SAND2022-16078C

Sandia National Laboratories

Exceptional service in the national interest

Systematic Investigation of SIR Testing Phenomena with Constant Capacitance Interdigitated Comb Patterns

SMTA-I – Nov. 1, 2022

M. Kottwitz,[a] B. Glidwell,[b] S. Grosso,[a]
M. McMeen,[b] M. Bixenman,[b] E. Fowler[a]

[a]Sandia National Laboratories, Albuquerque, NM

[b]Magnalytix, Nashville, TN

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. DEPARTMENT OF ENERGY

NNSA

Motivation

IPC
ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES ®

3000 Lakeside Drive, Suite 309S
Bannockburn, IL 60015-1249

IPC-TM-650
TEST METHODS MANUAL

1 Scope This test method is used to quantify the deleterious effects of fabrication, process or handling residues on Surface Insulation Resistance (SIR) in the presence of moisture. The electrodes are long parallel traces (printed interdigitated comb patterns) on a standardized printed board or assembly. Samples shall be conditioned and measurements taken at a high humidity. Electrodes are electrically biased during conditioning to facilitate electrochemical reactions.

Specifically, this method is designed to:

- Simultaneously assess
  a) leakage current caused by ionized water films and
  b) electrochemical degradation of test vehicle, (corrosion, dendritic growth).
- Provide metric(s) that can appropriately be used for binary classification (e.g., go/no go, pass/fail).
- Compare, rank or characterize materials and processes.

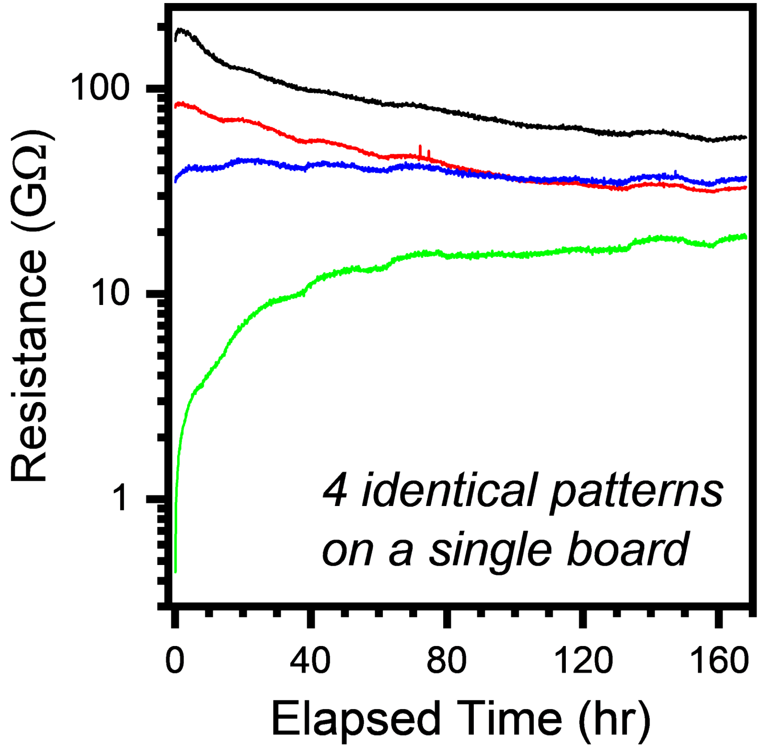
Binary classification

↓

Fundamental understanding of physical phenomena occurring during an SIR test

↓

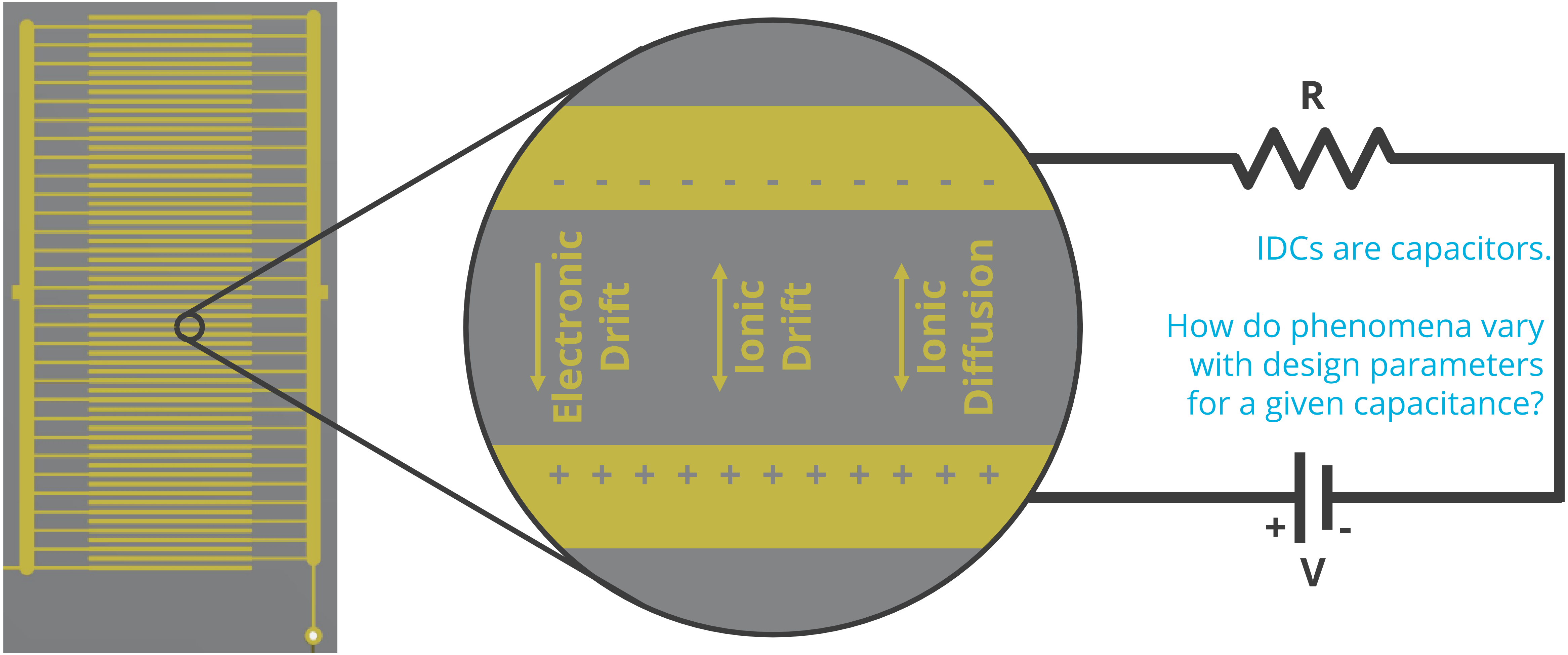
Materials/process characterization



S. Grosso

How to reliably reproduce SIR test results?

SIR Phenomena

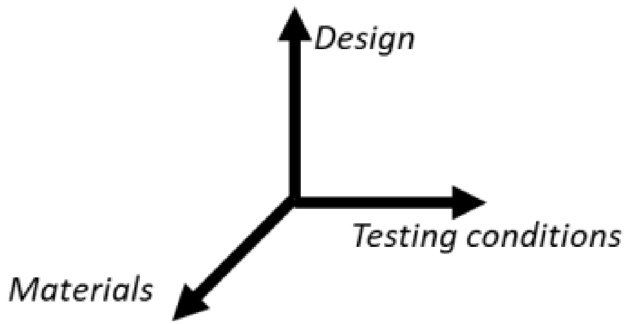


IDCs are capacitors.

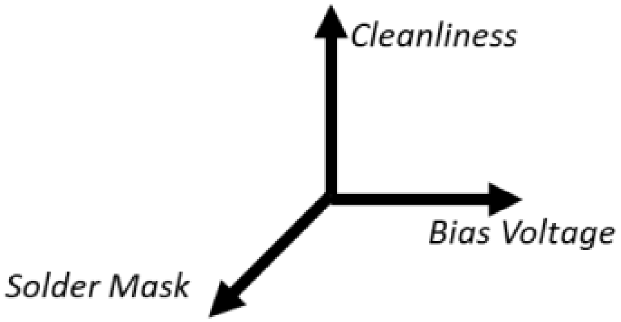
How do phenomena vary with design parameters for a given capacitance?

