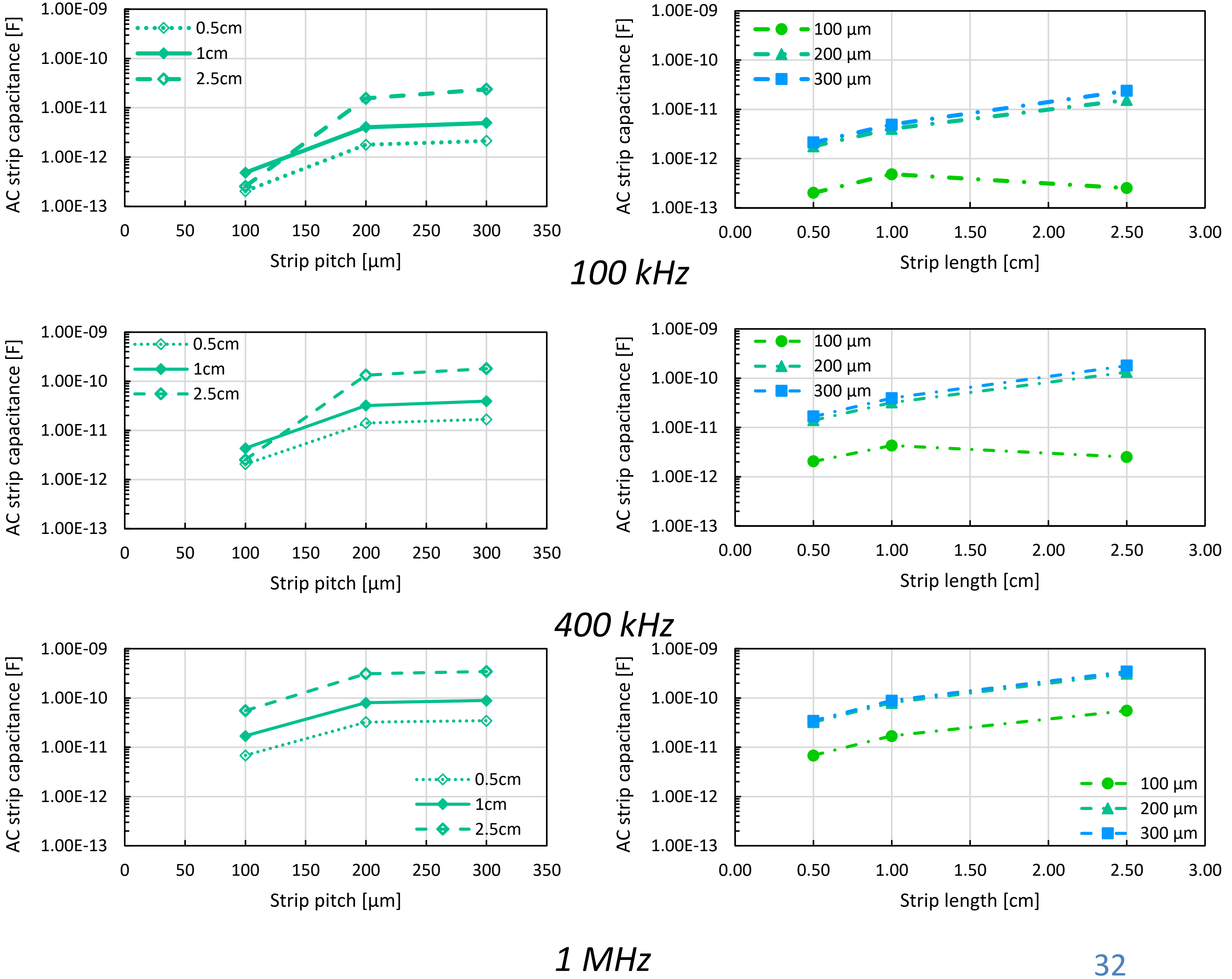




J. Ott et al, AC-LGAD capacitances

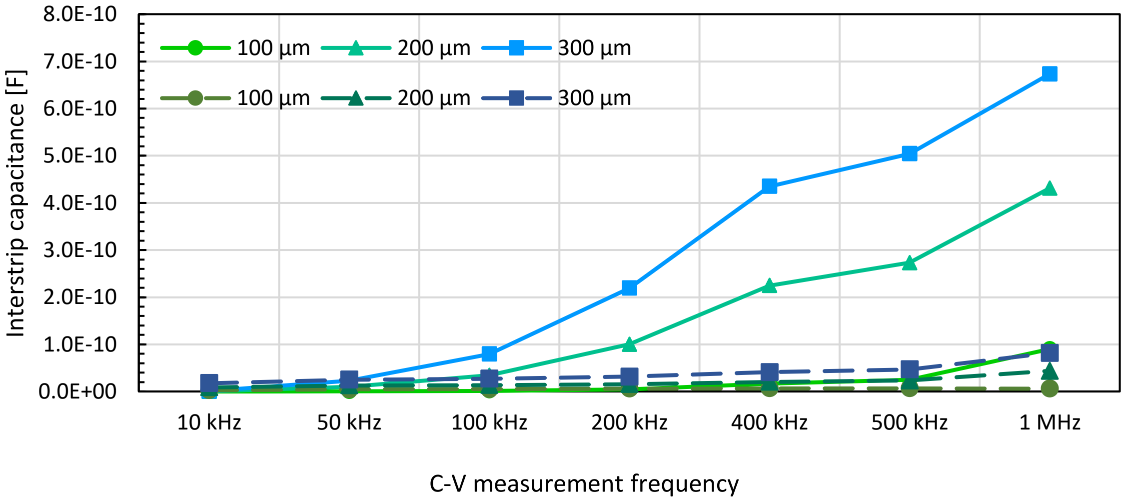
BNL new(est) production: strip length and pitch

- Strip pitch could also be swapped to strip width

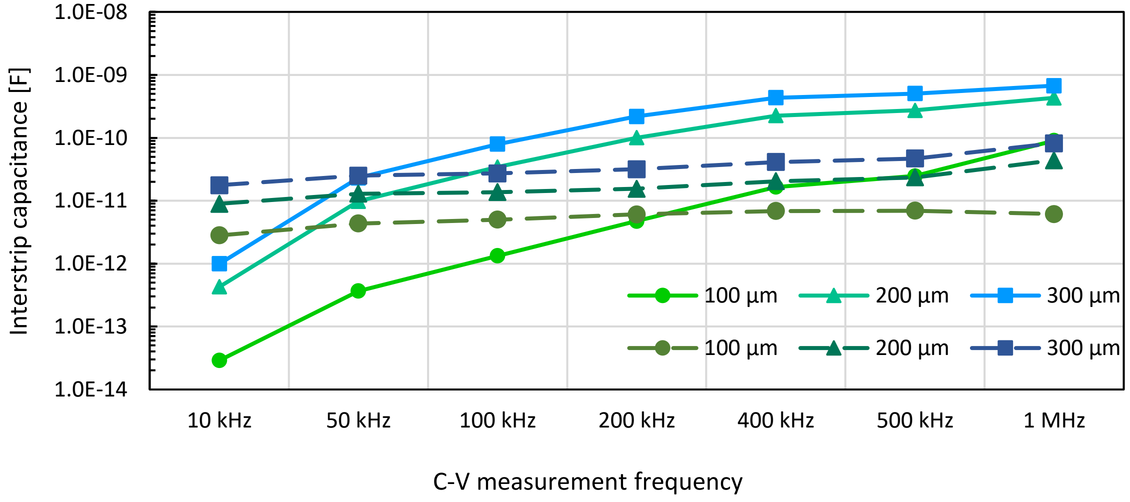


BNL multipitch interstrip capacitance

- Less frequency dependency in older production with identical metal geometry
  - Impact of production
  - Gain layer
  - n^+ doping
  - Bulk



