# Investigating Cracks in ATLAS ITk Strips

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***From a collective effort of the ITk HV Task Force***

**Forum on Tracking Detector Mechanics**

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# Acknowledgements

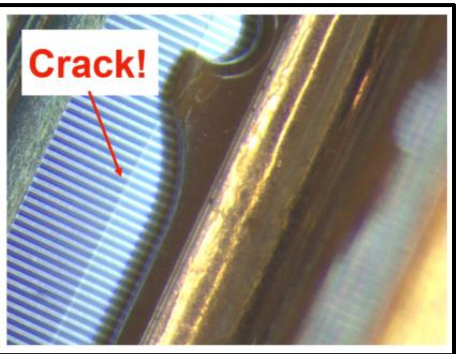
Task force members with key contributions to this talk:

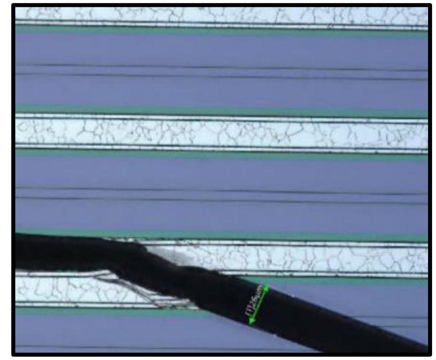
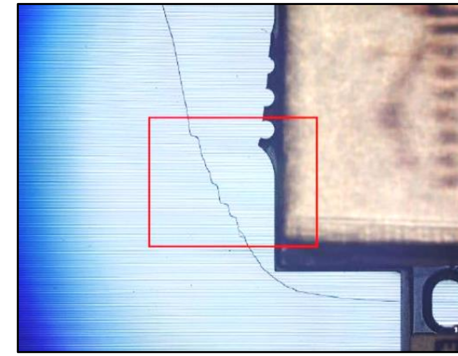
A. Affolder, G. Beck, A. Blue, M. D. Celuch, J.F. Croteau, S. Diez Cornell, A. Fortman, C. Haber, T. Heim, C. M. Helling, T. Johnson, D. Lynn, B. Matthews, M. Moori, A. T. Perez Fontenla, A.L. Poley, O. Sacristian, C. Sawyer, S. Wonsak, S. Yang

# Outline

- **Introduction**
- Numerical Modeling
- Mitigation Strategies
- Conclusions

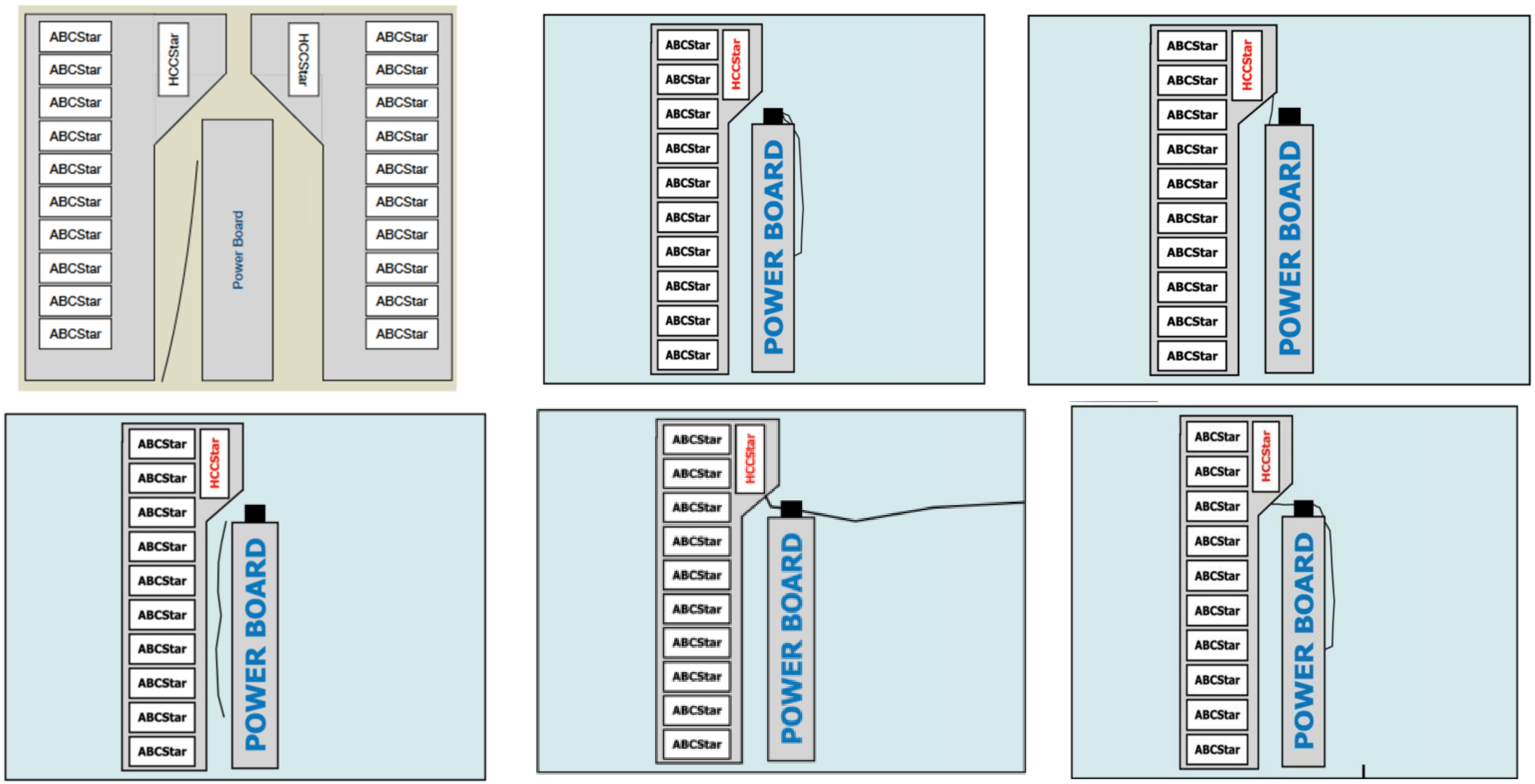
# Introduction



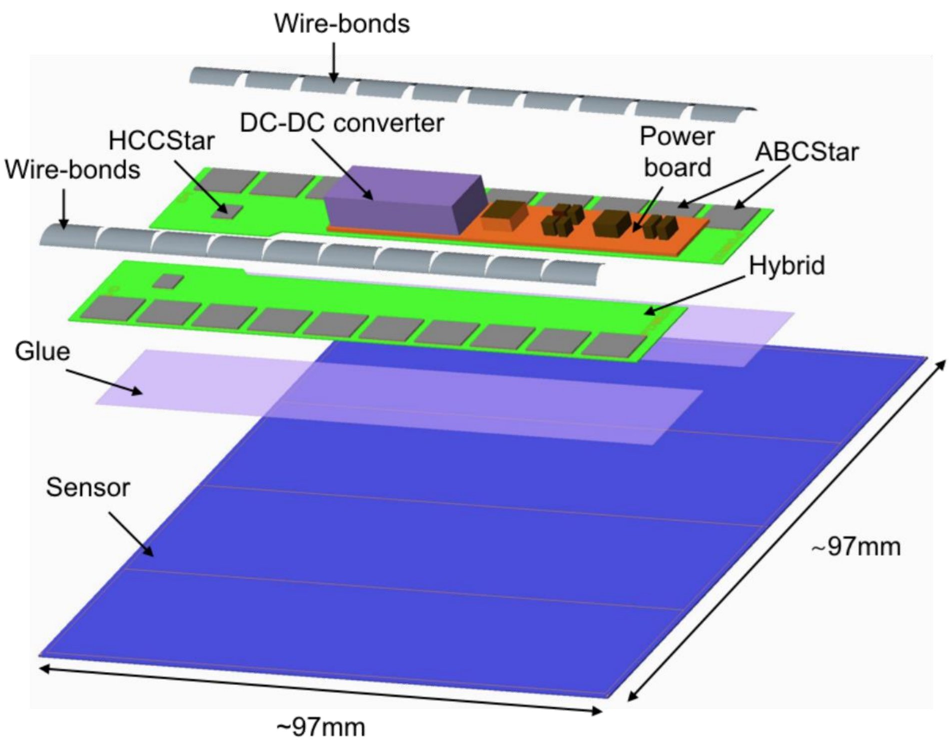
- Some sensors failed high voltage testing (early breakdown)
- After visual inspection, **mechanical failures** were detected across sensors during thermal cycling
  - Failed areas look like a '**crack**'
- As part of a task force effort, we have developed numerical simulations and performed mechanical tests to better understand:
  - **Why/when** it fails
  - How the design can be **improved** to avoid further failures

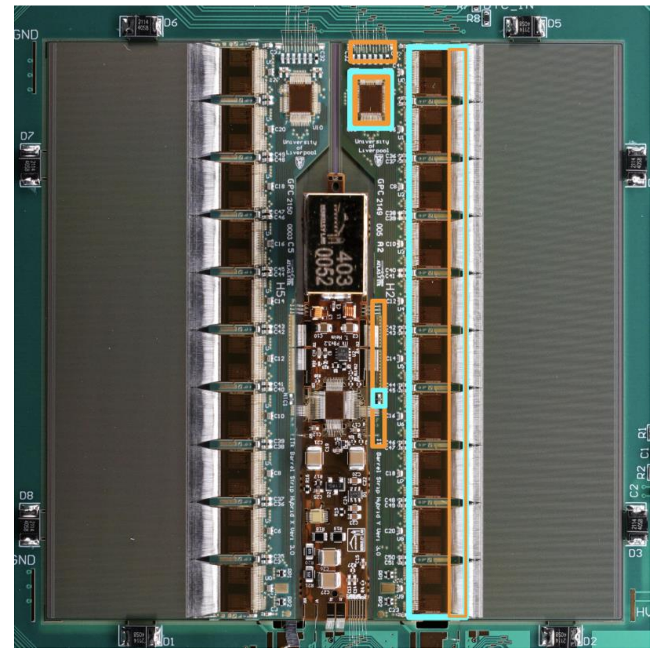
# Crack Locations



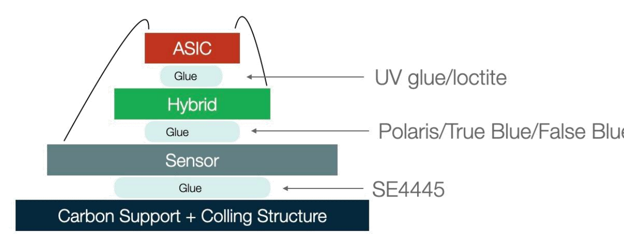

- Cracks seem to appear at some point during **thermal cycling/powering** at -40 C, only on some modules
- Not clear why, when, and where they start

