Design and Fabrication of a PCB MEMS Module with Integrated Switches and Sensor Suite

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Acknowledgement

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Outline

- Why PCB MEMS
- PCB MEMS Module - objectives
- Fabrication and assembly process
- Device Testing
  - Mechanical switches
  - Acceleration/tilt sensors
  - Humidity sensors
  - Pressure sensors
  - Temperature sensors
- Summary

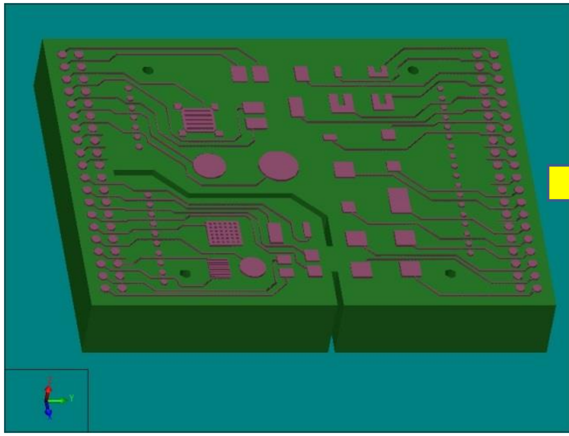
Why PCB MEMS

- Simple, low-cost manufacturing of MEMS devices using PCB manufacturing technology
- Meso-scale devices (100 um to a few mm’s)
- Monolithic integration with PCB and electronics
- Suitable for high-volume manufacturing and large area devices
- Examples of PCB MEMS demonstrated by other research groups:
  - Flow sensors, tactile sensors, accelerometers, RF switches, tunable antennas

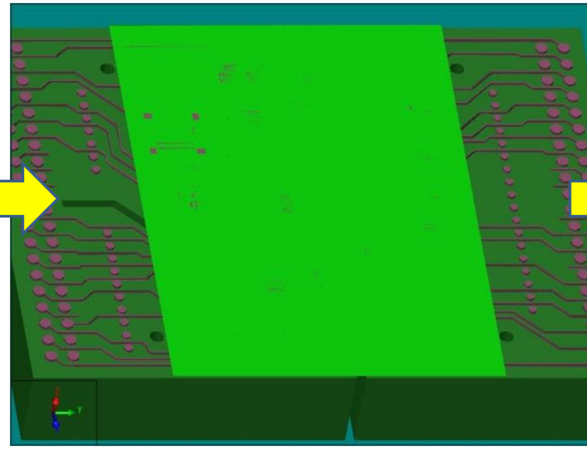
PCB MEMS Module Objectives

- **Demonstrate a suite of different MEMS devices in a single PCB module, fabricated together in the same process**
- **Mechanical switches, accelerometer/tilt sensors, pressure sensors, humidity sensors, and temperature sensors.**
- **Apply nano-scale technologies, e.g. atomic layer deposition/molecular layer deposition processes to enhance PCB MEMS device performance**
  - **Atomic layer deposition: nano-scale conformal inorganic coating, built up monolayer by monolayer**
  - **Does not require line-of-sight**

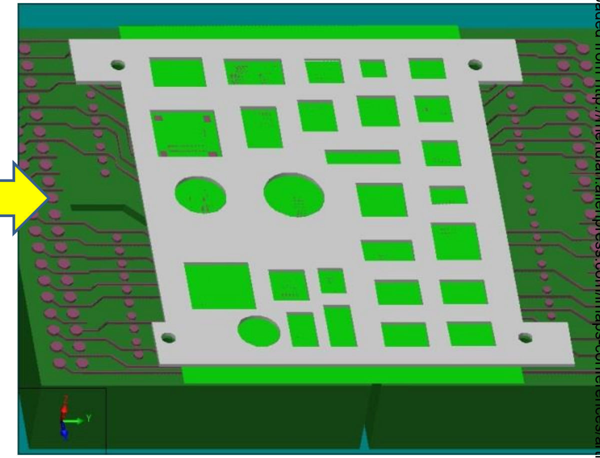
PCB MEMS Module - Fabrication



PC board with copper traces, bondpads and ground electrodes

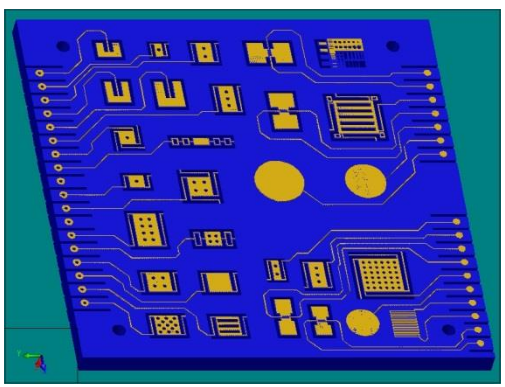


1 um BCB dielectric layer
ALD Al2O3 overcoat

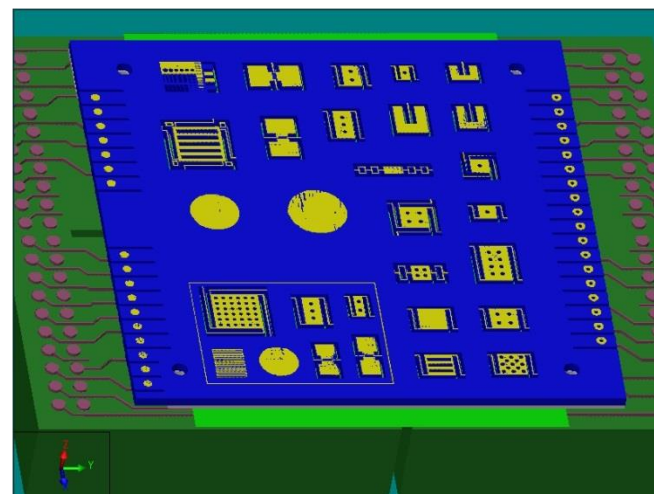


25 um-thick Polyflon bondfilm

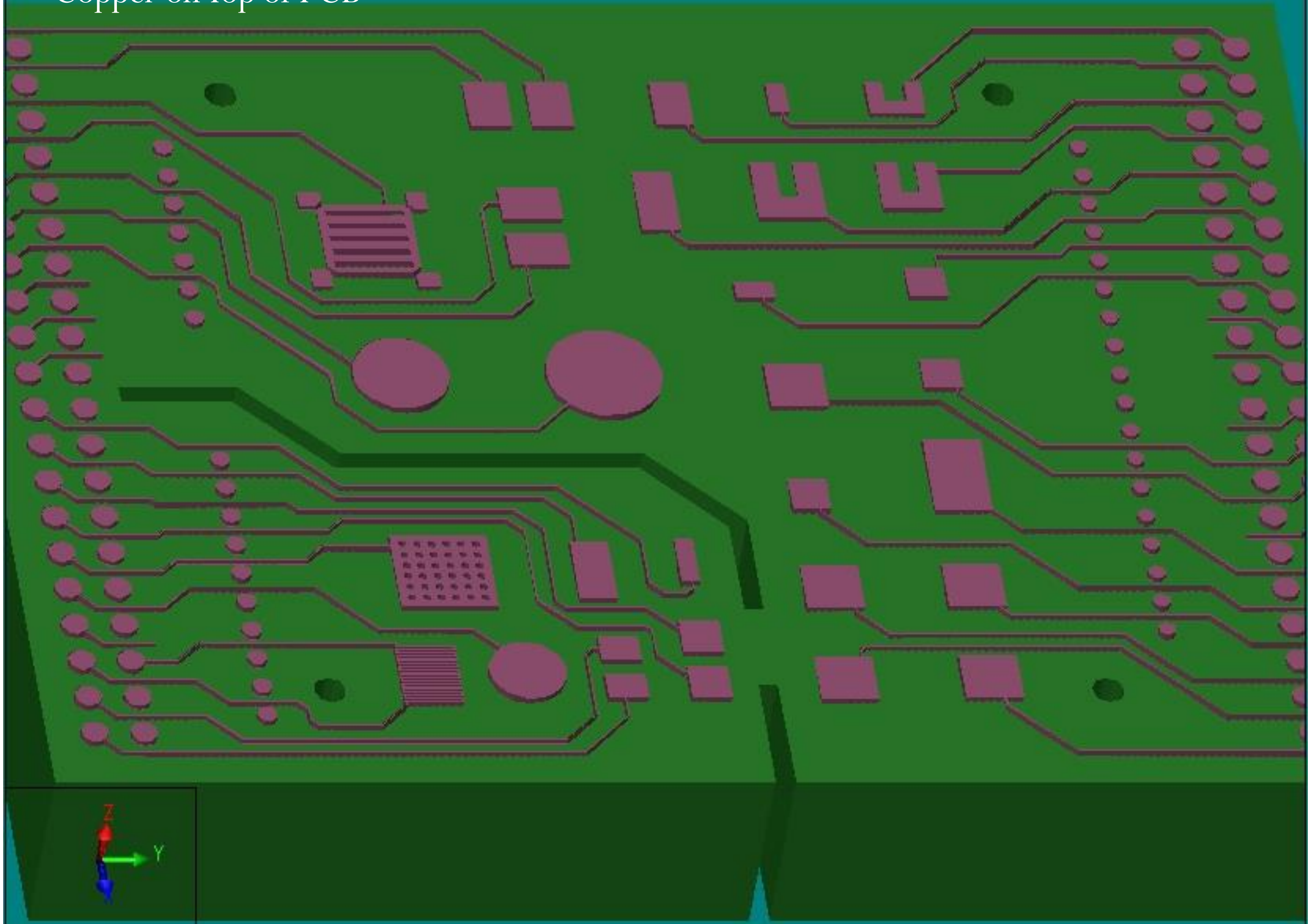
Copper-cladded Kapton with etched structures and copper traces, bondpads and top electrodes

