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TOWARDS A MECHANISTIC UNDERSTANDING OF SURFACE INSULATION RESISTANCE

Climatic Reliability of Electronics – Challenges and Perspectives
Mar. 21-22, 2024

Matthew A. Kottwitz and J. Elliott Fowler

Magnalytix

Case Western Reserve University & University of Central Florida

Georgia Institute of Technology & University of New Mexico

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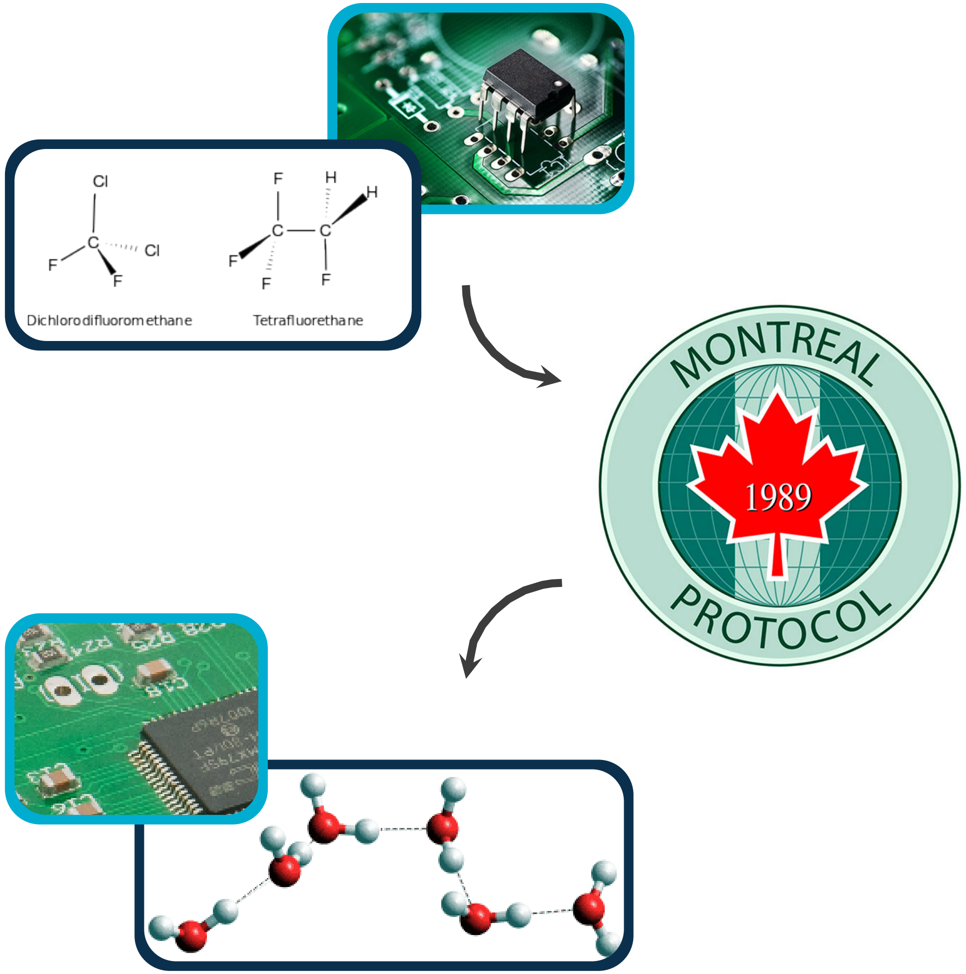
SAND2024-03108C

IPC J-STD-001H → HOW DID WE GET HERE?



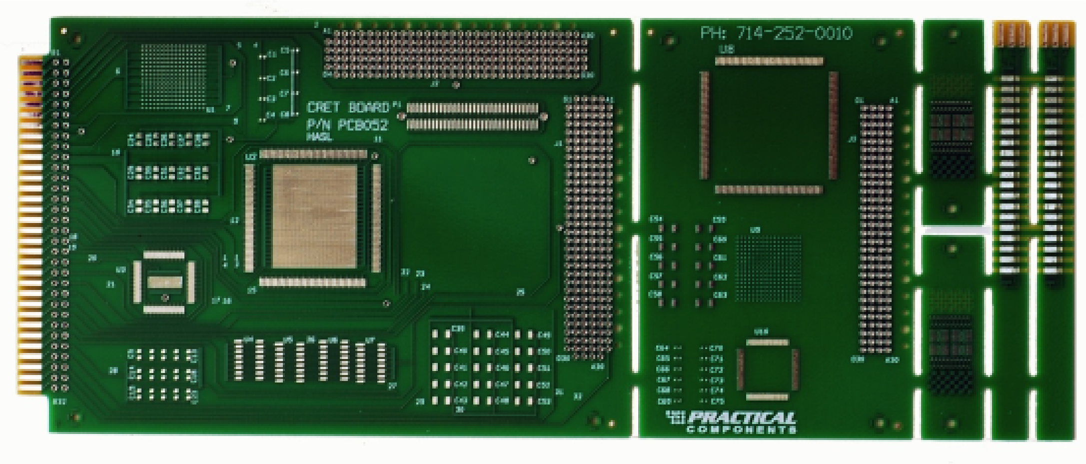
8.1 Qualified Manufacturing Process

…the Manufacturer **shall** qualify soldering and/or cleaning processes that result in acceptable levels of flux and other residues. Objective evidence **shall** be available for review…

…This may include

1. *Surface insulation resistance (SIR)*, possibly in combination with ion chromatography…
2. Historical evidence…
3. Electrical testing results… during extremes of temperature and humidity

FROM IPC-B-52 TO SNAP-OFF COUPONS



IPC-B-52

→ "...manufactured *using the same manufacturing process* and surface finish intended for the end-product."

→ Multiple test coupons assembled together (Main, IC, Solder Mask Adhesion, SIR mini,...)

Towards "snap-off" coupons

→ Manufactured *concurrently with* the end-product

→ Per panel qualification of cleanliness & reliability

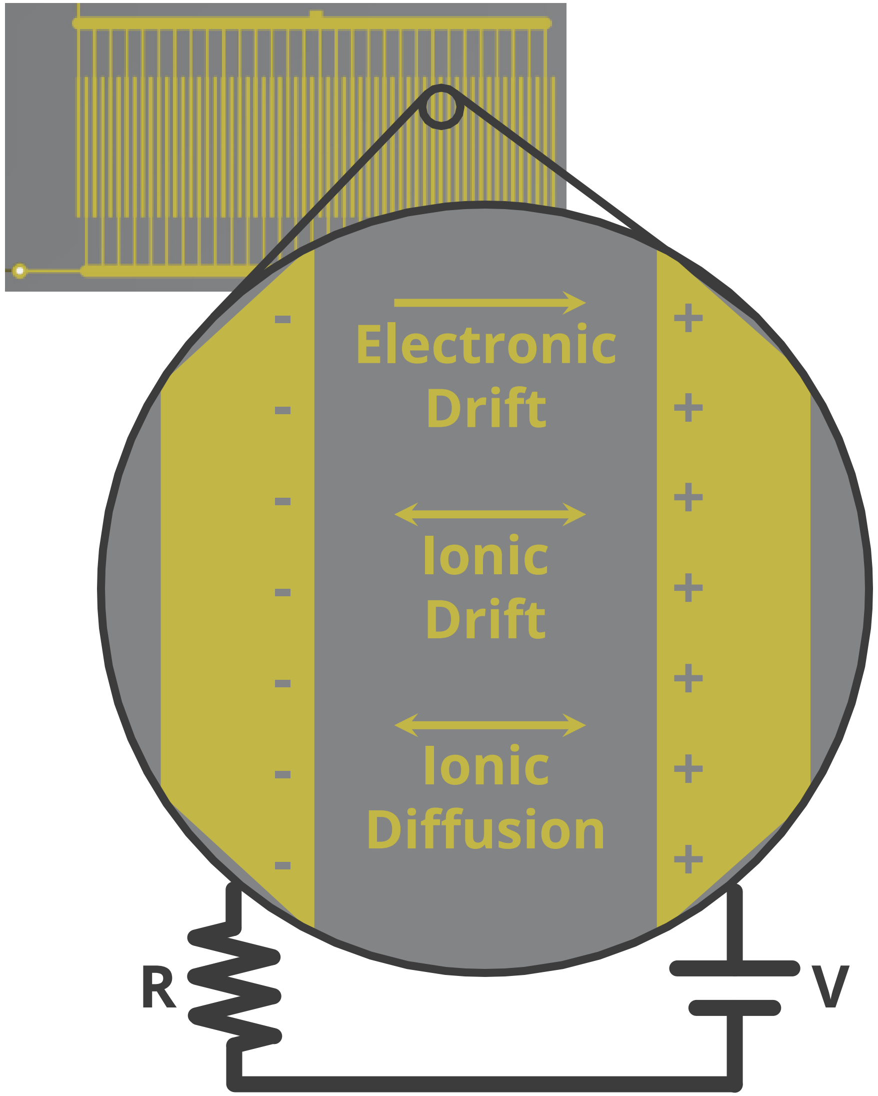
In either case...