# Module Anatomy

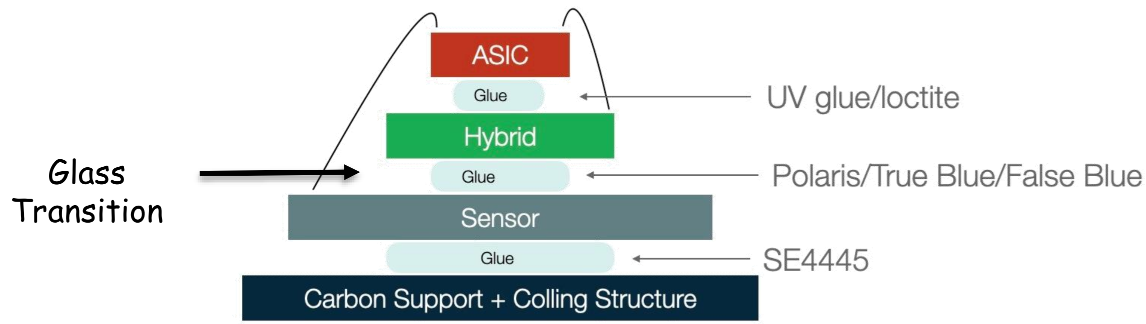


- Different sensor layouts in different regions, but all share similar characteristics
- Short strip staves contain a ‘**stack**’ of 4 layers, **bonded** together by different glues



# Tested Module History

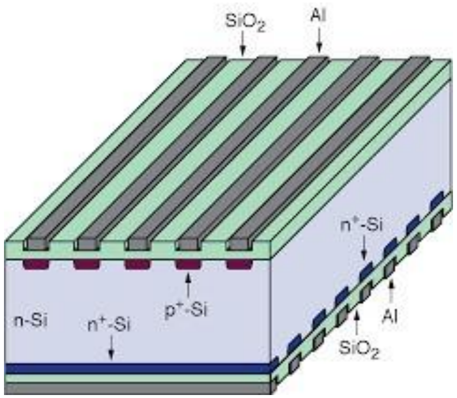


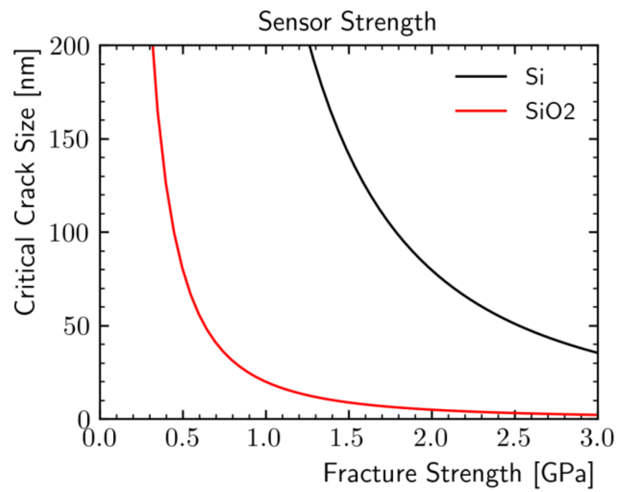

Not all the tested modules experienced the same temperatures/loads, but typically:

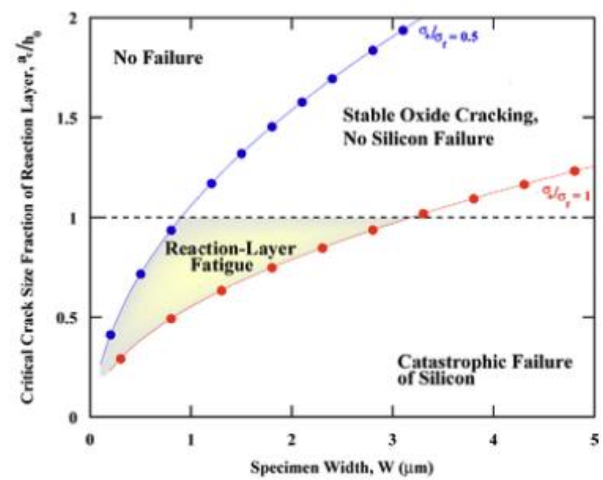
1. **Thermal cycling** (with or without powering) between R.T. and **20** or **40** C
   - Measurements show a **permanent deformation** (‘bow’) after cooldown, probably due to glass transition of the HB/PB glue (not fully cured at R.T.)
2. Sensor is **bonded** on the **stave**
   - 2 different procedures: BNL/RAL, with different loads/constraint on the sensor
3. **Thermal cycling** between R.T. and **-40 C**, with powering tests

# Silicon Strength

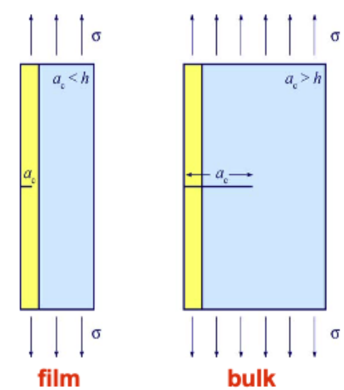
From: R. O. Ritchie – Failure of Silicon: Crack Formation and Propagation



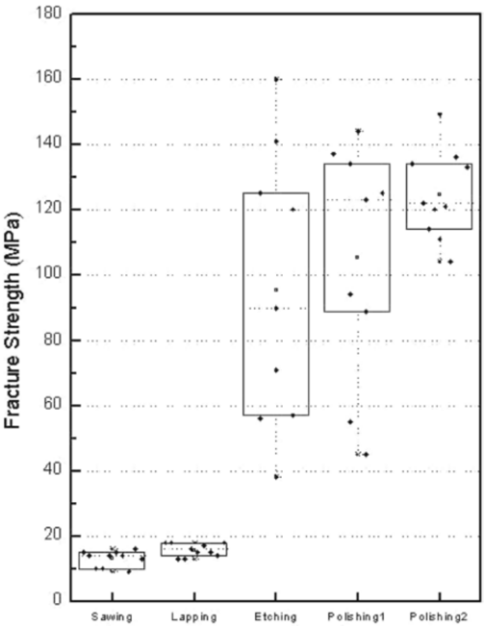



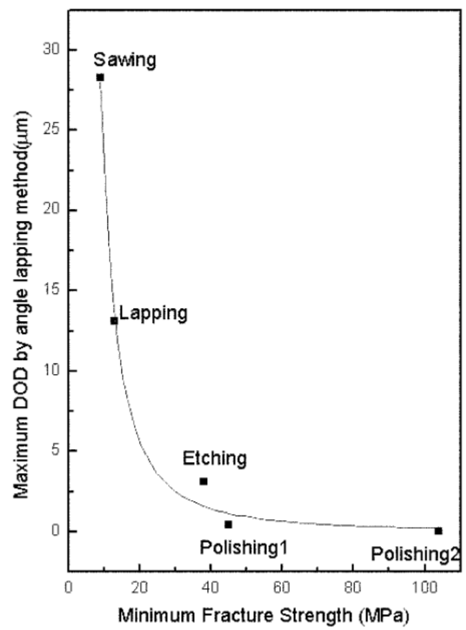




- Silicon becomes **brittle** below 500 C
  - E~169 MPa, $K_{Ic}$ = ~1 MPa $m^{0.5}$
- Strength is a function of **defect size**
- Not clear if the failure is in the whole layer limited to the **$SiO_2$** film
  - SiO2 has lower modulus and same fracture toughness
    - $SiO_2$ ~E=70 GPa, $K_{Ic}$ = ~1 MPa $m^{0.5}$, $R_m$=700 MPa (typical defect)
    - Fracture toughness of SiO2 can decrease to 0.25 in moisture
  - If film SiO2 **thickness**<<Si the crack will **not propagate** beneath
    - Not clear if/how it would appear on diagnostic systems



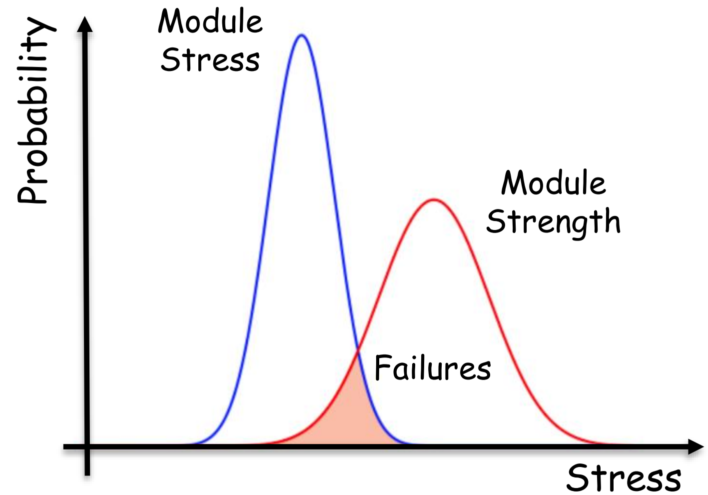
# Silicon Strength - Practical



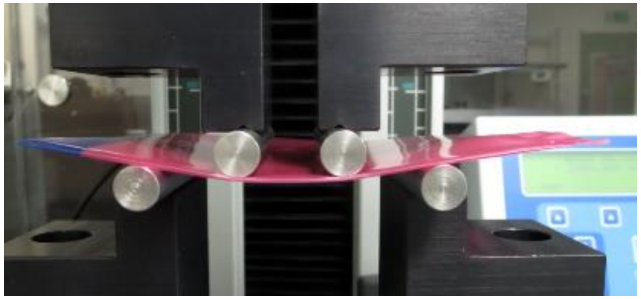

**Evaluation of damage on silicon wafers using the angle lapping method and a biaxial fracture strength test**

**Seong-Min Jeong, Sung-Eun Park, Han-Seog Oh and Hong-Lim Lee***
*Department of Ceramic Engineering, Yonsei University, 134 Shinchon-dong, Seodaemun-gu, Seoul 120-749, Korea*

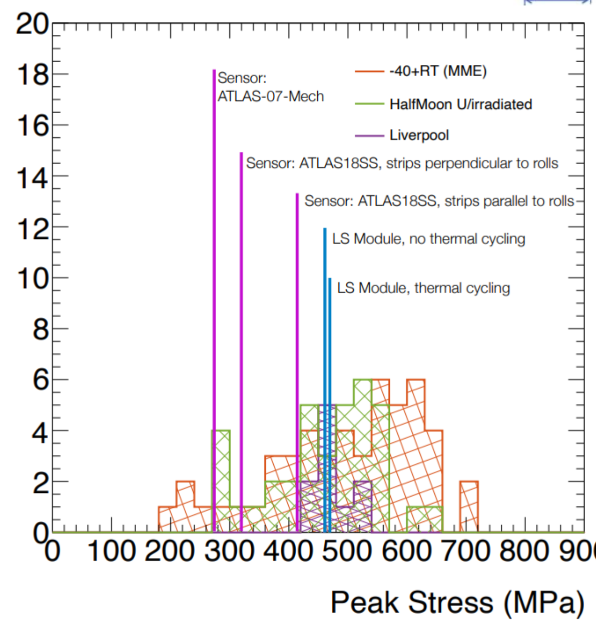



- Defect size can bring the failure stress from 1 GPa to 80 MPa….
  - Defects are randomly distributed → '**probability**' of failure
    - Silicon production dictates average and distribution
    - Random strength distribution, superimposed with random stress distribution…
  - Full wafers (D = 200 mm) strength ranges between 100 and 150 MPa after polishing

# Silicon Strength – Testing




- Different sets of measurements available, more in progress
  - 4-point bending on 'similar' wafers (not showed)
  - 4-point bending on full sensors (3 samples - **expensive**!)
  - 4-point bending on half-moons (multiple sets)
- Some results show higher strength/small defect size w.r.t. literature
  - However, the halfmoon results seem to suggest a 'long' tail, with some failures at stresses as low as **150/200 MPa** (coherent with literature)
- Additional measurements in progress