*Light colors: W3072 (newest, **20 µm**!), dark colors: W1 (2021 or early 2022, **50 µm**!)*

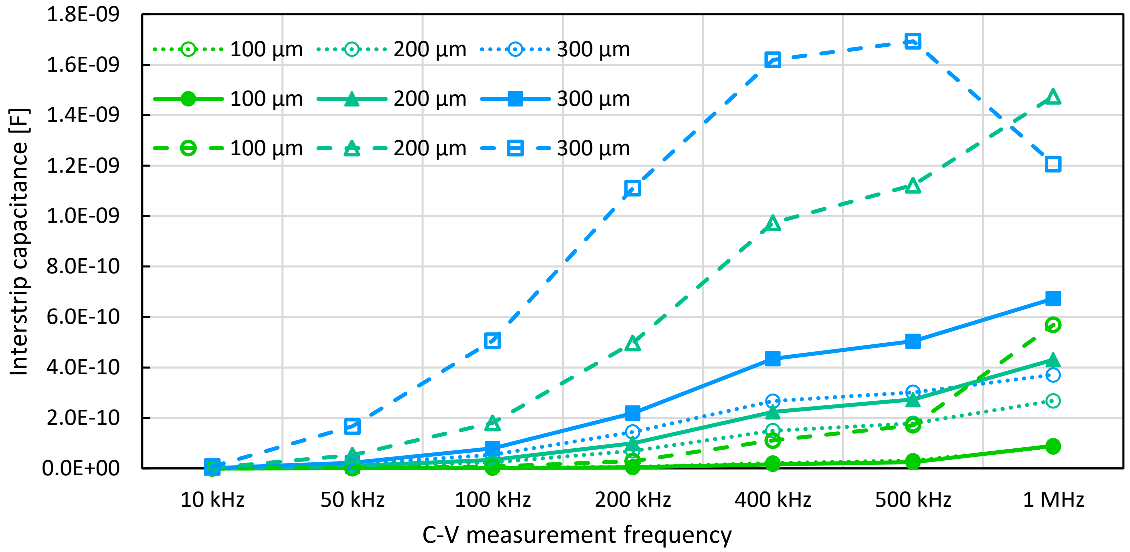


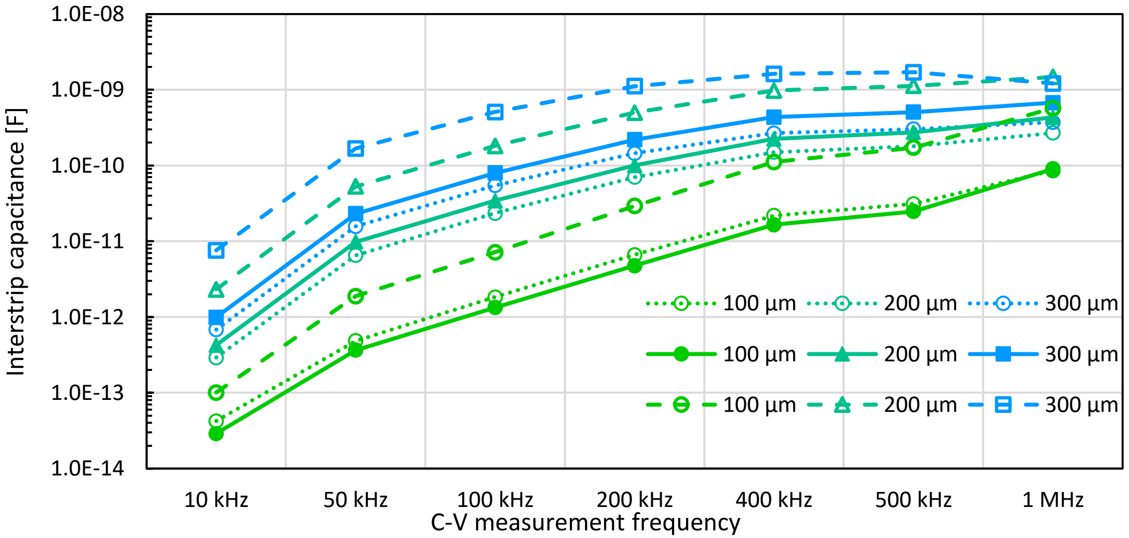
J. Ott et al, AC-LGAD capacitances

BNL new(est) production: strip length

Dotted line: 0.5 cm
Solid line: 1 cm
Dashed line: 2.5 cm

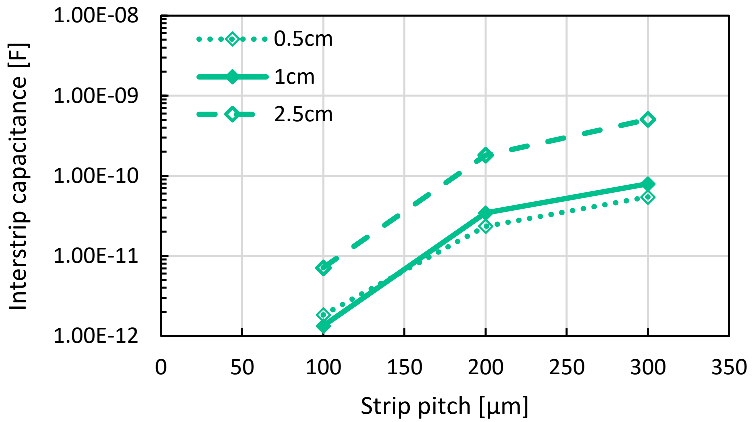
- Higher interpad capacitance for:
  - Larger pitch = wider metal
  - Longer strips