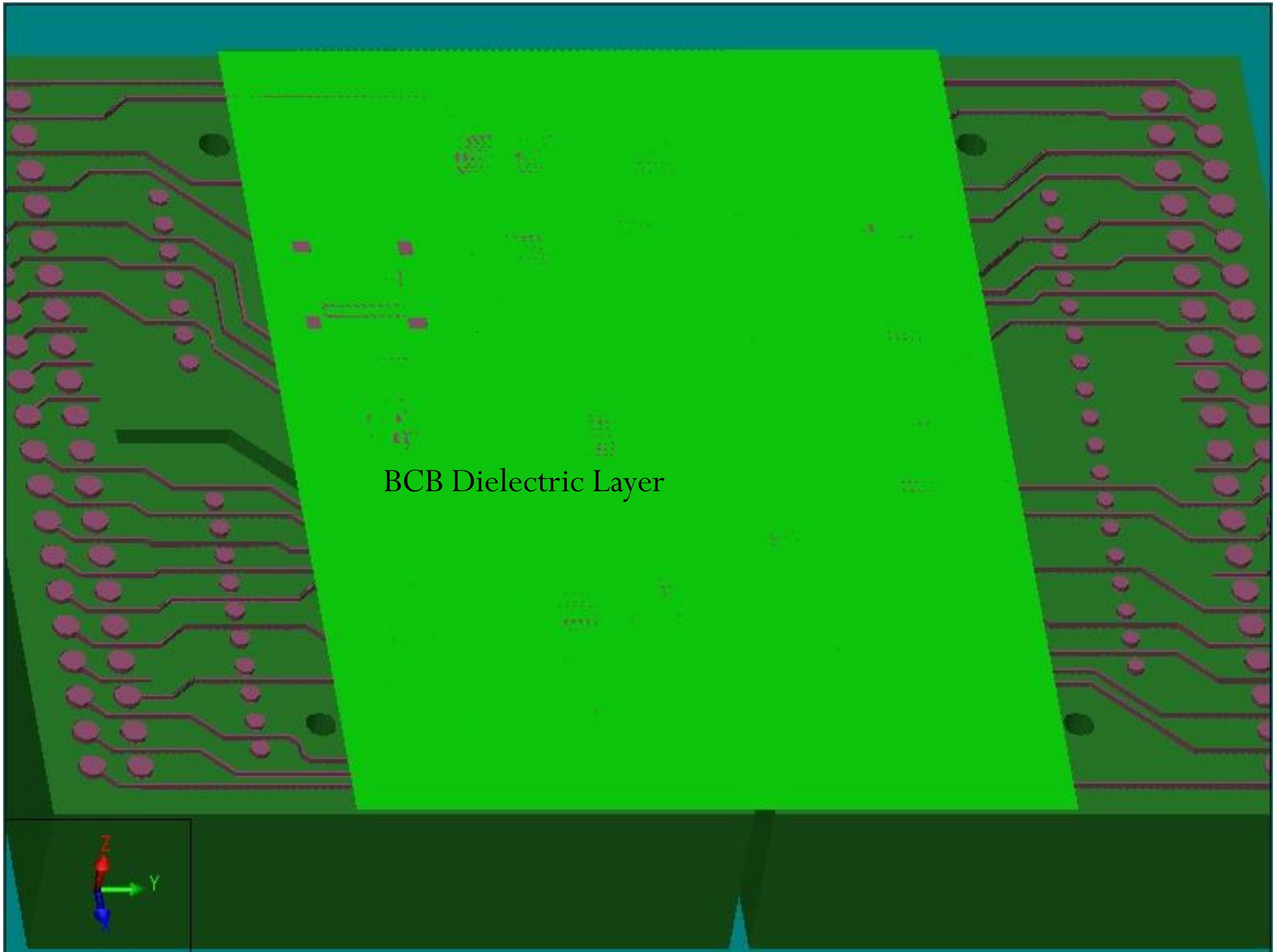


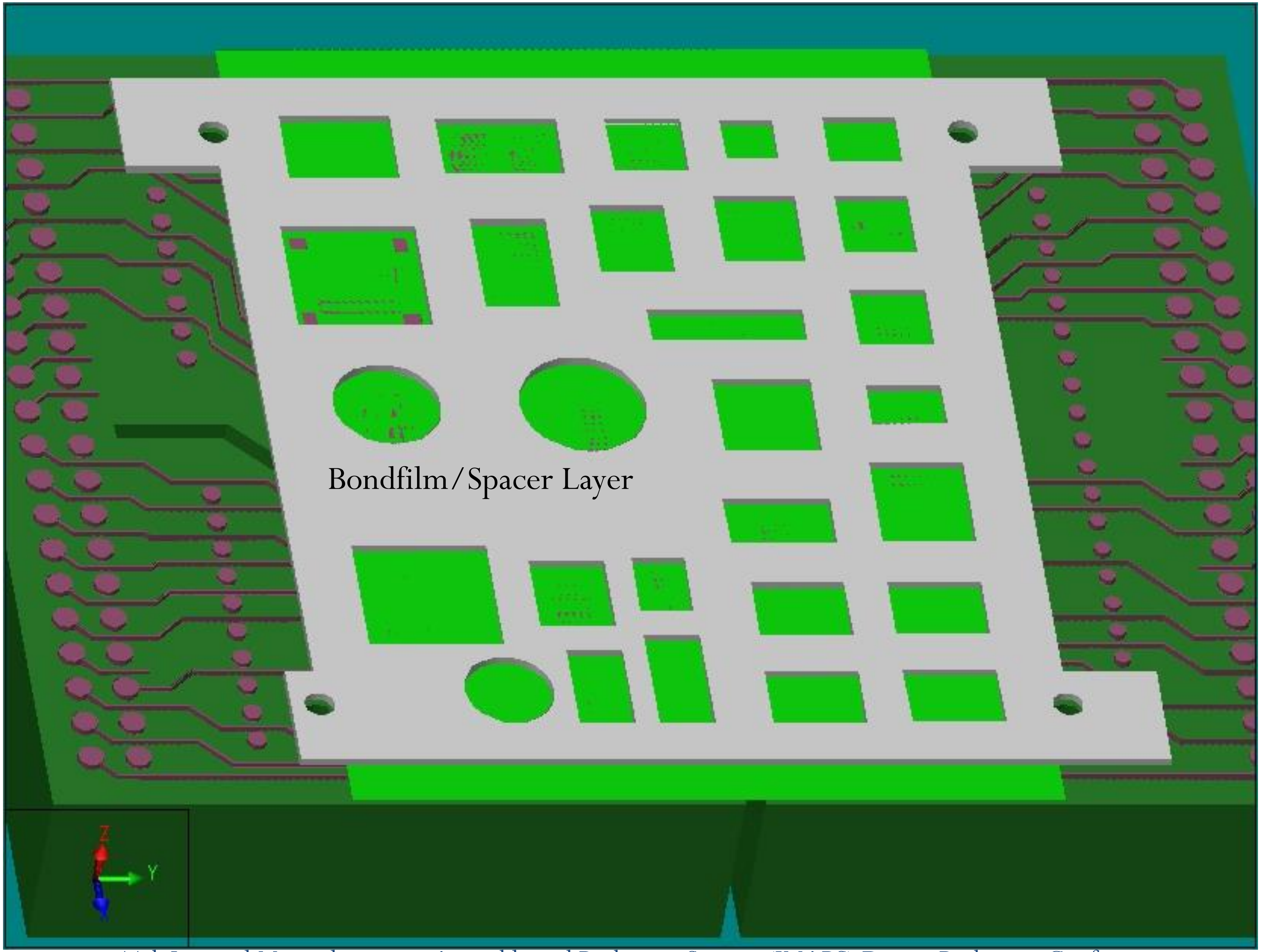
Bond

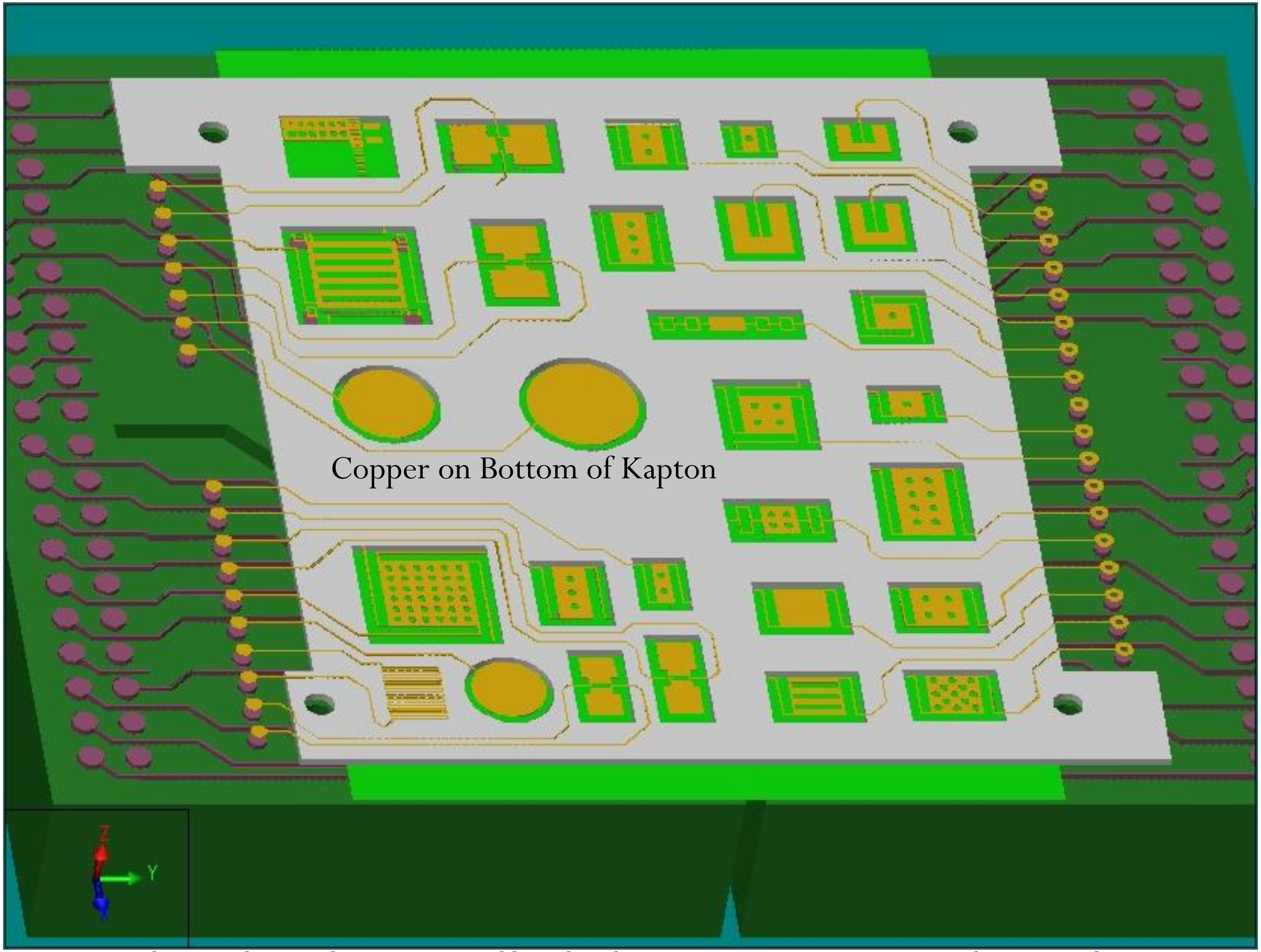


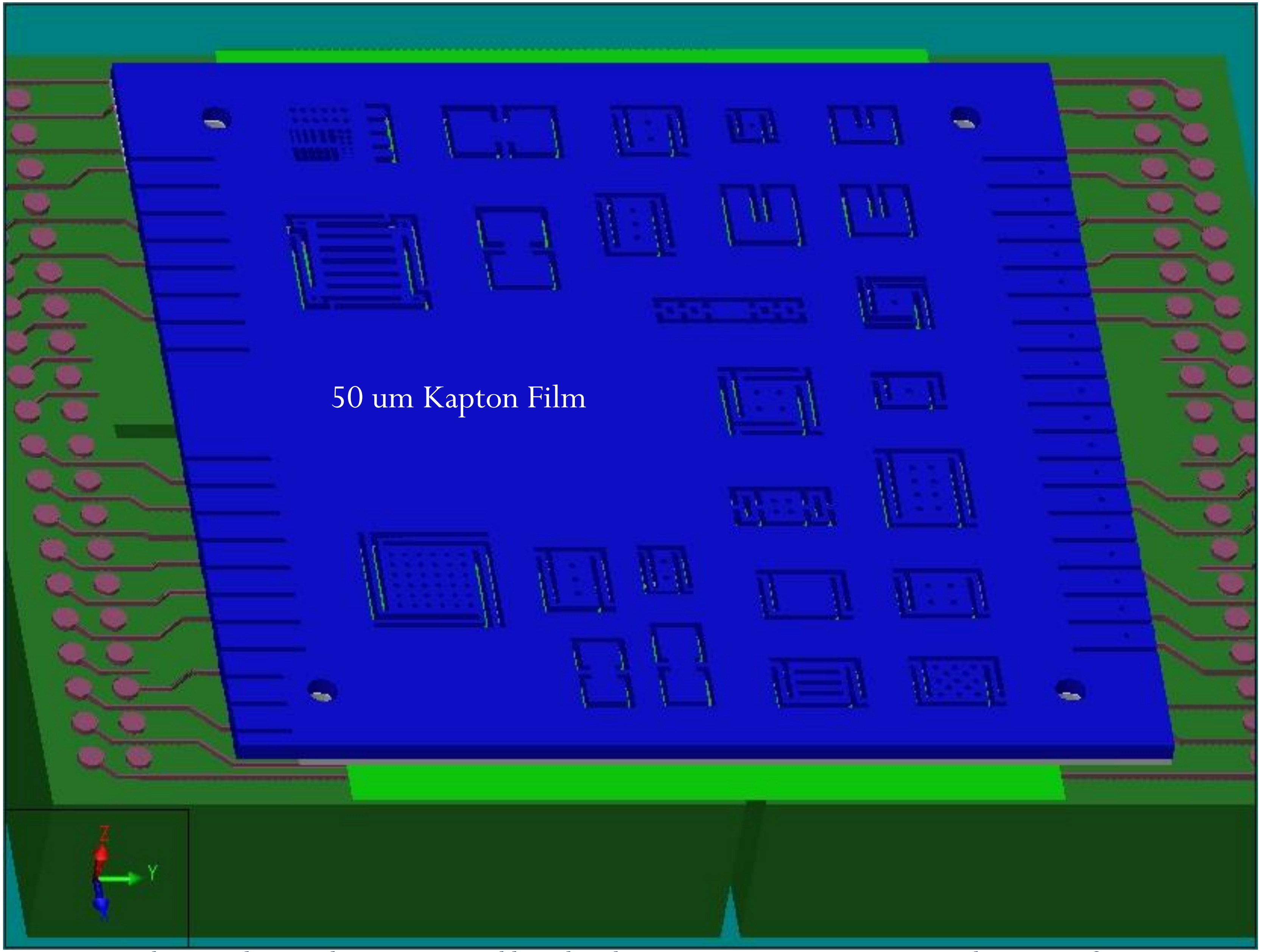
Copper on Top of PCB

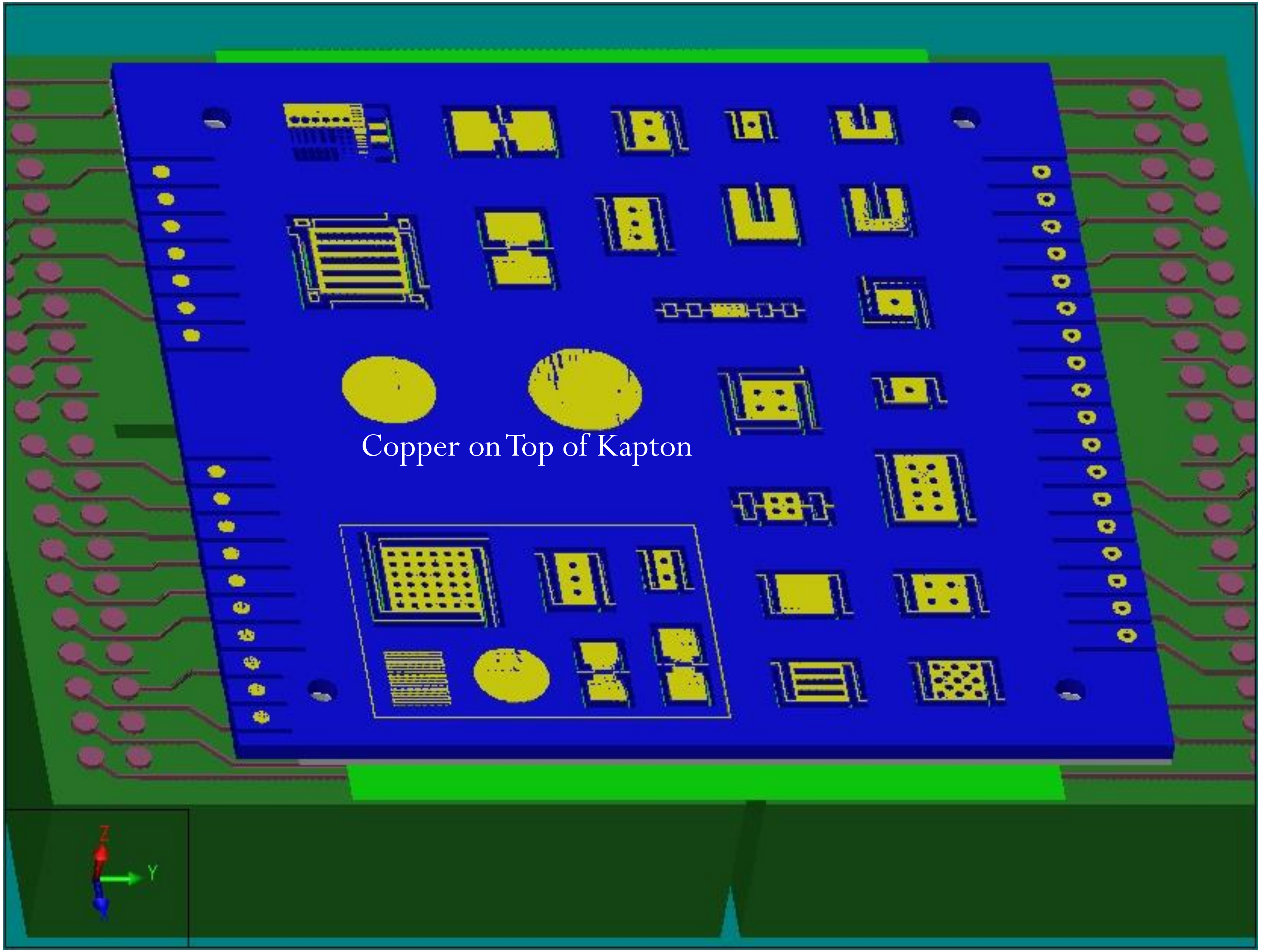



BCB Dielectric Layer
Z
Y

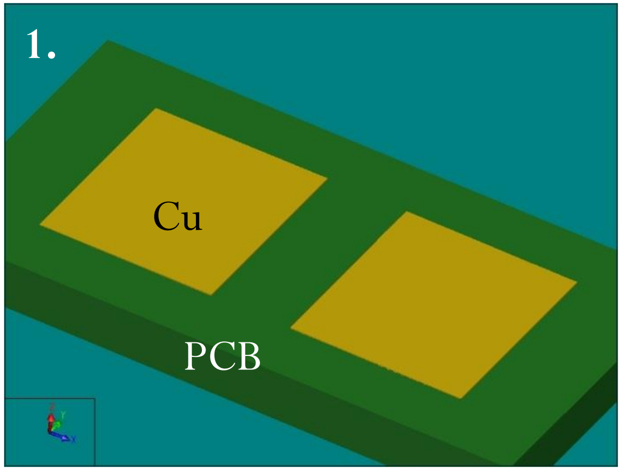

Bondfilm/Spacer Layer
Z
Y


Copper on Bottom of Kapton
Z
Y

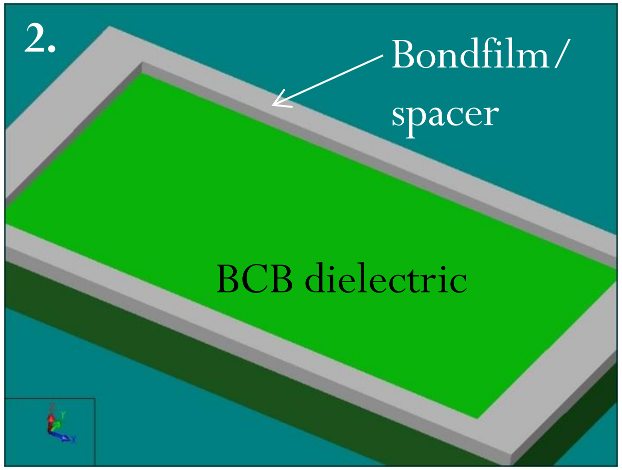

50 um Kapton Film
Z
Y


Copper on Top of Kapton
Z
Y

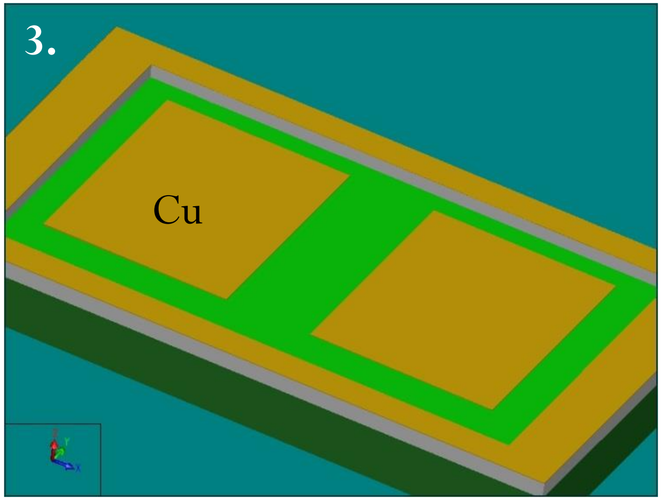
Example: Acceleration/tilt sensor construction



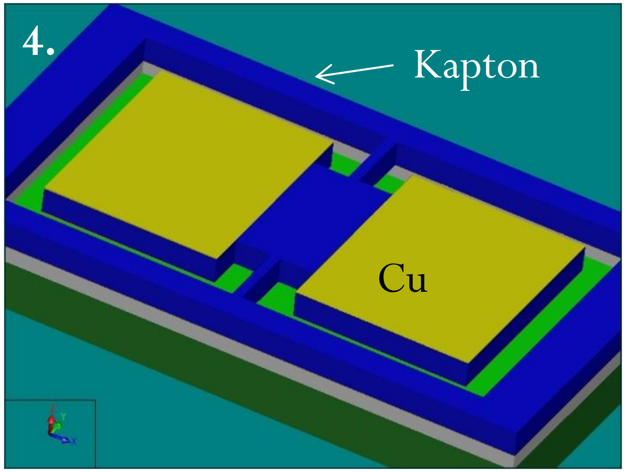
PCB with Copper lower capacitive electrodes



Polyflon bondfilm is an adhesive layer and a spacer to define the gap between the kapton and the PCB

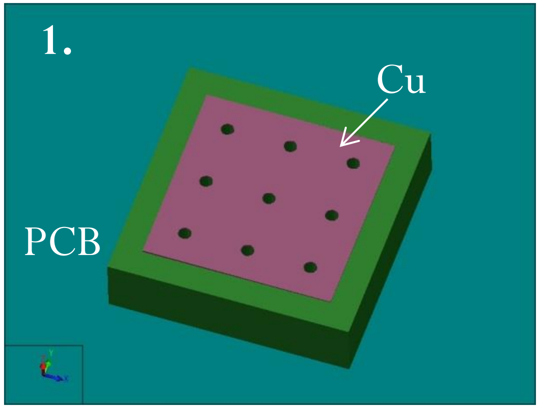


Upper capacitive electrodes on the underside of the bonded Kapton

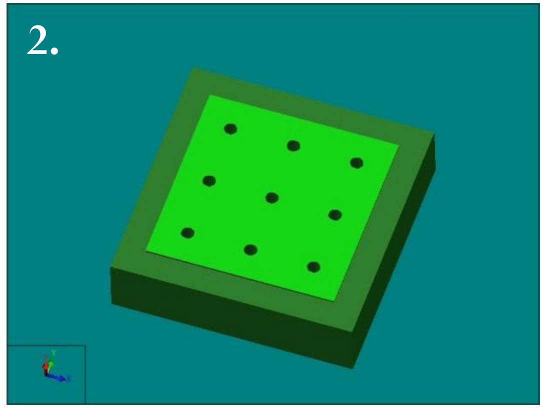


Kapton suspended structure with torsional hinge

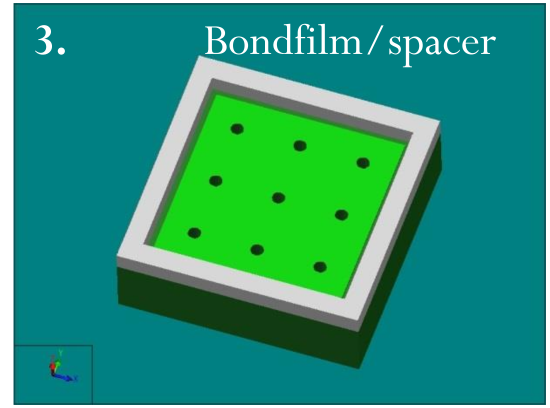
Example: Pressure Sensor Construction



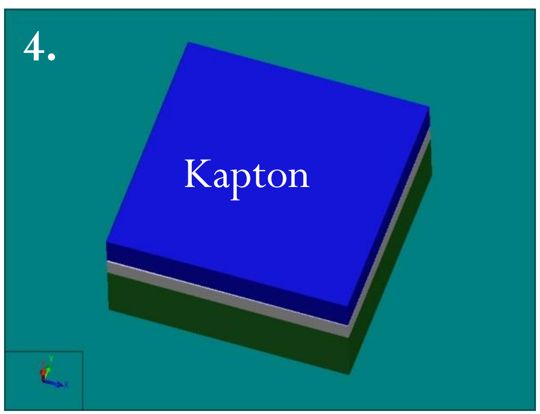
Holes in PCB for ALD coat and pressure reference



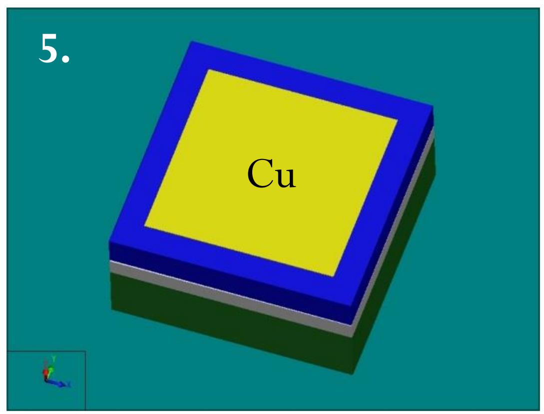
BCB dielectric layer prevents shorting if membrane collapses



Polyflon bondfilm also acts as a spacer to create air cavity and gap between capacitive plates



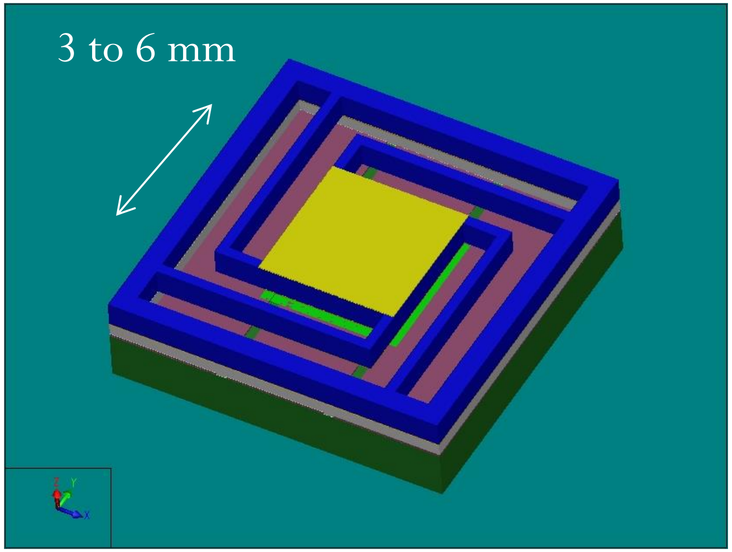
Kapton membrane with Cu electrode underneath