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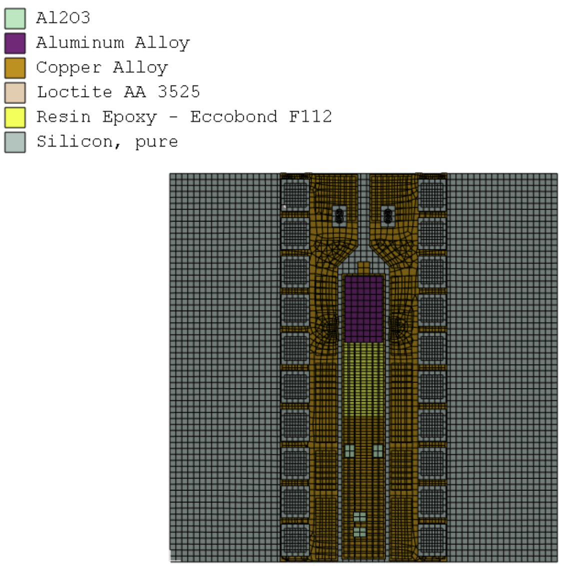
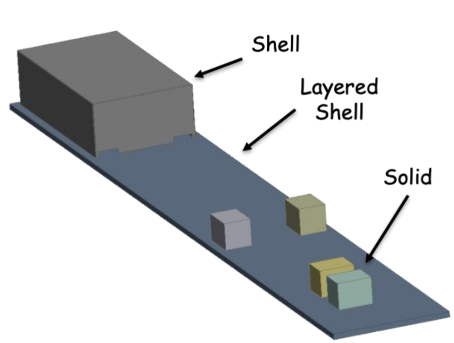
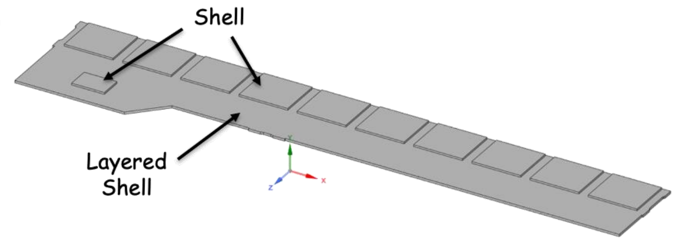
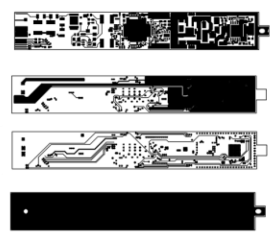
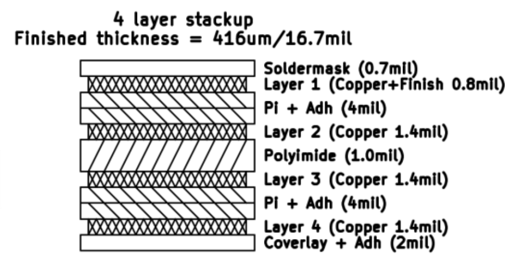
# Numerical Modeling Assumptions



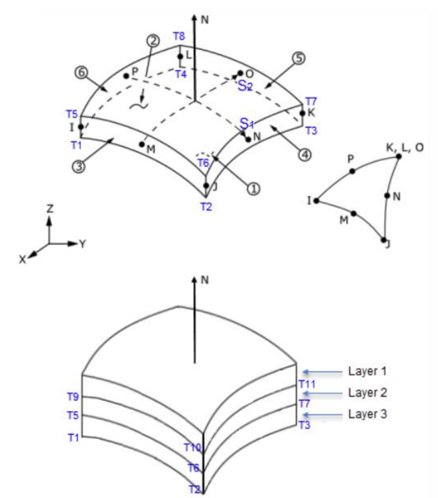



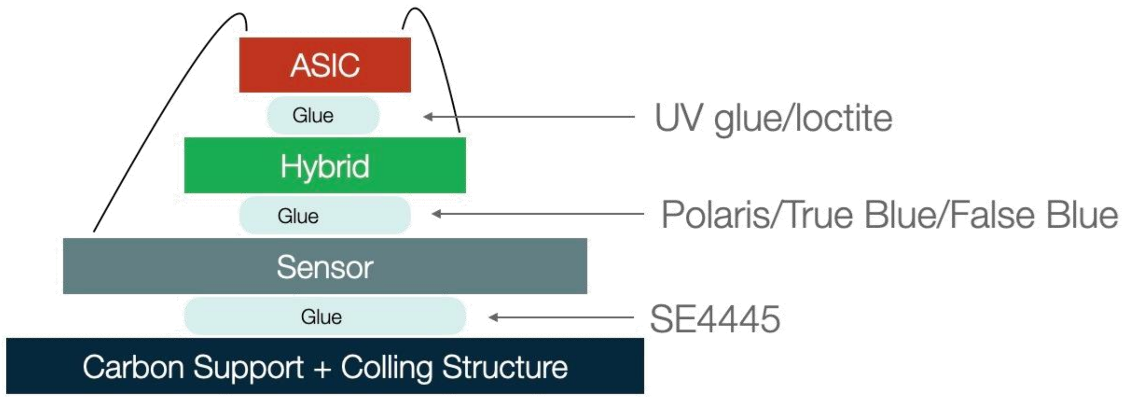



Layered Shell Elements




- Highly **simplified** model
  - **Solid** bodies: glues, capacitors, DCDC
  - All other components modeled as **shell** elements (2D), **layered shell** elements used for hybrid and powerboard
    - Material, thickness, and position assigned to each layer
    - A good assumption up to 'moderately' thick shells

# Glue Stack Modeling

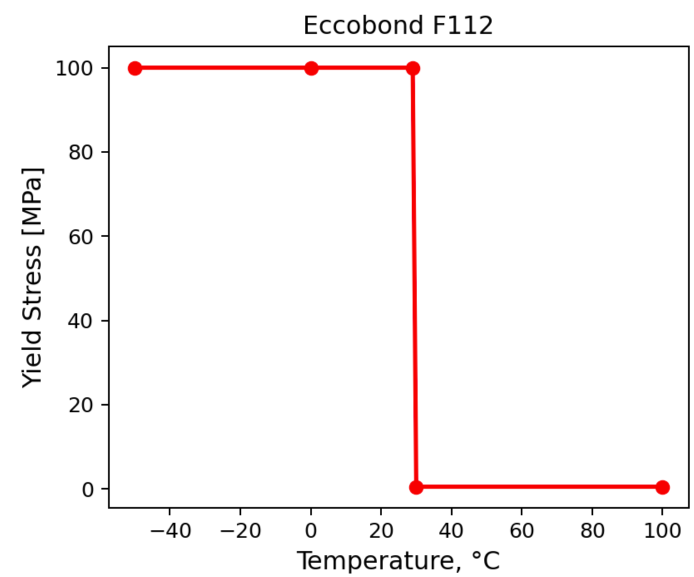



Linear

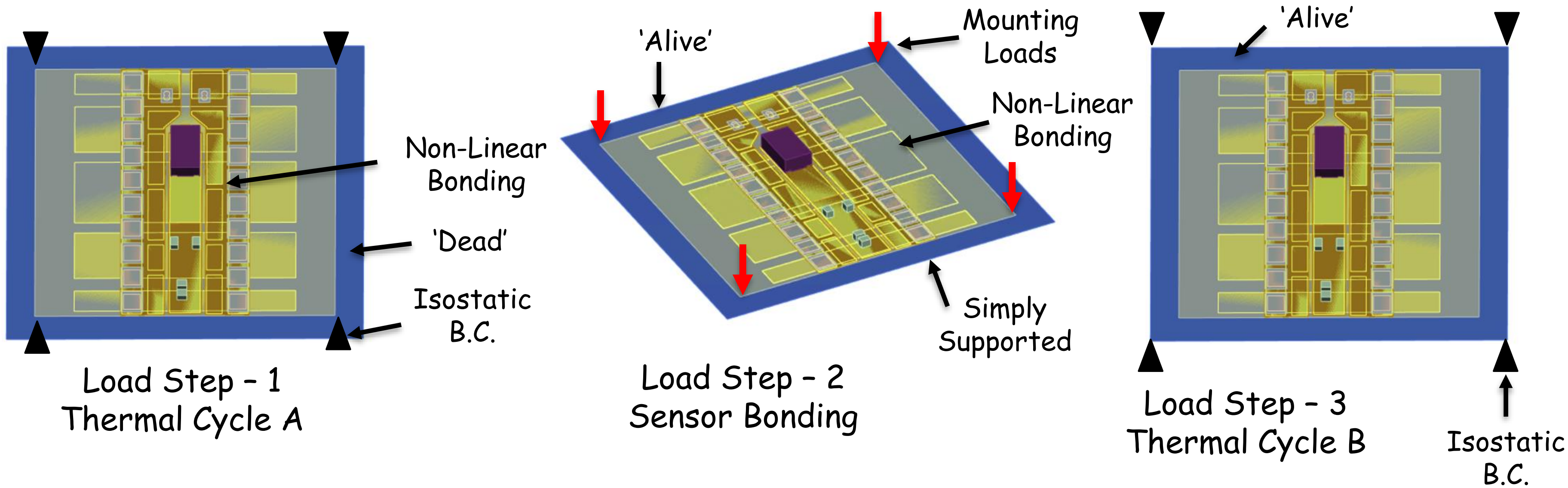
Non-Linear (Tg exceeded)

Non-Linear (Curing)

- **Glue stack**:
  - ASIC/HCC: **Loctite 3525**
  - Sensor/Hybrid or PB: **Eccobond F112**
    - Non linear model to introduce **Tg** transition
  - Stave/Sensor: **SE4445**, Epoxy
    - Very soft, modeled with linear contact elements
    - Non-linear model to simulate **curing** was also tested



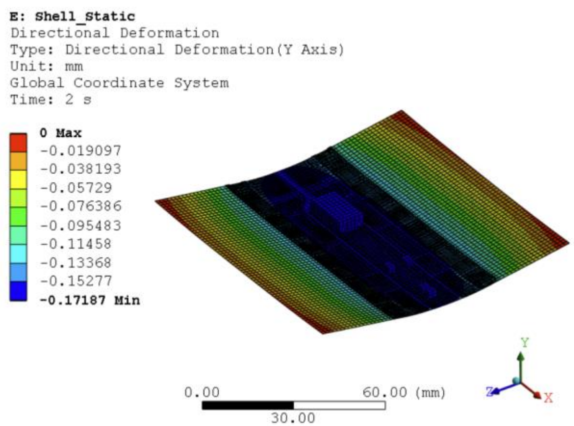
# Simulation Strategy

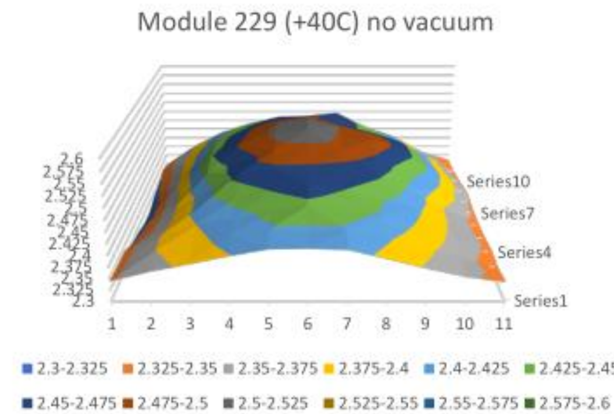



3 'step' simulation:

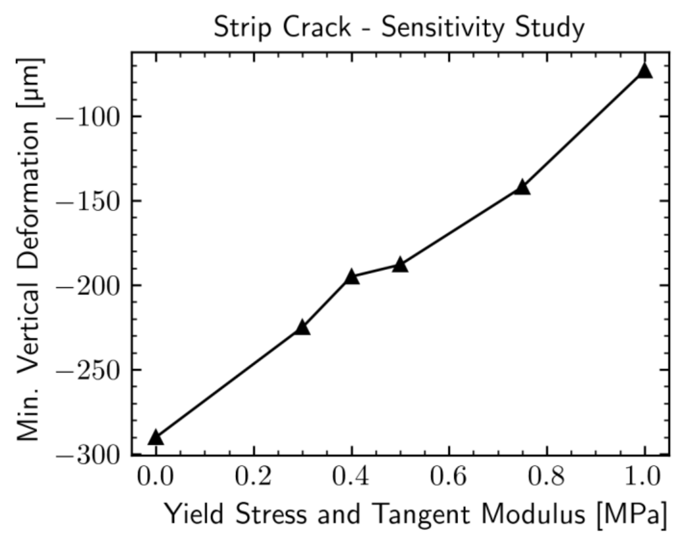
- **Step 1**: thermal cycling A to 40 C:
  - Introduces permanent deformation due to Hybrid/Powerboard glue glass transition
- **Step 2**: sensor bonding on the stave
- **Step 3**: thermal cycling B to -40 C
  - Temperature distribution during powering from thermal model

# FE Results – Step 1 - Displacements

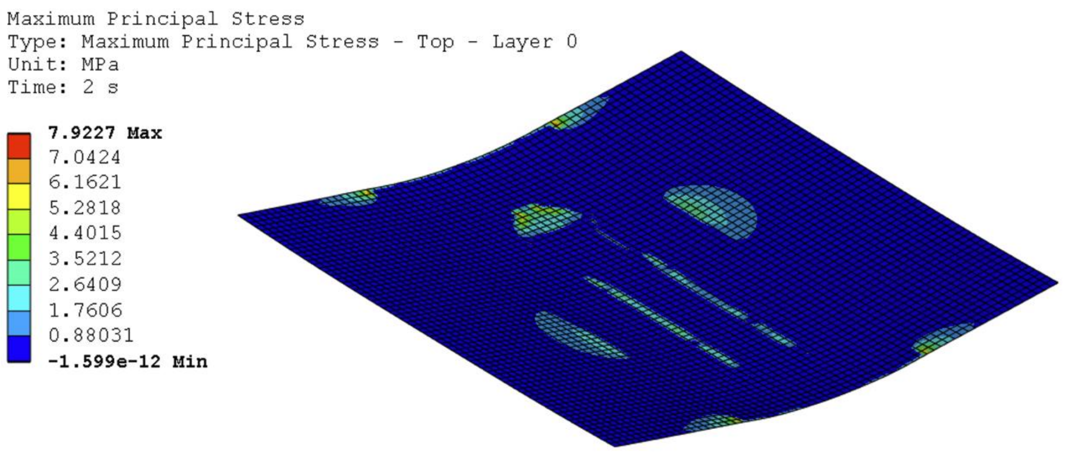



- **Measured bow** at R.T. (average): 213 μm
- Model results depend on assumptions on Tg, and on remaining stiffness after Tg
  - With current assumptions, reasonable **range** between **200 and 300 um**.
  - Glue measurements would narrow prediction
- **Shape** difference FE/meas.
  - Likely due to gravity+initial shape

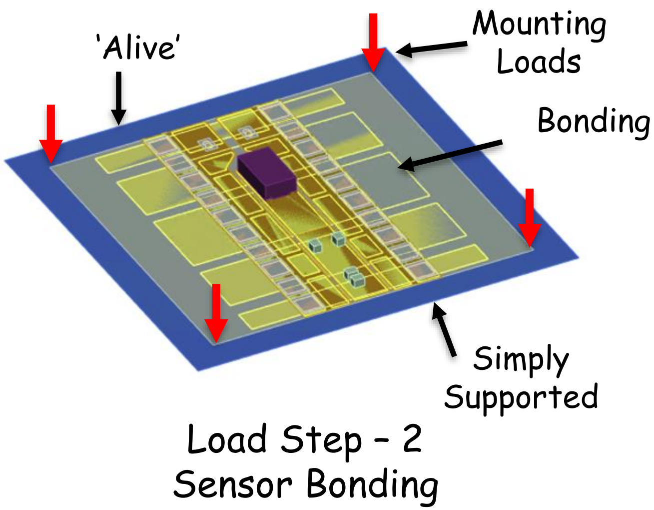


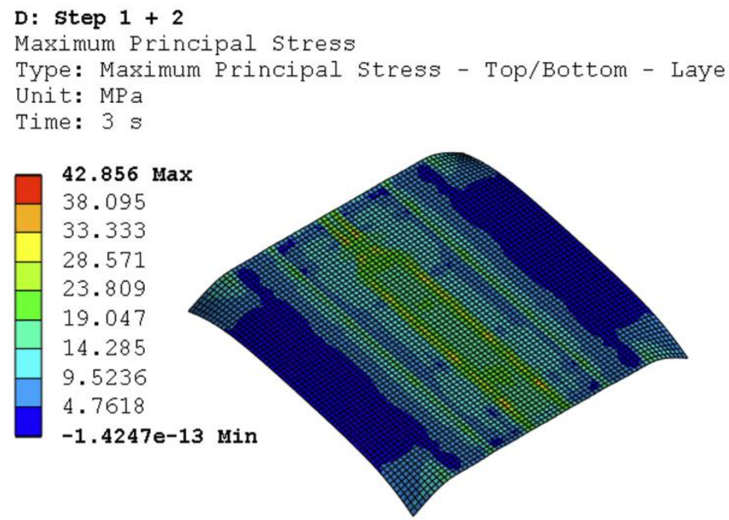
# FE Results – Step 1 - Stresses




- **Brittle failure** verified against **first principal stress** (crack opening) for simplicity
  - Showing only the sensor, free state after going back to room temperature
- Value is relatively low after step 1, peak on the bottom side
- Even if the stress is low now, maybe the shape change can introduce significant stresses during mounting?

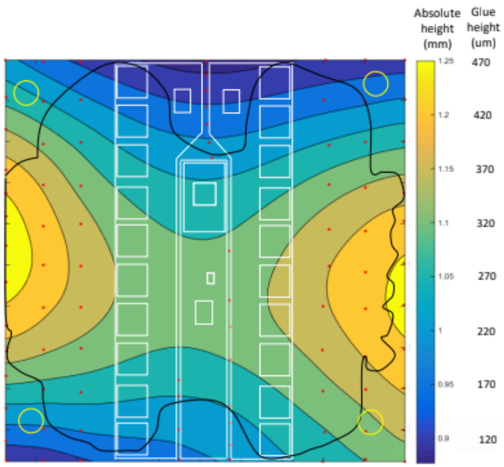
# FE Results – Step 2a

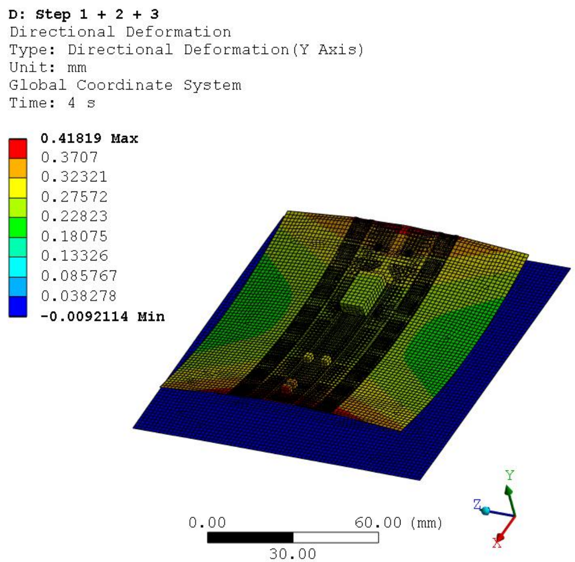


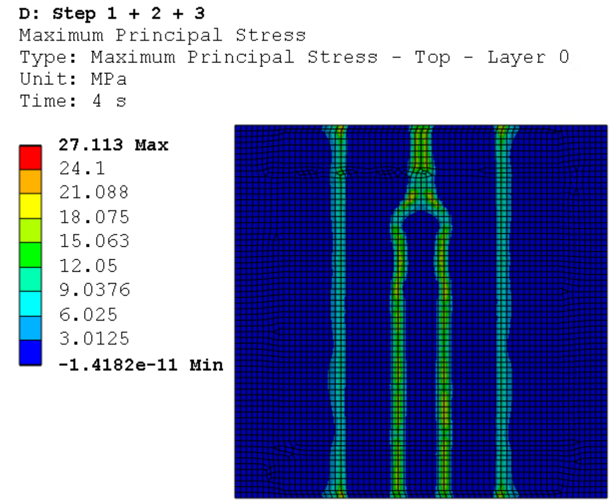




- **Mounting loads** applied at the edge of the sensor
  - Stress is going up because of the applied **forces** and sensor '**flattening**'
- Tested a simulation introducing non-linear SE4445 properties to reproduce the gluing process
  - Very complicated and deemed unnecessary