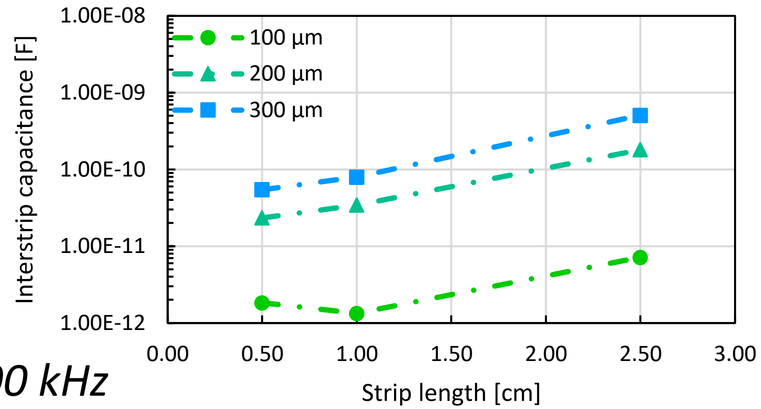




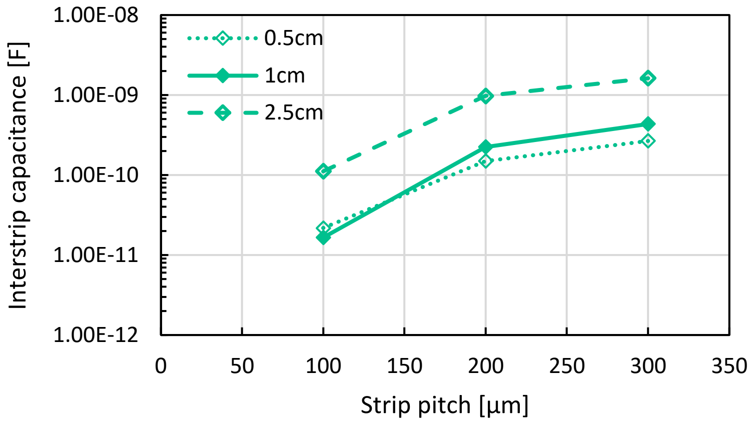
BNL new(est) production: strip length and pitch

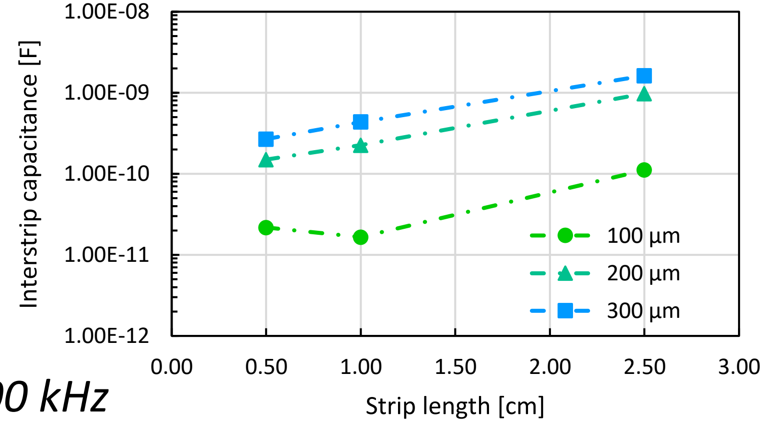
- Strip pitch could also be swapped to strip width



