WIREBONDING BONDING

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OUTLINE

- What is wire bonding?
- Types of wire bonder
- Examples of detector
- Galvanic corrosion
- Resonant vibrations
- Mechanical vibrations
- Other considerations

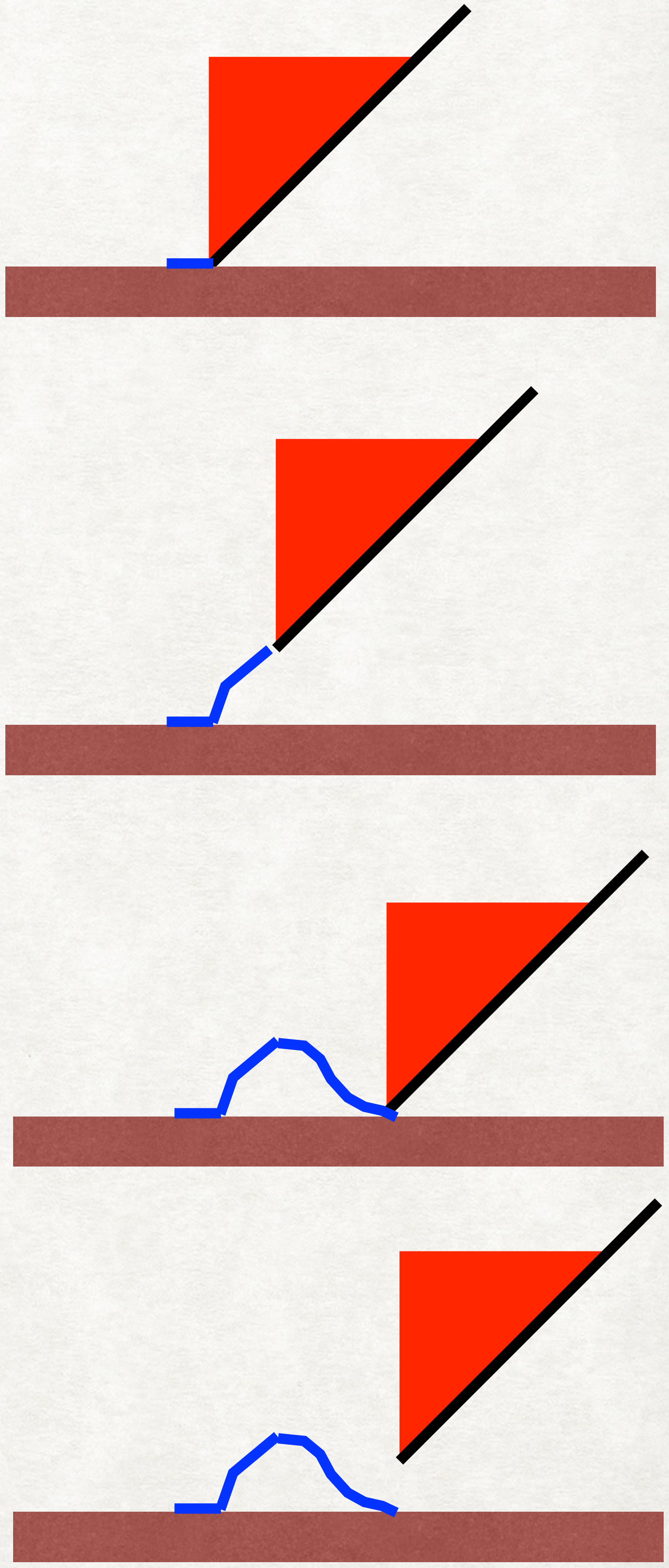
WHAT IS WIRE BONDING?

- A means to connect a sensor (in industry - some component) to part of a circuit to read out the device.
    - More than 90% of IC chips use wire bonds.

Z. W. Zhong and K. S. Goh, Microelectronics J. 37 (2006) 107-113

- Different materials are used for this:
    - Au: Normally use a heated chuck, but one can bond Au-Au without this on some machines.
    - Ag: Can be used; galvanic corrosion leads to catastrophic failure at end of life.
    - Cu: Becoming more common place in industry given the price of gold.
    - Al: Typical material used in particle and nuclear physics applications as Al does not activate (as much as other materials), and does not require a heated chuck.

WHAT IS WIRE BONDING?



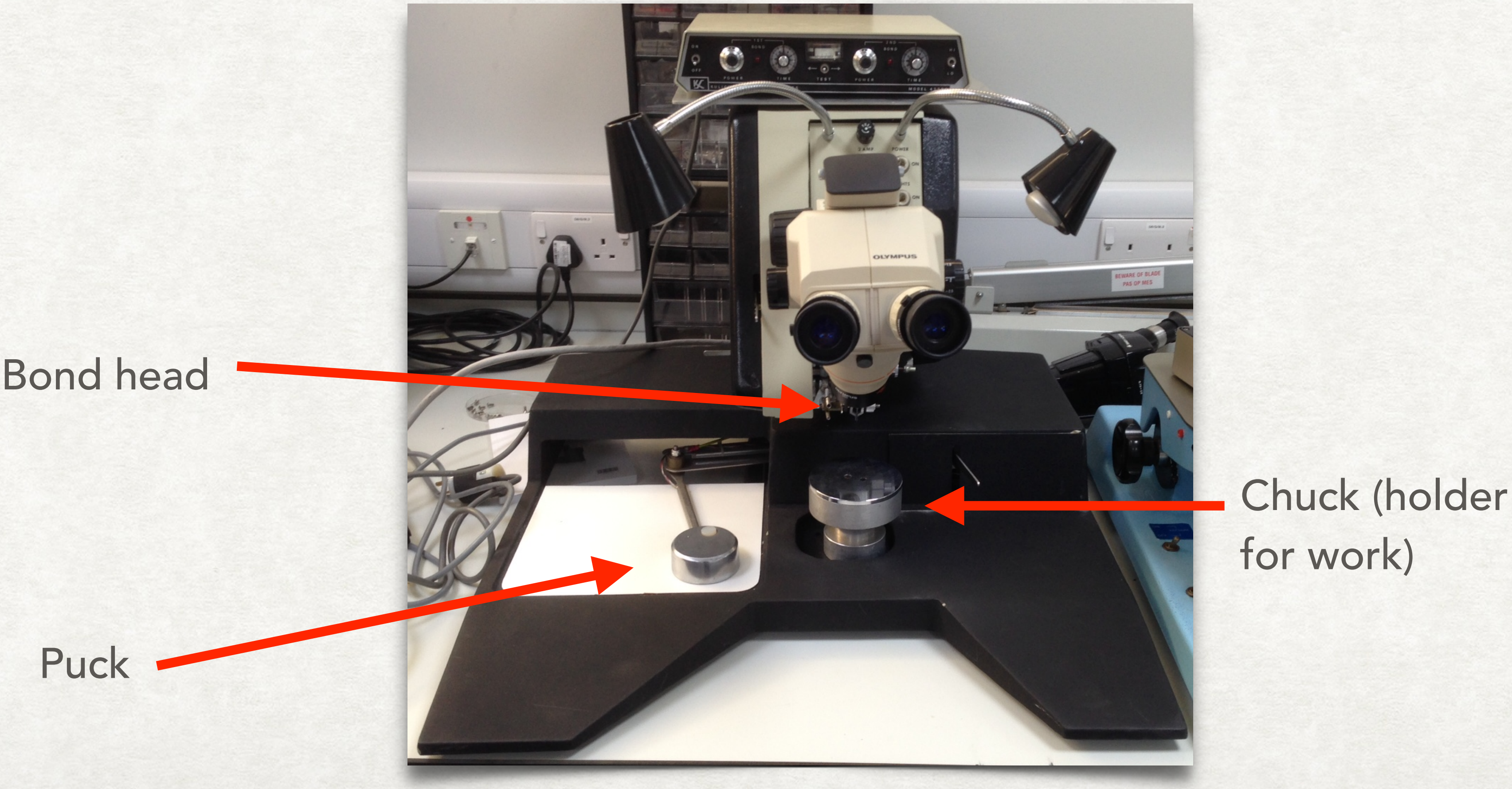
- 1) Start with the first bond of wire to the sample
- 2) make the loop by moving bond head, paying out wire
- 3) Make the second bond, closing the loop.
- 4) Tear wire/close clamps to complete the bond loop.

  Clamp tears can be performed for thin wire (e.g. the wire used in a particle physics experiment ~20um).

- N.B. same procedure for ribbon bonds.

TYPES OF BONDER

- Manual bonder:
    - Positioning the sample to be bonded to under the bond head, making the bond, making the loop of wire (shape is important) and making the final connection, before ripping off the wire is all done by hand.
    - Requires skill that has to be developed over time.
    - Poor quality bonds are common with unskilled users.



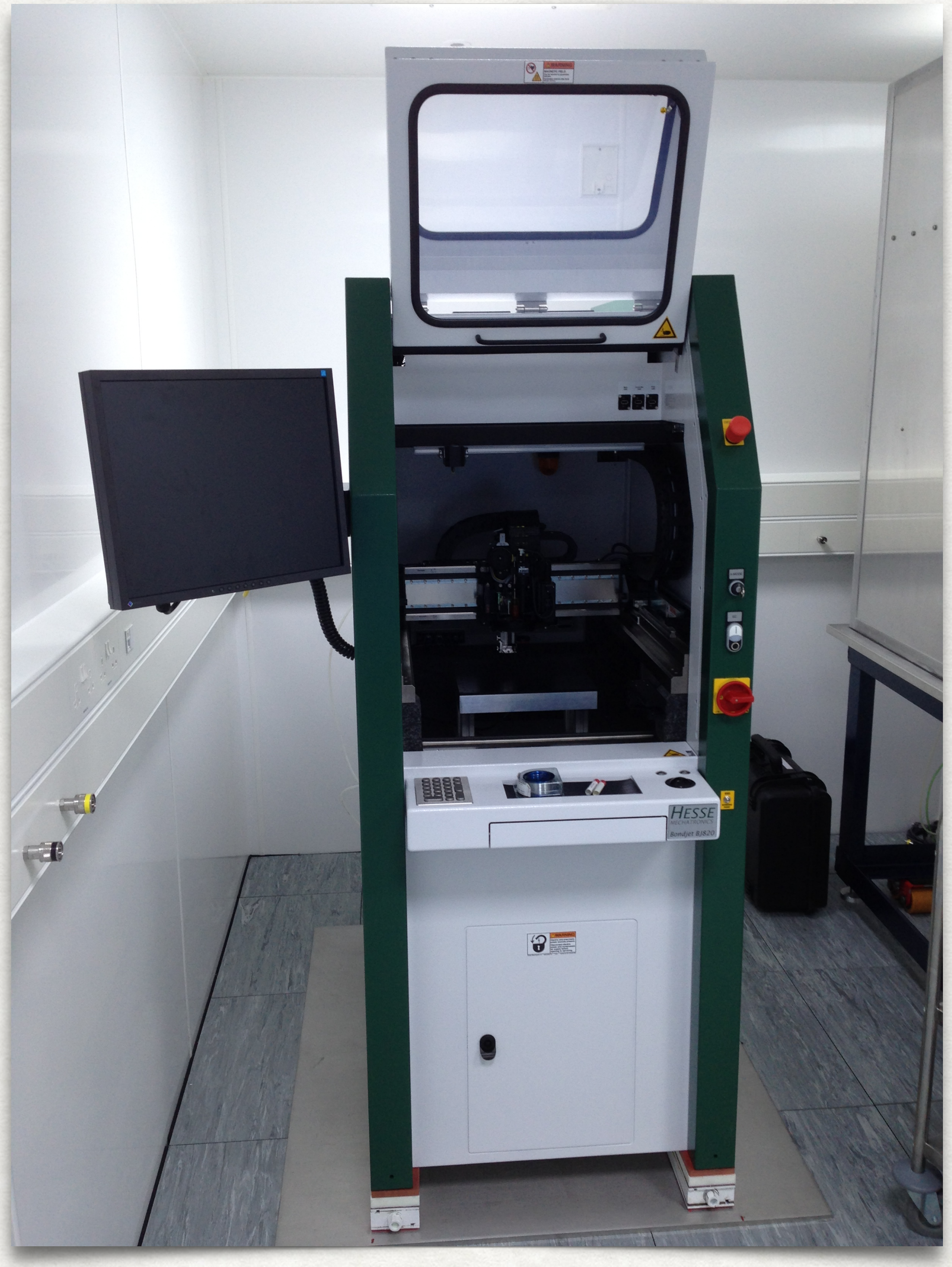
This manual bonder was used at QMUL for testing sensors for the ATLAS Semiconductor Tracker, and for a number of R&D programmes.

