Microfabrication, Characterization and Sensor Development in the Industrial Space

Nithin Raghunathan,
Birck Nanotechnology Center
Purdue University
nithin@purdue.edu

Birck Nanotechnology Center

A unique instrument for nanoscale research

25,252 square feet of cleanroom

- Semiconductor Fabrication Cleanroom
  - PVD, CVD, PECVD, Litho, ebeam, ALD, …
- Pharmaceutical-Grade Cleanroom
- ISO Class 3, 4, 5 (Class 1, 10, 100)
- Bay-Chase Design
- Most equipment 4’’; few up to 6’’ wafers

21,296 square feet of laboratory

- Heavy Equipment Labs (MBE, CVD, Optics)
- Light General Labs (Biological, Chemical, Characterization)
- SEM, FIB, TEM, XPS, AFM

- The Center hold some tools that can help with the development of some unique processing capabilities.
- Wide area of expertise among the research engineers to aid and develop fabrication processes and technologies

https://www.purdue.edu/discoverypark/birck/

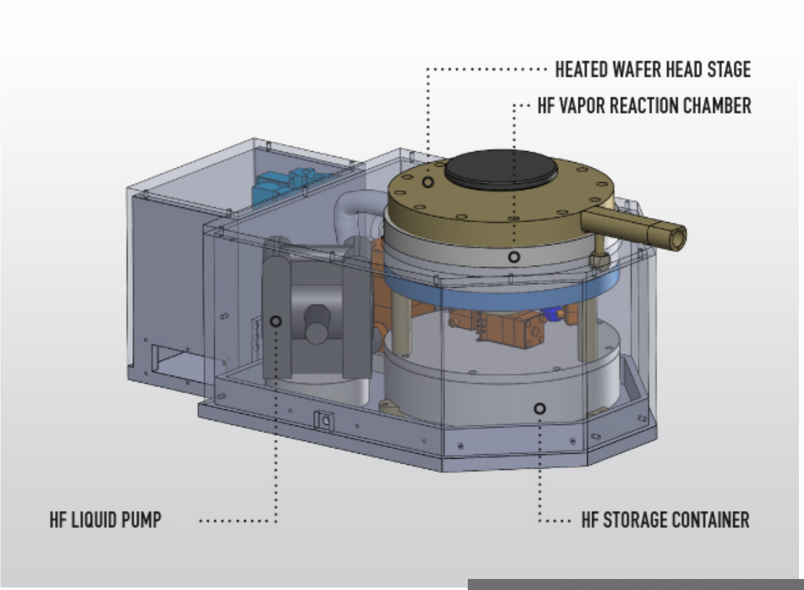
ETCH TOOLS

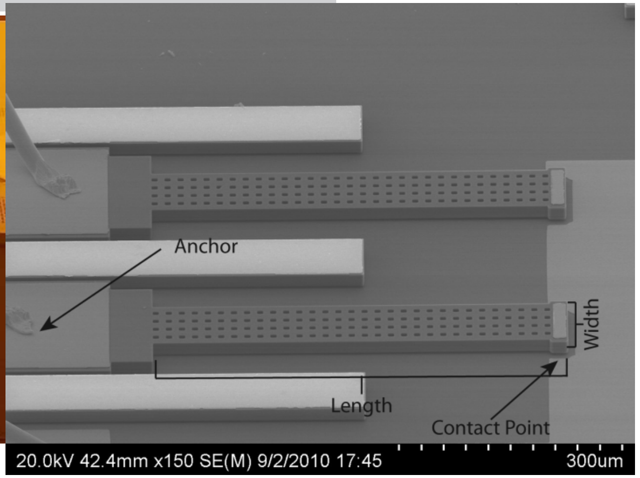
Xenon Diflouride Etcher (XeF2)

Name: Xenon Difluoride Etcher
Location: Cleanroom – S bay
Owner: Sean Rinehart

- Isotropic etch system
- Can accommodate up to 4 inch wafers
  - See through window to view etch progress
- High selectivity to Si
  - Silicon dioxide
  - Photoresist
  - Silicon Nitride
- Can be utilized as a Moly Etcher
- Etch rates dependent on Exposed area.
- Excellent alternative to HNO3:HF

AMMT Hydrofluoric Acid Vapor Etcher





Tool name: HFVE
Location: Cleanroom

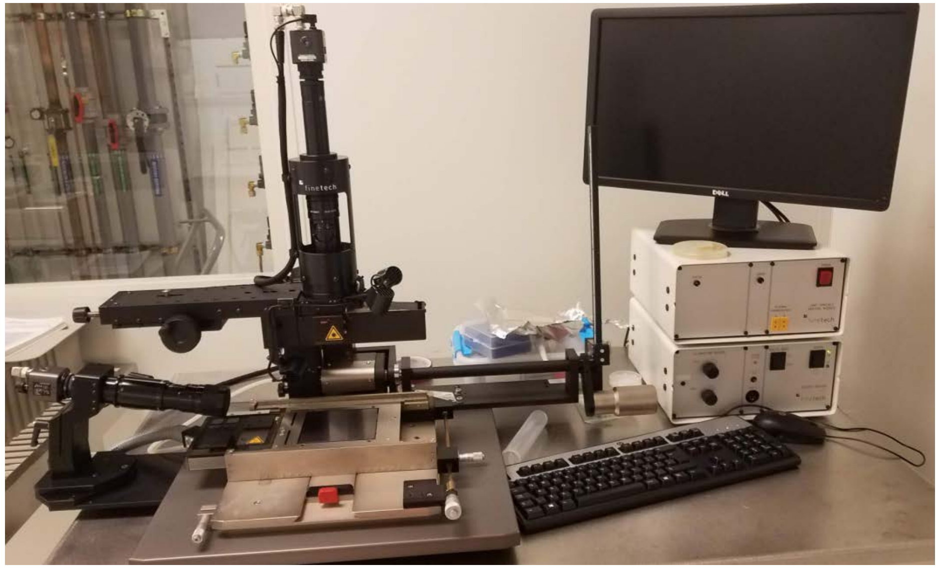
- Alternative to silicon dioxide wet etching
- Passive HF vapor generation.
  - System is flushed after etch time is reached
- Wafer is mounted with the etching side facing down
  - Vapors are generated due to vapor pressure
  - HF vapor react with the Silicon Dioxide
  - By heating the sample, the etch rate can be controlled
- Ideal solution for dry release of MEMS devices with sacrificial Oxides

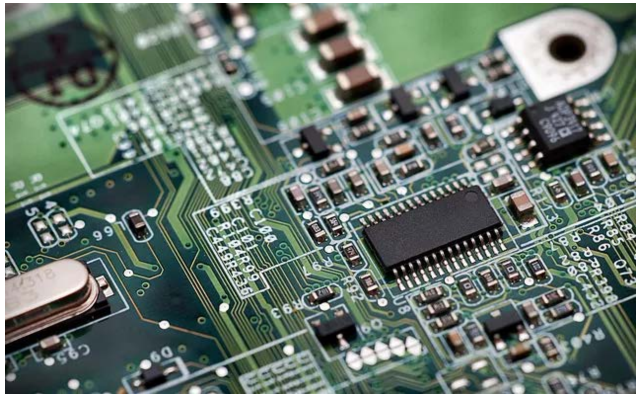
$$SiO_2 + 2H_2O \rightarrow Si(OH)_4$$

$$Si(OH)_4 + 4HF \rightarrow SiF_4 + 4H_2O$$

PACKAGING TOOLS

Pick and Place





- Prototyping Pick and place system
- Die bonding capabilities
- Optical overlay alignment
  - Vision alignment system (VAS)
- Force
  - 0.1N to 700 N
- Thermal bonding capable
- Can be used to align chip-scale packages
- Assemble printed circuit boards

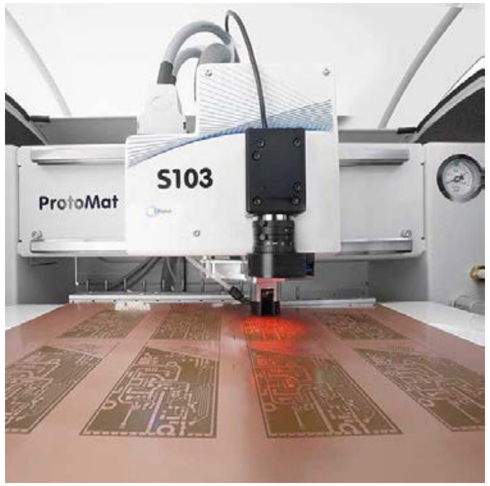
Dicing Tools – DiscoDAD 641

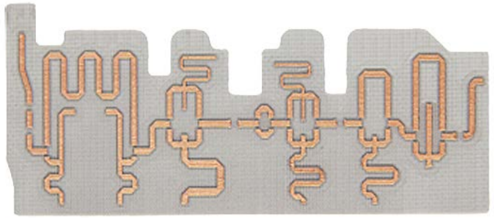
- Fully automatic dicing Saw
- Can handle up to 8 inch wafers.
- Also capable of dicing 0.1 um streets.
- Capable of asymmetric dicing.
  - i.e. the samples can have different spacings in each axis.
  - Can also preform angular cuts
- Fully automatic dicing
  - Cuts performed based on program parameters.
- Common errors and best practices:
  - Dicing streets to enable easy alignment for dicing
  - Allows for fully automatic operation

Tool name: DiscoDAD 641
Location: 1st floor galley
Owner: Timothy Miller

PCB Milling Tool and Plater : LPKF S103

PURDUE UNIVERSITY Discovery Park





- High Precision milling tool
  - Useful for creating PCB prototypes
  - Can handle boards of different thicknesses
  - Optional solder paste dispenser for mounting surface mount components.
- Plater
  - Used for plating through holes
  - Utilizing the laminator you can create multilayer PCBs.
- Laminator/press
  - Used to create multilayer PCBS

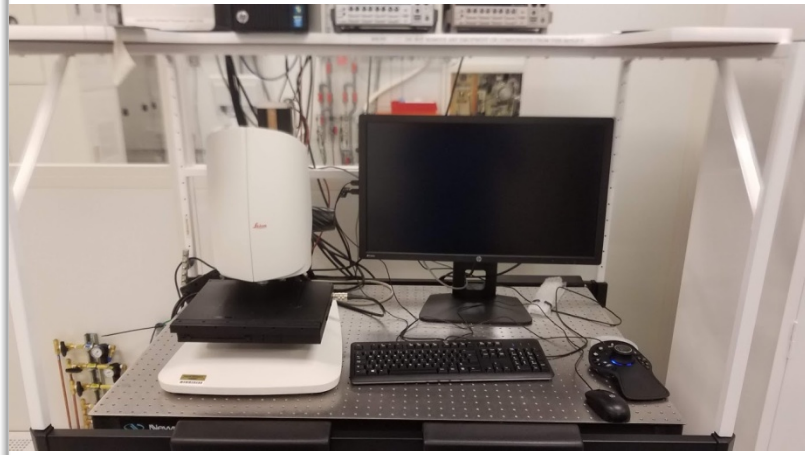
Location: 2nd floor Galley

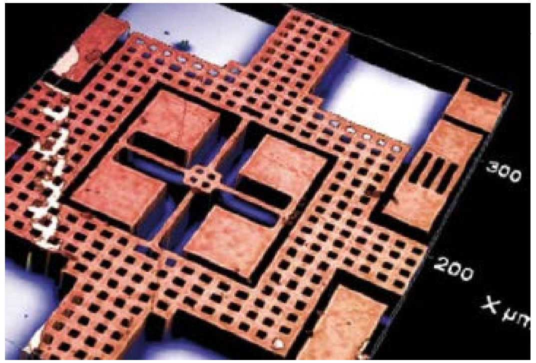
Owner: Jerry Shepard

CHARACTERIZATION TOOLS

Confocal Microscopy & Probe Stations

PURDUE UNIVERSITY Discovery Park





Courtesy of Leica systems

Tool Name : Leica Confocal Microscopy
Location: 2100-J

Leica Confocal Microscopy

- Primarily for surface characterisation
- HD imaging
- 3D Topography
- Profiles
- Thickness Roughness
- Interferometry
- Resolutions :
  - Vertical :<2nm
  - Optical resolution : 140nm