→ Need for paradigm shift:
Qualitative (Binary) → Quantitative

→ *Mechanistic understanding of SIR*

IPC-B52 from Practical Components, Inc.
IPC-9203A

BASICS OF SIR



→ Test cards composed of interdigitated comb (IDC) or other (i.e., BGA, LGA, etc.) patterns

→ Elevated temperature/humidity chamber, DC bias (5 V), resistor (1 MΩ)

→ Current measured periodically

→ Underlying physical phenomena:

Electronic drift

Ionic drift/diffusion

→ Affected by:

Pattern design

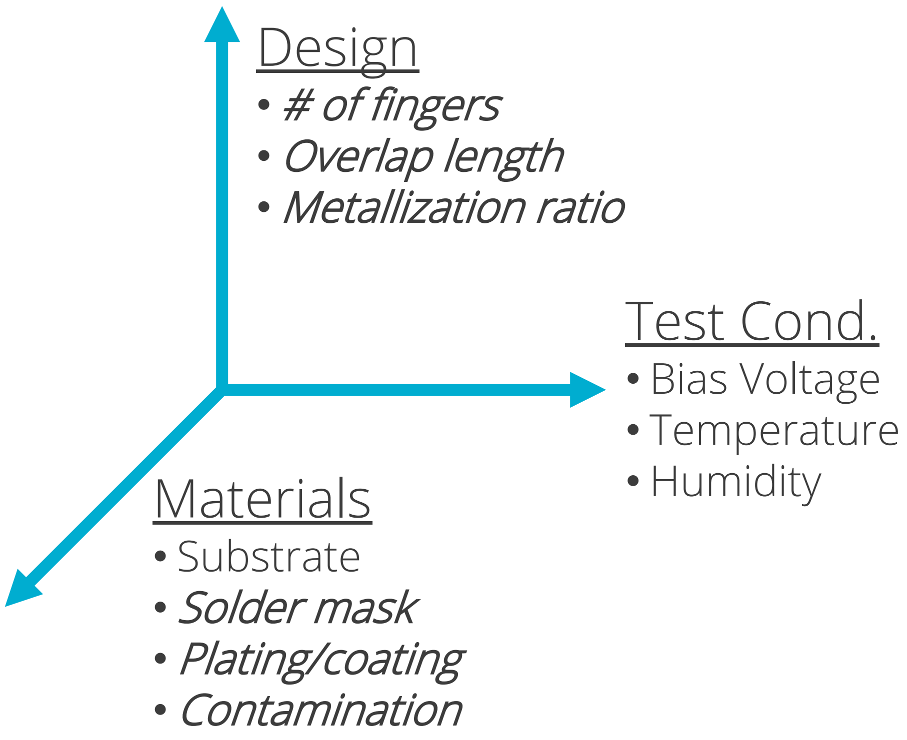
Materials

Test conditions

SYSTEMATIC EXPLORATION OF SIR PARAMETER SPACE

SIR Total Parameter Space

$$I = f(a, b, c, d, e, \ldots)$$



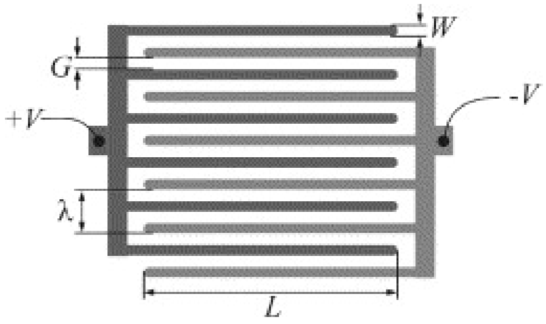
Explored Subspaces:

1. Square IDCs w/ constant capacitance
   FR-4 & Cu trace → cleaned
   25 °C & 40 %RH
2. Square IDCs w/ constant capacitance
   FR-4 & Cu trace → cleaned
   Varied temperature/humidity
3. Square IDCs w/ constant capacitance
   FR-4 & Cu trace *plus* ENEPIG and/or SM
   40 °C & 65 %RH
   Contamination type/level