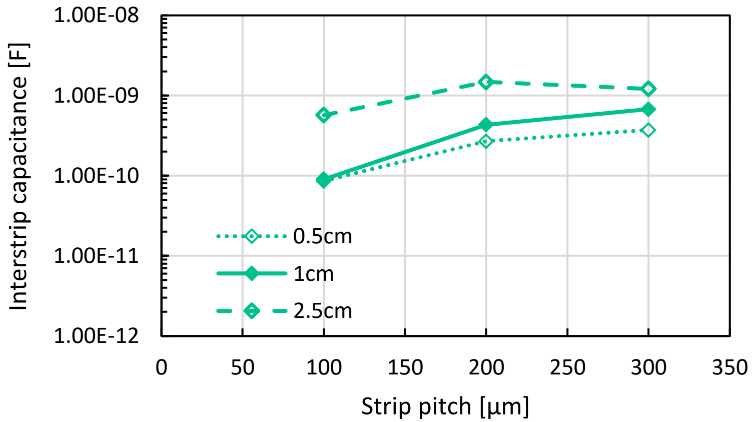


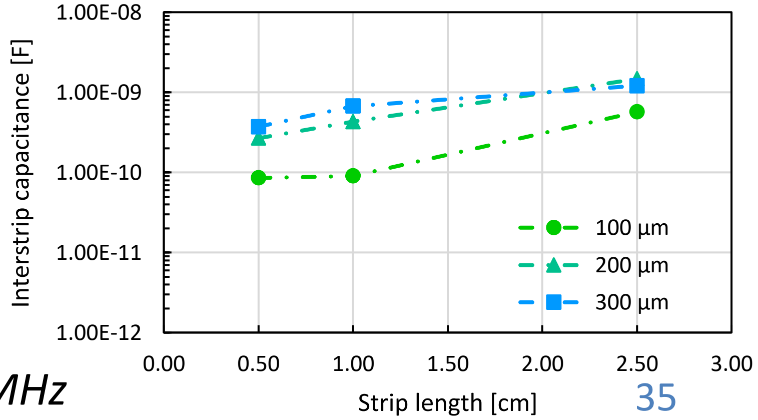
100 kHz





400 kHz

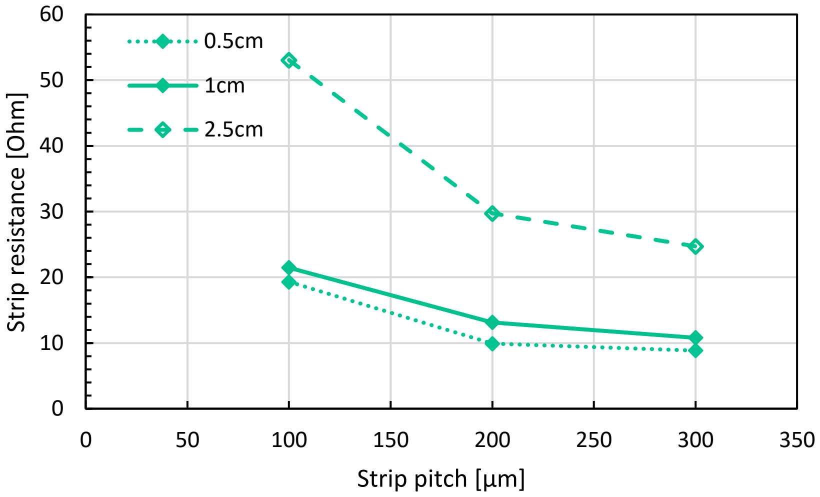


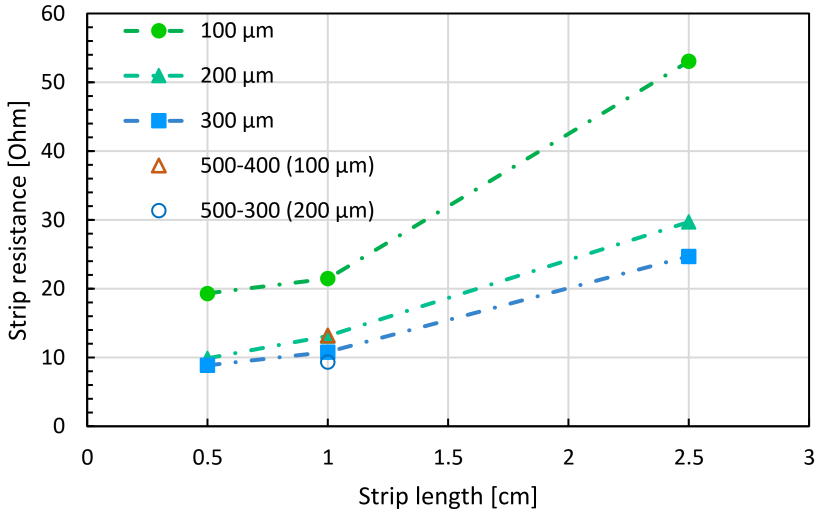


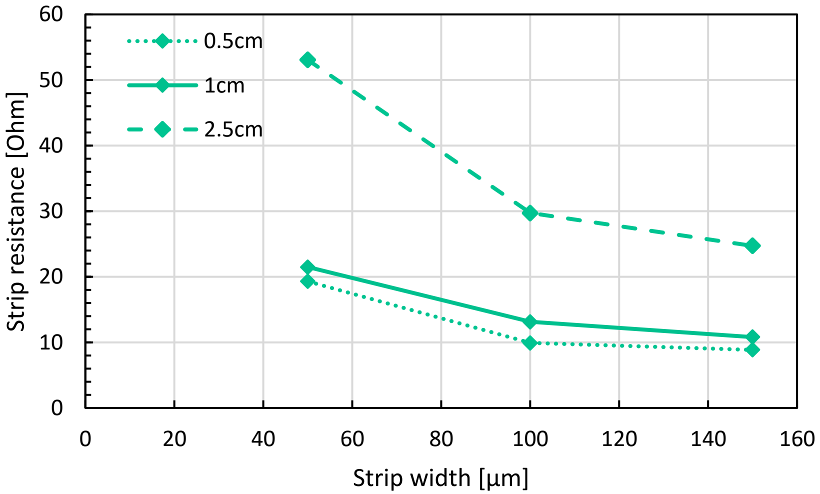
1 MHz

BNL new(est) production: strip resistance

- Higher resistance for:
  - Narrower strip
  - Longer strip
- Not linearly proportional



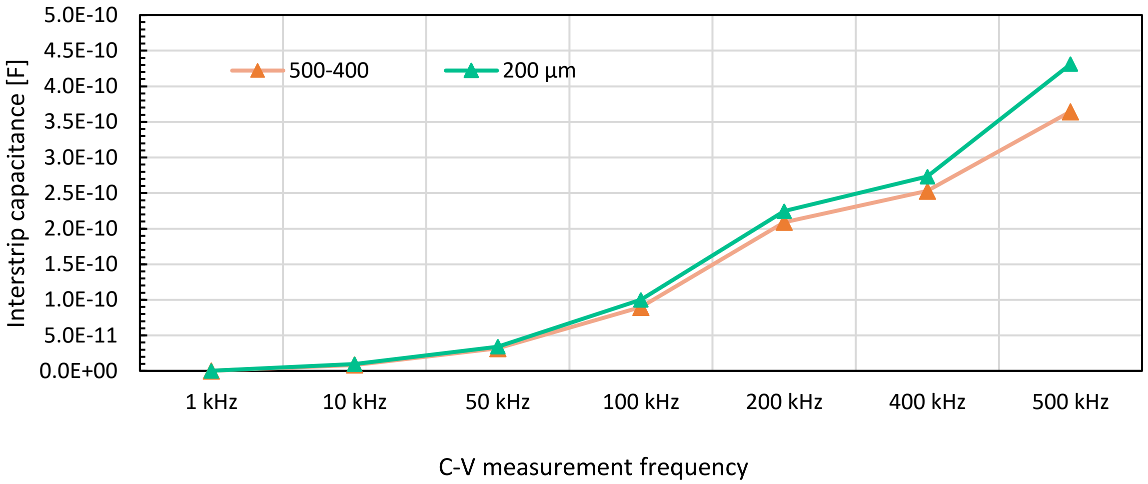




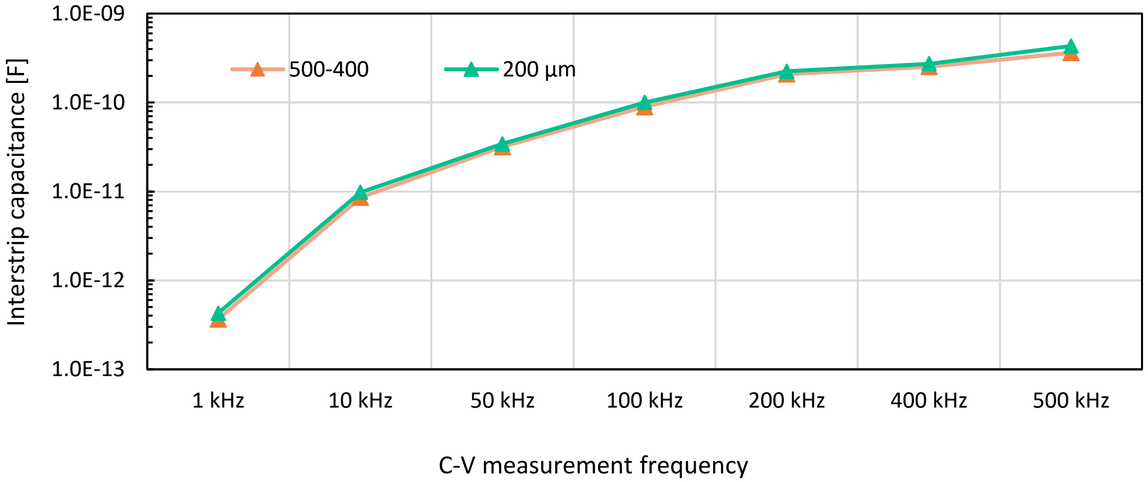
J. Ott et al, AC-LGAD capacitances

BNL new(est) production: strip pitch and gap

- 100 µm strip metal width, but 500 vs 200 µm pitch and 400 vs 100 µm gap
- Smaller interstrip capacitance for wider pitch and gap, but effect small compared to strip length and width
- Supports theory that interstrip capacitance is governed by the strip area and the sensor (bulk, backplane, and/or n$^+$), not the physical distance between strips



1 cm length, 100 µm strip metal width



Newer BNL strips

- Multipitch sensors, IV
  - Relatively low breakdown voltage for some samples; lower leakage current levels than W1, but lower breakdown voltage
  - Higher current for larger sensors
- 500 µm strips, 300 / 400 µm gaps
  - AC capacitance is lower for 100 µm metal: expected

➢ **Interstrip capacitances are higher than AC strip capacitances; depend on strip length and pitch/width**

