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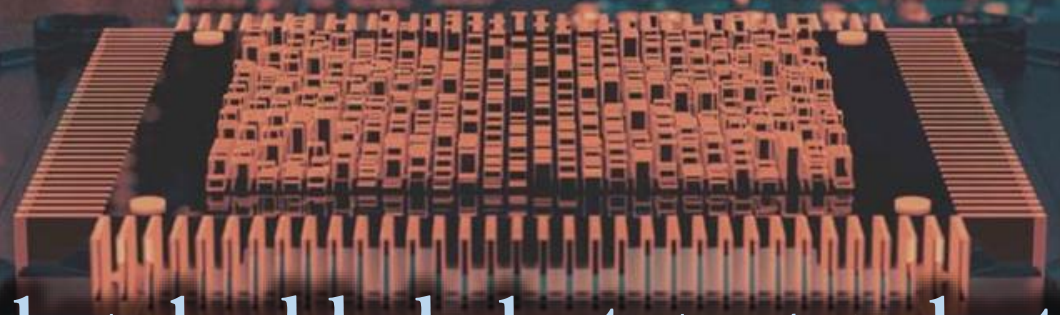

Liquid metal embedded elastomers: electromigration characterization and use in stretchable sensors

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April 2024

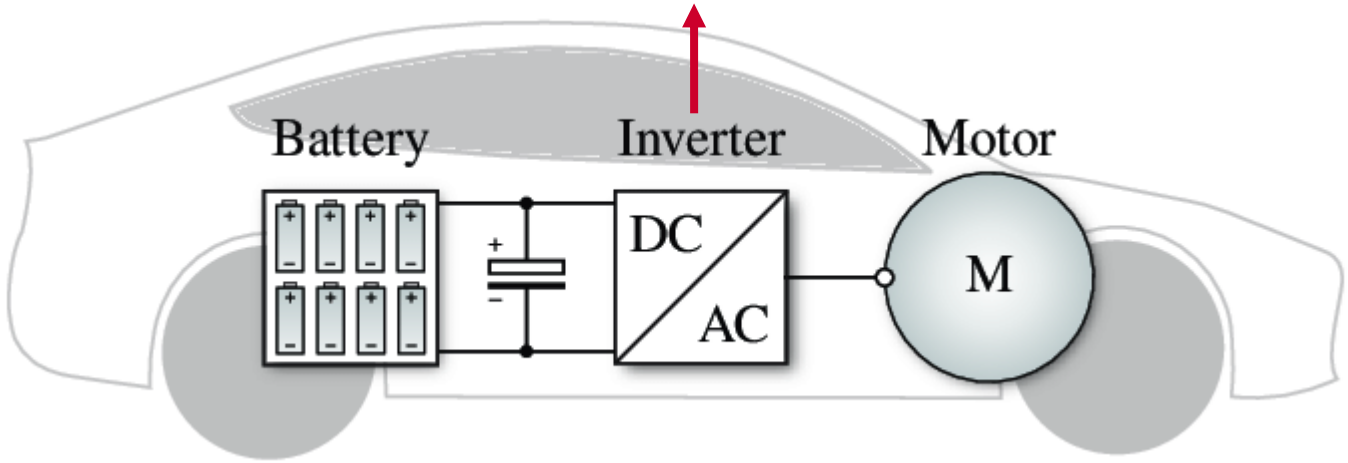
FMEA for ion migration and electromigration

FMEA: Failure mode and effects analysis

Motivation for studying ion migration & electromigration

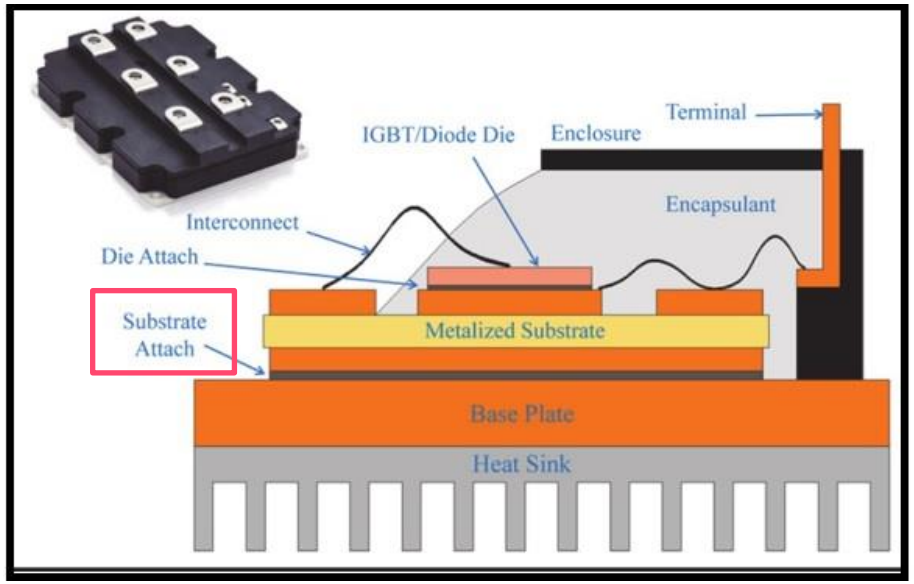
- Power inverters drive the motors in EVs
- Managing their thermal output (heat) requires substrate attach materials,
- These degrade under applied external field

Fisher Electronic, GmbH



Cittanti, IEEE Access, 2022

Montazeri, J. Elec. Pack., 2023



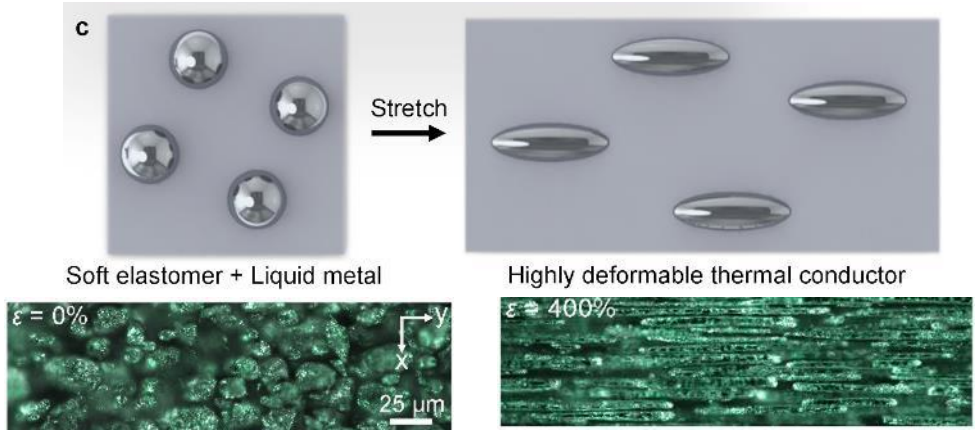
Universal Instruments Company

Internship objective to enable studies

- Design a test apparatus and protocols for characterization of the ion migration and electromigration failure mode for:
  - Electrically insulating materials (e.g., thermal interface material)
  - Electrically conductive materials (e.g., conductive inks)

Liquid Metal

from Chiechi, Angew. Chemie - Int. Ed. 2008



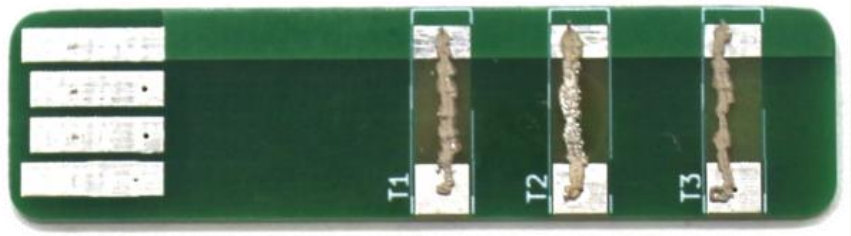
Liquid Metal Embedded Elastomers (LMEE)

