ON PHOTOSENSORS FOR DUNE

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Outline

- Historical recap
- ICASiPM and vendor contact
- Reliability engineering
- Towards SiPM requirements

Pre-proto-DUNE R&D

- Sustained photosensor R&D for DUNE carried out primarily at CSU, Hawaii and IU.
- Devices from a number of vendors tested especially Hamamatsu and SensL
- After pulsing issues (cryogenic temperatures) with Hamamatsu devices of that era were observed
- Also packaging was susceptible to cracking though not necessarily correlated with changes to electrical properties
- SensL devices did not show any anomalies physically or electrically
- SensL C-Series device chosen as the photosensor for protoDUNE

Proto-DUNE Experience

- 1700 MicroFC-60035-SMT were ordered
- Same part number as was used in years of pre-protoDUNE R&D
- After arrival, the devices were mounted on readout boards while observing all soldering and humidity constraints recommended by the vendor
- A very significant fraction (upto 50%) started physically cracking on their very first dipping into LN_2
- This (the cracking) was independent of whether the devices were mounted or unmounted
- The cracking rendered the devices non-functional
- Dipping procedures had not been modified

Note that….

- The devices were being operated way outside their recommended operational temperatures
- Since operation at these cryo temperatures was not certified by vendors the fact that devices worked without issues was in some sense good luck
- This also meant that changes in the production process could have unforeseen consequences at LAr or LN_2 temperatures since they were in principle outside the range of applicability of the devices as tested by vendors
- Many “undamaged” devices exhibited elevated noise rates

Risk Mitigation

- Probably a "…mold compound change…" was the culprit
- The devices exhibited no issues within the vendor specified operability ranges
- We were definitely operating outside that range
- What can be done to avoid a repeat of this unfortunate situation especially since going to the "old formulation" may not be feasible for the vendor
- Possible paths:
  - Process control
  - "cryo" testing as part of vendors program
  - Self-packaging

Process Control

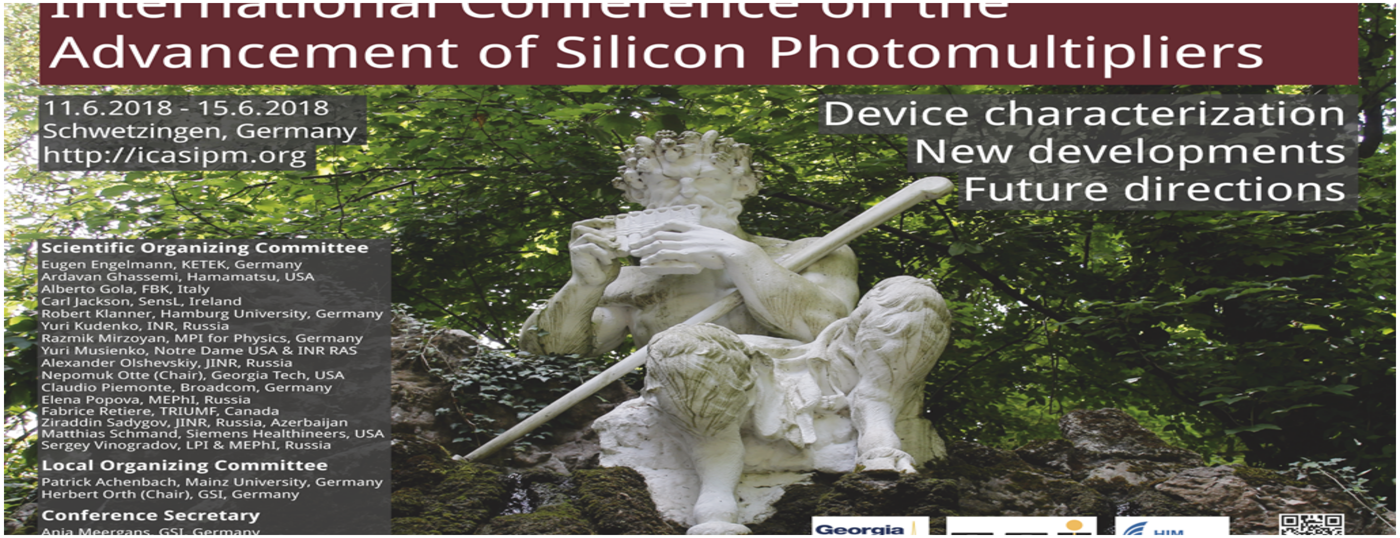
- Once you are happy with a set of devices; request the vendor for the exact same product (same part number is not enough)
- Sounds easy but may not be practically feasible
- Fast-moving field with process improvements
- What does “exactly same” mean? What are the relevant changes to this application?
- Vendor privileged information