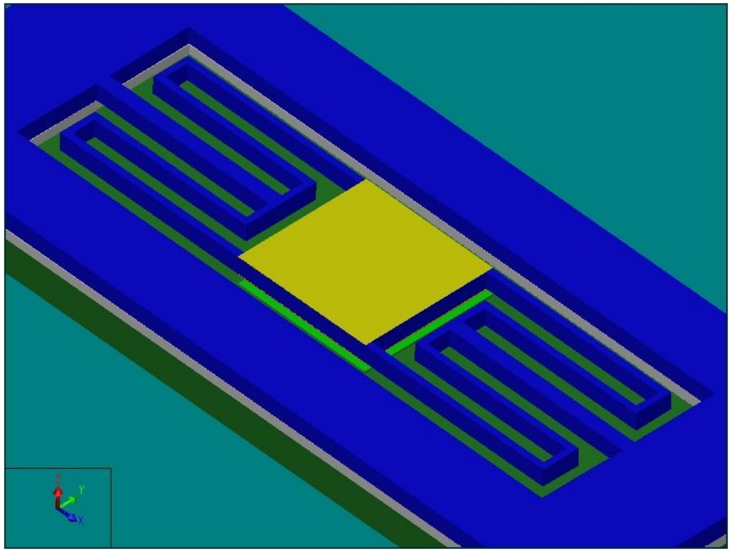


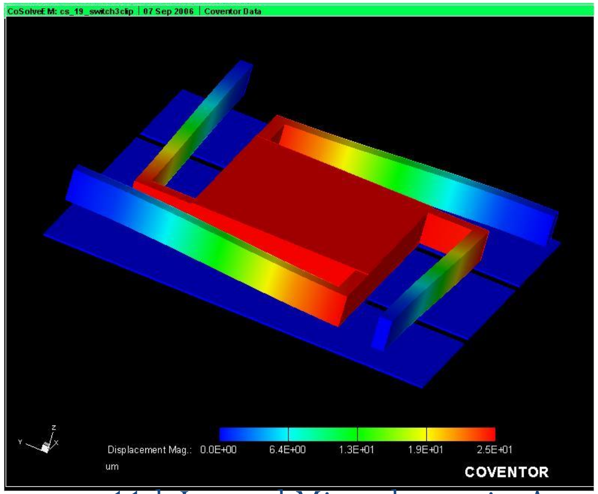
Cu on top surface is for stress relief

ALD coating is done through the holes. Holes are sealed with solder after assembly to create a reference pressure inside the cavity

Example: Switch Construction





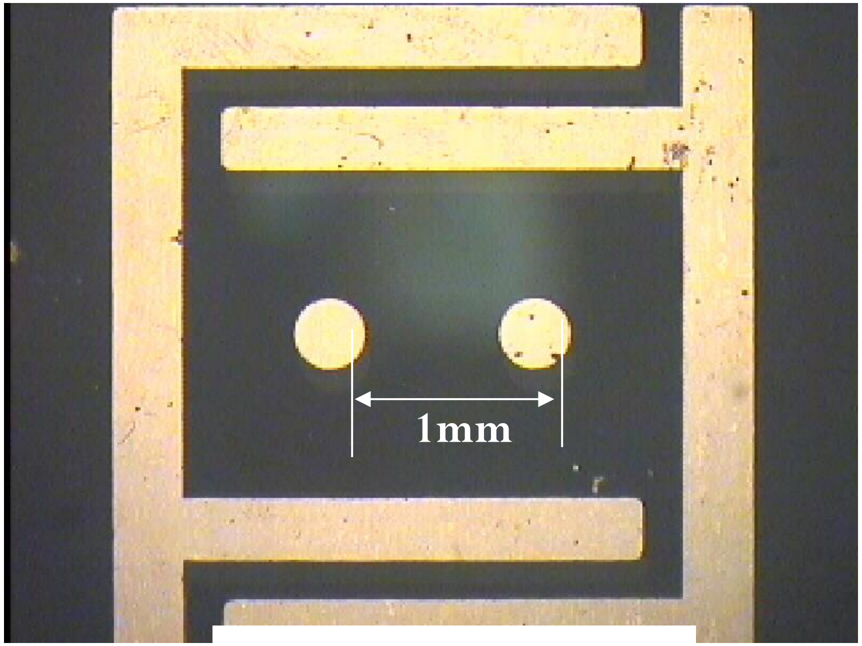


Switches normally “up”, snap-down from electrostatic force

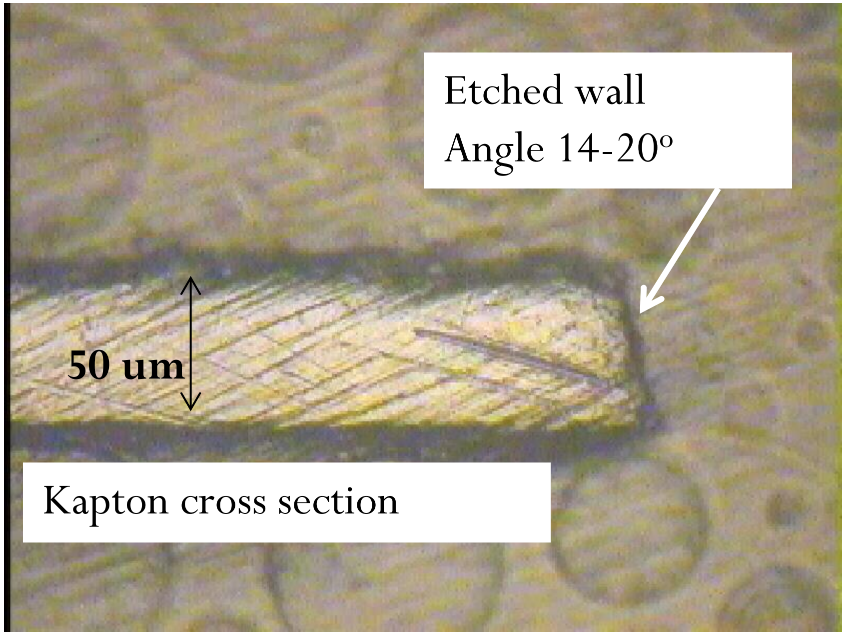
BCB dielectric prevents shorting between upper and lower electrodes

Kapton Fabrication

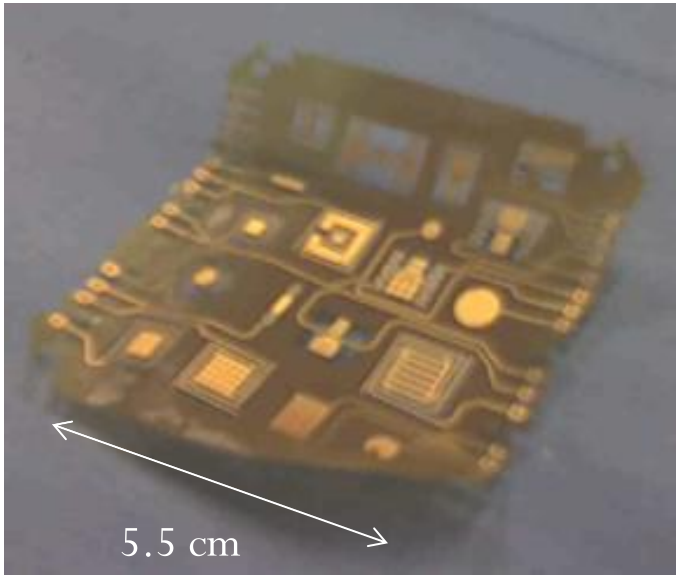
- 50 um thick Kapton, with 10-15 um thick copper cladding on both sides
- Copper cladding (top and bottom) was patterned by wet-etching
  - Bottom copper: electrodes, wiring
  - Top copper: stress relief patterns to prevent Kapton warping
- Kapton was etched by reactive ion etching to create mechanical structures



Dark : Kapton film
Bright : etched regions

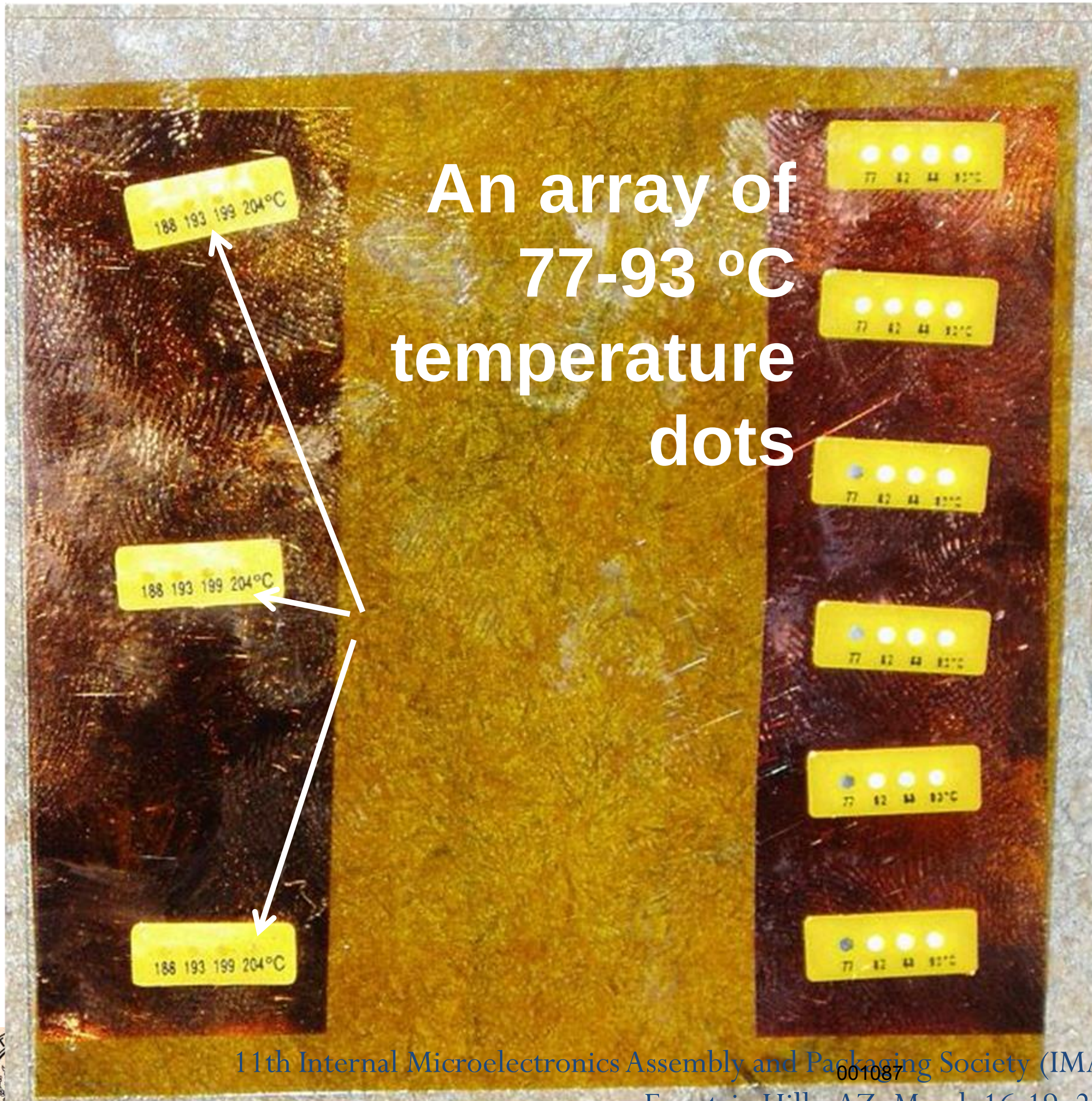


Warping of Kapton during RIE



- Reactive Ion Etch used to "cut" the Kapton into structures
- Initially resulting in severe warping
- Non-planar devices

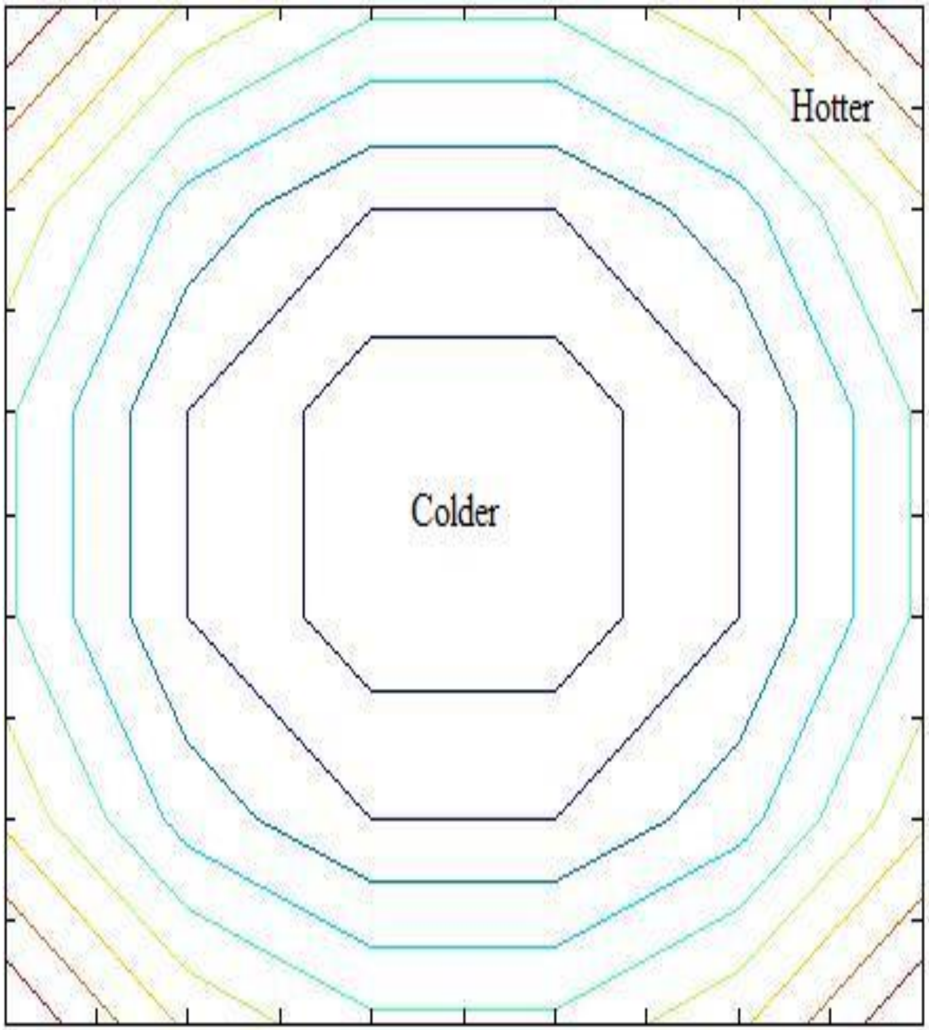
Temperature measurement during RIE



* Max sample temperature was determined via commercial “temperature dots” stuck to the sample. These dots show the maximum temperature reached during the process (their color changes permanently).

* Maximum temperature was below 93ºC with multiple-step RIE (30-min etching/15-min cooling).

Temperatures were location-dependent



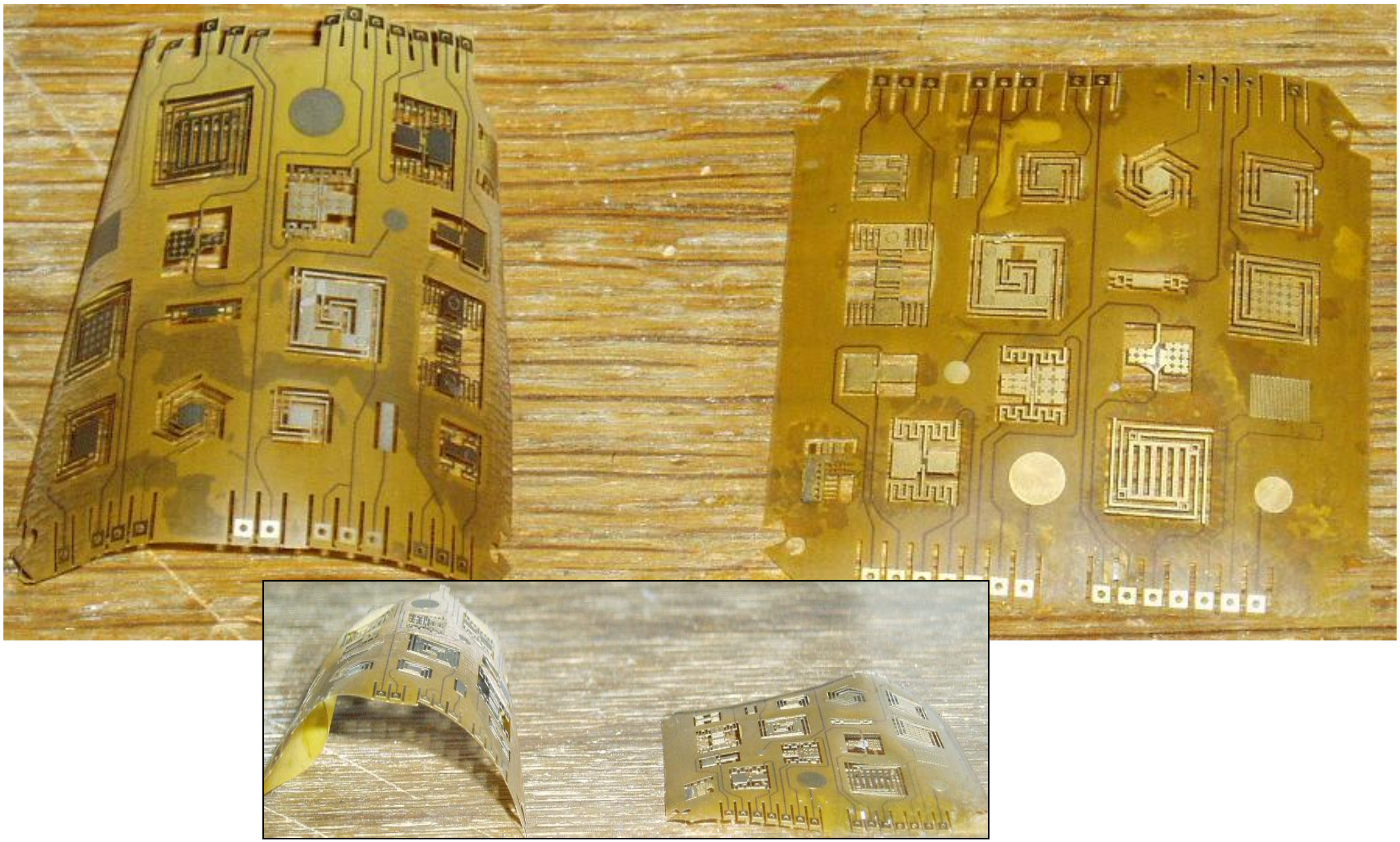
- Center of RIE chamber had the lowest temperature, e.g. <77 ^{o}C, and lowest etch rate.

- As the distance from the center was increased so did the temperature (93 ^{o}C) and the etch rate.