from Bartlett, PNAS, 2017

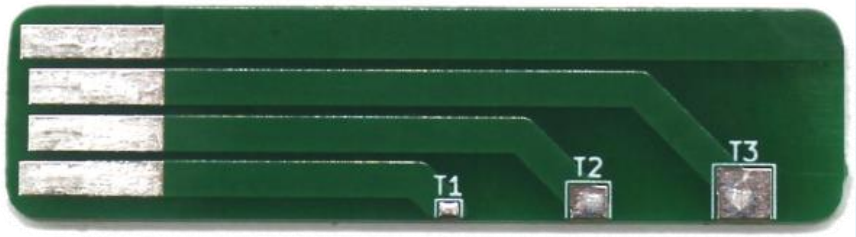
Initial prototype of the test apparatus

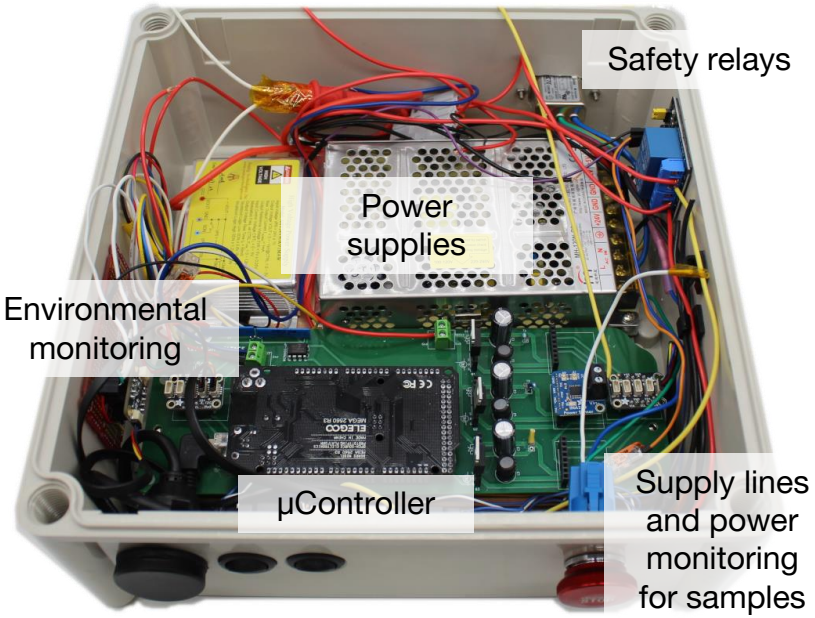
- Designed logic board to connect components, assembled on lab bench
- Main features
  - Controlled current through sample,
  - Controlled voltage across sample thickness,
  - Measure electrical resistance,
  - Establish high voltage field