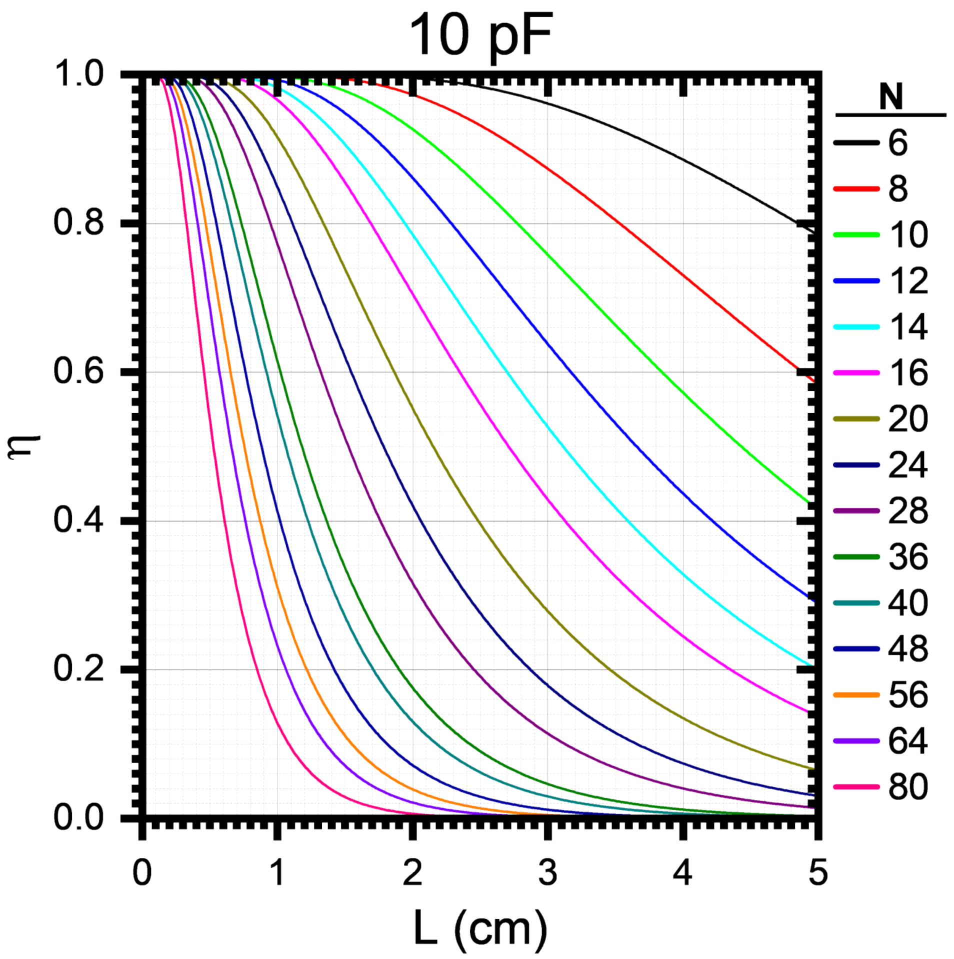
CAPACITANCE COMPUTATION

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

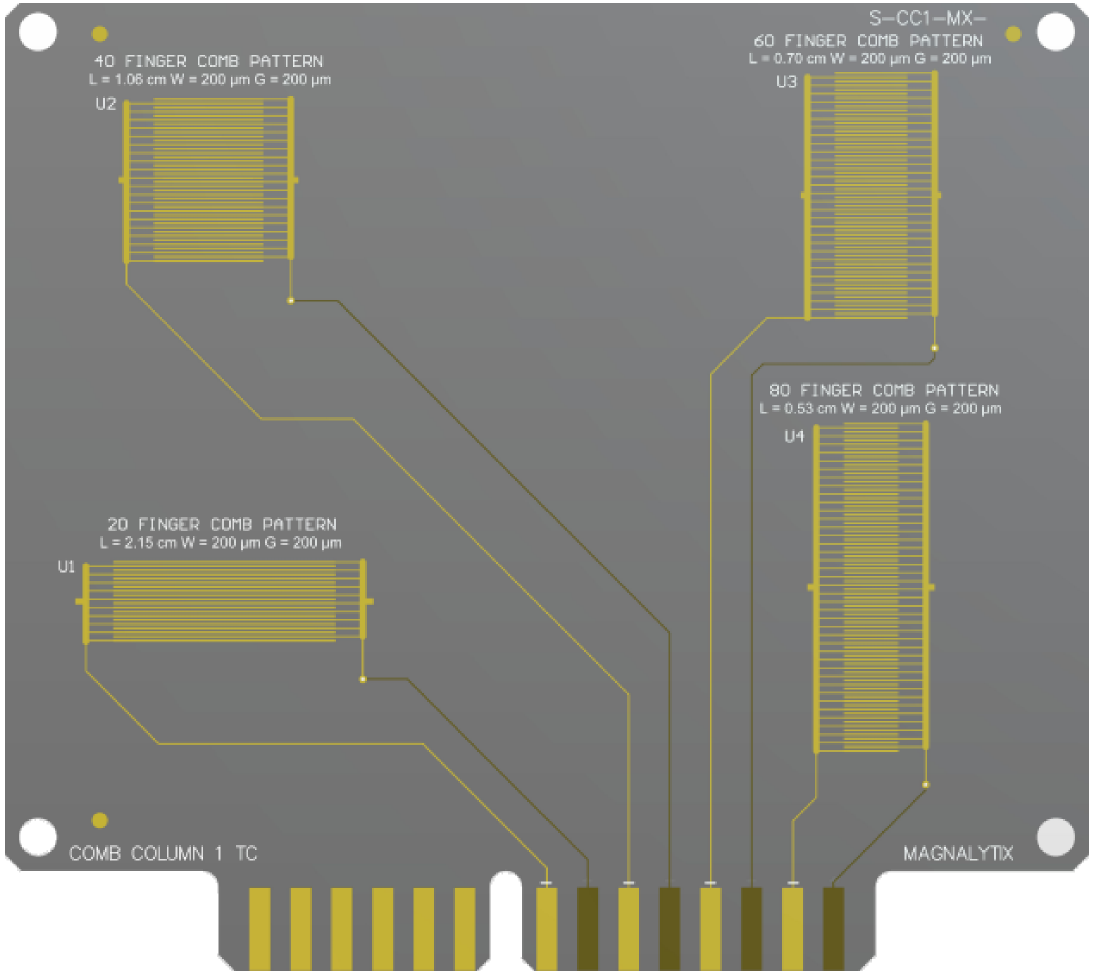
G – finger gap width

ε_r – relative permittivity

10 pF = 0.009 jars

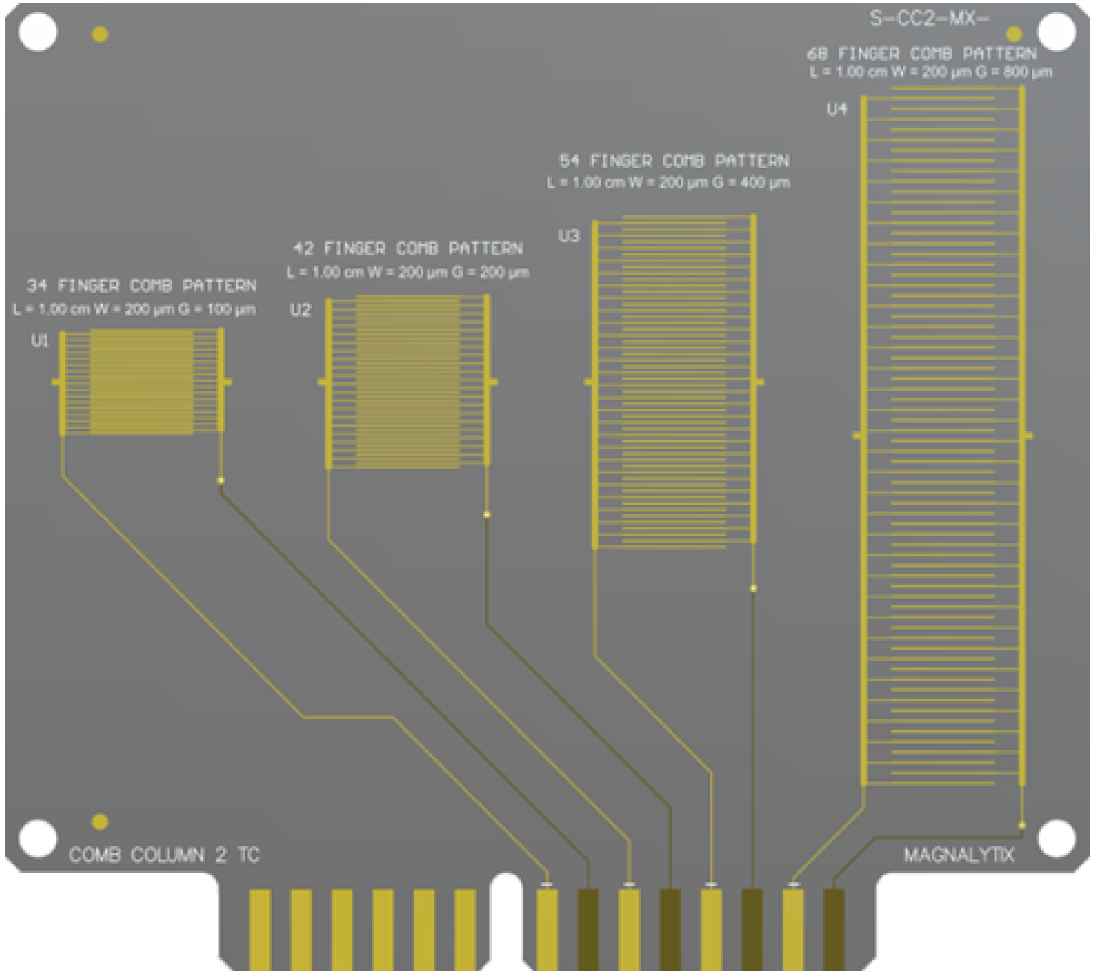
Further detail in supplementary slide

BOARD DESIGN 1



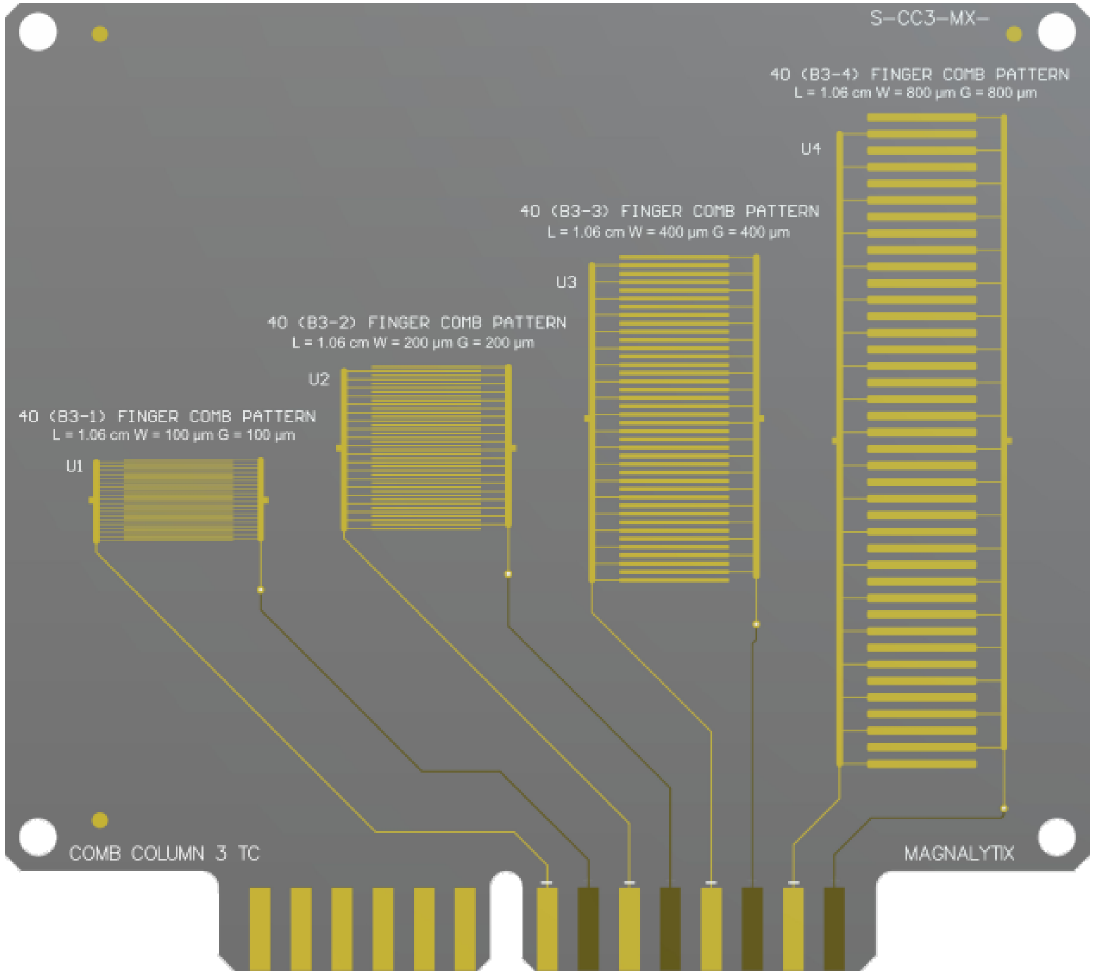
Design-Pattern	N	L (cm)	η	W (µm)	G (µm)	C (pF)
1-U1	20	2.15	0.5	200	200	9.99
1-U2	40	1.06	0.5	200	200	9.99
1-U3	60	0.70	0.5	200	200	9.95
1-U4	80	0.53	0.5	200	200	10.07

BOARD DESIGN 2



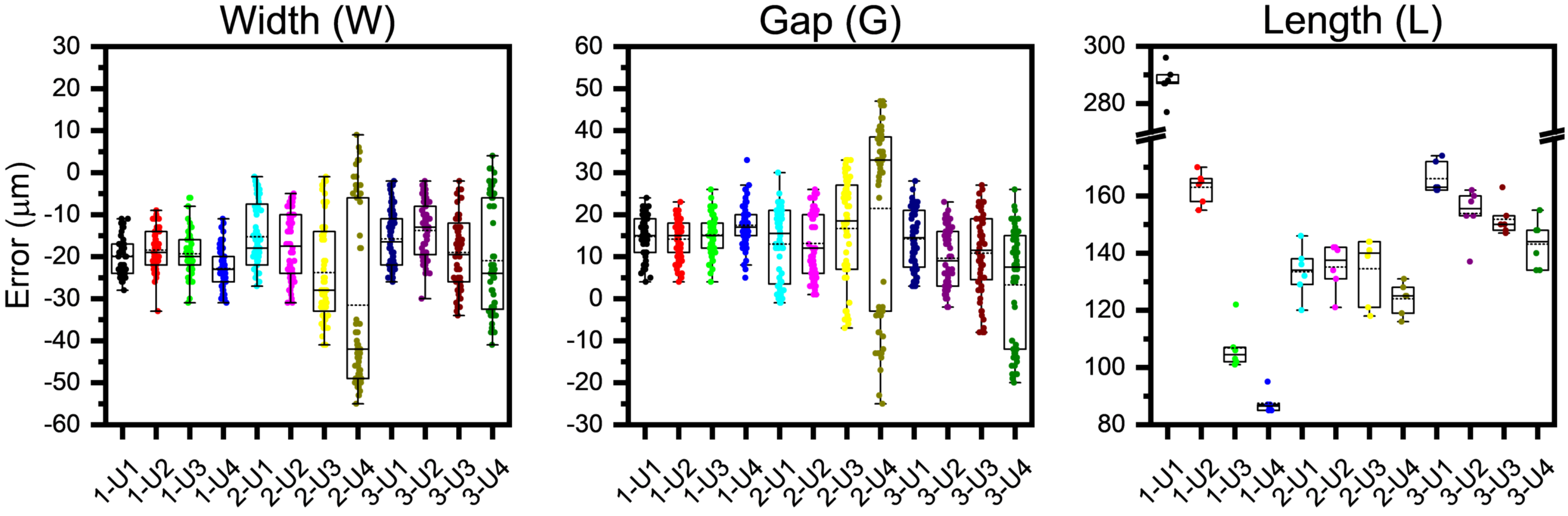
Design-Pattern	N	L (cm)	η	W (µm)	G (µm)	C (pF)
2-U1	34	1.00	0.67	200	100	10.21
2-U2	42	1.00	0.5	200	200	9.91
2-U3	54	1.00	0.33	200	400	10.00
2-U4	68	1.00	0.2	200	800	10.00