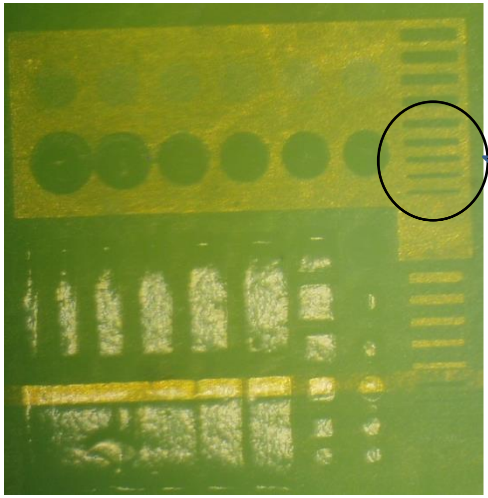
Minimizing warping of Kapton

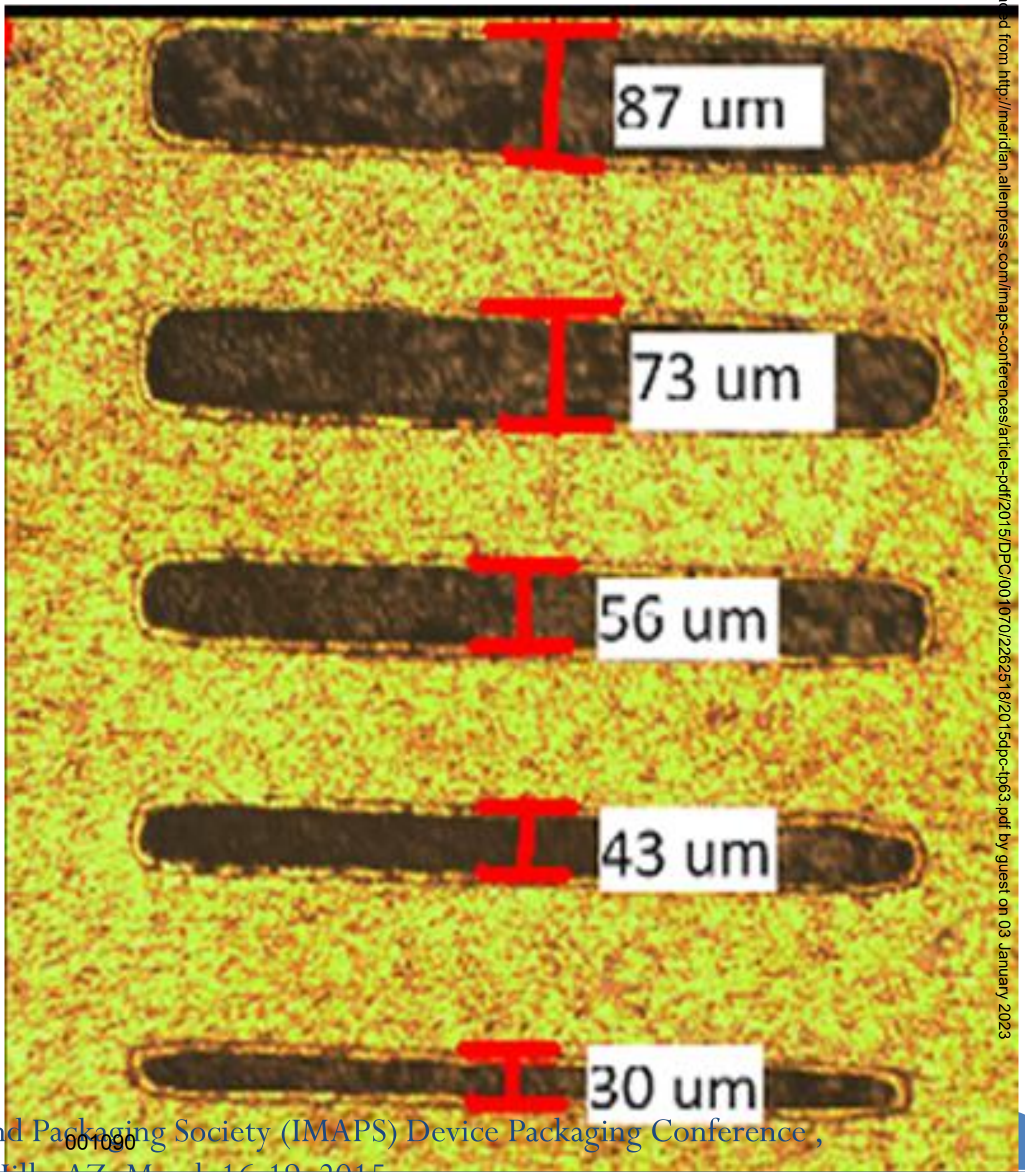
Initial RIE process

Substantially reduced warpage with multiple RIE steps (30-min etching/15-min cooling).



Kapton RIE feature sizes



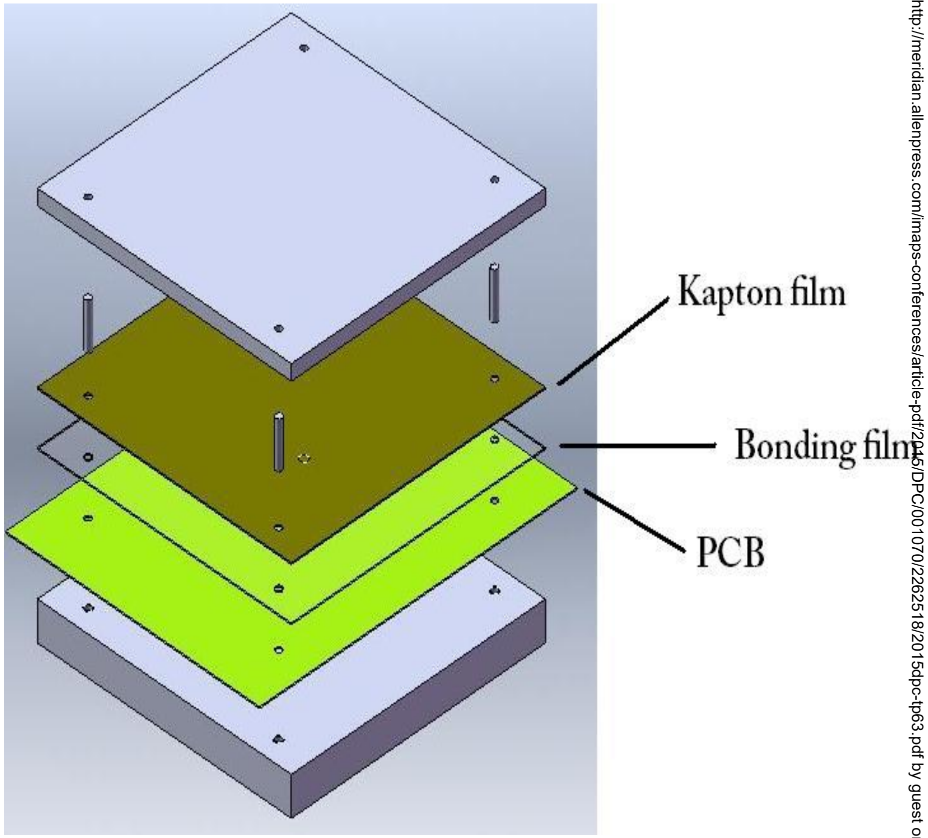


30µm opening slot etched through a 50µm thick Kapton.

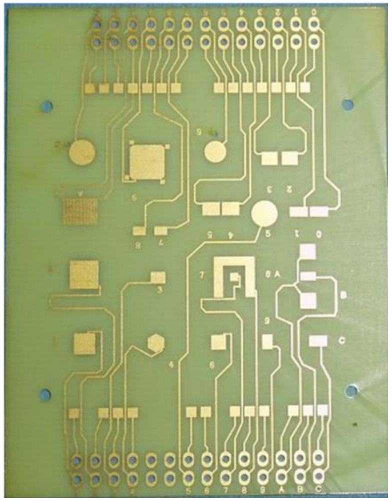
We should be able to design and fabricate much smaller PCBMEMS in the future.

Assembly

- The module is assembled by bonding the Kapton film to the PCB board
- This process involves compressing a layer of bonding film between Kapton and PCB in a 130° C environment and with 10 psi
- Bonding film provides not only adhesion but a gap between the kapton and PCB

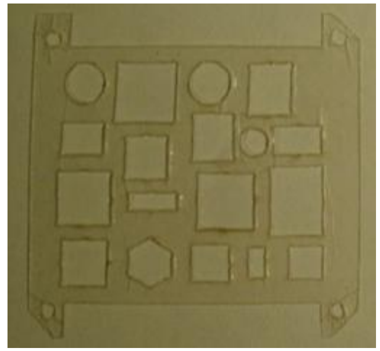


Assembly



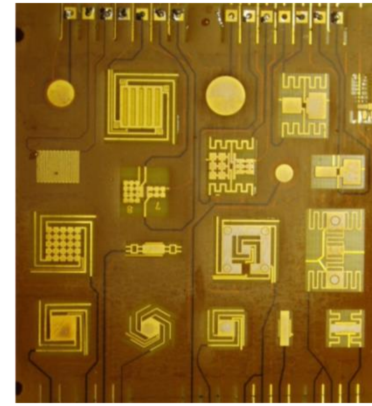
Duroid board (fabricated by an external vendor)

+

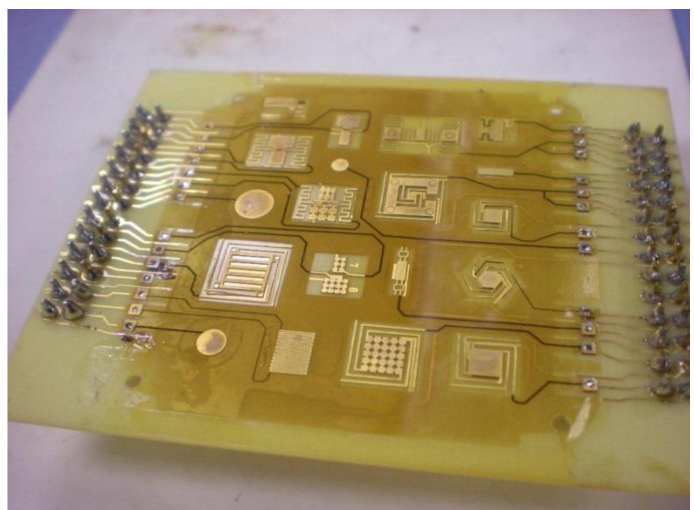


Polyflon bondfilm (25 um thick)
Stenciled and cut by razor blade or laser cutter

+

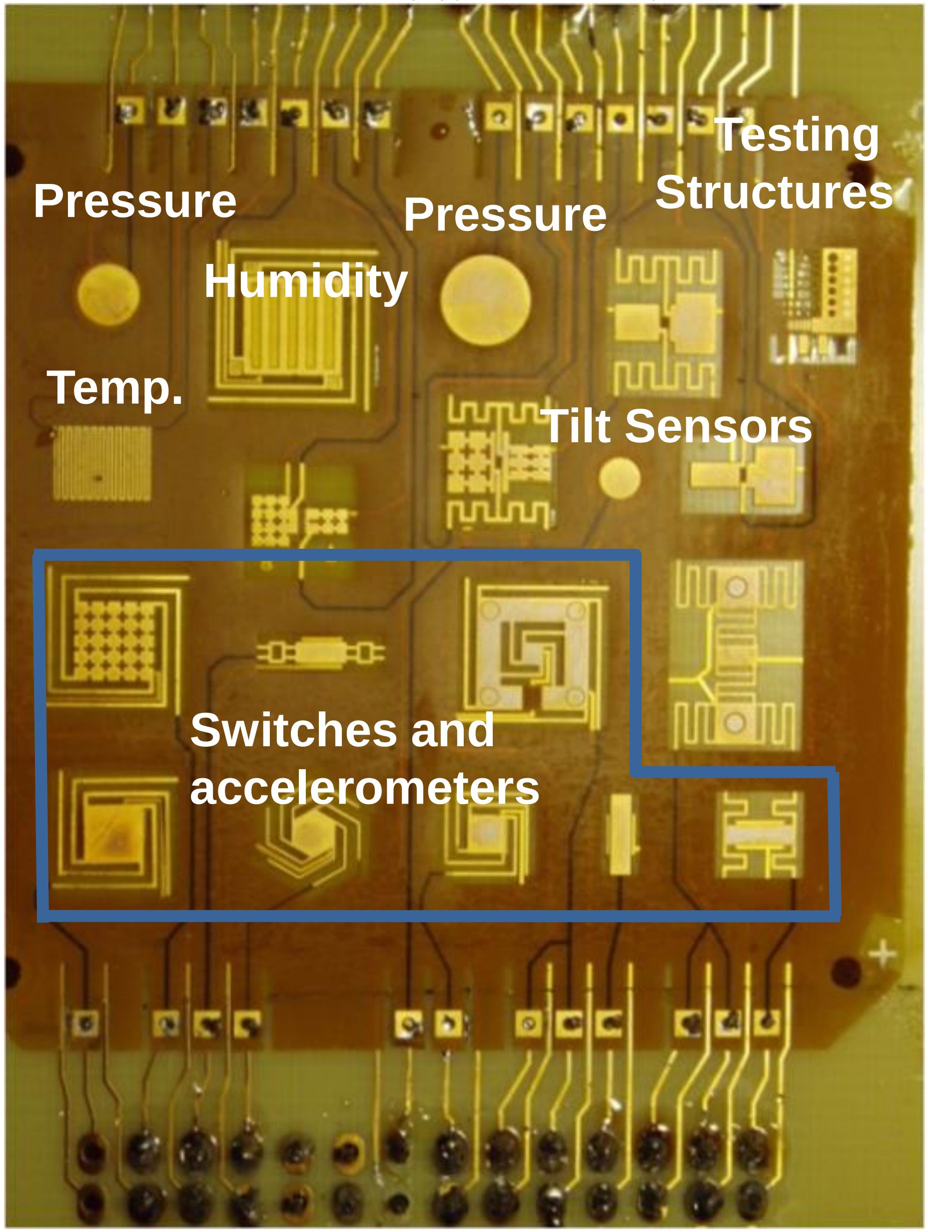


Kapton (50 um thick with 10-15 um-thick copper cladding)



Bonded assembly

Bonding parameters:
10 psi, 130 °C, 5 minutes

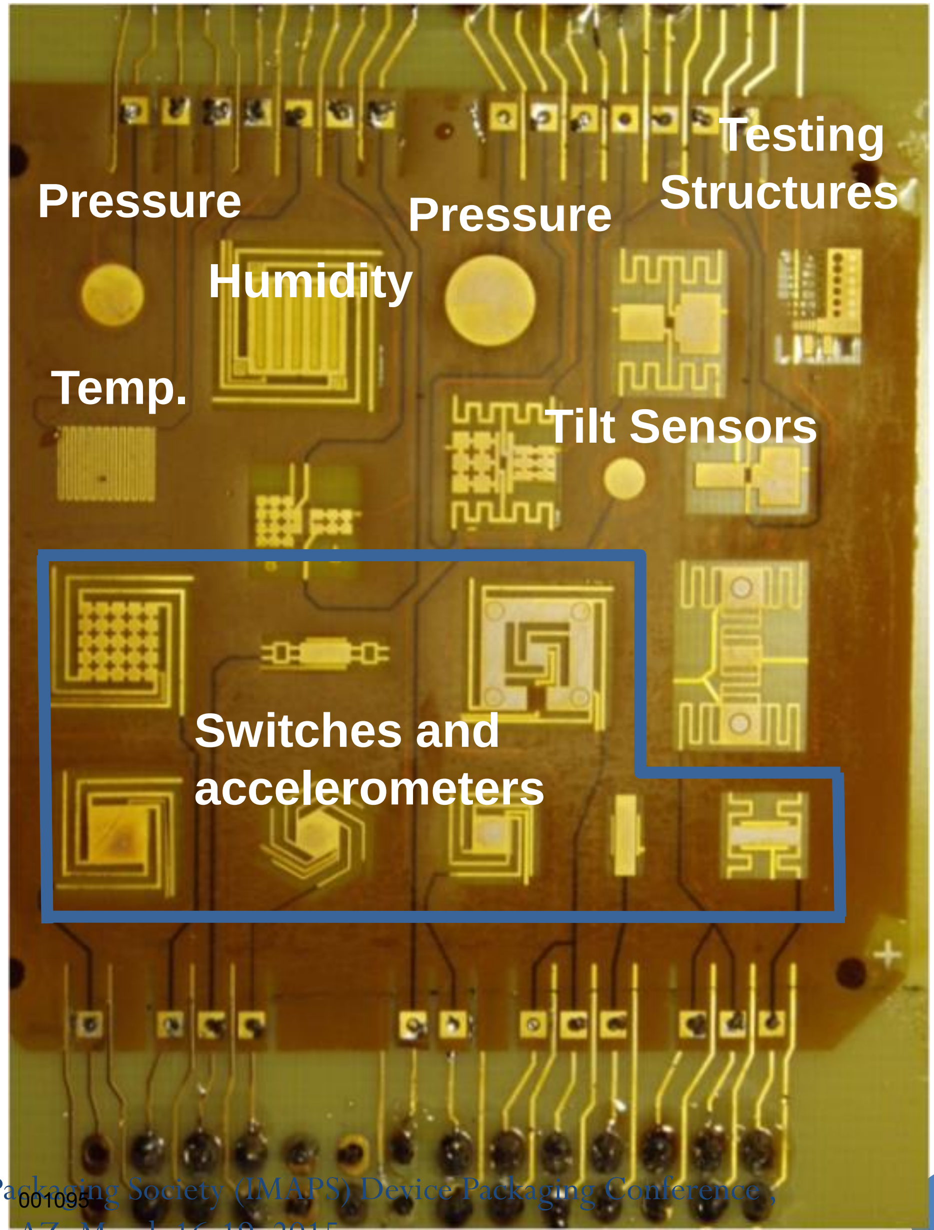

Testing
Structures
Pressure
Pressure
Humidity
Temp.
Tilt Sensors
Switches and
accelerometers

Device Testing

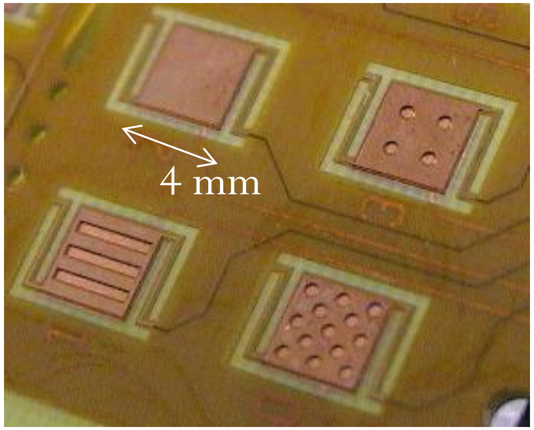
- Simple, proof of concept testing
- Short term testing
- Longer-term testing for reliability and repeatability is needed

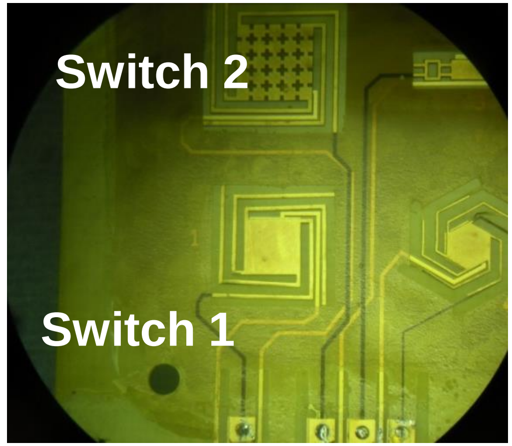
Device Testing

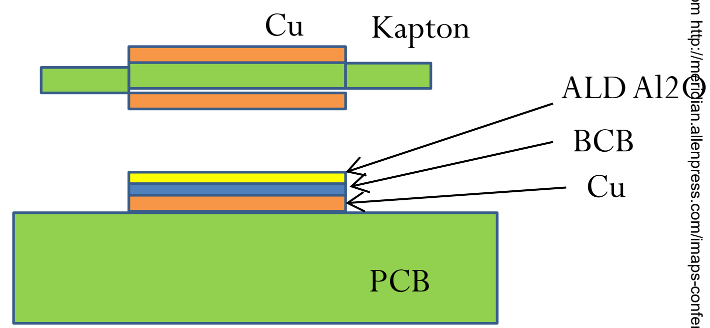
- Switches
- Acceleration/tilt sensors
- Humidity sensors
- Pressure sensors
- Temperature sensors