➢ Cascade MPS 150

- DC probe station
- Hydraulic Microscope mount
- Air cooled wafer chuck
  - 25C to 250 C
- High resolution microscope
- Low-noise DPP10 probes
- 150 mm chuck with two AUX chucks.
- Fully capable to do CV measurement and various electrical characterization

Tool Name : Probe 1
Location: 2100-J
Owner: Nithin Raghunathan

Probe Stations (2)

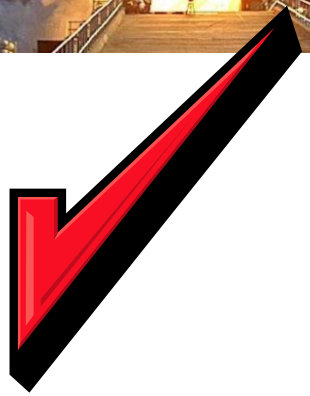
Tool Name : Micromanipulator 8860
Location: 2100-J
Owner: Nithin Raghunathan

- Micromanipulator 8860
  - Semi-automatic probe station
  - 150mm chuck
  - Fully programmable
    - Controllable via Keithley S4200 semiconductor characterization system
    - Controllable via LabView
  - High resolution optics
  - Low-noise, and low parasitic chucks
  - Can do a fully automatic testing of a wafer .

HIGH-G SWITCHES

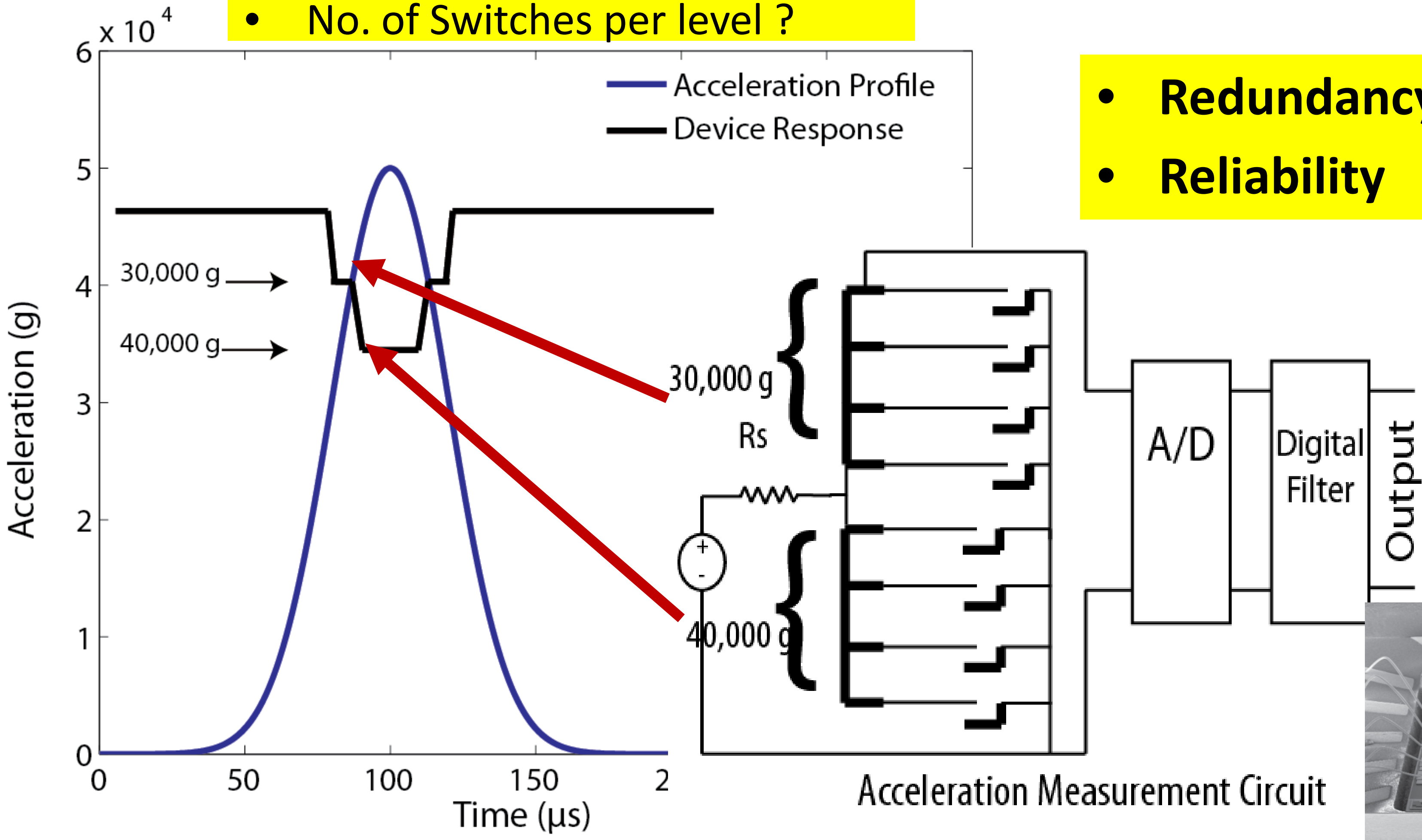
Introduction

- Impact monitoring
  - Defense & Commercial applications
  - Structural destruction
  - Collision processes
  - Short durations
    - order of 100 µs

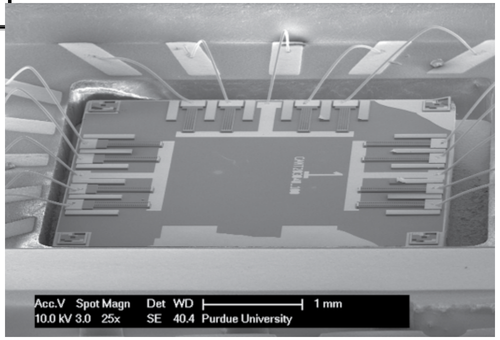


Digital Accelerometer Concept

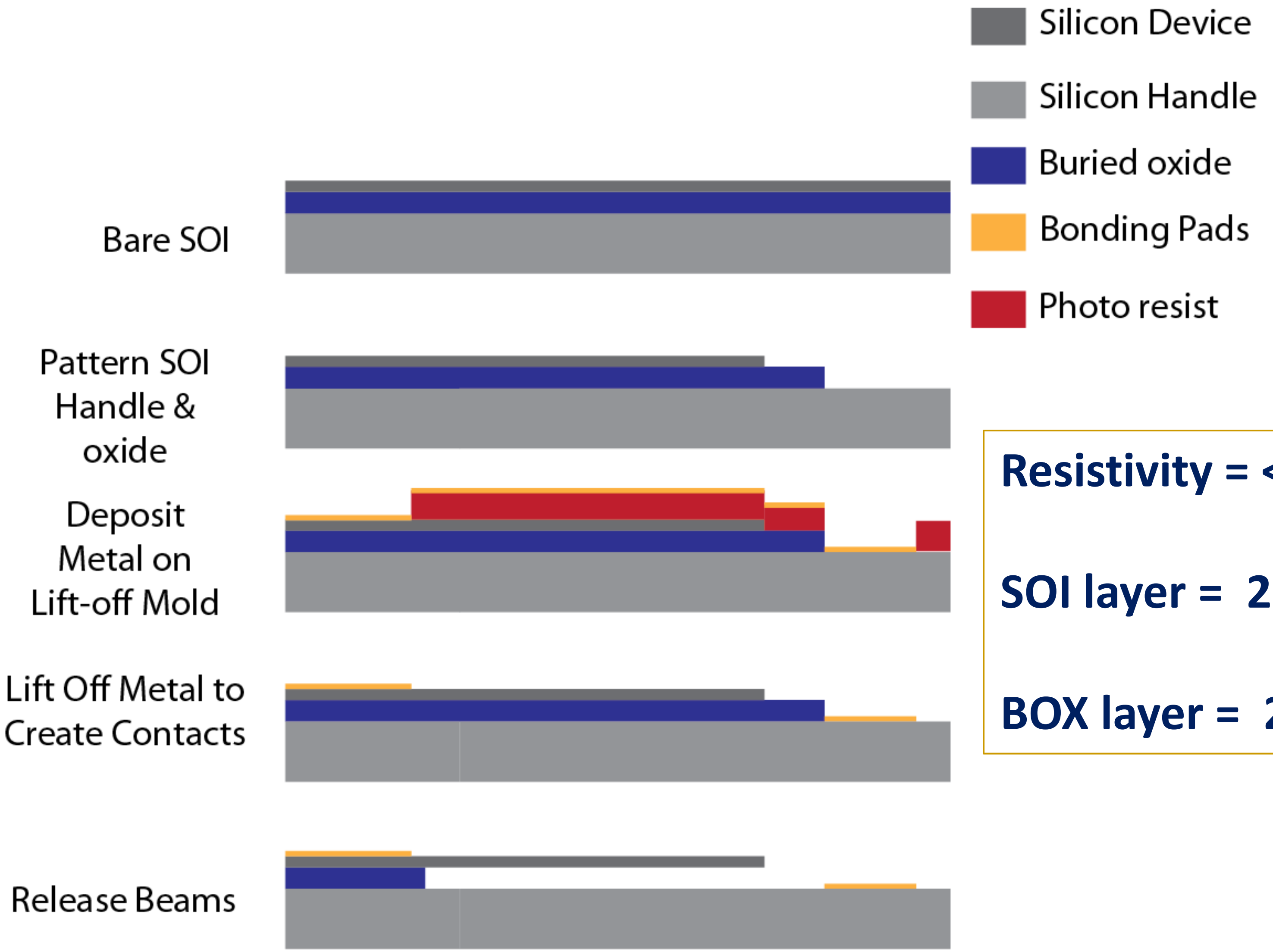
- No. of levels ?
- No. of Switches per level ?