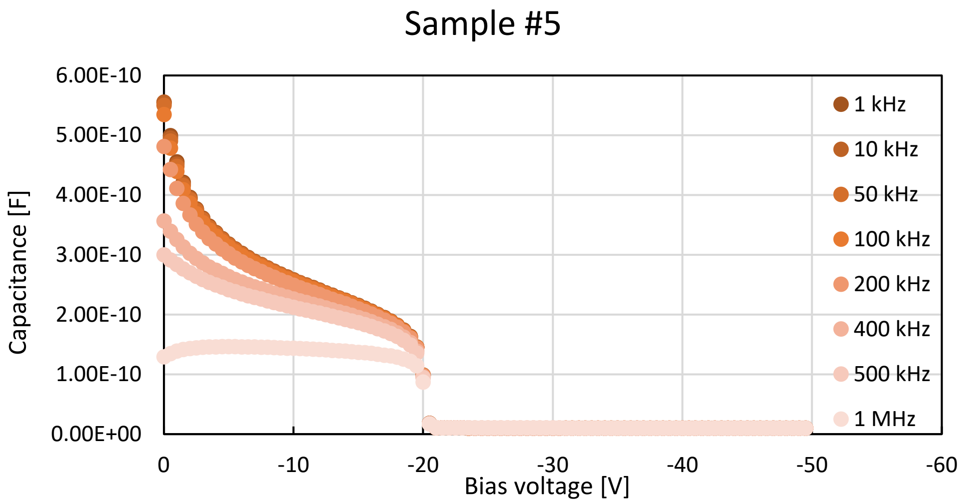
➢ **Strong dependency of AC and interstrip capacitance on frequency even after full depletion – unusual compared sensors from other vendors!** Not in line with physical mobility of charge carriers in bulk, which is observed more regularly in the DC configuration

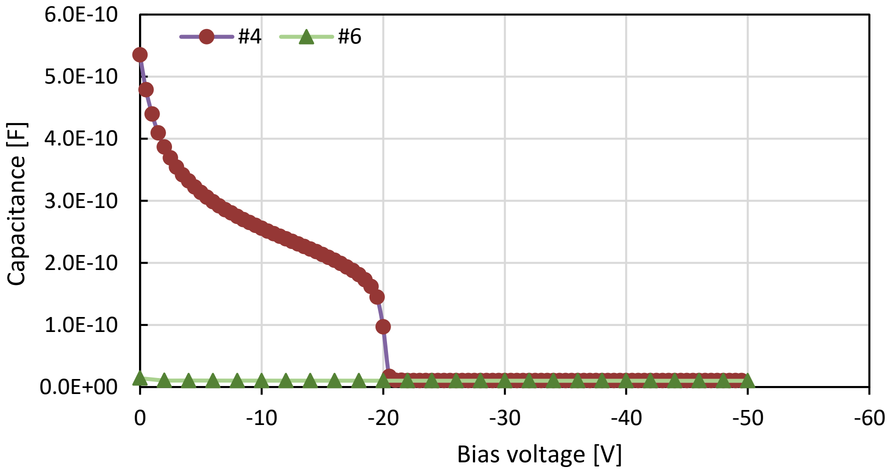
➢ **Impact of pitch and distance on interpad capacitance actually appears to be quite small – strip width and length more important**

- W.I.P. on more variations with even narrower strips, and also bulk thickness (20 vs 50 µm)

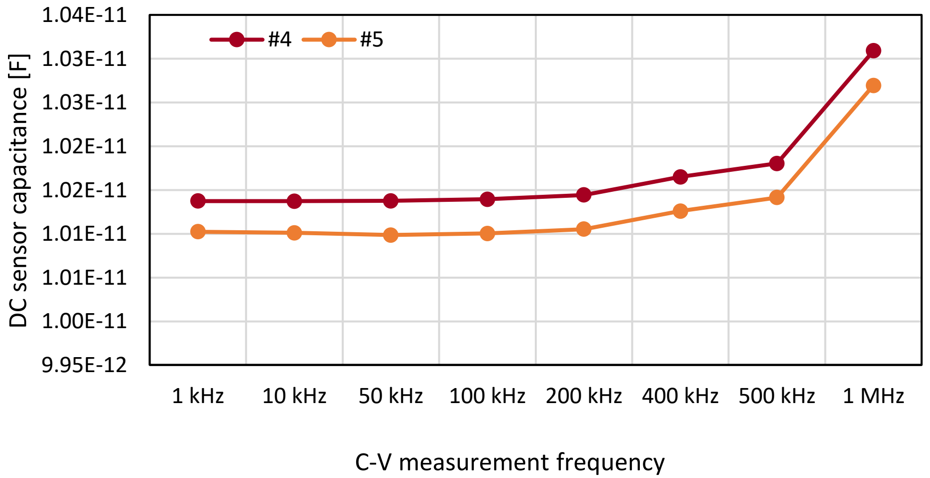
20 µm DC-LGADs

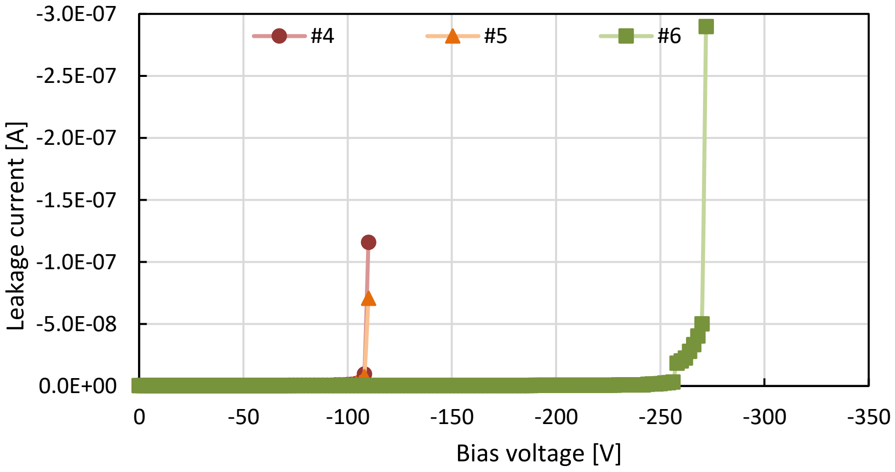
- Final capacitance for 1 mm pad: ca. 10 pF, compared to 4 pF for 50 µm





#6 is a PiN :)