TYPES OF BONDER

- Semi-automatic wire bonder:
  - Can be used in a fully manual mode.
  - Can have some features programmed into it:
    - e.g. loop shape, power dissipation settings and motion
    - Depends on make/model as to how “automatic” the bond process is.
    - Does require the user to identify the first point of contact with the device.
  - Significant benefit over manual bonder, with a cost that reflects the additional functionality.

TYPES OF BONDER

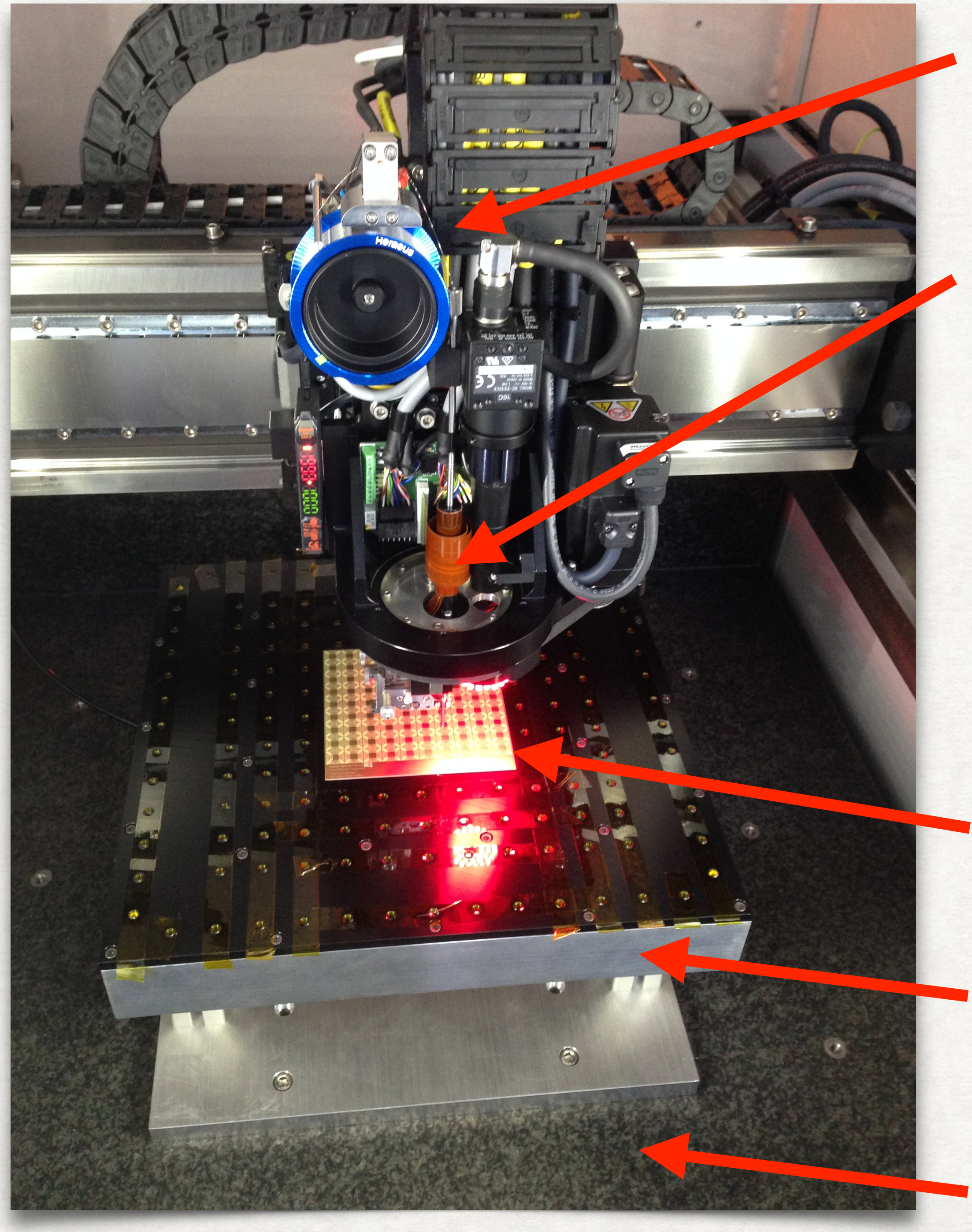
- Automatic wire bonder
  - Can be used as a manual or semi-automatic device.
  - Built in intelligence to be able to locate fiducial marks on a piece of work to be bonded and use that to match up with steps in a programme.
  - Reduces the amount of work that needs to be done by an operator to placing and aligning the piece, once a program has been written.
  - Can make several bonds per second.



This bonder (Hesse Bondjet BJ820) is used for the ATLAS ITk upgrade at QMUL, and with R&D programmes.

TYPES OF BONDER

- The bonder has a work surface and a bond head; the head on the BJ820 moves to the work.



Wire spool: The wire rides on a cushion of air and auto feeds as bonds are produced.

Bond Head: responsible for ensuring appropriate movement of wire to work, and power settings to ensure that an initial bond is made, wire is paid out to make a loop, and a second bond is made.

Finally the wire is broken. For thin wire (e.g. 25um) xy movement relative to the stage is used to tear the wire and complete the bond.

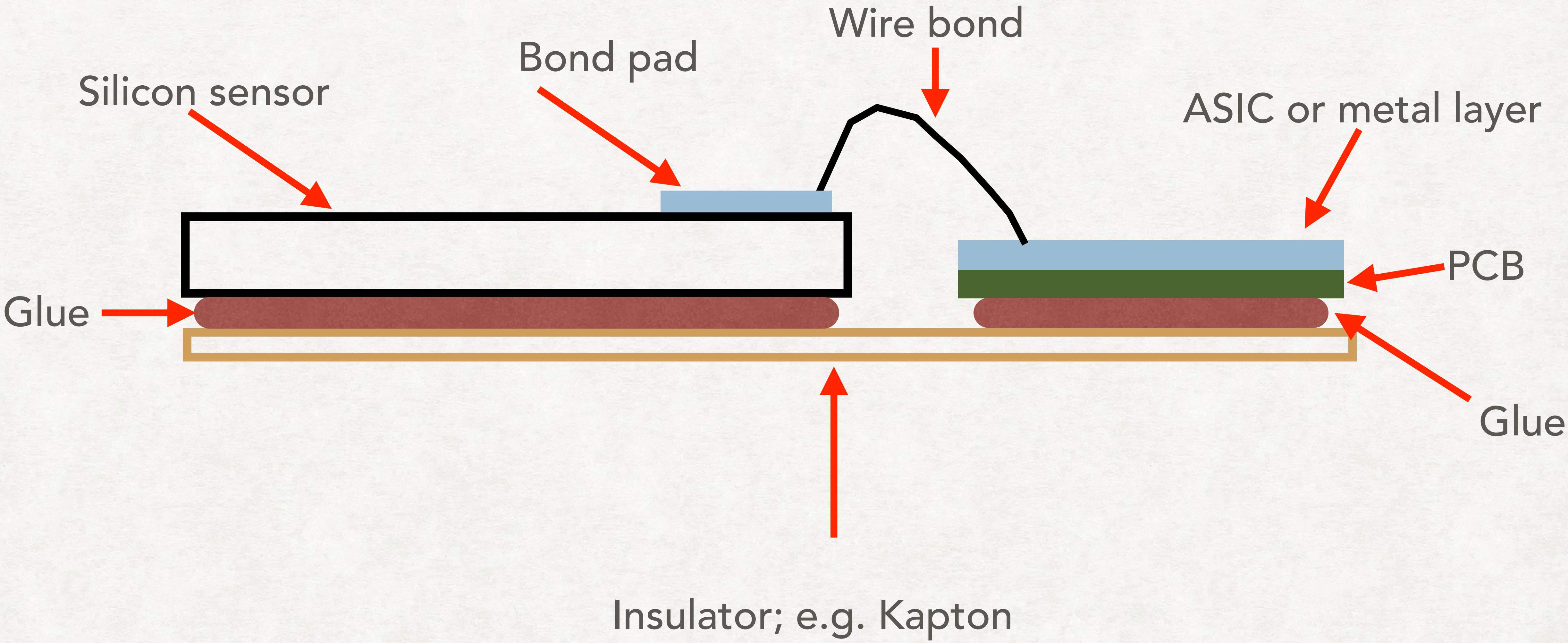
Work: in this case a test piece used for wire bonder testing and training.

Vacuum plate: for holding work down to ensure it is stationary.

Granite table: for stability.

EXAMPLES OF DETECTOR

- Wire bond out from a sensor to a circuit board or ASIC used for processing and signal readout.