BOARD DESIGN 3

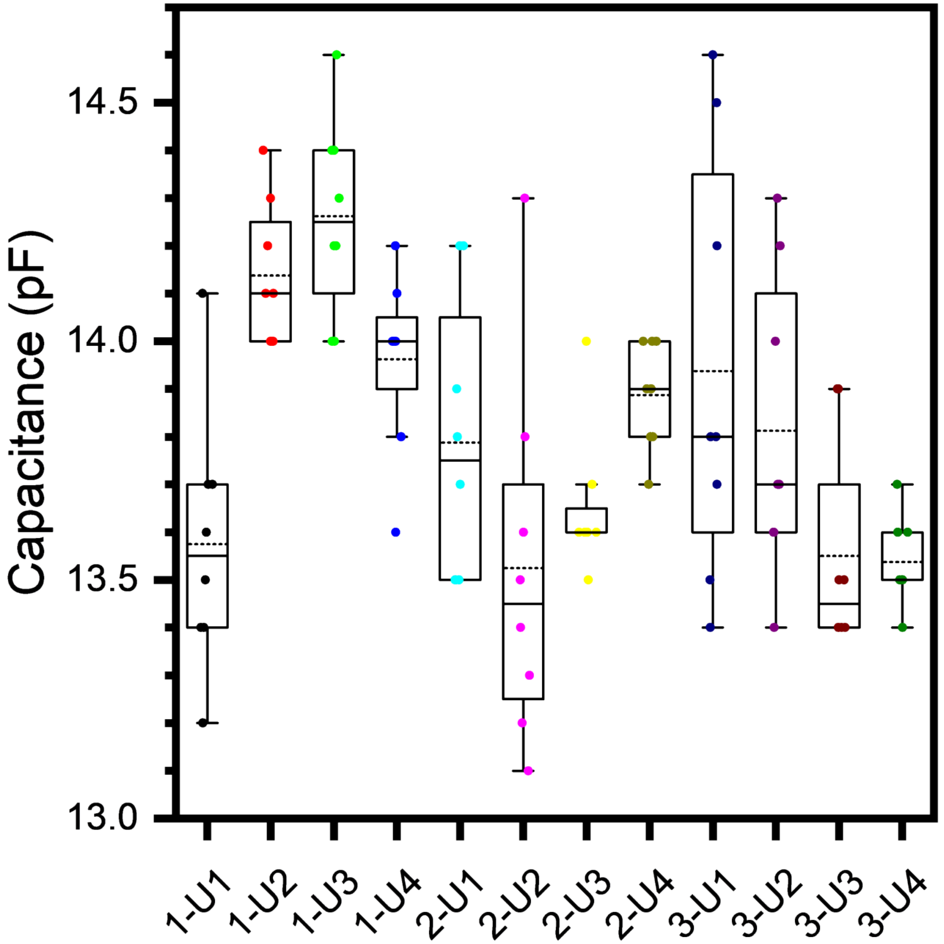


Design-Pattern	N	L (cm)	η	W (µm)	G (µm)	C (pF)
3-U1	40	1.06	0.5	100	100	9.99
3-U2	40	1.06	0.5	200	200	9.99
3-U3	40	1.06	0.5	400	400	9.99
3-U4	40	1.06	0.5	800	800	9.99

HOW WELL DID THE FAB SHOP DO?



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

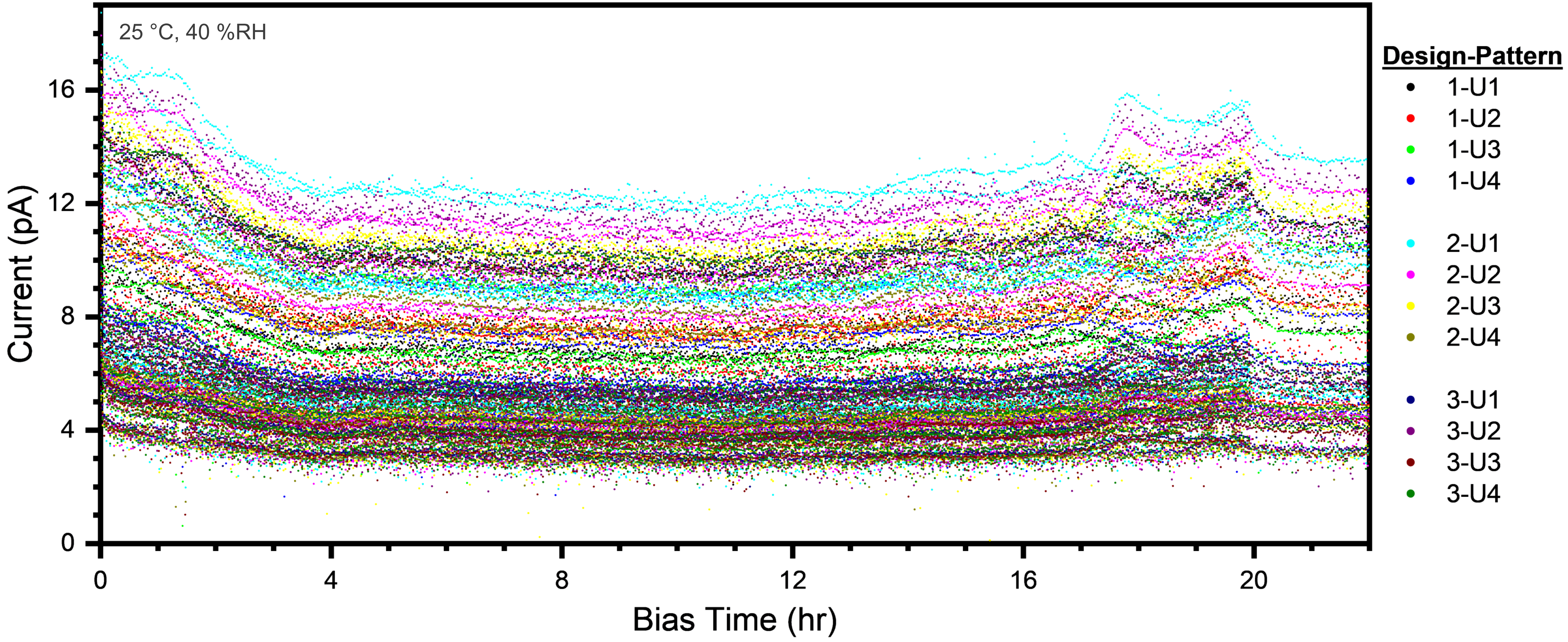
*assumes relative permittivity (ε_r) of 4.4

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

ALL DATA – SUBSPACE #1

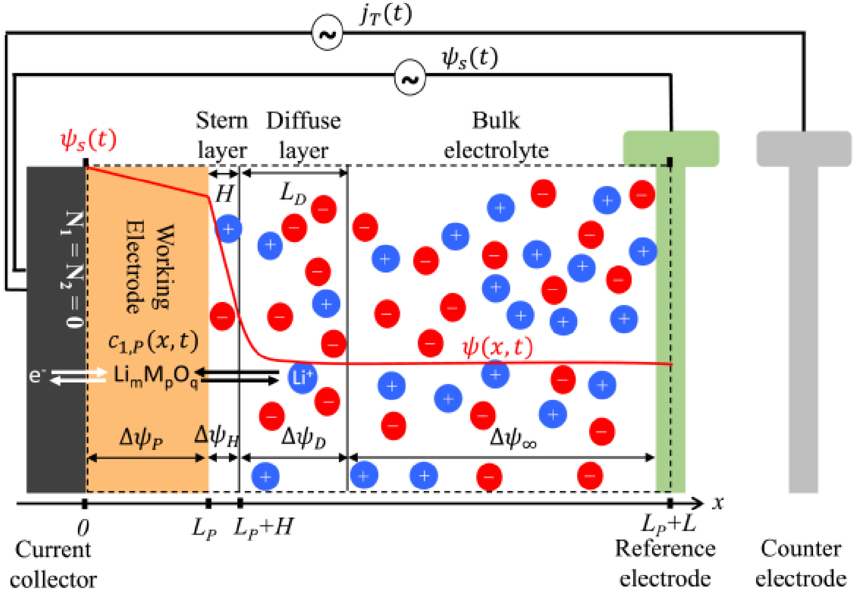
10 pA = 62,400,000 electrons/s



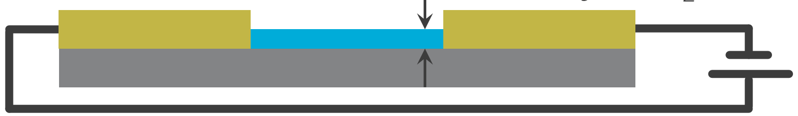
CHRONOAMPEROMETRY – A PLAUSIBLE MODEL

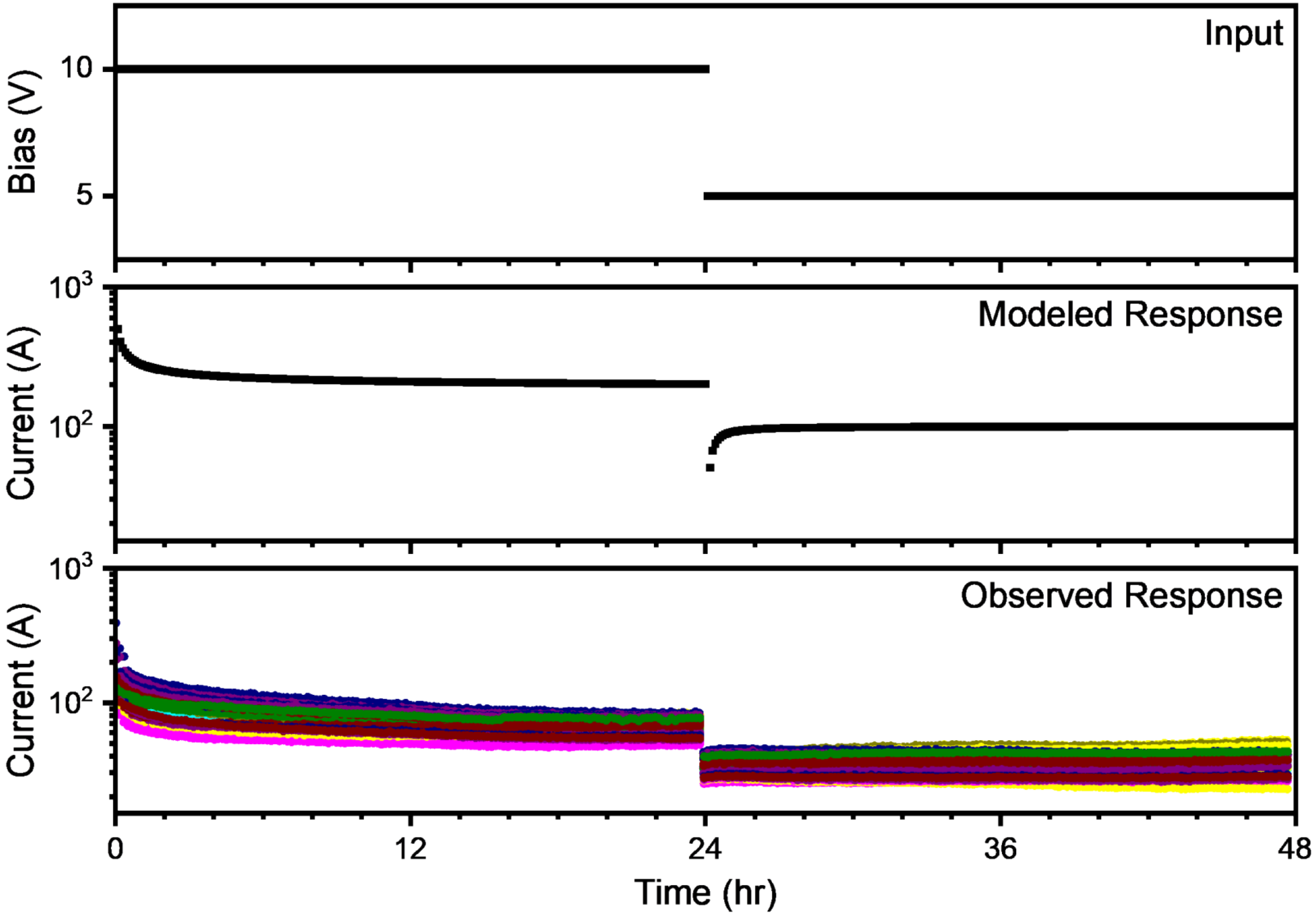
Sam Grosso
University of New Mexico
(Prof. Fernando Garzon)