Systematic Approach

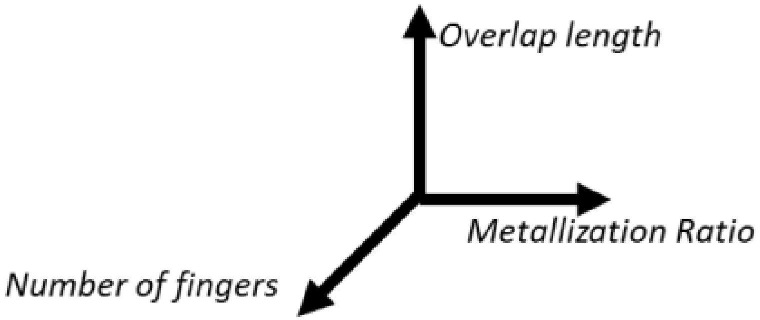
SIR total parameter space



Reduced dimensionality #1



Reduced dimensionality #2

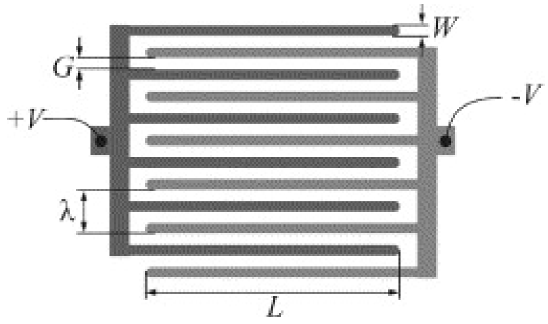


SIR is a multivariate function of…

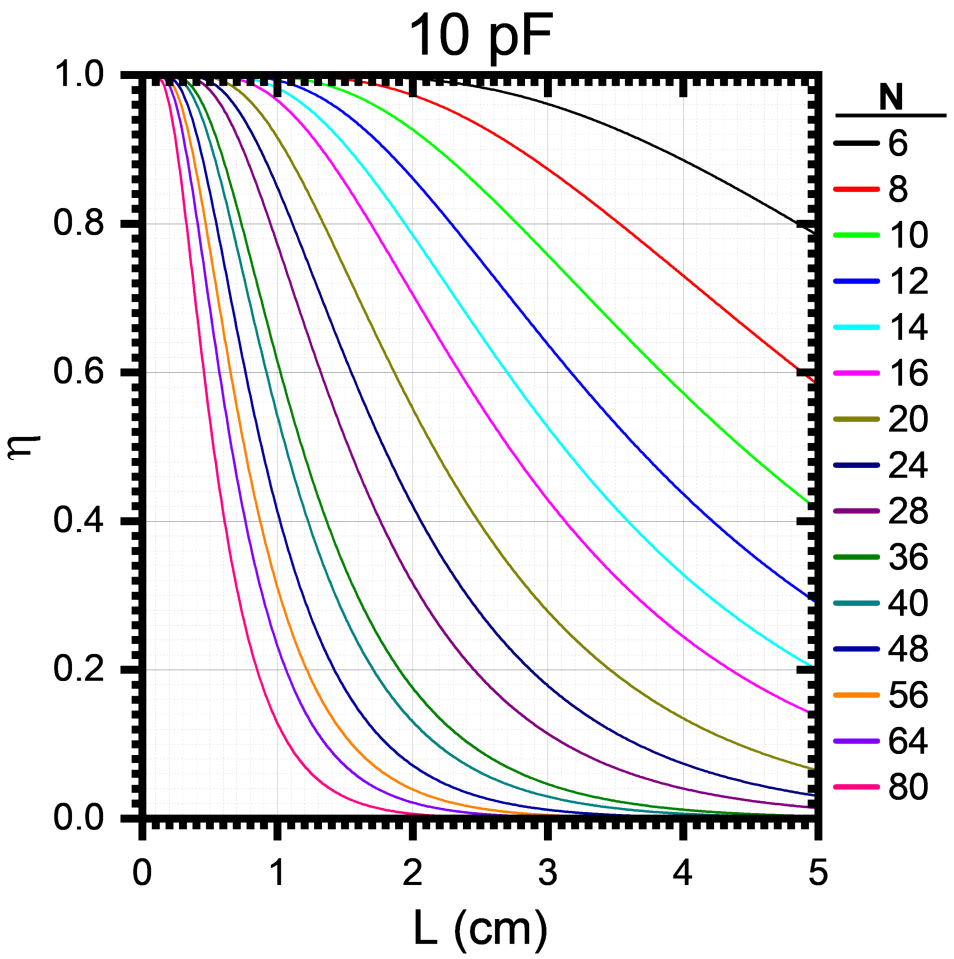
- Board design parameters – number of fingers, overlap length, metallization ratio
- Testing conditions – bias voltage, temperature, humidity
- Materials – dielectric substrate, plating/coating, solder mask, contamination

Capacitance Computation

Analytical Evaluation of the Interdigital Electrodes Capacitance for a Multi-Layered Structure
Sensors and Actuators A: Physical **2004**, 112, 291



Conformal Mapping



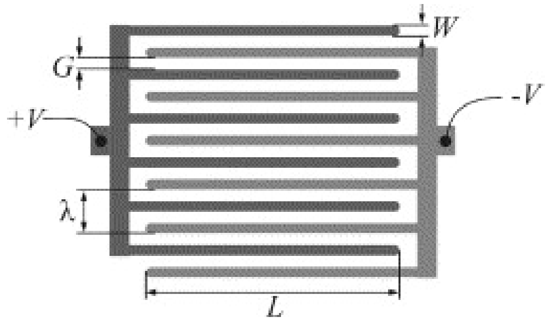
N – number of fingers
L – finger overlap length
η – metallization ratio
  W – finger width
  G – finger gap width
ε_r – relative permittivity

10 pF = 0.009 jars

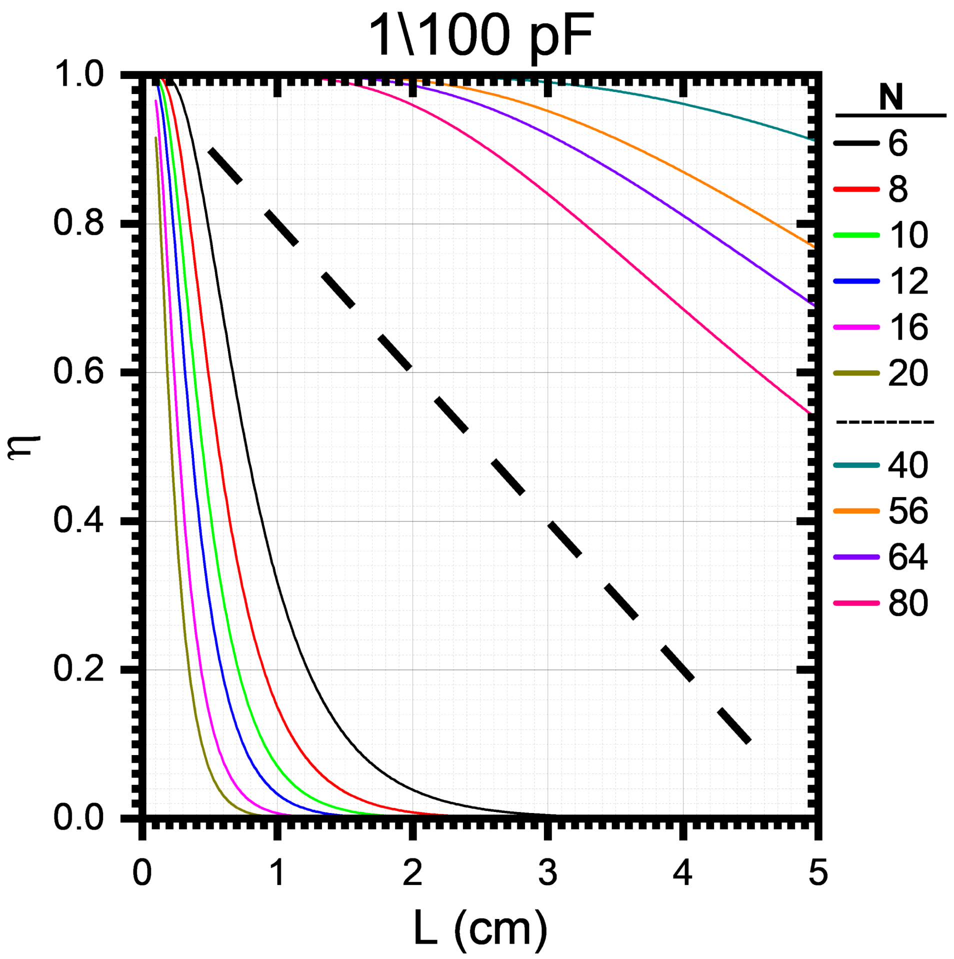
Capacitance Computation

Further detail in supplementary slide

Analytical Evaluation of the Interdigital Electrodes Capacitance for a Multi-Layered Structure
Sensors and Actuators A: Physical **2004**, 112, 291