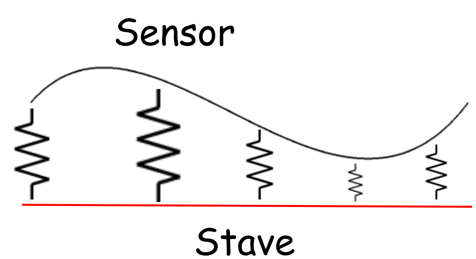
# FE Results – Step 2b



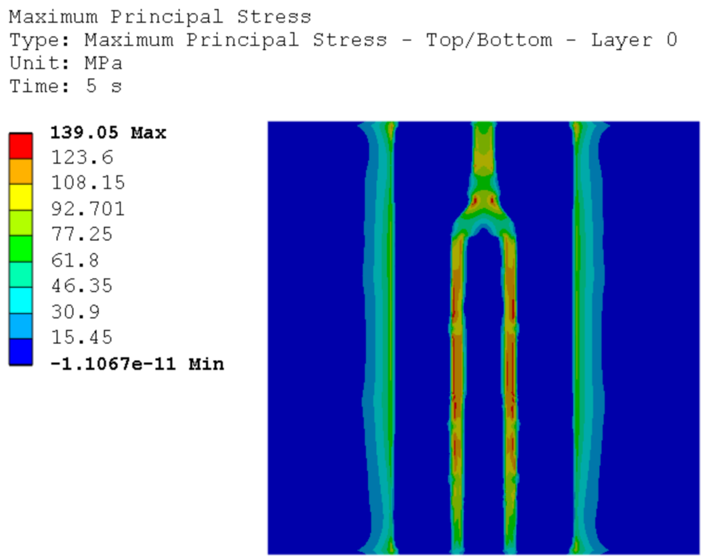



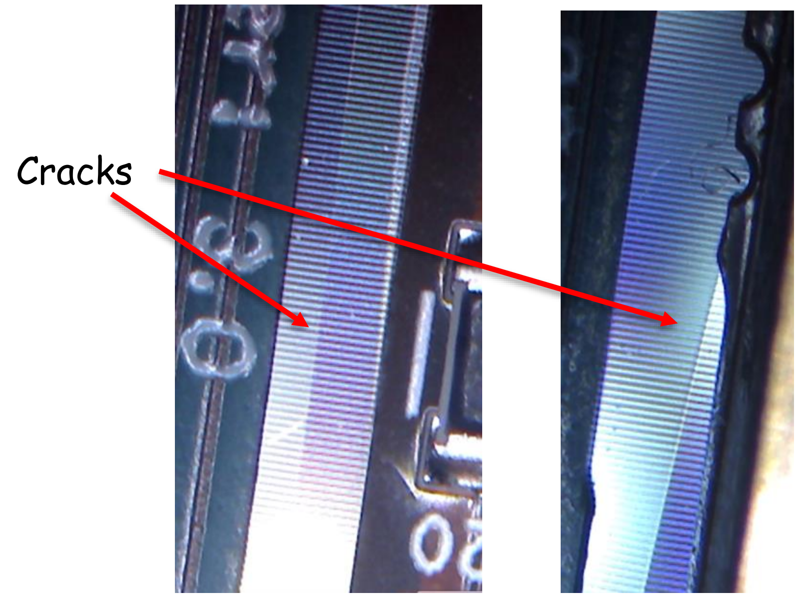




- '**Bonded**' shape as input in the mechanical model
  - Introduced as a **contact** interference **offset** model
  - Can assign either an interference **table**, or an (x,z) **function**
  - Glue properties as **contact** 'isotropic' **stiffness**
  - Mapped to measurements
  - Might **underestimate** local peaks (smoothing deformations)
- Stress still not very high at the end of step 2



# FE Results – Step 3

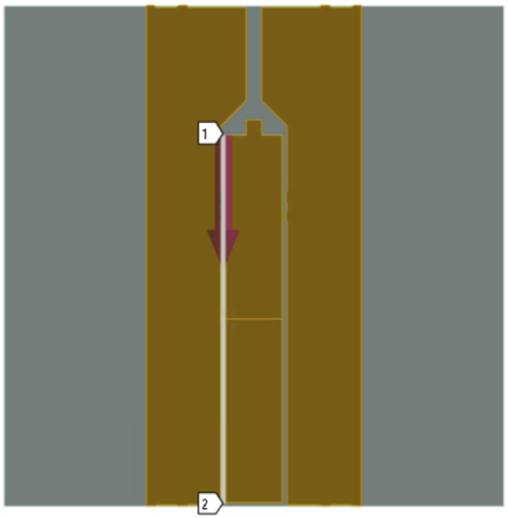


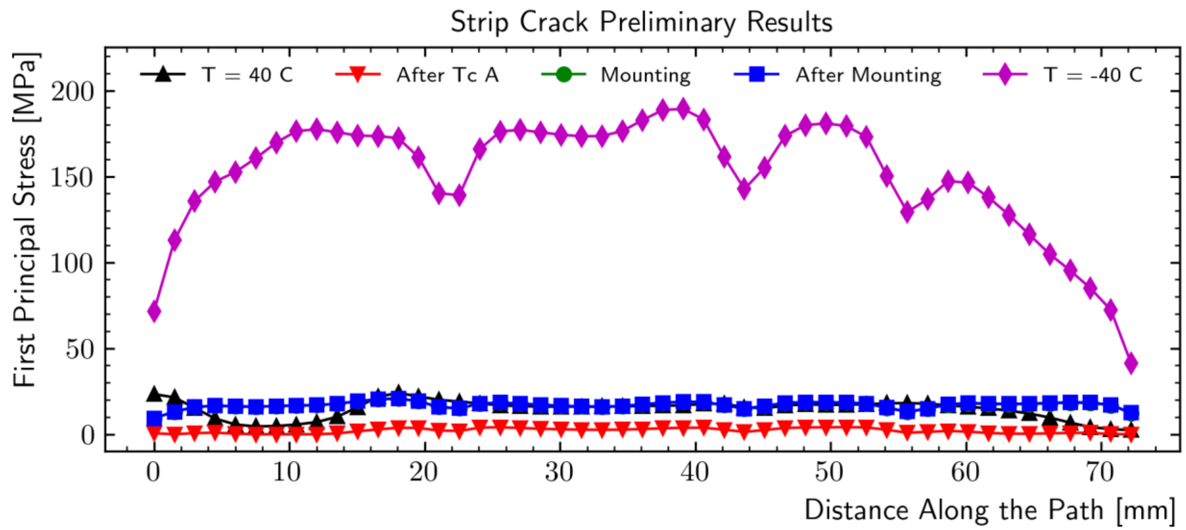




**Step 3:** cooldown to -40 C

- **Uniform temperature** constraint on all the components
  - Thermal model produces lower stresses
- **Peak** first principal **stress** reaches '**dangerous**' values, and location consistent with failure location
  - Failure stress consistent with literature data and measurements
  - Stress peaks are in the ~middle of non-glued areas

# FE Results – Summary

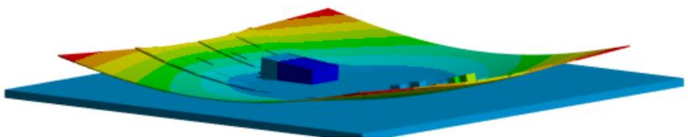


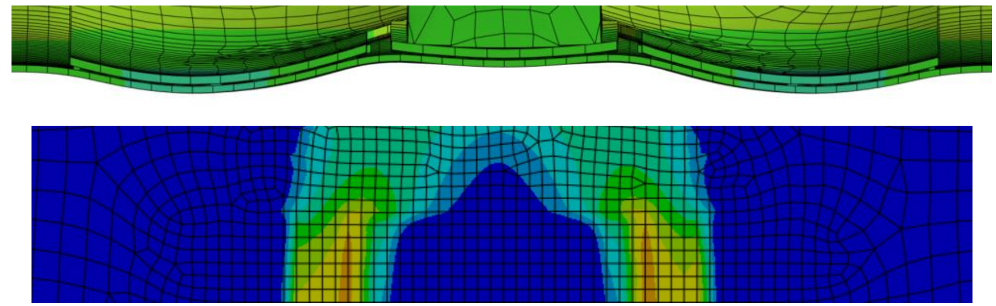

- Stresses on the sensor, ‘region’ between the hybrid and the powerboard
  - **Stress** during **first thermal cycle** is **negligible**
  - **Mounting** introduces ~**25 MPa**
    - Different shapes/mounting procedures should be investigated, but results depend strongly on non-linear glue properties
  - **Peak** stress around **150/200 MPa at the interface,** depending on the assumptions
    - **Coherent** with measured ‘strength’ limit!

# Where is the stress coming from?

Free Sensor

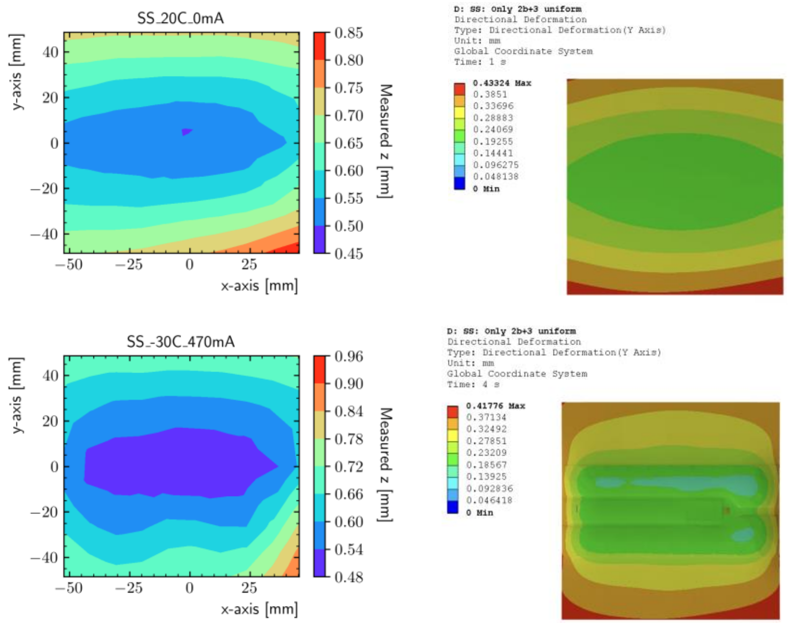


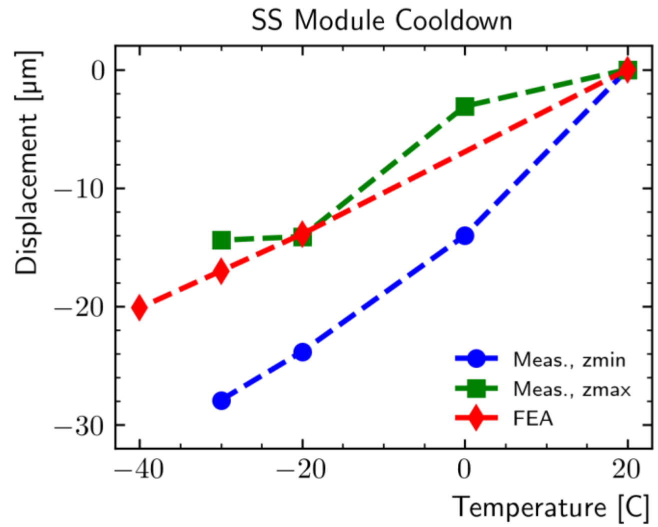
Sensor Bonded to Stave



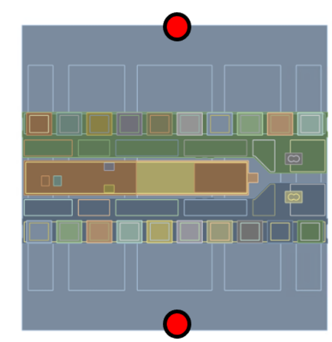
- The differential thermal contraction creates a ‘**bi-metallic**’ effect, bending the sensor
  - The free sensor would like to bend up in a ‘bowl’ shape
- The **bonding** to the stave **constrains** this effect, creating local bent regions with tensile stress states on the top surface
  - **Bonding distribution**, local geometry changes can affect the stress field e.g. creating local peaks

# Measurements Comparison – Step 3




- **Metrology** measurements performed for the SS module on stave
- Results suggest that the model is **catching** the **overall** behavior
- Two points used for comparison during cooldown
  - FEA (symmetric) **not too far** off
    - The 'ideal' value might be between the two curves



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# Mitigation Strategies

| Mitigation | Status |
|---|---|
| **Stave - Sensor glue** | Stiffer glue is better - Can reach to 20-30% reduction<br>Glue gaps are important for stiffer glue |
| **Flexes** | Thinner, softer flexes are better<br>Barrel -> EC stackup → atleast O(10)% less stress |
| **Gap between hb - pb** | Larger gaps are better<br>1mm more → O(10)% less stress |
| **Gap pattern under hybrid** | Less coverage is better - increases effective gaps<br>if not possible, then full coverage is better -<br>O(20)% less stress |
| **Hybrid glue thickness** | Thinner glue is better<br>20um less glue - O(5)% less stress |