3-Electrode Schematic



SIR Schematic





Electrochimica Acta (2019) 321, 134648
Encyclopedia of Applied Electrochemistry, pp 207-214

$$i = \frac{nFAc_j^0\sqrt{D_j}}{\sqrt{\pi t}}$$

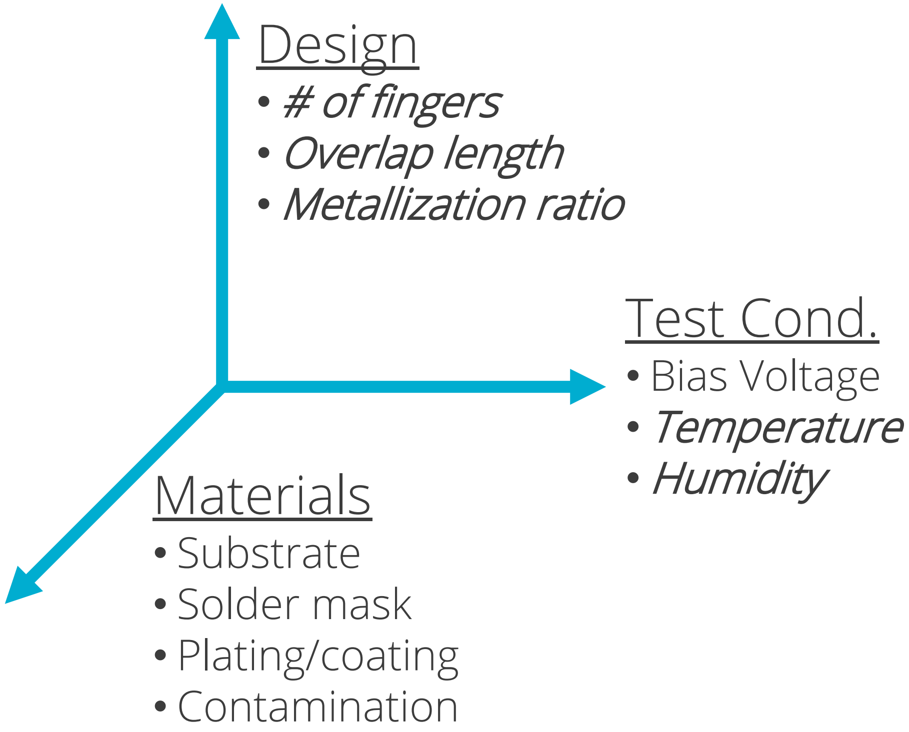
n = # of e^-
c_j^0 = initial conc.
F = Faraday const.
D_j = diff. coeff.
A = electrode area
t = time

UUR

SYSTEMATIC EXPLORATION OF SIR PARAMETER SPACE

SIR Total Parameter Space

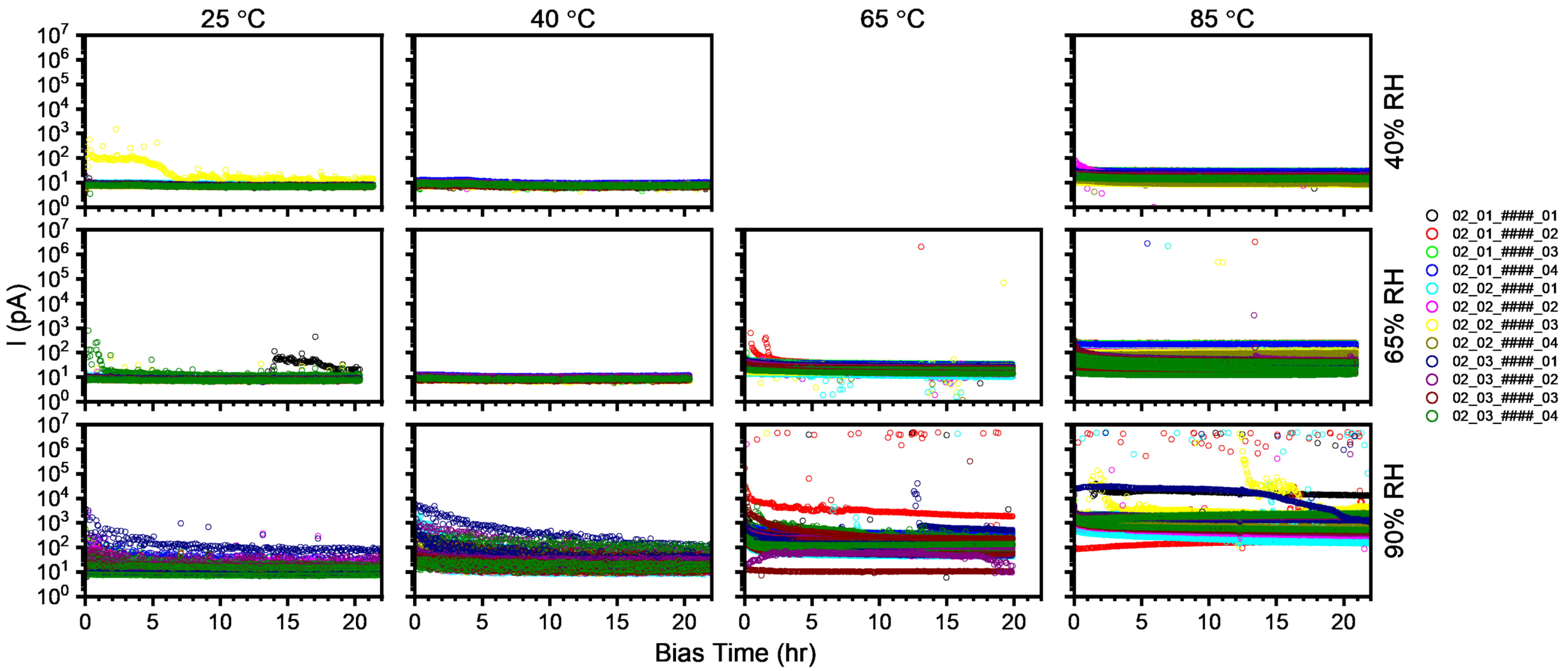
$$I = f(a, b, c, d, e, \dots)$$



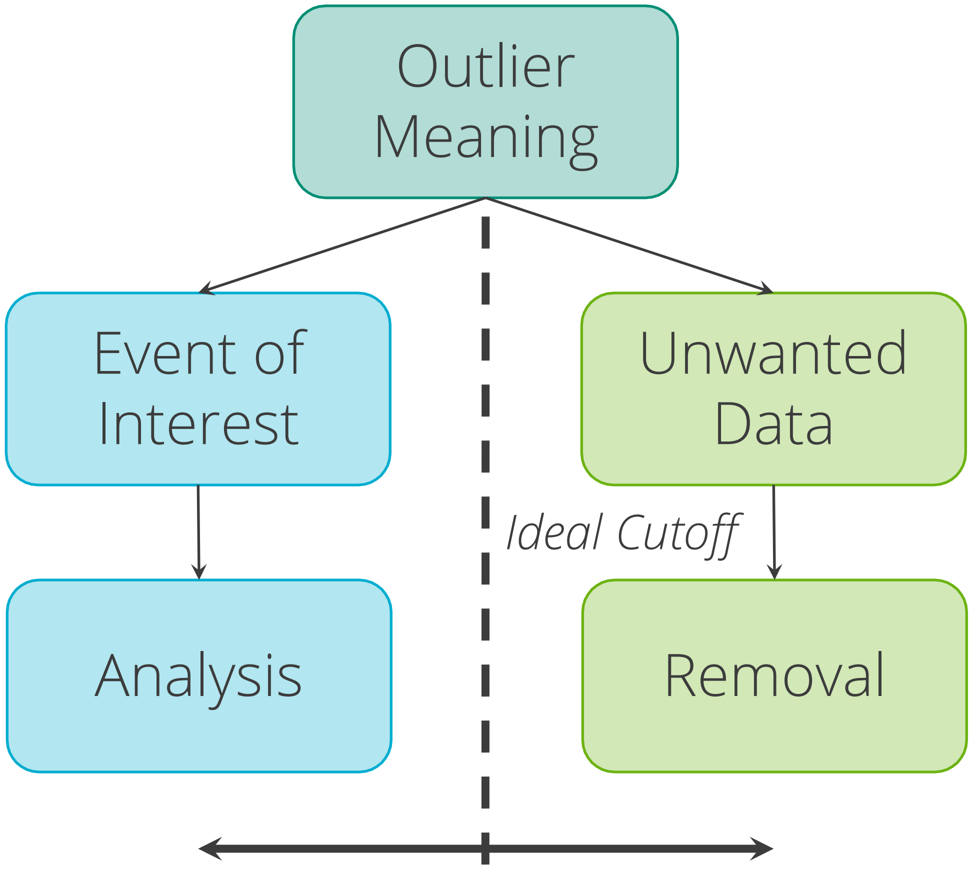
Explored Subspaces:

1. Square IDCs w/ constant capacitance
   FR-4 & Cu trace → cleaned
   40 °C & 90 %RH
2. **Square IDCs w/ constant capacitance**
   FR-4 & Cu trace → cleaned
   Varied temperature/humidity
3. Square IDCs w/ constant capacitance
   FR-4 & Cu trace *plus* ENEPIG and/or SM
   40 °C & 65 %RH
   Contamination type/level

