Wirebond Encapsulation for HL-LHC Tracking Detectors

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on behalf of the
Oxford Physics Microstructure Detector Laboratory
and ATLAS-UK Pixel Group

Outline

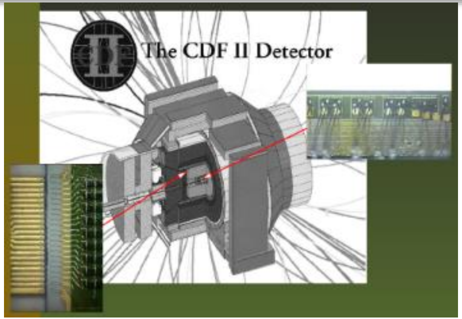
- Motivation for encapsulation
- Encapsulation in the past
- Current studies of material and methods for encapsulation

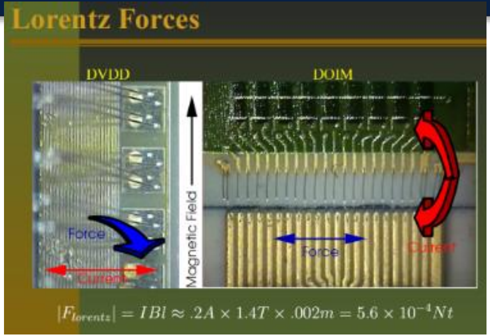
Context

Damage to wire bond experienced by CDF, ATLAS and CMS

- CDF SVX - broken wires due to resonance
- ATLAS IBL - corrosion due to saline residue + condensation
- CMS BPIX - shorts due to condensation + electrolyte (flux residue) + voltage
- CMS Strips - broken wires in modules due to vibration and handling accidents

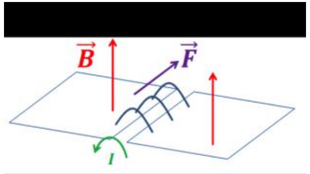
CDF Silicon Detector: Wirebond Failures Induced by Resonant Vibrations



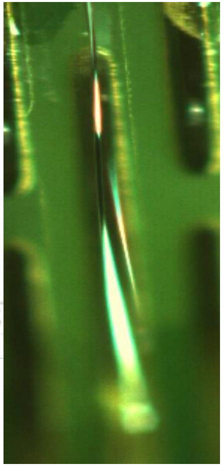


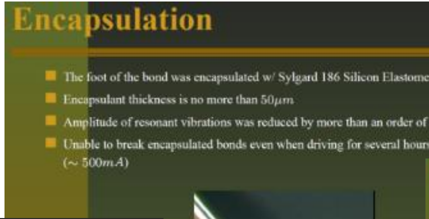
Lorentz Forces

$$|F_{lorentz}| = IBl \approx .2A \times 1.4T \times .002m = 5.6 \times 10^{-4}Nt$$



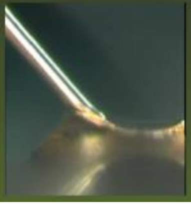
Lorentz forces in a magnetic field and resulting wirebond failure





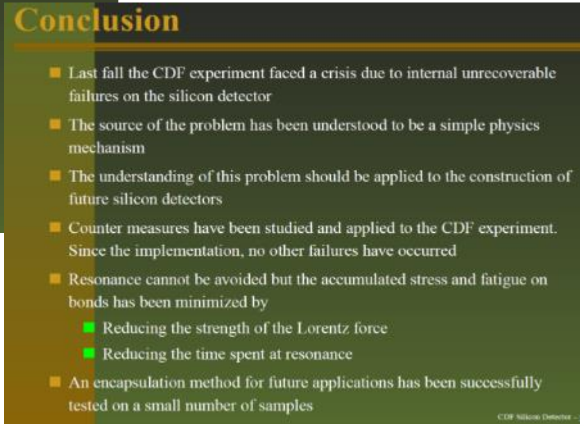
Encapsulation

- The foot of the bond was encapsulated w/ Sylgard 186 Silicon Elastomer
- Encapsulant thickness is no more than $50\mu m$
- Amplitude of resonant vibrations was reduced by more than an order of magnitude
- Unable to break encapsulated bonds even when driving for several hours with large currents $(\sim 500mA)$



Foot Fatigue

- On the time-scale of minutes, a resonating bond will fail
- At 10kHz this is about $10^5 - 10^6$ cycles.
- Breakage occurs at the bond's foot
- Breakage is due to stress fracture that forms during vibration

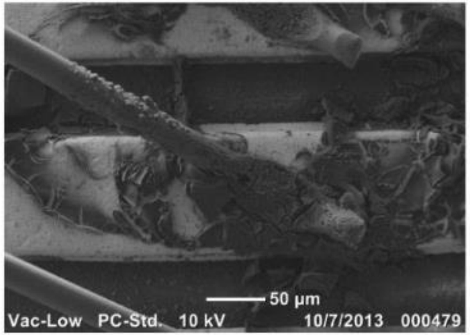


Conclusion

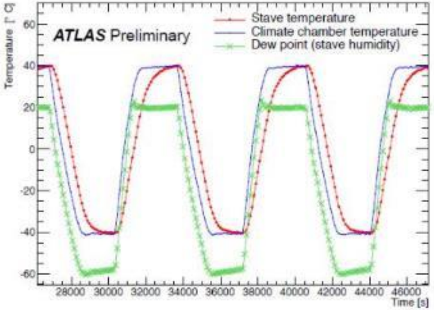
- Last fall the CDF experiment faced a crisis due to internal unrecoverable failures on the silicon detector
- The source of the problem has been understood to be a simple physics mechanism
- The understanding of this problem should be applied to the construction of future silicon detectors
- Counter measures have been studied and applied to the CDF experiment. Since the implementation, no other failures have occurred
- Resonance cannot be avoided but the accumulated stress and fatigue on bonds has been minimized by
  - Reducing the strength of the Lorentz force
  - Reducing the time spent at resonance
- An encapsulation method for future applications has been successfully tested on a small number of samples

CDF Silicon Detector –

ATLAS IBL wire bond corrosion



SEM picture of the saline residual.
The crystalline powder is responsible of the corrosion of the aluminum wire bonds.



Temperatures during Thermal cycle procedure. The stave temperature is lower than the dew point temperature for part of the cycle. This led to condensation on the wire bonds. The effect is due to the PVC handling frame used as protection during the stave production.

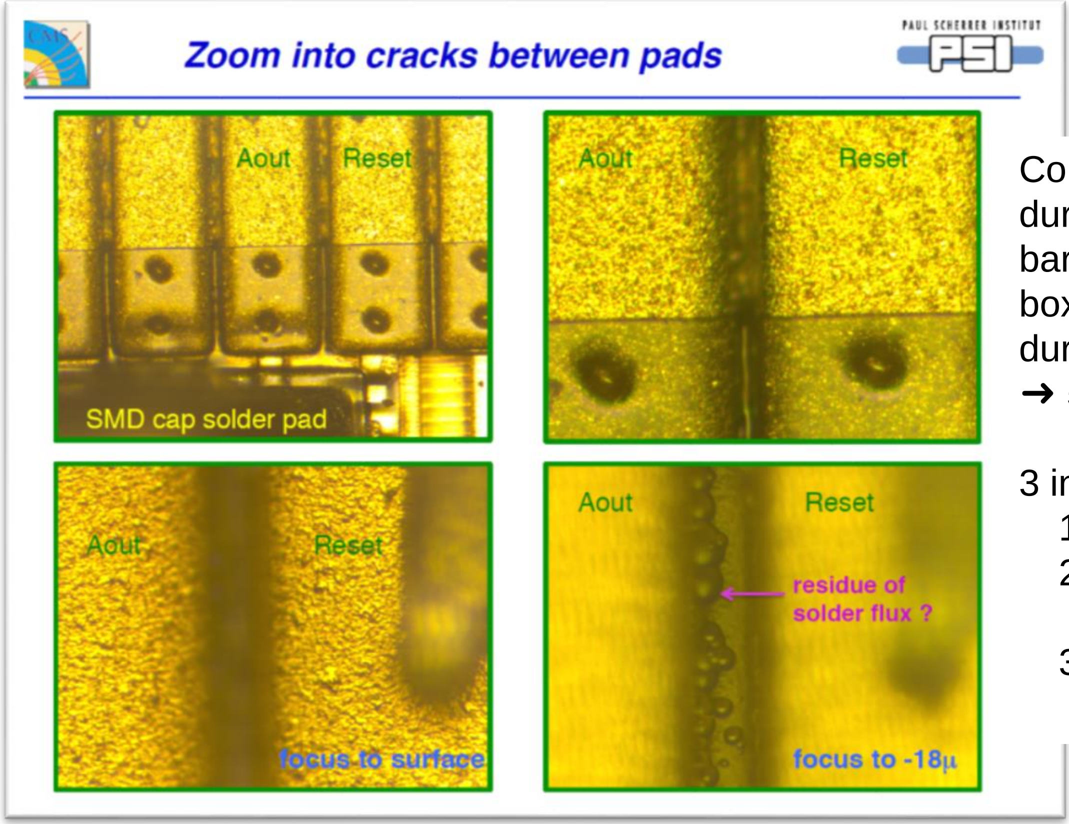
The issue

- A corrosion phenomenon was observed on wire bonds during stave production.
- A saline powder was found on the wire bond footages.
- Condensation during the thermal cycles of the staves.
- Climate chamber was flushed with dry air, but due to a PVC handling frame the stave temperature was slightly lower than dew point temperature.

Actions taken

- The stave production was stopped until a complete understanding of the issue
- Review of the quality assurance setups and stop of the thermal cycle responsible of the condensation.
- Cleaning and re-bondings of all the affected staves (all the ones that went through the thermal cycle procedure).
- Systematic pull test on the wire bonds.

CMS BPIX HDI shorts on defect modules



PAUL SCHERRER INSTITUT

Zoom into cracks between pads

Condensation accident during calibration runs of a barrel quadrant in cooling box at -16C on the surface during LS1
→ 55 modules not working

3 ingredients for deposits:
1) Humidity (condense)
2) Electrolyte (solder flux residues?)
3) Voltage applied at a bad moment

Halogen Attack*

- The attack mechanism is simple enough, but prevention is nigh on impossible…a major recurring theme in Microelectronics and Packaging conferences, and books too!
- Great deal of evidence that even a very small amount of free halogenic ions are very bad – the chemistry dictates that they are involved in the reaction and then liberated once the damage is done, causing more damage.
- A specification such as 'every bondable surface (must be) kept completely clean of any ionic (halogenic) contamination' is good as an aspiration but completely impractical.
- To avoid potting, one must find economical methods for reducing corrosive attack rates to an acceptable level. You can either:

1) Build based on guidance from standards/best industry practice and best efforts reasoning
    - Cleanliness level at all stages of production must be identified and 'guaranteed'
    - Fully dry (and keep dry) all components/assemblies before, during, and after assembly

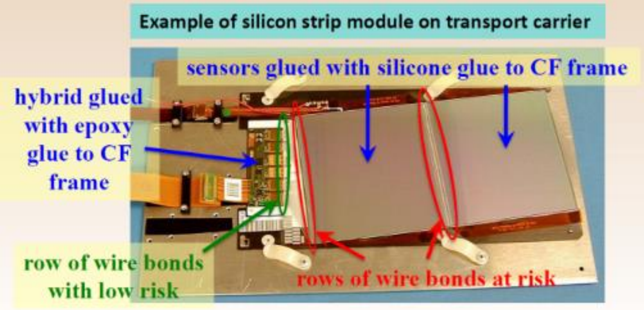
2) Invest decades more effort working out methods to achieve the completely halogen free ideal

→ #1 is difficult - lots of validation, including HAST testing

→ #2 is between impractical/uneconomical and impossible!

** in consultation with John Lipp, RAL*

CMS Strip Module reinforcement



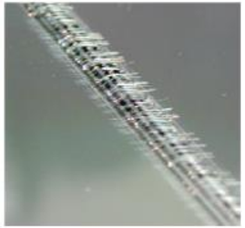
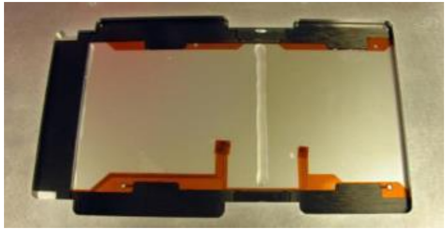
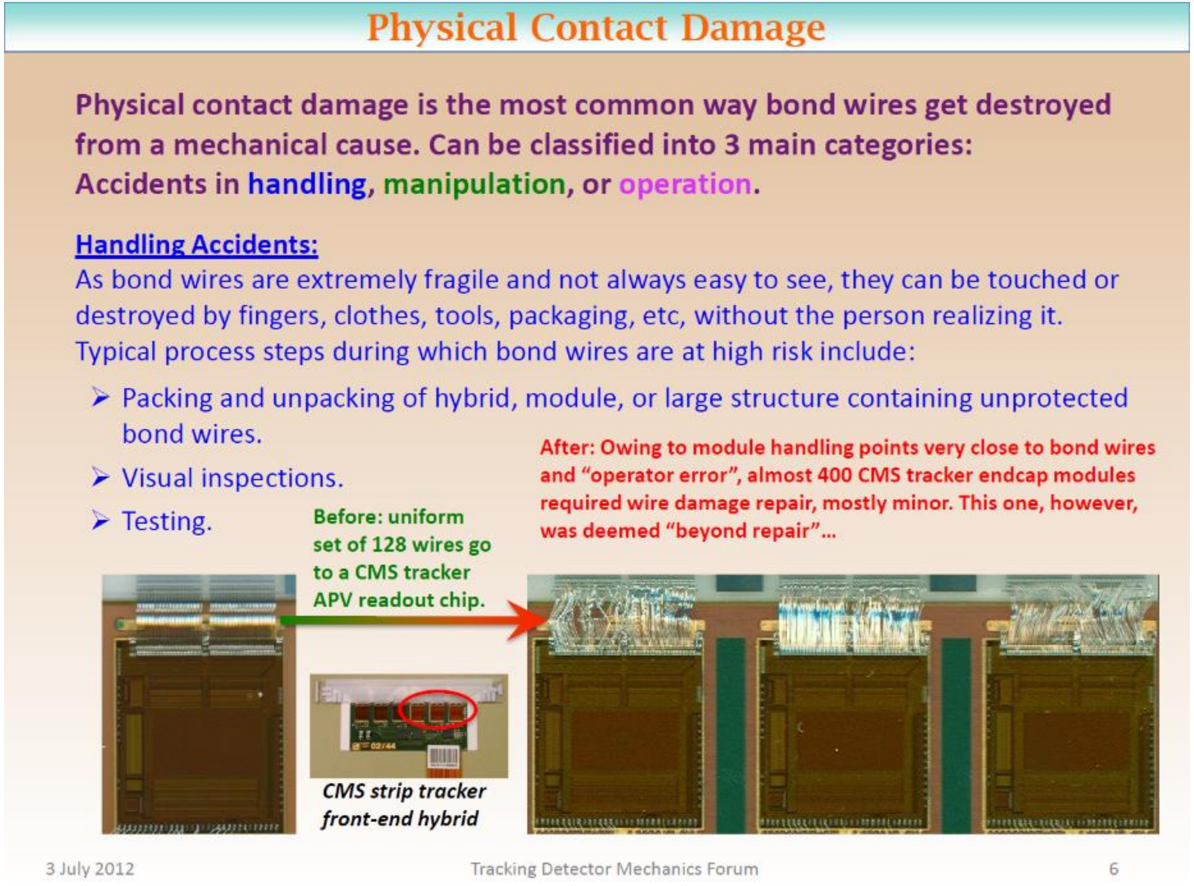


Figure 19: Broken wirebonds between sensors following module transport.