- **Redundancy**
- **Reliability**



Fabrication Process



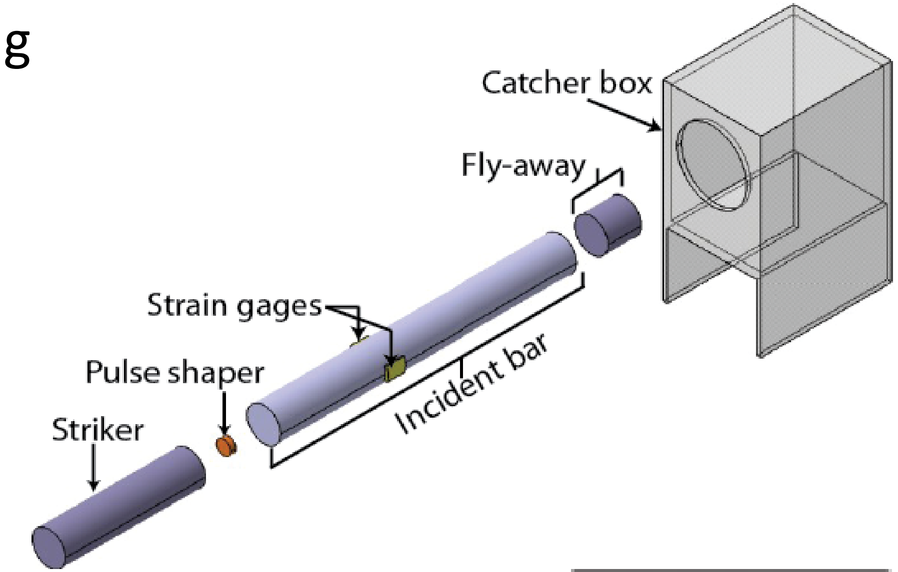
Resistivity = <0.01 Ω-cm

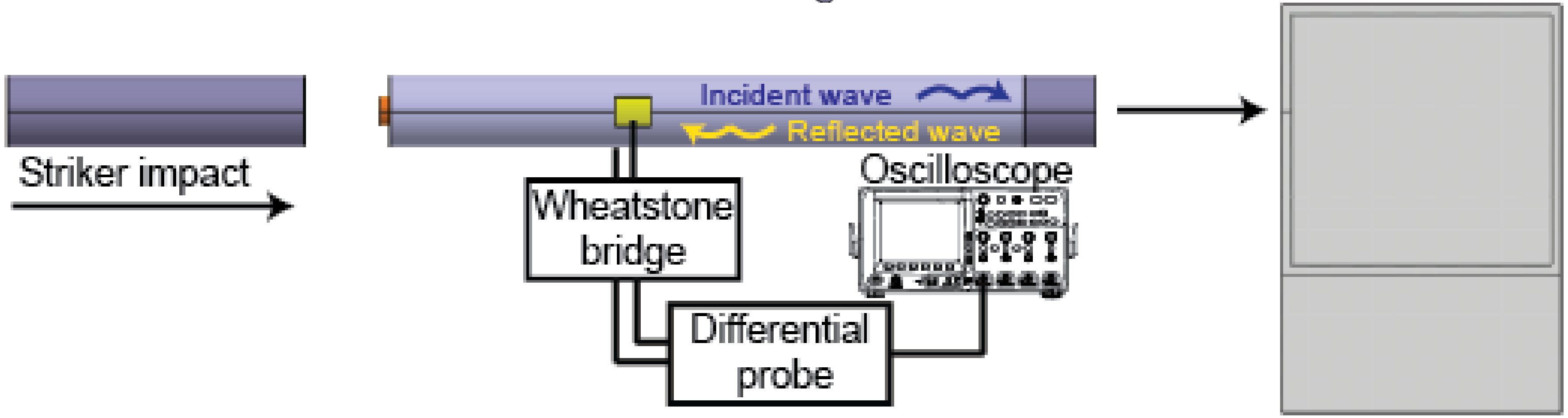
SOI layer = 20 μm

BOX layer = 2 μm

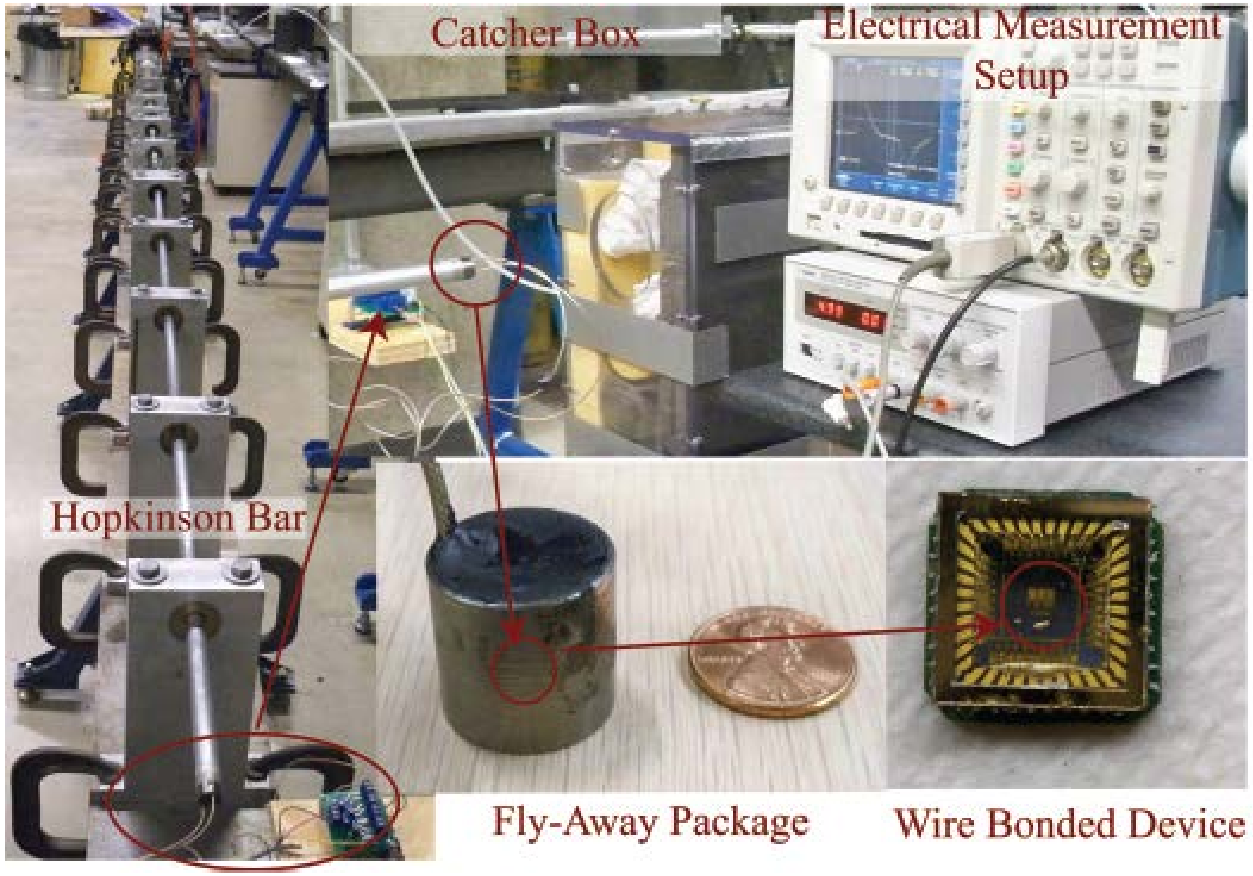
Acceleration Evaluation Setup

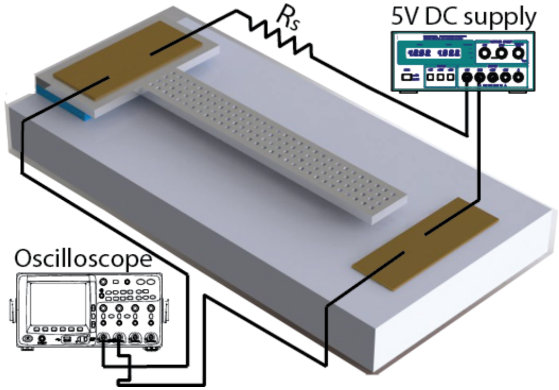
- Hopkinson bar techniques
  - Acceleration levels up to 120,000 g
  - Rise time as short as 20 µs
  - Fly away package - MEMS device
  - Courtesy of Prof Chen’s Lab