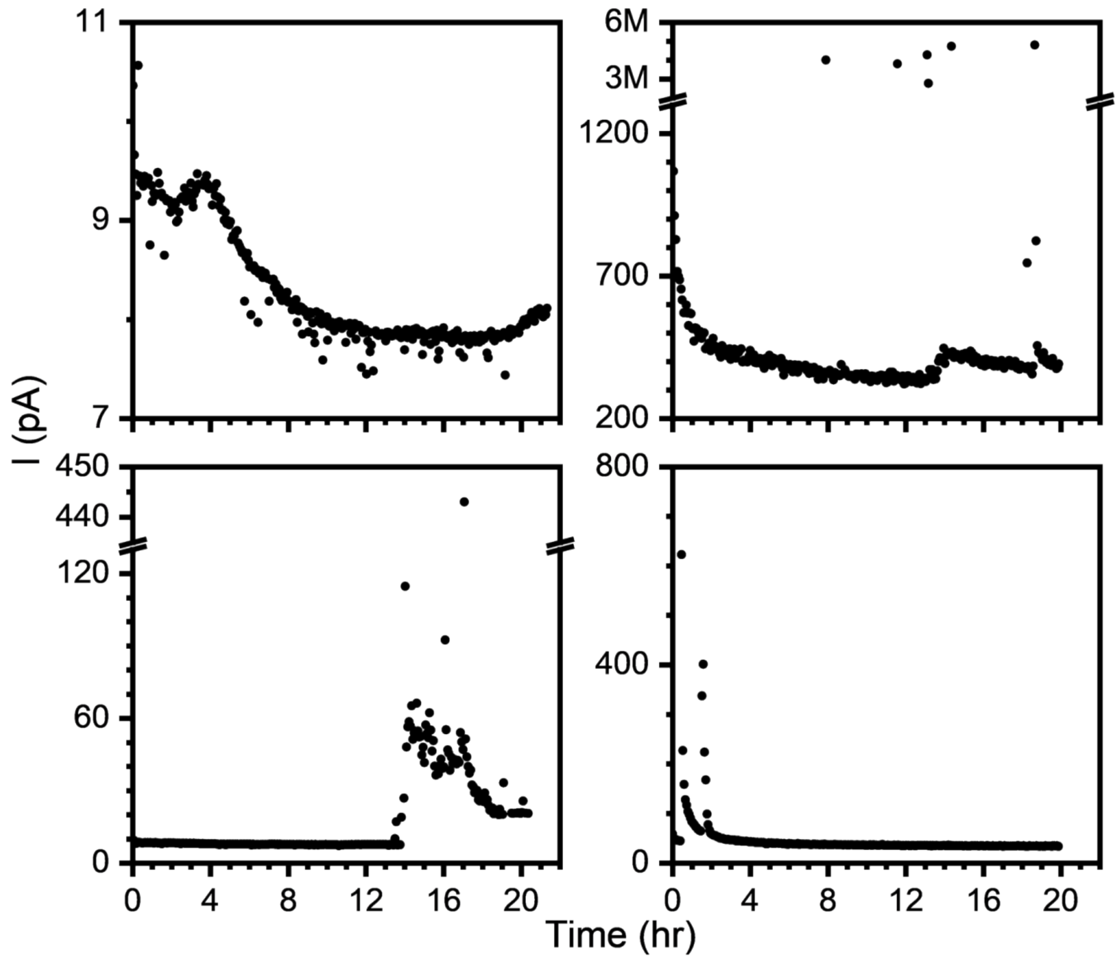
ALL DATA – RAW (SUBSPACE #2)



TIME SERIES ANOMALY DETECTION

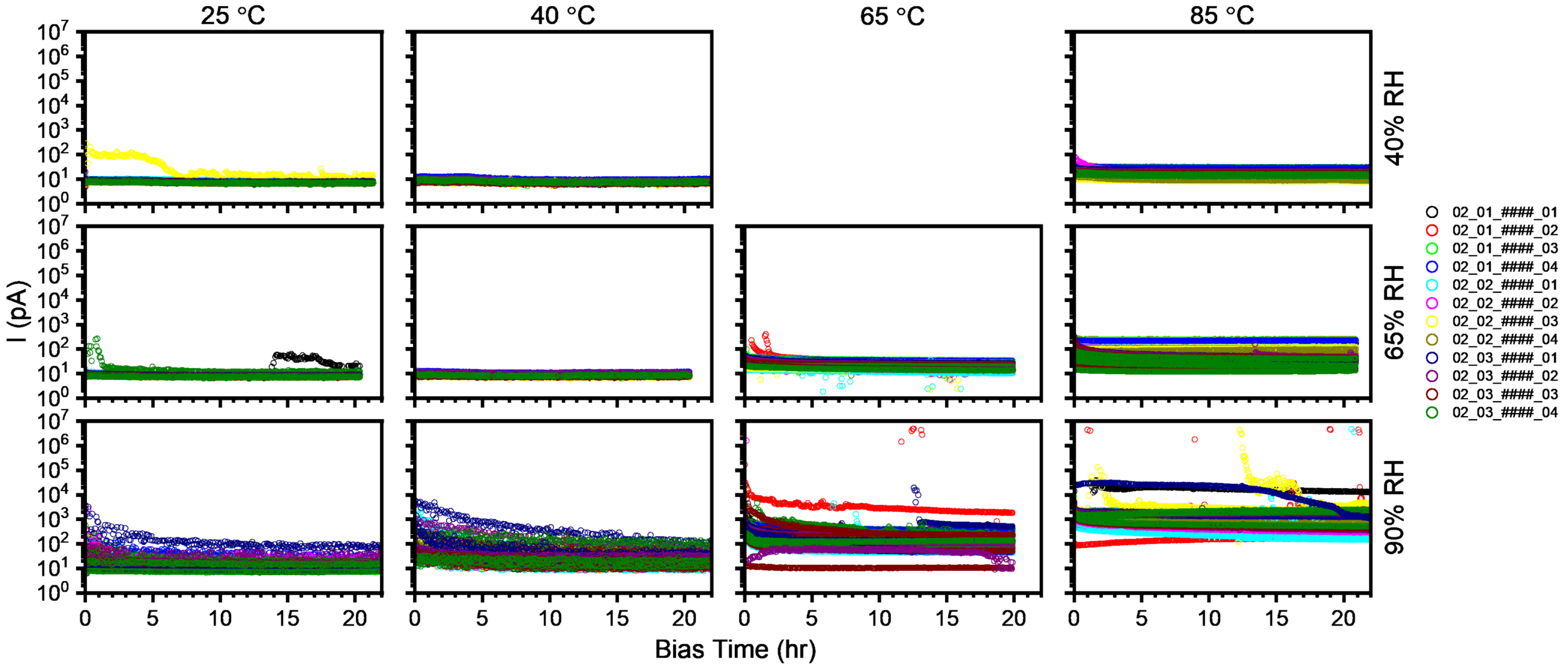


Adapted from neptune.ai/blog/anomaly-detection-in-time-series

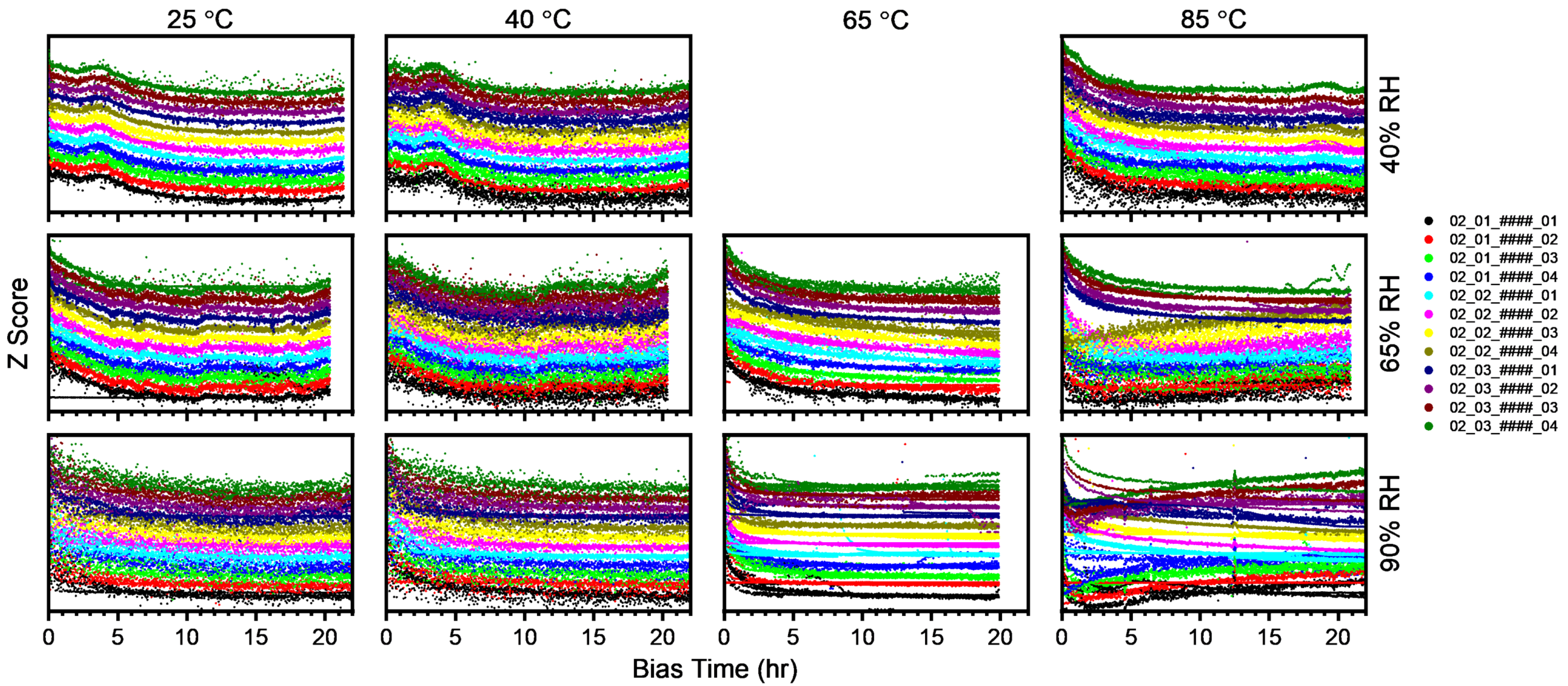


(TL) 02_03_0251_01 @ 25 °C, 40% RH; (TR) 02_01_0057_02 @ 65 °C, 90% RH; (BL) 02_01_0176_01 @ 25 °C, 65% RH; (BR) 02_01_0002_02 @ 65 °C, 65% RH;