Self-packaging

- Since the issue is mostly about the packaging and not the silicon, the experiment takes it upon itself to package the device
- Probably the safest bet
- However, requires a large infrastructure, know-how, manpower etc.
- The costs may out-weigh the benefits unless one is looking for a very custom arrangement

Vendor Testing

- May offer the happy medium
- If a “cryo” testing suite could be part of the vendors QA/QC process a number of issues may be put to rest
- Would the vendors consider entertaining such a request?
- What would the request be? What testing (and it would have to be fairly simple and efficient) would we be interested in?
- With what frequency?
- Not the total solution but a key ingredient towards one



- ➢ Excellent opportunity to interface with vendors and share our needs and concerns
- ➢ Discussions with FBK, Hamamatsu, KETEK, SensL
- ➢ All recognized both the promise and challenges a detector like DUNE poses for SiPMs
- ➢ All, except SensL, were willing to work with us to see if a mutually acceptable solution could be arrived at
- ➢ Other potential vendors: Broadcom, Excelitas etc.

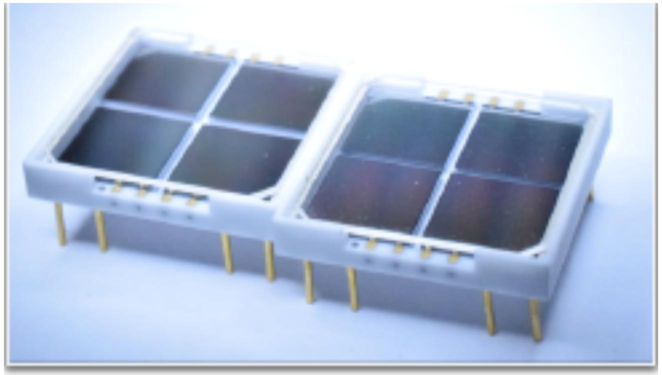
Communication from Hamamatsu

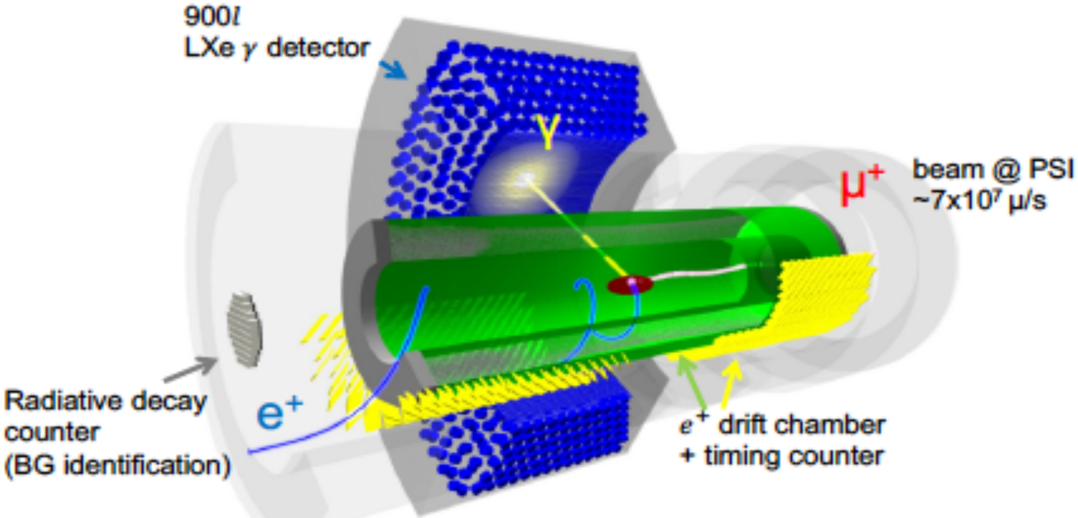
- After device **specification** and mutual agreement:
  - Hamamatsu will be willing to warrant the operation of the device down to LN_2 temperature
  - Would be willing to perform in-house qualification tests before shipment "free-of-charge"
  - The "qualification" would of course include thermally stressing the devices and visual and electrical before-after measurements
  - The specifics of the procedure (number of samples, ramps, number of cycles, frequency) I view as a matter of discussion but this is, in my opinion, a very welcome step