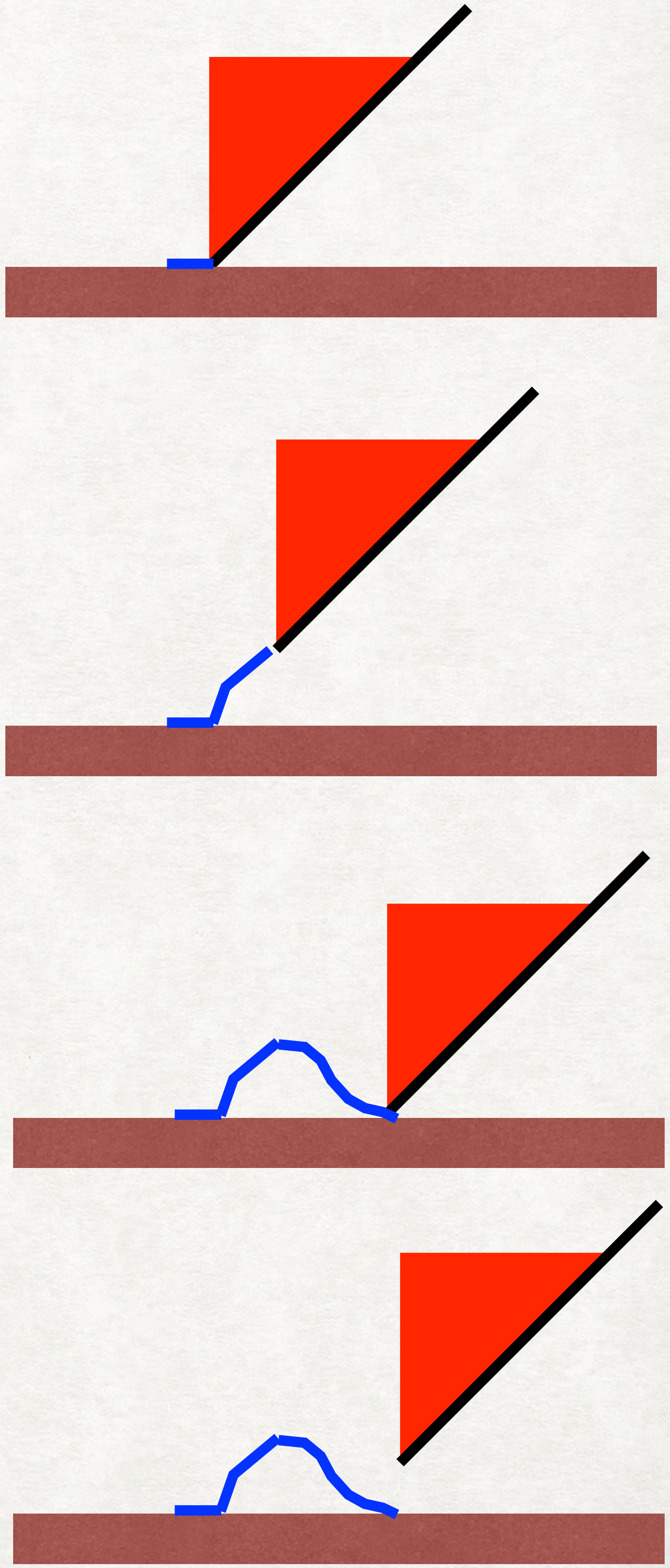
- The method requires the regions where contact is made between the wire and the circuit or sensor to be supported so that some minimal pressure can be applied at the same time as ultrasonic pulse melts the wire onto the bond pad.

CONSIDERATIONS FOR BONDING

- To make a bond you need to consider the following aspects*
  - Touchdown
    - How the bond head approaches the work for the initial and second bond.
  - Bonding
  - Loop
    - The bond head motion required to construct a loop.
  - Welding
    - How power is applied to weld the wire to the bond pad.
  - Tear Off
    - How the wire is broken after the second bond, to complete the process.

*These aspects are relative to the settings of the BJ820, however the process of wire bonding requires that any bonder (manual or automatic) will have the same configuration "settings". Manual bonders may require the skill of the user to achieve these.

WHAT IS WIRE BONDING?



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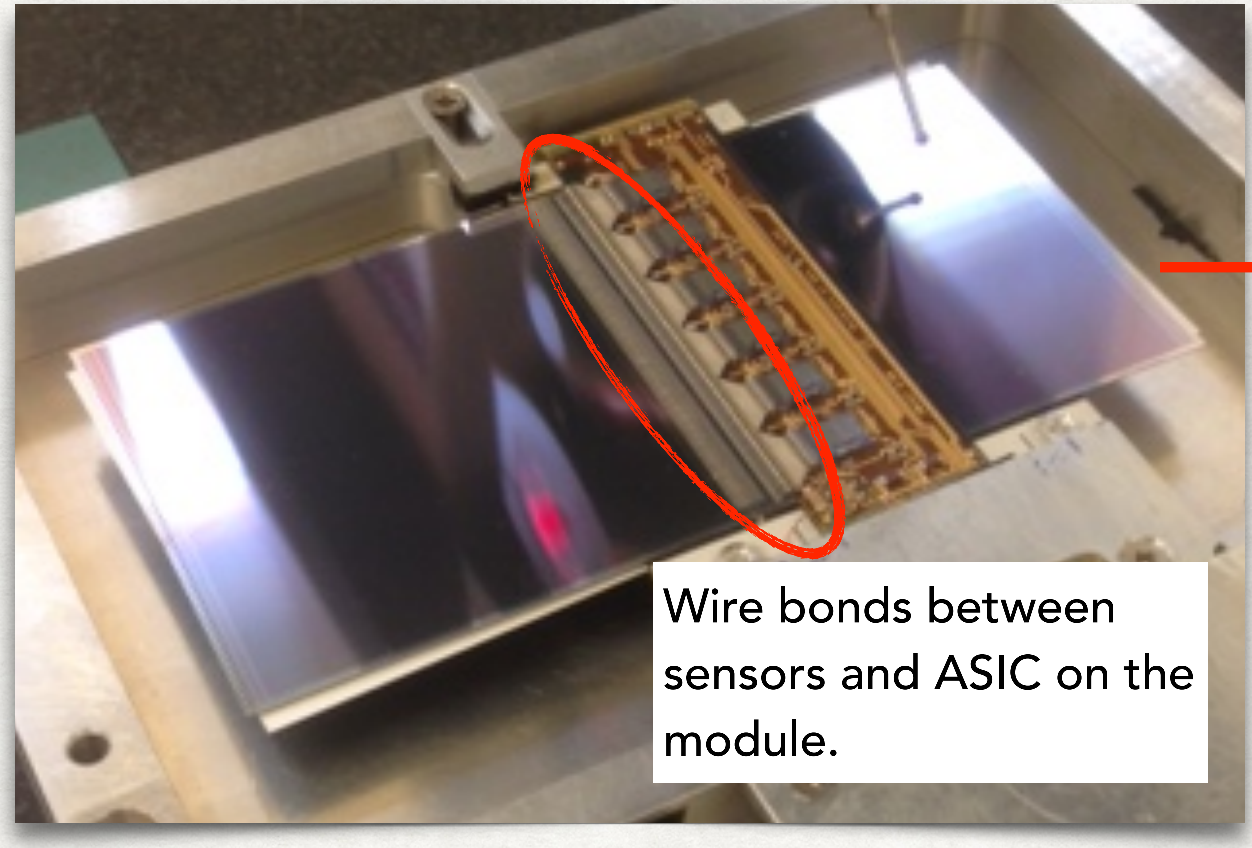
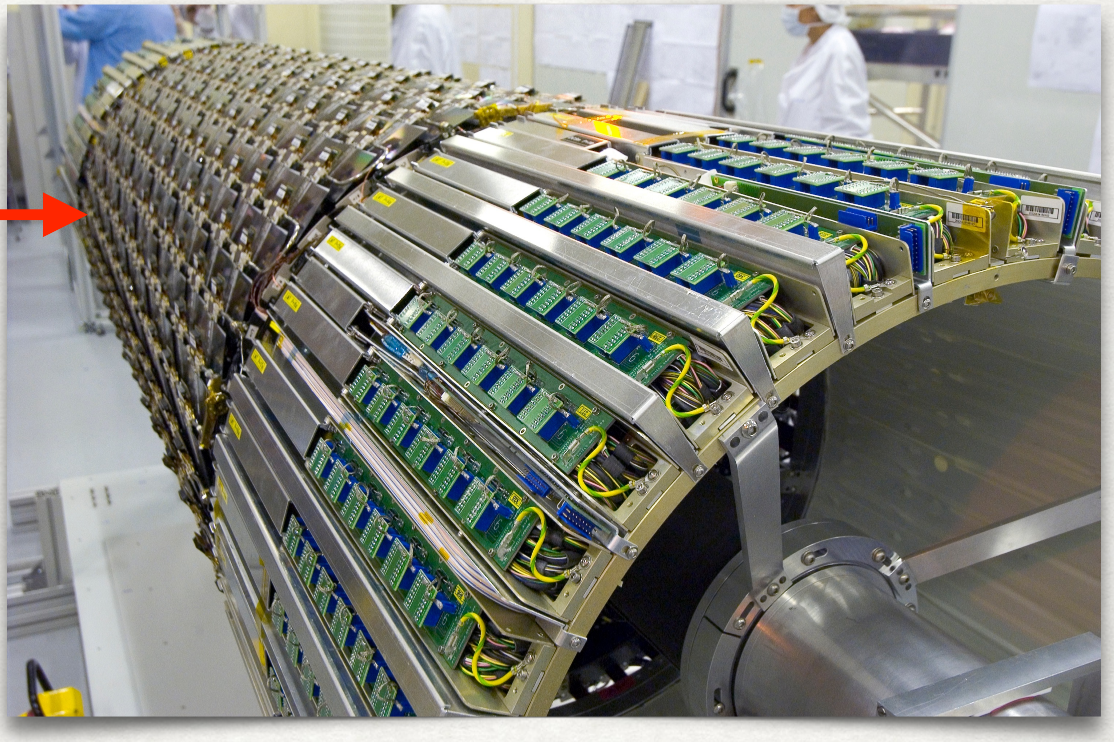
- N.B. same procedure for ribbon bonds.

EXAMPLES OF DETECTOR: ATLAS (SCT)

- Silicon microstrip tracking detector constructed using a module approach: 4 sensors per module.



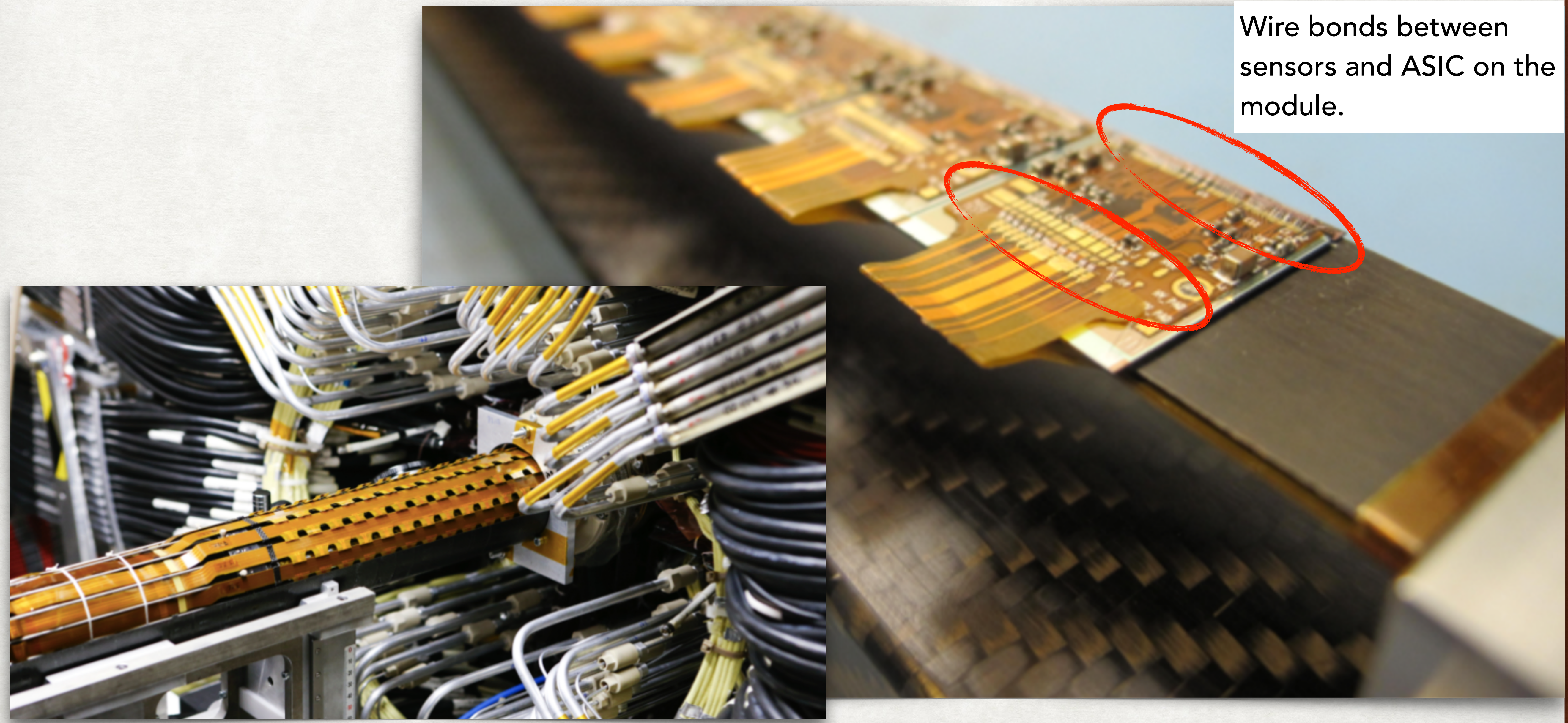
Wire bonds between sensors and ASIC on the module.