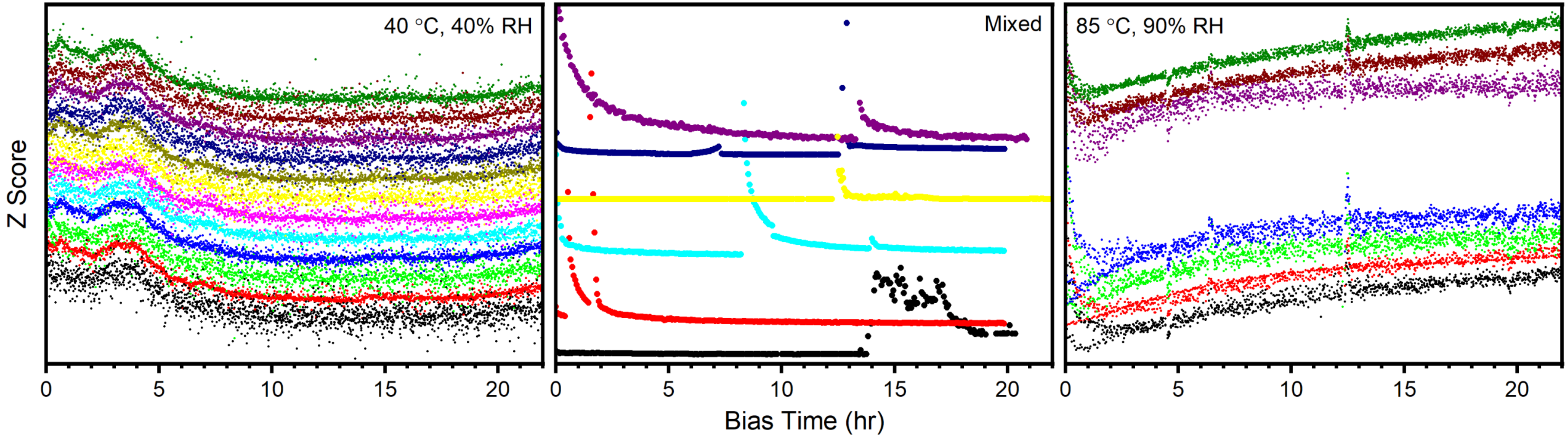
ALL DATA – CLEANED



ALL DATA – CLEANED & NORMALIZED (W/ OFFSET)



(SOME) ARCHETYPES OF DEVIATION



Early (3-4 hr) bump in current
→ Also seen in 25 °C, 40% RH
→ "Delayed Faradaic Response"?
→ Related to Rel. Humidity (water layer thickness)?

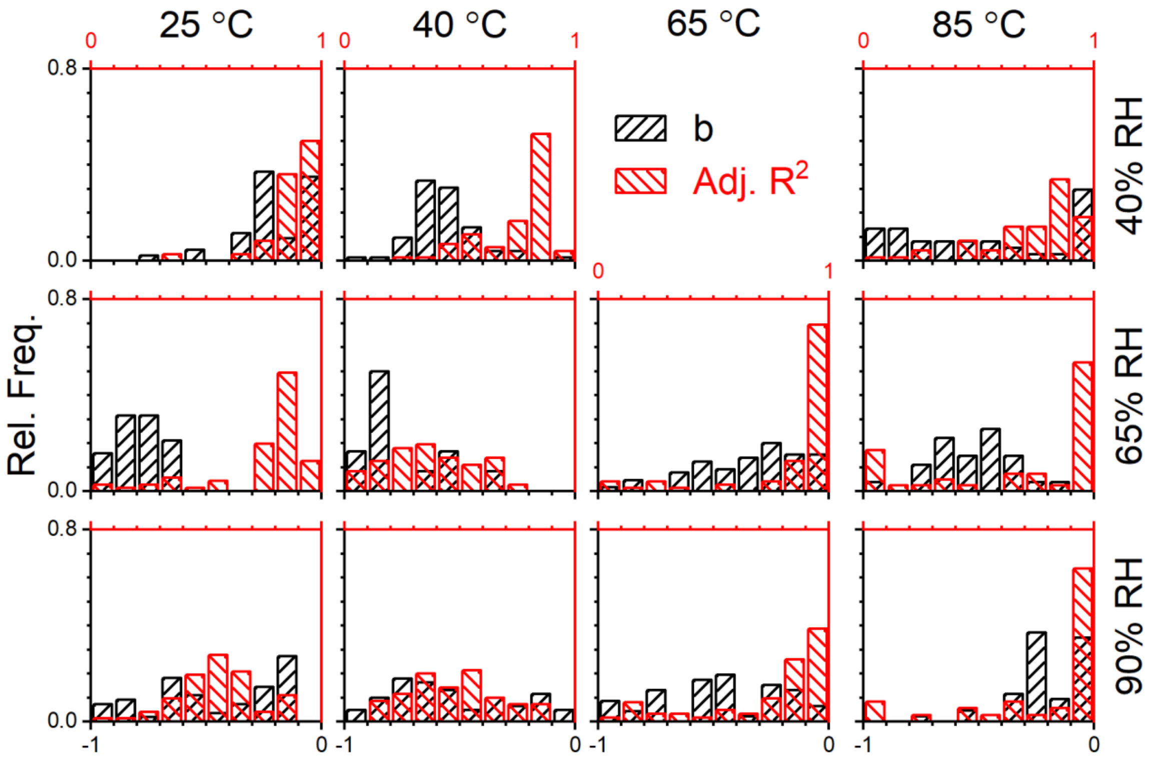
Current spikes
Early → water droplets?
Late → ECM?
→ Likelihood predicted by early current response?

Increasing baseline current
→ Unique to high Temp. (more water in chamber)
→ Induced materials degradation?
Current spike (~12-13 hr)
→ Instrument issue

POWER SERIES FITTING → COTTRELL + LEAKAGE?

Cottrell: $i = \frac{nFAc_j^0\sqrt{D_j}}{\sqrt{\pi t}} = kt^{-1/2}$

Power Series: $i = at^b + c$



c → Leakage Current?

°C\% RH	25	40	65	90
40	1.9 ±2	6.2 ±0.6		15 ±7
65	7.8 ±0.9	8.1 ±0.7	12 ±10	95 ±70
85	9.0 ±8	10 ±8	1600 ±9000	2200 ±8000

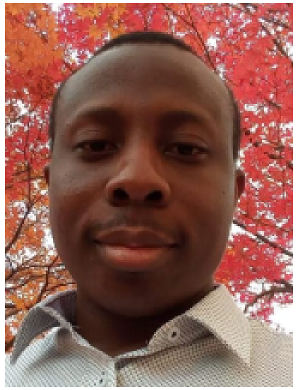
↓ Fitted "Leakage Current" values increase with temp., rel. humidity

→ Inconsistent fitting results – exponent (b) and quality (adj. R^2)

CALLING ON (REAL) STATISTICIANS

Variable	Importance Score for Predictor to Current
L = 1.06 cm	22.26
L = 2.15 cm	3.08
L = 0.53 cm	18.97
L = 0.7 cm	22.85
G = 200 µm	13.88
G = 400 µm	17.57
G = 800 µm	29.68
W = 200 µm	11.08
W = 400 µm	3.42
W = 800 µm	13.79
Temp.	204.61
Rel. Hum.	297.63

Increase with contamination? (mass transport)



Ayorinde Olatunde
Case Western Reserve University
(Prof. Anirban Mondal)

SYSTEMATIC EXPLORATION OF SIR PARAMETER SPACE

SIR Total Parameter Space

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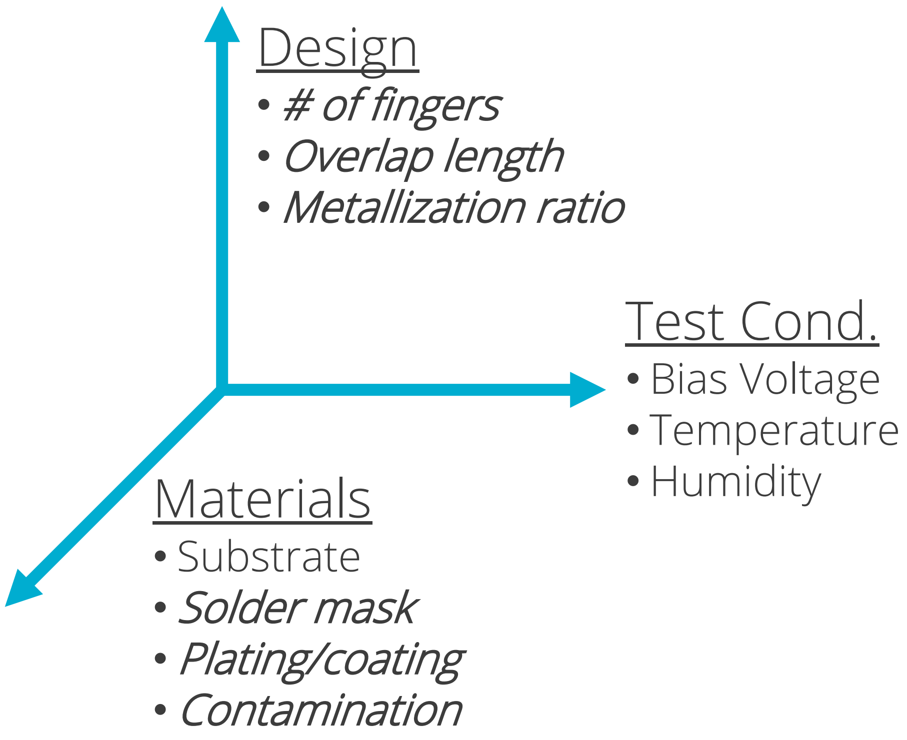

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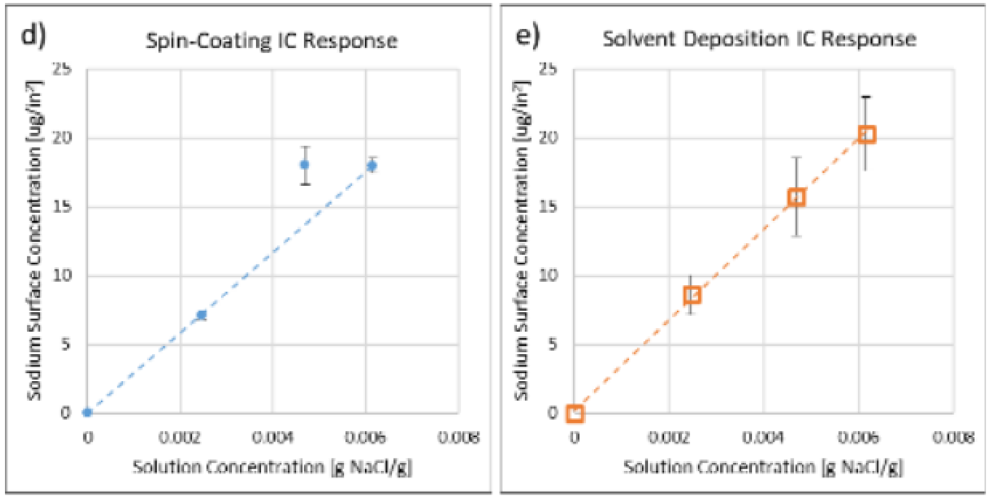
   Contamination type/level

DELIBERATE CONTAMINATION

Indium 8.9 HF POP LV
- Adipic Acid
- Succinic Acid

(High) & (Low) contamination levels
- Relevant surface concentrations?