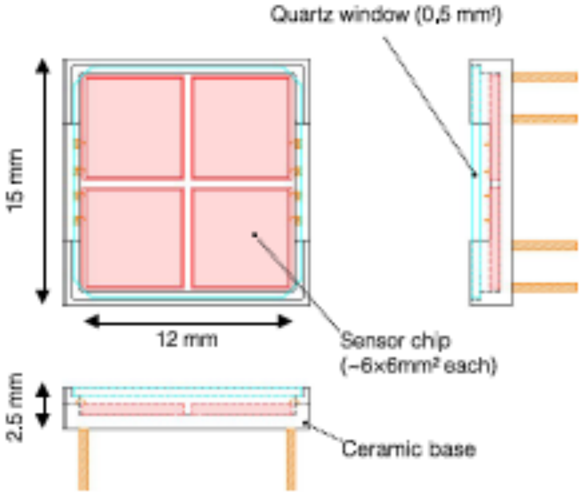
SiPMs in Noble Liquids

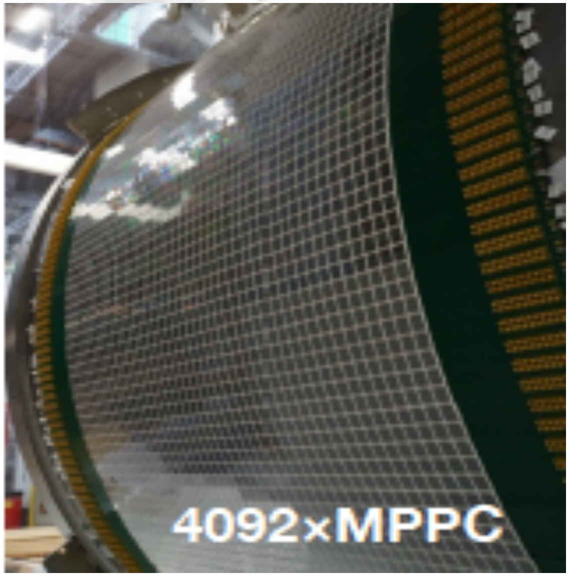
- Relatively young field
- Some experiments/installations one can hope to learn from:
  - GERDA (LAr veto shield, running)
  - MEG II (commissioning)
  - Darkside, nEXO etc. (at various stages of preparation)
- Observations:
  - have generally worked rather closely with the SiPM vendors (there is an implicit customization)
  - pre-protoDUNE state of mind
  - in principle do not have the accessibility and longevity constraints we have

MEG II




900l
LXe γ detector
γ
μ+
beam @ PSI
~7x10⁷ μ/s
Radiative decay
counter
(BG identification)
e+
e+ drift chamber
+ timing counter


Quartz window (0.5 mmᵗ)
15 mm
12 mm
Sensor chip
(~6x6mm² each)
2.5 mm
Ceramic base