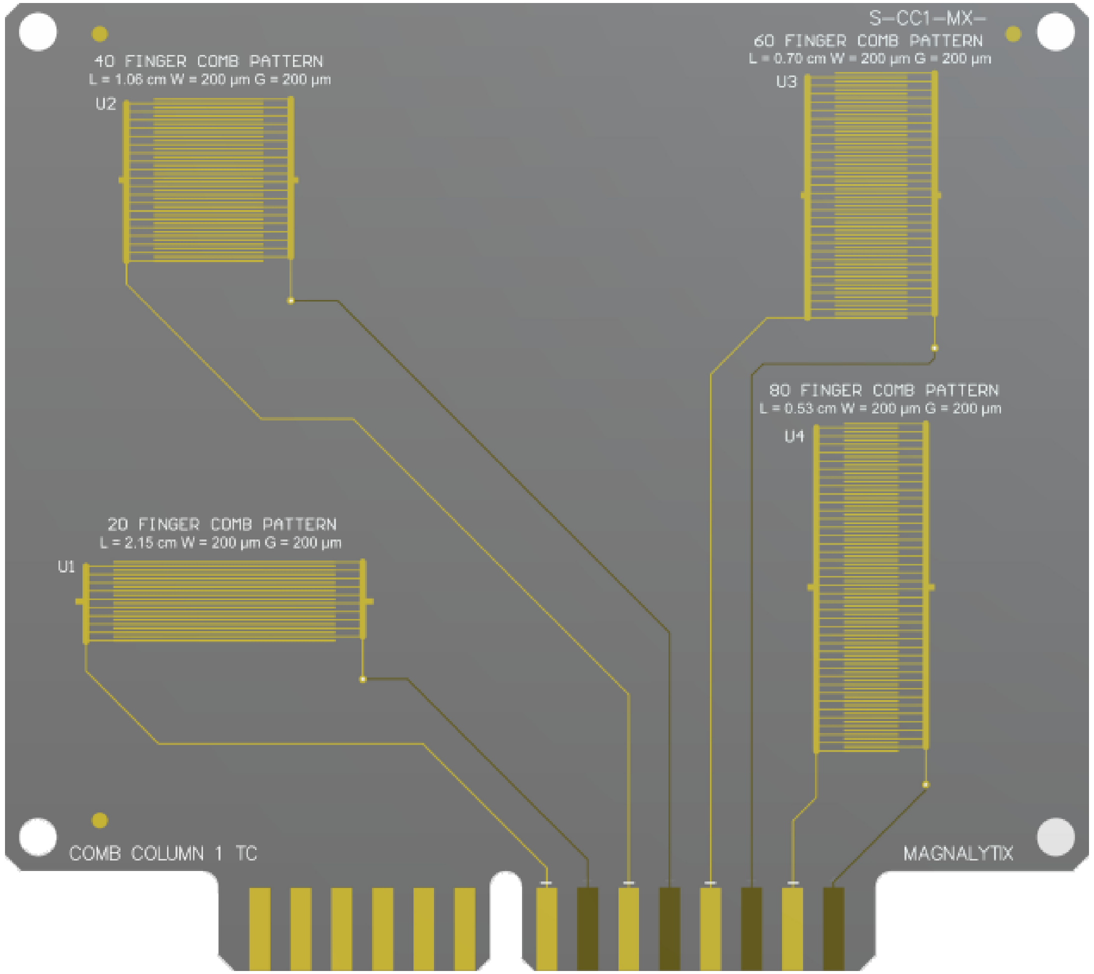


Conformal Mapping



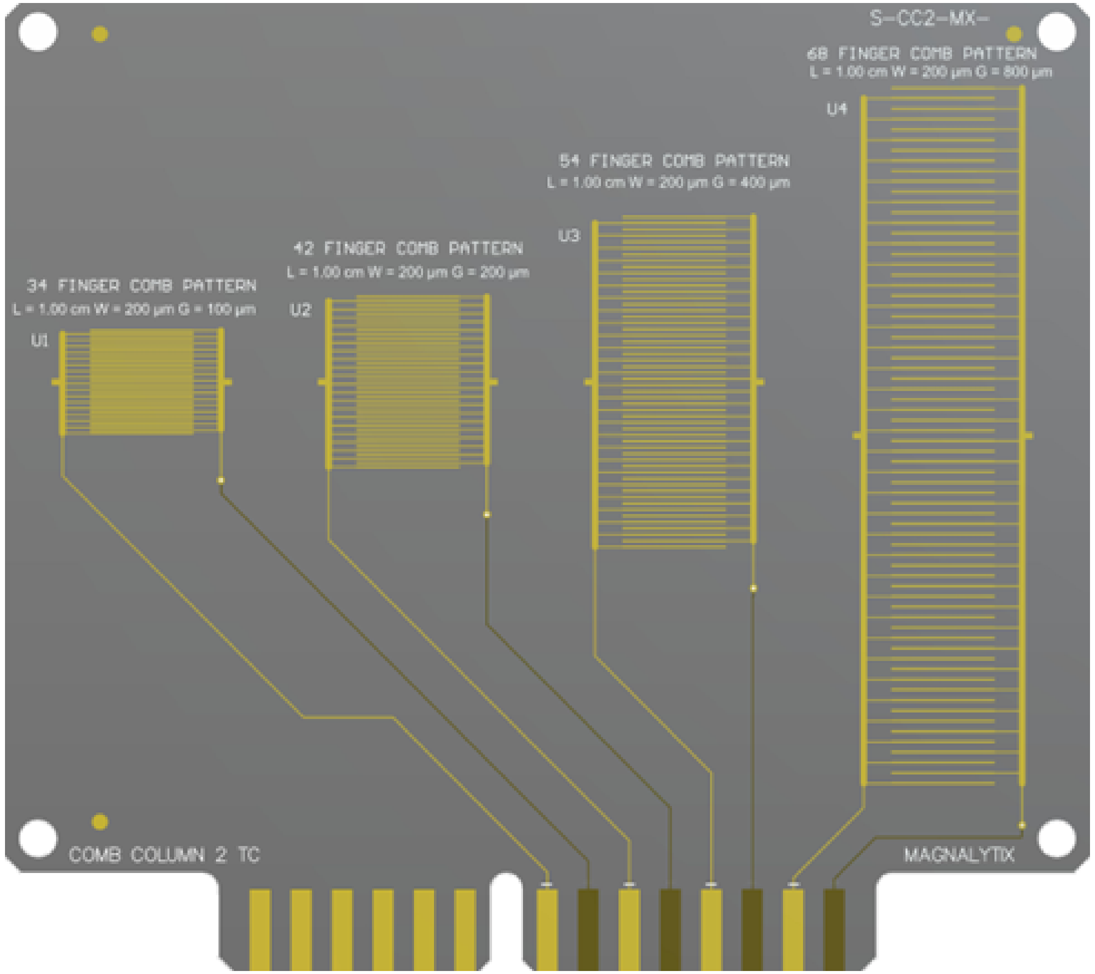
N – number of fingers
L – finger overlap length
η – metallization ratio
W – finger width
G – finger gap width
ε_r – relative permittivity

Board Design 1



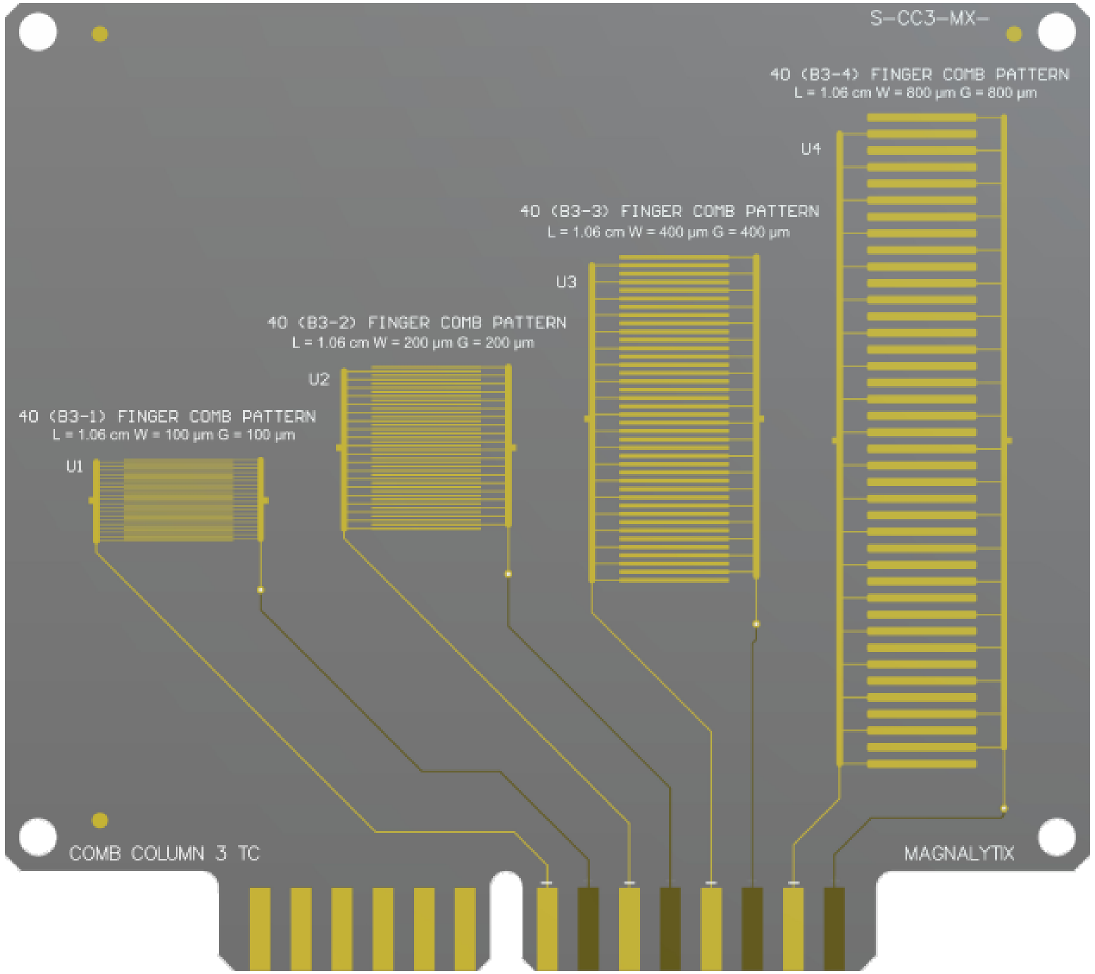
Design-Pattern	N	L (cm)	η	W (μm)	G (μm)	C (pF)
1-U1	20	2.15	0.5	200	200	9.99
1-U2	40	1.06	0.5	200	200	9.99
1-U3	60	0.70	0.5	200	200	9.95
1-U4	80	0.53	0.5	200	200	10.07

Board Design 2



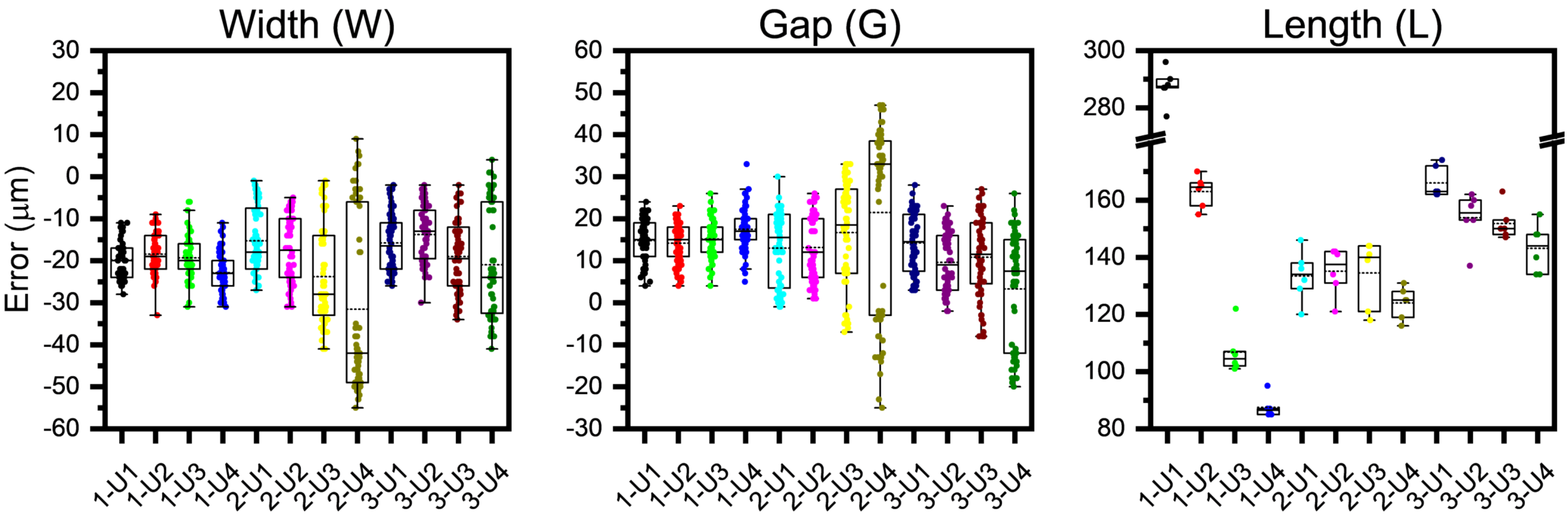
Design-Pattern	N	L (cm)	η	W (µm)	G (µm)	C (pF)
2-U1	34	1.00	0.67	200	100	10.21
2-U2	42	1.00	0.5	200	200	9.91
2-U3	54	1.00	0.33	200	400	10.00
2-U4	68	1.00	0.2	200	800	10.00