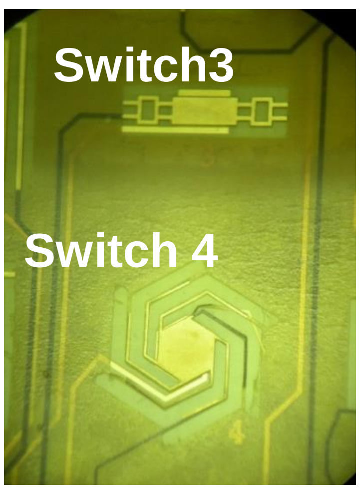


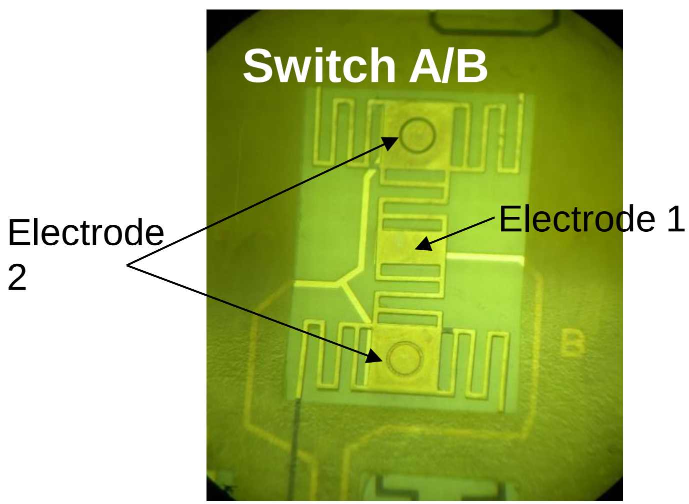
Switches

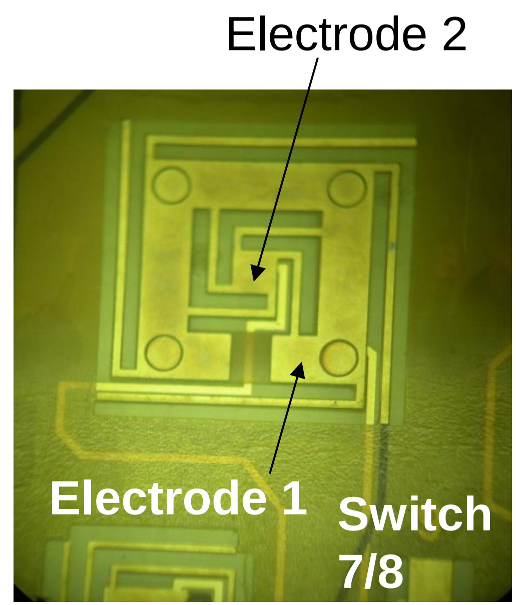

4 mm


Switch 2
Switch 1


Cu
Kapton
ALD Al2O3
BCB
Cu
PCB

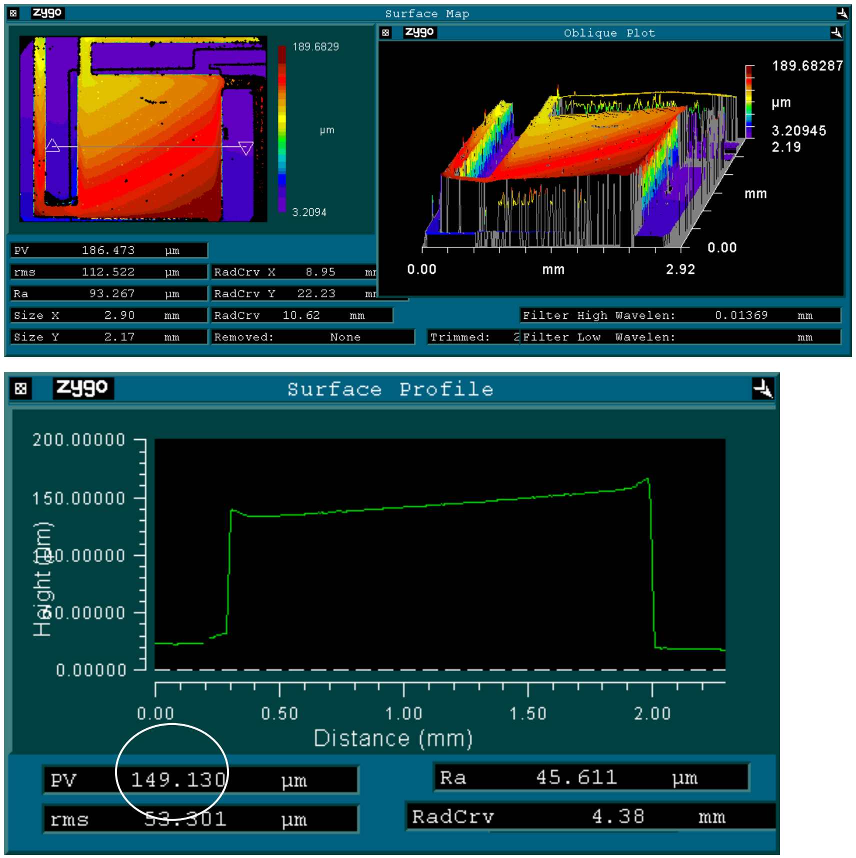

Switch3
Switch 4


Switch A/B
Electrode 2
Electrode 1

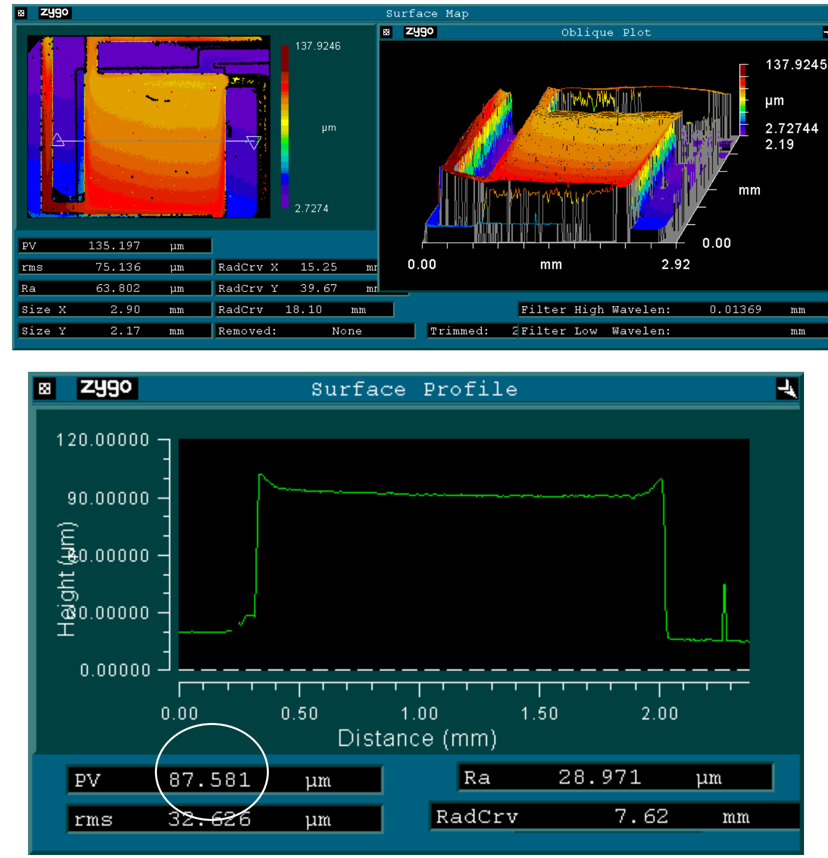

Electrode 2
Electrode 1
Switch 7/8

Switch Static Characterization

0 volts

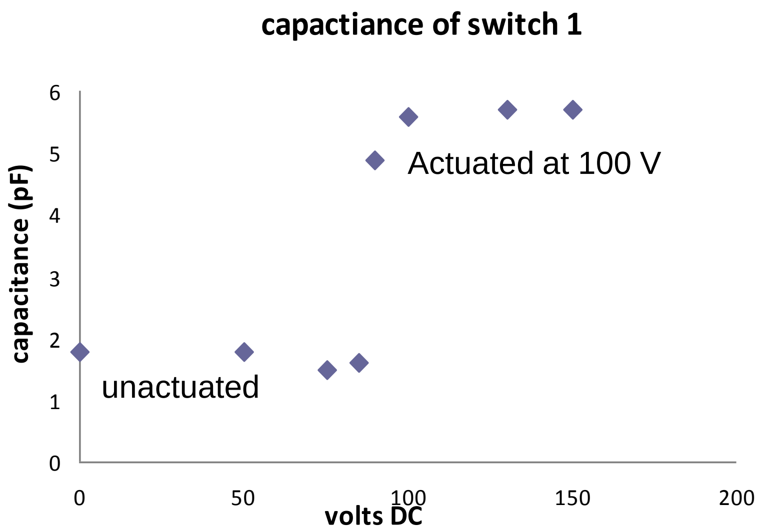


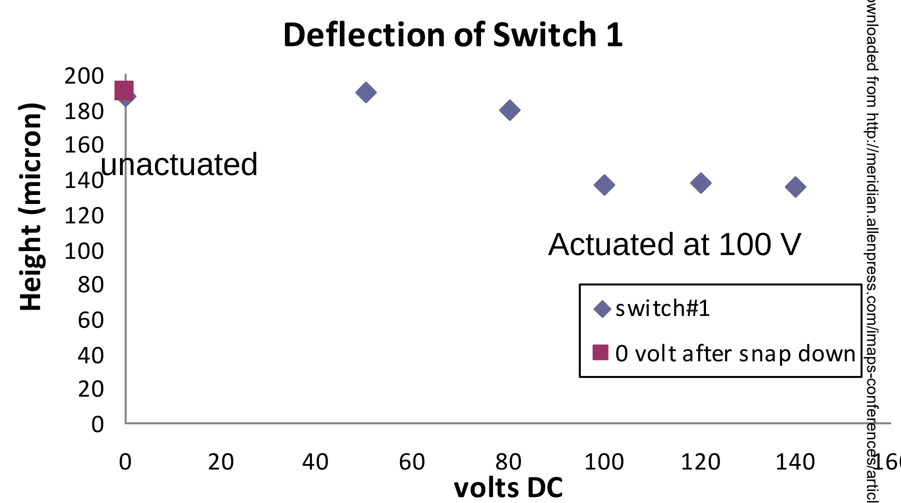
140 volts



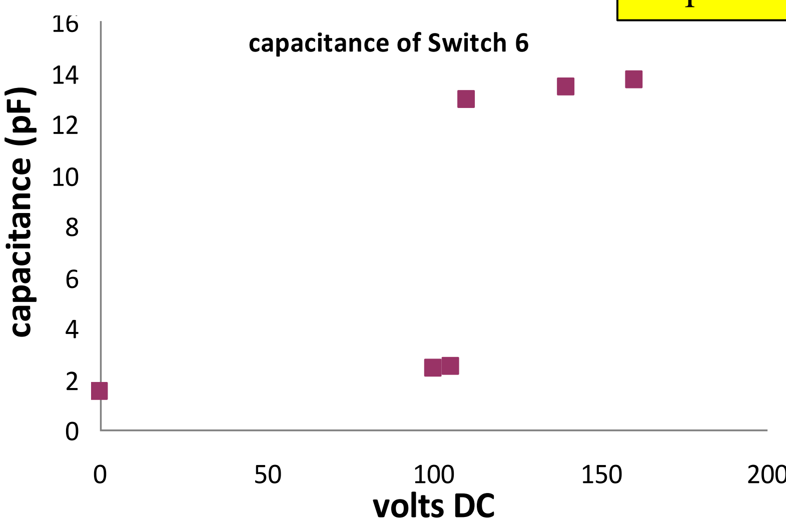
- Characterized the switches with two independent techniques:
  - Capacitance change
  - Deflection of membrane measured with optical interferometer

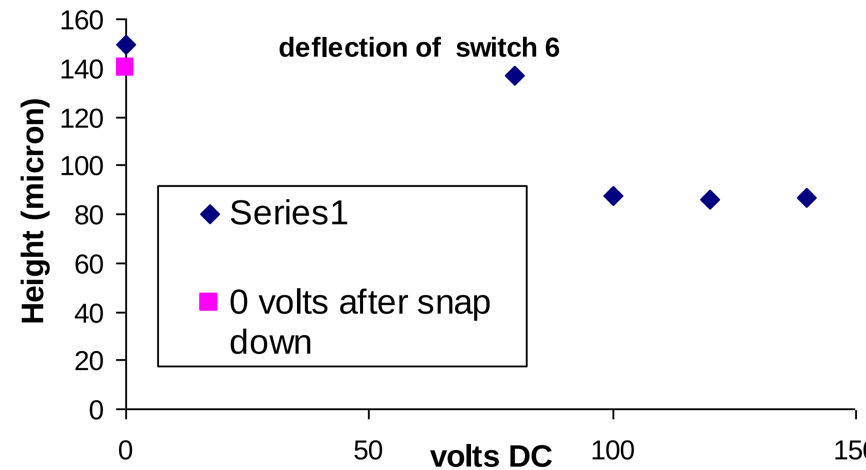
Switch static characterization





Repeatable pull-in voltage at 100 V



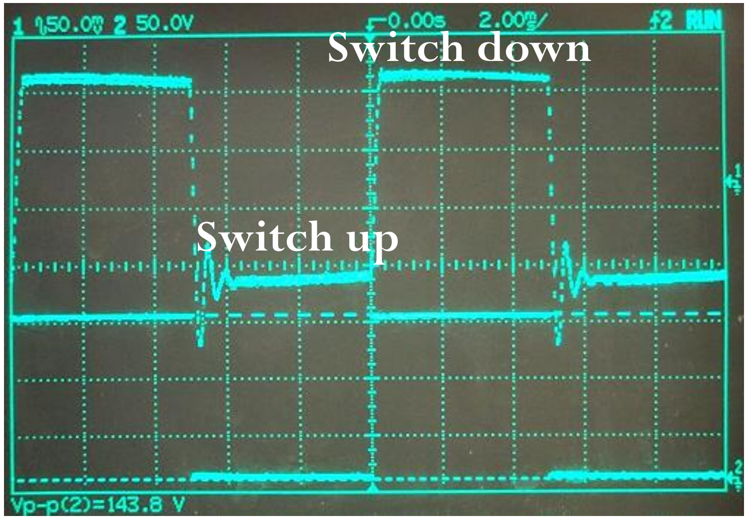


Switch Dynamic Characterization

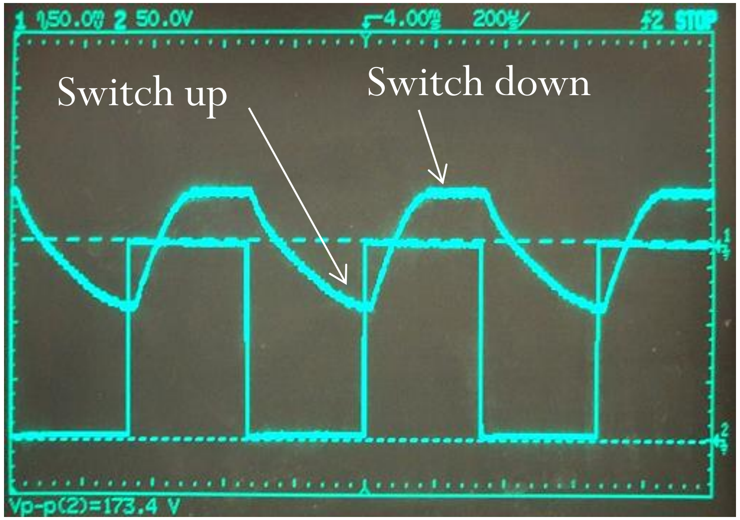
* Switches were driven with a square wave and measured with laser vibrometer

* Increase driving frequency until plate does not have time to mechanically settle (max operating frequency)

* Switches limited by their settling time in the 'up' position



f = 100 Hz

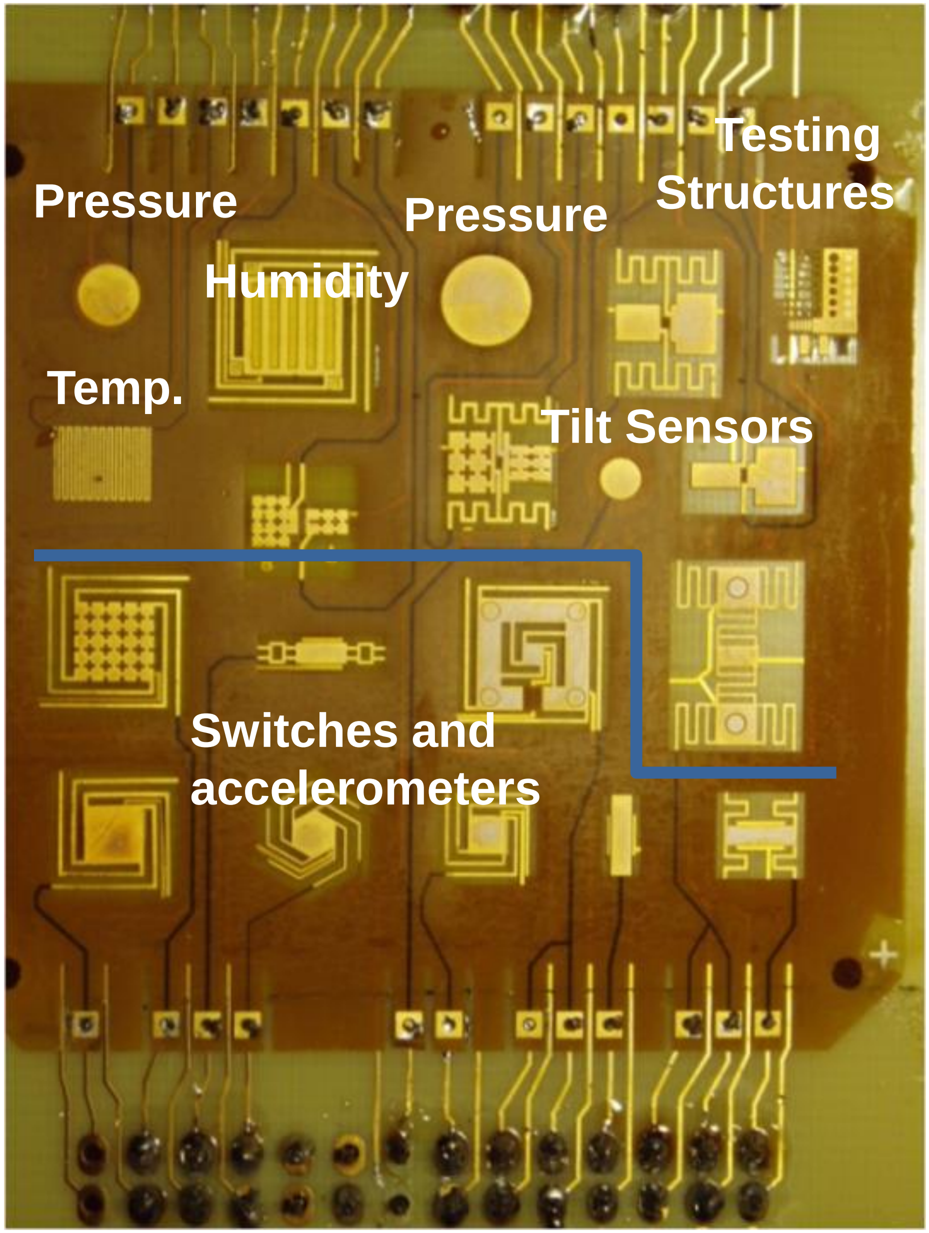


f = 1.4 kHz

Switch summary

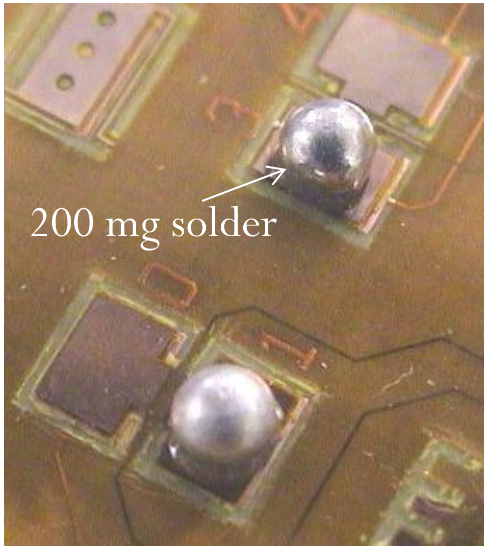
- Plate dimensions ~ 5 mm x 5 mm
- Repeatable pull-in voltages of 80- 100 V
- Max operating frequency 1.4 kHz