Configuration 1: for conductive traces

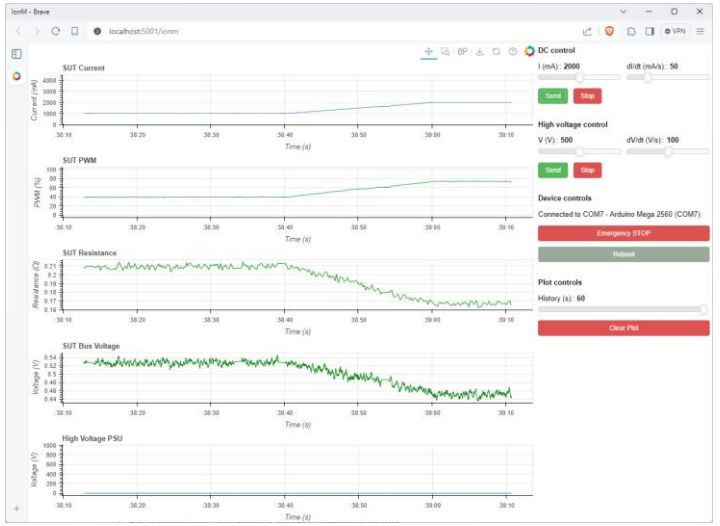


Configuration 2: for non-conductive interfaces



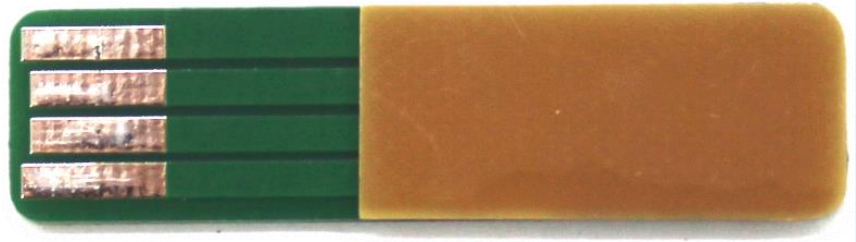


Custom Datalogger Software

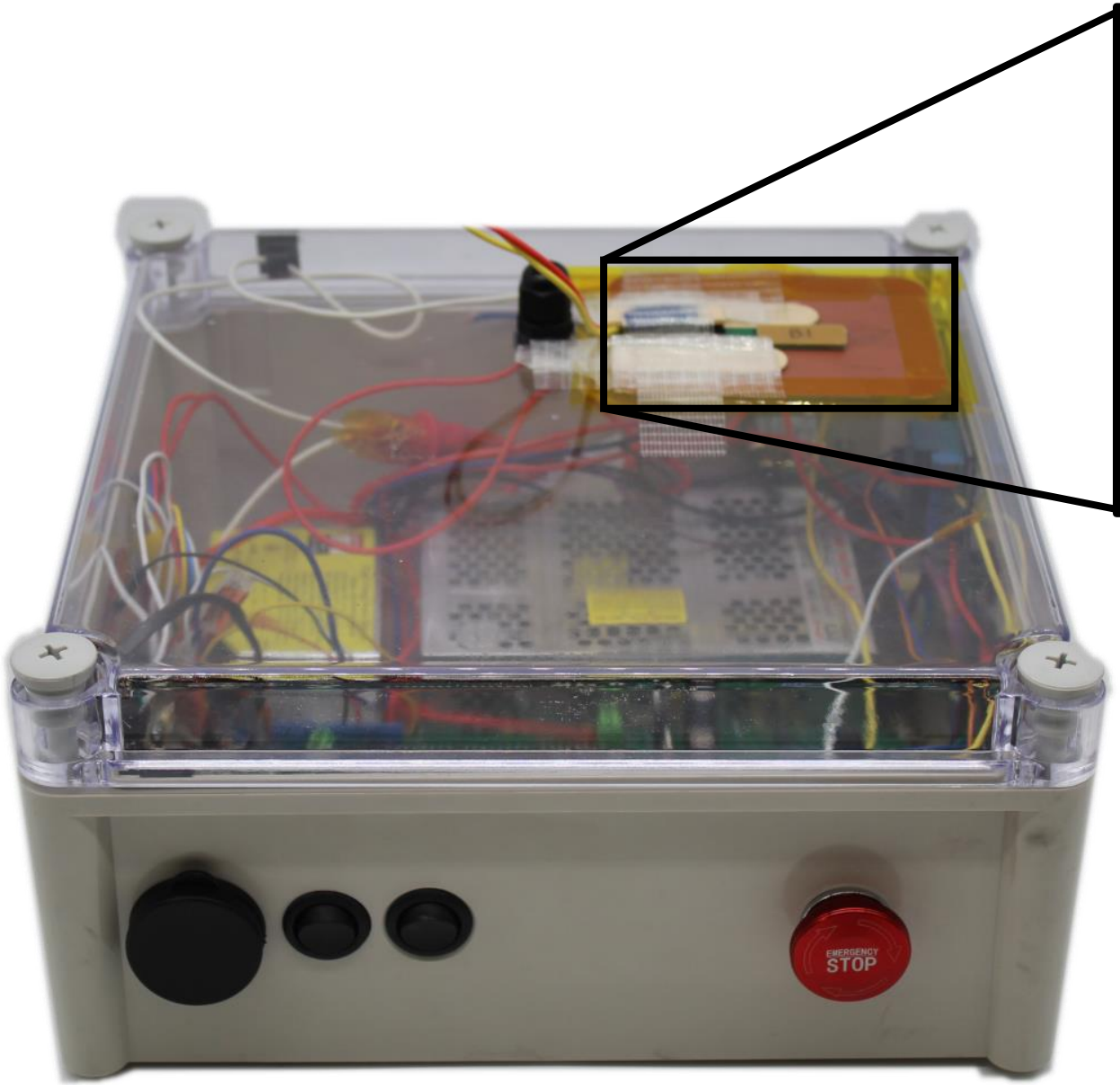


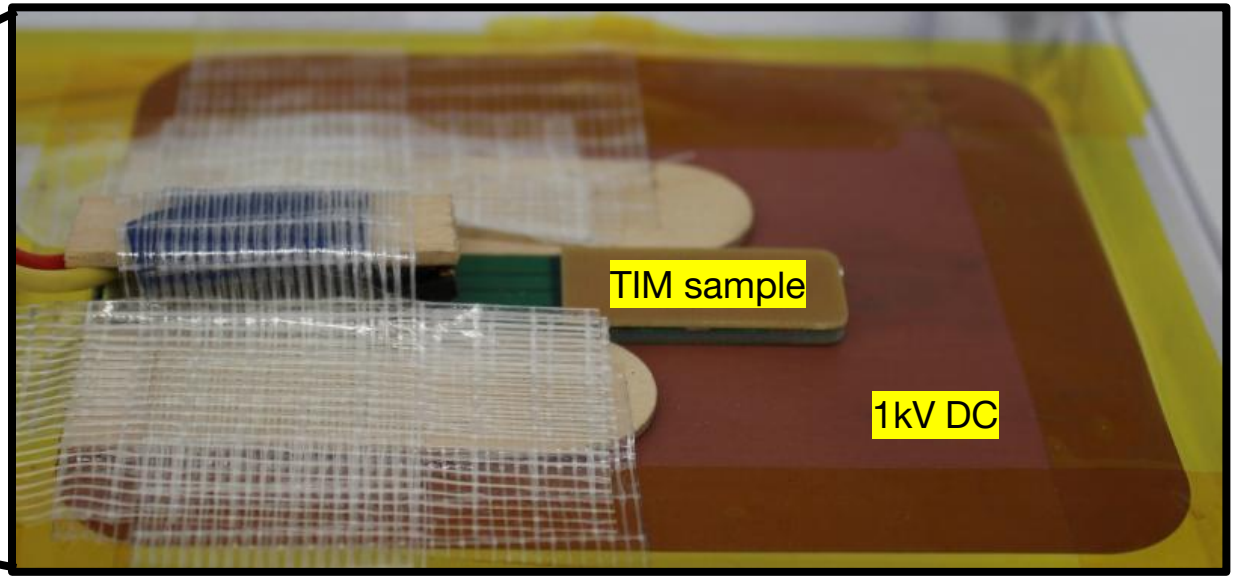
Unstacked

Stacked



Operating with sample under test





- Sample slides under spring contacts for biasing (TIM) or current delivery (trace)
- Directly on top of large-area copper-clad polyimide electrode
- TIM stack-up (from top): bias electrode, TIM, bias electrode, 0.8mm FR4, polyimide, high voltage electrode

Trace testing with oxidized liquid metal (OGaIn)

Capabilities:

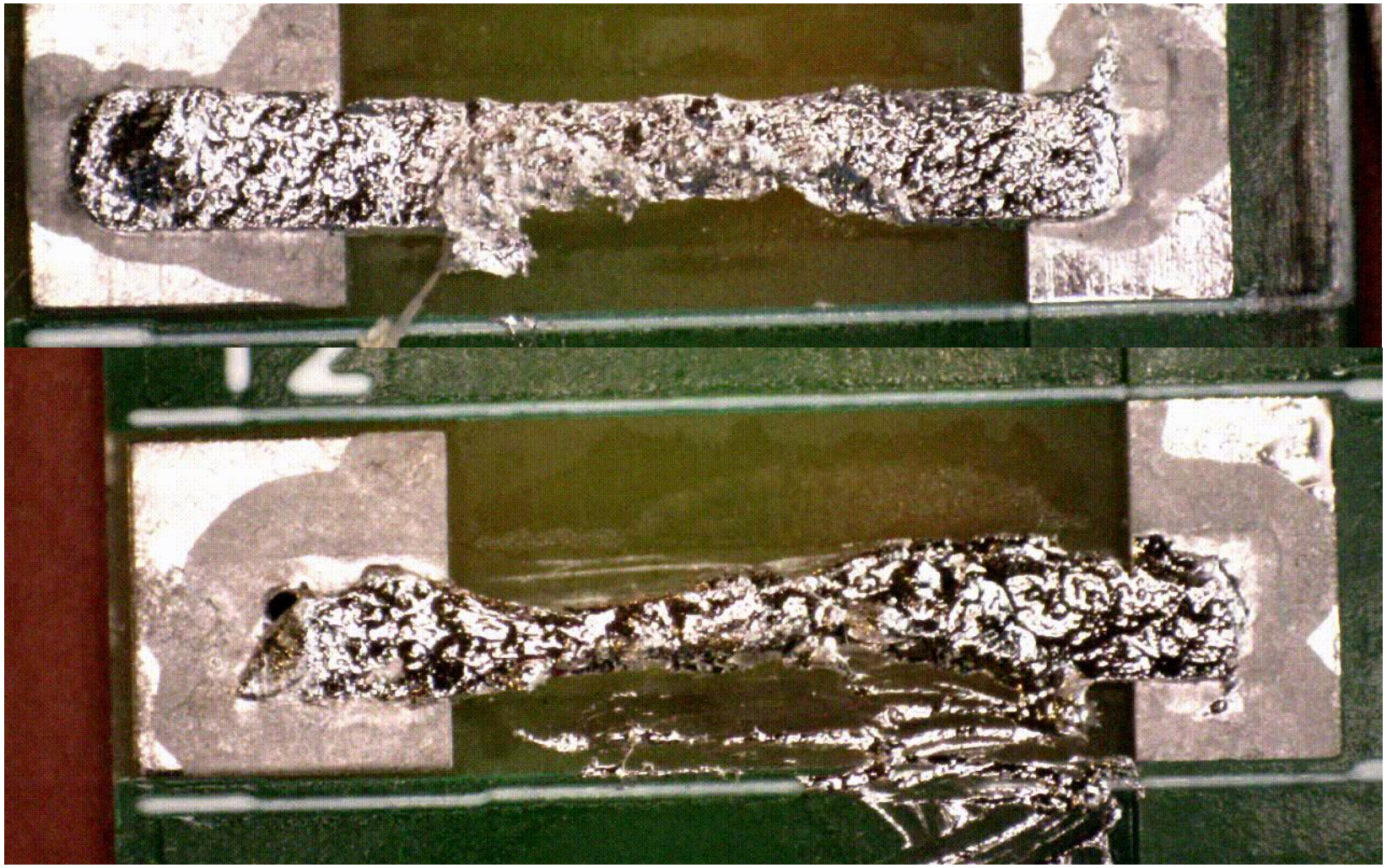
- Measure current, voltage, resistance
- With/without high voltage
- Observe failures

Current progress:

- Observed some failure modes (burning, migration)

Future:

- Identify useful metrics to quantify performance
- Compare conductive LMEE performance against baselines (EGaIn, OGaIn, etc)



Arieca ALT thermal interface material (TIM) analysis

Setup and initial results:

- Sampled 2x2mm TIM, ~100µm bond line thickness (BLT)
- **Test 1:** Voltage resist evaluation when voltage potential is directly connected to TIM
  - Current flow starts after ~70V bias
- **Test 2:** TIM has low voltage bias (2V), with and without a nearby high voltage field
  - No current flows for >1 hour, even in the presence of a 1kV potential

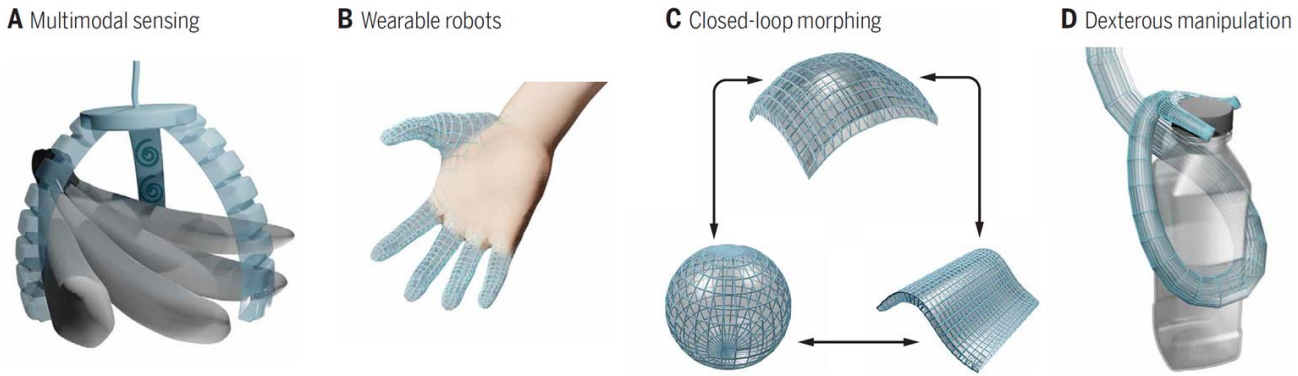
Future work:

- Investigate additional material parameters
  - It's not clear if electromigration will ever cause conductivity, but may degrade e.g., shear strength, adhesion, or thermal resistance
- Longer collection times and more samples

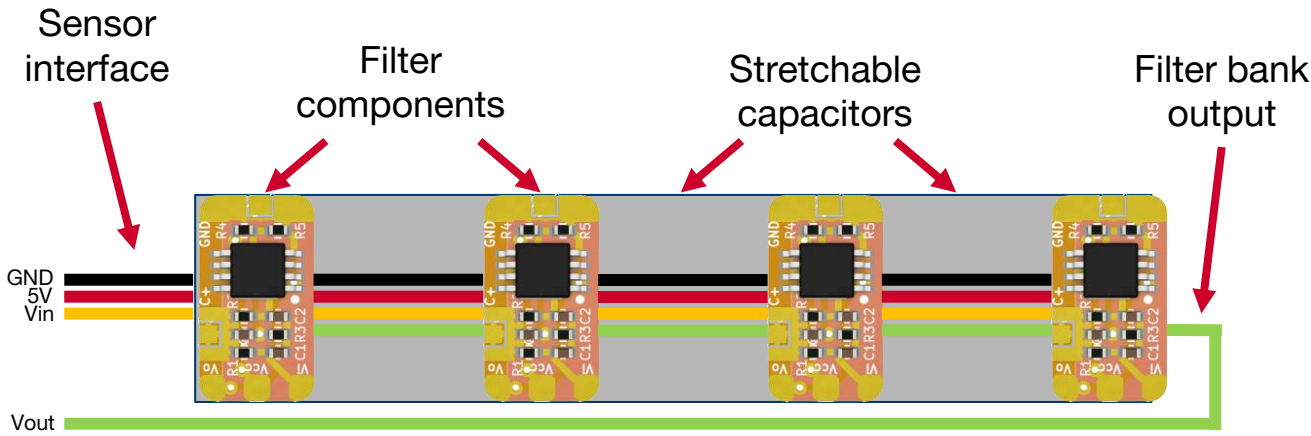
Localized configuration sensing for deformable objects

Motivation

- Shape sensing of deformable structures is difficult
- Current approaches require either:
  - Oversimplified models to estimate the configuration instead of measuring it
  - Cumbersome wiring to integrate multiple sensors along a structure
- Our proposal:
  - Distribute stretch sensors along surface, each sensor implementing a notch filter with location-dependent frequency response
  - Only a single interface required to measure all sensors

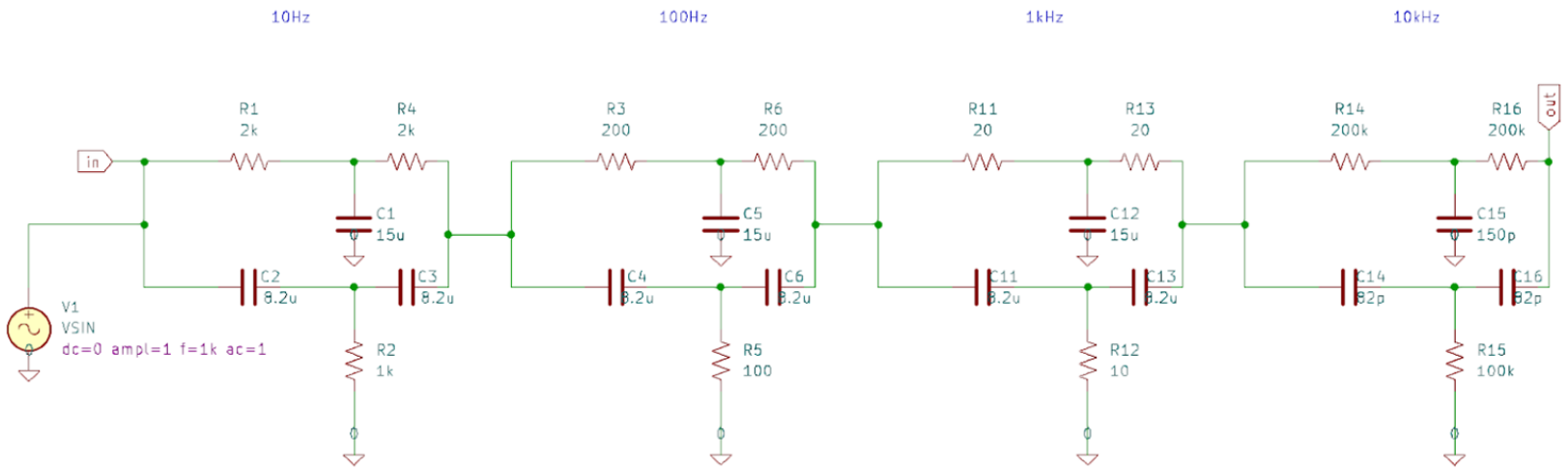


Shih, Science Robotics, 2020

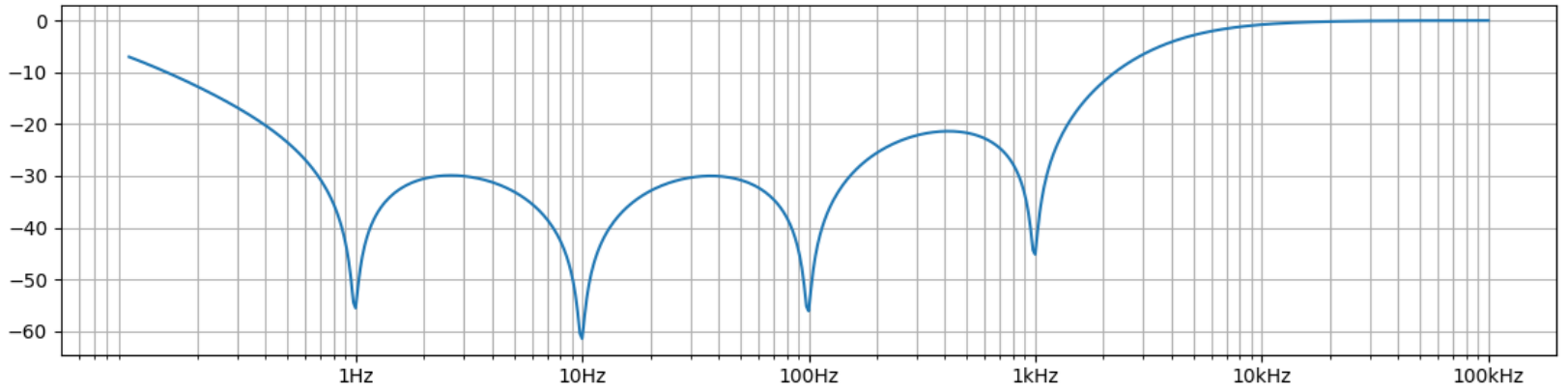


Circuit design and simulation

- Twin-T passive notch filters in series



- Simulation shows detectable, well-separated peaks



Breadboard prototyping and improvements

Breadboard:

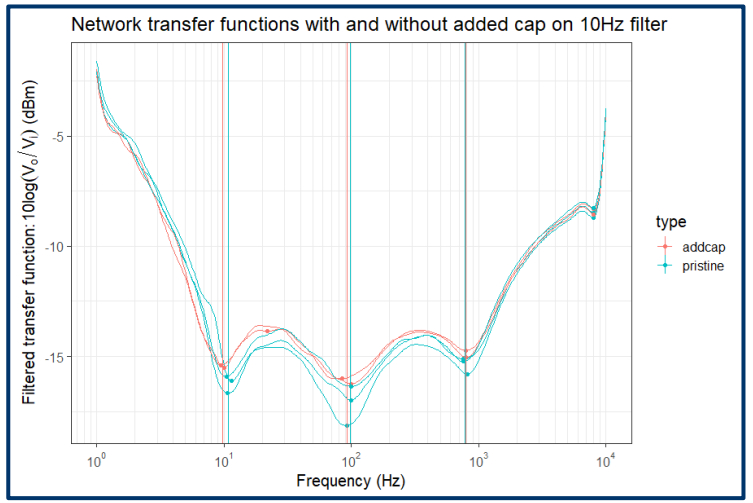
- Setup a series of 3 filters
- Added parallel capacitance to simulate strain