4092xMPPC

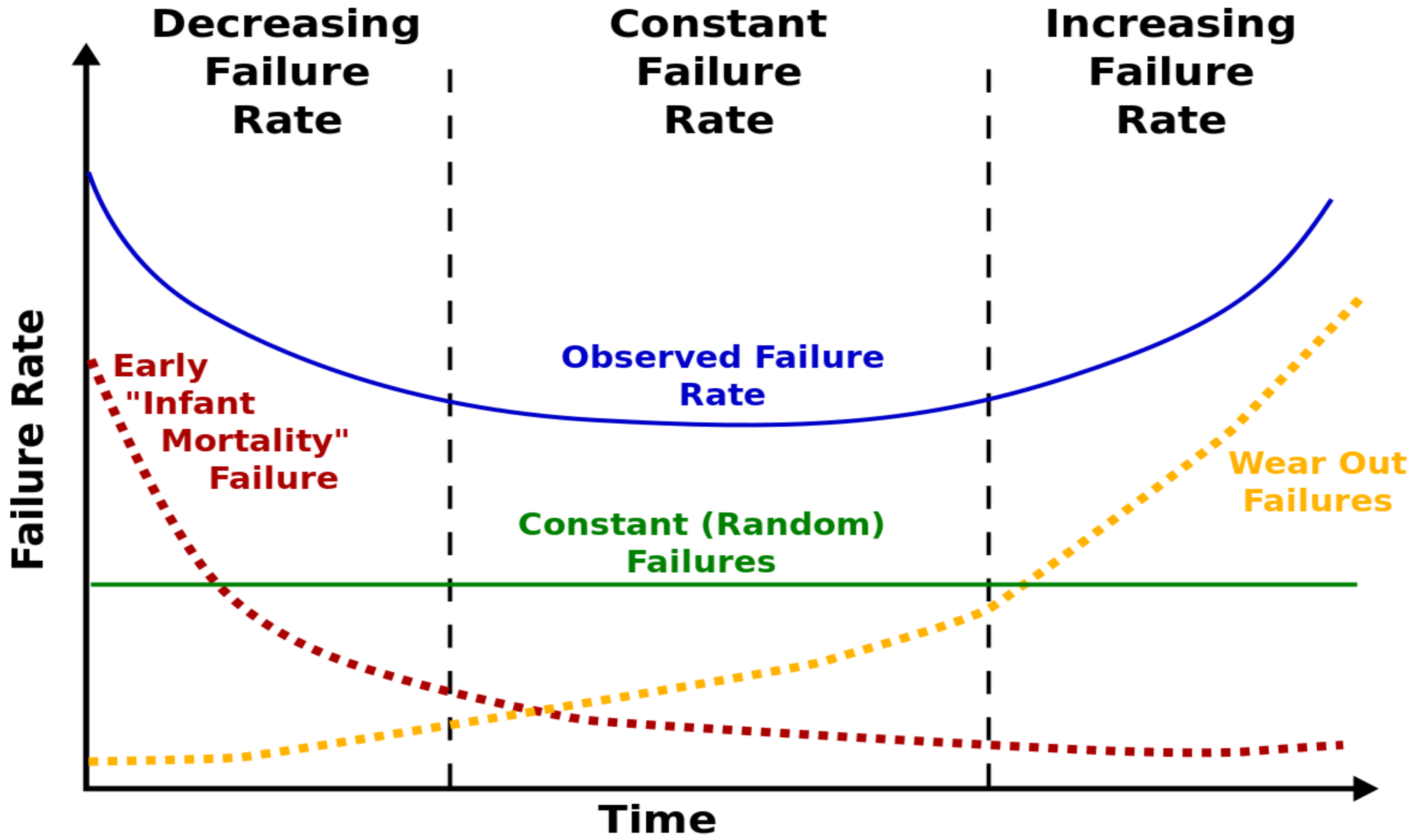
Space you say…

- Initiated contact with some JPL folks
- Payload and cost considerations points towards advantages of operating in ambient conditions
- Clearly operating conditions involve cryogenic temperatures
- Their apparatus undergoes far more cycles than our situation
- On the other hand we are asking for greater operational life
- Same-day-same-batch components a big priority for them
- Both a science and an art

Reliability

- Probability that system will function as required under the target operating and environmental conditions
- Empirical testing/cycling
- Physics of failure
- Number of quantitative tools available for extrapolation based on input test data

Bathtub Curve



Failure Modes

Stress Mechanisms

Mechanical
- **Brittle fracture**
- Plastic deformation
- **Die cracking**

Electrical
- Radiation damage
- Dielectric breakdown
- **Change in R/C**

Chemical
- Material degradation
- **Temp-dependent phase transformation**

Time Dependent Mechanisms

Mechanical
- **Fatigue**
- Creep
- Stress-driven voiding

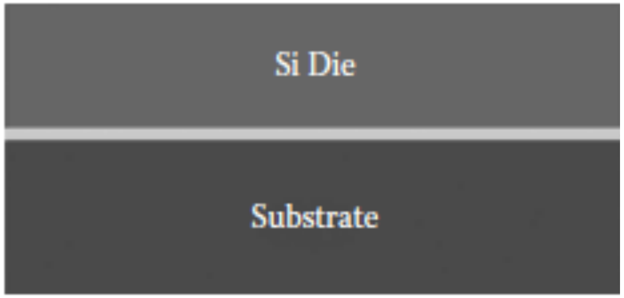
Electrical
- Electromigration
- **Change in R/C**

Chemical
- Diffusion
- Oxidation
- Phase transformations

Packaging and Low Temperatures

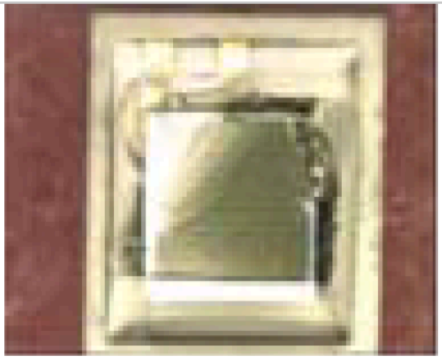
- Provides protection to the die, a means of connecting electrically and thermally to the die
- Primary issues are changes in material properties and stressed induced due to differential CTEs
- In general:
  - increased modulus of elasticity for metals and polymers
  - decreased elongation(brittleness)
  - CTE decreases
  - phase transitions in metals, particularly solders