- Vibration and shock damaged wires in transportation
- Minimize differential motion between substrates that carry the bond feet
- **Recommend encapsulation of bond wires whenever possible**

Mechanical Risks to Bond Wires
A. Honma, CERN PH/DT



Physical Contact Damage

Physical contact damage is the most common way bond wires get destroyed from a mechanical cause. Can be classified into 3 main categories: Accidents in handling, manipulation, or operation.

Handling Accidents:

As bond wires are extremely fragile and not always easy to see, they can be touched or destroyed by fingers, clothes, tools, packaging, etc, without the person realizing it. Typical process steps during which bond wires are at high risk include:

- Packing and unpacking of hybrid, module, or large structure containing unprotected bond wires.
- Visual inspections.
- Testing.

After: Owing to module handling points very close to bond wires and “operator error”, almost 400 CMS tracker endcap modules required wire damage repair, mostly minor. This one, however, was deemed “beyond repair”…

Before: uniform set of 128 wires go to a CMS tracker APV readout chip.

CMS strip tracker front-end hybrid

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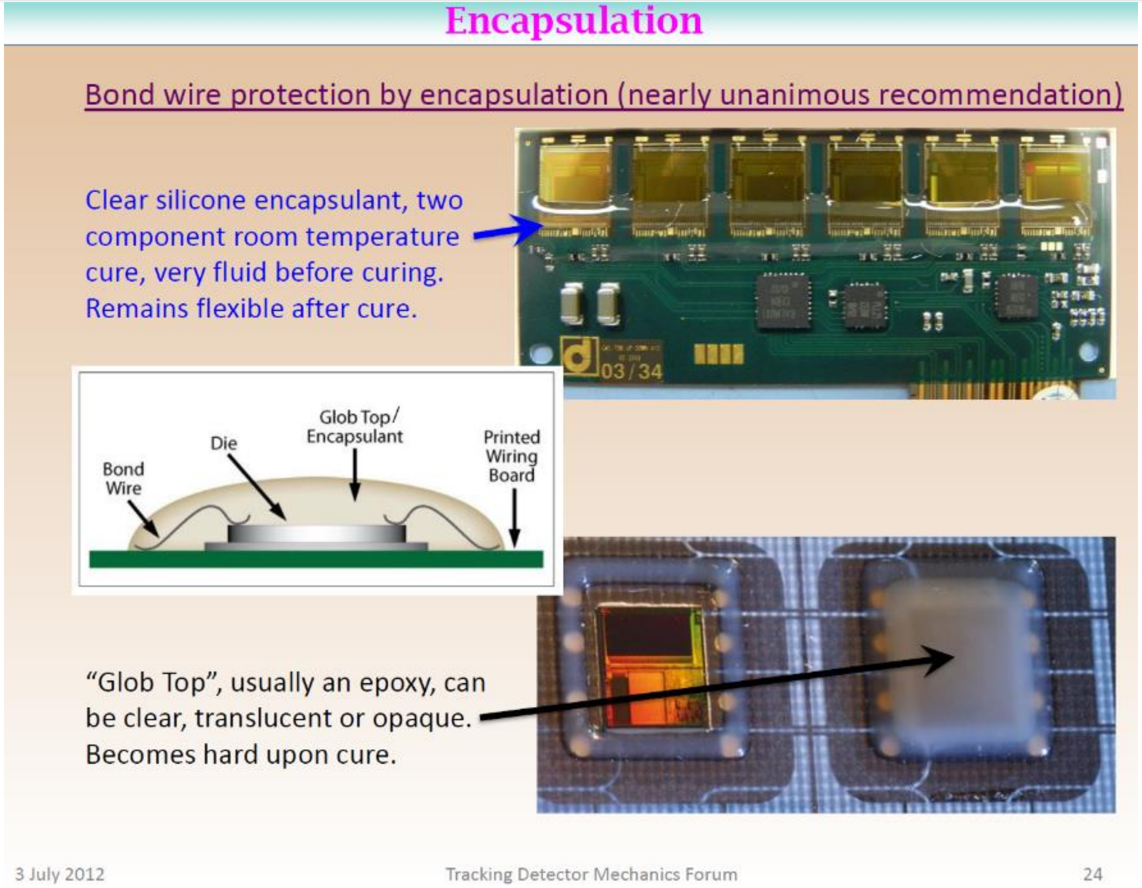
Mitigate Mechanical Risks to Bond Wires
A. Honma, CERN PH/DT



Encapsulation

Bond wire protection by encapsulation (nearly unanimous recommendation)

Clear silicone encapsulant, two component room temperature cure, very fluid before curing. Remains flexible after cure.

“Glob Top”, usually an epoxy, can be clear, translucent or opaque. Becomes hard upon cure.

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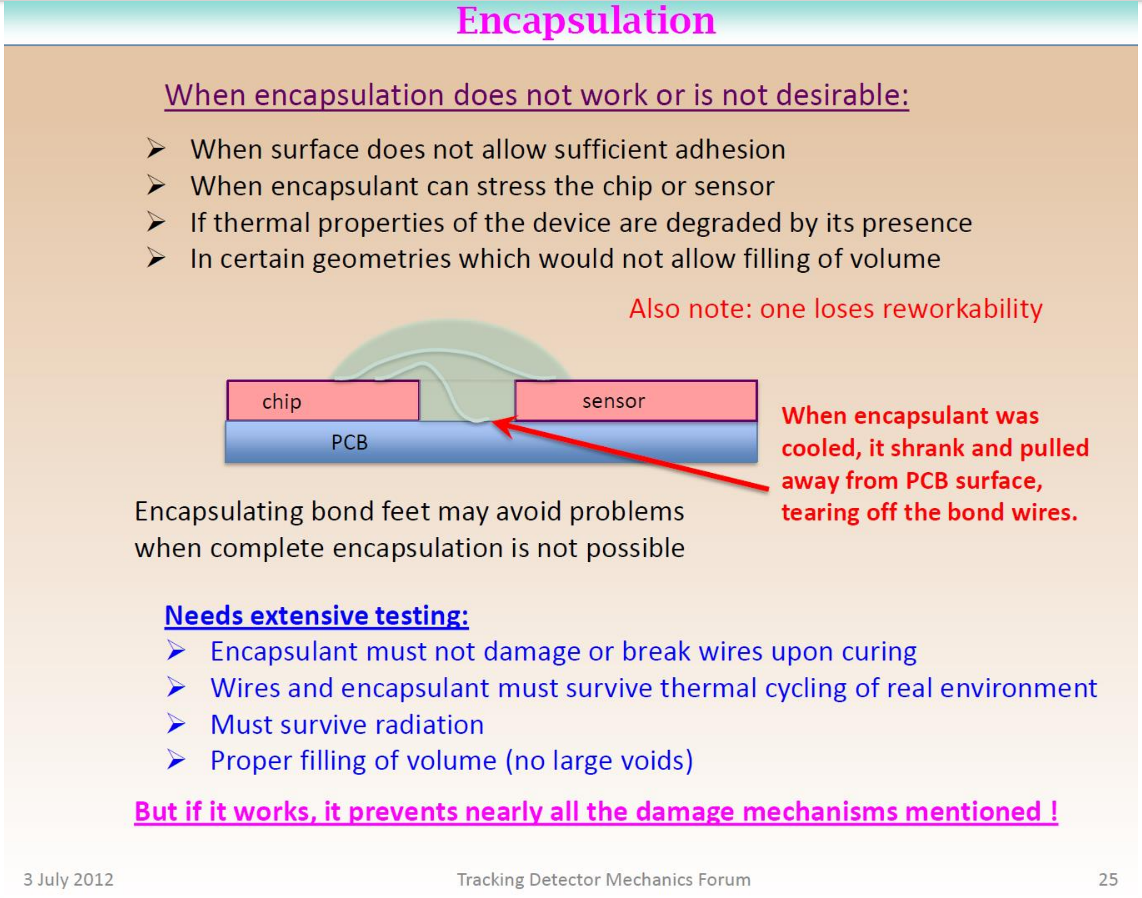
Mechanical Risks to Bond Wires
A. Honma, CERN PH/DT



Encapsulation

When encapsulation does not work or is not desirable:

- When surface does not allow sufficient adhesion
- When encapsulant can stress the chip or sensor
- If thermal properties of the device are degraded by its presence
- In certain geometries which would not allow filling of volume

Also note: one loses reworkability

When encapsulant was cooled, it shrank and pulled away from PCB surface, tearing off the bond wires.

Encapsulating bond feet may avoid problems when complete encapsulation is not possible

Needs extensive testing:

- Encapsulant must not damage or break wires upon curing
- Wires and encapsulant must survive thermal cycling of real environment
- Must survive radiation
- Proper filling of volume (no large voids)

But if it works, it prevents nearly all the damage mechanisms mentioned !

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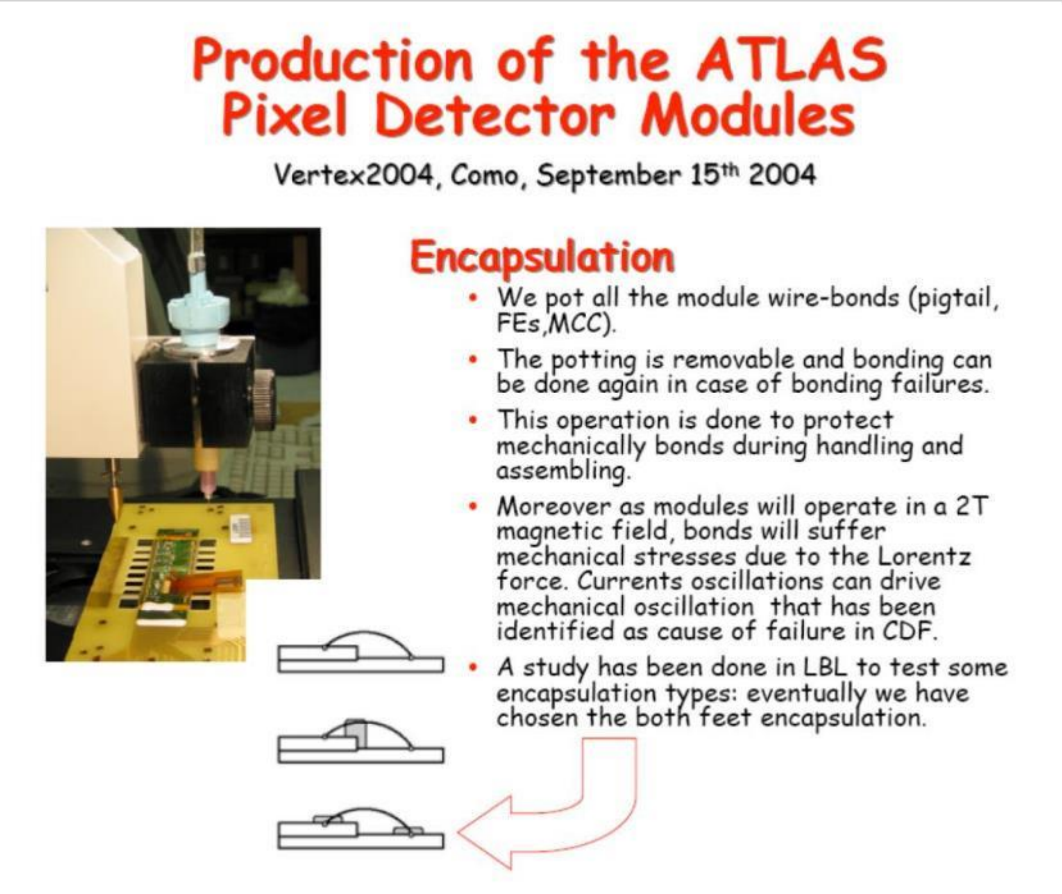
study for ATLAS pixels circa 2004



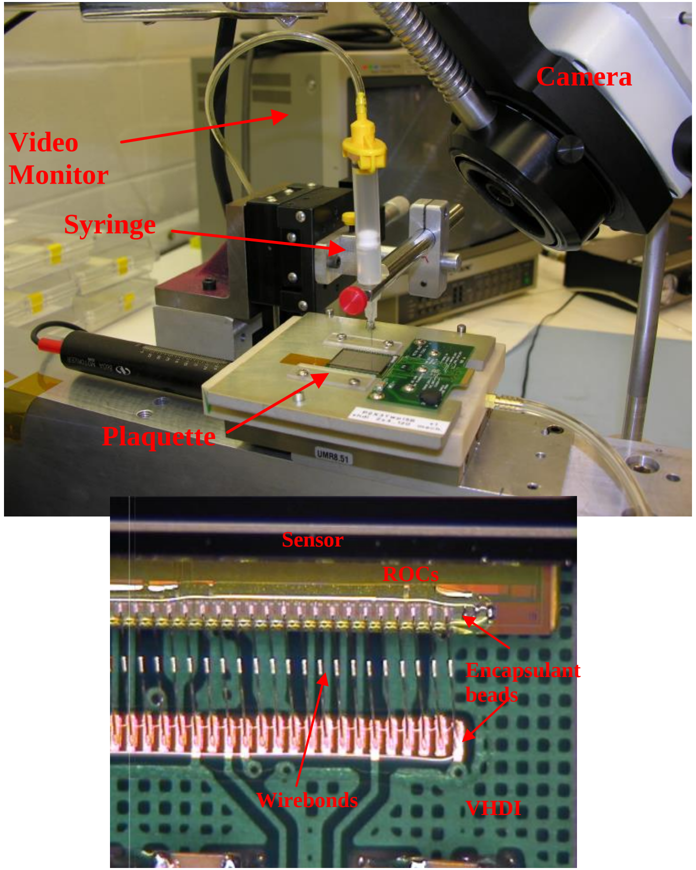
Production of the ATLAS Pixel Detector Modules