Board Design 3



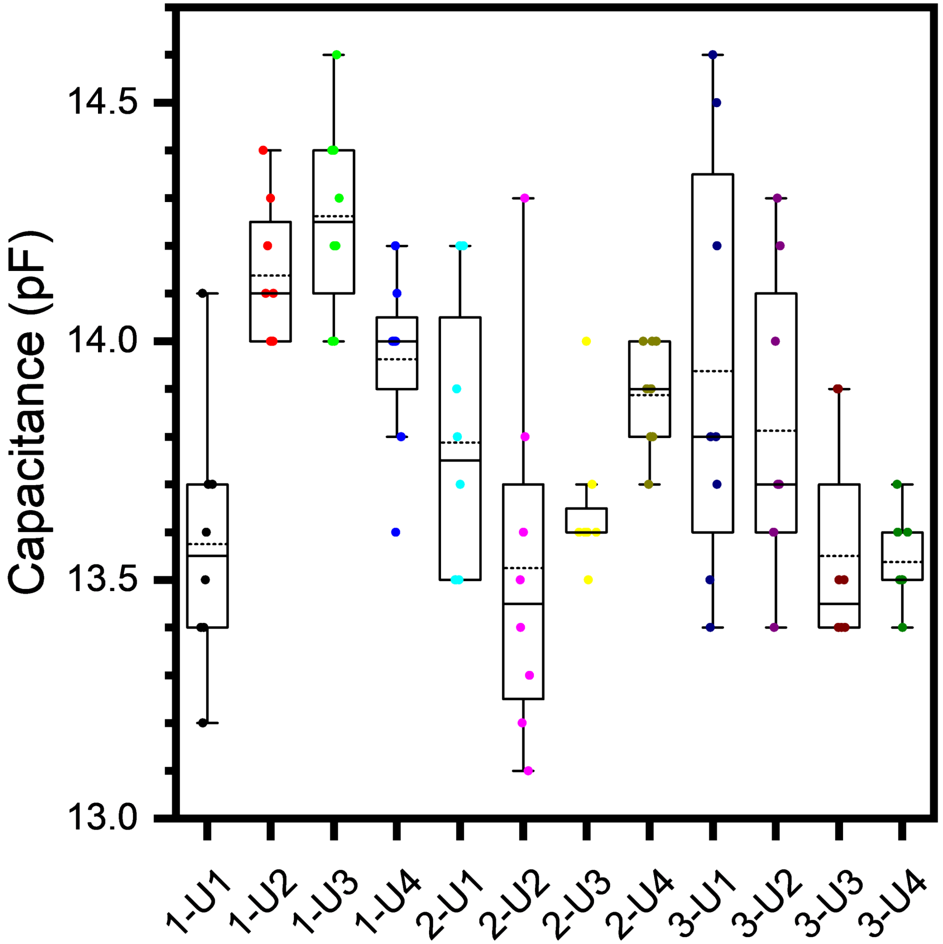
Design-Pattern	N	L (cm)	η	W (µm)	G (µm)	C (pF)
3-U1	40	1.06	0.5	100	100	9.99
3-U2	40	1.06	0.5	200	200	9.99
3-U3	40	1.06	0.5	400	400	9.99
3-U4	40	1.06	0.5	800	800	9.99

How well did the fab shop do?



Keyence VHX-7000 optical microscope
W, G: 3 board designs x 6 boards x 4 patterns x 10 measurements
L: 3 board designs x 6 boards x 4 patterns x 1 measurement

Discrepancy in Capacitance



Measured with Agilent E4980A Precision LCR Meter at 1 kHz

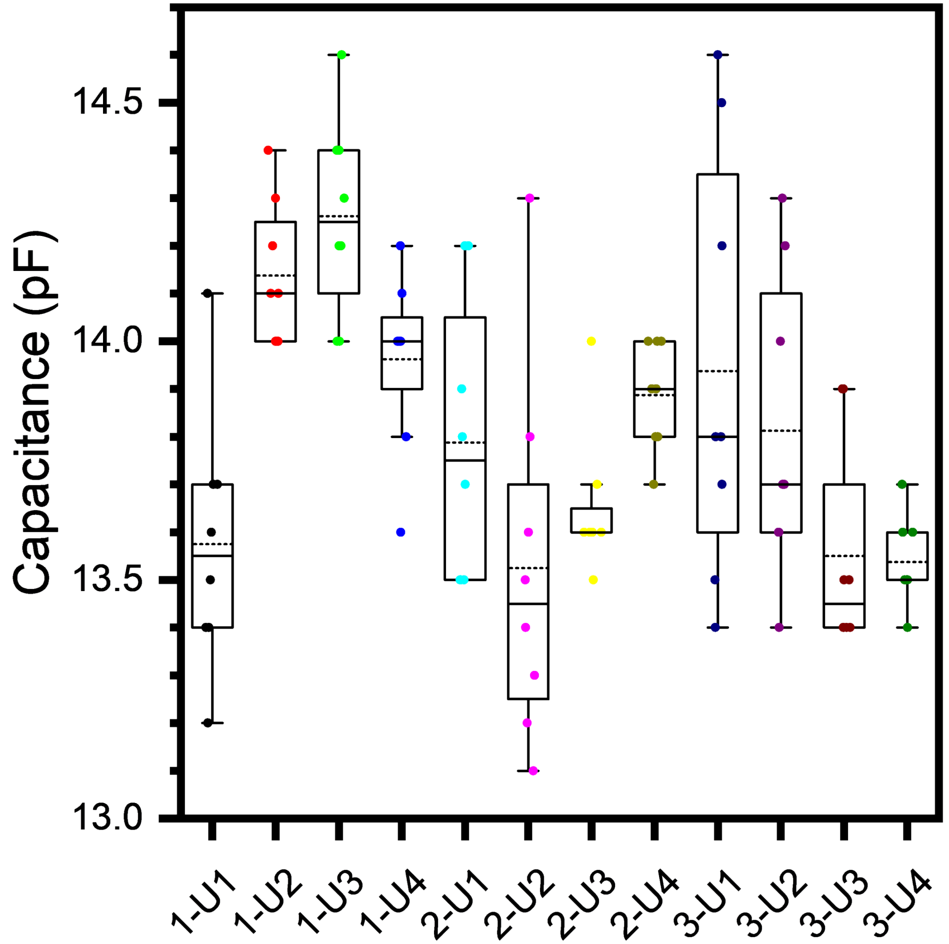
Board-Pattern	$C_{Des.}$* (pF)
1-U1	9.99
1-U2	9.99
1-U3	9.95
1-U4	10.07
2-U1	10.21
2-U2	9.91
2-U3	10.00
2-U4	10.00
3-U1	9.99
3-U2	9.99
3-U3	9.99
3-U4	9.99

*assumes relative permittivity (ε_r) of 4.4

Possible causes of discrepancy:

- Capacitance measurement at single frequency (1 kHz)
- Room conditions
- Copper traces too thick for accurate description by model
- Variation in FR-4 substrate relative permittivity

Discrepancy in Capacitance



$R^2 = 0.66$ (for $C_{Meas.}$ and ε_r)

Board-Pattern	$C_{Des.}$* (pF)	N	$L_{Meas.}$ (cm)	$\eta_{Meas.}$	$W_{Meas.}$ (μm)	$G_{Meas.}$ (μm)	$C_{Meas.}$ (pF)	ε_r
1-U1	9.99	20	2.12	0.456	180	215	13.58	6.92
1-U2	9.99	40	1.04	0.459	182	214	14.14	7.23
1-U3	9.95	60	0.69	0.456	181	215	14.26	7.37
1-U4	10.07	80	0.52	0.449	177	217	13.96	7.20
2-U1	10.21	34	0.99	0.620	185	113	13.79	6.93
2-U2	9.91	42	0.99	0.461	183	213	13.53	6.90
2-U3	10.00	54	0.99	0.297	176	417	13.65	6.92
2-U4	10.00	68	0.99	0.170	168	821	13.89	7.08
3-U1	9.99	40	1.04	0.424	84	114	13.94	7.53
3-U2	9.99	40	1.04	0.470	186	210	13.81	6.90
3-U3	9.99	40	1.04	0.481	381	411	13.55	6.63
3-U4	9.99	40	1.05	0.492	779	803	13.54	6.50

*assumes relative permittivity (ε_r) of 4.4

Avg. = 7.01

Measured with Agilent E4980A Precision LCR Meter at 1 kHz

SIR Methodology

	Slot	Chamber A	Chamber B	Chamber C
Day 1	1	1-34	3-25	2-30
	2	2-21	1-25	3-19
	3	3-11	2-15	1-19
	4	1-11	3-34	2-36
	5	2-34	1-36	3-30
	6	3-21	2-25	1-30
	7	1-21	~~3-15~~	2-19
	8	2-11	~~1-15~~	3-36

	Slot	Chamber A	~~Chamber B~~	Chamber C
Day 2	1	1-35	~~3-29~~	2-31
	2	2-24	~~1-29~~	3-20
	3	3-14	~~2-16~~	1-20
	4	1-14	~~3-35~~	2-39
	5	2-35	~~1-39~~	3-31
	6	3-24	~~2-29~~	1-31
	7	1-24	~~3-16~~	2-20
	8	2-14	~~1-16~~	3-39