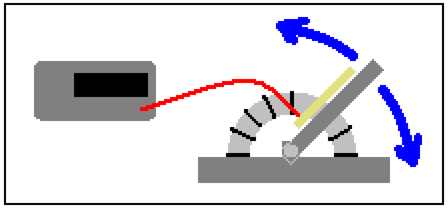
- Switches
- Single-axis acceleration/tilt sensors
- Humidity sensors
- Pressure sensors
- Temperature sensors

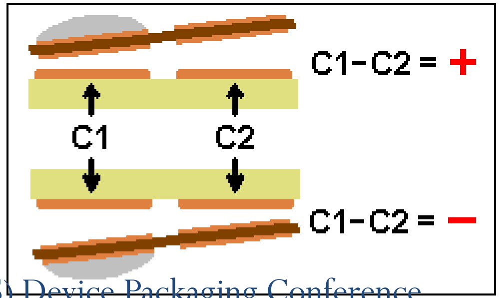


Single-axis acceleration/tilt sensors-static measurement (tilt)

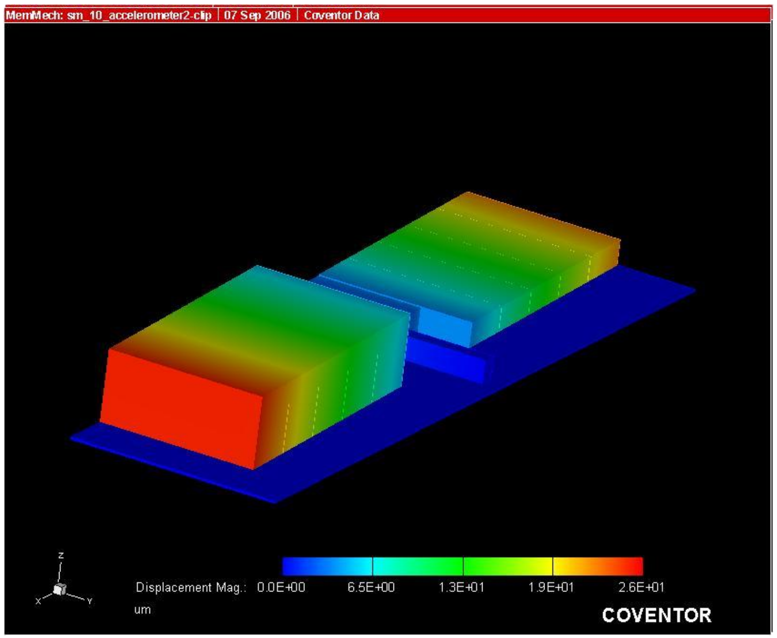
- 2 suspended kapton plates joined by a torsional hinge
  - Capacitive electrodes under the plates
- 200 mg solder ball added as proof mass
- PCB mounted to platform that can be inclined through 180° range
- Capacitances of each end of sensor are measured (C1 and C2 in picture)
- Differential capacitance = C1 – C2
- Can also measure in single-mode instead of differential
- Commercial IC chip for capacitance sensing

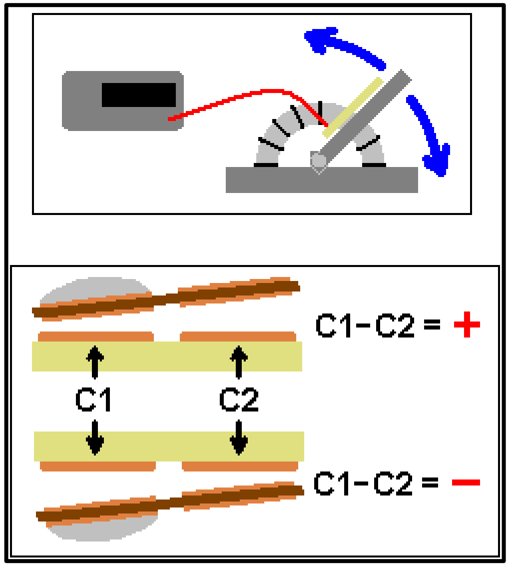






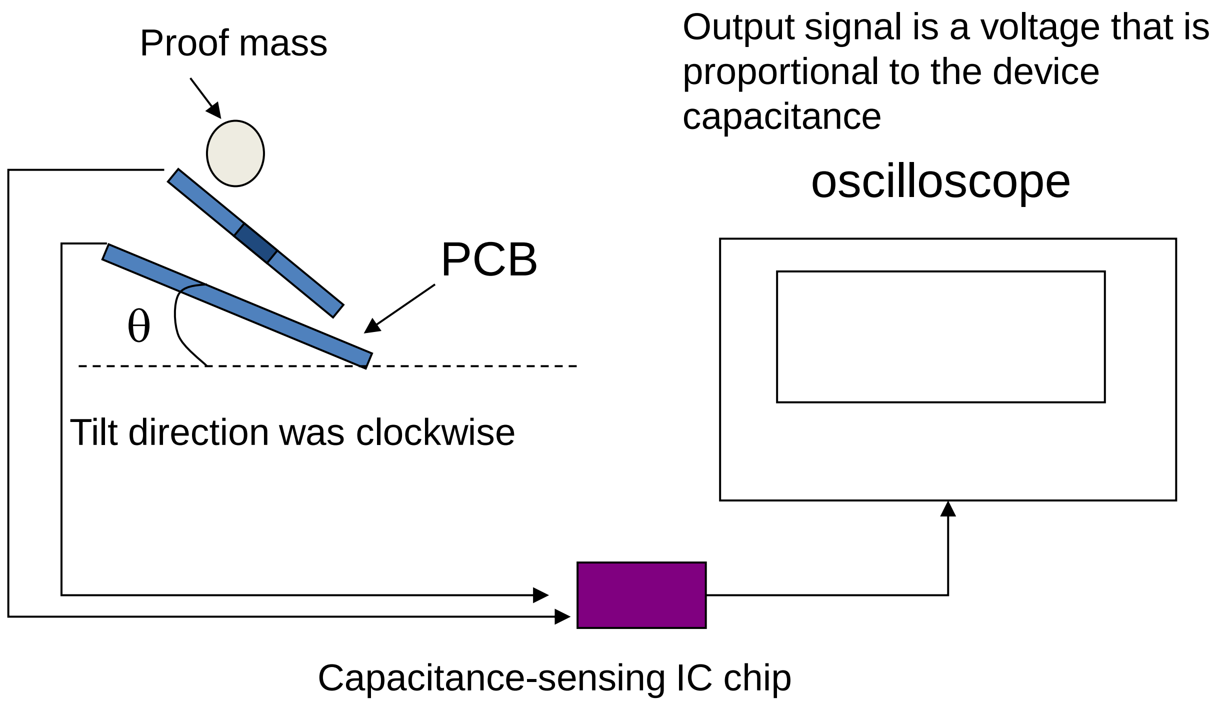
Differential mode





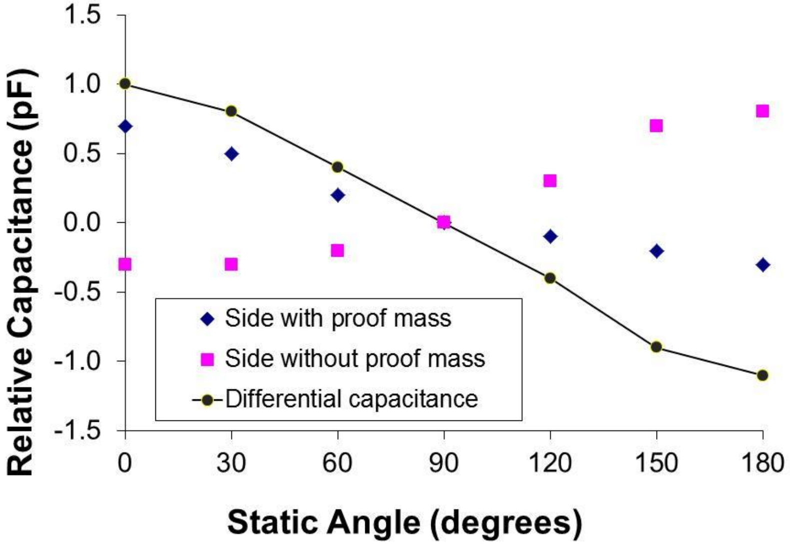
- Capacitances of each end of sensor are measured (C1 and C2 in picture)
- Differential capacitance = C1 – C2

Single-mode

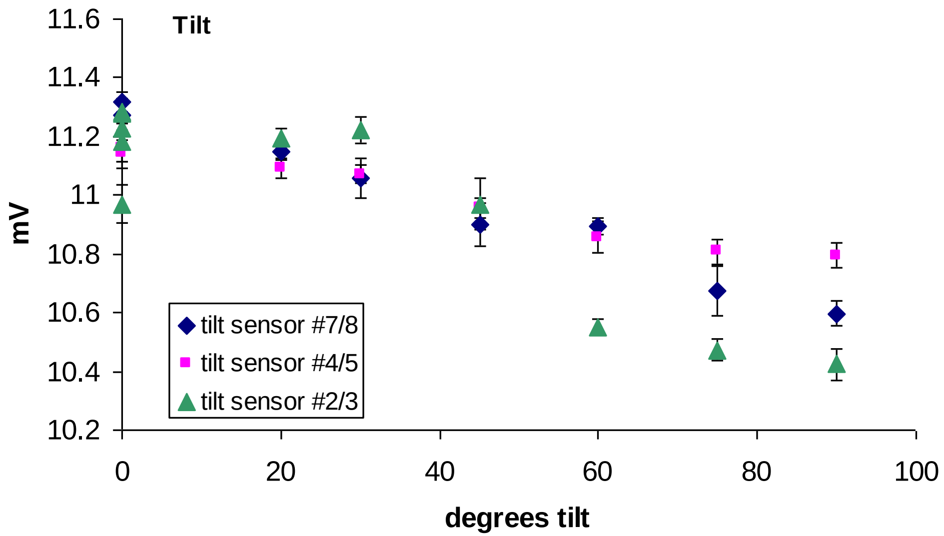

Proof mass
Output signal is a voltage that is proportional to the device capacitance
oscilloscope
PCB
θ
Tilt direction was clockwise
Capacitance-sensing IC chip

Static (tilt) tests

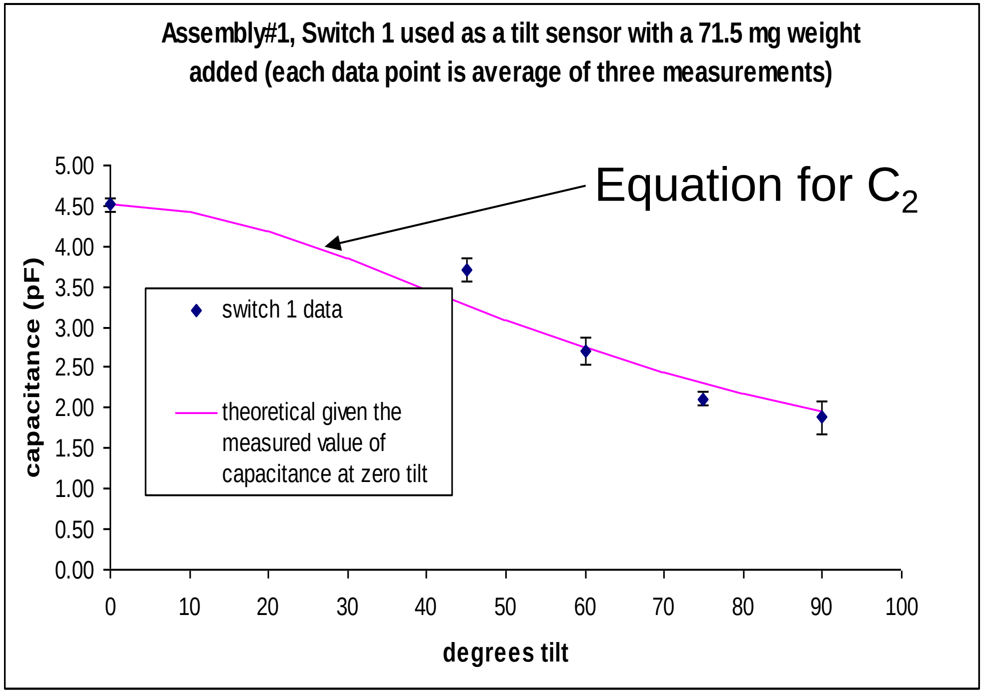
Differential mode

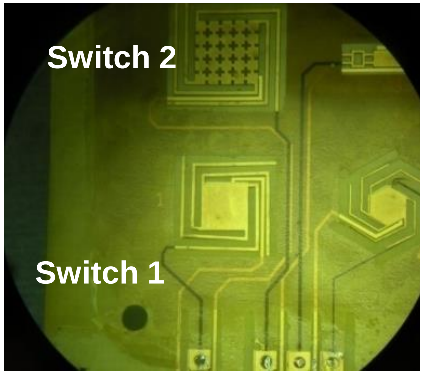


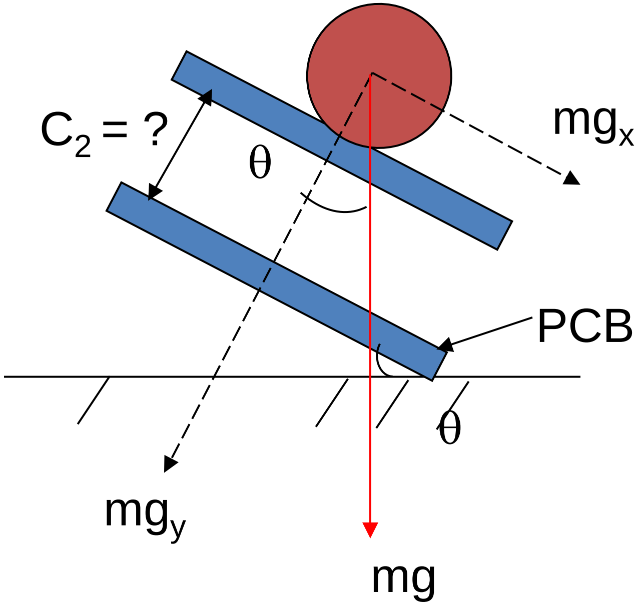
Single mode



Switches as single-mode tilt sensors





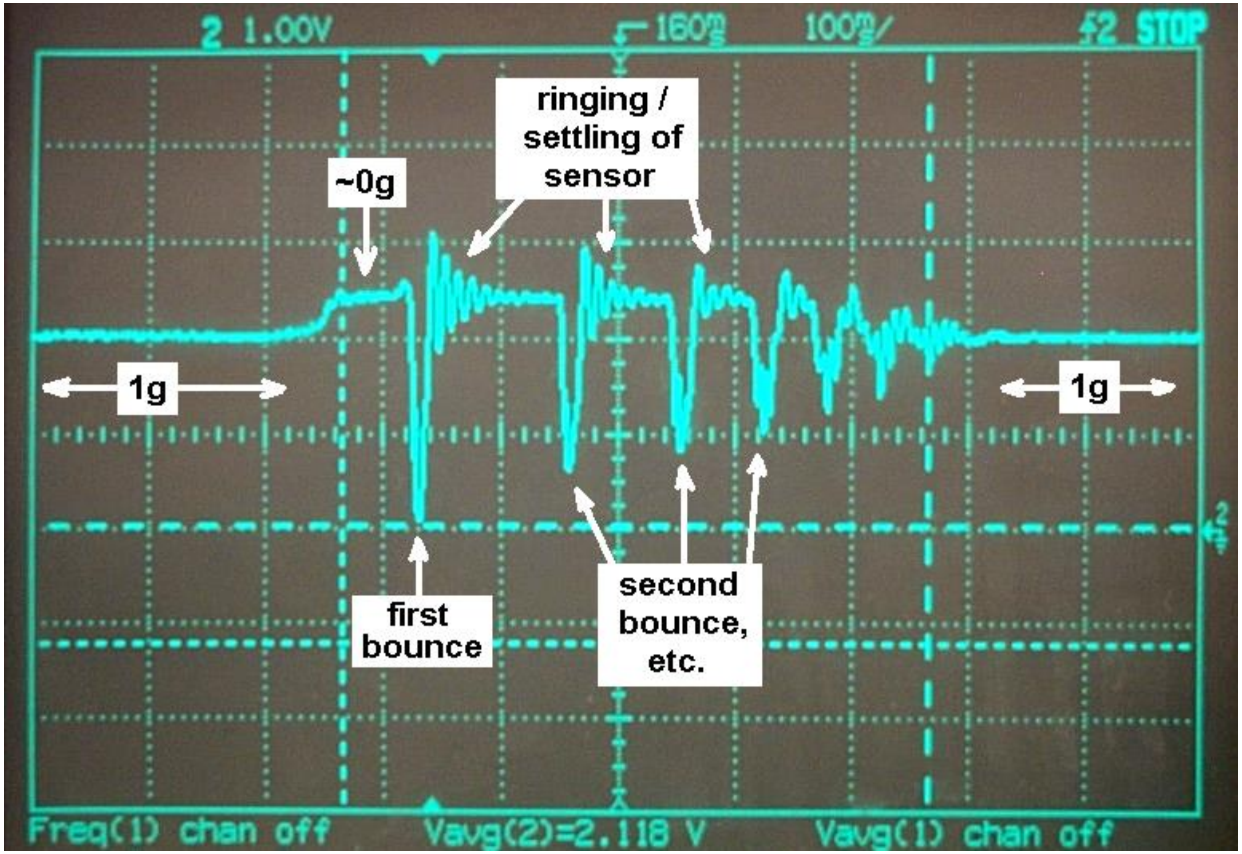


$$C_2 = C_1 \frac{\text{Gap} - Z_1}{\text{Gap} - Z_1 \cos\theta}$$

Or, because $Z_1 = \text{Gap}\,[1 - (C_0/C_1)]$,

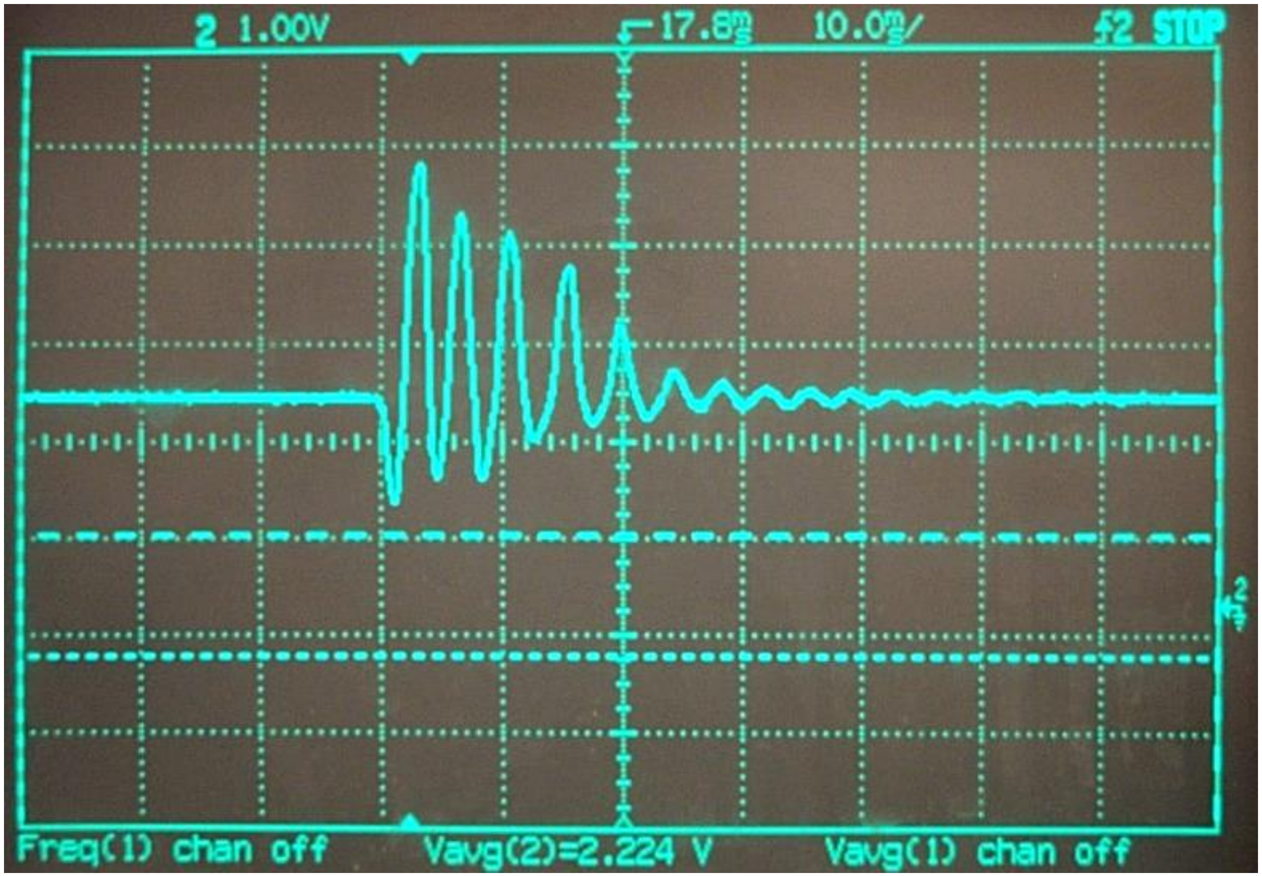
$$C_2 = \frac{C_0}{1 - (\cos\theta)(1 - C_0/C_1)}$$