Vertex2004, Como, September 15th 2004

Encapsulation

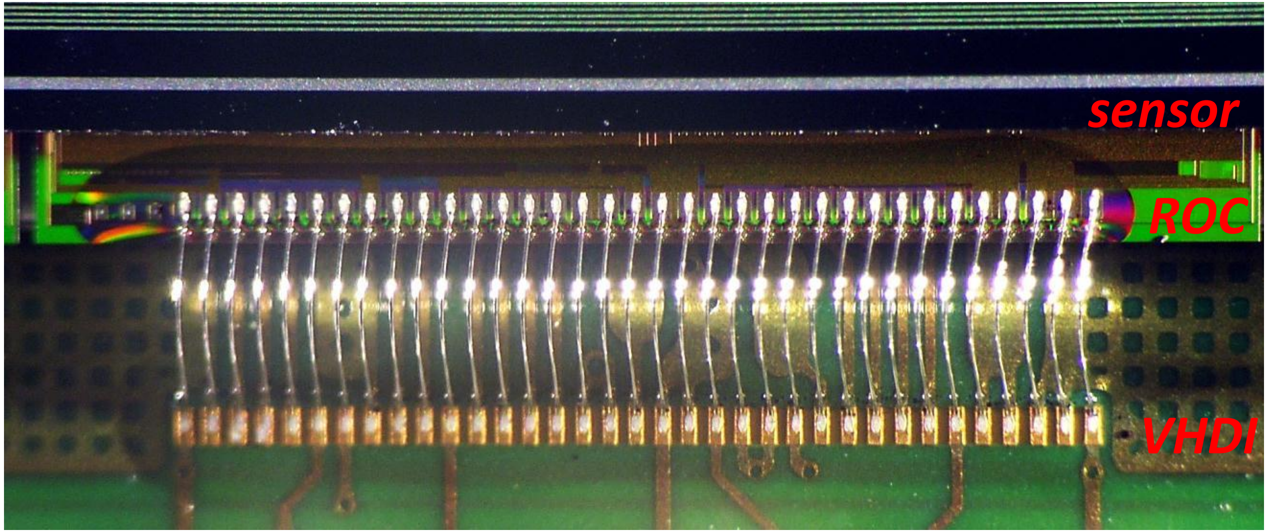
- We pot all the module wire-bonds (pigtail, FEs,MCC).
- The potting is removable and bonding can be done again in case of bonding failures.
- This operation is done to protect mechanically bonds during handling and assembling.
- Moreover as modules will operate in a 2T magnetic field, bonds will suffer mechanical stresses due to the Lorentz force. Currents oscillations can drive mechanical oscillation that has been identified as cause of failure in CDF.
- A study has been done in LBL to test some encapsulation types: eventually we have chosen the both feet encapsulation.

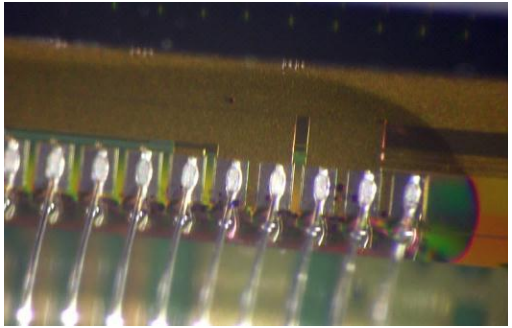
CMS FPIX Module Encapsulation in 2006



- The encapsulant (Dow Corning Sylgard 186) is removable. Wirebonding can be done again in case of failures.
- 2-part encapsulant is mixed, poured into a syringe and degassed in a vacuum or centrifuge
- Syringe is connected to an air powered fluid dispenser and inserted into a holder on a 3-axis stage (motion along rows of bond feet is motor-controlled).
- Shape of encapsulant beads is determined by the rate of volume dispensed and the rate of motion of the syringe
- Mixed encapsulant should be used between ~0.5 and ~1.5 hours after mixing. Fixture cure at room temp. is ~8 hours, full cure in 48 hours or 0.5 hrs. at 60C in an oven
- **Estimate ~3 hours to encapsulate up to 6 modules (including mixing and clean-up time)**
- See section 3.3 “Wirebonding and encapsulation” in Assembly and qualification procedures of CMS forward pixel detector modules, Nucl. Instrum. Meth. A638, Issue 1, 11 May 2011, Pages 55–62, doi:10.1016/j.nima.2011.02.106

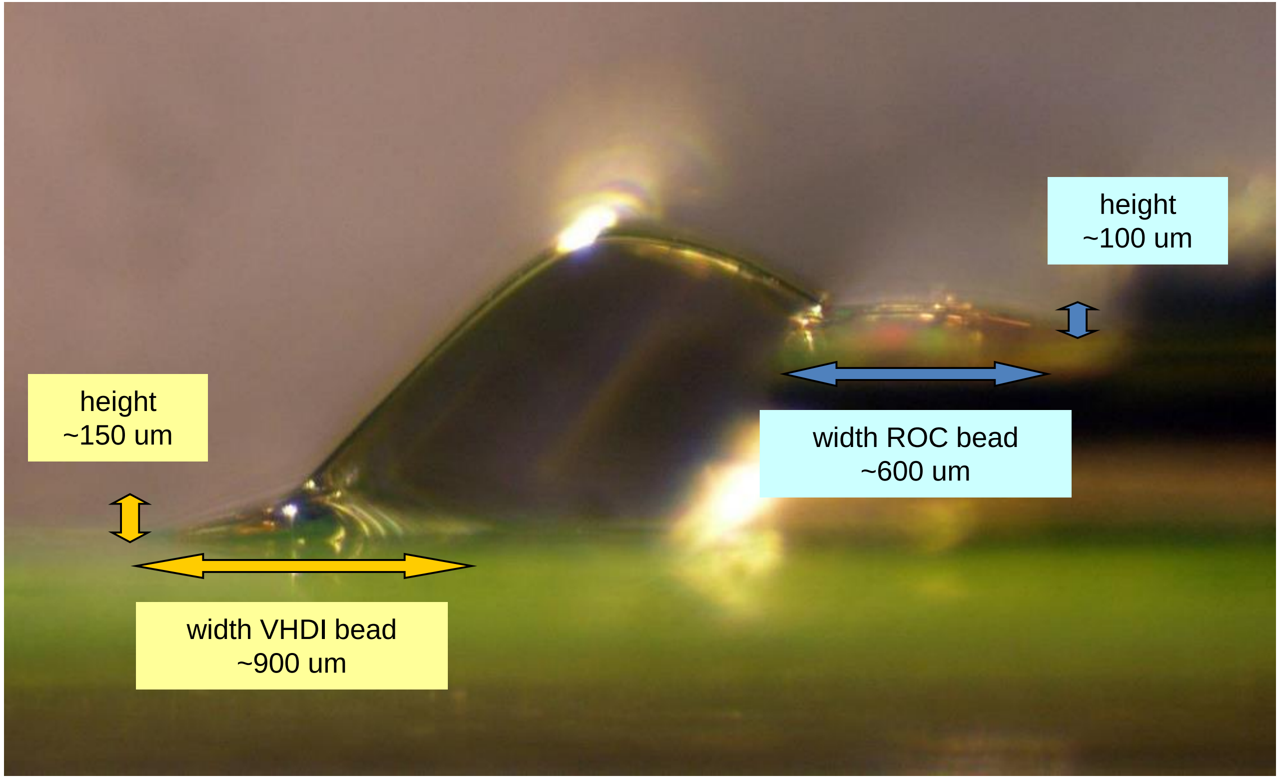
CMS FPIX encapsulation result





ROC and VHDI wire bond feet were potted in separate encapsulant beads for each ROC

CMS FPIX encapsulant bead dimensions


height
~150 um

width VHDI bead
~900 um

height
~100 um

width ROC bead
~600 um

Risks for unpotted wirebonds

- I’ve heard it said that encapsulation is not needed because past tracking detectors were OK without it
- This statement does not recognize the lower coolant temperature during operation of the trackers for the HL-LHC compared to the LHC
  - corresponds to significantly higher risk of accidently being near or below the dewpoint and condensing water on assemblies during cold testing
- Difficult to ensure that one “avoids all contact with moisture” at all times when cold testing modules, sub-systems and full-systems through-out pre-production and production
- Also possible exposure to high humidity (and handling mistakes) during integration, transportation, installation and commissioning. This is historically when accidents resulting in corrosion/electro-migration problems (or wirebond damage) have occurred.

Context

- Experiences argue for encapsulation whenever possible for mechanical/chemical/environmental protection

  …in addition to cleanliness, dry environment, and caution regarding resonant driving frequencies

- Years of experience in CLEO SVX, CMS Phase0 and Phase1 Forward Pixels, STAR Silicon Tracker, and others

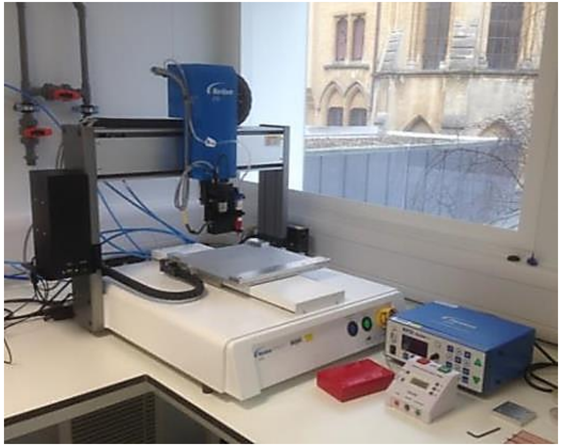
  → no failures of encapsulated wires

Wirebond Encapsulation

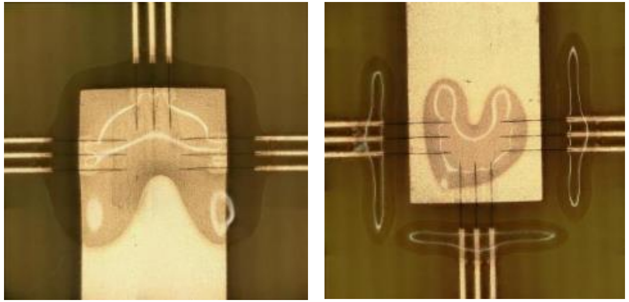
- Ideally, strips and pixels would:
  - Clean (and keep clean) all components before, during, and after assembly
  - Fully dry components/assemblies
  - While in that clean/dry state, encapsulate wirebonds to prevent moisture ingress and reduce ion mobility
- Encapsulating wirebonds is
  - standard practice in industry
  - programmatic and repeatable with the proper equipment
  - provides a large measure of environmental and mechanical protection
  - considerably less onerous than meeting requirements (set out by reviewers) for proceeding without encapsulation

Encapsulation studies for HL-LHC

- For HL-LHC detectors, demonstrate that damage to wirebonds from oscillations, vibrations, or corrosion is mitigated by encapsulating the whole wires or bonds at their heels
- In 2016, performed an initial demonstration of Dow Corning Sylgard 186 Silicone Elastomer potted wires on simple PCBs:
  - ✓ feasibility
  - ✓ reworkability
  - ✓ Si pad diode electrical compatibility
  - ✓ mitigation of resonance, corrosion + thermal cycle effects
  - ✓ **1 MGy radiation tolerance, sufficient for ATLAS ITk Strip and CMS 2S Strip modules**



Vision guided fluid dispensing robot used to encapsulate wirebonds on sample PCBs with entire wires or just the bond feet potted



Trial for ATLAS ITk strip module hybrids

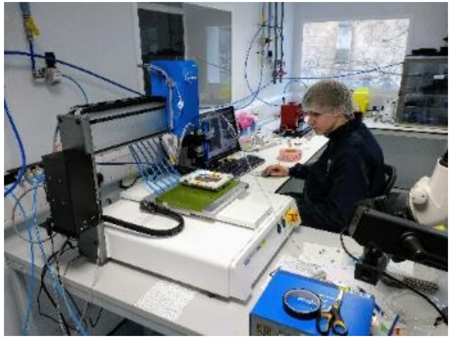
In March 2018, performed trial encapsulating ATLAS strip hybrids using Sylgard 186

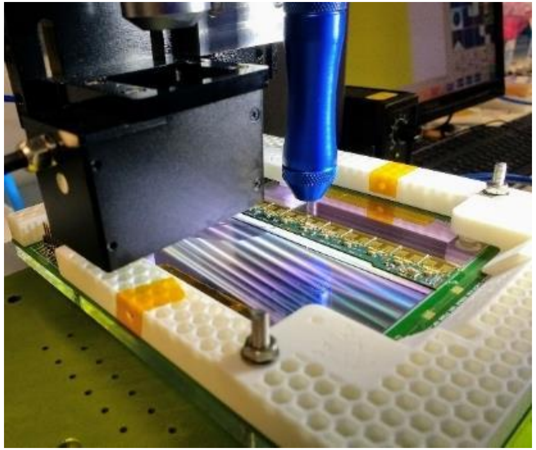
Objectives:

- Fully encapsulate strip hybrid ASIC BE wires
  - Discrete, non-continuous beads
  - Limit distance encapsulant flows from edge of chip
- Electrical characterization before and after potting
- Electrical characterization before and after thermal cycles
- Assess the time and equipment required to dispense

Note:

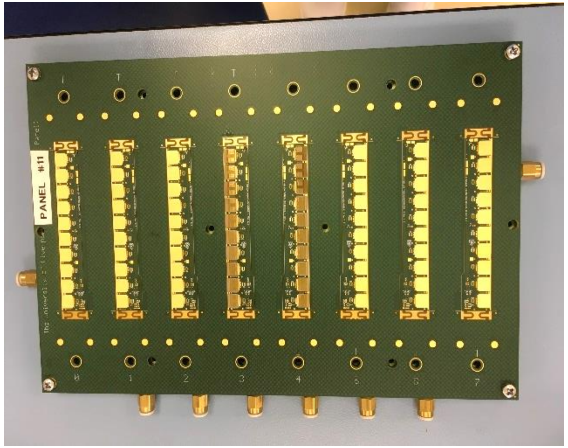
CMS (organized by Alan Honma at CERN) is currently potting all wirebonds on upgrade strip tracker module prototypes with a mix of Sylgard 184 and 186