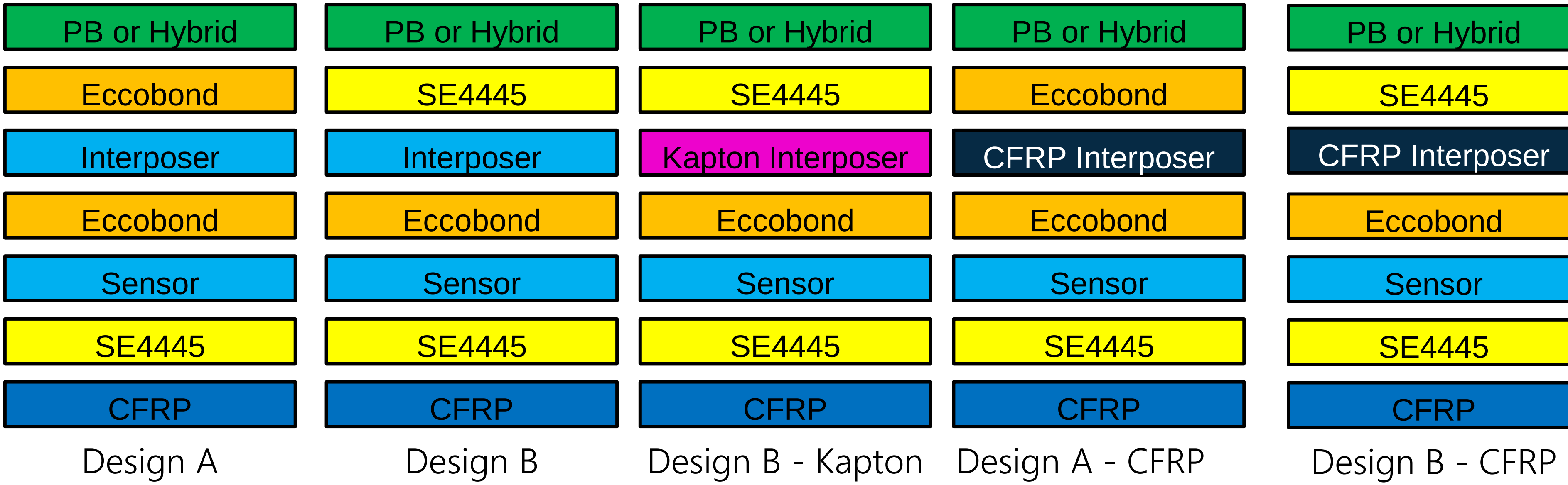
~ impact of mitigation techniques

These are expected to change

Once we add solution together the impact will not scale linearly

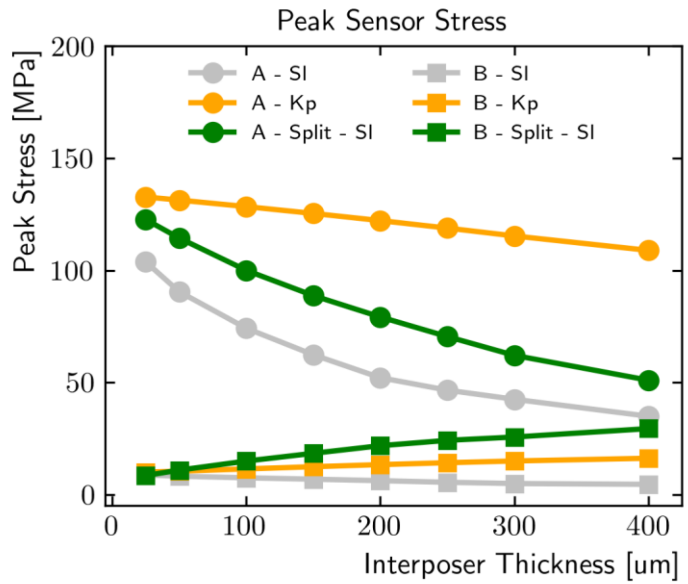
- Many **mitigation solutions** were proposed, investigating changes in:
  - **Copper** content of the flexes
  - **Spacing** between the flexes
  - **Stiffness** of the **glue** between the sensor and the stave
  - Glue **patterns**
- All these solutions brought only **fractional reductions** of the overall stress level

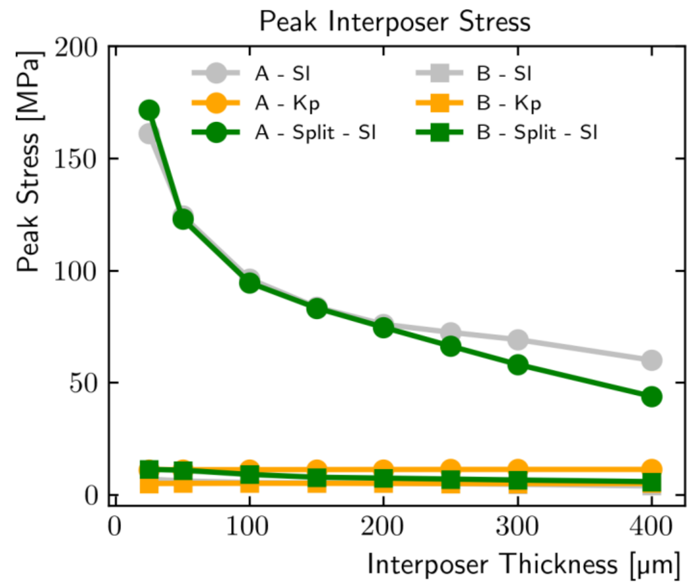
# The Interposer Solution




- We proposed to add an additional component to the stack, the '**interposer**'
  - Added between the **sensor** and the **flexes** in an attempt to reduce stresses
  - Multiple **strategies** proposed
  - Two main 'families':
    - Design A: **stiff** interposer and glue
    - Design B: **soft** interposer and glue

# The Interposer Solution - Results




- **Stiff** solutions (design A) can significantly reduce the stress seen by the sensor
- **Soft** solutions (design B) introduces a mechanical separation between flexes and silicon
  - **This can reduce the stress due to differential thermal contraction effects of 95%!**

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# Conclusion

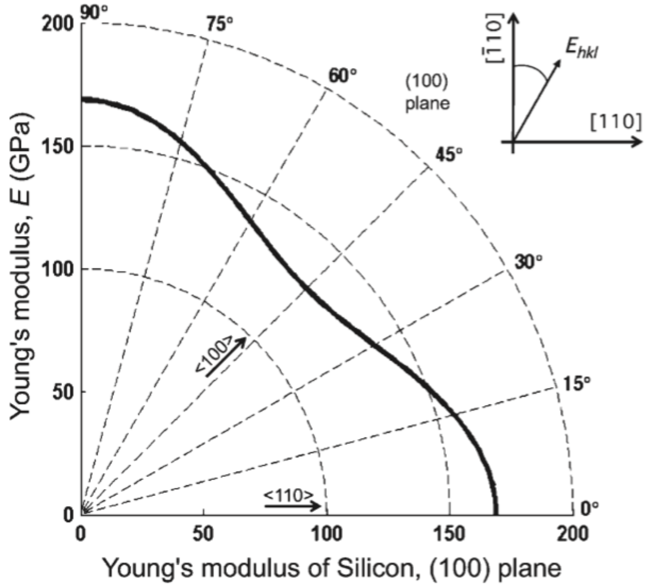
- **Simulations** suggest that **high stresses** are introduced in the silicon by differential thermal contraction effects
  - The model was **validated** against **displacements** measured on real modules
  - The predicted **stresses** are very **close** to **failure** stresses from literature and measurements on relevant samples
  - The failure locations are consistent with the computed peak stress areas
- Multiple **mitigation** strategies were studied
  - The '**soft interposer**' solution can reduce the stresses by 95%

**Future work**

- Improve accuracy of the **failure envelope** with additional bending tests
- Work in progress to **assemble** a full stave with **interposer** modules
- We would like to further **validate** the **simulations**, and improve our understanding of the failure mechanism
  - Silicon strain gauges are a promising solution, testing in progress

# Extra

# Silicon Anisotropy




$$E_x = E_y = 169 \text{ GPa} \qquad E_z = 130 \text{ GPa}$$

$$\nu_{yz} = 0.36 \qquad \nu_{zx} = 0.28 \qquad \nu_{xy} = 0.064$$

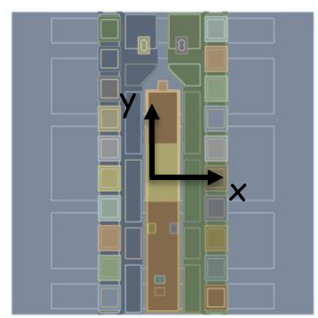
$$G_{yz} = G_{zx} = 79.6 \text{ GPa} \qquad G_{xy} = 50.9 \text{ GPa}$$

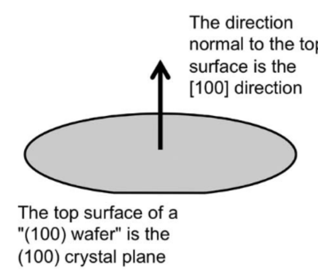
$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} 194.5 & 35.7 & 64.1 & 0 & 0 & 0 \\ 35.7 & 194.5 & 64.1 & 0 & 0 & 0 \\ 64.1 & 64.1 & 165.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 79.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 79.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 50.9 \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix}$$

**What is the Young's Modulus of Silicon?**

Matthew A. Hopcroft, *Member, IEEE*, William D. Nix, and Thomas W. Kenny

- Our wafer is (100)
  - Ex = Ey=169 GPa,
    - Decreases to 130 MPa at 45 degrees
  - Ez = 130 GPa (normal to the sensor)



# Silicon Anisotropy

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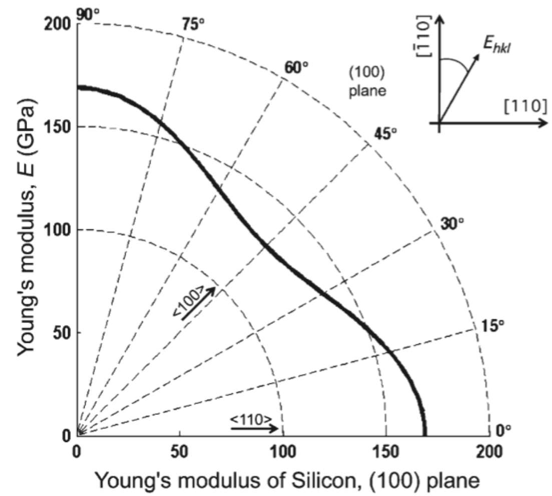
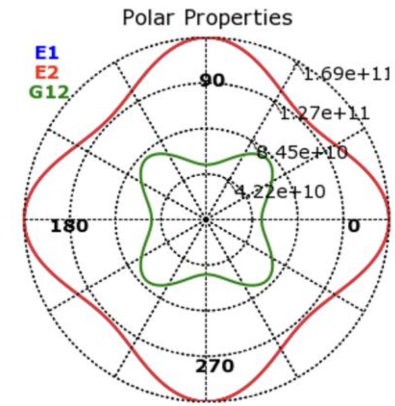
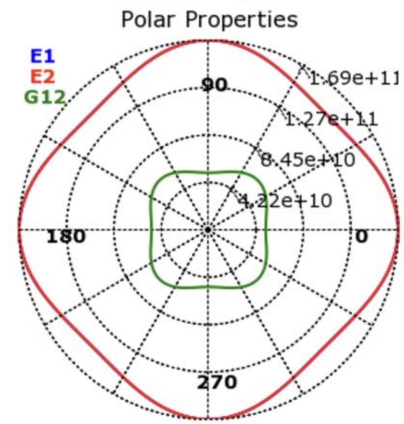