Dynamic tests (drop test)



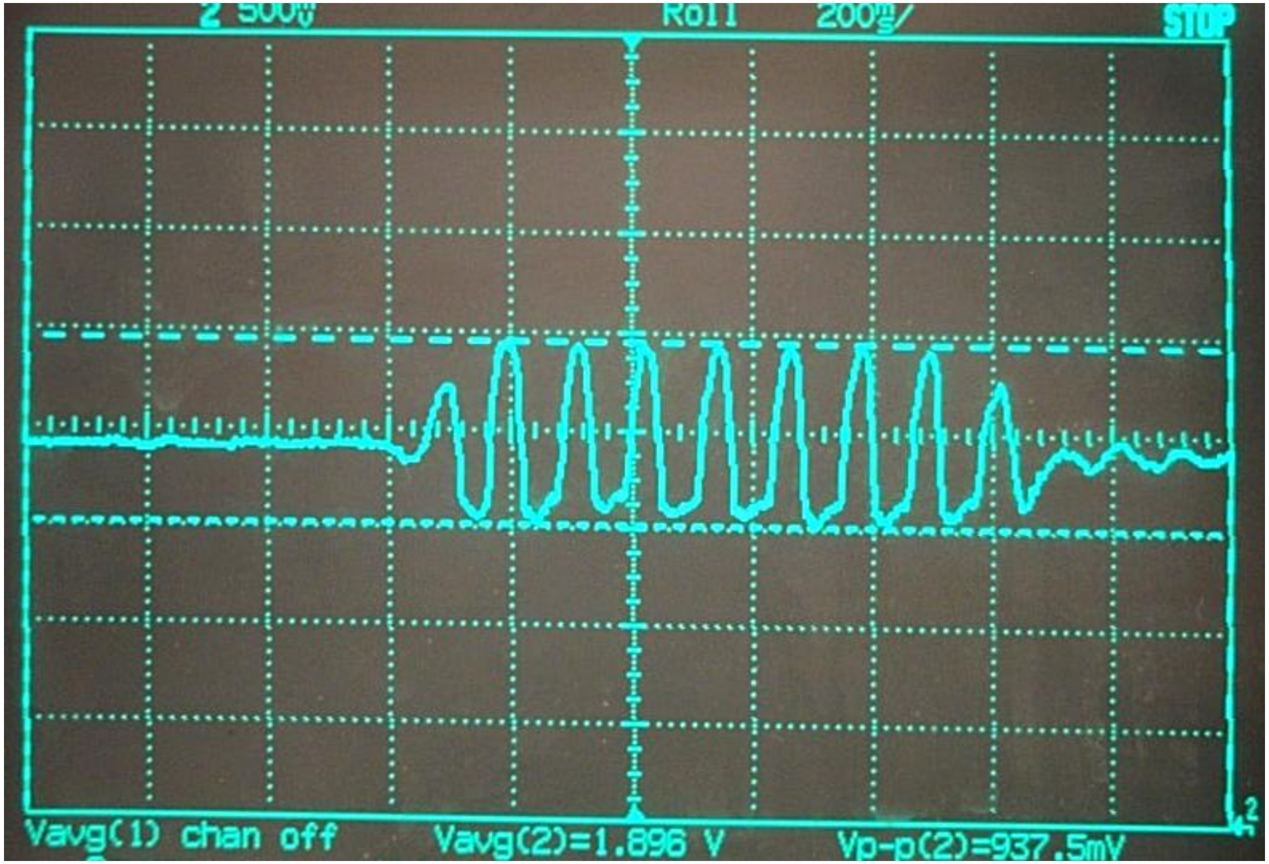
- Total timespan shown: 1 second
- 1g before platform release & after test
- ~0g as platform is in freefall
- Platform typically bounces several times on impact
- Sensor resonates and settles to ~0g between bounces

Dynamic test (impulse response)



- Timespan: 0.1 s
- A single “tap” causes oscillation of sensor at its natural frequency *(~250 Hz in this case – varies with sensor design and proof mass size)*
- As shown here, not all sensors respond linearly / symmetrically

Dynamic test (low-freq oscillation)

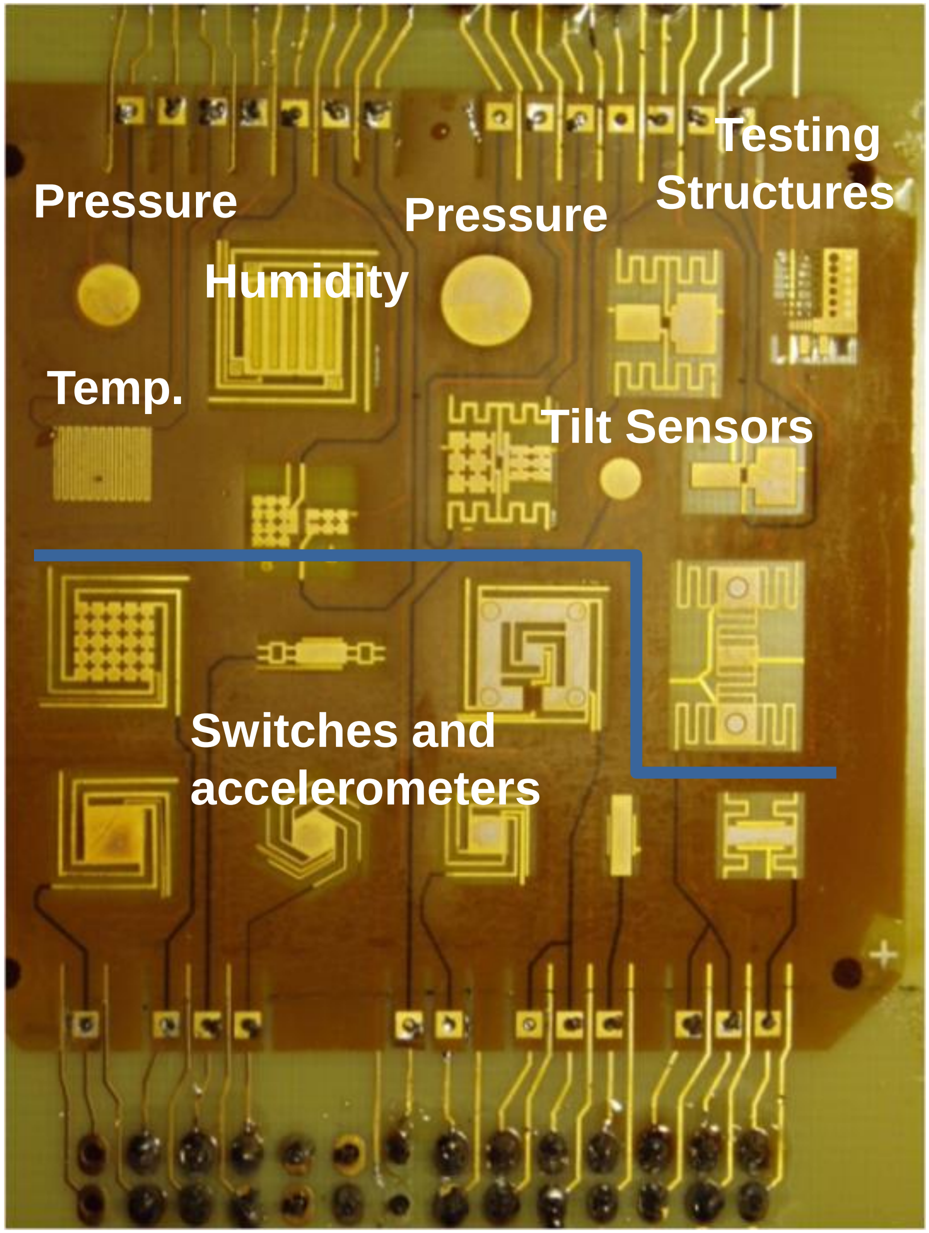


- Timespan: 2 s
- PCB held in hand
- Gentle back-and-forth shaking in linear manner at ~9 Hz produced this result

Acceleration/tilt sensor summary

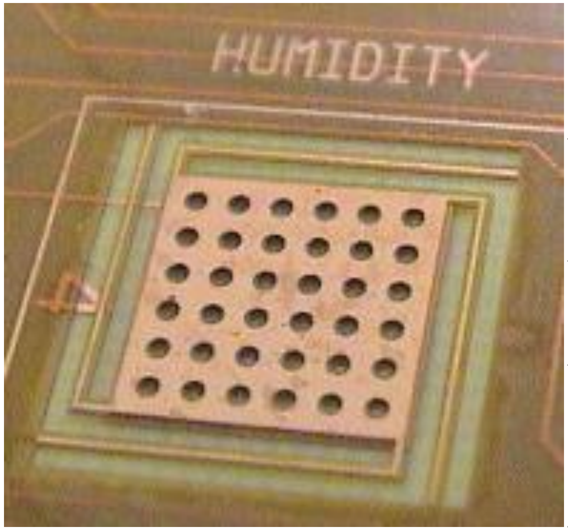
- Plate dimensions ~ 3 mm x 3 mm
- Sensitivity ~ 0.01 to 0.02 pF/degree
- Natural frequencies ~ 100 Hz (due to large proof mass)
- Current sub-pF sensor capacitive output is sufficiently large for measurement with commercially-available ICs
- Current tilt/acceleration sensors respond primarily to tilting/acceleration about or along specific axes; alternate designs necessary for sensitivity to all axes of motion

- Switches
- Acceleration/tilt sensors
- **Humidity sensors**
- Pressure sensors
- Temperature sensors

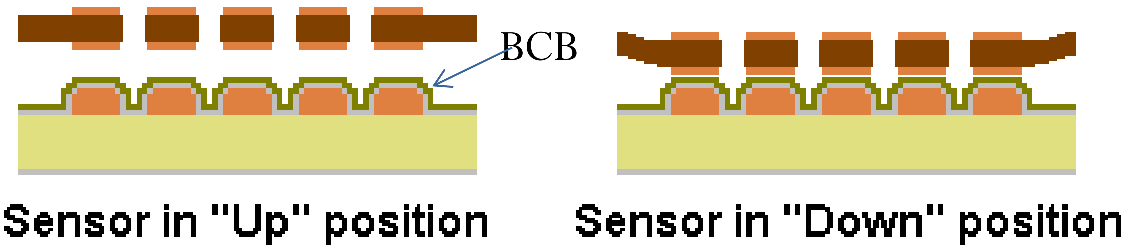


Humidity Sensor

- BCB layer absorbs/desorbs moisture, changes dielectric constant



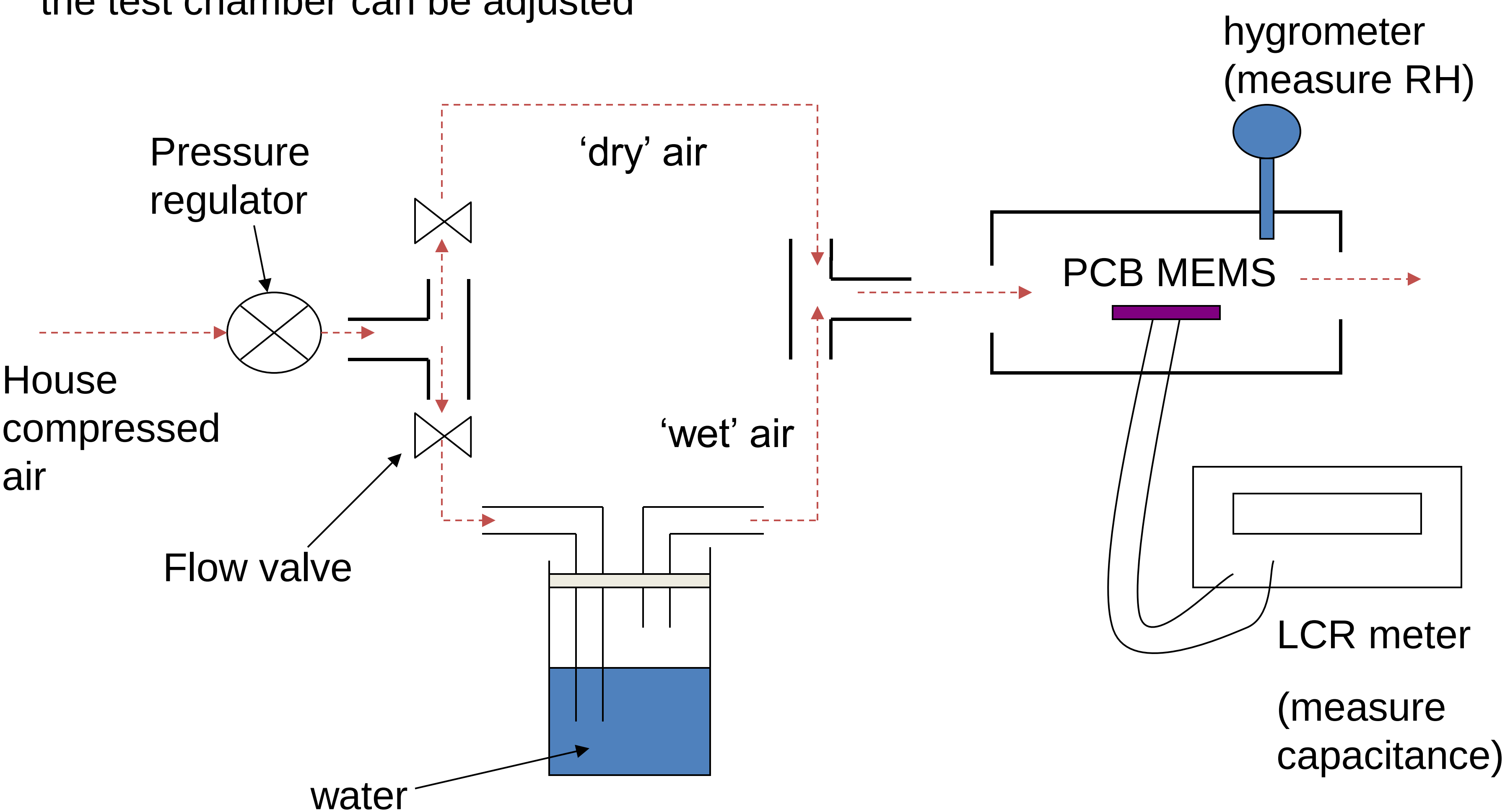
- Apply and maintain biasing voltage to pull Kapton membrane into "down" position* (similar to switches)



- Vary chamber humidity while collecting data in real-time:
  - chamber humidity, as indicated by hygrometer
  - sensor output, using capacitance-measurement equipment

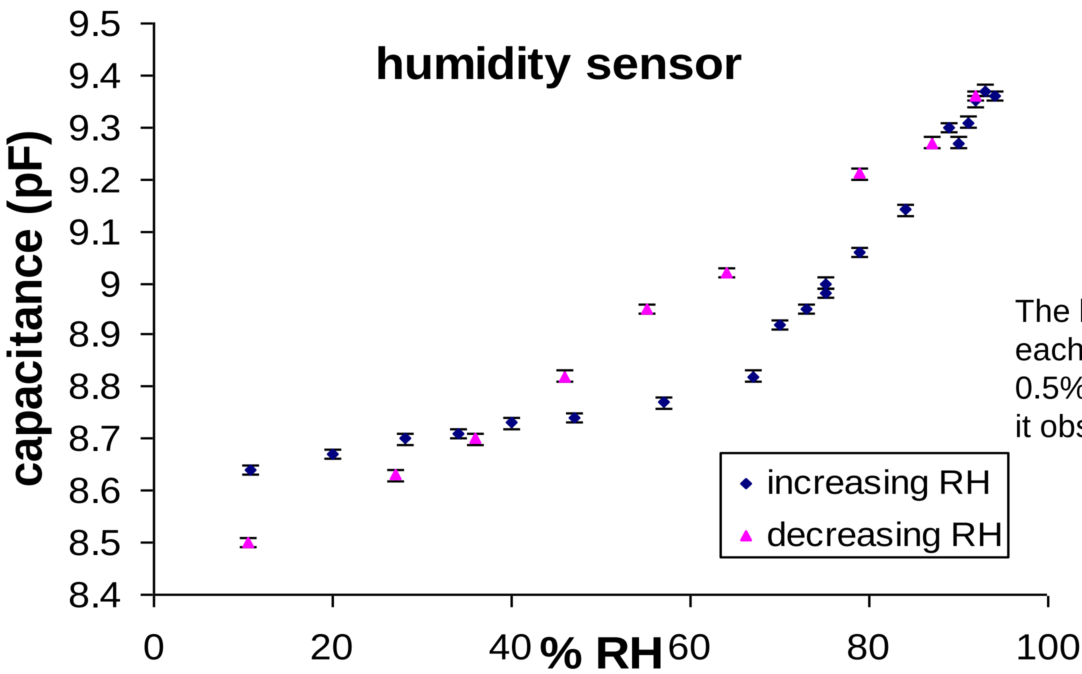
Humidity Test

By adjusting the two flow valves, the relative humidity of the air going into the test chamber can be adjusted