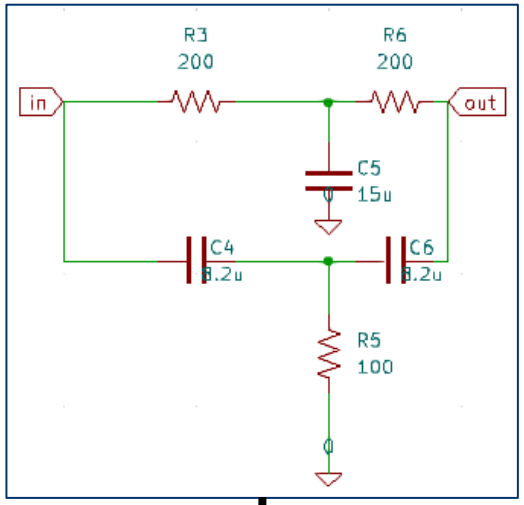
Issues:

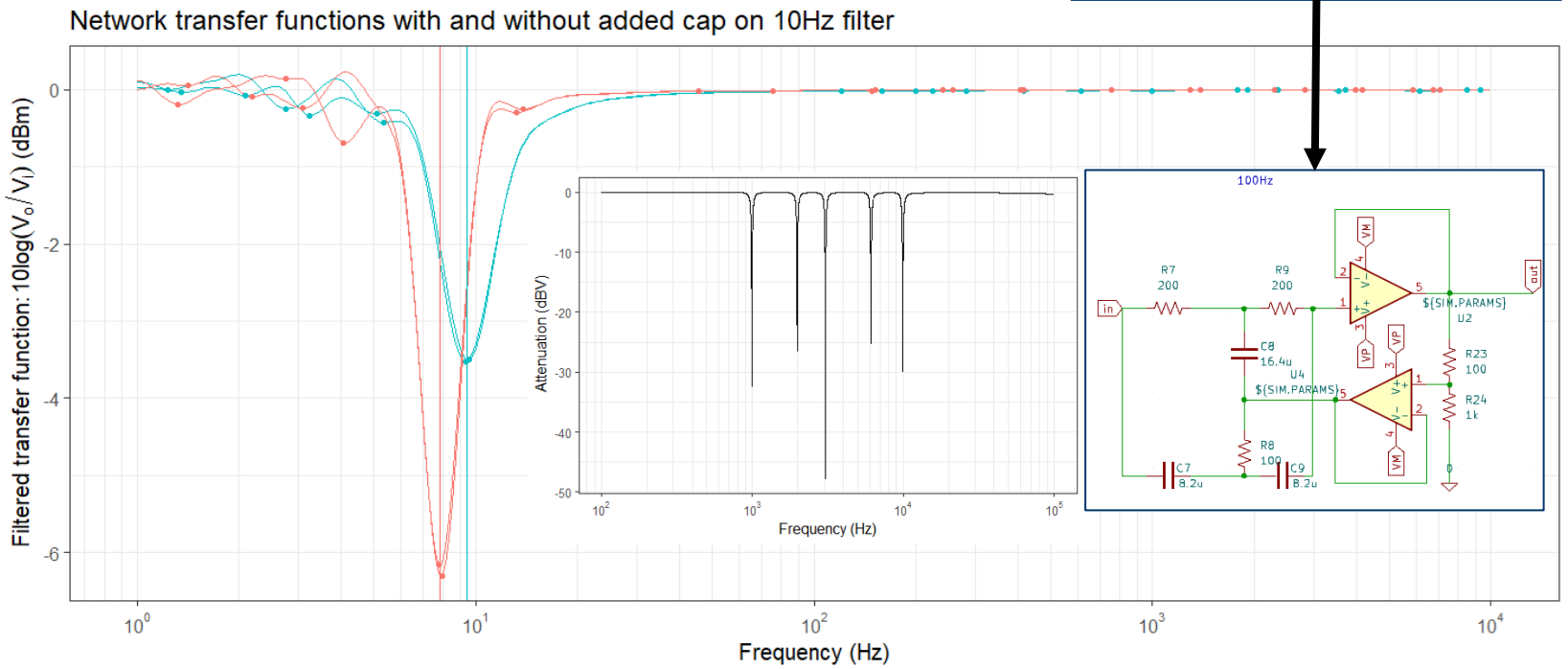
- Large broadband attenuation
- Large filter bandwidth

Resolution:

- Add buffering

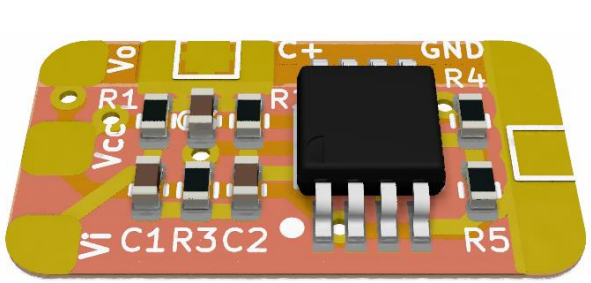


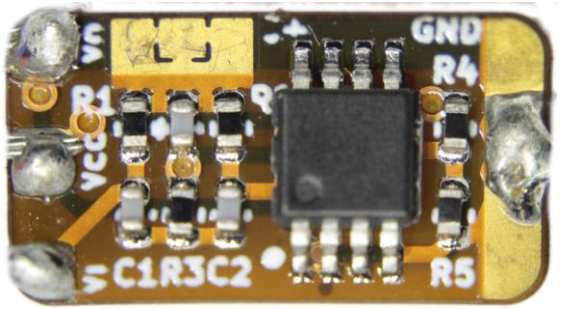


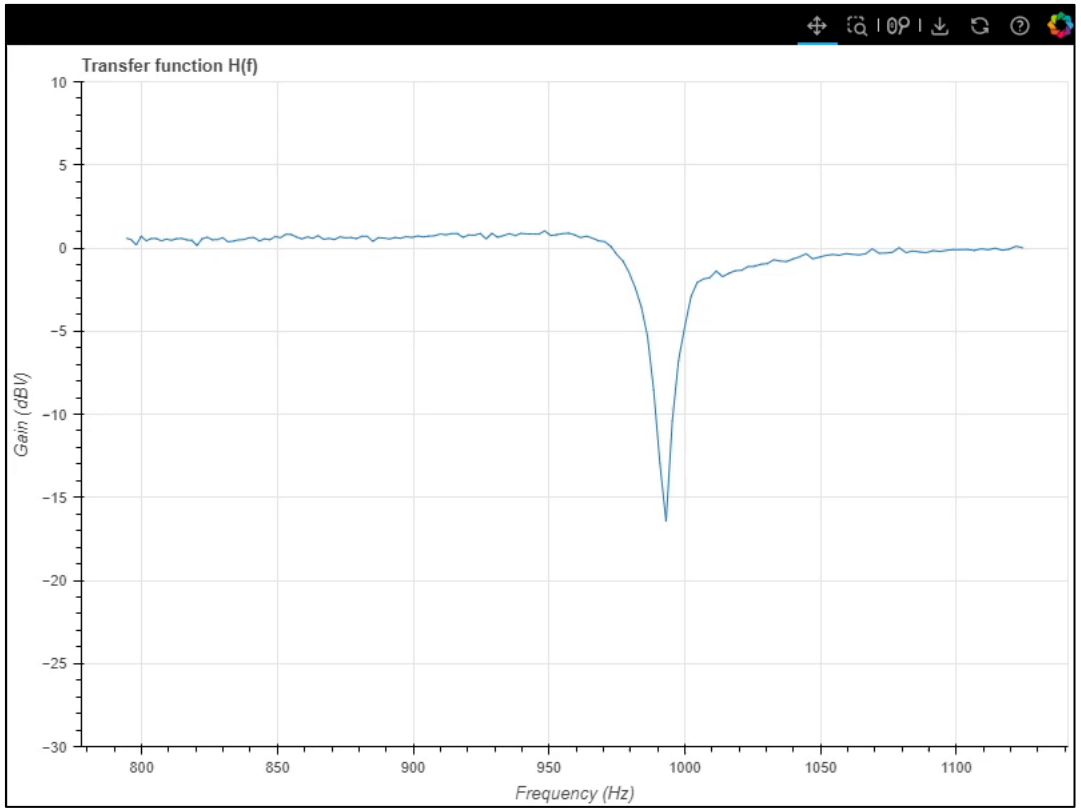


Flexible printed circuit board (flex PCB) design

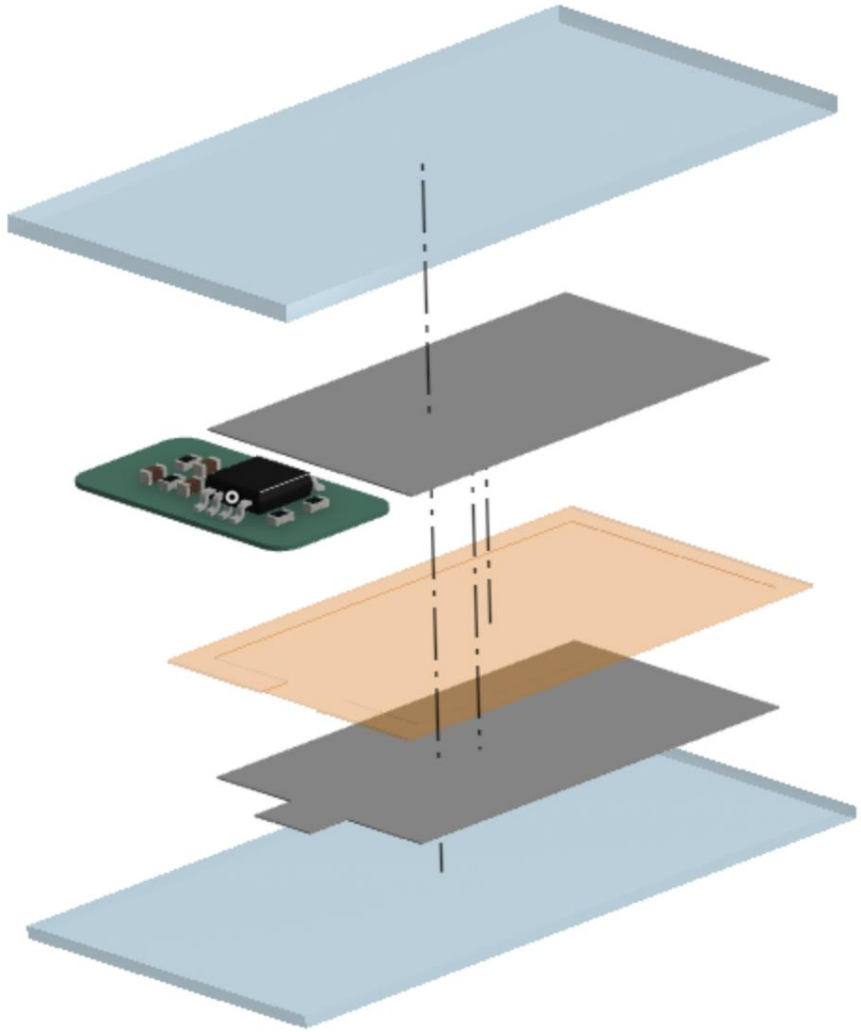
- Designed small (11.7x6.5mm) flex PCB for filter
  - Flex PCB to bond to stretch capacitor connected in parallel to filter capacitor
  - Stretch capacitor can be connected with liquid metal ink traces
- Validated hardware by adding and removing parallel capacitance, as in the breadboard case