$\nu_{xy} = 0.064$




$\nu_{xy} = 0.36$

- There is a typo in the paper:
  $K_{11} = \dfrac{E_x}{1 - \nu_{xy}\nu_{yx}}, \nu_{yx} = \dfrac{E_y}{E_x}\nu_{xy} = \nu_{xy} = 0.064 \rightarrow K11 = 168\ GPa$
- To get 194.5 GPa, one needs $\nu_{xy} = 0.36$ (actually 194.1 GPa)
- Polar plot matched for $\nu_{xy} = 0.064$, assuming this is the correct number

# Glues – Typical Properties

**TYPICAL PROPERTIES OF CURED MATERIAL**

**Physical Properties**

| | | |
|---|---|---|
| Coefficient of Thermal Expansion, ISO 11359-2 $K^{-1}$: | | |
| Alpha 1 | | $97\times10^{-6}$ |
| Alpha 2 | | $215\times10^{-6}$ |
| Glass Transition Temperature, ISO 11359-2, °C: | | |
| (Tg) by TMA | | 50 |
| Shore Hardness, ISO 868, Durometer D | | 60 |
| Refractive Index, ASTM D542 | | 1.51 |
| Elongation, ISO 527-3, % | | 260 |
| Tensile Strength, at break, ISO 527-3 | $N/mm^2$ | 24 |
| | (psi) | (3,500) |
| Tensile Modulus, ISO 527-3 | $N/mm^2$ | 175 |
| | (psi) | (25,000) |

Loctite 3525

**TYPICAL PROPERTIES OF CURED MATERIAL**

**Physical Properties** :

| | |
|---|---|
| Coefficient of Thermal Expansion, cm/cm/°C | $6.20\times10^{+01}$ |
| Glass Transition Temperature (Tg), ultimate, °C | 102 |
| Hardness, Shore D | 86 |
| Refractive Index | 1.51 |
| Water Absorption , after 24 hours saturation, % | 0.07 |

Eccobond F112

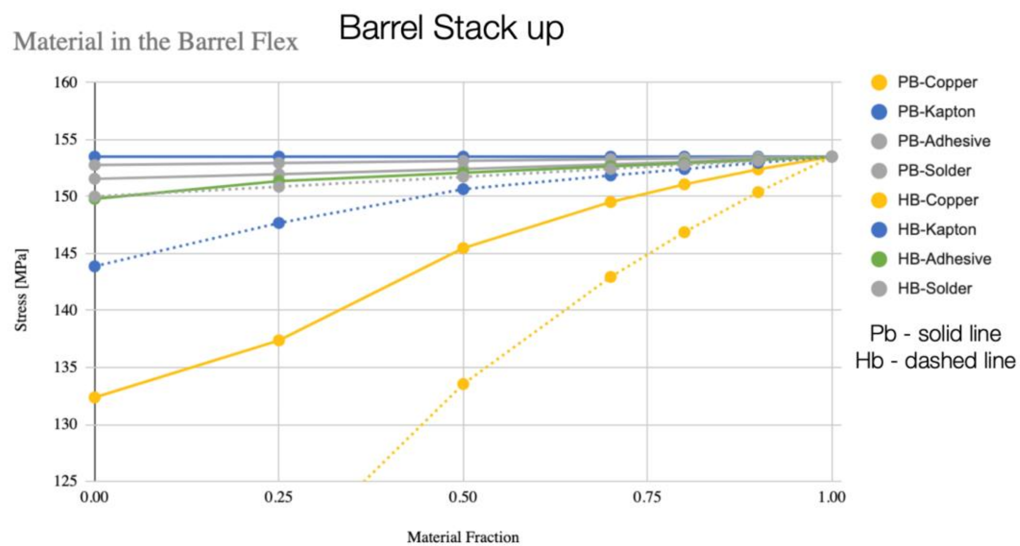
| | | | |
|---|---|---|---|
| CTM0022 | Density[4] (Cured) | $g/cm^3$ | 2.36 |
| CTM0155 | Penetration[5] | mm/10 | 50 |
| | Thermal Conductivity[6] | W/m • K | 1.3 |

SE4445

- **Loctite 3525**
  - Modulus = 175 MPa, very low
  - Alpha 2 above Tg
- **Eccobond F112**, we can assume typical **epoxy** properties:
  - CTE ~ 60-80 ppm/C, E~2-3 GPa, Thermal Conductivity 0.2-0.5 W/m
  - **Tg** = 102 ° C ? What do they mean by 'ultimate'…?
  - This seems to contradict experience. Is it possible that the glue is not transitioning, but just not fully cured – then cure is completed when temperature is increased?
- **SE4445**
  - Little info on the tech data sheet, assuming typical epoxy properties

# Flex Content Sensitivity

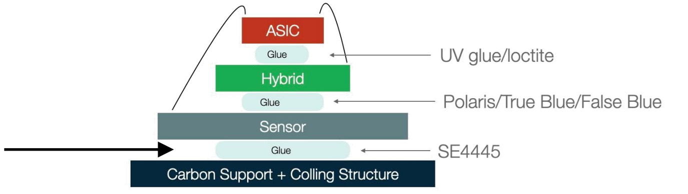
- Copper is the main offender
  - Increases stiffness of flex
- Kapton core has a non-negligible role
  - Barrel - 50um core
    EC - 25um core



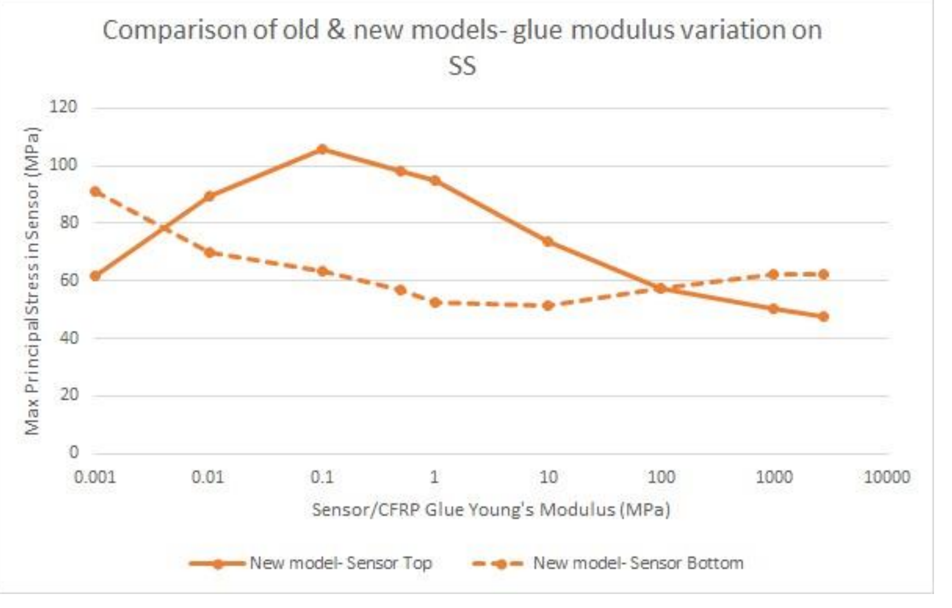

| For every 10% change in | PB-Copper | PB-Kapton | PB-Adhesive | PB-Solder | HB-Copper | HB-Kapton | HB-Adhesive | HB-Solder |
|---|---|---|---|---|---|---|---|---|
| % Stress | 0.73 | 0.00 | 0.15 | 0.05 | 2.03 | 0.35 | 0.19 | 0.23 |

# Sensor – Stave Glue

- Large impact of the Young's modulus of the glue
  - SE4445 – 0.5 MPa
  - Hysol – ~3 Gpa
- Some concern that stiffer glue can peel the bus tape – Impact thermal performance
- Open question: How does properties change with irradiation?

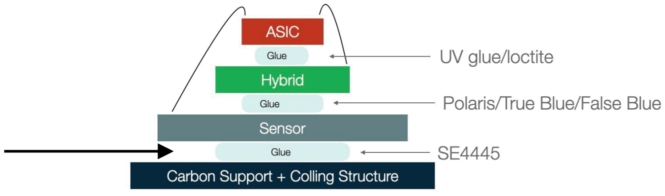



~20-30% reduction in stress

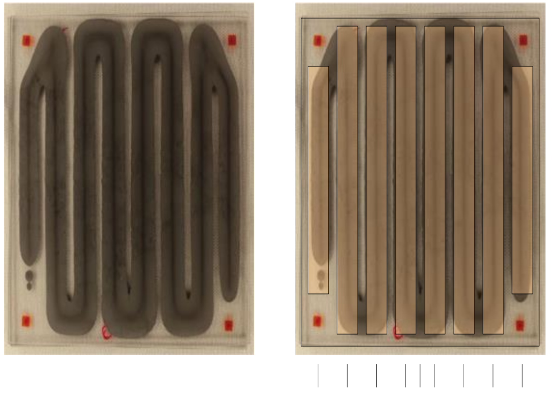


# Sensor – Stave Glue Pattern

- Cannot have 100% glue coverage – have long gaps
  - Glue dispensing potentially create non-uniform coverage
- Stiffer glues have a much larger relatively impact from glue gaps
- New pattern being studied in simulation to reduce sensivity