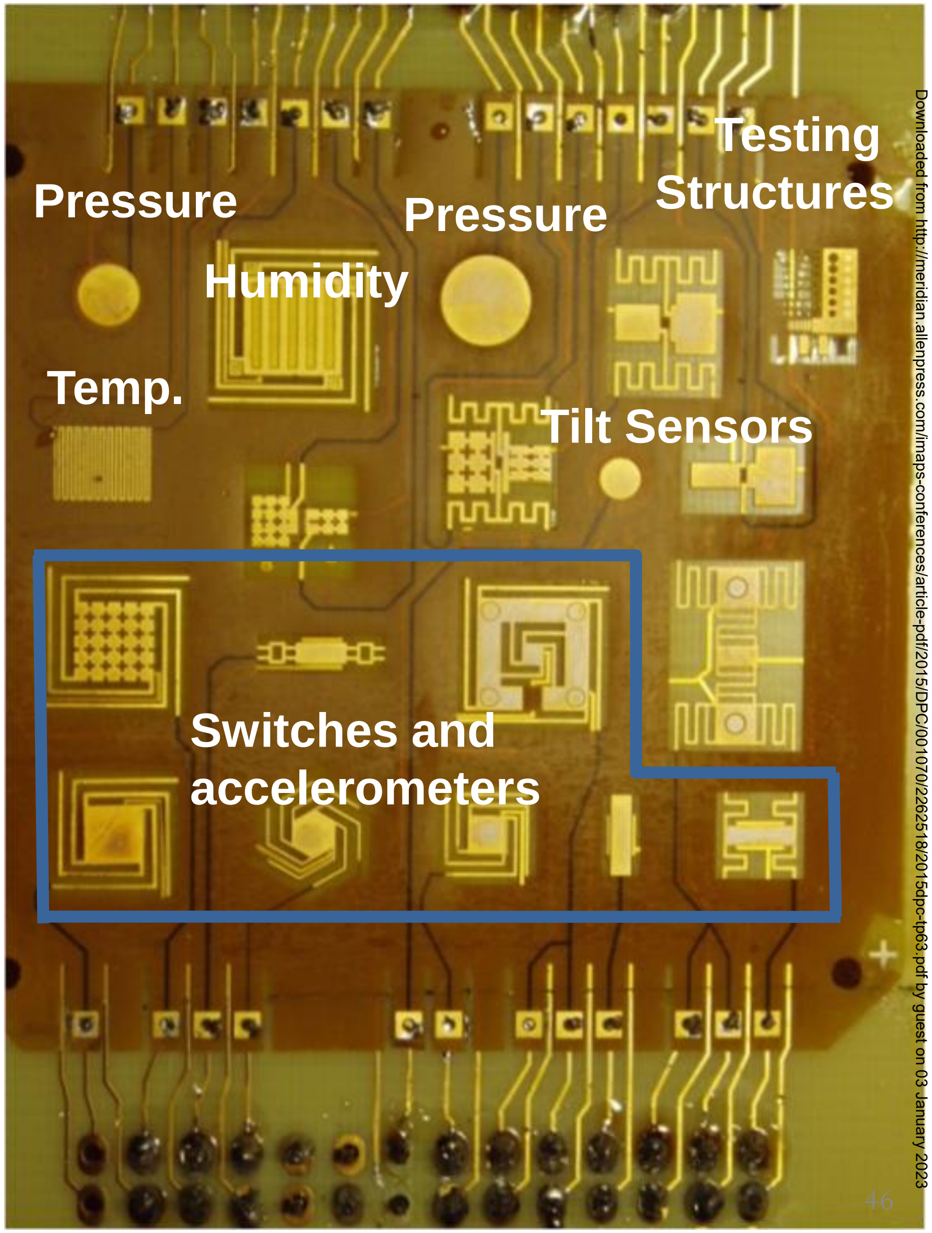
Humidity test

- Put the PCB in a container, flowed in a stream of dry air and a stream of water vapor, and used a commercial hygrometer to measure the % relative humidity of the atmosphere.
  - Simultaneously we used the LCR meter to measure the capacitance of the humidity sensor.
- Total capacitance change is about 1 pF, but the individual readings were very stable to within 0.01 pF.
- Target value of RH was held constant for about 30 seconds to one minute (to allow for equilibrium) before capacitance of the PCBMEMS was taken.



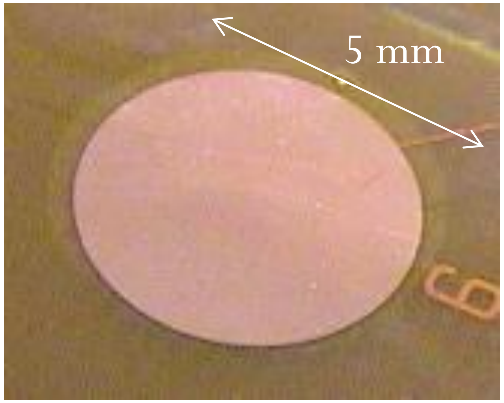
The horizontal error bar for each data point should be +/- 0.5% (but if I put it in the graph it obscures the data point)

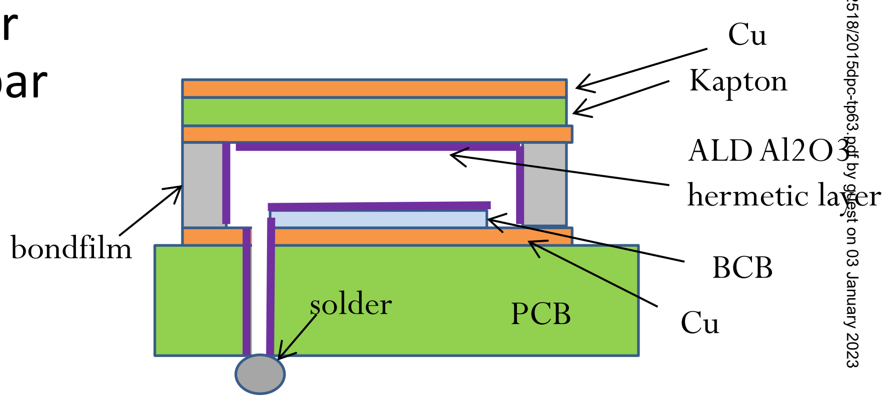
- Switches
- Acceleration/tilt sensors
- Humidity sensors
- **Pressure sensors**
- Temperature sensors



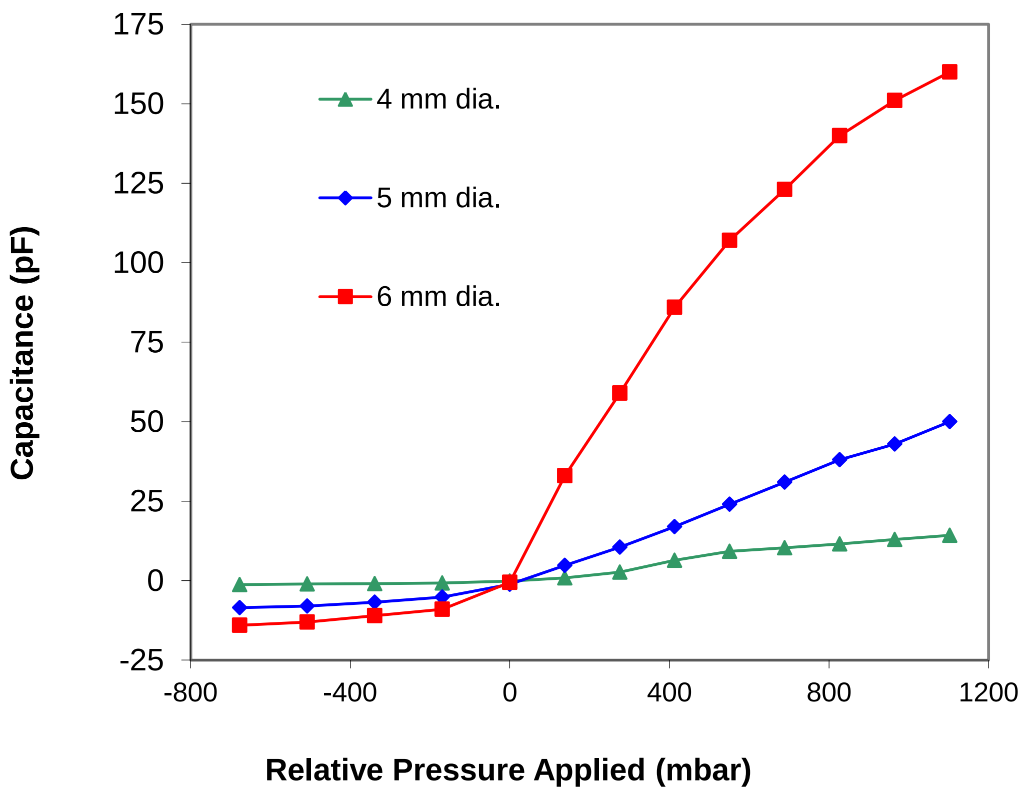
Pressure sensor

- Reference pressure port sealed with solder
- ALD alumina overcoat (60 nm thick) for hermeticity
- Enclose PCB in pressure/vacuum chamber
- Zero out capacitance meter with sensor connected and chamber at ambient pressure
- Vary chamber pressure between -700 mbar and +1100 mbar gage (about 300-1900 mbar absolute, or ~0.3-1.9 atmospheres)
- Record sensor capacitive output at each pressure level





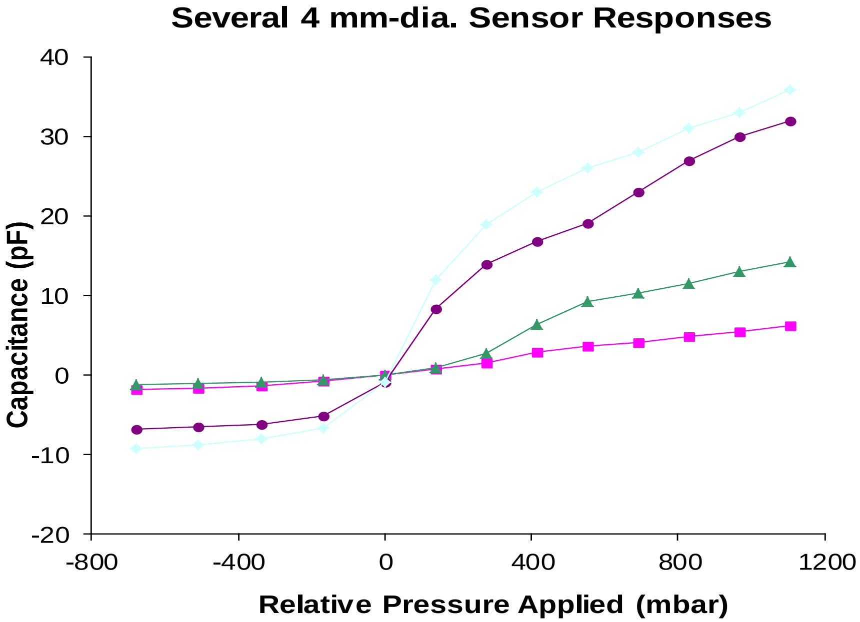
Relative pressure test



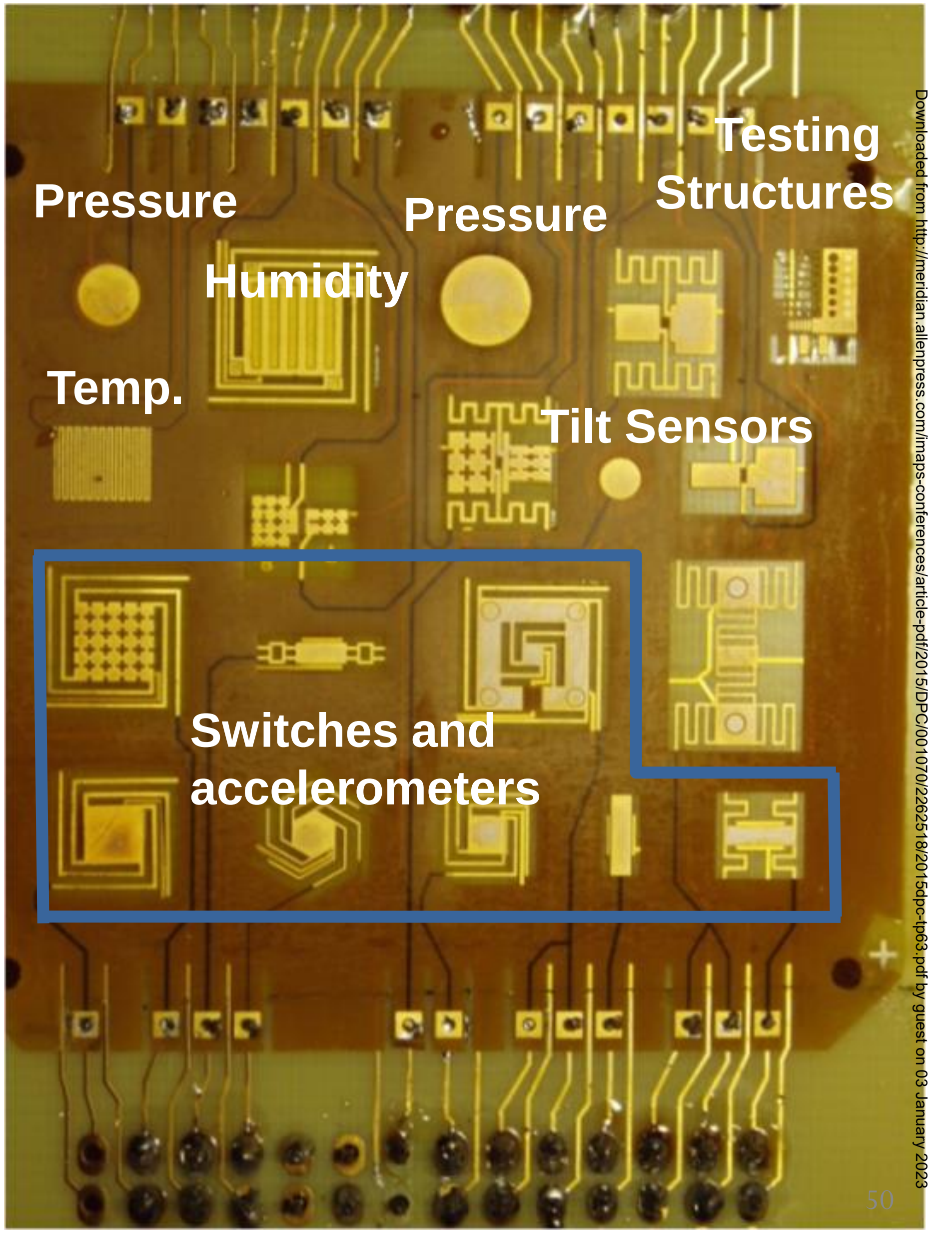
- Three sensor designs with different sensitivities and pressure ranges:
  - 4 mm diameter; most compact, suitable for largest pressure ranges
  - 5 mm diameter
  - 6 mm diameter; most sensitive
- Nonlinear responses as expected; higher sensitivities at higher pressures
- Relatively large capacitive responses

Pressure sensor summary

- Short term relative pressure (static)
- Sensitivity ~ 0.125 pF/mbar
- Large variation in sensitivity of same design from one module to another (repeatability of assembly process)

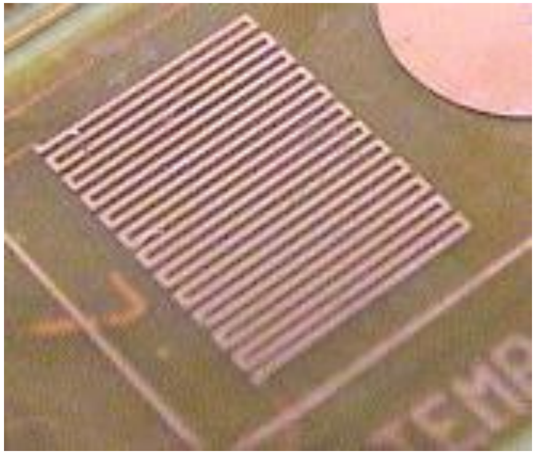


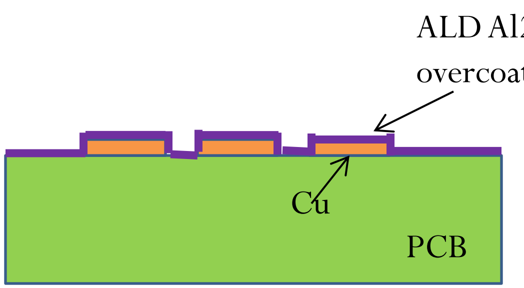
- Switches
- Acceleration/tilt sensors
- Humidity sensors
- Pressure sensors
- Temperature sensors



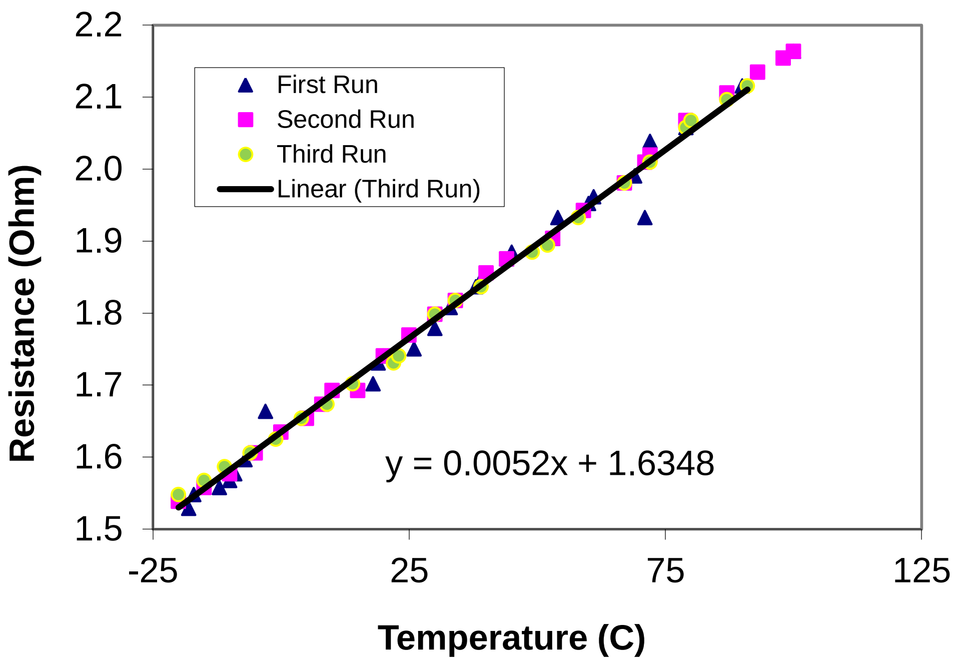
Temperature Sensor

- Resistance of copper trace (15 um thick) increases in proportion to temperature
- ALD Al_2O_3 overcoat to protect copper from oxidation
- PCB placed in environmental chamber
- Temperature varied from -25 °C to 100 °C
- 4 point probe resistance measurement





Temperature sensor



- One sensor measured several times to confirm repeatability of readings
- Good consistency between runs
- ~0.2°C/mΩ sensitivity
- Similar responses from other PCB-based sensors tested
- Minor board-to-board variation in slope/offset of calibration curve

Summary

- Demonstrated a monolithic PCB-MEMS sensor suite
  - Switches
  - Single-axis acceleration/tilt sensors
  - Humidity sensors.
  - Pressure sensors
  - Temperatures sensors
- Devices fabricated simultaneously in one module
- Use of Atomic Layer Deposition (ALD) coatings to improve PCB MEMS performance
  - Hermetic barrier layer for pressure sensor
  - Oxidation protection coating for temperature sensor
  - Extra dielectric protection layer for capacitive devices

Monolithic integration of different MEMS devices into a single PCB module may be useful for applications in mobile electronics.