Design-Board

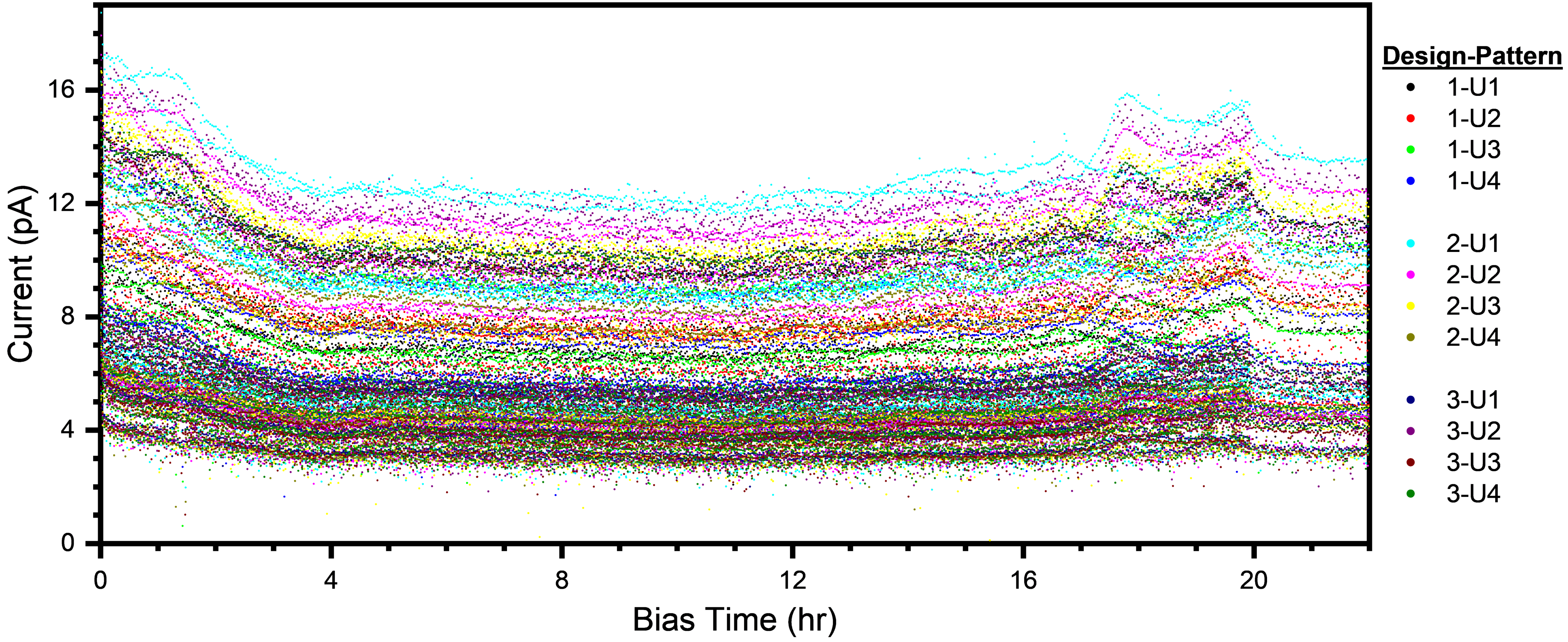
Chamber conditions: 25 °C and 40% RH – 1 hour stabilization

Sequentially measure current (under reverse bias) while all other channels under forward bias (5 V)