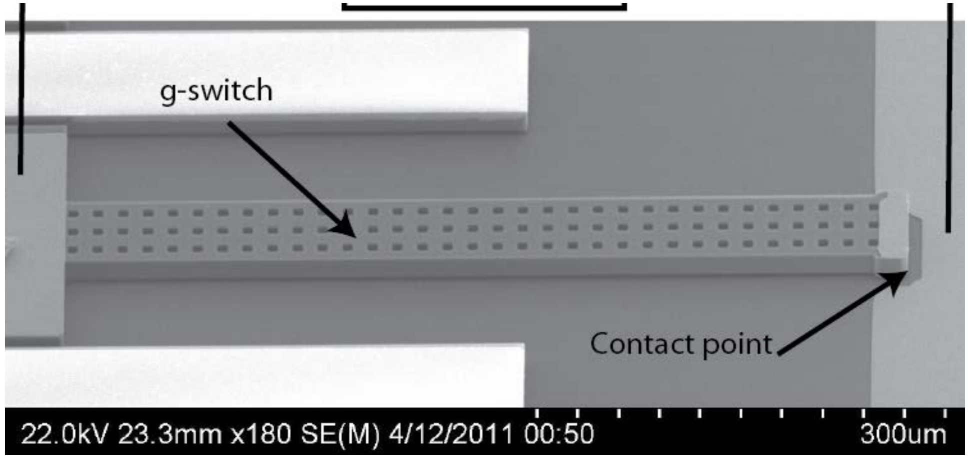


Measurement Setup





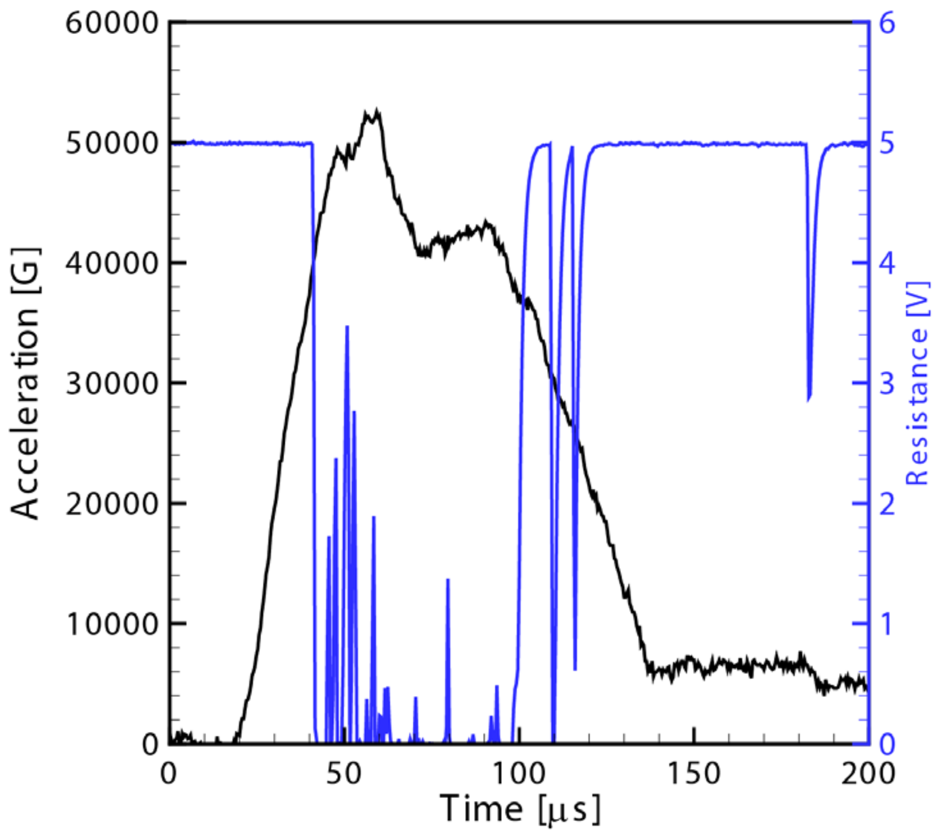
Electrical Setup

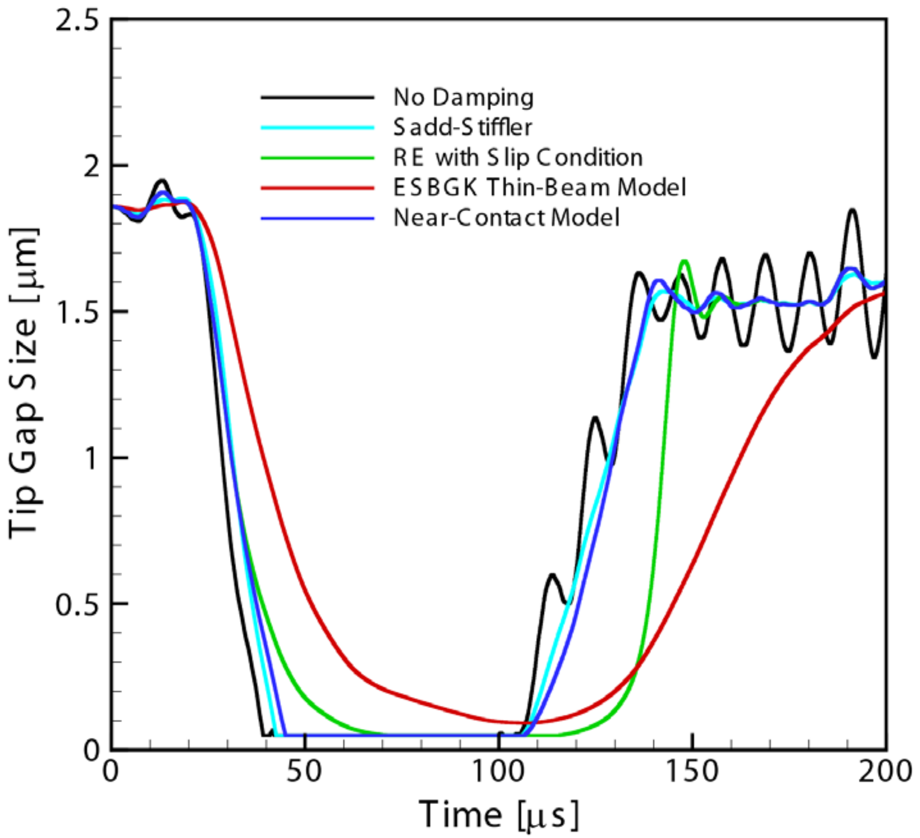


Key Features:

- Quicker disconnects and reconnect
- Faster measurements

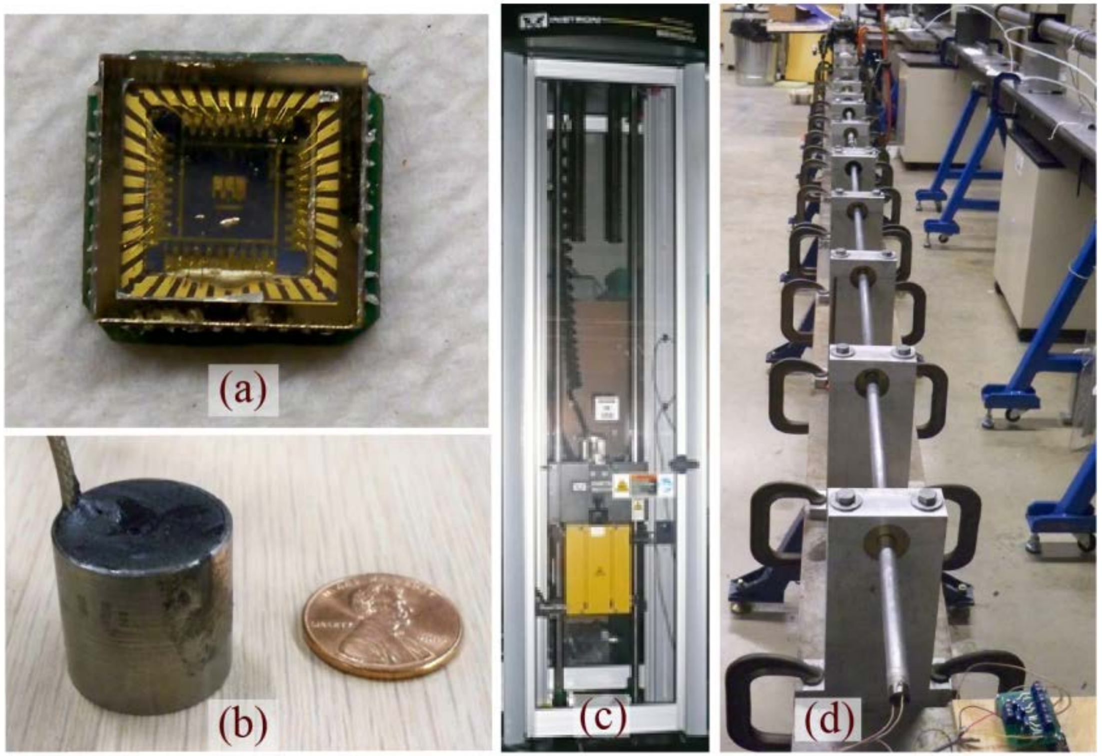
Measurements

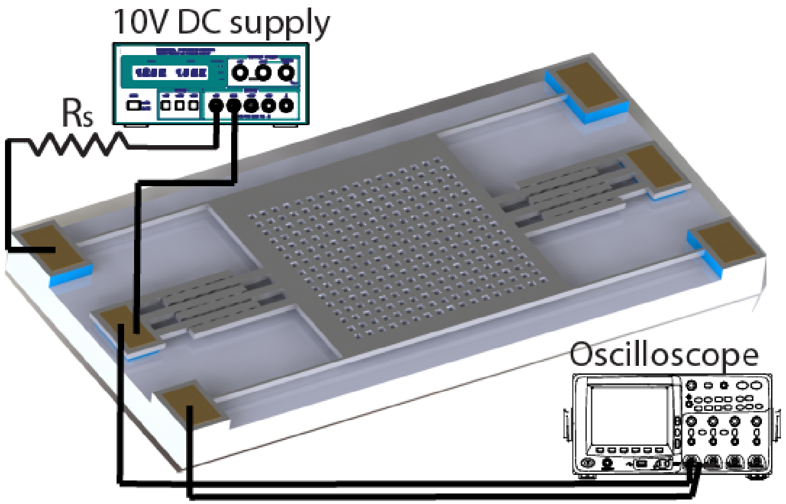




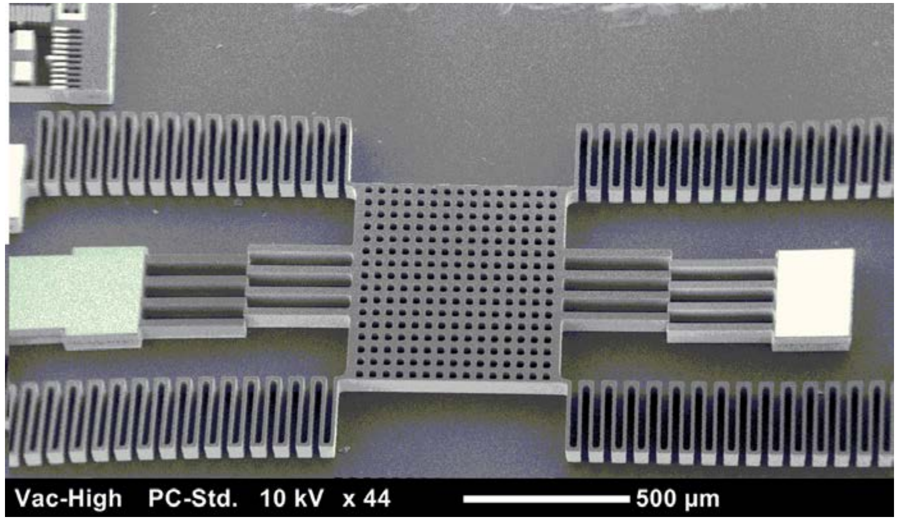
Measured and simulated response of 527.5-µm long g-switches under a typical applied acceleration load