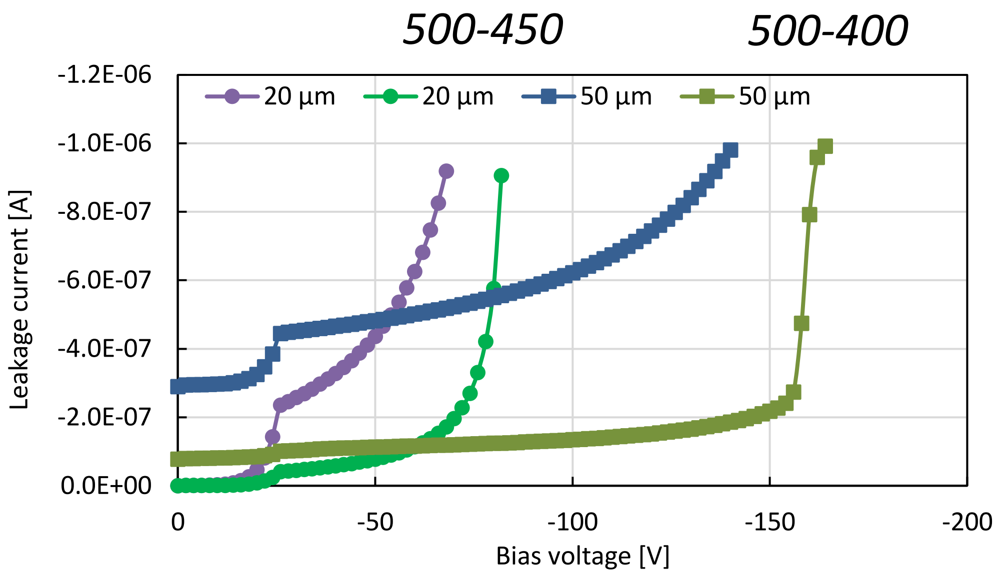


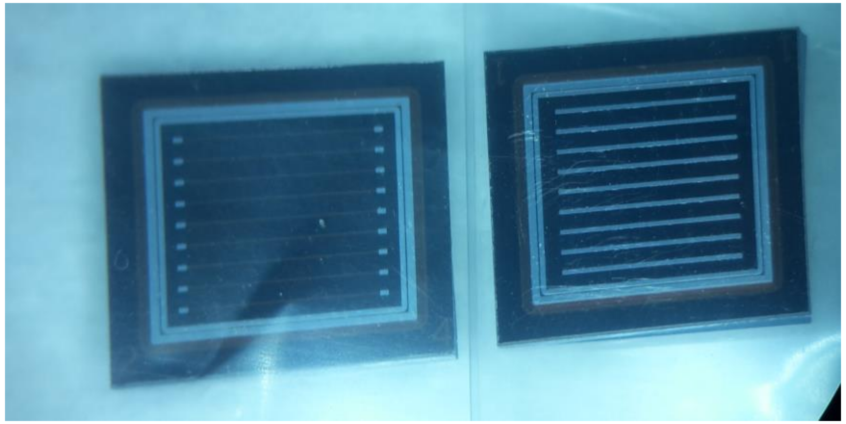
J. Ott et al, AC-LGAD capacitances

20 µm and 50 µm AC-LGADs

- Strips with 500 µm width and 100 / 50 (?) µm metal width (500-400, 500-450)
- 0.5 cm length
- On 20 µm and 50 µm wafers