Nuclear Instruments and Methods in Physics Research A 568 (2006) 642–671
Nuclear Instruments and Methods in Physics Research A 578 (2007) 98–118

EXAMPLES OF DETECTOR: ATLAS (IBL)

- Inner most silicon detector layer on ATLAS.
  - Pixel detector, 3.3cm from the beam axis.
  - 3D CMOS technology.

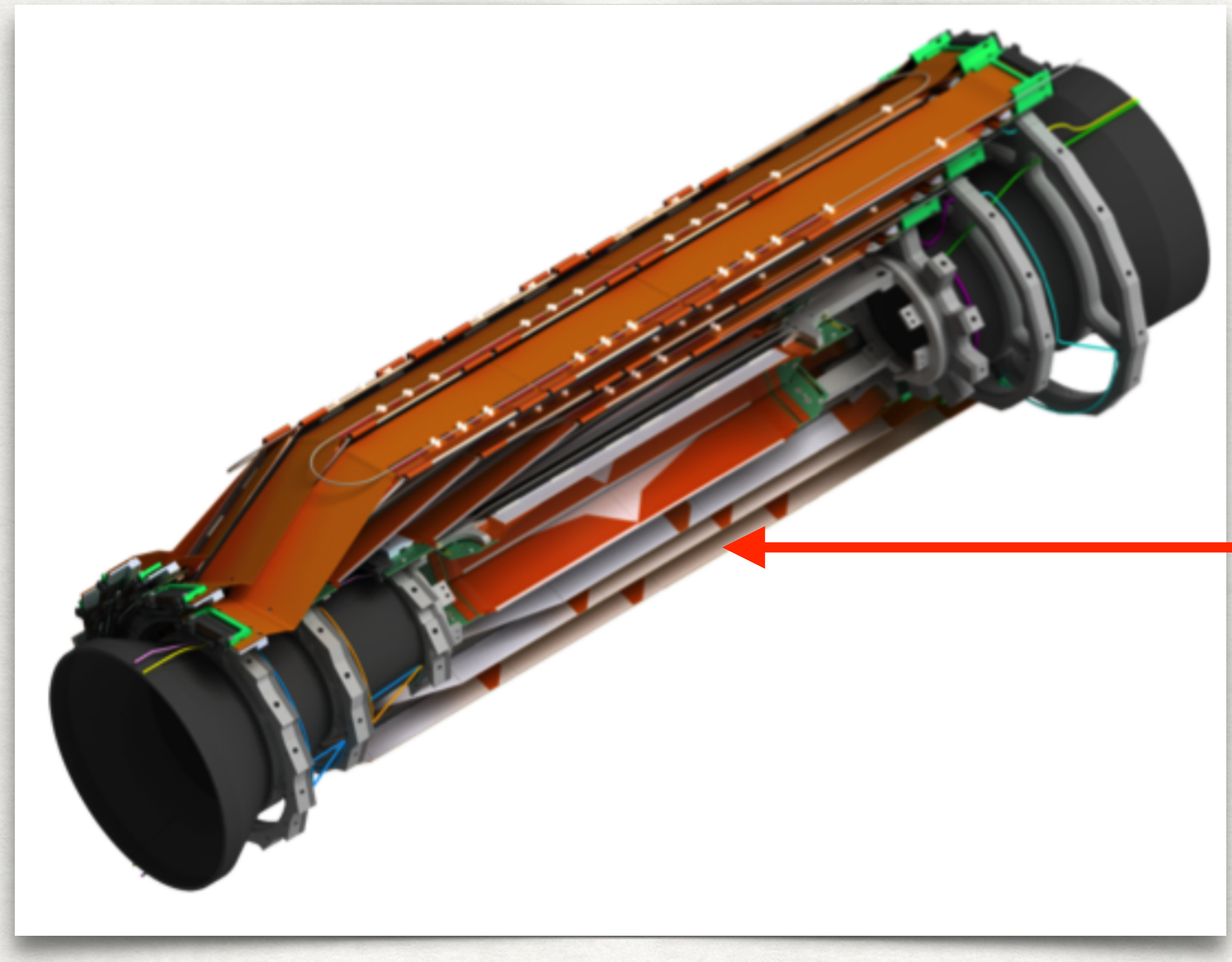


Wire bonds between sensors and ASIC on the module.

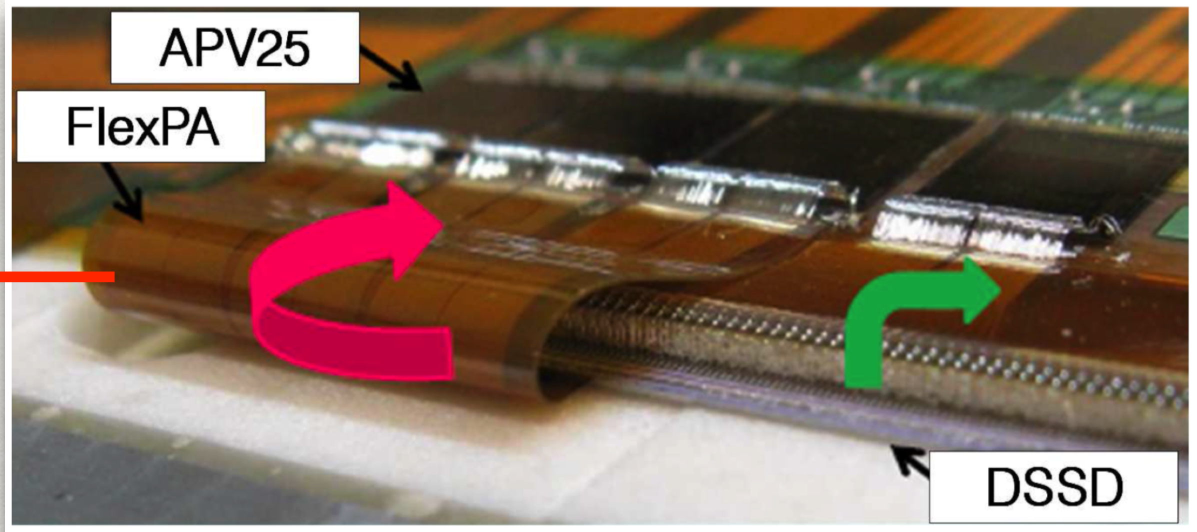
JINST (2016) 11 C12036; arXiv:1610.01994

EXAMPLES OF DETECTOR: BELLE II

- B Factory at the KEK Laboratory, Tsukuba, Japan



APV25 is the ASIC used to process signals from the double sided silicon detector (DSSD).



This photo is for one of the strip detector modules from this detector.

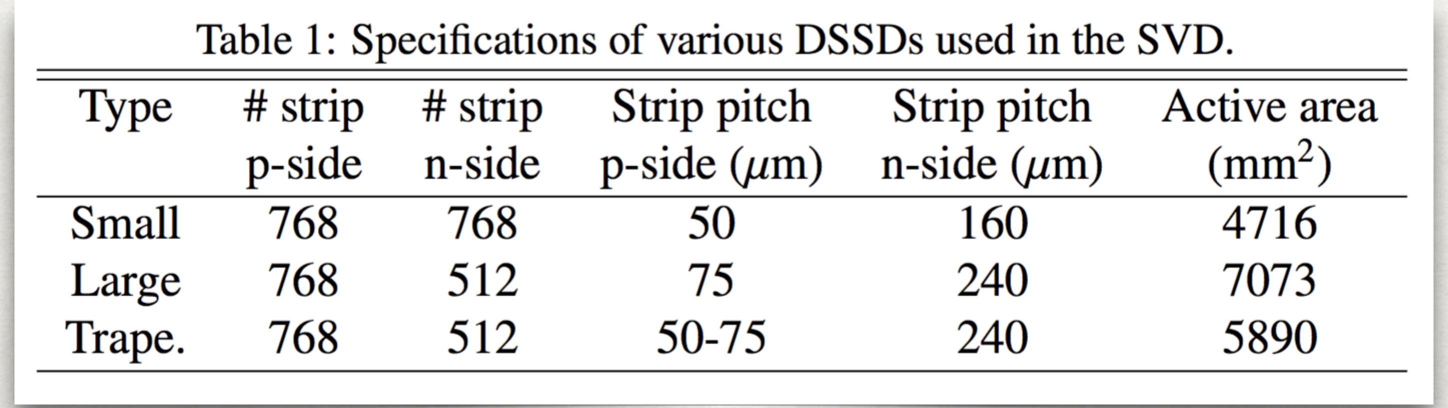


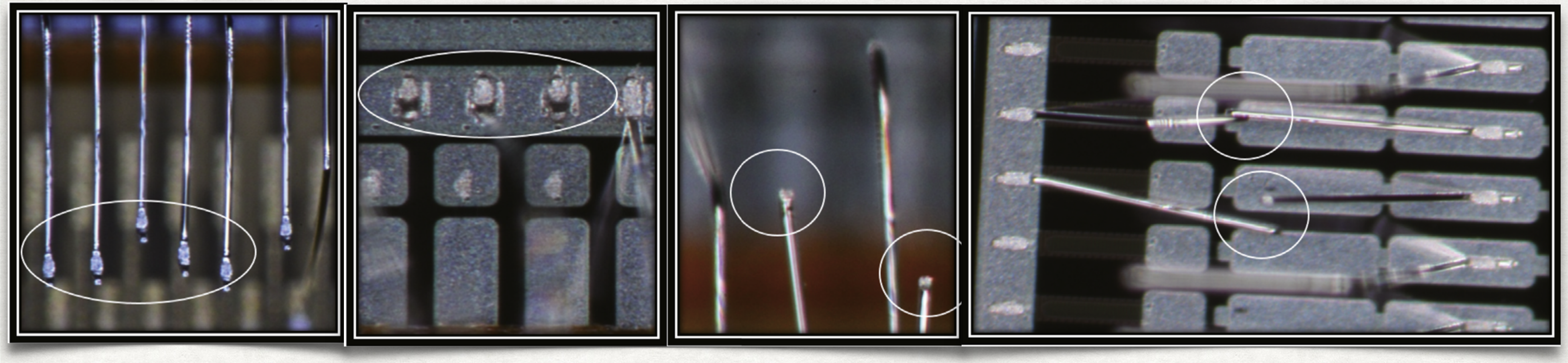
Table 1: Specifications of various DSSDs used in the SVD.