Setup Overview





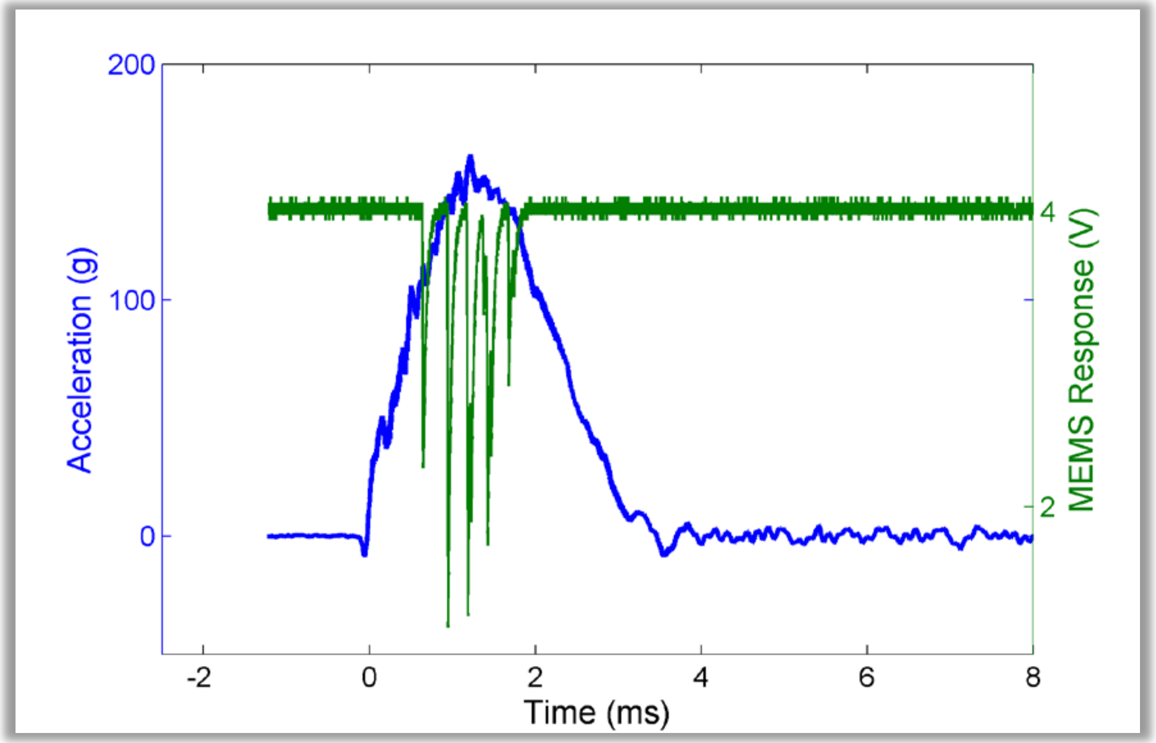
- Electrical Setup



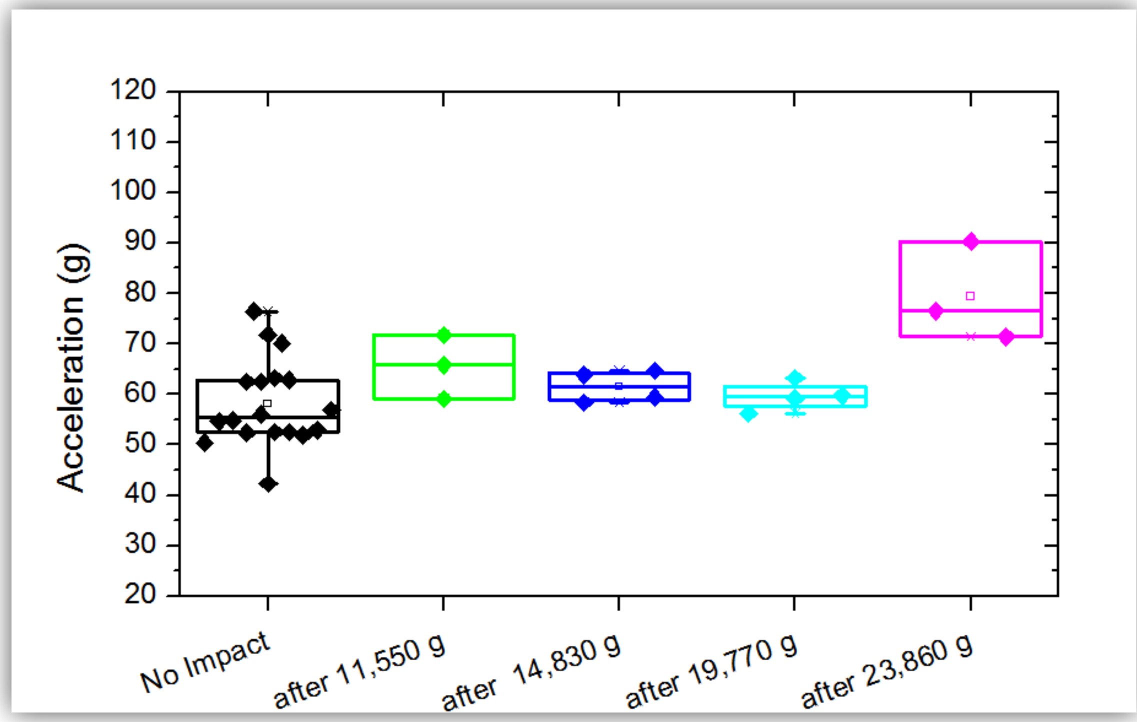
- Similar packaging process as high-g switch
- Low-g tests: Instron Dynatup 9250 HV drop tower courtesy of Prof Chen’s group.
- Acceleration measured using Endevco 7270-2K
- Testing Process:
  - Low-g test → High-g tests → Low-g tests

Results

PURDUE UNIVERSITY Discovery Park



Parallel combination of 130-g switches triggering at 129 g for a peak applied profile of 147 g. Contact bouncing is also observed



Trigger acceleration before and after high-g impact tests using the 60-g design. Failure occurred after 23,860 g

ELECTRONIC RADIATION DOSIMETRY

Personal Radiation Dosimetry

Necessary for

- Personnel working close to radiation sources (e.g. doctors, miners)
- Monitoring of area/environmental levels
- Radiation assessment situations (routine or emergency)
- Measurements of clinical dosage

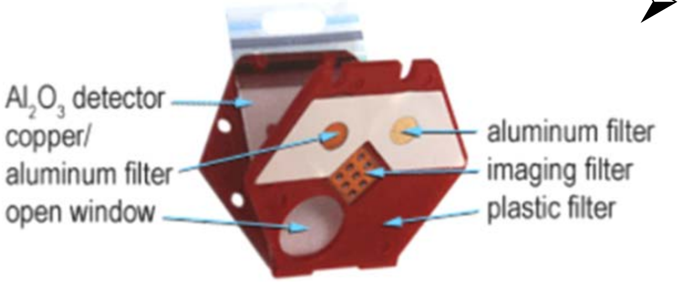
Examples of detector technologies

Active detectors

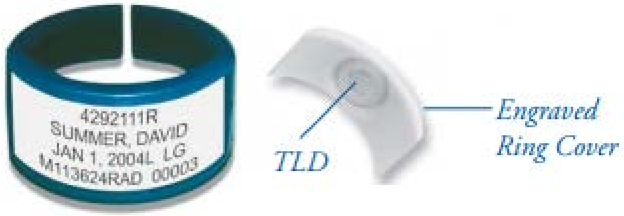
- Ionization Chambers
- Scintillators

Passive detectors

- OSL (Optically Stimulated Luminescence)
- TLD (Thermally Stimulated Luminescence)
- RadFETs (MOS-based)



Structure of an OSL dosimeter



TLD-based ring dosimeter

Source: Landauer

MOSCAP Sensor: 2D Geometry

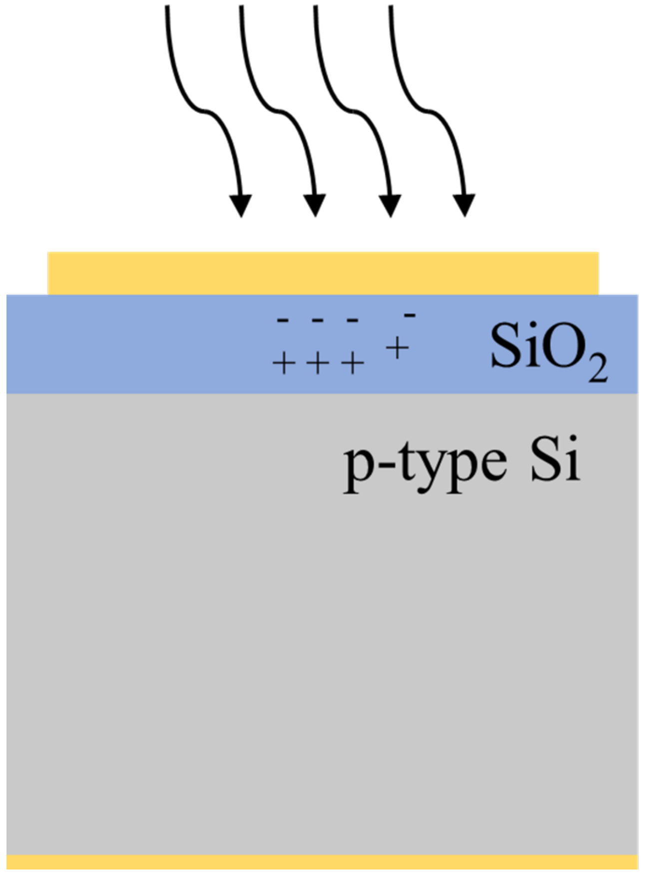
PURDUE UNIVERSITY Discovery Park

Principle of operation

- Radiation creates electron-hole pairs in SiO_2
- A positive bias drives electrons to the gate and holes to Si/SiO_2 interface
- Holes get captured in the SiO_2/Si interface

Sensor architecture

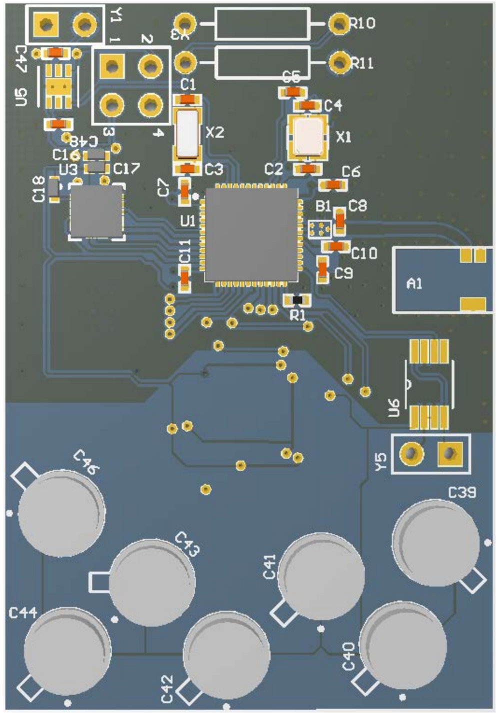
- 2x2 mm^2 active area
- ~ 450 nm dry-wet-dry SiO_2
- p-type silicon substrate
- Ti/Au top electrode and back contact

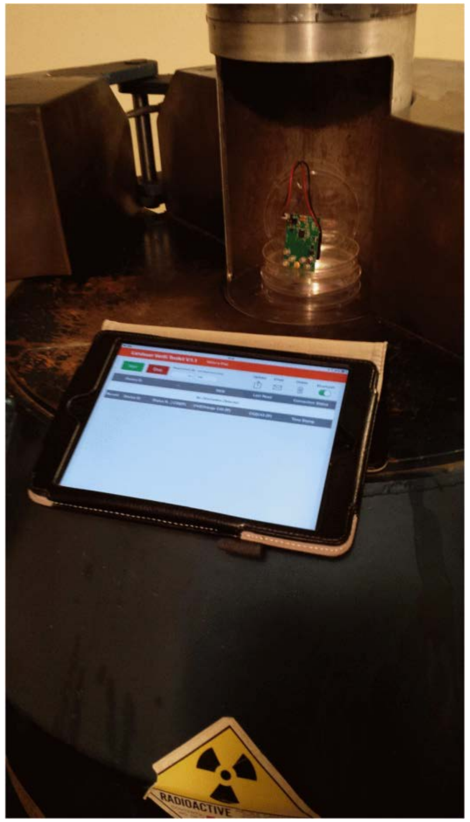


MOSCAP sensing principle [1]