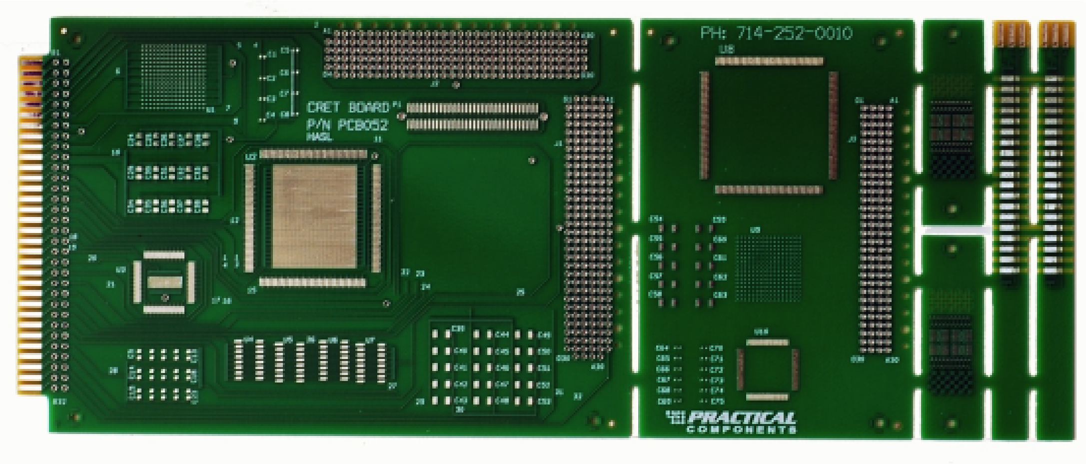
Currently developing methodology
- High throughput needs → 60-80 boards in < 4 hours
- Dip coating?
- Aerosol?



Evaluation of Techniques for Intentional Contamination of PWB Substrates for Quantitative Cleanliness Analysis
SMTA Pan Pac

Dr. Adam Klett
KYZEN

CLOSING THOUGHTS



Towards Mechanistic Understanding

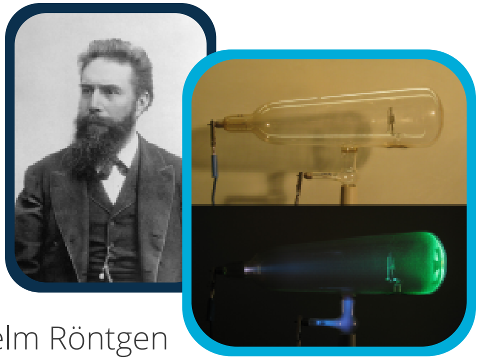
→ Contamination effects

→ Real geometries

→ Model refinement

→ Behavior prediction

IPC-B52 from Practical Components, Inc.

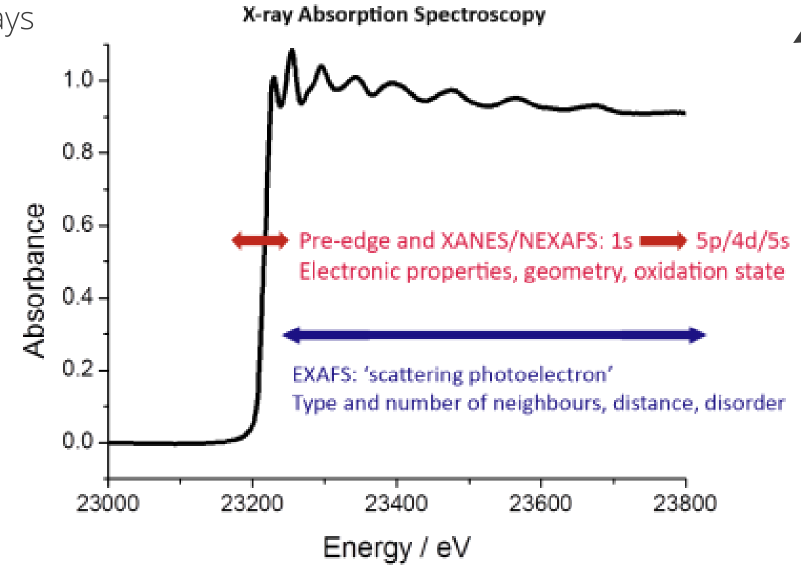


Wilhelm Röntgen
Nobel Prize in Physics 1901
Discovery of X-rays

Binary:
Flesh vs Bone/Metal
(i.e. 1E8 Ohms)

Method Development

SIR as a ***quantitative*** probe of physical phenomena



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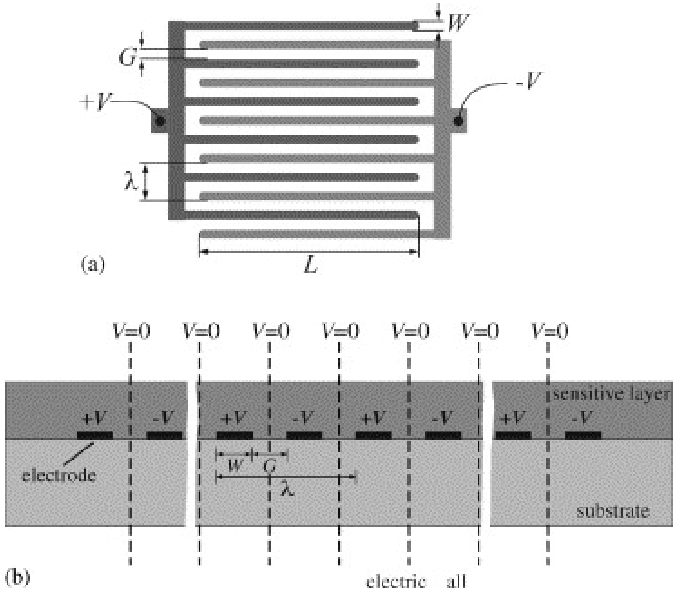
SAND2024-03108C

CAPACITANCE COMPUTATIONS



N – number of fingers

L – finger overlap length

η – metallization ratio

W – finger width

G – finger gap width

ε_r – relative permittivity

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

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

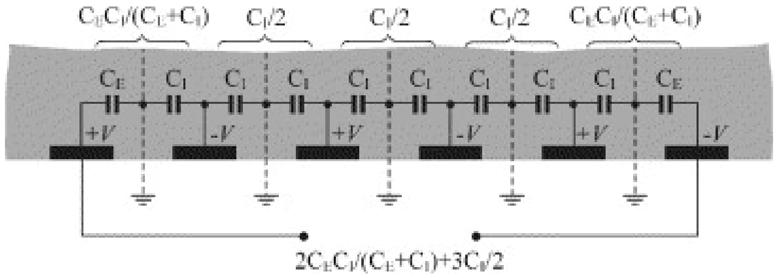
$$C_E = C_{E,air} + C_{E,S} = \varepsilon_0 L(K(k_{E\infty})/K(k'_{E\infty}) + \varepsilon_S\, K(k_{E\infty})/K(k'_{E\infty}))$$

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

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

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

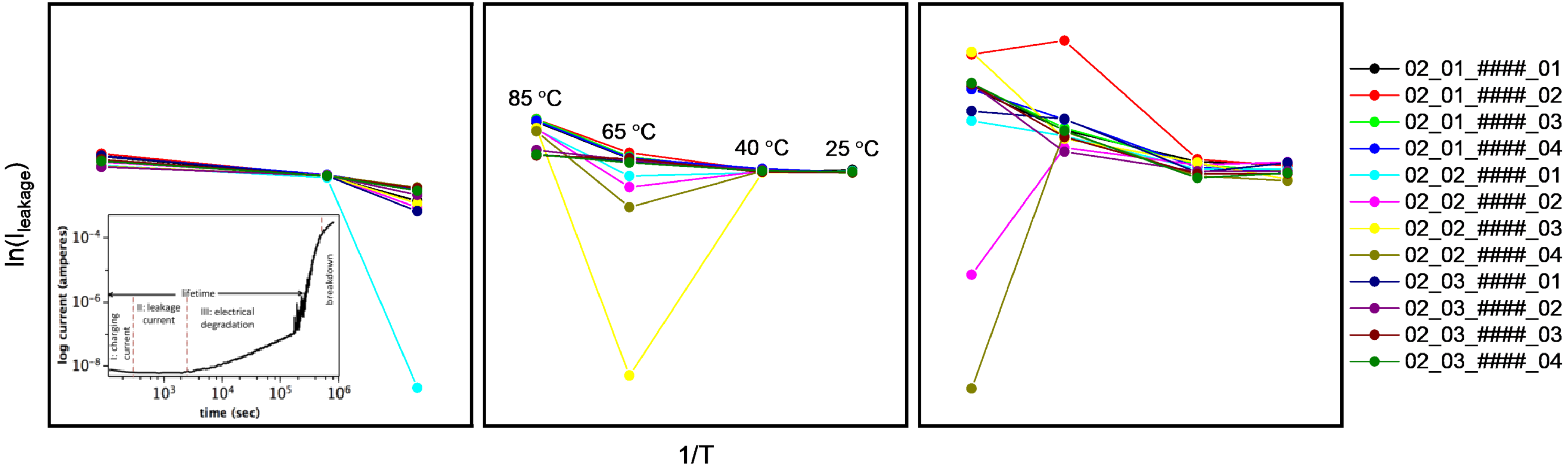
$$k' = \sqrt{1-k^2}$$



"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

ARRHENIUS PLOTS → E_A OF DEGRADATION?



Cottrell:

$$i = \frac{nFAc_j^0\sqrt{D_j}}{\sqrt{\pi t}} = kt^{-1/2} \quad \rightarrow$$

Power Series:

$$i = at^b + c$$

$$c = \text{leakage current}$$

Fitting Restraints:
$b < 0 < a, c$