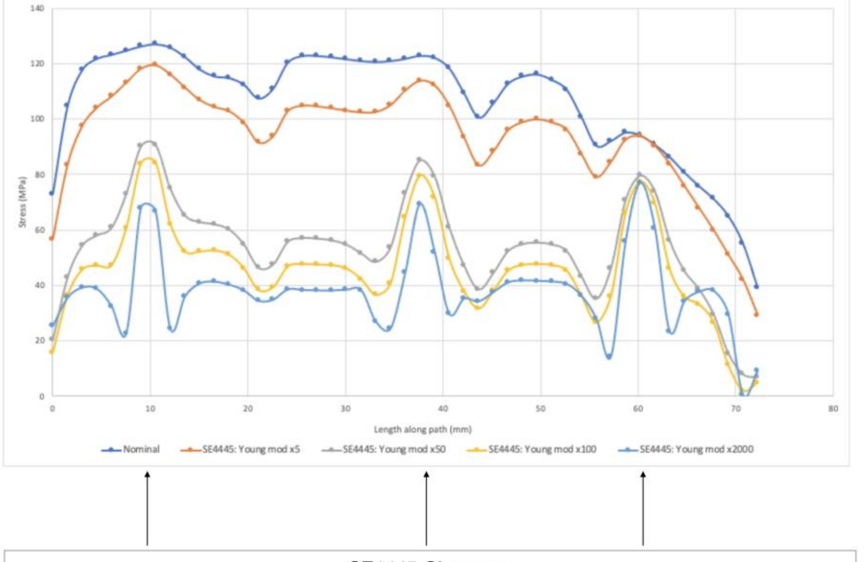



.
Long glue strips are 92 mm x 8.5 mm
The two short glue strips are 68 mm x 8.5 mm
Center of module is (0,0). 3.125 mm x 3.125 mm
are placed at (+/- 42 mm, +/- 42 mm)



mm ⟶ -42 -30 -18 -6 0 6 18 30 42

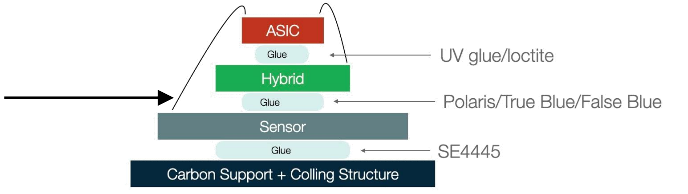
Typical pattern

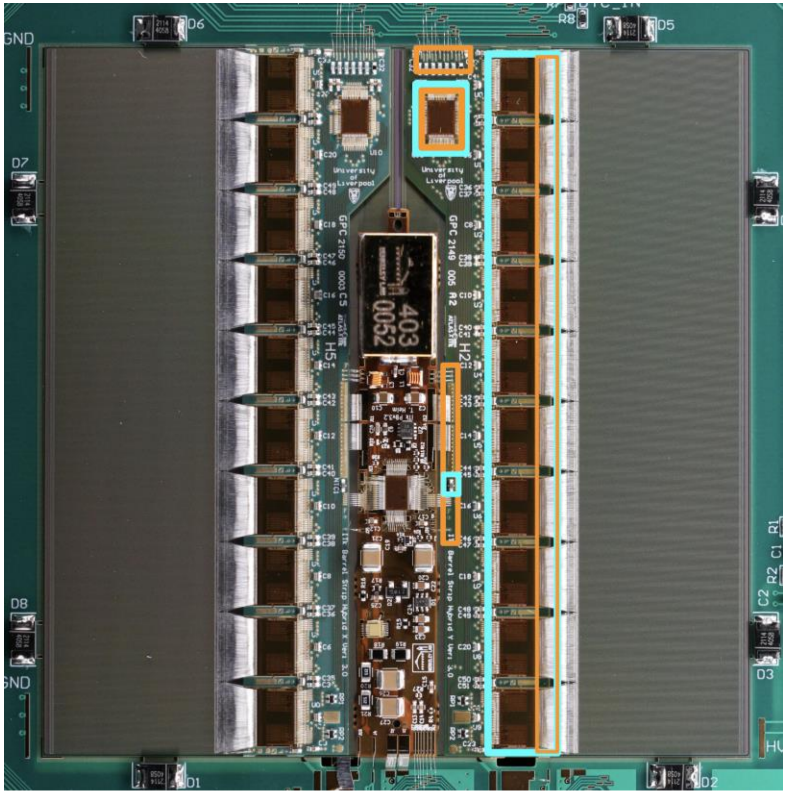



SE4445 Glue gaps

# Hybrid - Glue Pattern

- Necessary for thermal contact and wire bonding

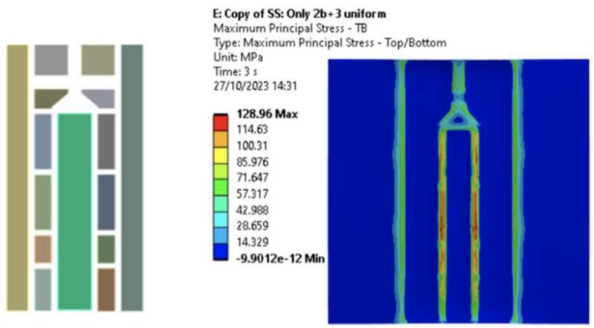


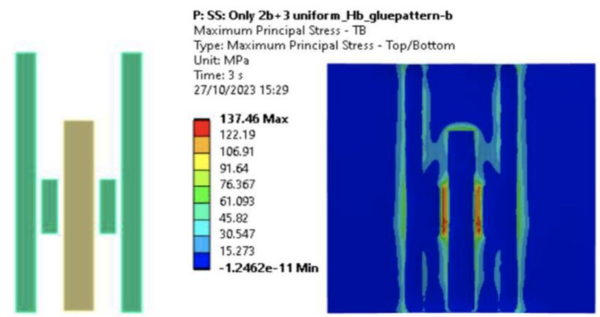
Blue for thermal contact
Orange for wire bonding

# Hybrid - Glue Pattern

Standard

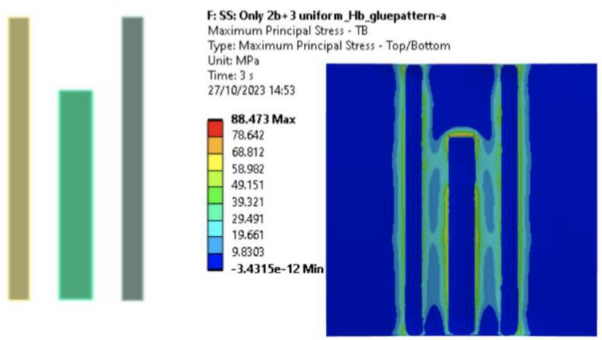


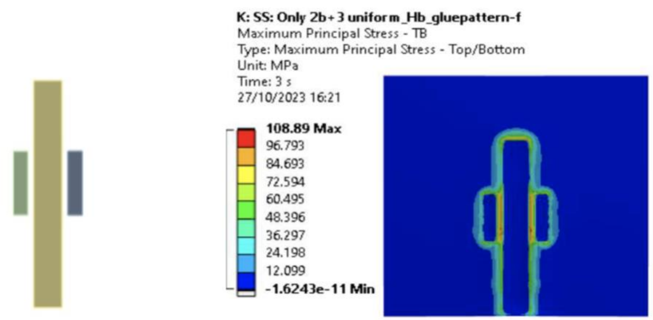

6% increase in stress




Pattern-b

Pattern-a




Pattern-c

30% reduction in stress

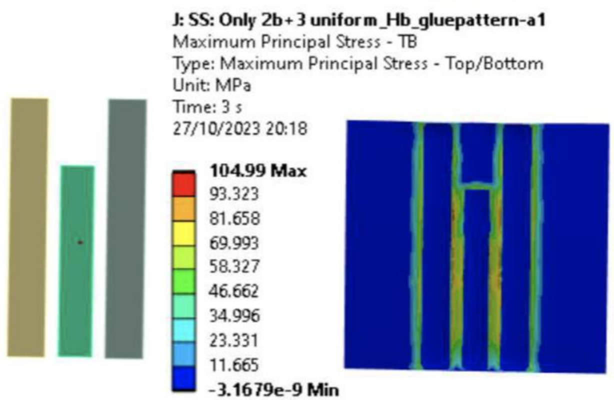
15% reduction in stress

Long asic strip couples the hybrid to sensor, and then the small strip reduces the effective area for bending

# Hybrid - Glue Pattern

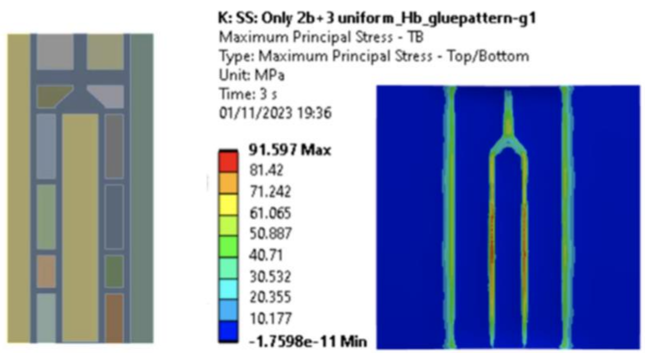
20% decrease in stress

Extended 5mm to the width of the two long strips




**For this, need to move wire bonding pattern on flex**

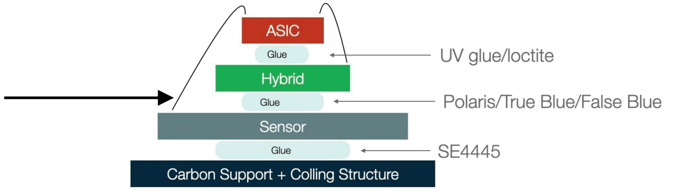
Full coverage



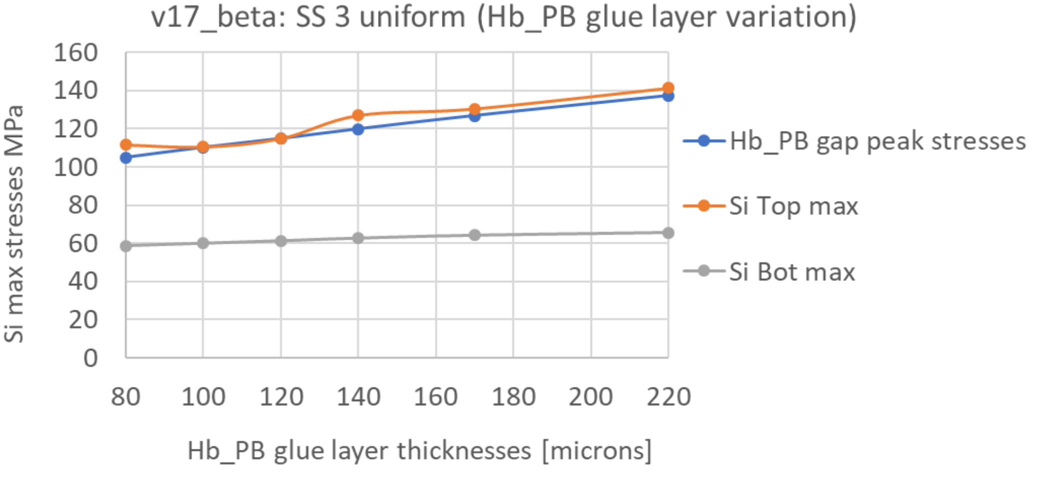

**If not possible,**
**Full coverage is only possibility**

# Hybrid - Glue Height

- Limited room to reduce stress by reducing height
  - Thinner glue lead to lower stress
- **Extremely difficult to control**

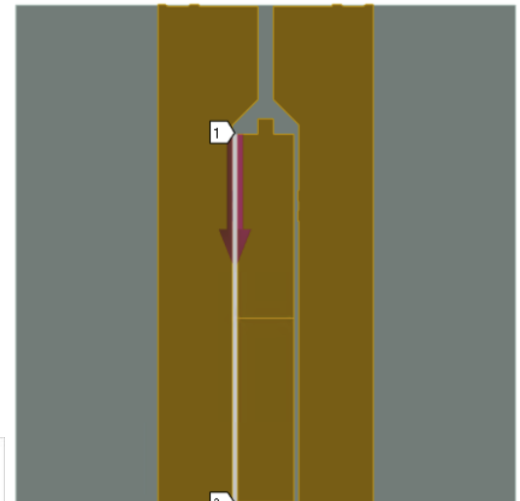



~5% change for every 20um decrease



# Hybrid – Powerboard spacing

- Larger gaps lead to lower stress
- **Wire-bonding constraint limit what is doable**




Spacing along the line

~10% change for every 1mm increase