[1] Scott et al., IEEE Sensors 2015

Readout Circuit





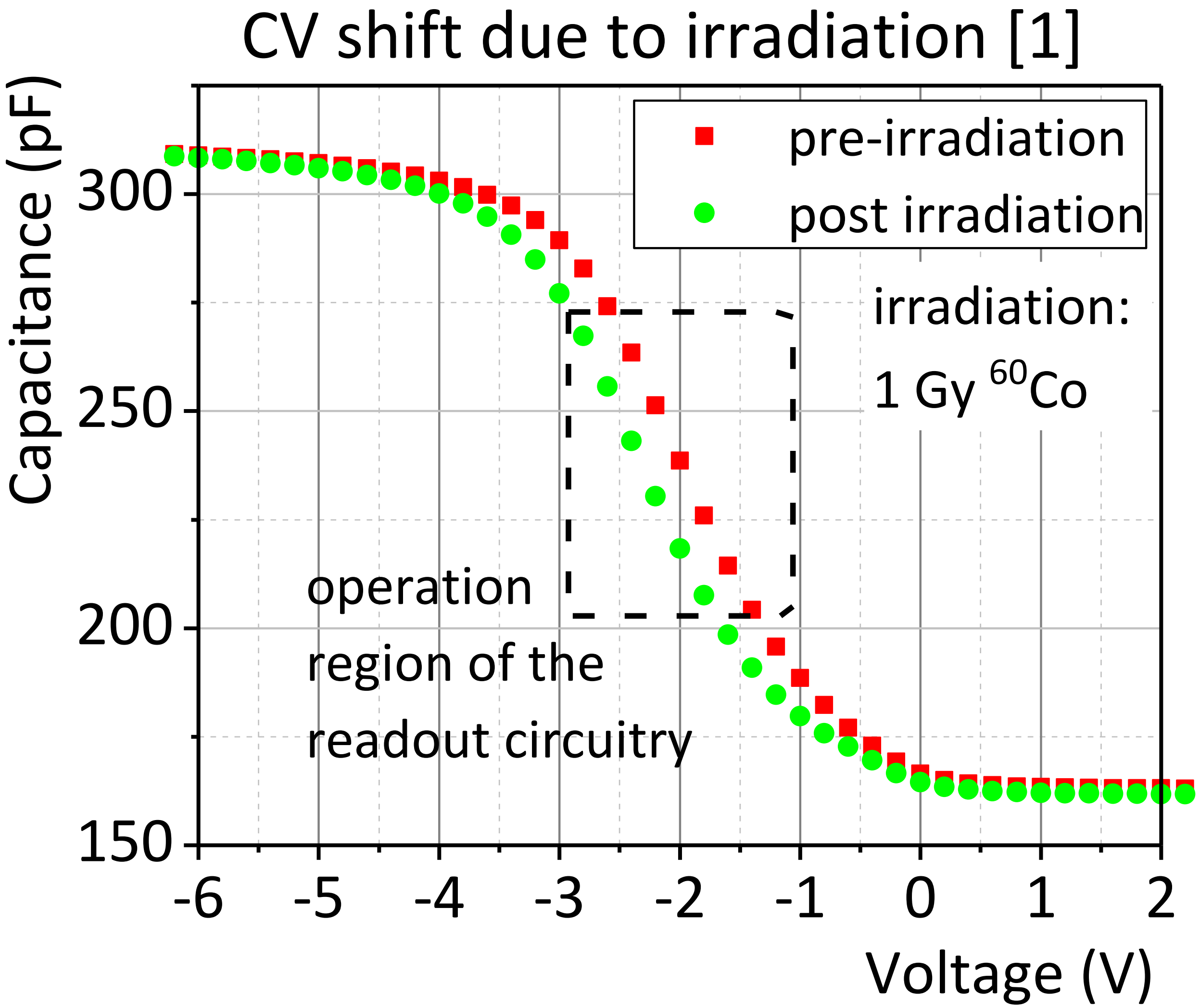
- The dimensions of the board are approximately 20 mm by 50 mm
- The circuit contains the integrated circuits for the capacitance measurements, the storage and wireless transmission of the measurements through Bluetooth or ANT protocols
  - The PCB can accommodate up to 7 sensors and is powered by coin-cell batteries.
  - Cap-to-digital module: ams PCAP01AD (resolution ~17bit)
  - Data processing and transmission (BT): Nordic nRF51422
  - Single coin cell battery operation

Courtesy of Harris Mousoulis

Readout Mechanism

Capacitive sensing

- Trapped positive carriers create a shift in the C-V curve of the MOS sensor
- A high resolution capacitance-to-digital module compares discharge time to a reference



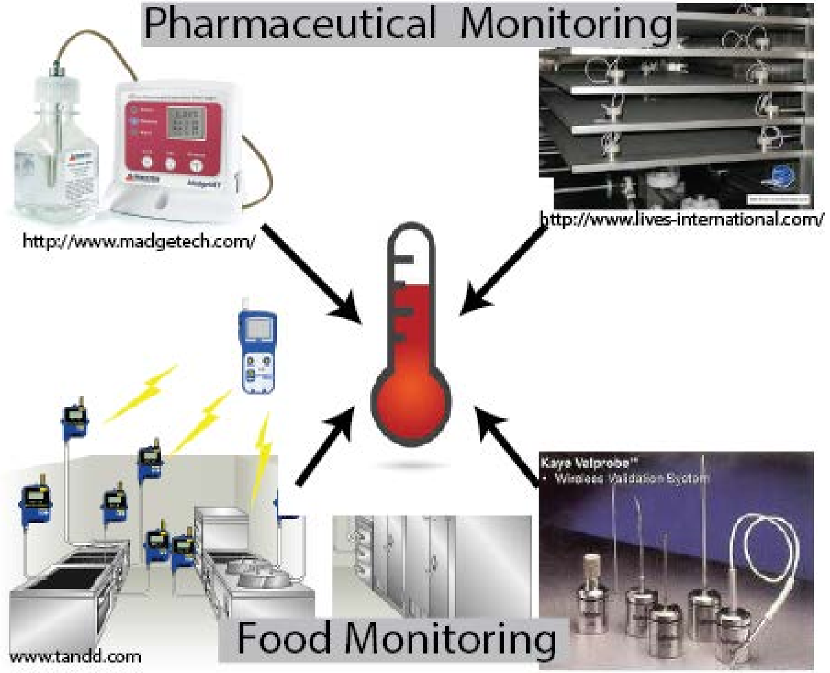
[1] Mousoulis et al. IEEE Sensors 2016
[2] Scott et al., EuMC 2015, pp 706-709

SENSORS FOR LYOPHILISATION

Motivation & Current Technologies

PURDUE UNIVERSITY Discovery Park

Messy cables in development dryers!!

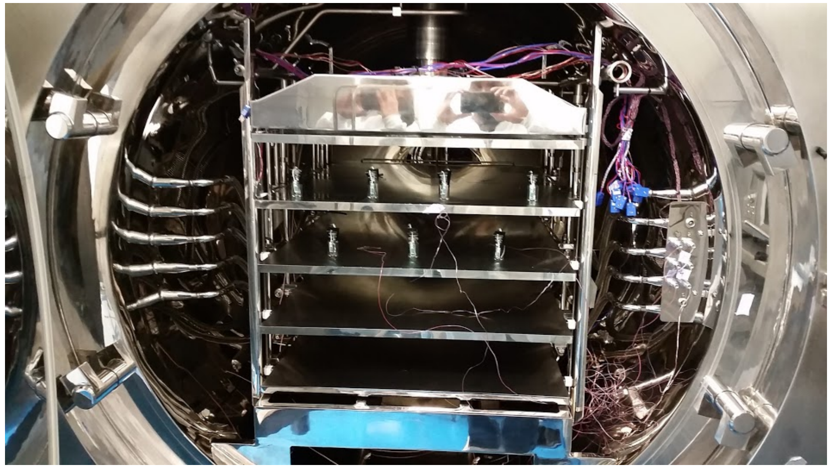


- Current Technologies

Elllabs

Tempris

Madgetech



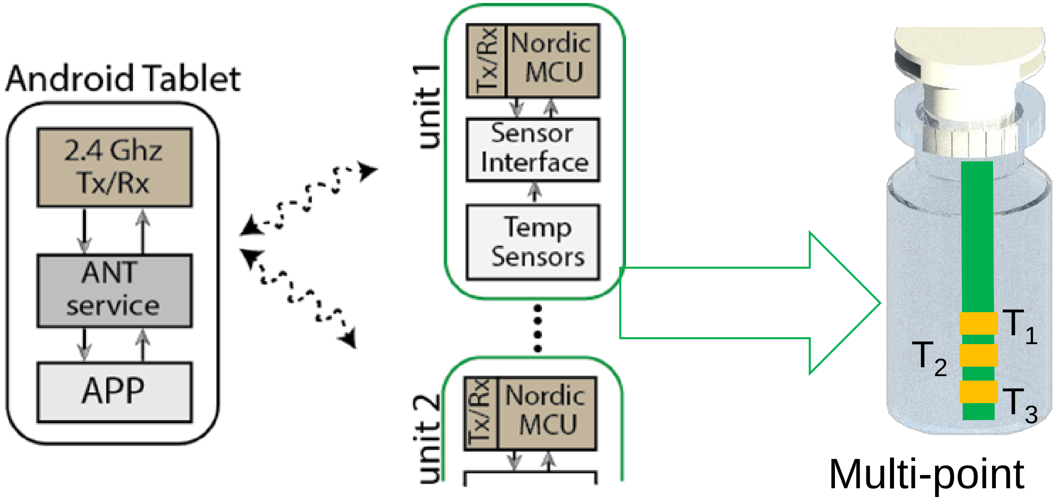
- *Limited to 16 sensors maximum*
- *Few are wirelessly powered*
- *Many limited to battery operation*
- *Most expensive solutions, rarely used in lab*

Multipoint Sensor design

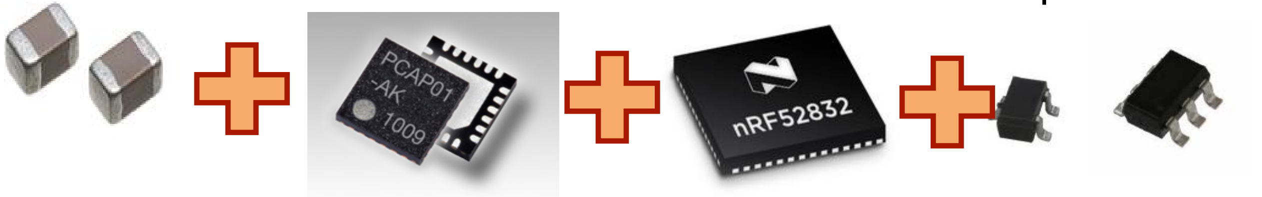
PURDUE UNIVERSITY Discovery Park

ANT™

ANT+™



Multi-point temperature

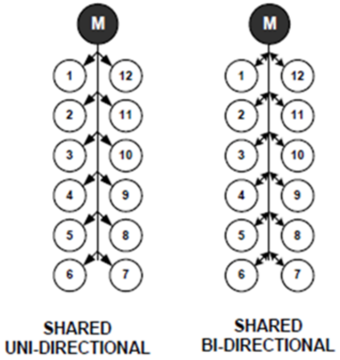


Temperature Sensing elements	Capacitive measurement module	Radio & Computing Unit	Wireless powering module

- **Proposed System**

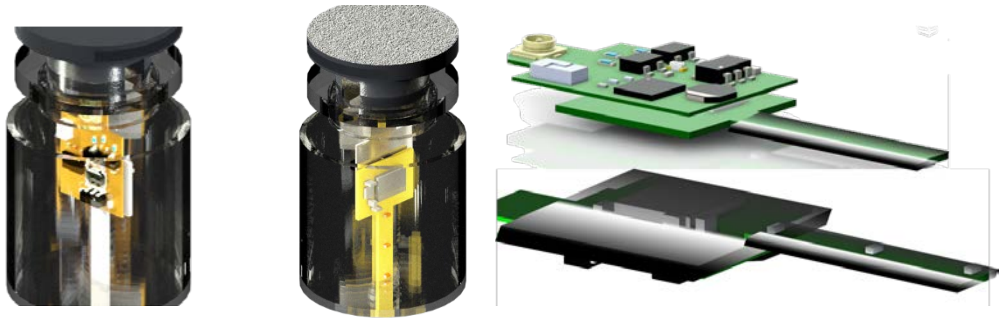
  ANT- based 2.4 GHz system

  - Sensor (Leaf) Node
    - Capacitive Temperature sensors
    - ANT transceivers
  - Base-station (Central Node)