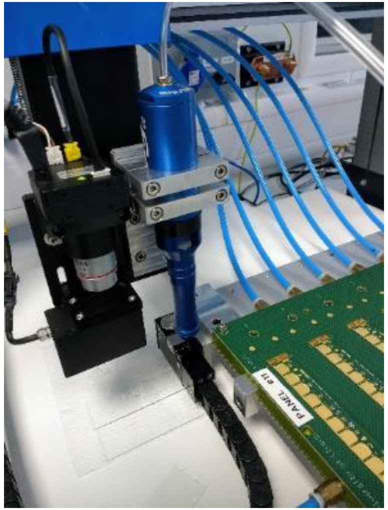


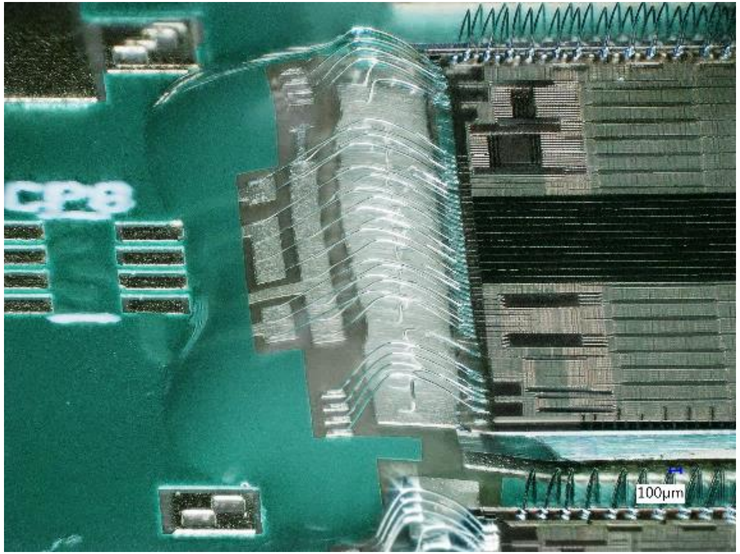


Procedure

- Initially programmed robot to dispense on a single ASIC’s BE wires
- On mech. grade hybrids, dispensed Sylgard 186 at different settings, inspecting the resulting beads to find suitable needle size, air pressure, height and position of needle, and number of passes

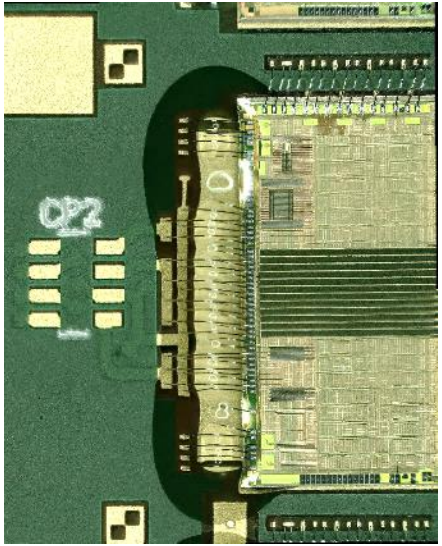


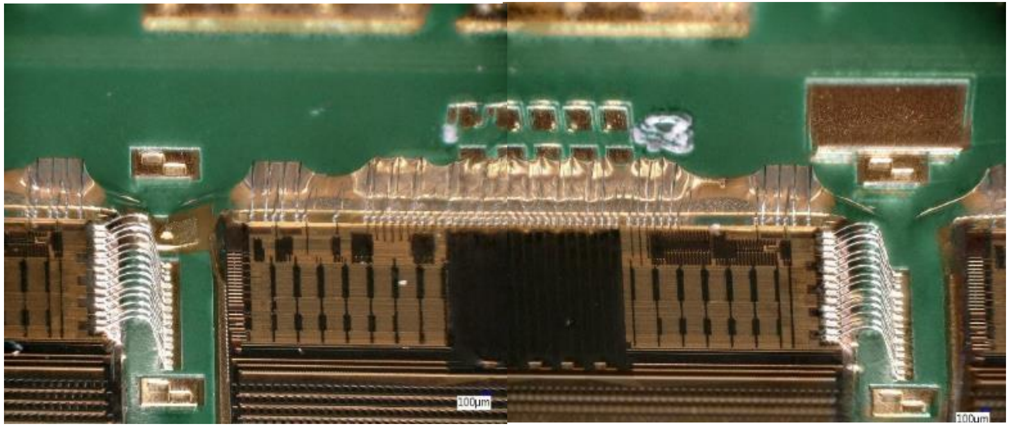




Procedure and Results

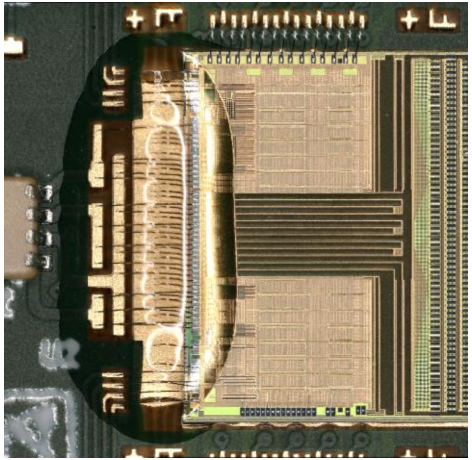
- Programmed robot to dispense on 10 ASIC’s BE wires (in order ASICs #1-10 first pass, repeated for 2nd pass)
- Dispensed on mech. grade hybrid using the best settings found for limiting the flow onto top of ASICs → very sensitive to dispense settings and concern that wires are fully covered
- Thermal cycled hybrids with ASIC BE wires before and after encapsulation
- Wires and chip mounting appear unaffected

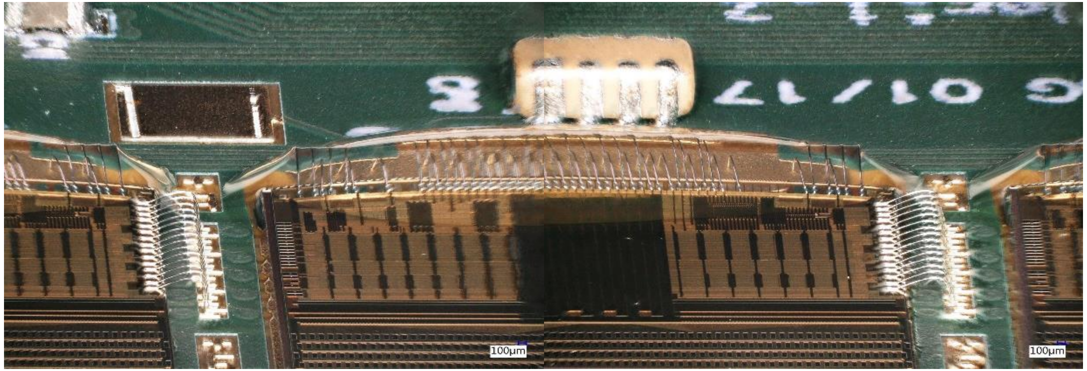




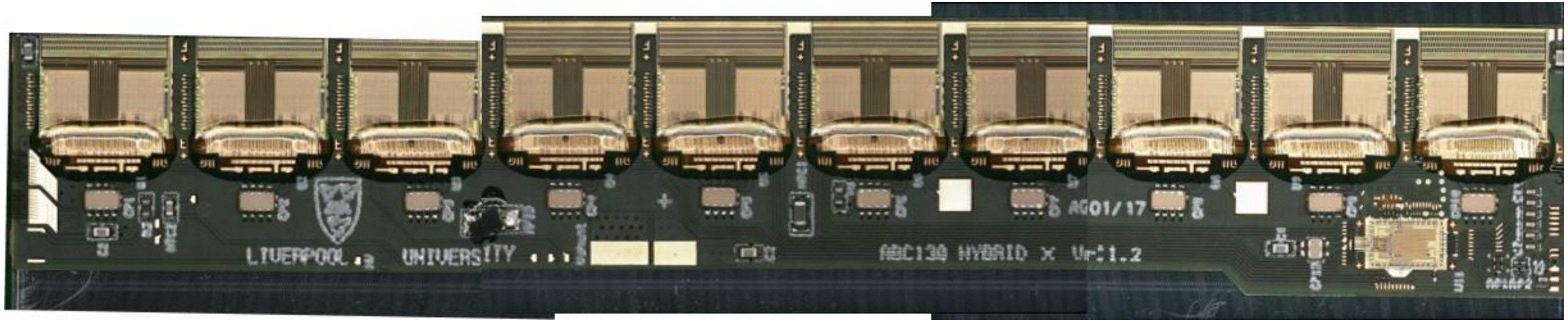
Procedure & Results (cont.)

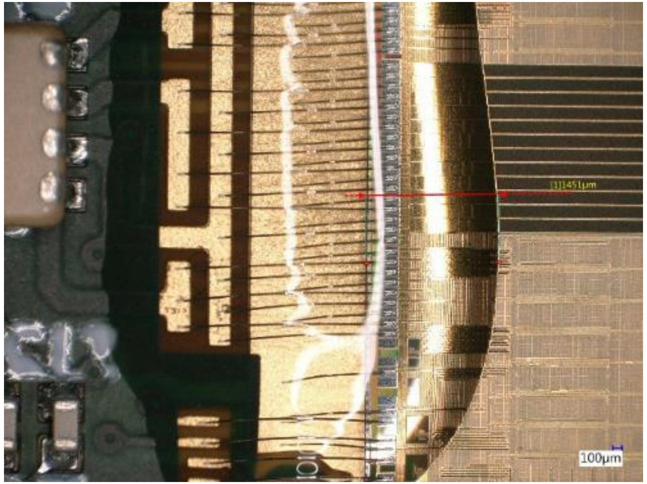
- Received an electrical grade hybrid, performed electrical characterization test before and after thermal cycles (wirebond pull strengths previously measured)
- Dispensed Sylgard 186 using settings found previously on mech. grade hybrid to more fully cover of wires (see video at https://www.youtube.com/watch?v=oHZvOJa_5Ak)
- Cured the encapsulant at room temperature for 90 minutes + 1 hour at 40C
- Performed visual inspection, wires and chip mounting appear unaffected
- Electrical characterization before and after potting and thermal cycles → all tests results look identical





Extent of encapsulant on ASICs

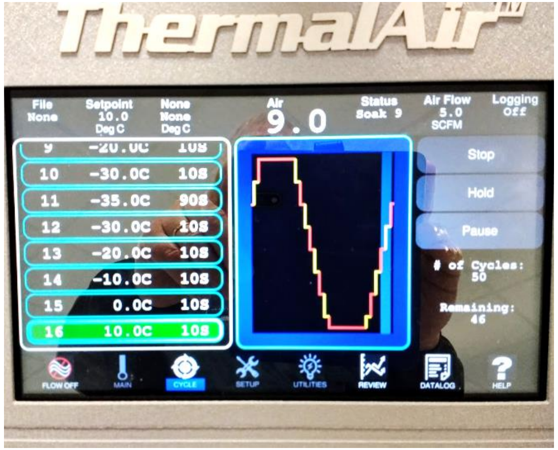




Maximum flow onto the electrical grade hybrid ASICs = 1.5mm from back edge

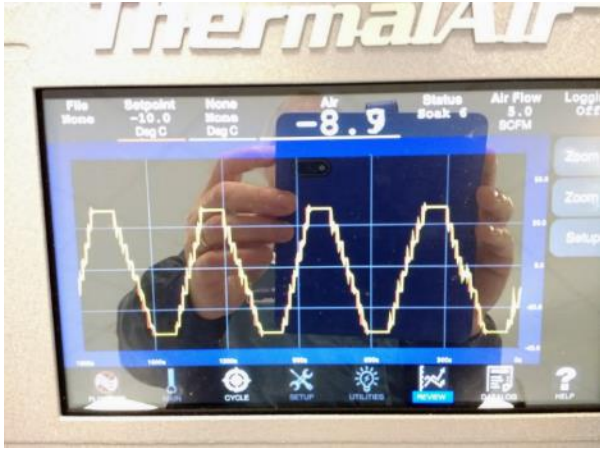
Thermal tests

- All thermal tests using ThermalAir system : -35C to +40C, 50 cycles
- Temperature change in 10C steps with 10 second dwell time at each step, ~1C per second ramp rate
- No change in electrical performance


File None
Setpoint 10.0 Deg C
None None Deg C
Air 9.0
Status Soak 9
Air Flow 5.0 SCFM
Logging Off

9	-20.0C	10S
10	-30.0C	10S
11	-35.0C	90S
12	-30.0C	10S
13	-20.0C	10S
14	-10.0C	10S
15	0.0C	10S
16	10.0C	10S

# of Cycles: 50
Remaining: 46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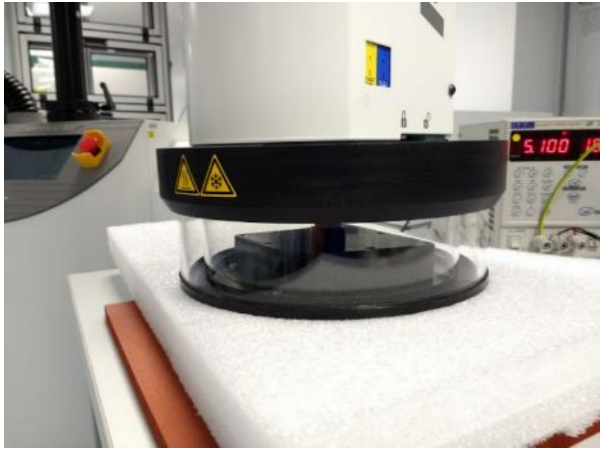
Setpoint -10.0 Deg C
None None Deg C
Air -8.9
Status Soak 6
Air Flow 5.0 SCFM



Timing

Time required to perform potting steps:

- 10 min. Mix, fill syringe, degassing, mount syringe on robot
- 5 min. Needle tip detect, index to part using pattern recognition, trial dispense to purge needle

- 6 min. 1st pass 10 ASICs (with program stop after each ASIC)
- 6 min. 2nd pass 10 ASICs (with program stop after each ASIC)

= 12 min. per hybrid

Estimate 10 min. per hybrid without program stops + HCC wires

→**75 min. total for 6 hybrids** (15 min. setup + 6x10 min. per hybrid)
…plus time for clean-up

Useful pot life of Sylgard 186 from time of mix = **90 min.**

Liquid dispensing kit

Nordson EFD Automated Dispensing Systems

- £30K
- Smart hi-res camera and pattern recognition
- Tip detector included
- Closed loop motion control

+/- 4 micron repeatability

- £16K with tip detector option
- Pencil camera and pattern recognition
- Open loop motion control

+/- 8 micron repeatability

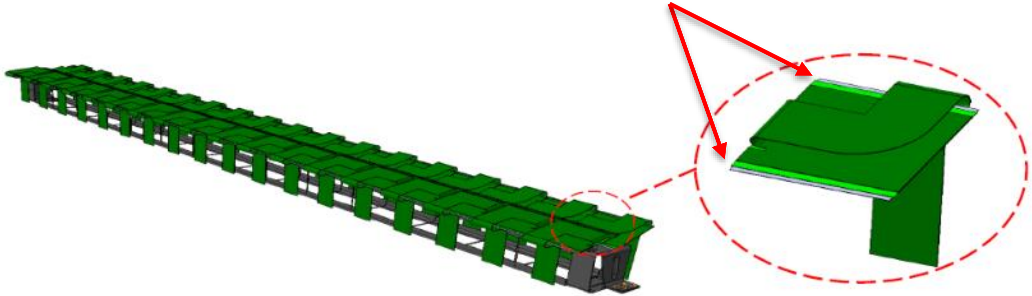
Both with 400 x 400 x 100mm table travel and software driven

- EV system has pattern recognition with a lower resolution camera and open loop motion control
- Recommend a demonstration at the showroom to confirm, but we think the EV system is capable for fully potting strip wires
- Pro4 system required when potting only the feet of wirebonds