Sencel stackup



Ecoflex 00-30

SIS ink, PCB

Ecoflex

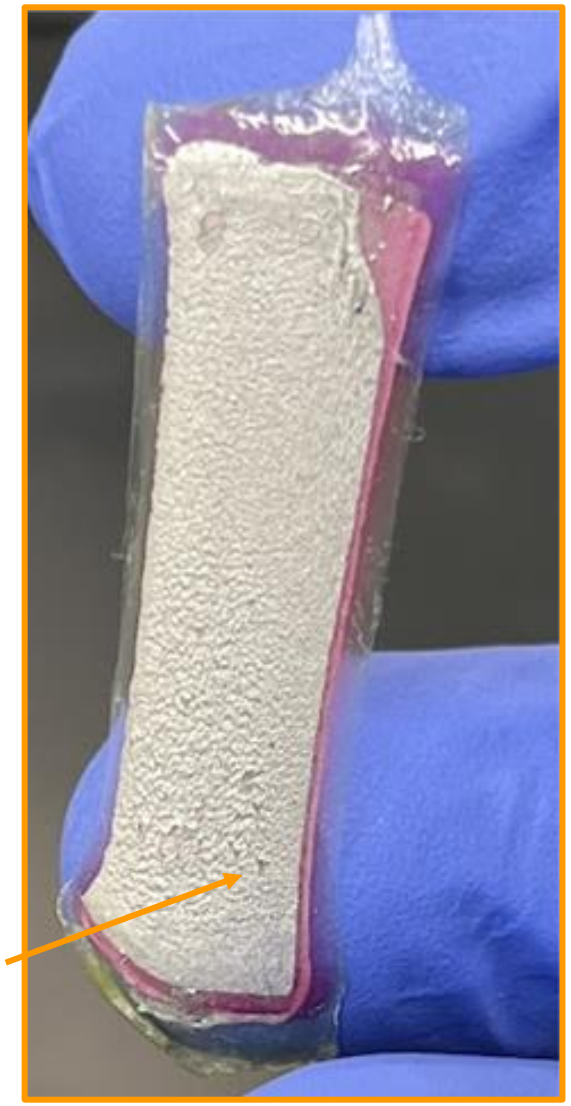
SIS ink

Ecoflex

Encountered issues fabricating the flexible capacitor

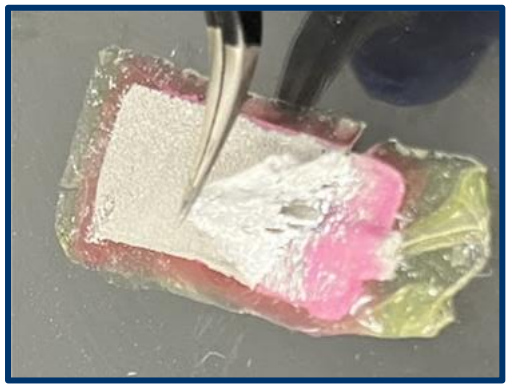
WPU ink very easy to tear

SIS ink tears, but not as badly



Without plasma

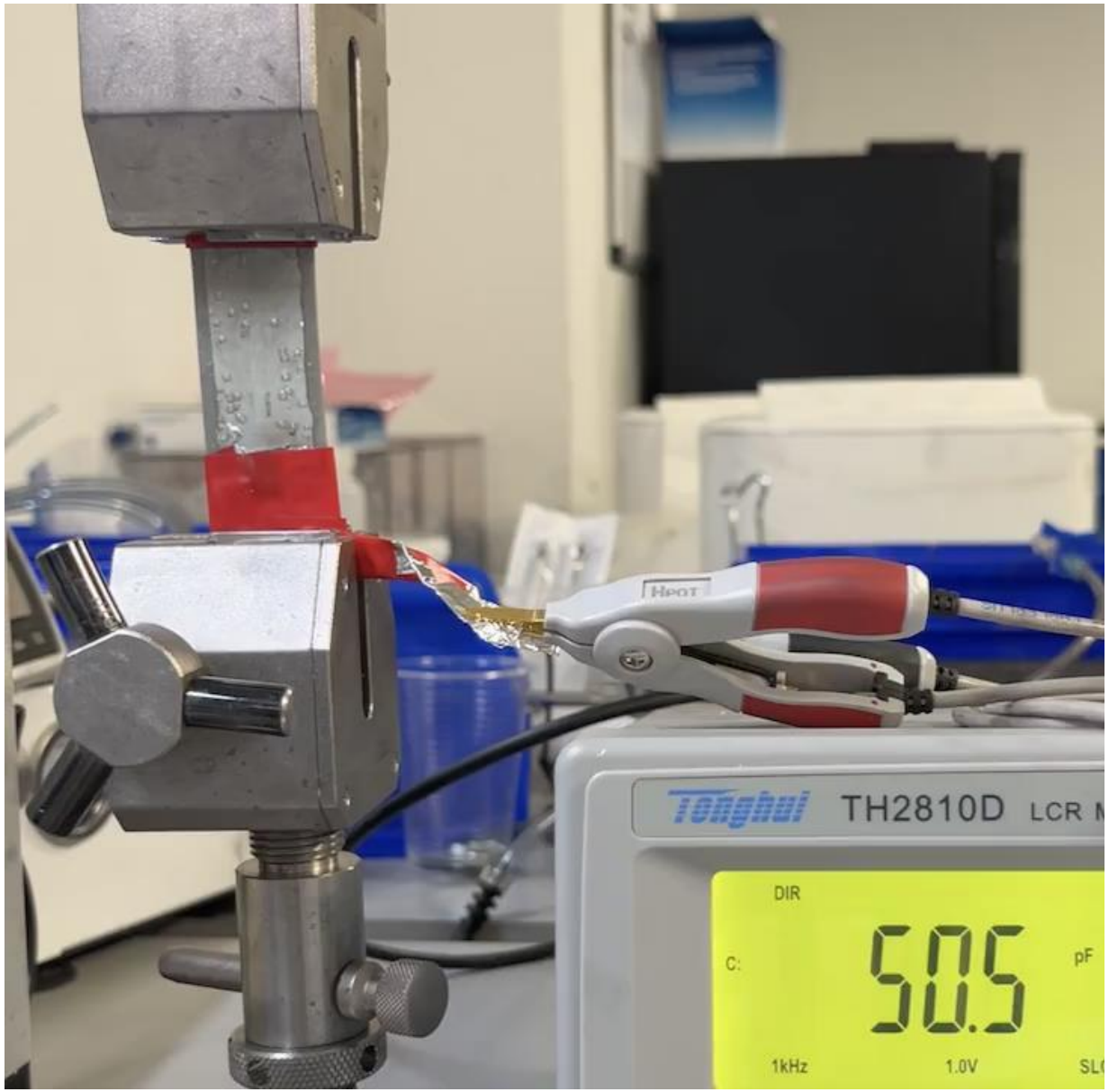
With plasma



- Some formulations tear too easily
- Bonding layers with silicone is tricky
- Stenciling thin (~76µm) layers of polymer with a high solvent content may lead to tearing or pores

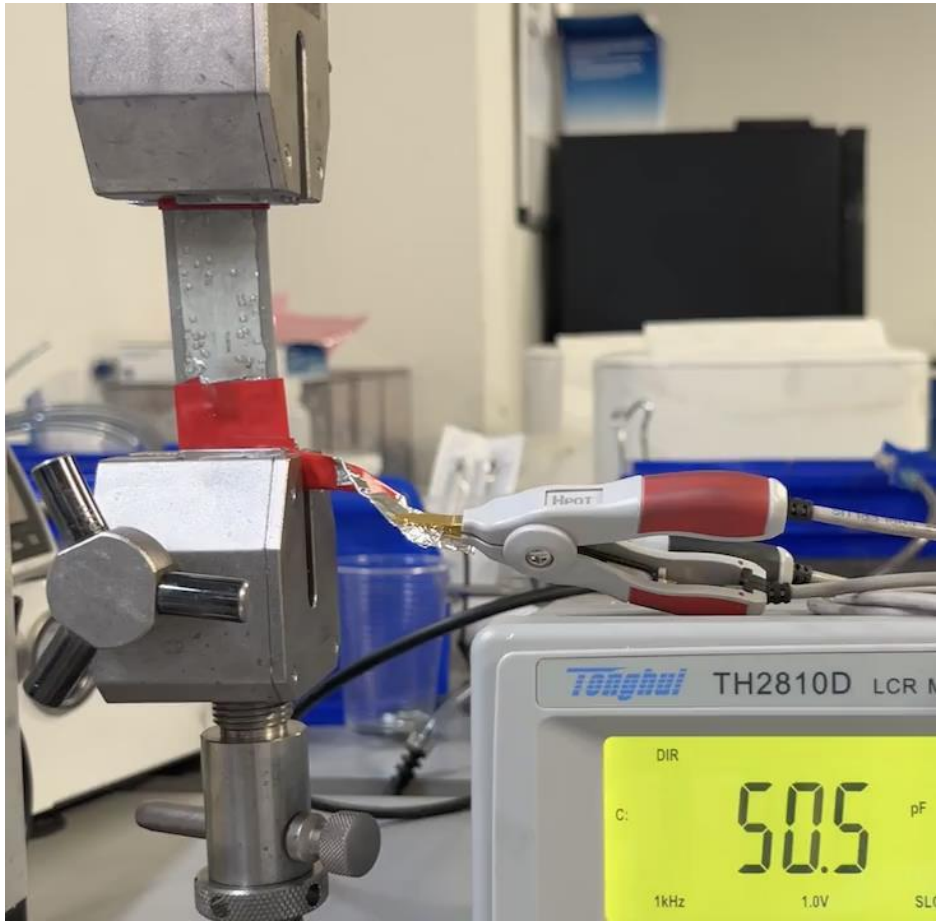
Future work: Finish capacitor implementation

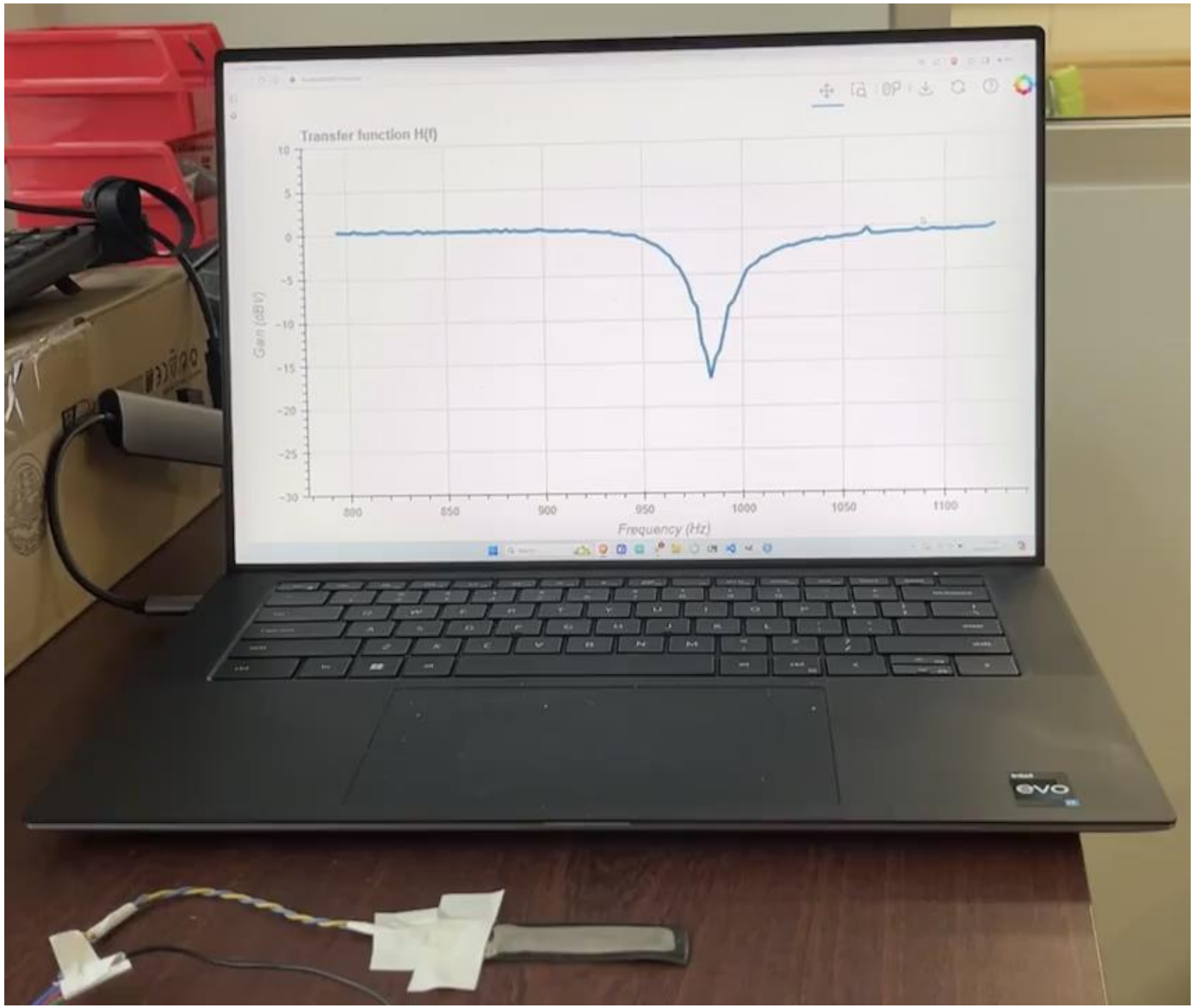
Temporary capacitor design



- For proof of concept, simplify stackup and fabrication:
  - Latex
  - OGaIn
  - VHB (0.5-1mm) dielectric
  - OGaIn
  - Latex
- Conductive ink to bridge OGaIn and external circuitry