Type	# strip p-side	# strip n-side	Strip pitch p-side (μm)	Strip pitch n-side (μm)	Active area (mm^2)
Small	768	768	50	160	4716
Large	768	512	75	240	7073
Trape.	768	512	50-75	240	5890

arXiv:1511.06197

EXAMPLES OF DETECTOR: BELLE II

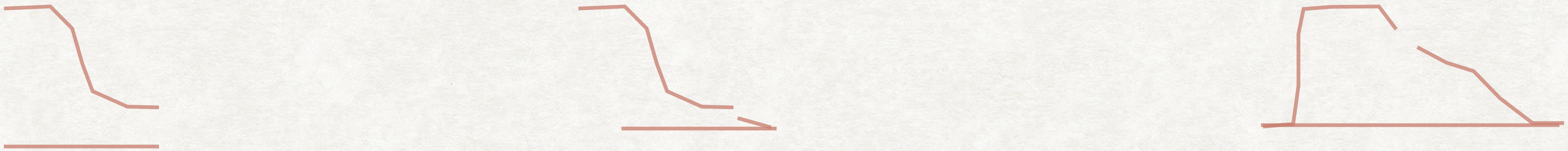
- Bond failure examples:
  - Depth of field is limited when looking at features of this size (wires of ~15-25μm diameter).



Bond lift

Bond heel break

Mid-span break



GALVANIC CORROSION

- Also called bimetallic corrosion.
  - The same electrochemical process used in batteries.

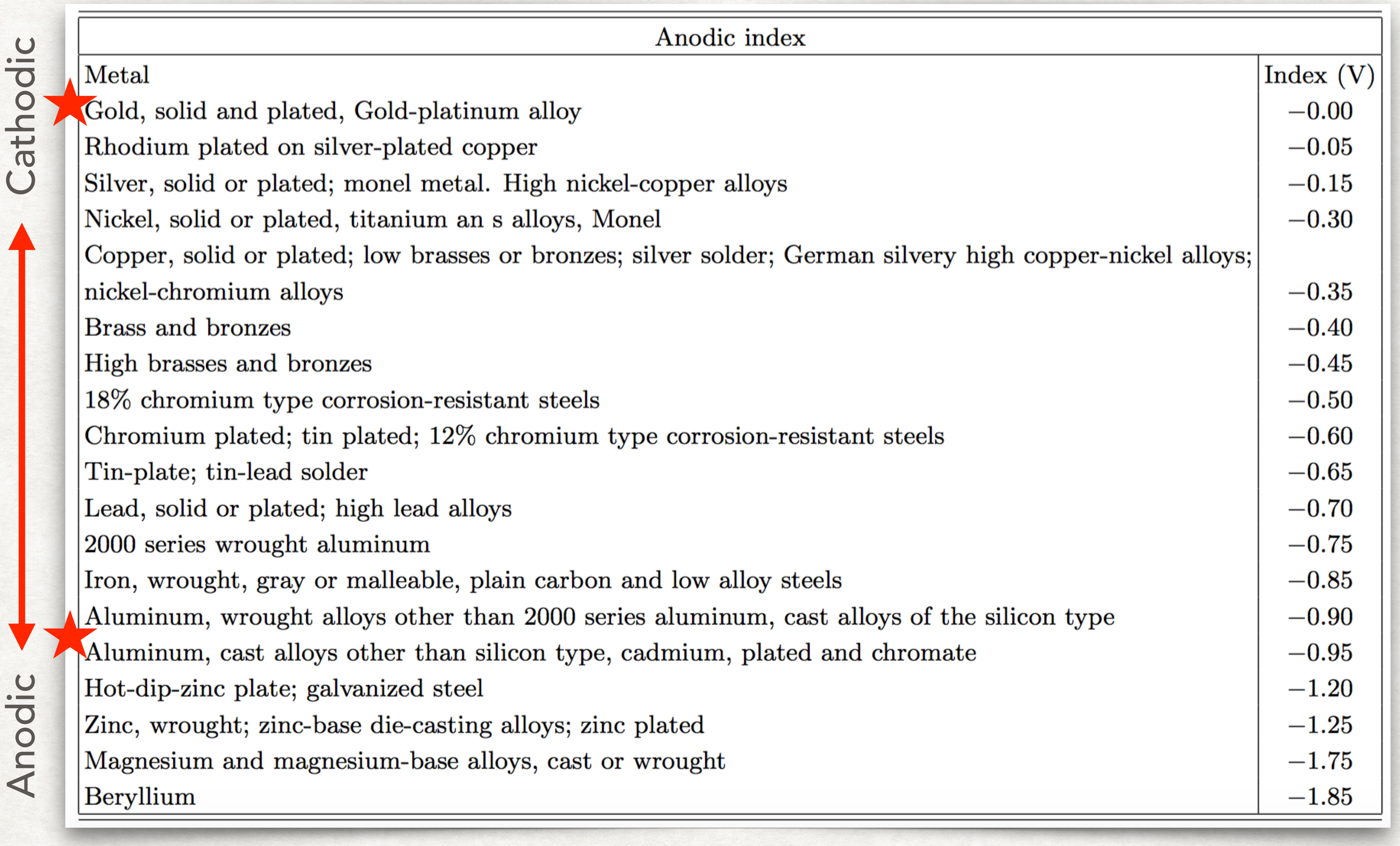
- Halides are used in fabrication of electronic components and combined with humidity, can lead to corrosion.

- One metal acts as an anode, the other as a cathode.

- The potential difference between different metals can lead to corrosion that results in;
  - Physical bond failure
  - Electrical conduction failure (resistive layer forms)
- as the anode dissolves into the electrolyte and collects on the cathode.

- This is an important issue as it can lead to device failure.

GALVANIC CORROSION



Cathodic

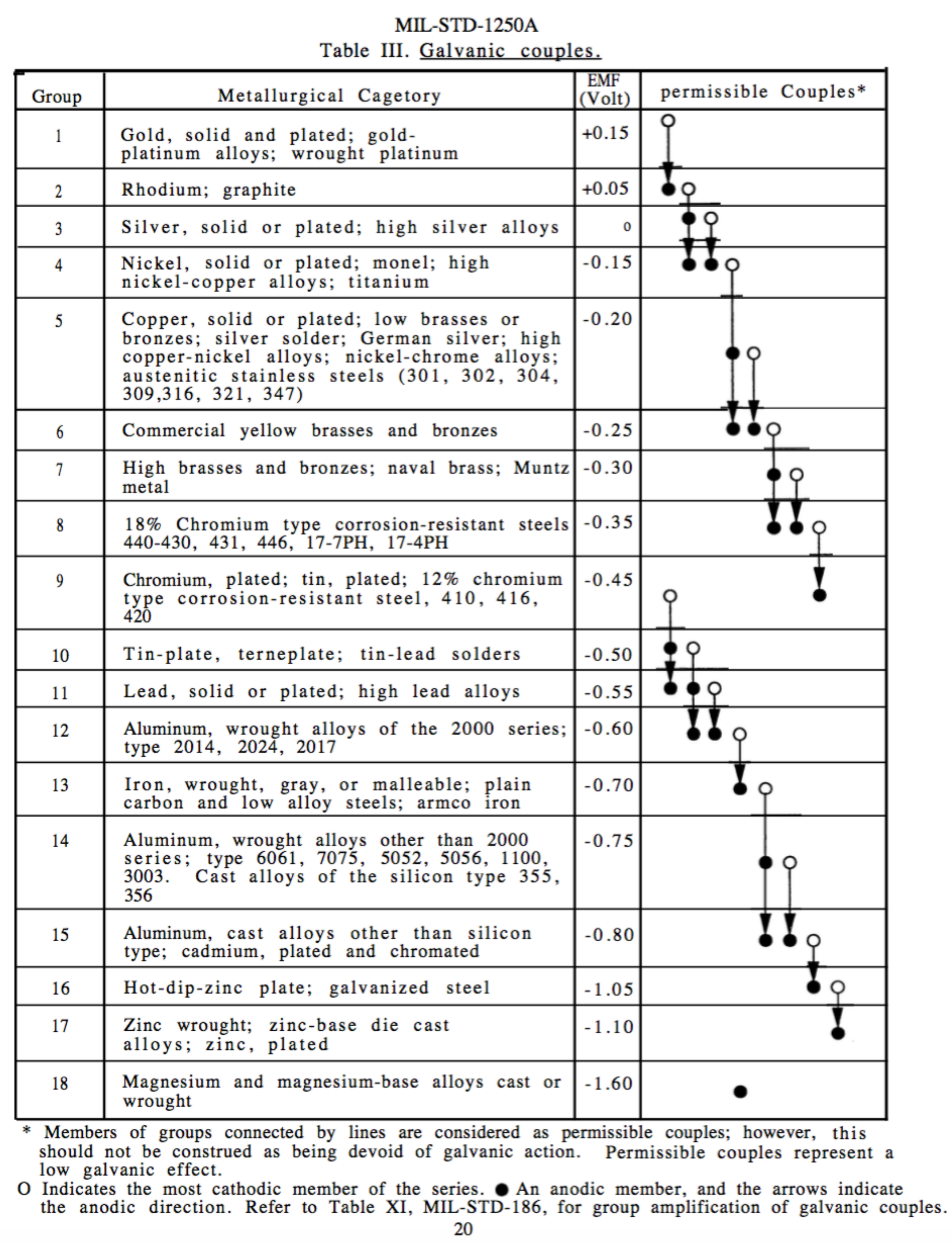
Anodic index	
Metal	Index (V)
Gold, solid and plated, Gold-platinum alloy	−0.00
Rhodium plated on silver-plated copper	−0.05
Silver, solid or plated; monel metal. High nickel-copper alloys	−0.15
Nickel, solid or plated, titanium an s alloys, Monel	−0.30
Copper, solid or plated; low brasses or bronzes; silver solder; German silvery high copper-nickel alloys; nickel-chromium alloys	−0.35
Brass and bronzes	−0.40
High brasses and bronzes	−0.45
18% chromium type corrosion-resistant steels	−0.50
Chromium plated; tin plated; 12% chromium type corrosion-resistant steels	−0.60
Tin-plate; tin-lead solder	−0.65
Lead, solid or plated; high lead alloys	−0.70
2000 series wrought aluminum	−0.75
Iron, wrought, gray or malleable, plain carbon and low alloy steels	−0.85
Aluminum, wrought alloys other than 2000 series aluminum, cast alloys of the silicon type	−0.90
Aluminum, cast alloys other than silicon type, cadmium, plated and chromate	−0.95
Hot-dip-zinc plate; galvanized steel	−1.20
Zinc, wrought; zinc-base die-casting alloys; zinc plated	−1.25
Magnesium and magnesium-base alloys, cast or wrought	−1.75
Beryllium	−1.85

Anodic

Indium on aluminium seems to be OK for detectors; used in bump bonding.

Handbook of corrosion engineering, McGraw-Hill; Publication Date: 2000; ISBN 007-076516-2; 1140 pages by Pierre R. Roberge

GALVANIC CORROSION



MIL-STD-1250A

Table III. Galvanic couples.