Summary of study for ATLAS ITk Strips

- Fully encapsulated ASIC BE wires using Sylgard 186
- Possible to limit flow on top of ASICs to <2mm from back edge of chip without a ‘dam’
- Suggested next step: fully encapsulate Hybrid Control Chip wires and partially encapsulate hybrid-testframe wires, then thermal cycle and test again
- Encapsulate more electric grade hybrids to increase statistics
- Proceed to irradiation dose, followed by thermal cycles and test
- Perform an effective corrosion test (i.e. a test that induces corrosion of unpotted wires)
  - Deionized water droplet ala ATLAS IBL
  - HAST testing at 85degC/85%RH

Encapsulation for ATLAS ITk pixel outer barrel



Wirebond areas

Wirebond area

In pixel barrel section, module flexes are routed across module wirebonds → full coverage of bonds with encapsulation is required

Status for Pixels

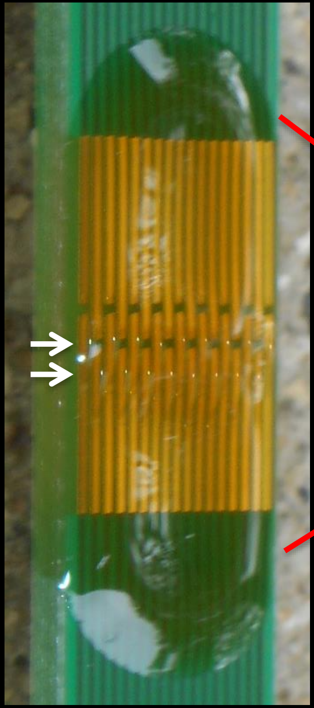
- Ongoing tests to find a suitable “glob top” encapsulant
- Silicones (Sylgard 170, 182, 184, 186) are radiation tolerance to ~2 MGy and still soft
- Test results from proton irradiation (TID ~10 MGy) in Japan show:
  - Sylgard 184, 186 and TSE3032 (silicones) hardened and cracked
  - Dymax 9001 v.3.1 and v.3.7 (urethanes) had wire disconnections in -55 to +60C thermal cycles
- Nicola Pacifico, Joe Izen, Manabu Togawa and I are working to identify candidate products that may be sufficiently radiation tolerant for pixels
  - Literature says radiation tolerance of silicone is enhanced by phenyl. Sylgard 170 is high in phenyl groups. However, the mixed viscosity of Sylgard 170 is low (2135 cP)
  - Also looking at urethanes which should have remarkable radiation hardness characteristics, and there are some that are fairly soft:
    - Dymax 9037-F is an acrylated urethane with relatively low hardness, modulus, and high elongation. Also moderate viscous, 45,000 cP.
    - Dymax 9008 is an acrylated urethane that is relatively soft, high glass transition temperature that remains flexibility to -40C, low viscosity 4,500 cP.

Status for Pixels

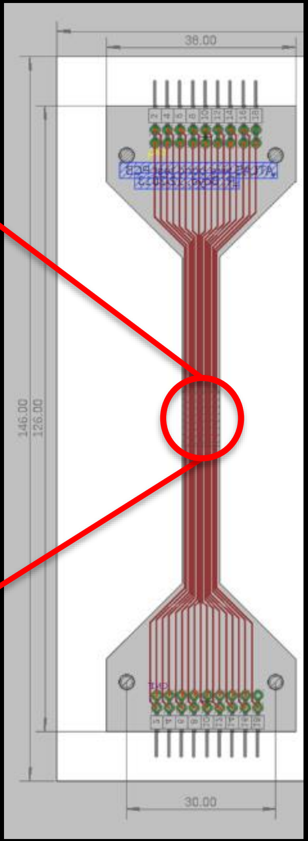
- Epoxies are among the most radiation tolerant plastics
- An alternative to finding a product that remains sufficiently soft when irradiated is to focus on an epoxy with a low CTE
  - Example: Masterbond EP42HT-2LTE, a two component room temperature cure epoxy with a very low CTE (9-12 x 10-6 in/in/°C) and cryogenic service temperature range
  - Also pursuing RAL formulated flexible/low modulus and low CTE epoxies developed for use in ATLAS End Cap Toroid magnets and ITER
- Preparing samples for proton irradiation in Japan and the CERN irradiation campaign this summer

Glob Top Encapsulation – Long Oil Alkyds

- complex oil-modified polyester resin
- More flexible than Alkyd+PU *e.g.* CellPack
- First CTE test – glob top
  - 1 Epifanes 17-wire board
  - 1 McCloskey 17- wire board
- 4 cycles: -20C to +60 C
  - All wires fine (so far)
- Irradiation, spraying studies planned



Epifanes glob top



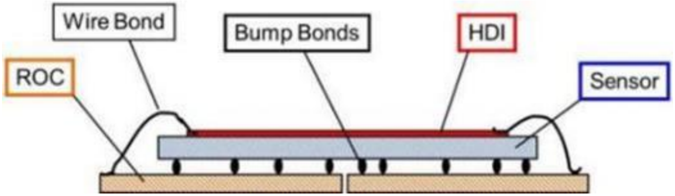
CellPack D2091 Spray Coating

- Spraying feasibility demonstrated
- Corrosion protection, no CTE problems
- Protection mechanisms understood
  - Encapsulated foot
  - Increased oscillator mass
  - Flexible coating lowers Q
- O.D. >100µm protects against worst case oscillation
  - ($I_{p\text{-}p}$ =100 mA, B=2T) equiv. @ f_{res} -20C, end-cap
- Rad-hard: >10x ITk Strip dose, >1x ITk Pixel dose

- Scale-up to production needs to be understood (i.e. semi-automated spraying)

Cellpack D2091 light coat ~50µm OD

Parylene for wire bonds



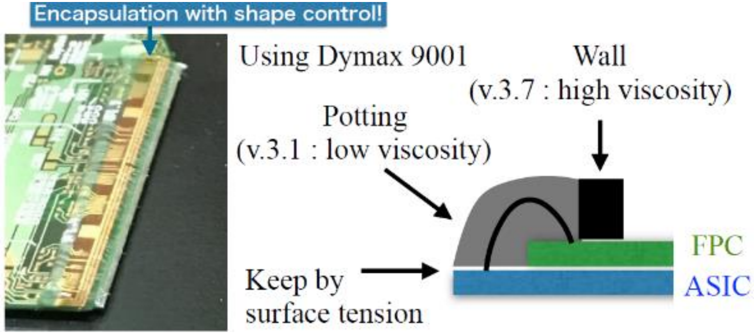
Interest in parylene coating for HV isolation to prevent arcing between pixel sensor (single-side processed without guard rings) and front-end chips

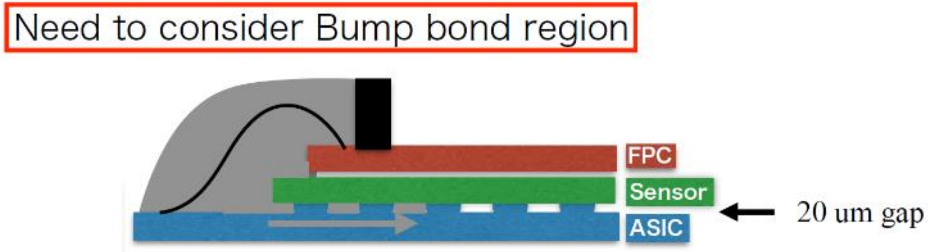
- Increased pull strength of wire bonds coated with parylene is well documented, but we would want to test that parylene coating alone prevents breakage due to resonance induced by a magnetic field
- Increased strength of parylene coated wirebonds would give extra margin against thermal stress from encapsulation

Next steps for Pixels

- Encapsulate and irradiate more samples to evaluate radiation tolerance of candidate materials
- Concern for potting/coating entire wires between pixel FE chips and flex hybrid: partial underfill in the gap between bump-bonded sensor and FE chips

  →Noisy pixels? Radiation effect on dielectric strength?
- Plan to glob top/coat entire wires on single chip pixel modules followed by irradiation to evaluate this…





Manabu Togawa, ITk Japan group

Summary

- Millions of wirebonds are needed and must withstand the harsh operational and environmental conditions of the HL-LHC
- Exposure to moisture, ionic (halogen) contaminants, and mechanical/thermal stresses can be highly detrimental and have led to unexpected wirebond failures in past large-scale silicon detectors
- Evaluations of materials and methods for protection of wirebonds for HL-LHC inner trackers are ongoing

For strips:

- Initial evaluation of Sylgard 186 silicone on simple PCBs and strip hybrids is complete and 'mini-staves' is in progress

For pixels:

- Evaluation of glob top encapsulation with Polyurethanes, Epoxies, and Long Oil Alkyd is in progress
- Also evaluating Polyurethane, Long Oil Alkyd, and Parylene coatings

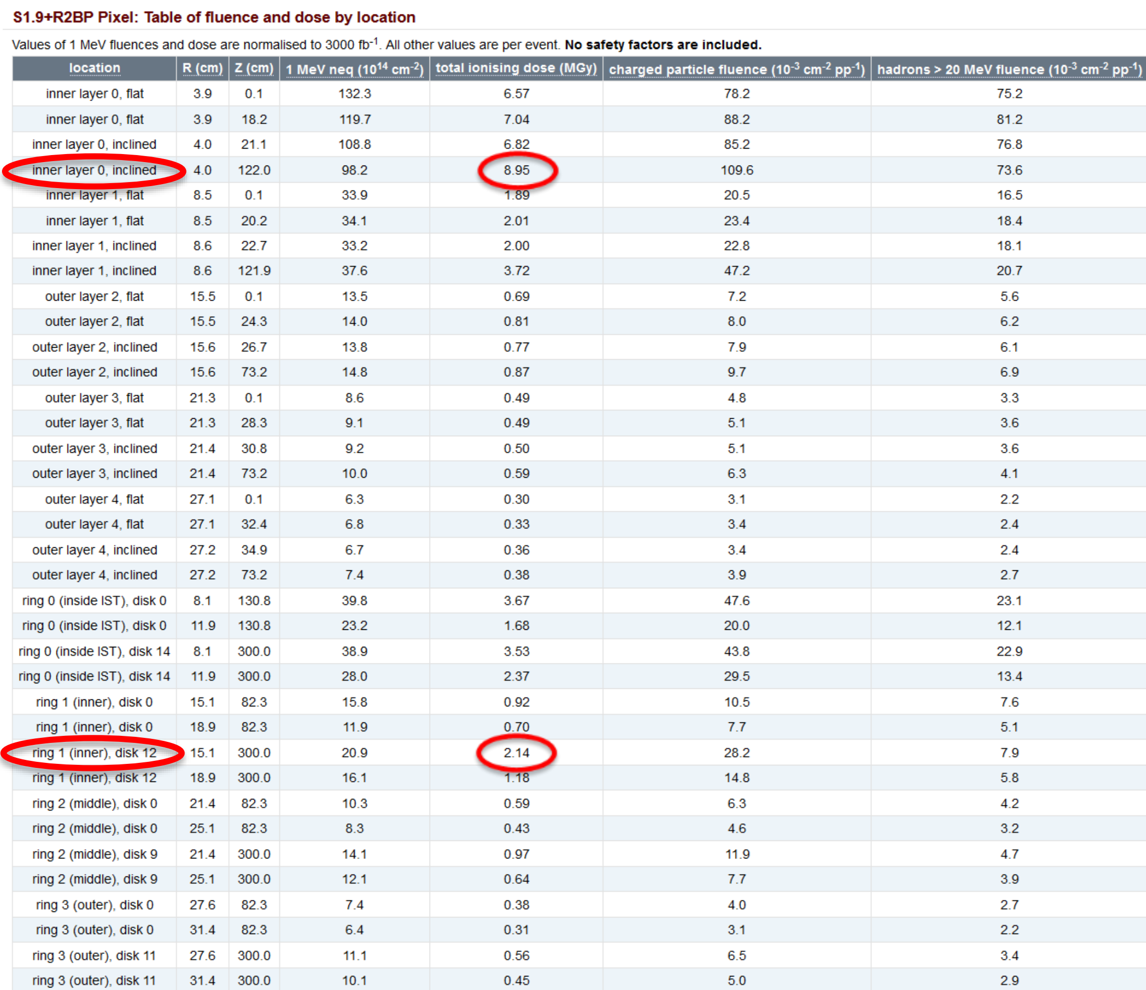
Backup slides

Radiation Background Simulation

https://twiki.cern.ch/twiki/bin/view/Atlas/RadiationBackgroundSimulationsFullyInclinedAt4

Highest ATLAS dose is inner pixel layer 0 at highest Z
Normalized to 3000 fb^{-1}, but inner pixels replaced after 2000 fb^{-1}, so 8.95 x 2/3 x 1.5 SF = **9 MGy TID**

Highest dose in outer pixel endcaps is innermost ring at highest Z
Normalized to 3000 fb^{-1}, but current requirement is 4000 fb^{-1}, so 2.14 x 4/3 x 1.5 SF is **4.3 MGy TID**



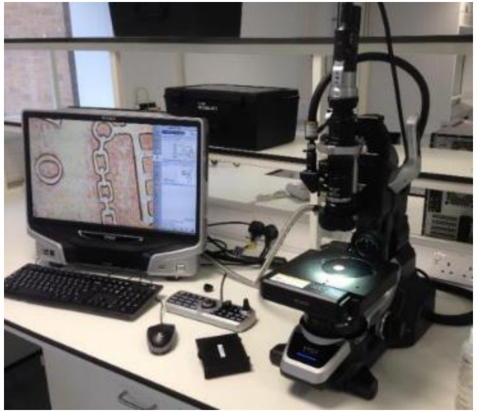
S1.9+R2BP Pixel: Table of fluence and dose by location