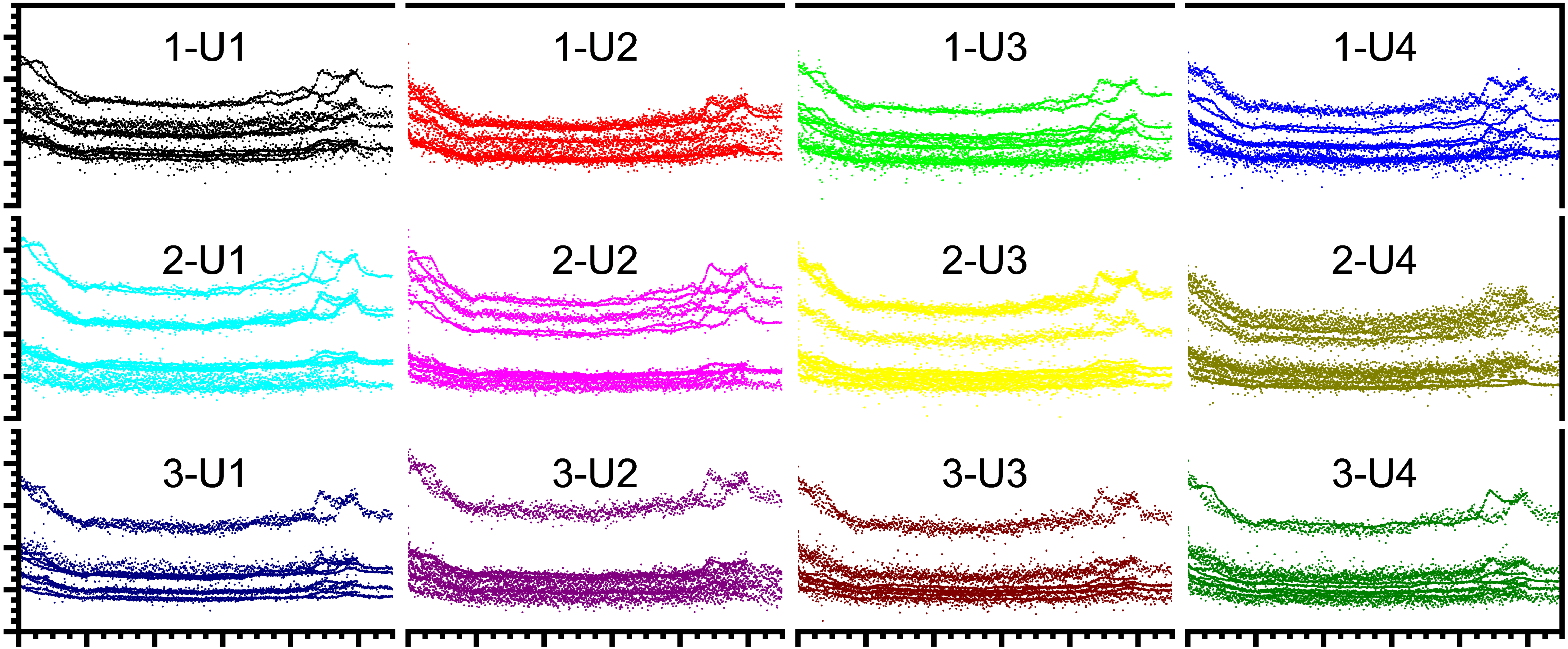
Measurement cycle begun every 2 minutes

All Data

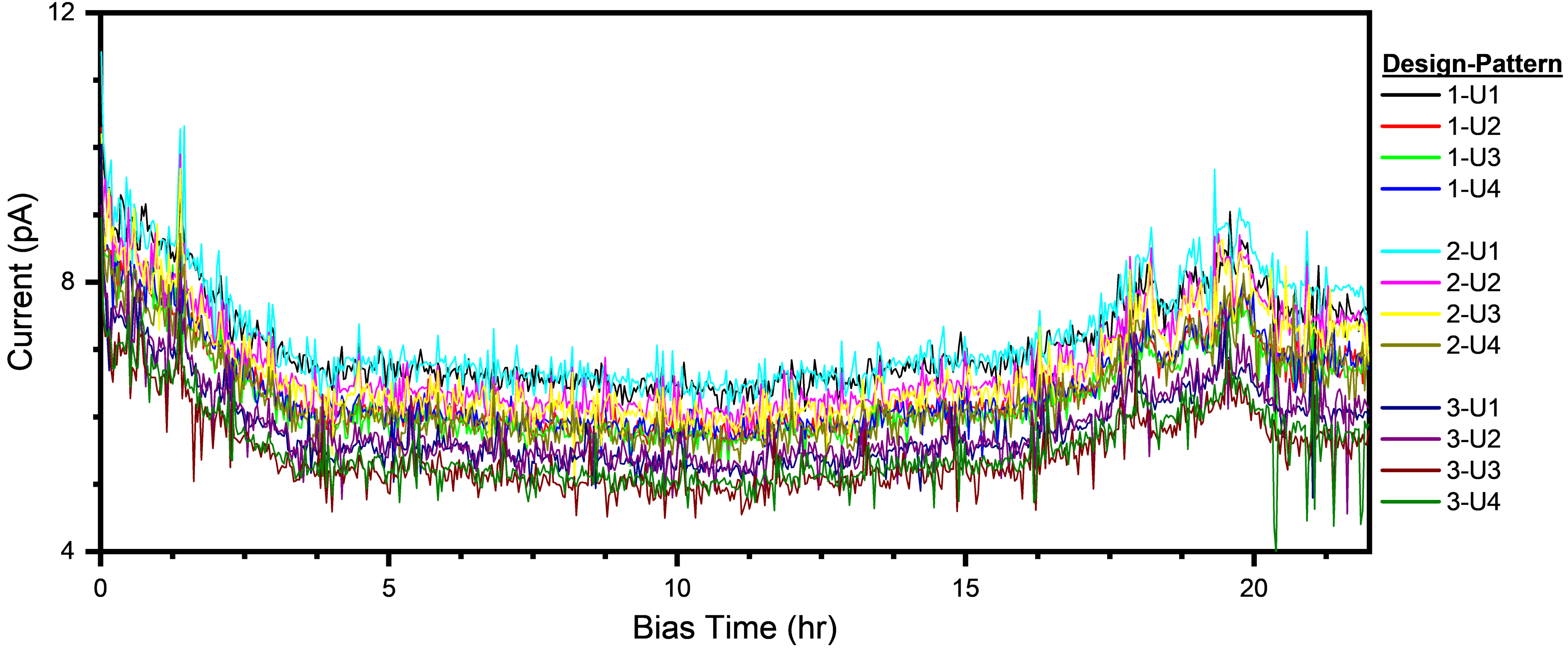
10 pA = 62,400,000 electrons/s



All Data – By Pattern

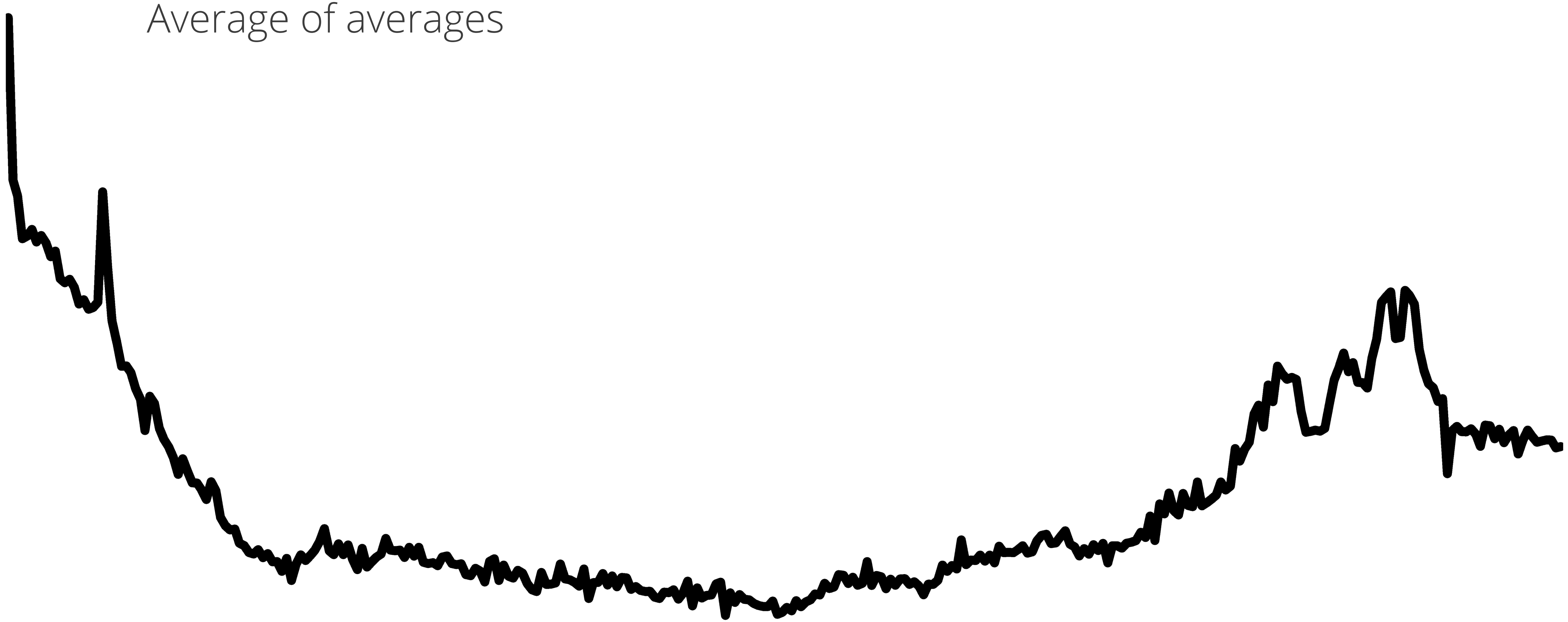


All Data – Averaged in 2 Minute Windows



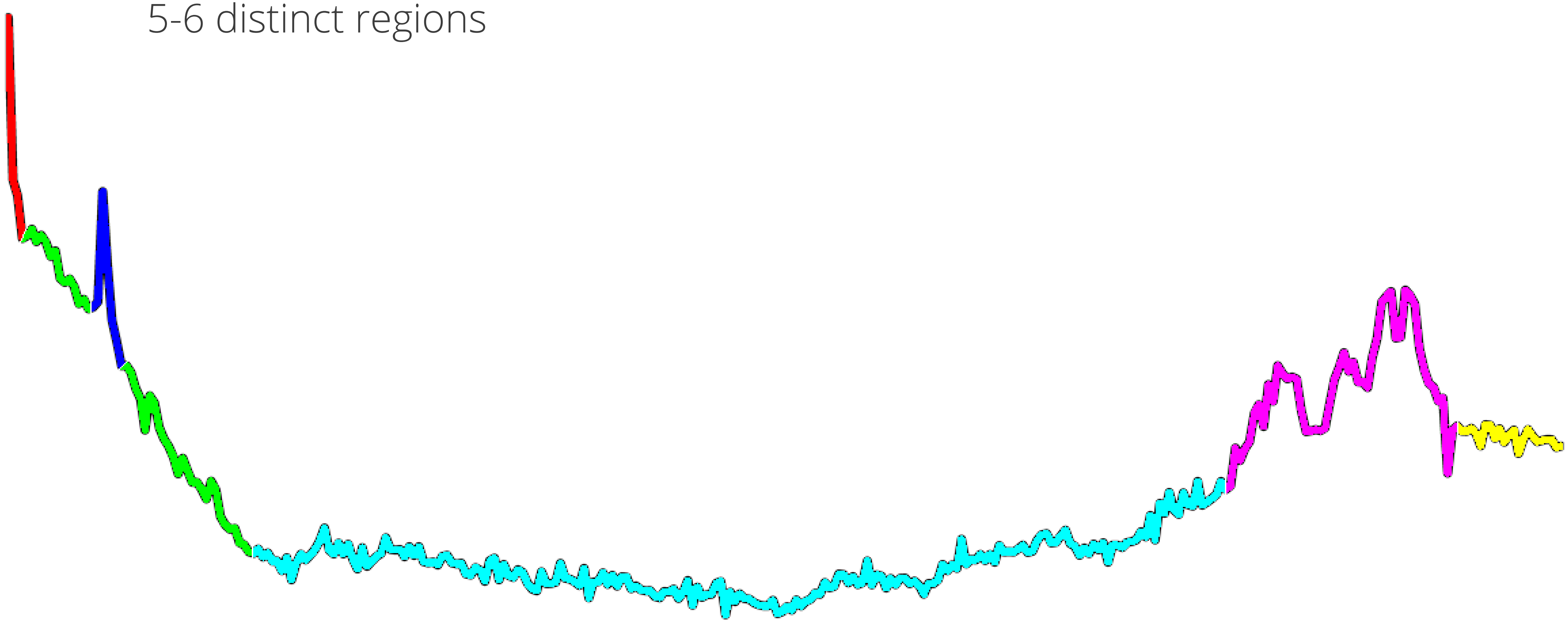
Parameterizing SIR

Average of averages



Parameterizing SIR

5-6 distinct regions

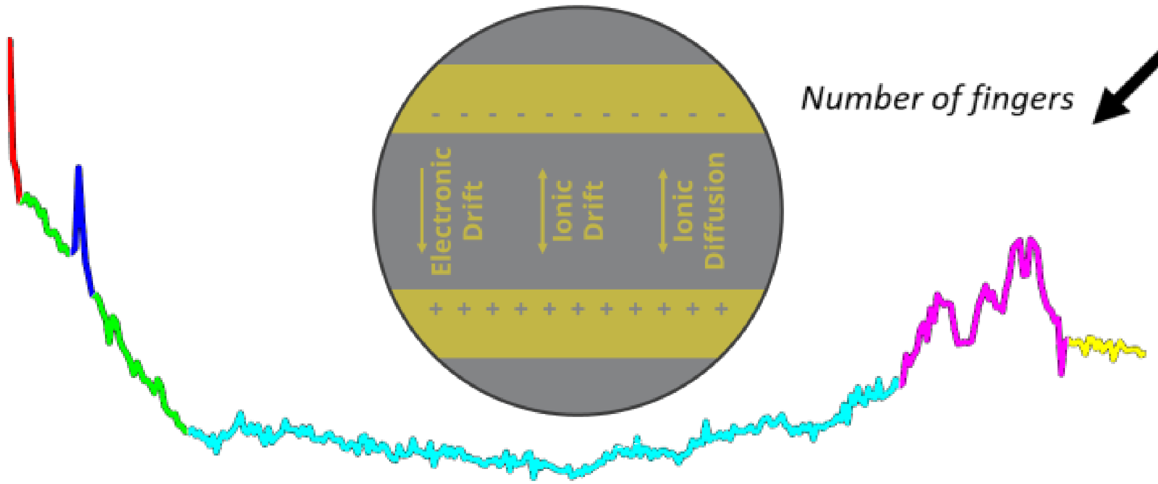


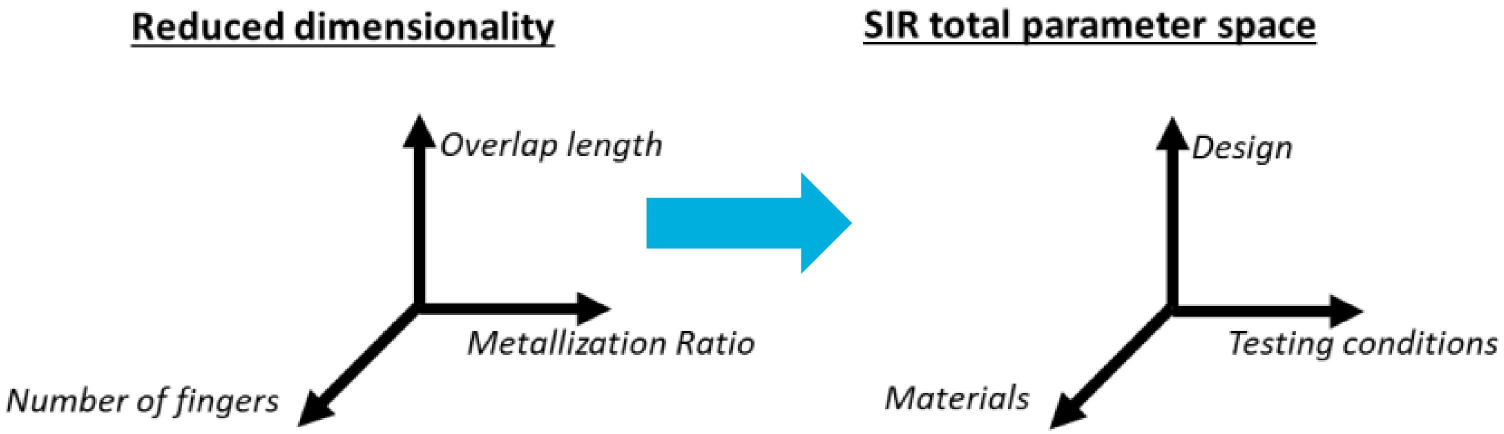
Conclusion

Proof of concept achieved: 12 unique comb patterns → 2 pA span in average response

Next Steps:

- ➢ Increase dimensionality
- ➢ Correlate failure modes, SIR response, phenomena





- ➢ Towards real geometries and/or representative square comb patterns

Sandia National Laboratories

Exceptional service in the national interest

Systematic Investigation of SIR Testing Phenomena with Constant Capacitance Interdigitated Comb Patterns