- ***2^{32} devices possible & Wirelessly Powered***

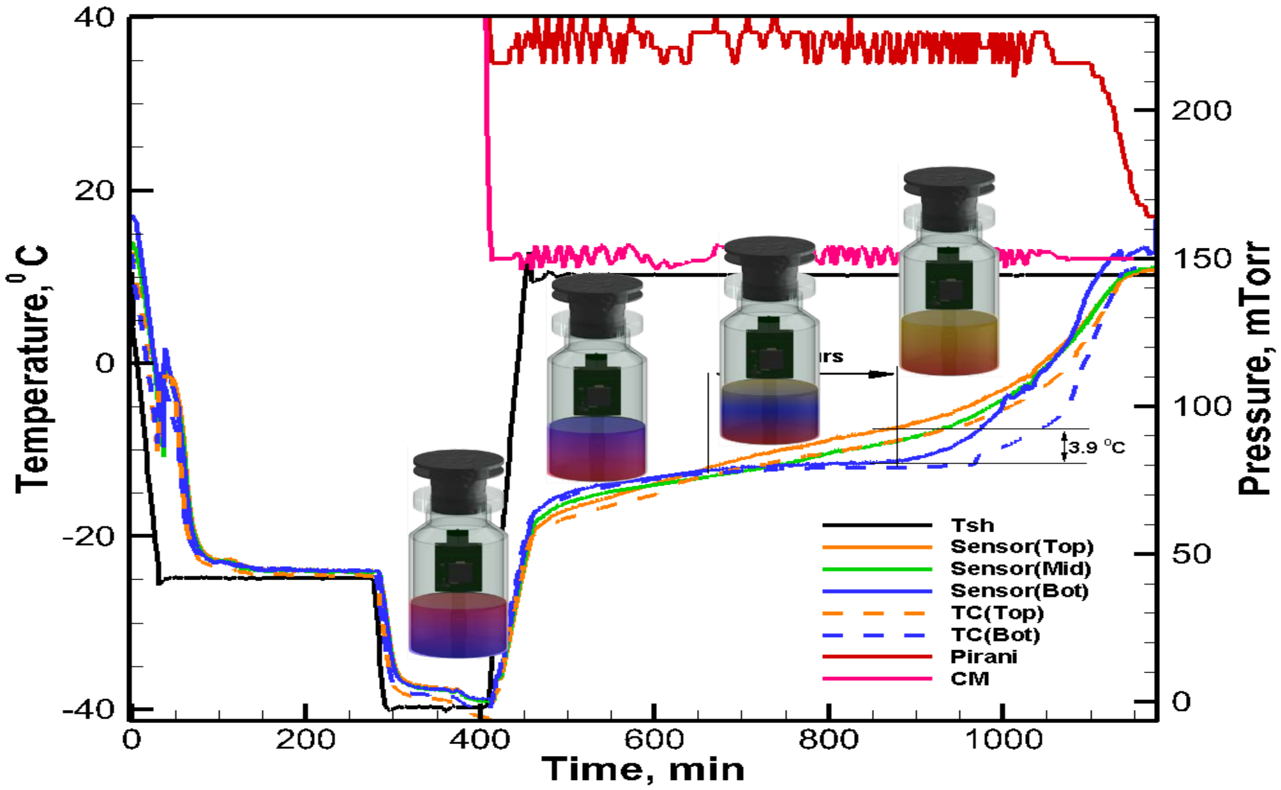
Results



Designed footprint of 25 mm X 10.40 mm

- Low power transmission: < 1mW
  - Active phase 1-2s
- CPU current consumption: 0.285 mA
- Sleep Current 530nA

Under battery operation:
Transmitting twice a min
*CR2032 : **1 year***
*AAA : **2-3 years***



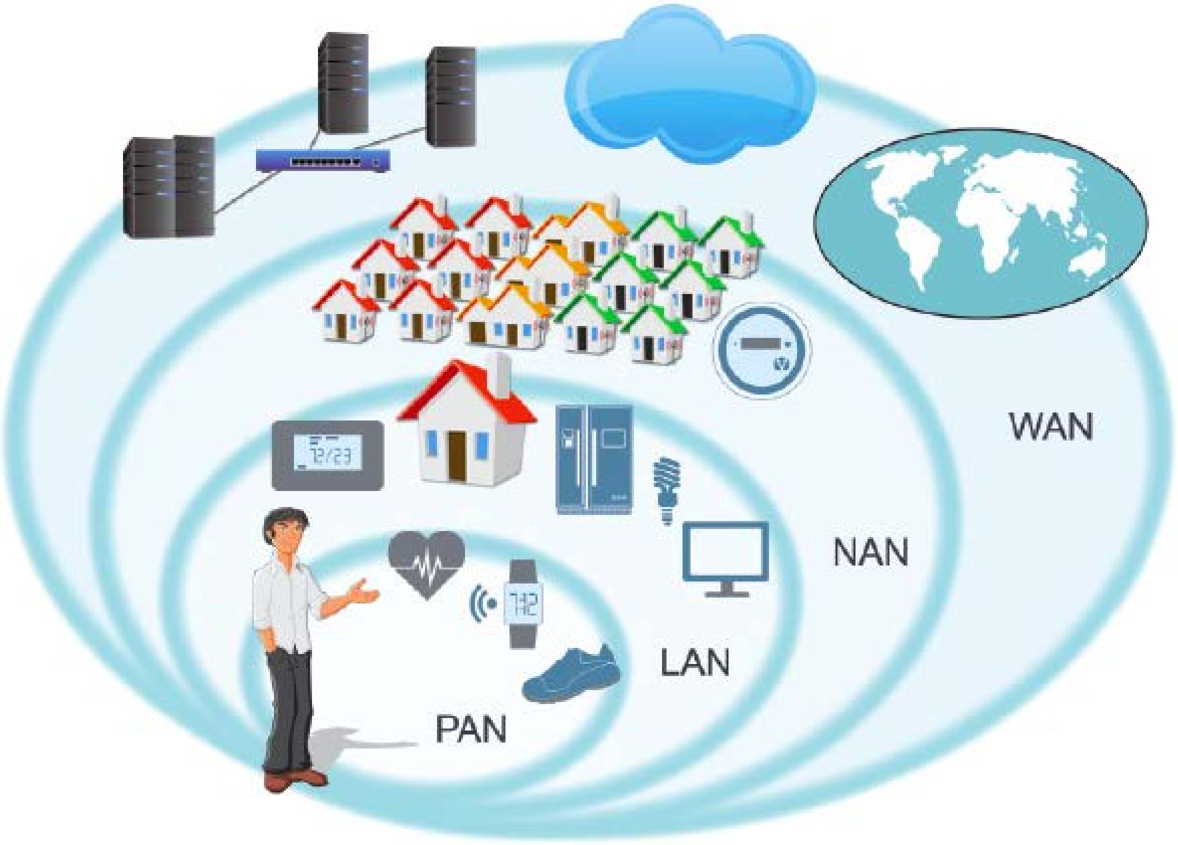
Track nucleation, equilibrium in freezing, primary drying and end in drying with changes in heat flux at production scale in aseptic environment

Resolutions of < 0.01°C achieved!

SENSORS IN AGRICULTURE & MANUFACTURING

Internet of things (IoT) – Connectivity to the world

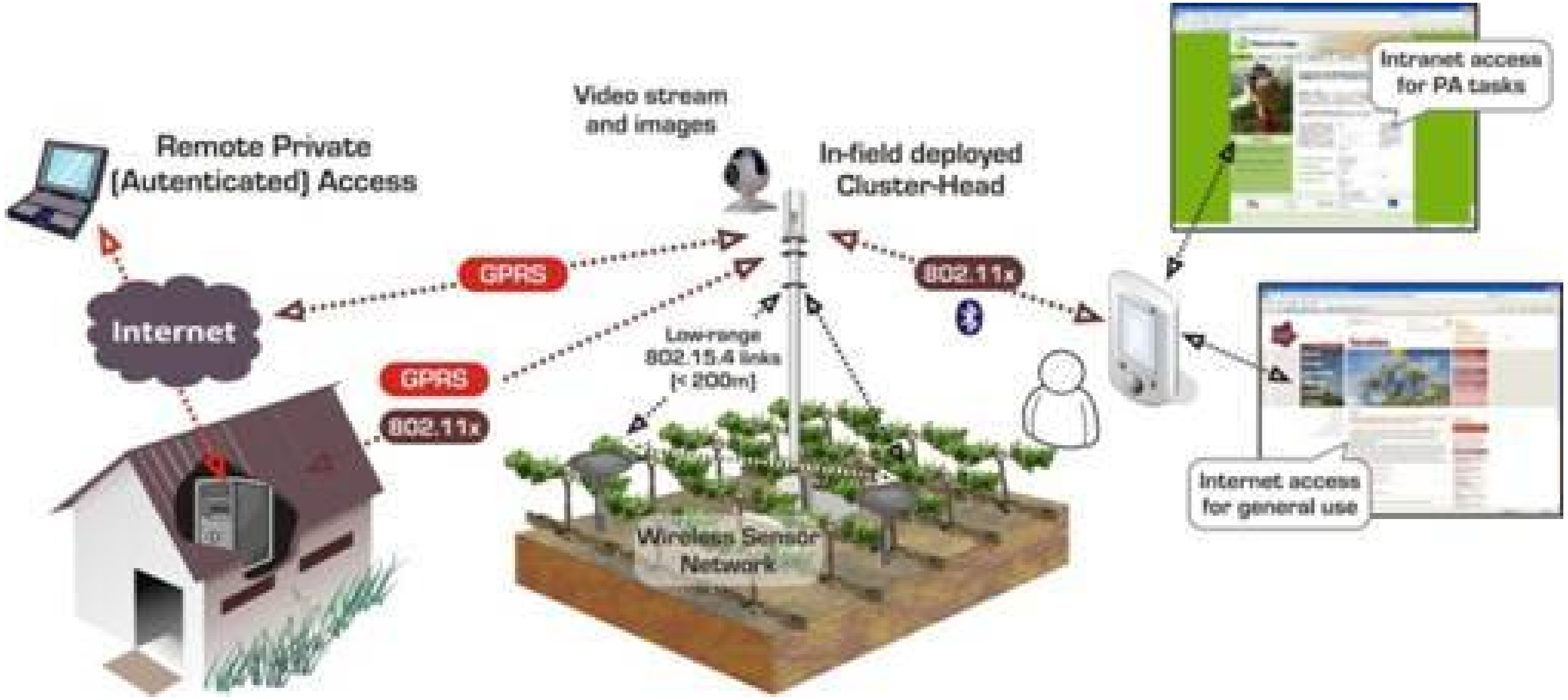
- To enable a connected world: sensors need a network
- Networks can be classified according to covered area
  - **A**rea **N**etworks
    - **P**ersonal
    - **L**ocal
    - **N**eighborhood
    - **W**ide
  - IoT devices typically use
    - PAN
    - LAN
    - NAN



Source: https://thesedays.com/thoughts/understanding-connectivity-for-internet-of-things

LoRa - Agricultural sensors networks

PURDUE UNIVERSITY Discovery Park



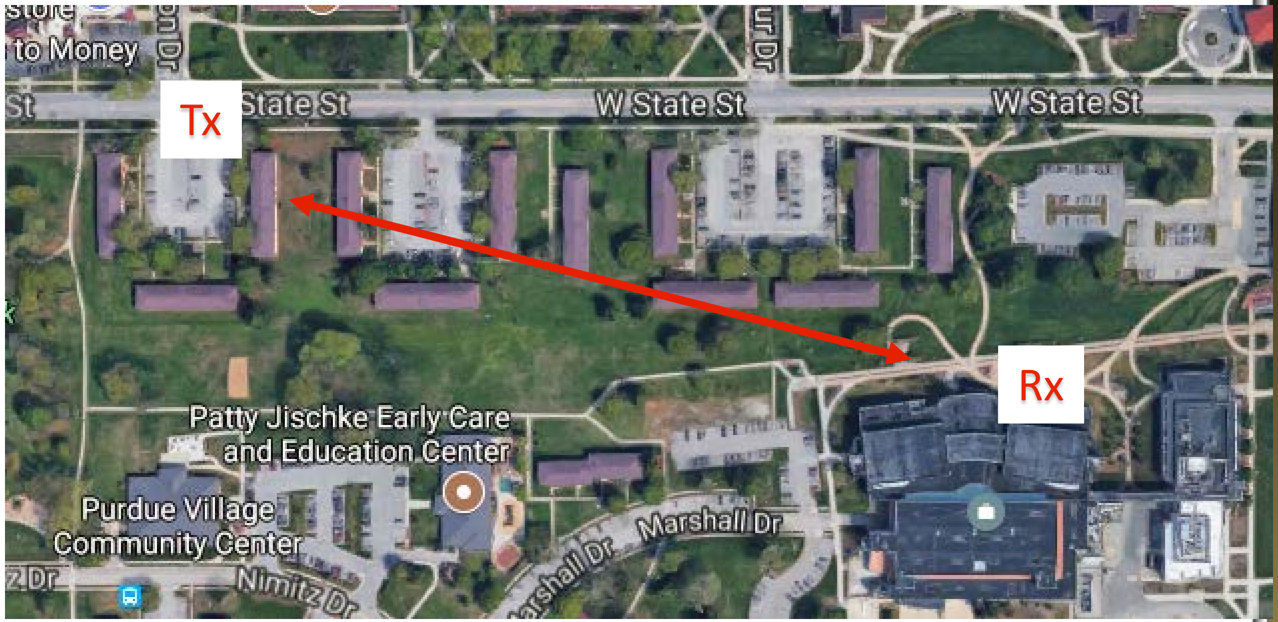
- Mesh network implementation benefits agricultural environments.
- Monitoring of soil and other environmental conditions benefits farmers
- Integration with Personal area networks such as ANT or Bluetooth sensors:
  - Creates a truly integrated mesh network.