Values of 1 MeV fluences and dose are normalised to 3000 fb^{-1}. All other values are per event. **No safety factors are included.**

location	R (cm)	Z (cm)	1 MeV neq (10^{14} cm^{-2})	total ionising dose (MGy)	charged particle fluence (10^{-3} cm^{-2} pp^{-1})	hadrons > 20 MeV fluence (10^{-3} cm^{-2} pp^{-1})
inner layer 0, flat	3.9	0.1	132.3	6.57	78.2	75.2
inner layer 0, flat	3.9	18.2	119.7	7.04	88.2	81.2
inner layer 0, inclined	4.0	21.1	108.8	6.82	85.2	76.8
inner layer 0, inclined	4.0	122.0	98.2	8.95	109.6	73.6
inner layer 1, flat	8.5	0.1	33.9	1.89	20.5	16.5
inner layer 1, flat	8.5	20.2	34.1	2.01	23.4	18.4
inner layer 1, inclined	8.6	22.7	33.2	2.00	22.8	18.1
inner layer 1, inclined	8.6	121.9	37.6	3.72	47.2	20.7
outer layer 2, flat	15.5	0.1	13.5	0.69	7.2	5.6
outer layer 2, flat	15.5	24.3	14.0	0.81	8.0	6.2
outer layer 2, inclined	15.6	26.7	13.8	0.77	7.9	6.1
outer layer 2, inclined	15.6	73.2	14.8	0.87	9.7	6.9
outer layer 3, flat	21.3	0.1	8.6	0.49	4.8	3.3
outer layer 3, flat	21.3	28.3	9.1	0.49	5.1	3.6
outer layer 3, inclined	21.4	30.8	9.2	0.50	5.1	3.6
outer layer 3, inclined	21.4	73.2	10.0	0.59	6.3	4.1
outer layer 4, flat	27.1	0.1	6.3	0.30	3.1	2.2
outer layer 4, flat	27.1	32.4	6.8	0.33	3.4	2.4
outer layer 4, inclined	27.2	34.9	6.7	0.36	3.4	2.4
outer layer 4, inclined	27.2	73.2	7.4	0.38	3.9	2.7
ring 0 (inside IST), disk 0	8.1	130.8	39.8	3.67	47.6	23.1
ring 0 (inside IST), disk 0	11.9	130.8	23.2	1.68	20.0	12.1
ring 0 (inside IST), disk 14	8.1	300.0	38.9	3.53	43.8	22.9
ring 0 (inside IST), disk 14	11.9	300.0	28.0	2.37	29.5	13.4
ring 1 (inner), disk 0	15.1	82.3	15.8	0.92	10.5	7.6
ring 1 (inner), disk 0	18.9	82.3	11.9	0.70	7.7	5.1
ring 1 (inner), disk 12	15.1	300.0	20.9	2.14	28.2	7.9
ring 1 (inner), disk 12	18.9	300.0	16.1	1.18	14.8	5.8
ring 2 (middle), disk 0	21.4	82.3	10.3	0.59	6.3	4.2
ring 2 (middle), disk 0	25.1	82.3	8.3	0.43	4.6	3.2
ring 2 (middle), disk 9	21.4	300.0	14.1	0.97	11.9	4.7
ring 2 (middle), disk 9	25.1	300.0	12.1	0.64	7.7	3.9
ring 3 (outer), disk 0	27.6	82.3	7.4	0.38	4.0	2.7
ring 3 (outer), disk 0	31.4	82.3	6.4	0.31	3.1	2.2
ring 3 (outer), disk 11	27.6	300.0	11.1	0.56	6.5	3.4
ring 3 (outer), disk 11	31.4	300.0	10.1	0.45	5.0	2.9

Equipment @ OPMD

Nordson EFD Pro4 vision guided liquid dispensing robot and Ultimus V controller
Cost £30K (ex. VAT)



Keyence VHX-5000 digital microscope w/ 50x to 2500x zoom lenses
Cost £50K (ex. VAT)

SpeedMixer DAC 150.1 FVZ-K Small batch mixer/degassing system
Cost £9K (ex. VAT)

Thermal Testing QA

ThermalAir TA-5000A

An Evolution in Localized Temp

Performance Plus! - Productivity!

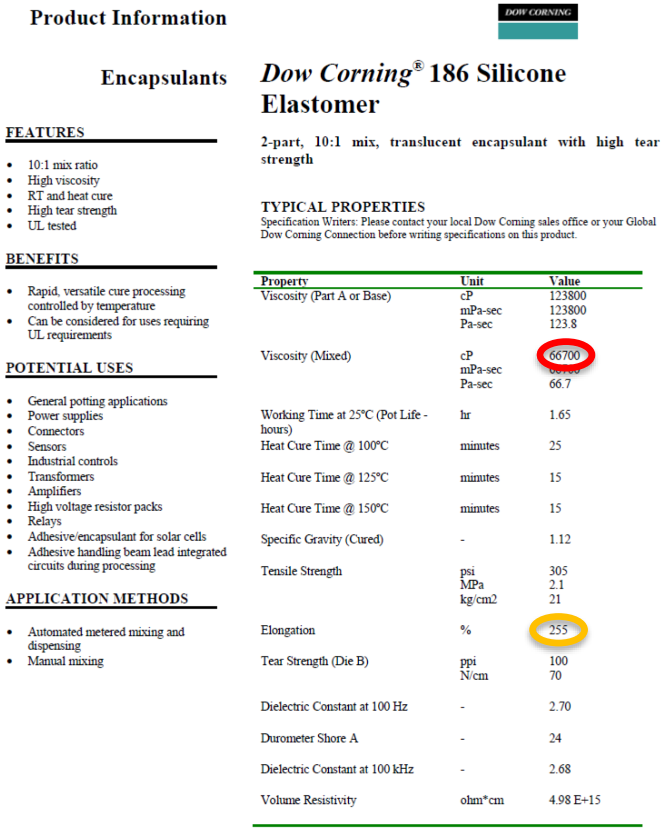
- Continuous Air Flow up to 20 SCFM @-80C/+225C
- -55C to +125C/ +125C to -55C less than 10 sec
- Ultra Stable DC Temperature Control
- Frost Free Operation / Built-in Air Dryer
- No LN2 or CO2 Required
- CFC Free / CE Mark

- Proposed (early 2017) QA testing for pixels:
  - **100 thermal cycles between -55C and +60C**
  - Some modules to undergo 100 thermal shock stress cycles between **+25C and -35C with temperature fall time > 6°C per sec**
  - Electrical measurements of bump bond connectivity after every 20 repetitions
- Hard to get thermal test systems to these numbers without a decent amount of work
- ThermalAir system for thermal shock and testing
  - -80C to +225C range
  - Typical temperature transition rate -55C to +125C / +125 C to -5C is <10 sec.
- Installed @ Oxford in November 2017

Next step for ATLAS ITk Strip Staves

- Tests of bus tapes co-cured + EOS-like PCBs glued to a ‘mini-stave’ + wirebonds fully-potted with Sylgard 186
- Thermal cycles (-40C to +60C) showed no connectivity problem on the 4 unirradiated EOS-like PCBs
- Handling problems during proton irradiation at Birmingham damaged all wires and was not rebondable
- Preparation of new mini-staves for proton irradiation at Birmingham in progress

Material properties



Product Information

Encapsulants

DOW CORNING

Dow Corning® 186 Silicone Elastomer

2-part, 10:1 mix, translucent encapsulant with high tear strength

FEATURES

- 10:1 mix ratio
- High viscosity
- RT and heat cure
- High tear strength
- UL tested

BENEFITS

- Rapid, versatile cure processing controlled by temperature
- Can be considered for uses requiring UL requirements

POTENTIAL USES

- General potting applications
- Power supplies
- Connectors
- Sensors
- Industrial controls
- Transformers
- Amplifiers
- High voltage resistor packs
- Relays
- Adhesive/encapsulant for solar cells
- Adhesive handling beam lead integrated circuits during processing

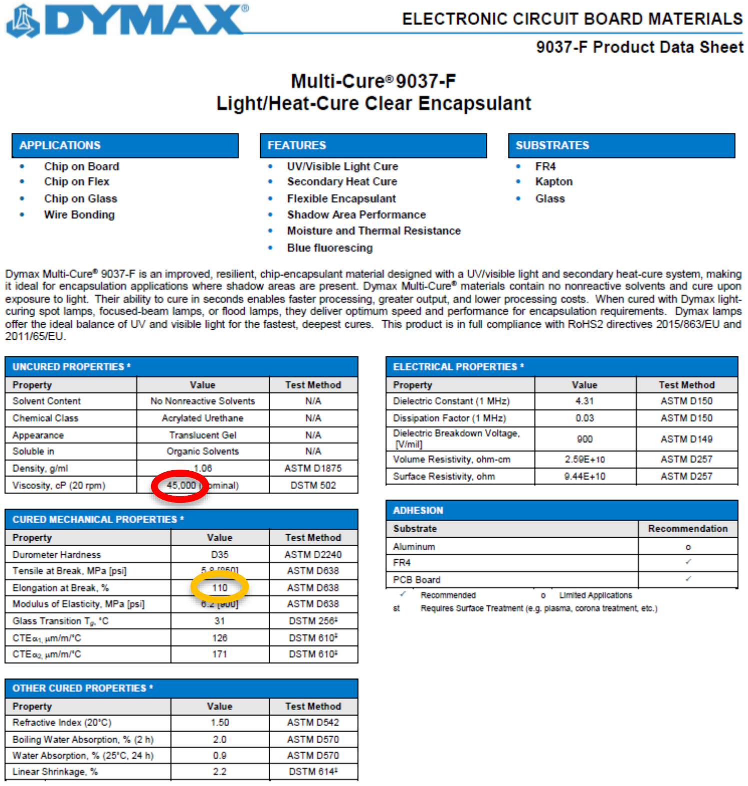
APPLICATION METHODS

- Automated metered mixing and dispensing
- Manual mixing

TYPICAL PROPERTIES

Specification Writers: Please contact your local Dow Corning sales office or your Global Dow Corning Connection before writing specifications on this product.

Property	Unit	Value
Viscosity (Part A or Base)	cP mPa-sec Pa-sec	123800 123800 123.8
Viscosity (Mixed)	cP mPa-sec Pa-sec	66700 66700 66.7
Working Time at 25°C (Pot Life - hours)	hr	1.65
Heat Cure Time @ 100°C	minutes	25
Heat Cure Time @ 125°C	minutes	15
Heat Cure Time @ 150°C	minutes	15
Specific Gravity (Cured)	-	1.12
Tensile Strength	psi MPa kg/cm2	305 2.1 21
Elongation	%	255
Tear Strength (Die B)	ppi N/cm	100 70
Dielectric Constant at 100 Hz	-	2.70
Durometer Shore A	-	24
Dielectric Constant at 100 kHz	-	2.68
Volume Resistivity	ohm*cm	4.98 E+15



DYMAX®

ELECTRONIC CIRCUIT BOARD MATERIALS

9037-F Product Data Sheet

Multi-Cure® 9037-F
Light/Heat-Cure Clear Encapsulant

APPLICATIONS

- Chip on Board
- Chip on Flex
- Chip on Glass
- Wire Bonding

FEATURES

- UV/Visible Light Cure
- Secondary Heat Cure
- Flexible Encapsulant
- Shadow Area Performance
- Moisture and Thermal Resistance
- Blue fluorescing

SUBSTRATES

- FR4
- Kapton
- Glass

Dymax Multi-Cure® 9037-F is an improved, resilient, chip-encapsulant material designed with a UV/visible light and secondary heat-cure system, making it ideal for encapsulation applications where shadow areas are present. Dymax Multi-Cure® materials contain no nonreactive solvents and cure upon exposure to light. Their ability to cure in seconds enables faster processing, greater output, and lower processing costs. When cured with Dymax light-curing spot lamps, focused-beam lamps, or flood lamps, they deliver optimum speed and performance for encapsulation requirements. Dymax lamps offer the ideal balance of UV and visible light for the fastest, deepest cures. This product is in full compliance with RoHS2 directives 2015/863/EU and 2011/65/EU.

UNCURED PROPERTIES *

Property	Value	Test Method
Solvent Content	No Nonreactive Solvents	N/A
Chemical Class	Acrylated Urethane	N/A
Appearance	Translucent Gel	N/A
Soluble in	Organic Solvents	N/A
Density, g/ml	1.06	ASTM D1875
Viscosity, cP (20 rpm)	45,000 (nominal)	DSTM 502

CURED MECHANICAL PROPERTIES *

Property	Value	Test Method
Durometer Hardness	D35	ASTM D2240
Tensile at Break, MPa [psi]	5.8 [850]	ASTM D638
Elongation at Break, %	110	ASTM D638
Modulus of Elasticity, MPa [psi]	6.2 [900]	ASTM D638
Glass Transition T_g, °C	31	DSTM 256‡
CTE$_{\alpha 1}$, µm/m/°C	126	DSTM 610‡
CTE$_{\alpha 2}$, µm/m/°C	171	DSTM 610‡

OTHER CURED PROPERTIES *

Property	Value	Test Method
Refractive Index (20°C)	1.50	ASTM D542
Boiling Water Absorption, % (2 h)	2.0	ASTM D570
Water Absorption, % (25°C, 24 h)	0.9	ASTM D570
Linear Shrinkage, %	2.2	DSTM 614‡

ELECTRICAL PROPERTIES *

Property	Value	Test Method
Dielectric Constant (1 MHz)	4.31	ASTM D150
Dissipation Factor (1 MHz)	0.03	ASTM D150
Dielectric Breakdown Voltage, [V/mil]	900	ASTM D149
Volume Resistivity, ohm-cm	2.59E+10	ASTM D257
Surface Resistivity, ohm	9.44E+10	ASTM D257

ADHESION

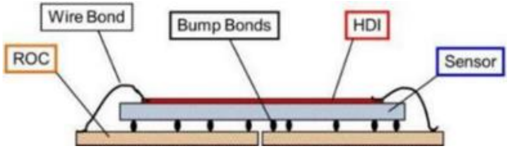
Substrate	Recommendation
Aluminum	o
FR4	✓
PCB Board	✓

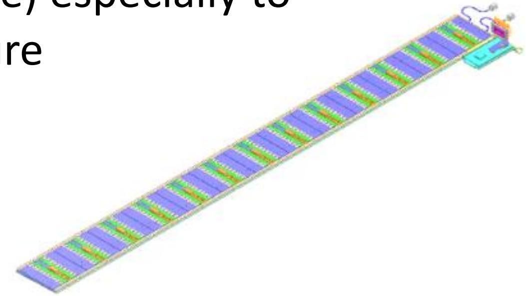
✓ Recommended o Limited Applications

st Requires Surface Treatment (e.g. plasma, corona treatment, etc.)