Group	Metallurgical Cagetory	EMF (Volt)	permissible Couples*
1	Gold, solid and plated; gold-platinum alloys; wrought platinum	+0.15	
2	Rhodium; graphite	+0.05	
3	Silver, solid or plated; high silver alloys	0	
4	Nickel, solid or plated; monel; high nickel-copper alloys; titanium	-0.15	
5	Copper, solid or plated; low brasses or bronzes; silver solder; German silver; high copper-nickel alloys; nickel-chrome alloys; austenitic stainless steels (301, 302, 304, 309,316, 321, 347)	-0.20	
6	Commercial yellow brasses and bronzes	-0.25	
7	High brasses and bronzes; naval brass; Muntz metal	-0.30	
8	18% Chromium type corrosion-resistant steels 440-430, 431, 446, 17-7PH, 17-4PH	-0.35	
9	Chromium, plated; tin, plated; 12% chromium type corrosion-resistant steel, 410, 416, 420	-0.45	
10	Tin-plate, terneplate; tin-lead solders	-0.50	
11	Lead, solid or plated; high lead alloys	-0.55	
12	Aluminum, wrought alloys of the 2000 series; type 2014, 2024, 2017	-0.60	
13	Iron, wrought, gray, or malleable; plain carbon and low alloy steels; armco iron	-0.70	
14	Aluminum, wrought alloys other than 2000 series; type 6061, 7075, 5052, 5056, 1100, 3003. Cast alloys of the silicon type 355, 356	-0.75	
15	Aluminum, cast alloys other than silicon type; cadmium, plated and chromated	-0.80	
16	Hot-dip-zinc plate; galvanized steel	-1.05	
17	Zinc wrought; zinc-base die cast alloys; zinc, plated	-1.10	
18	Magnesium and magnesium-base alloys cast or wrought	-1.60	●

* Members of groups connected by lines are considered as permissible couples; however, this should not be construed as being devoid of galvanic action. Permissible couples represent a low galvanic effect.

O Indicates the most cathodic member of the series. ● An anodic member, and the arrows indicate the anodic direction. Refer to Table XI, MIL-STD-186, for group amplification of galvanic couples.

20

- Mixing metals for bond wire and pads will result in galvanic corrosion.
- The only material we would want to use in a detector in a high radiation environment that pairs with Al is Al.

US DoD MIL-STD-1250A report on Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies.

GALVANIC CORROSION

- There is a lot of literature available on corrosion related to wire bonding as this is an important issue for the electronics industry.
  - Means that we can draw on that knowledge for our detector designs.
  - We have some additional constraints that are not shared with industry:
    - **Activation** on exposure to radiation; at the end of life of a detector used where hadronic material is created we need to understand if we have made that detector radioactive.
      - Gold, Silver and Copper activate significantly more than Aluminium.
    - **Mass.** We strive to build low mass detectors, as material leads to multiple Coulomb scattering and that degrades measurement resolution in tracking systems.

GALVANIC CORROSION

- Ageing is simulated by corrosion tests in an electrolyte and with heating.

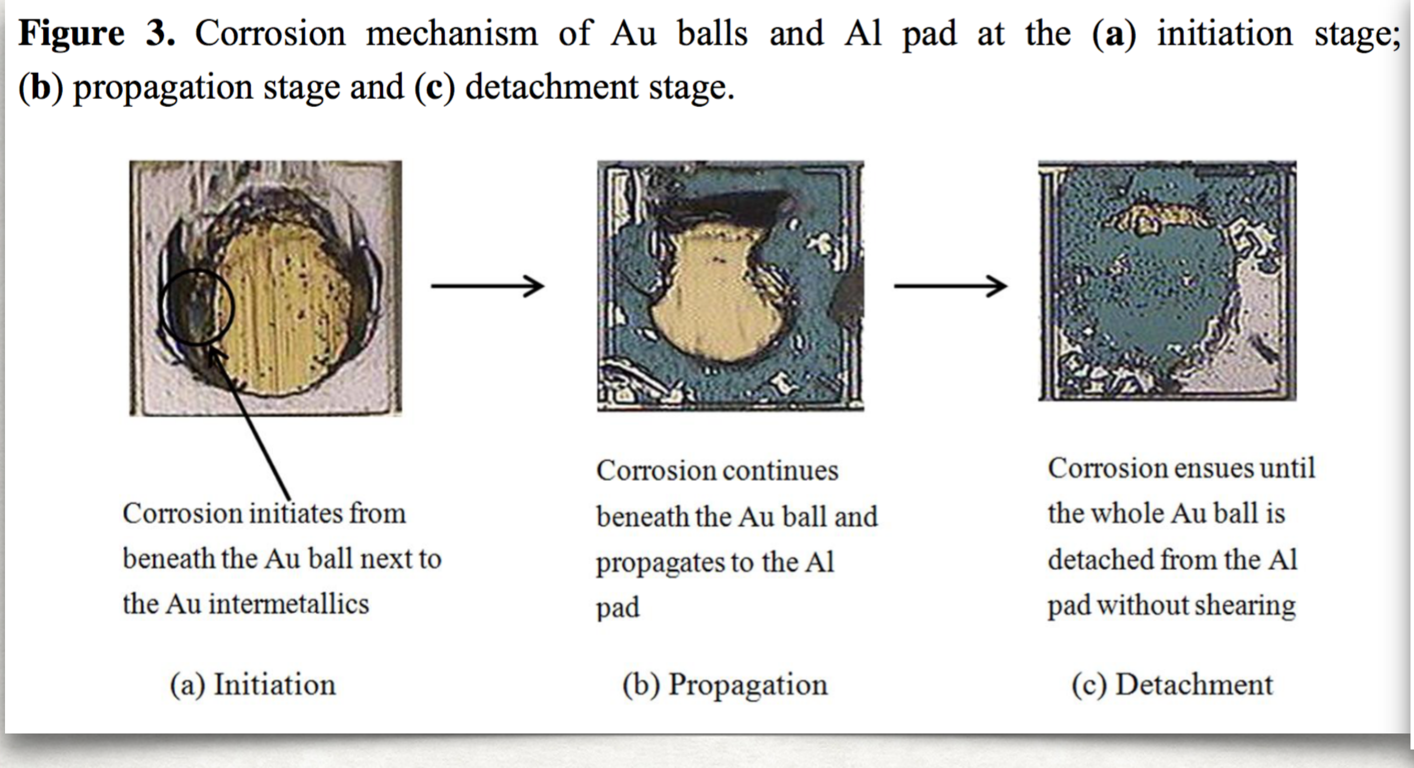


Figure 3. Corrosion mechanism of Au balls and Al pad at the (**a**) initiation stage; (**b**) propagation stage and (**c**) detachment stage.

Corrosion initiates from beneath the Au ball next to the Au intermetallics

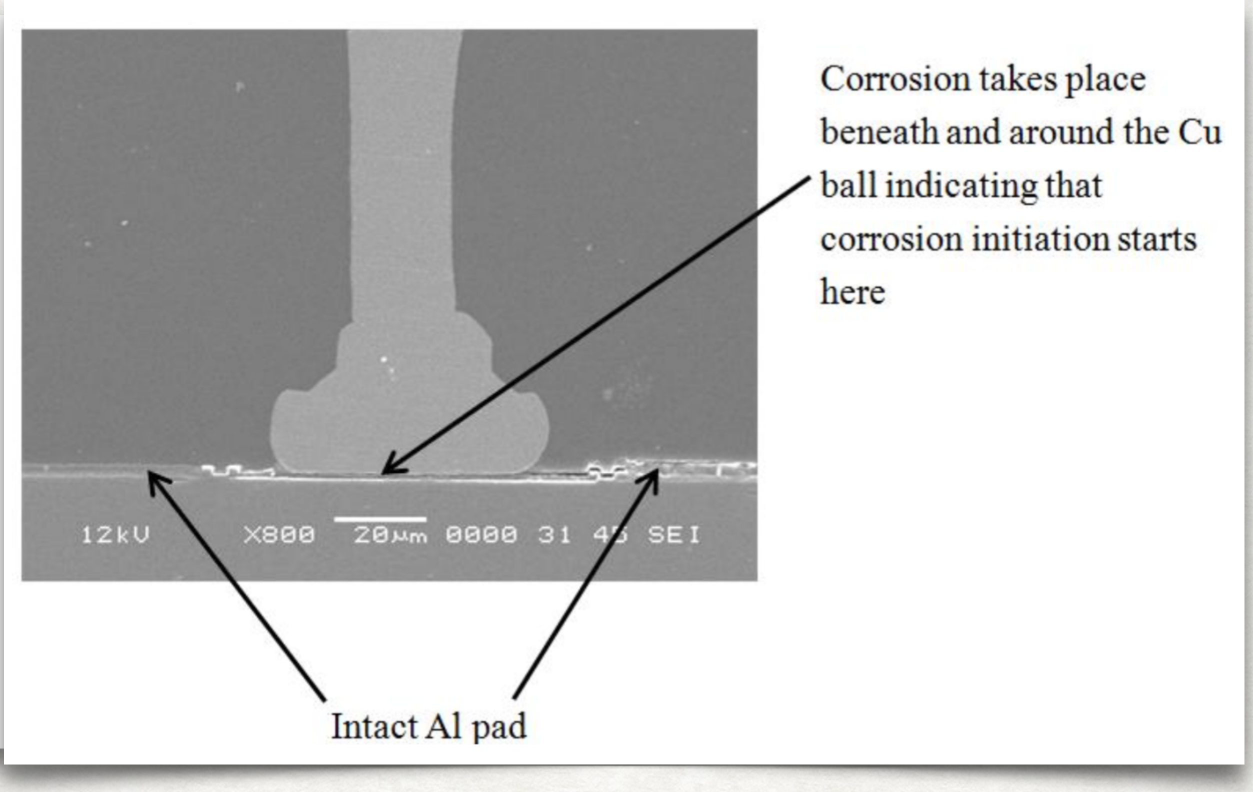
Corrosion continues beneath the Au ball and propagates to the Al pad

Corrosion ensues until the whole Au ball is detached from the Al pad without shearing

(a) Initiation

(b) Propagation

(c) Detachment



Corrosion takes place beneath and around the Cu ball indicating that corrosion initiation starts here

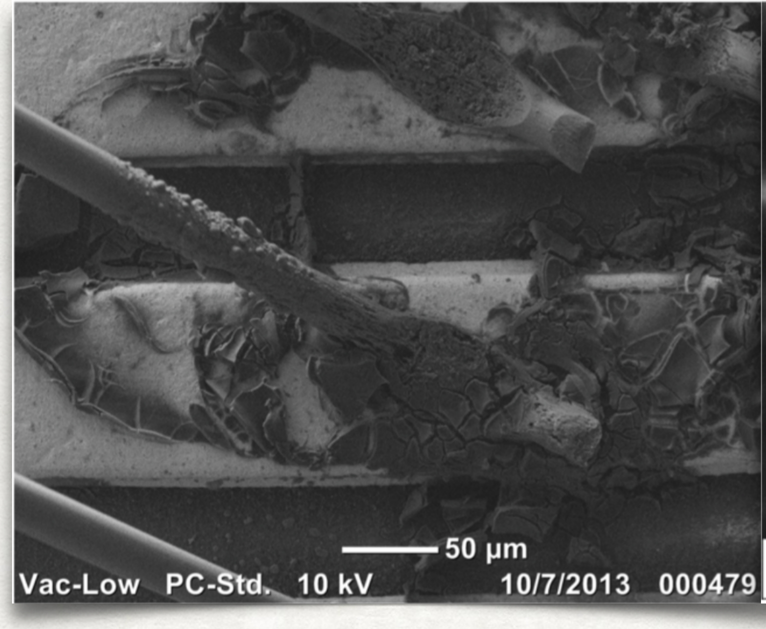
Intact Al pad

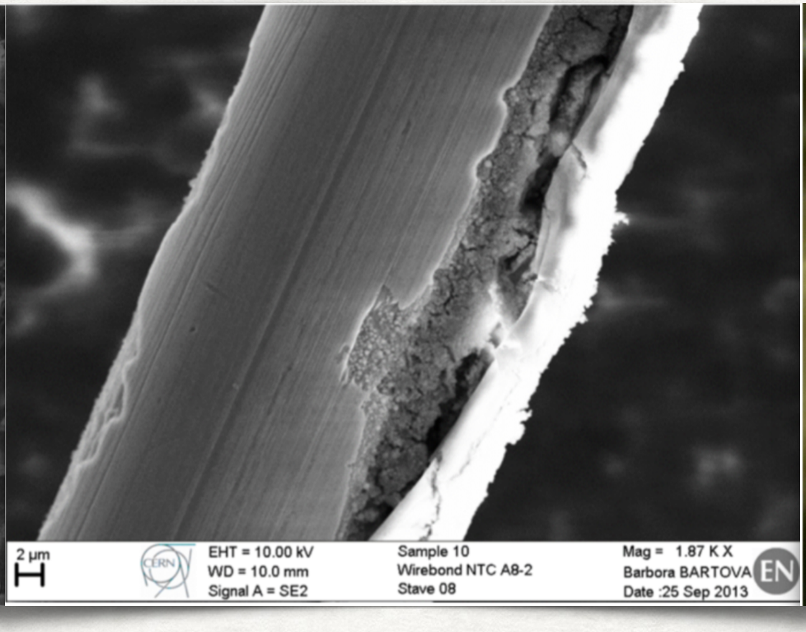
- Au-Al leads to a purple coloured corrosion (referred to as the purple plague).
- Ag-Al results in end of life catastrophic failure.