SMTA-I – Nov. 1, 2022

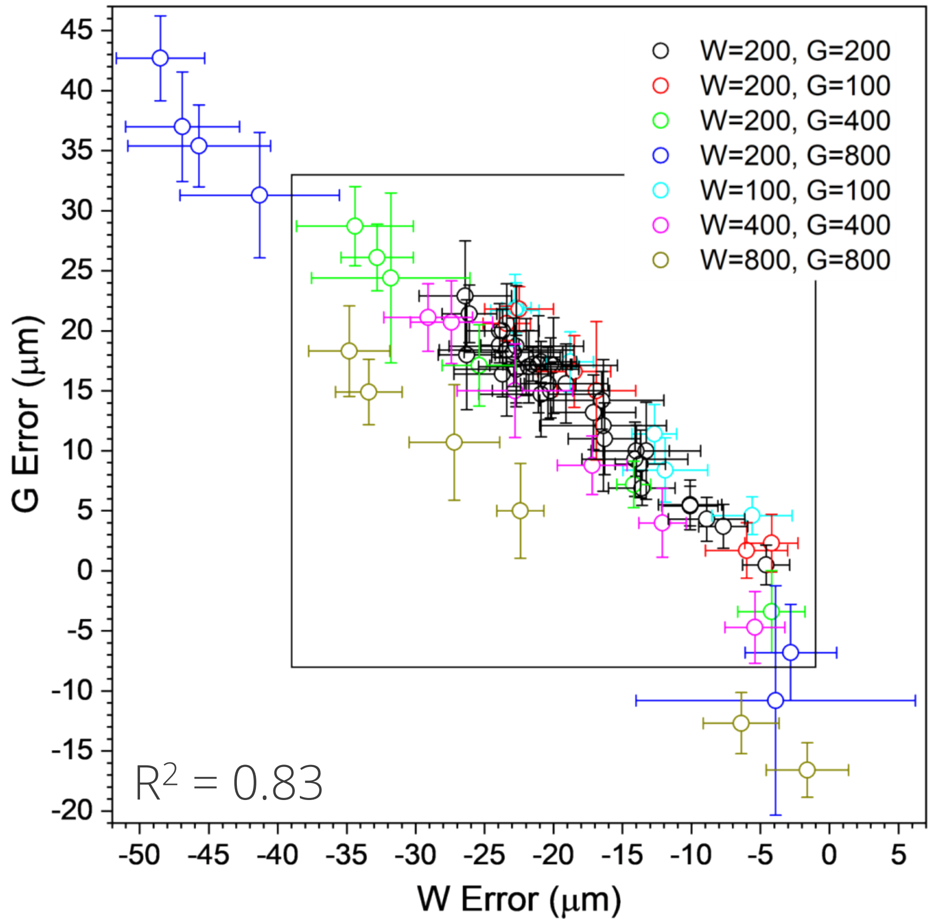
M. Kottwitz,[a] B. Glidwell,[b] S. Grosso,[a]
M. McMeen,[b] M. Bixenman,[b] E. Fowler[a]

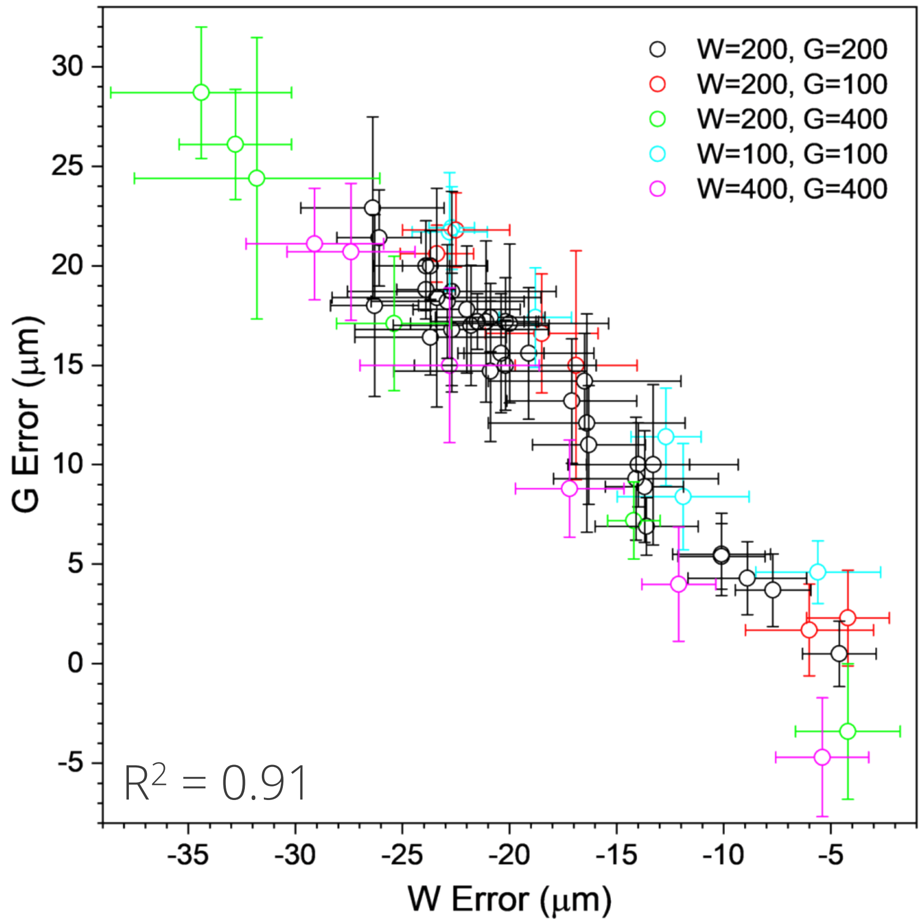
[a]Sandia National Laboratories, Albuquerque, NM

[b]Magnalytix, Nashville, TN

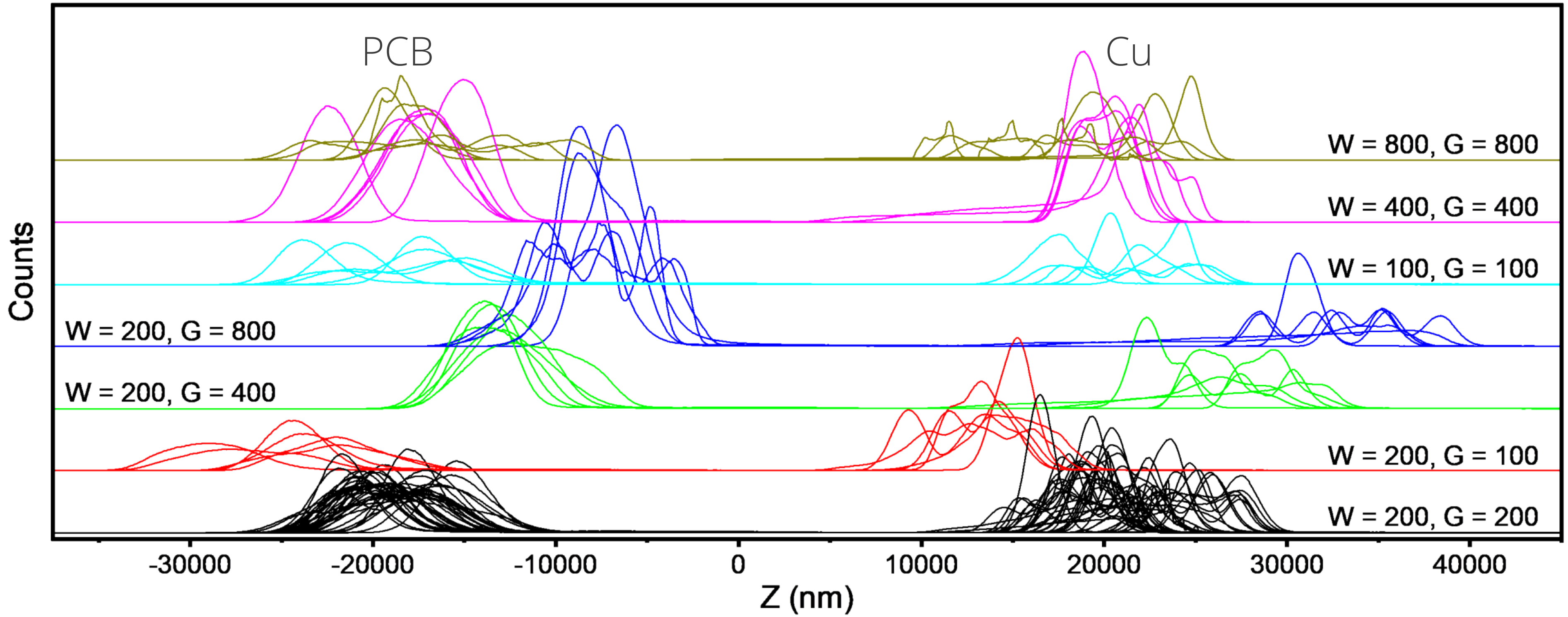
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