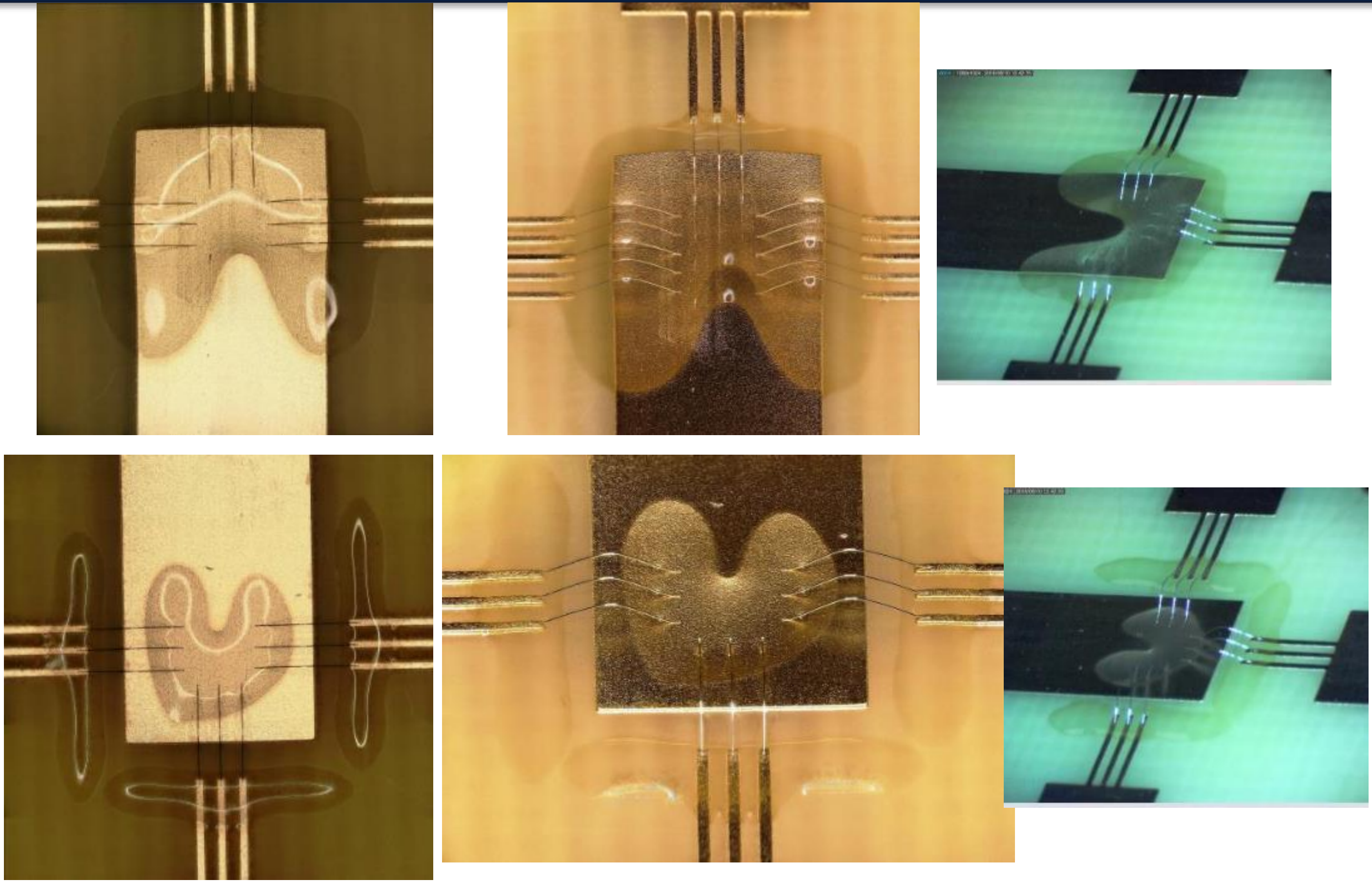
Encapsulation study for ATLAS ITk Upgrade

1) Initial evaluation of encapsulation materials: feasibility, reworkability, radiation, resonance and thermal cycle effects
   a) Two types of clear encapsulant: Thermoset (Dow Sylgard 186) and UV/Visible light-curable (Dymax 9100 series)
   b) Encapsulate wire bond feet vs. entire wires
2) Evaluation of suitable encapsulants on representative assemblies (i.e. strip hybrid, module, EOS, 'mini' stave, pixel module) especially to robustify single points of failure





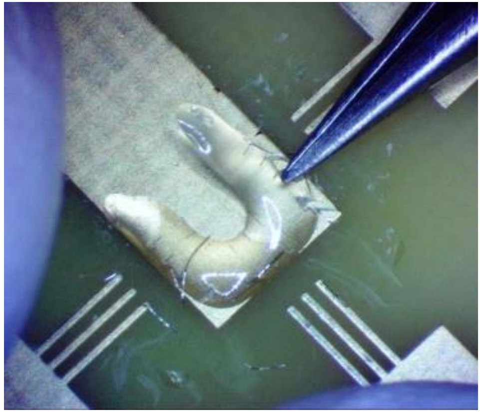
Wirebonds-on-sample-PCBs
with entire wires potted (upper pictures) or just the feet potted



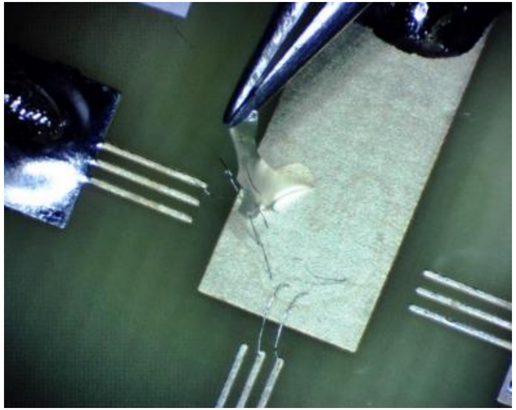
Rework

- Both Sylgard and Dymax result in a encapsulant which can be removed leaving no residue
- After air dusting, parts are rebondable

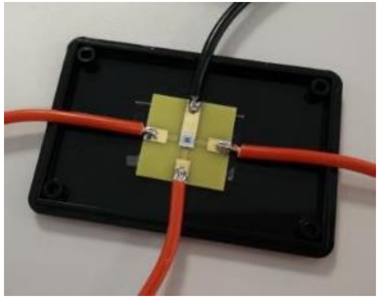
Dymax 9101 UV cured beads removed by applying a shear and lifting force with tweezers



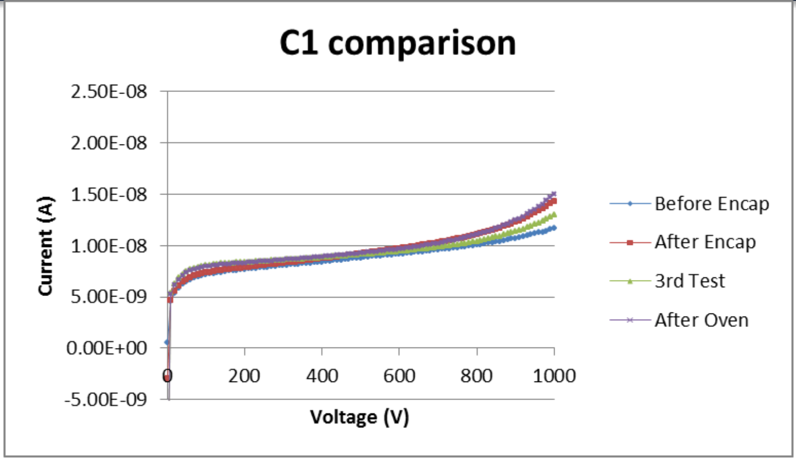
Sylgard 186 beads removed by lifting/peeling with tweezers

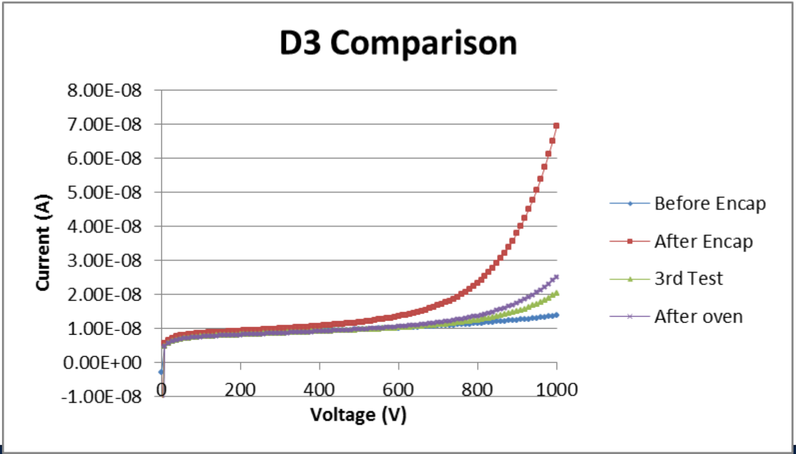


Pad Si diode I-V characteristics after Sylgard 186 encapsulation

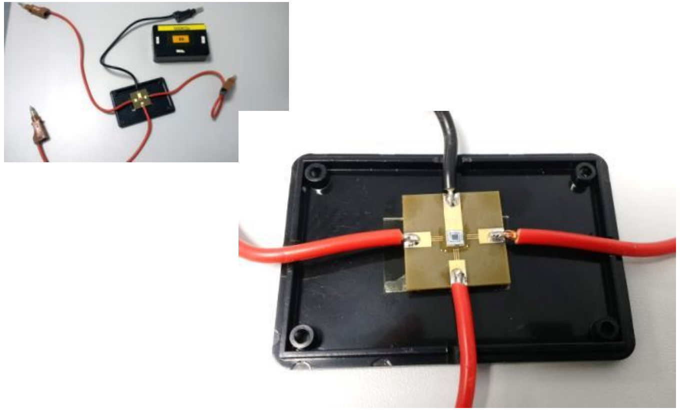


- Pad Si diodes (from ATLAS07 sensor wafers) glued with silver epoxy to PCBs and wirebonded
- Small change in I_{leak} directly after encapsulation with Sylgard 186
- No change in I_{leak} after curing
- Cure for 1 week at room temperature or oven cure for 0.5 hour at 60C is equally effective

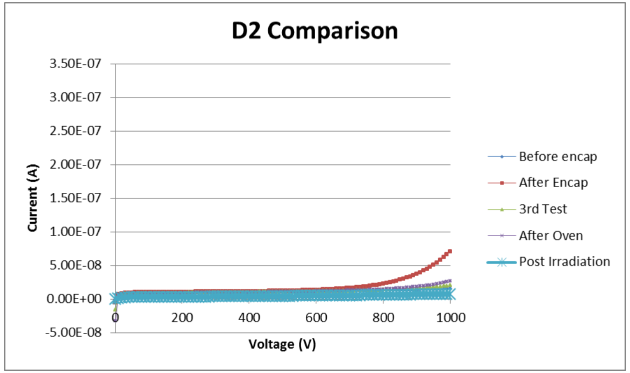




I-V characteristics after irradiation

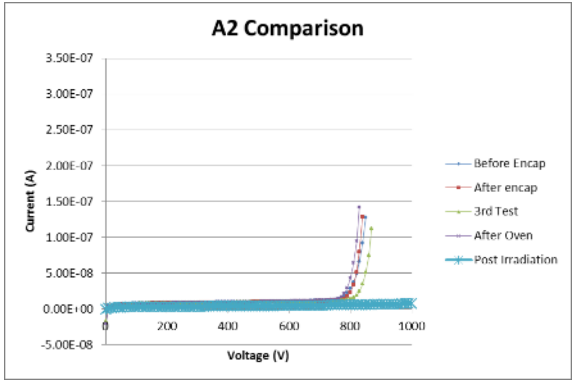


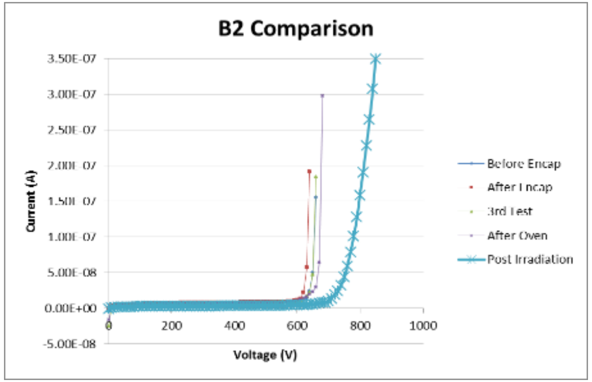
- 8 samples back from 500 kGy (Si) gamma irradiation
  - 2x Si diode w/potted feet
  - 2x Si diode w/ potted entire wires
  - 2x PCB w/ potted feet
  - 2x PCB w/ potted entire wires
- Appearance and compliance of Sylgard 186 encapsulant unchanged
- I-V measured on the Si diode samples → no adverse effect

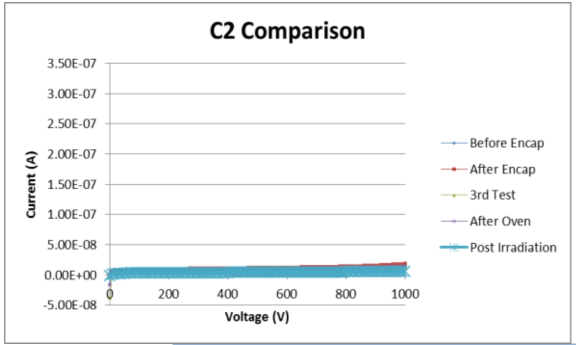


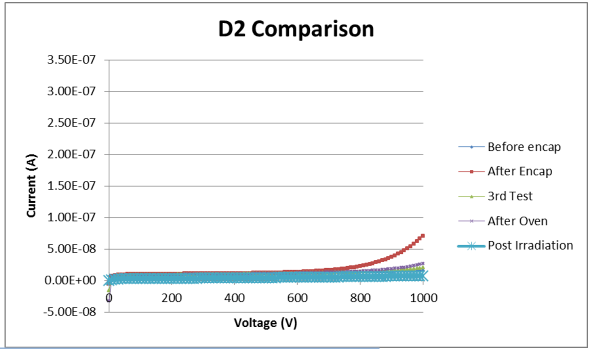
I-V characteristics after irradiation

Samples A and B - Si diode wirebonds **w/potted feet**









Samples C and D - Si diode wirebonds **w/potted entire wires**

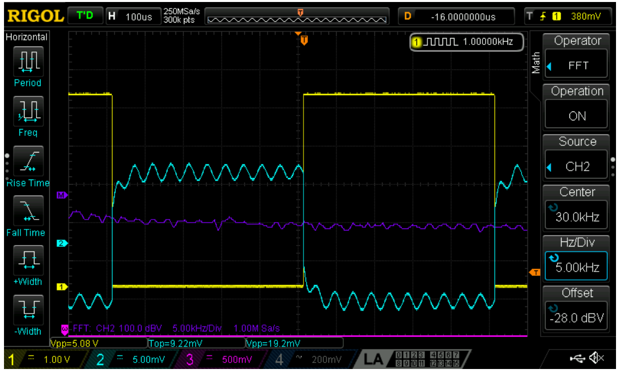
wire bond resonance study

- 20A electromagnet, 1T B-field measured with a Hall probe
- Un-potted (2.1mm length) wire bonds
  - Amplitude sine wave through each of 3 wires: 115 mA
  - Scan 10-25 kHz in 0.1 kHz steps
  - Resonance seen and finer scan done around resonance
  - Peak resonance @ 21.65 kHz
- Sylgard 186 potted feet wire bonds
  - Amplitude sine wave set to 150 mA
  - Scanned from 10 to 50 KHz in 0.1 kHz steps
  - No resonances seen