- *C-V measurements to come…*

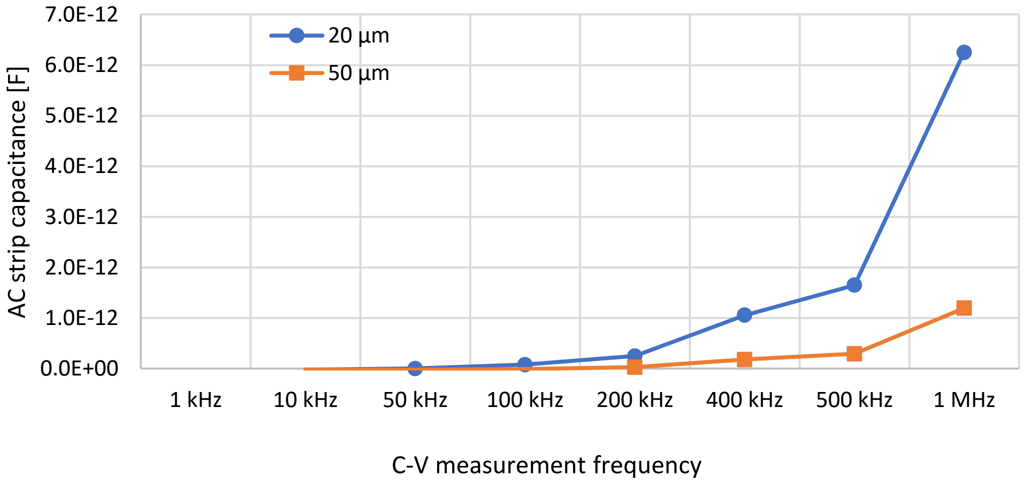


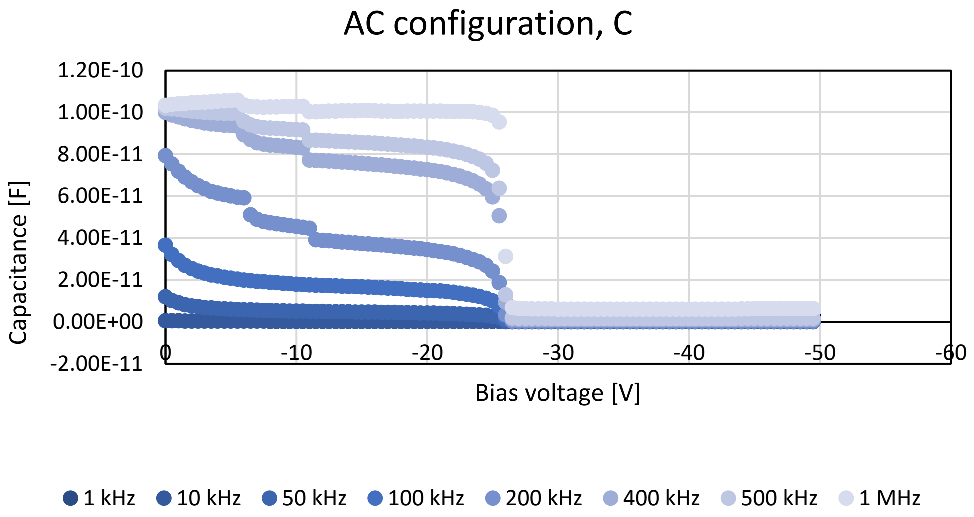


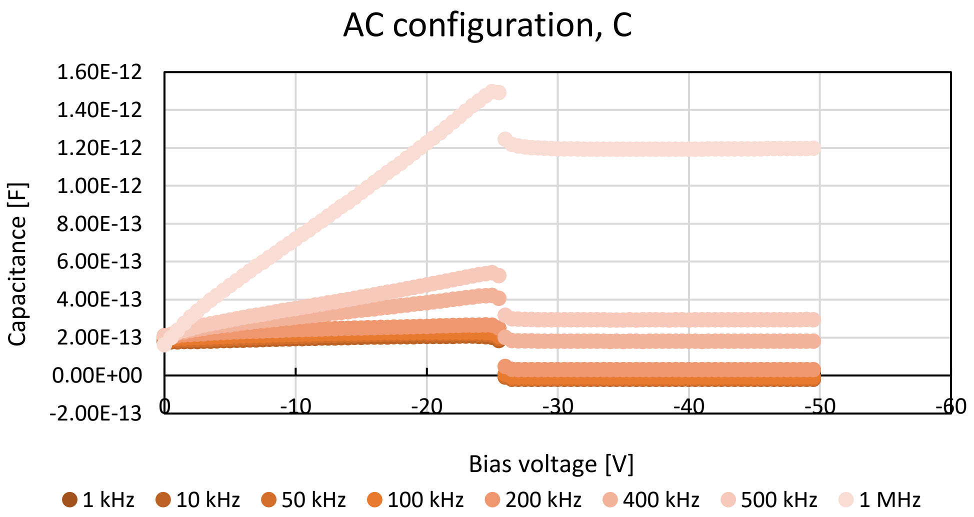
Update Feb 28

20 µm and 50 µm AC-LGADs, AC strip capacitance

- W3051: 50 µm
- W3075: 20 µm
- 500-400 = 100 µm metal



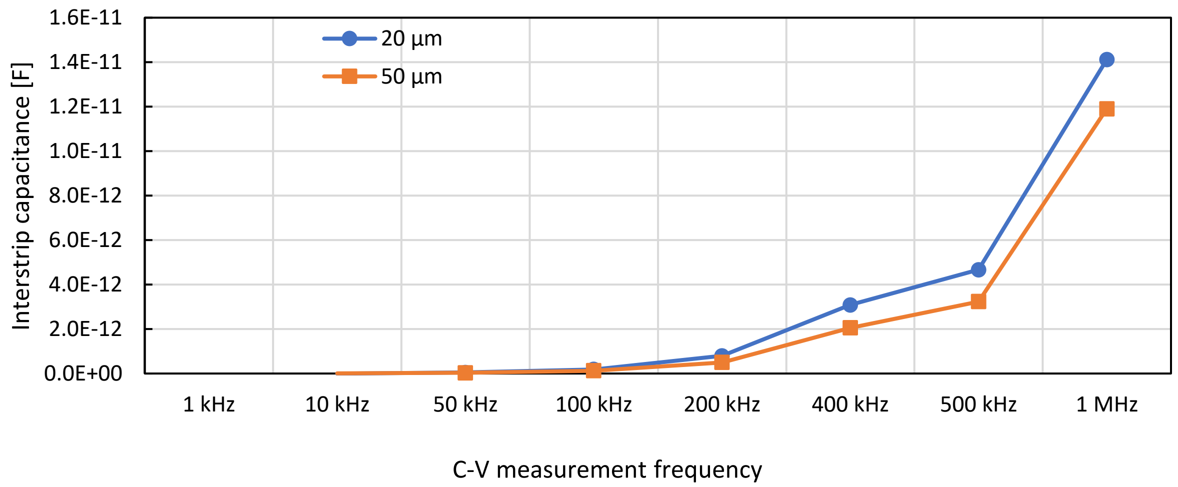


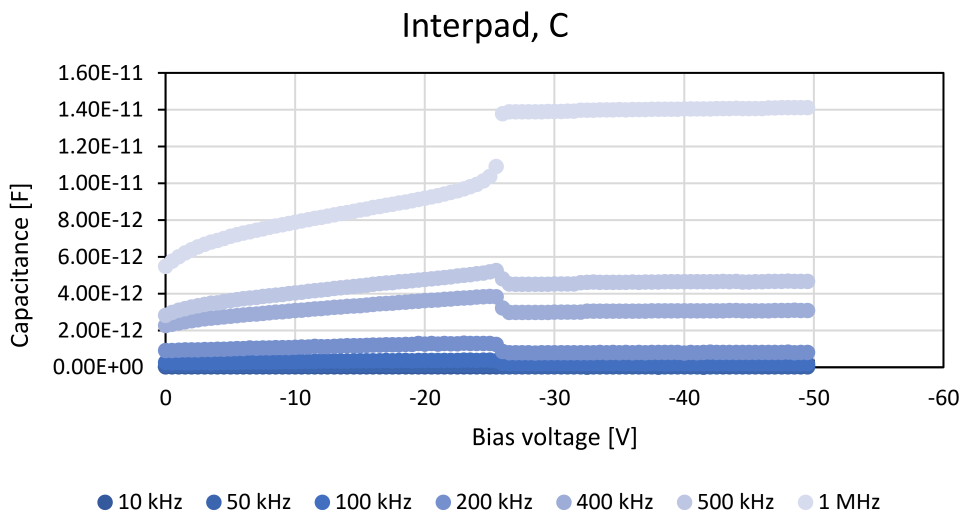


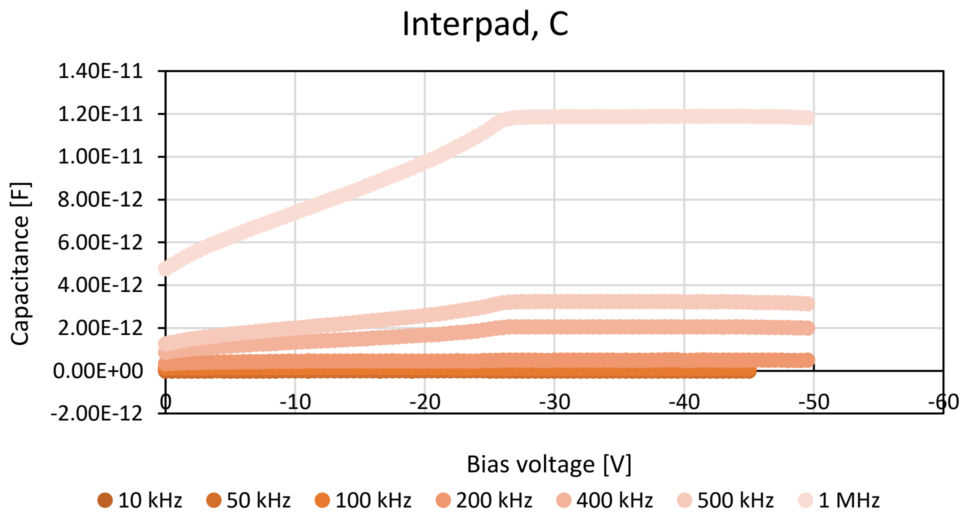
20 µm and 50 µm AC-LGADs, interstrip

J. Ott et al, AC-LGAD capacitances

- W3051: 50 µm
- W3075: 20 µm
- 500-400 = 100 µm metal



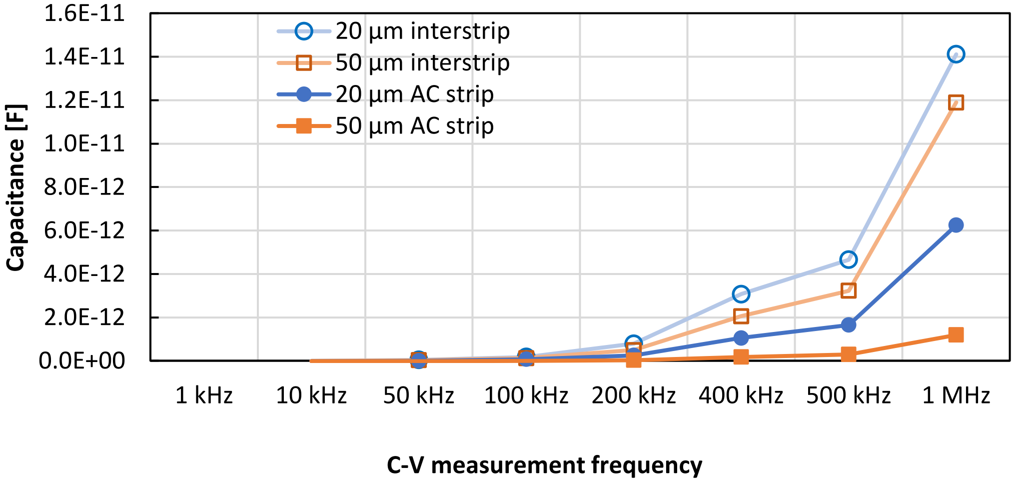




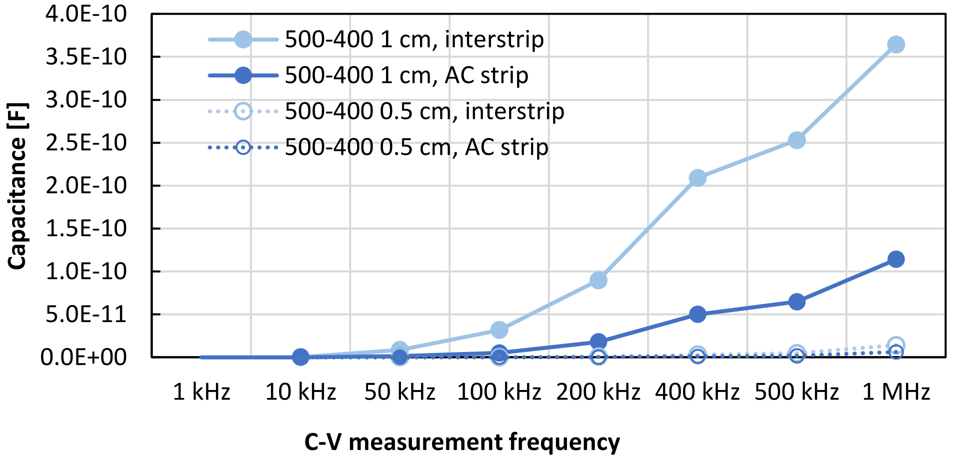
20 µm and 50 µm AC-LGADs, comparison

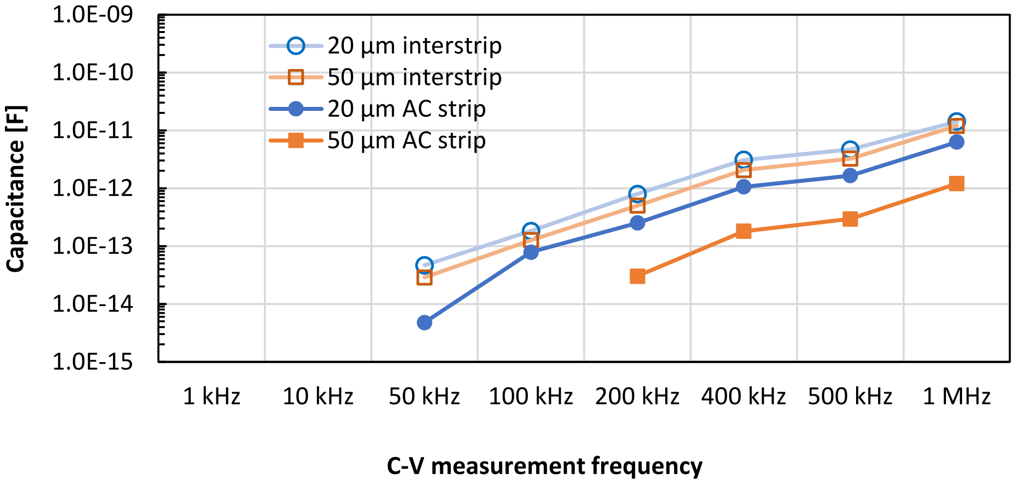
J. Ott et al, AC-LGAD capacitances

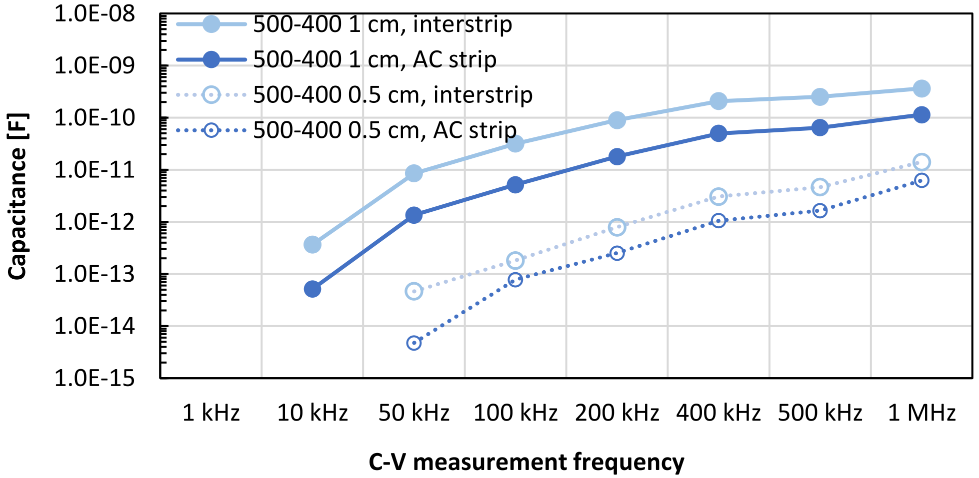
500-400 = 100 µm metal, 20 and 50 µm



500-400 = 100 µm metal, 0.5 and 1 cm, 20 µm







20 μm and 50 μm AC-LGADs

- All new wafers (3072, 3075, 3051) exhibit very frequency-dependent AC and interstrip capacitance, W1 did not
  - p-spray implant in the active area?? – not present in W1