S1 – Width and Gap Measurements





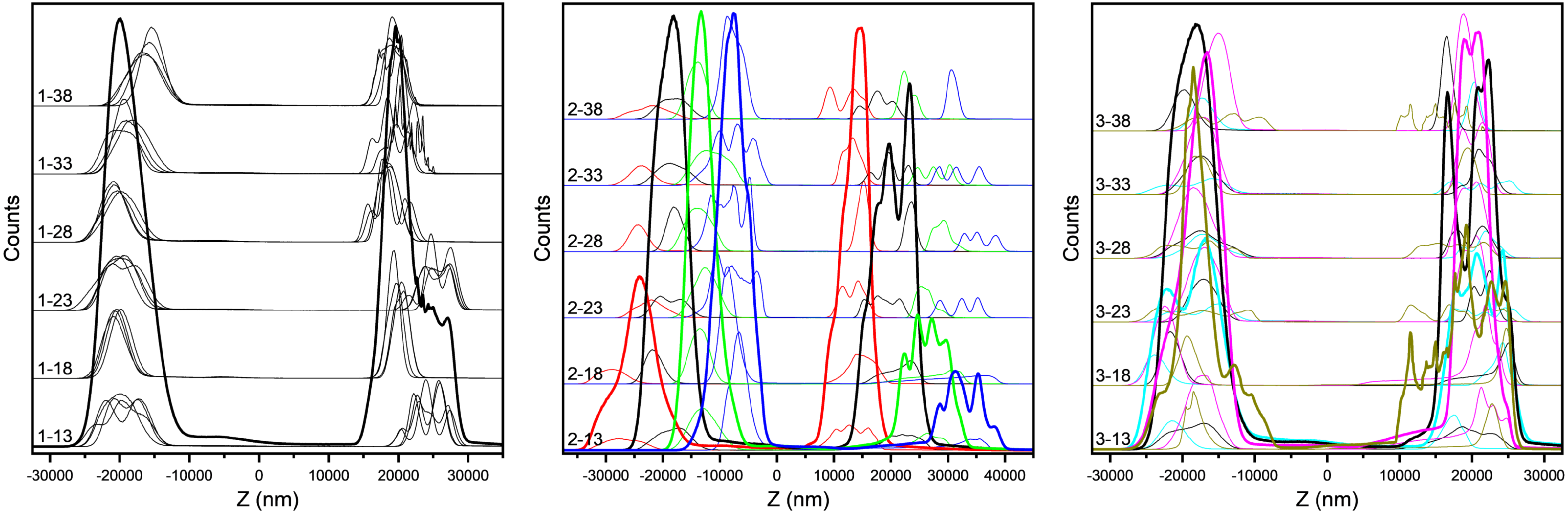
S2 – Height Measurements



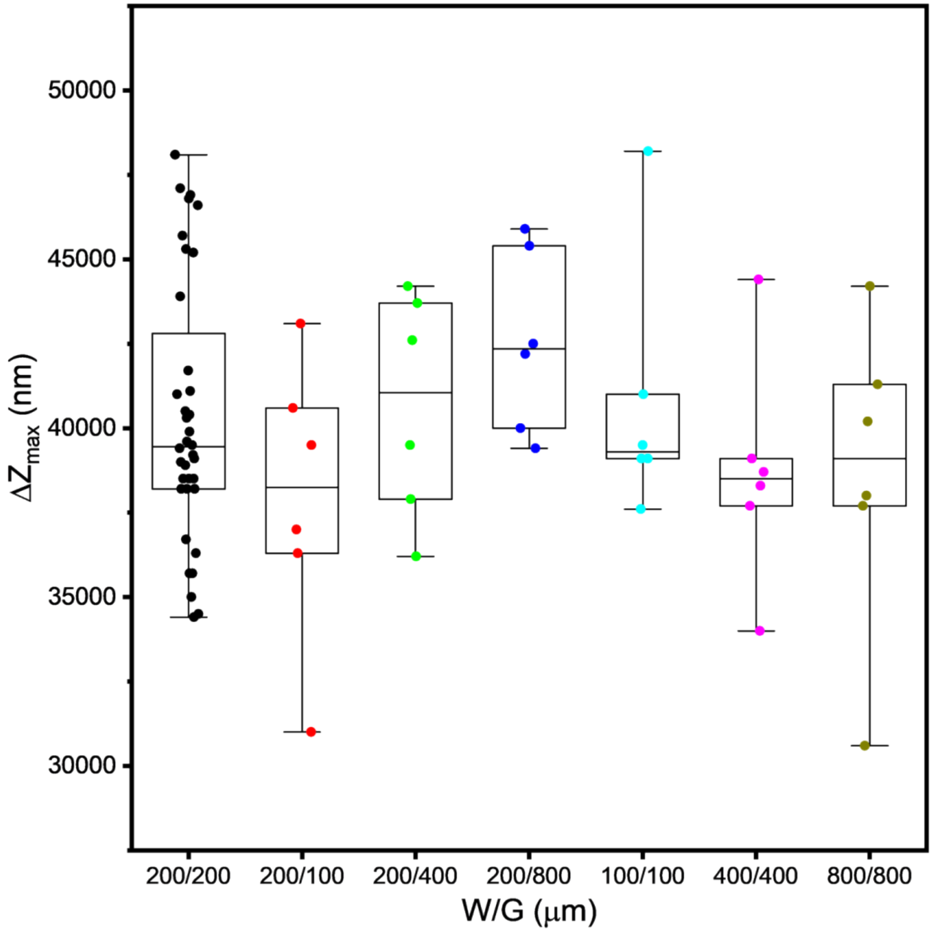
Profiles taken on Keyence VK-X150 confocal microscope (J. Faubel)

Subtract least squares plane → 0.1 µm binning of Z values

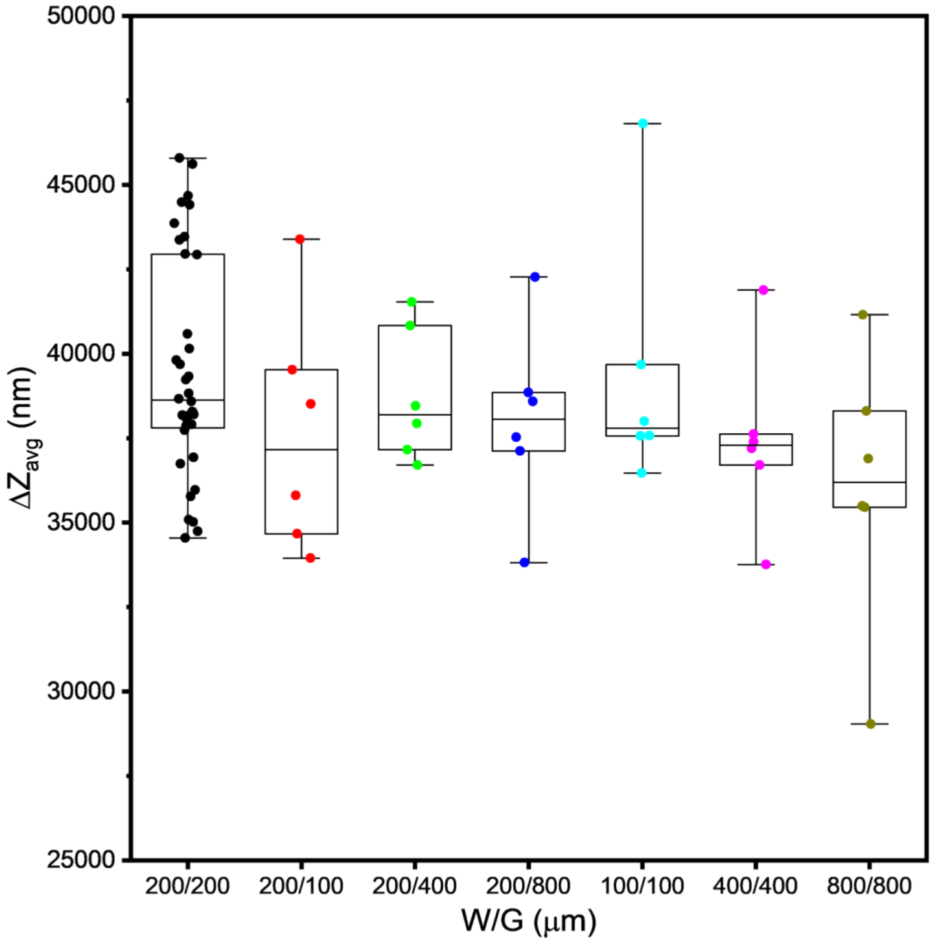
S2 – Height Measurements



S2 – Height Measurements

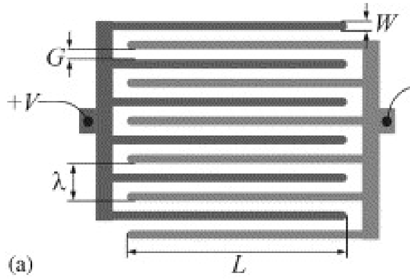


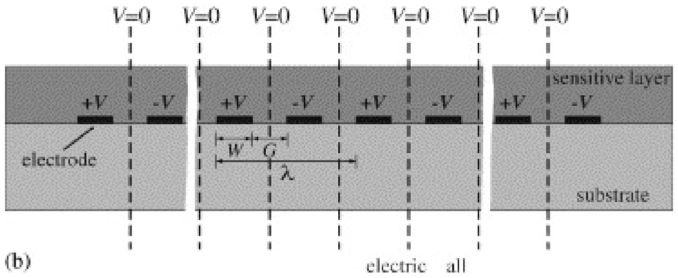
(Peak to Peak)



(Weighted averages)

S3 – Capacitance Computations





$$C = (N-3)\, C_I/2 + 2C_I C_E/(C_I + C_E)$$

$$C_I = C_{I,air} + C_{I,S} = \varepsilon_0 L(K(k_{I\infty})/K(k'_{I\infty}) + \varepsilon_S\, K(k_{I\infty})/K(k'_{I\infty}))$$

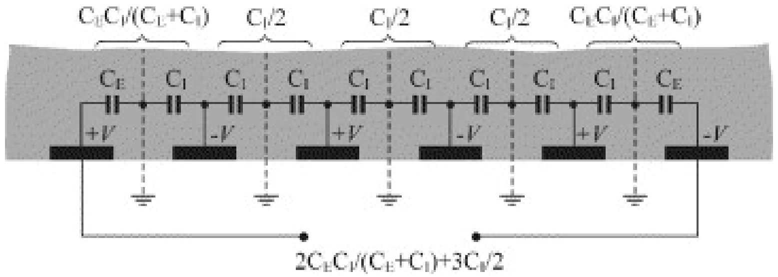
$$C_E = C_{E,air} + C_{E,S} = \varepsilon_0 L(K(k_{E\infty})/K(k'_{E\infty}) + \varepsilon_S\, K(k_{E\infty})/K(k'_{E\infty}))$$

$$K(k) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-k^2\sin^2\theta}} = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}} = \frac{\pi}{2}\sum_{n=0}^{\infty}\left(\frac{(2n)!}{2^{2n}(n!)^2}\right)^2 k^{2n} = \frac{\pi}{2\,\mathrm{agm}\left(1, \sqrt{1-k^2}\right)}$$

$$k_{I\infty} = \sin\left(\frac{\pi}{2}\eta\right)$$

$$k_{E\infty} = \frac{2\sqrt{\eta}}{1+\eta}$$

$$k' = \sqrt{1-k^2}$$



N – number of fingers

L – finger overlap length

η – metallization ratio

W – finger width

G – finger gap width

ε_r – relative permittivity

"One can also neglect the thickness of the electrodes (~50 nm) since they are much thinner than their width (>50 µm), and thus, the electric potential of the electrodes is specified at the interface between the upper and lower half planes. For thicker electrodes corrections can easily be made to take into account their thickness."

Sensors and Actuators A: Physical **2004**, 112, 291