Die Attach



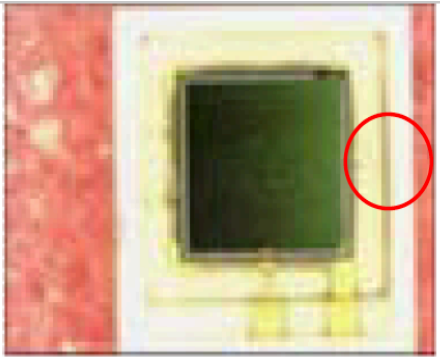
(a)

(b)



Epoxy resin
w/ conductive adhesive glue

cracked at 1cycle
conductivity: good > 20cycles

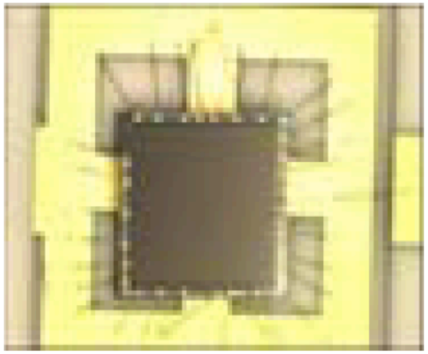


Silicone resin
w/ conductive adhesive glue

small crack at 10cycles
minor detachment at 20 cycles
conductivity: good > 20cycles

bare
w/ conductive adhesive glue

no visible damage: at > 20cycles
conductivity: good at > 20cycles



bare
w/o conductive adhesive glue

no visible damage: at > 20cycles
conductivity: good at > 20cycles

Hamamatsu Study

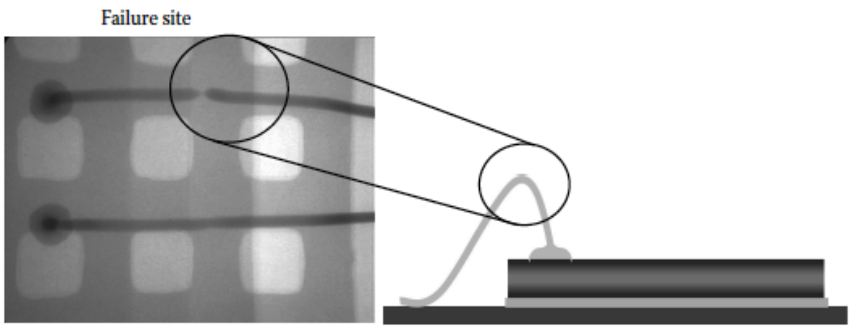
Die Attach

	CTE (ppm/°C)	Density (g/cm³)	Thermal Conductivity (W/mK)	Modulus of Elasticity (MPa)
Substrate polyimide	8.1	3.87	25.15	1.09E + 05
Substrate Al_2O_3	6.5	3.87	14.65	1.00E + 05
Substrate LTCC	15	1.937	0.445	1.68E + 04
Die attach epoxy	216	4.186	40	2883
Die attach silicone	340	1.17	1.26	1.1
Die attach indium	33	7.31	86	1.06E + 04
Die Si	2.6	2.33	146.51	4.70E + 04

Source: Shapiro, A.A. et al., *IEEE Trans. Adv. Packag.*, 33(2), 408, May 2010.

Not the only interface

- "packaging" in this sense; a collection of materials and interfaces
- Ideally you want to specify the system with minimal CTE mismatch with substances that will not undergo any drastic transformation
- Interfaces of interest to us:
  - die-to-substrate
  - substrate-to-potting mold
  - potting mold-to-encapsulation
  - solder joints to everything else



Solder Joints

TABLE 66.1 Ductile-to-Brittle Transition

Solder Alloy	Transition Temperature (°C)	Transition Characteristic
99%Sn	−125	Sharp
Sn-0.7Cu	−130	Sharp
Sn-0.7%Cu(Ni)	−130	Sharp
Sn-37%Pb	—	Gradual change
Sn-3%Ag-0.5%Cu	−78	Sharp
Sn-4%Ag-0.5%Cu	−58	Sharp
Sn-5%Ag	−45	Sharp

Source: Ratchev, P. et al., *IEEE Trans. Compon. Packag. Technol.*, 30(3), 416, September 2007.

Summary

- Photosensors for DUNE present a significant and unique challenge in terms of inaccessibility and years of operation
- Mitigation will involve both understanding the physics behind the failures and sample testing and qualification
- Suggested steps:
  - reliability testing of current devices
  - develop specification of devices with vendors minimizing CTE differentials and material transformation
  - specify qualification procedure at vendor and after receipt of sensors