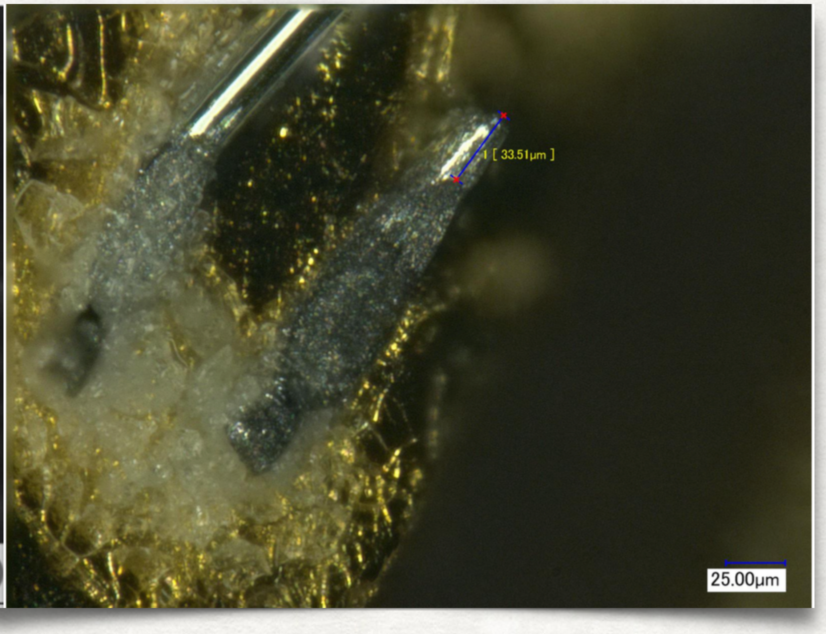
Crystals 2013, 3, 391-404; doi:10.3390/cryst3030391 [Open Access Journal]
Reliability Physics Symposium, 1982. 20th Annual, doi:10.1109/IRPS.1982.363032

GALVANIC CORROSION

- This was found to be a problem with the ATLAS IBL detector.







- “The corrosion of the staves was caused by water accumulating on the wire bond pad of the flexes; during the thermal cycle procedure each stave was embedded in a plexiglass handling frame.”
- White residue likely to be $Al(OH)_3$.
- Thermal cycling was done as part of the build QA testing of the staves before these were due to be installed.
  - The modules had to be cleaned and rework (re-bonded) in order to resolve this issue.
  - 0.1% of pixels were dead in the 14 staves of the IBL after rework.

GALVANIC CORROSION

- Parts can be cleaned with DI water or alcohol.
- Plasma cleaning can be required for removal of organic residue.
- Sometimes it is not possible to properly clean components.

    - To understand if corrosion is an issue, make samples and batch test (e.g. inspect wire bonds and pull test to gauge bond strength).

RESONANT VIBRATIONS

- Will discuss examples from:
  - ATLAS Semiconductor Tracker (at the LHC)
  - CDF detector (at the Tevatron)
    - Lorentz force induced resonances resulted in loss of channels/ modules for the silicon detector.

RESONANT VIBRATIONS

- A wire bond of length ℓ with a current I passing through it in a magnetic field *B* is subject to the Lorentz force:

$$F = BI\ell$$

- A bond in a 2T field of length 2mm with a current of 10mA is subject to a force of 4x10^{-5} N.
- Force required to break a bond is ~0.1N.
- Signal current alone is not enough to worry about this issue; however there are resonances that are a real concern.
- The first normal mode resonant frequency (treating the wire as a beam with fixed ends) is:

$$\omega = \frac{kd}{\ell^2}$$

k = constant
d = wire diameter
a = amplitude of oscillation
c = constant

- and the amplitude of oscillation scales as

$$a = c\ell^4$$

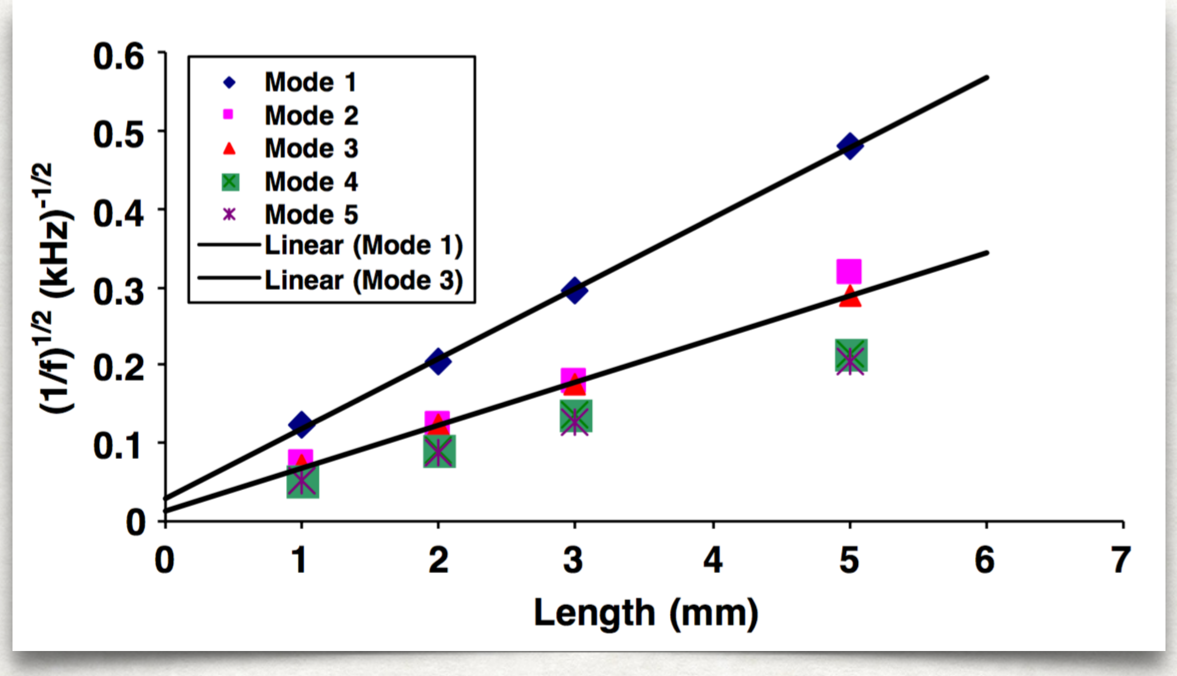
T. J. Barber et al., NIMA **538** (2005) 442-457.

RESONANT VIBRATIONS

- The analytic approach provides sufficient information for design, and indicates that:

$$\omega \propto 1/\ell^2, \;\; a \propto \ell^4$$

- There is a trade off between oscillation frequency and amplitude of oscillation, both of which are strongly dependent on bond length.
- Finite element analysis provides the following results.



- 2mm wire has the first resonance at 25kHz.
- 5mm wire has the first resonance at 4kHz.
- The transient signal frequency depends on the scenario and this in turn will affect the detector design.
- Serious problems (wire bond failure) arise if you design a detector that operates at or near a resonance.

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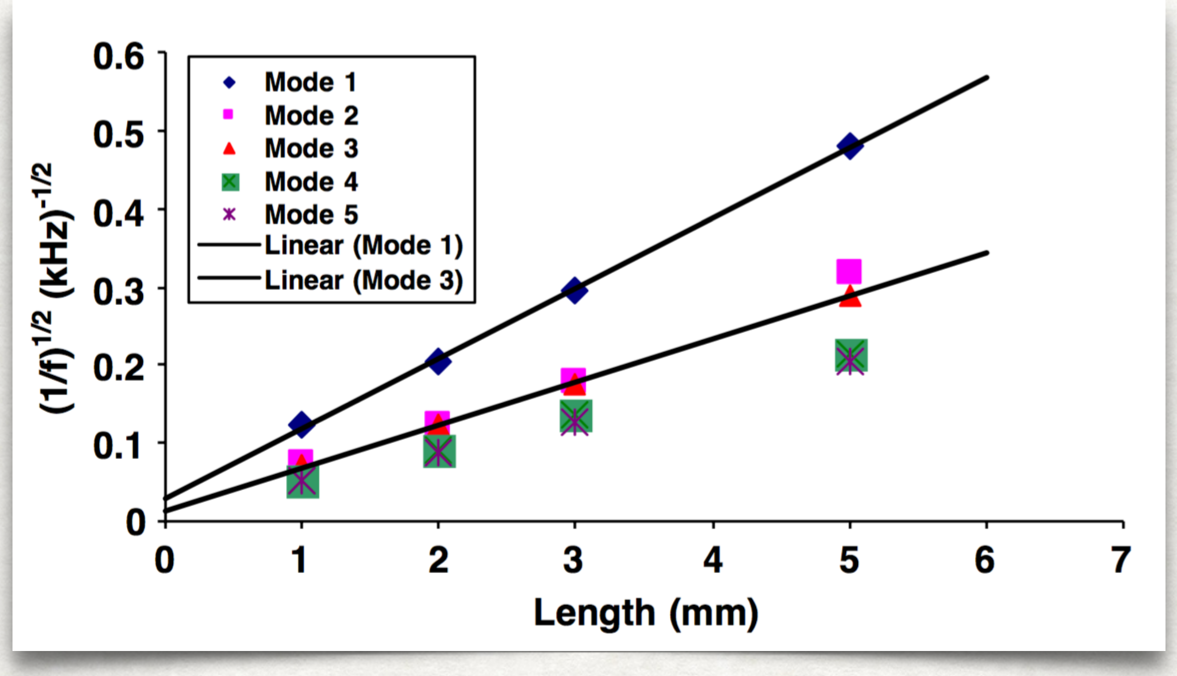