- For 0.5 and 1 cm lengths, AC and interpad capacitance seem to scale similarly as for the multipitch geometries (even though cross-comparing here W3075 and 3072)

- Small measured capacitances for W3051 and 3075 500-400, plus variation over frequency – hard to quantify the (visible!) impact of substrate thickness
  - In AC strip capacitance, difference larger than x 2.5
  - In interpad, difference smaller and almost constant

Info from Gabriele

- W3072 had phosphor implant 20keV 2e13 (n-res) through naked silicon, while w3075 had phosph implant 40keV 2e13 through ~ 12 nm of thermal oxide.
- After n+ implant, w3072 was oxidized for 30 min at 900C, instead w3075 was oxidized before the n+ implant
- Boron gain layer is the same, 380keV but 2.45e12 on w3075 , while 2.35e12 on wafer 3072
- VBD of wafer 3075 is 85V, VBD of wafer 3072 is 110V
- W3051 followed the same process of 3075, but 50 µm substrate

- W1:Oxide thickness is 150nm
- 3072:Oxide thickness is 120nm
- 3072 is 20um thick, W1 is 50 um thick.
- 3072 has pspray in the active area, W1 has not.
- W1 : N-res has been annealed at 900C (and then with boron gain layer)
- 3072 : annealed with boron only