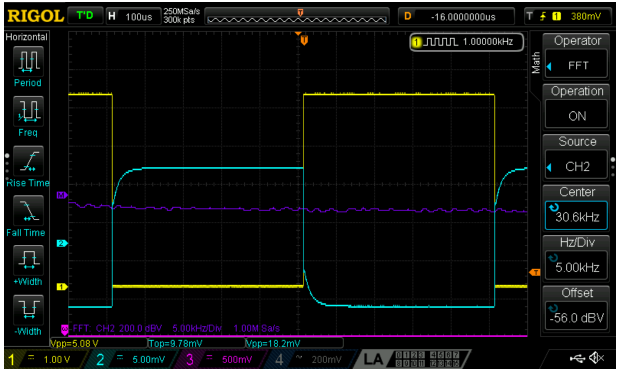
wire bond resonance study

Wire bonds pulsed with 1 kHz square wave and amplitude corresponding to ~150 mA, measured back-EMF

Not potted wire bonds, B field on, wire resonates at ~20 kHz


RIGOL T'D H 100us 250MSa/s 300k pts D -16.0000000us T 1 380mV
1.00000kHz
Operator FFT
Operation ON
Source CH2
Center 30.0kHz
Hz/Div 5.00kHz
Offset -28.0 dBV
FFT: CH2 100.0 dBV 5.00kHz/Div 1.00M Sa/s
Vpp=5.08 V Top=9.22mV Vpp=19.2mV
1 = 1.00 V 2 = 5.00mV 3 = 500mV 4 ~ 200mV

Potted wire bonds, B field on, wire resonance effectively dampened

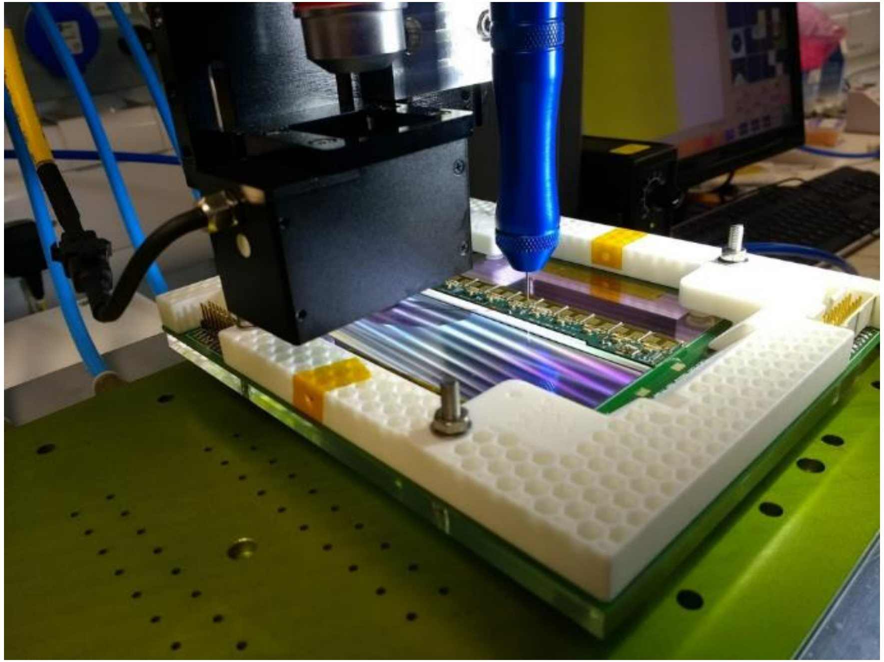

RIGOL T'D H 100us 250MSa/s 300k pts D -16.0000000us T 1 380mV
1.00000kHz
Operator FFT
Operation ON
Source CH2
Center 30.6kHz
Hz/Div 5.00kHz
Offset -56.0 dBV
FFT: CH2 200.0 dBV 5.00kHz/Div 1.00M Sa/s
Vpp=5.08 V Top=9.78mV Vpp=18.2mV
1 = 1.00 V 2 = 5.00mV 3 = 500mV 4 ~ 200mV

Thermal cycling

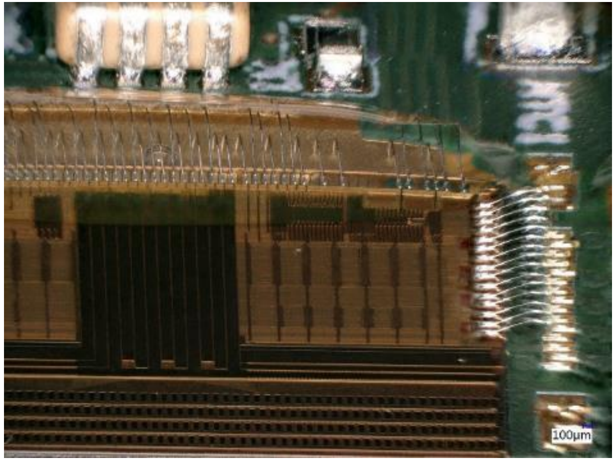
- Initial thermal cycles (RT to -40C) showed no connectivity problem on unirradiated and irradiated PCB samples. Also, wet/dry cycles showed no sign of corrosion.
- In Dec. 2017, we put into operation a MPI Thermal Air TA-5000A system (see http://www.mpi-thermal.com/products/thermal-air-5000/) allowing rapid thermal cycles.
- For unirradiated Dymax 9001v3.7, Dymax 9103 and Sylgard 186, we thermally cycled a sample PCB with potted feet and a sample PCB with potted whole wires
- 10 cycles between -55C and +50C.
- 1 of 3 wirebonds broke at the heel that were fully potted with the Dymax 9001 or 9103
- PCB samples with Dymax 9001 or 9103 potted feet, and the PCB samples with Sylgard potted feet or whole wires, did not break

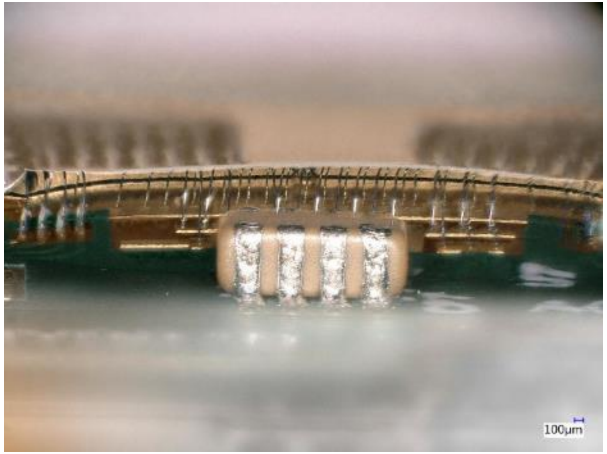
Electric grade strip module hybrid (assembled on mechanical sensor) Step by step process

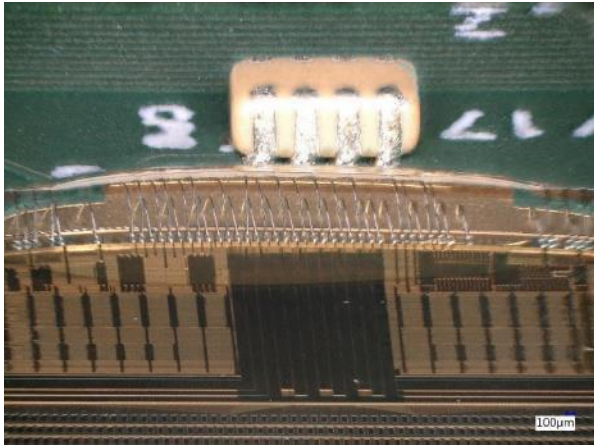
1. Electric test
2. Thermal test
3. Electric test
4. Encapsulation
5. Electric test
6. Thermal test
7. Electric test



Encapsulant beads on Electrical grade strip module hybrid



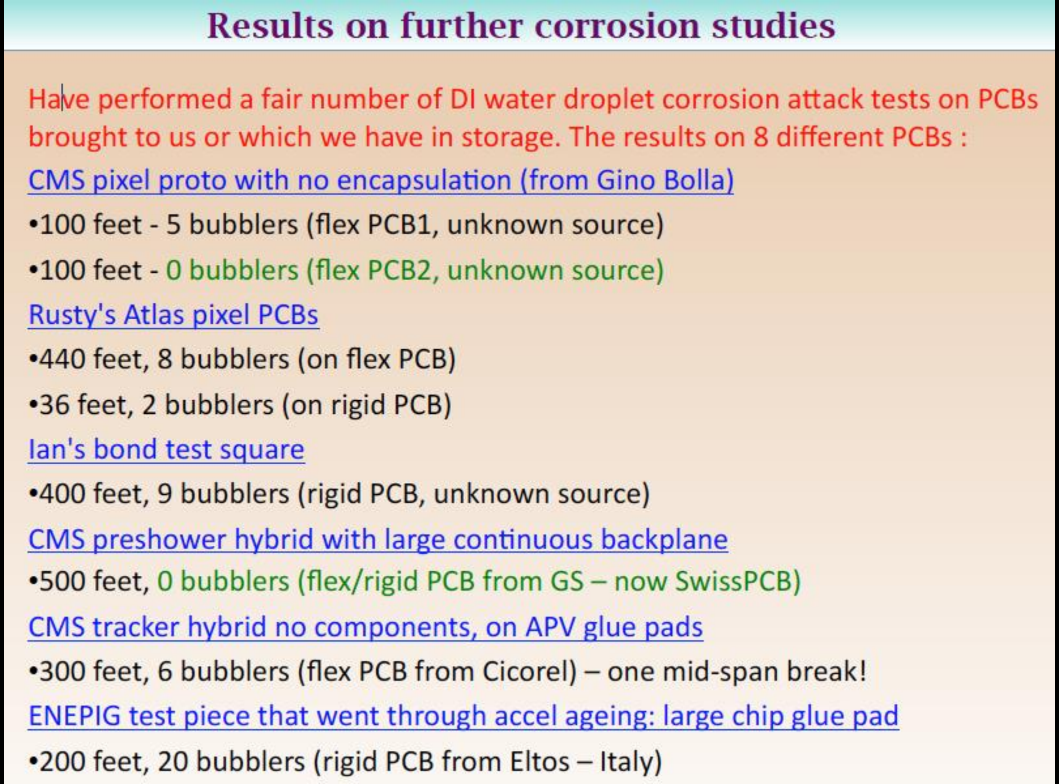




Corrosion Studies

A. Honma

https://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=283860, November 2013.



Results on further corrosion studies

Have performed a fair number of DI water droplet corrosion attack tests on PCBs brought to us or which we have in storage. The results on 8 different PCBs :

CMS pixel proto with no encapsulation (from Gino Bolla)

- 100 feet - 5 bubblers (flex PCB1, unknown source)
- 100 feet - 0 bubblers (flex PCB2, unknown source)

Rusty's Atlas pixel PCBs

- 440 feet, 8 bubblers (on flex PCB)
- 36 feet, 2 bubblers (on rigid PCB)

Ian's bond test square

- 400 feet, 9 bubblers (rigid PCB, unknown source)

CMS preshower hybrid with large continuous backplane

- 500 feet, 0 bubblers (flex/rigid PCB from GS – now SwissPCB)

CMS tracker hybrid no components, on APV glue pads

- 300 feet, 6 bubblers (flex PCB from Cicorel) – one mid-span break!

ENEPIG test piece that went through accel ageing: large chip glue pad

- 200 feet, 20 bubblers (rigid PCB from Eltos – Italy)

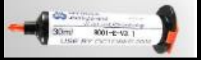
- “Seems most PCBs have the DI water droplet corrosion problem.”

Candidate Encapsulant Polymers

- “PolyUrethane” = Alkyd + some PU resin for toughness.
- Alkyd = fatty acid-modified polyester + other additives
  - Alkyd properties vary with fatty acid length, amount of crosslinking

- PolyUrethane: Cellpack D2091 liquid
  - Formulated for electrical insulation. (Composition proprietary)
  - Tested for: Radiation, CTE, Resonance suppression, spraying, encapsulation
- Long oil alkyds: marine spar varnishes (Epifanes, McCloskey 7509)
  - Formulated for flexibility. (Composition proprietary)
  - Spraying tests underway

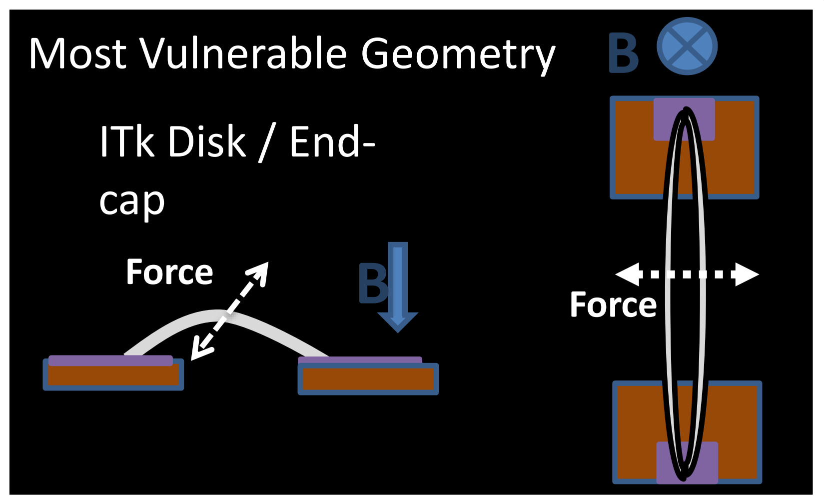
- UV-cured epoxy: Dymax® 9001, 9103:
  - CTE issues. Short span potting possible as for ATLAS Pixel disks



- Sylgard® 186 silicone elastomer: used by CDF, CMS
  - Silicone elastomer rad. hardness problematic. OK for ITk Strips

- Parylene conformal coating
  - Thin coating. Rad hardness needs testing, unlikely to suppress all oscillations?

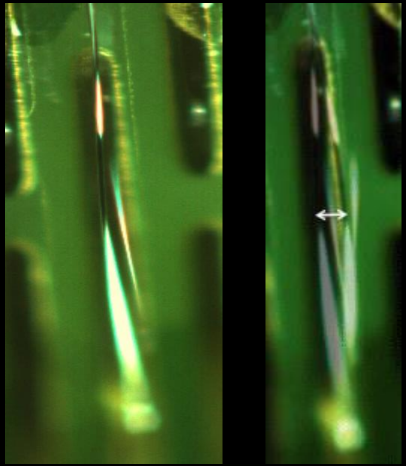
Periodic Lorentz Forces

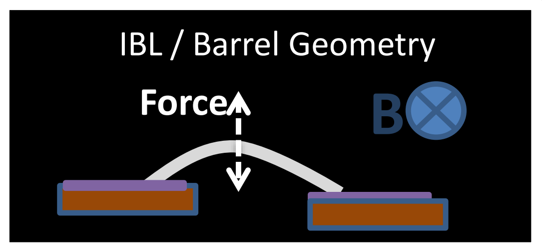


Most Vulnerable Geometry

ITk Disk / End-cap

“Guitar” Mode





IBL / Barrel Geometry

Barrel “Up and Down” mode hard to excite
Couples to “Guitar Mode”!
→ Barrel wire bonds not automatically safe

IBL (like SCT) is protected by firmware.