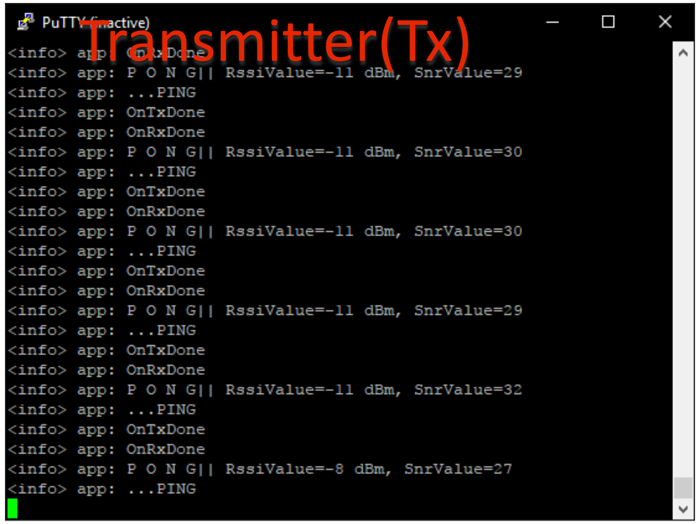
https://wirelessmeshsensornetworks.wordpress.com/tag/wireless-sensor-networks-and-its-applications/

LoRa – Semtech SX1272 at Purdue University

PURDUE UNIVERSITY Discovery Park

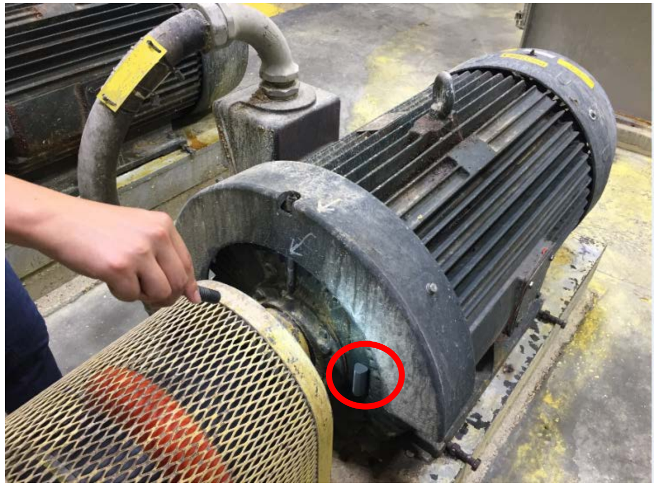
- High sensitivity :
  - Down to -137dBm
  - Low Rx current : ~10 mA
  - Development in progress
  - LoRaWAN implementation
  - Cloud Gateway developed





Data received over a distance of 1 km

Sensors in Manufacturing

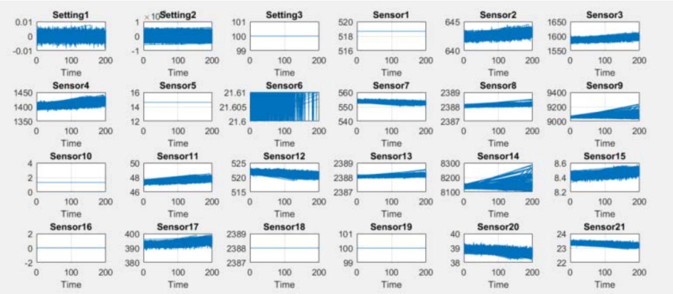



- Bluetooth based vibration sensors
  - BlueVision
- Monitoring vibration of pumps
  - At Tate & Lyle
- Bearing failure predictions
- Stator winding faults
- Communication via Bluetooth gateway and data remotely uploaded to the cloud

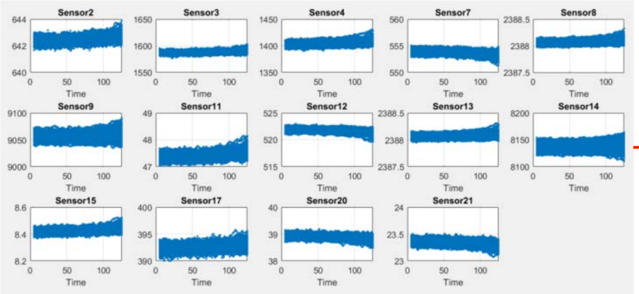
Courtesy of Woo Jae Lee

Predictive Analytics Technique

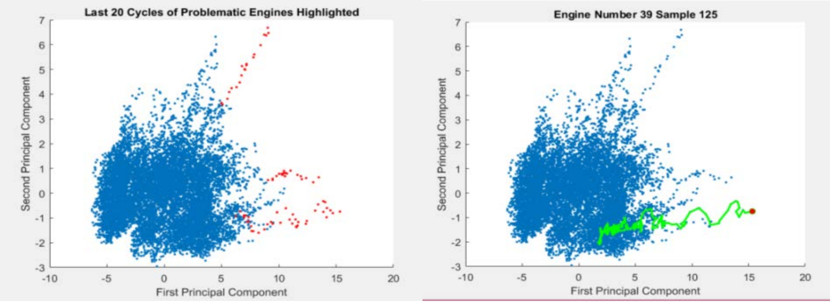
-Principal Component Analysis and Control Chart-



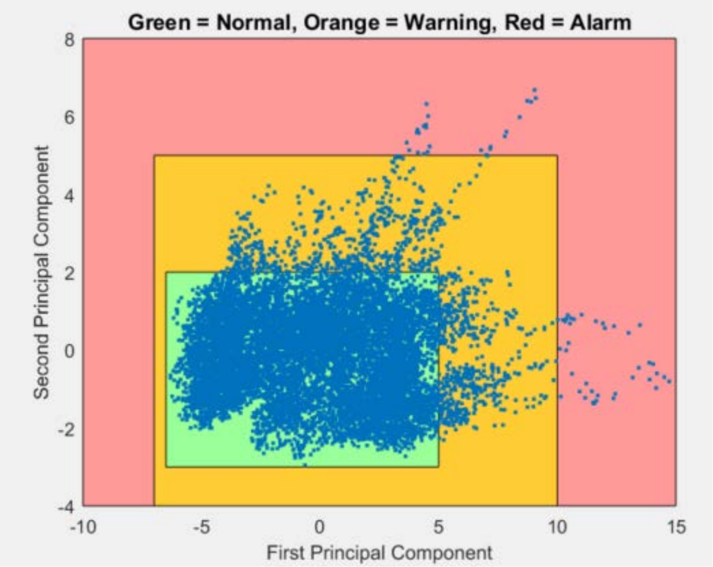
1. Read all sensor data



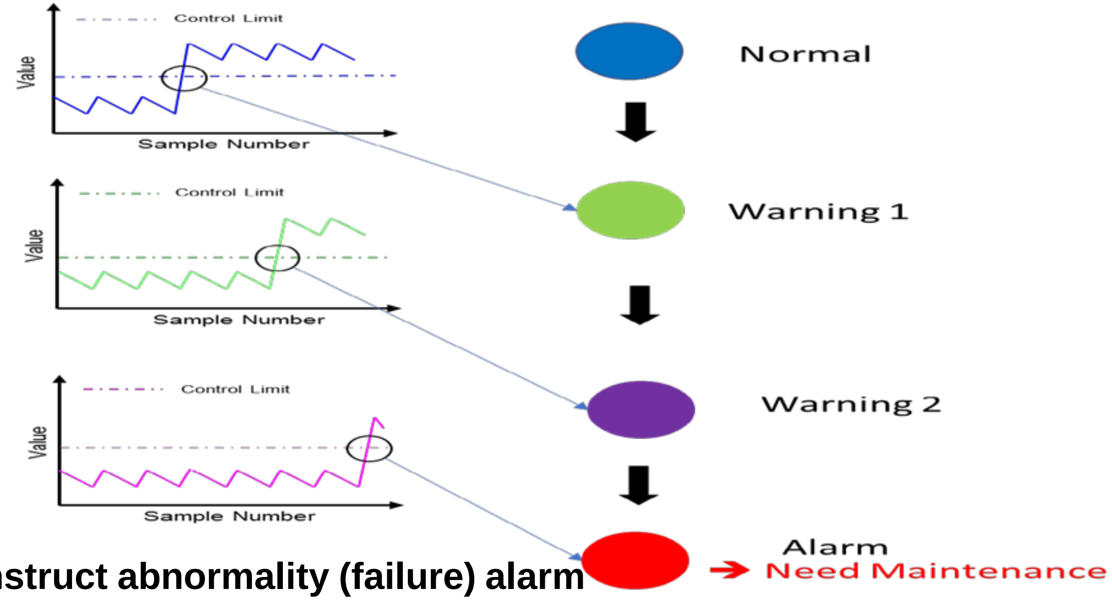
2. Remove noise and pick significant sensor data



3. Visualization to capture abnormal behavior (failure)



4. Detect abnormal behavior event (failure)



5. Construct abnormality (failure) alarm system using control chart

Courtesy of Woo Jae lee

Summary

- Birck Nanotechnology Center
  - Fabrication capabilities
  - Packaging Capabilities
  - Characterization Capabilities.
- Applications in sensor research at Birck
  - High-g MEMS switches
  - Radiation dosimeters
  - Lyophilisation sensors
  - Agriculture and Manufacturing Sensors.

ACKNOWLEDGEMENTS

- **IMA Life Team**
  - Ernesto Renzi, President IMA LIFE North America
  - Michele Arduini, Sales & Marketing Director
  - Arnab Ganguly (PhD), Technology Manager IMA LIFE FD
- Landauer Corp
- LyoHUB
- Dan Hosler, Research Engineer at Purdue
- Wesley Allen, Research Scientist at Purdue
- Charilaos Mousoulis, Research Scientist
- Xiaofan Jiang, Woo Jae Lee, and Heng Zheng, Graduate research Assistant

- Contact

  - Nithin Raghunathan
  - Email: nithin@purdue.edu
  - Phone: 1-765-496-7326
  - Office : BRK2038

Thank You!