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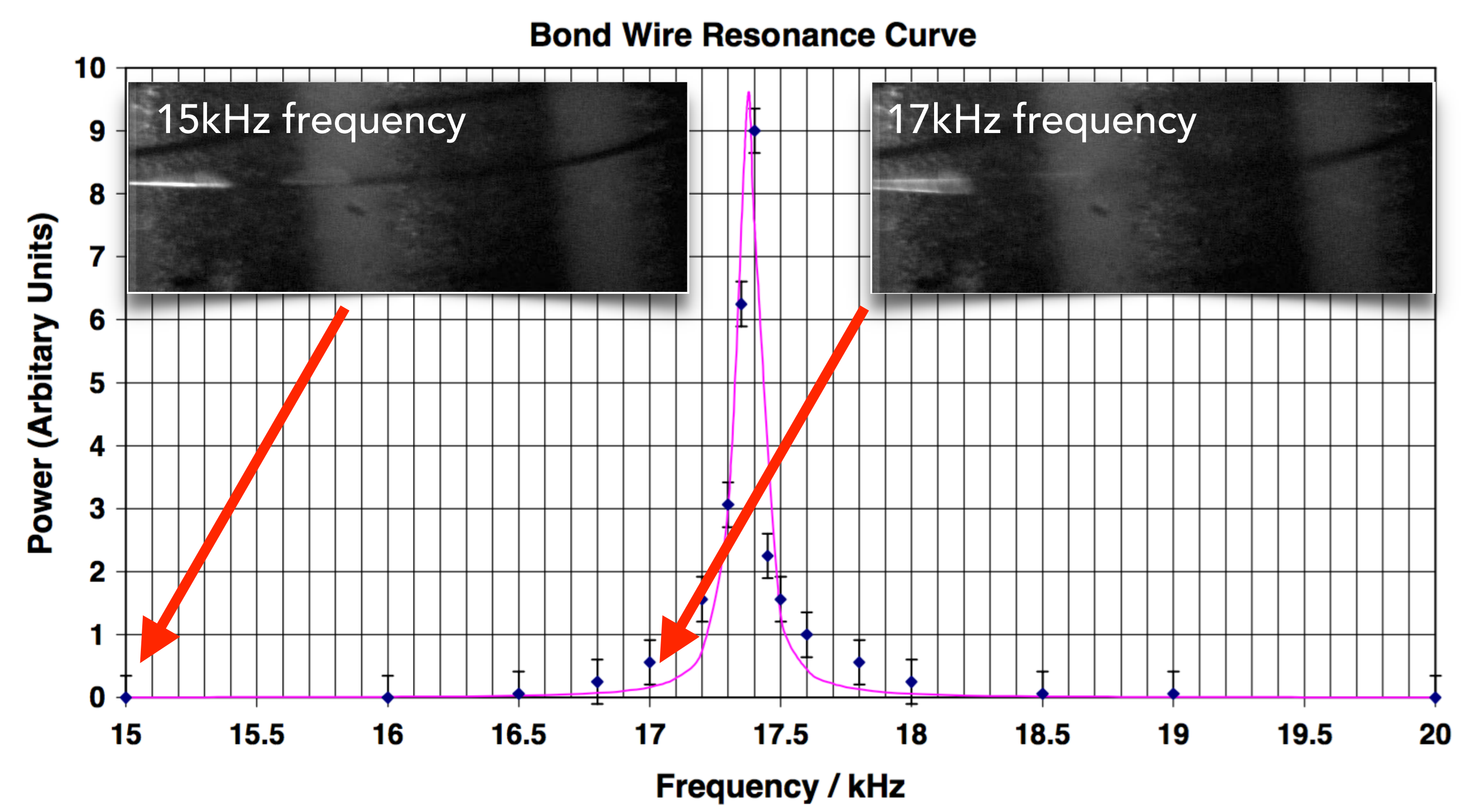
RESONANT VIBRATIONS

- Example: ATLAS



Resonance power (assuming simple harmonic motion) is given by:

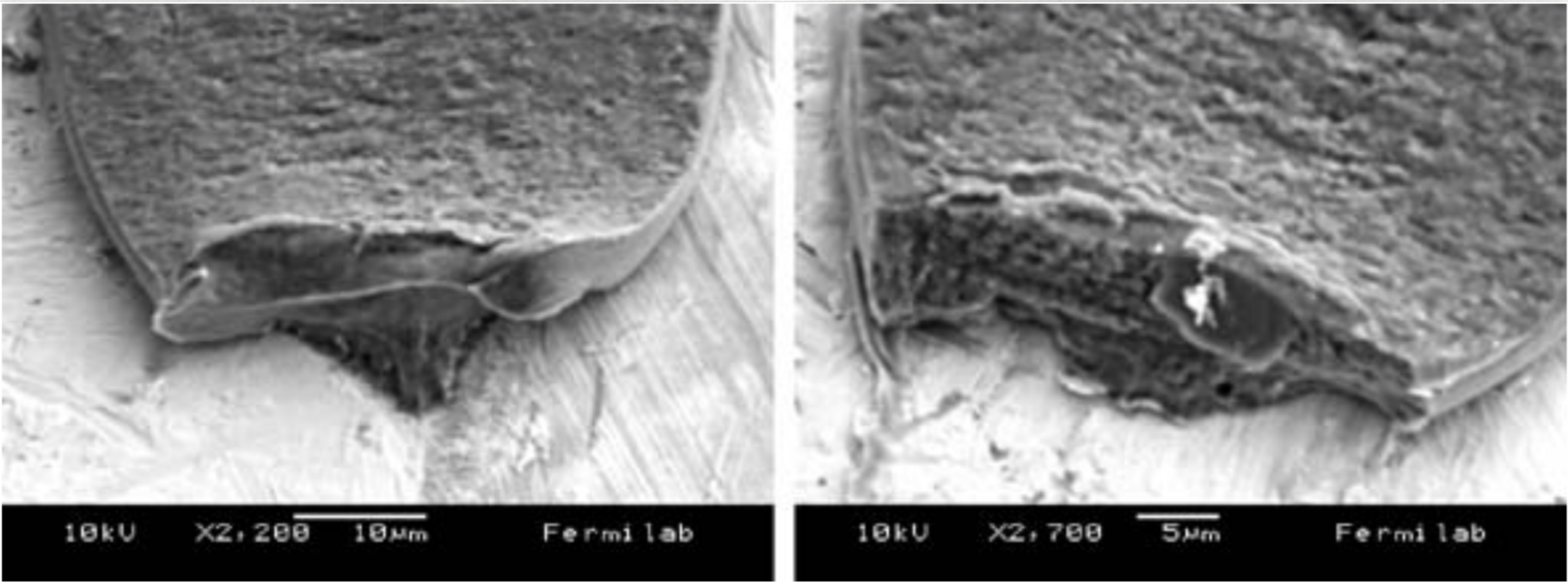
$$p = \frac{(\gamma^2/4)H}{(\omega - \omega_0)^2 + (\gamma^2/4)}$$

- Conditions required for resonant vibrations of the wires:
  - current change on receipt of L1 trigger >1 mA;
  - bond orientation relative to solenoid B field ~90°.
- A fixed trigger veto algorithm is implemented in ATLAS to avoid the possibility of a resonant vibration state being set up (based on the CDF experience).

T. J. Barber et al., NIMA **538** (2005) 442-457.

RESONANT VIBRATIONS

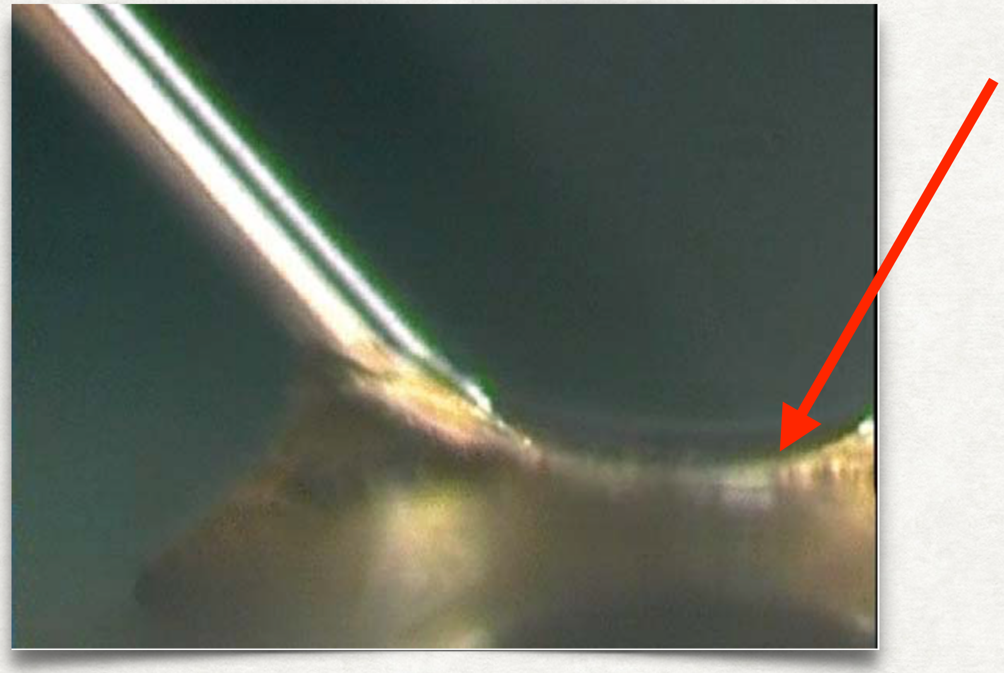
- Example: CDF Run 2 detector.
  - Unrecoverable failures were observed from installation of the detector.
  - These failures were die to fatigue forces from the 1.4T solenoidal B field in the detector.
  - Wire bonds fail at the bond heel.
  - 10kHz frequency for a few minutes (10^5-10^6 cycles) was sufficient to replicate this problem in the laboratory.



G. Bolla et al., NIMA **518** (2004) 227-280

RESONANT VIBRATIONS

- Example: CDF Run 2 detector.
  - Mitigation steps for this problem: avoid using the silicon detector with any fixed period trigger (to avoid the potential for any part being subject to resonances).
  - Add a FFT trigger to inhibit resonances detected in the data.
  - Use wire bond encapsulation (which does introduce other potential failure modes, while mitigating this one; e.g. thermal expansion).
    - Only encapsulate the foot of the bond to limit the effect of this problem.



Encapsulated bond heel.

This remedy was done using a 50μm layer of 186 Silicon Elastomer from Down Corning.

No failures observed after heel encapsulation.

* Encapsulating the whole bond would result in a mismatch of thermal expansion coefficients for the glue and wire bond material relative to the PCB and/or Sensor. Overtime this mismatch would be expected to lead to a fatigue failure mode.

G. Bolla et al., NIMA **518** (2004) 227-280

MECHANICAL VIBRATIONS

- Particle detectors experience mechanical vibrations during module/stave transport, and to a much lesser extent, during assembly.
  - Shipping with a courier does not guarantee treatment of modules as a fragile object.
  - e.g. The LHCb VELO modules were taken one at a time from the UK to CERN by plane doing that build to avoid risk of damage.

- Hubble Space Telescope (solid state recorder)
  - Long bond wires were used in the SSR. Extensive vibration fatigue tests were performed to understand how the bonds might survive during the life of the telescope. Samples were exposed to 1.4 billion vibrations and survived during those test (using Au bond wire).

DOI: 10.1109/ICMCM.1998.670799

OTHER CONSIDERATIONS

- The CERN bond lab has a summary of issues that have come up in the projects they are running. This is summarised by Alan Honma at:

- https://bondlab-qa.web.cern.ch/bondlab-qa/BondingIssues_Honma_Oct2015.pdf

- Definitely worth reading when designing a new detector.