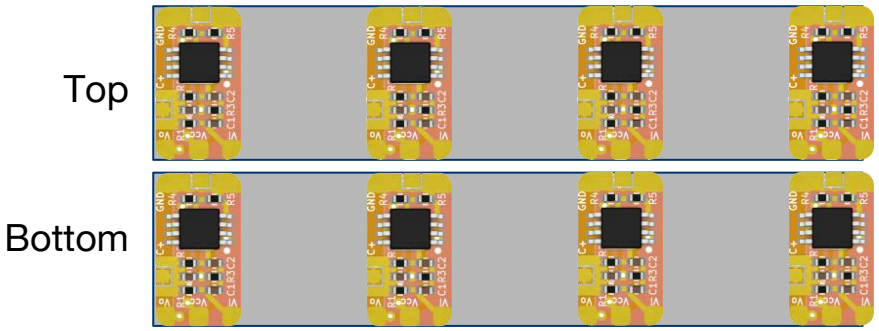
Sensor response proof of concept

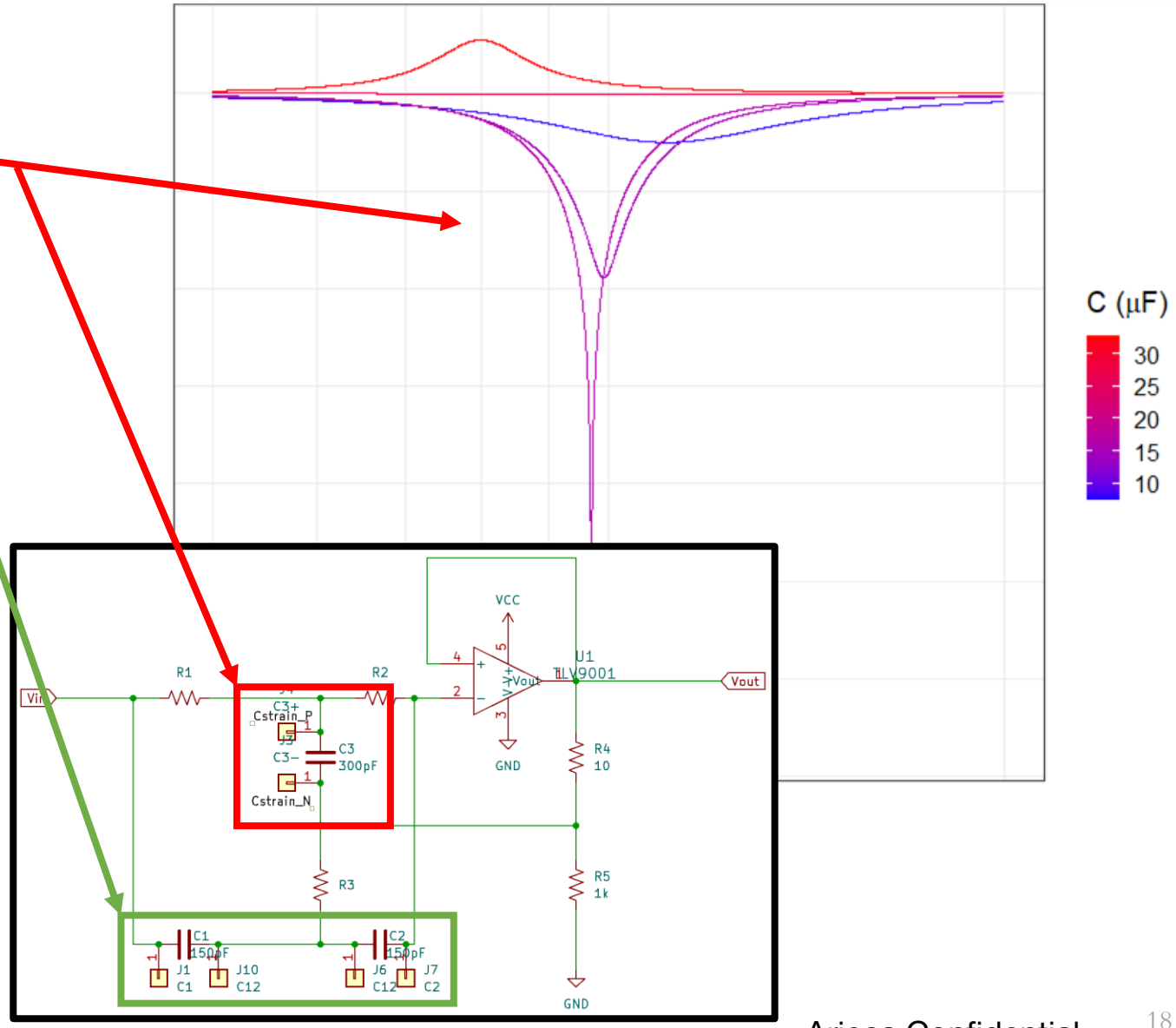




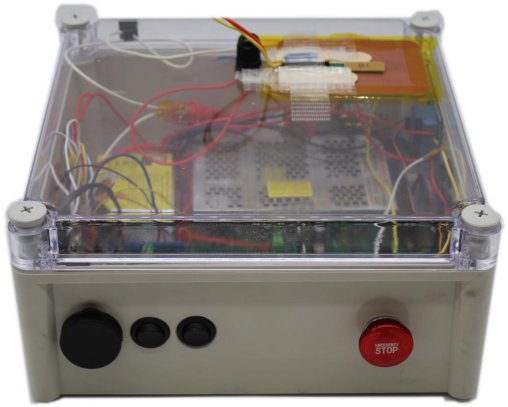
Future work: Tuned filter and multi-sensor devices

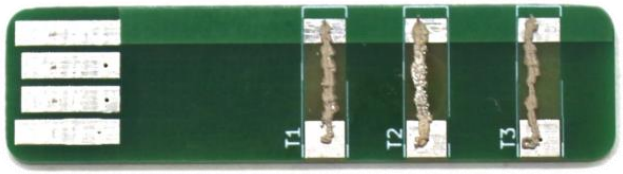
- Because strain only affects a single filter capacitor, the filter becomes detuned
  - Increases filter bandwidth
  - Decreases attenuation
  - May even cause signal gain
- We propose to resolve this by proportionally straining two additional capacitors to maintain filter performance
- Low gauge factor (~1 for parallel plate capacitor). Investigate other capacitor designs or strain sensitive resistors instead
- Expand to several sensors in series, then 2D sheets



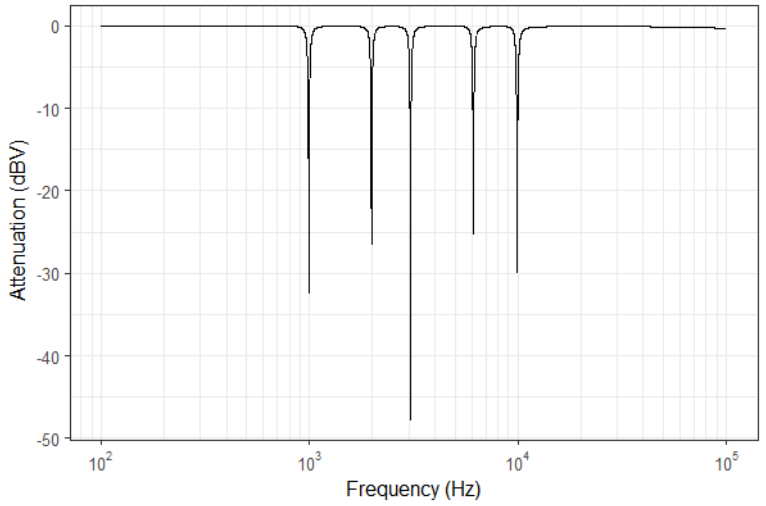


- Standardize FMEA for ion migration and electromigration
- Characterize materials





Internship summary



- Simple to interface sensor networks
- Continuum measurements for biomechanical and soft robotic applications