Electrical Transport Tutorial: The Final frontier

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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

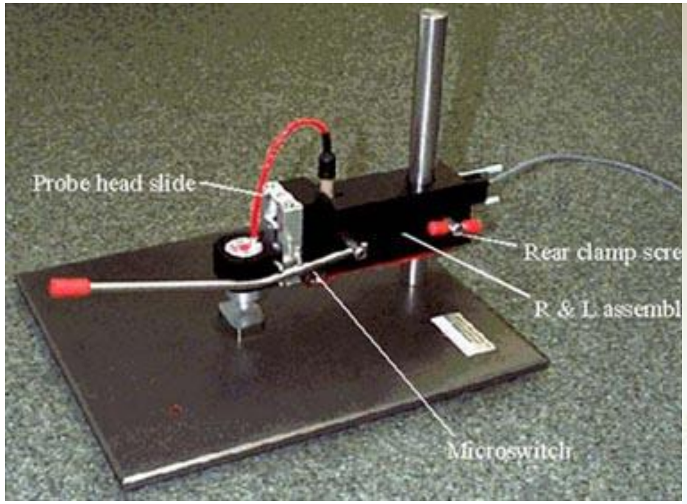
https://www.purdue.edu/discoverypark/birck/

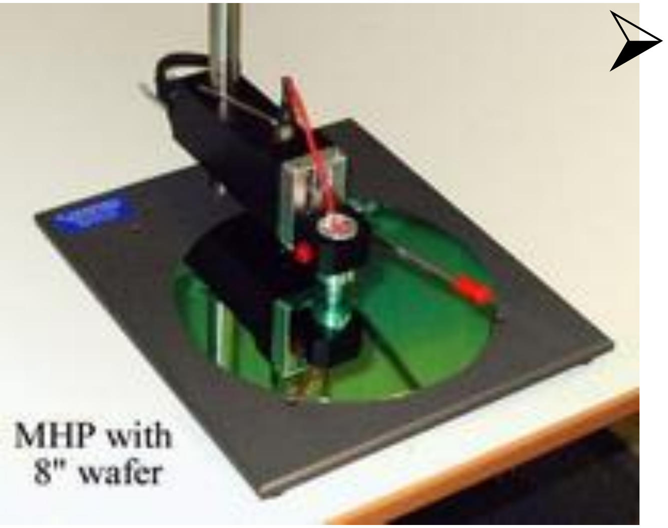
CHARACTERIZATION TOOLS

Probe Station : Overview

Station name	location	# probes	Sample size max	Chuck bias?	Stage temp range	Compatible electronics	Comments/features
Cascade MPS150 DC probe station	J Bay	4	4 inch	yes	20 to 200 C	4200-SCS	
Cascade PMC 200 DC/RF probe station	J Bay	4/ 2 Rf	6 inch	Yes	7 to 473 K	4200-SCS	Low Noise, high vaccum Probe Station. PI; Dana Weinstein
Jandel 4-point probe	J Bay	N/A	N/A	N/A	N/A		Sheet resistance measurements
LakeShore DC probe station	J Bay	4	2 inch		3.2K to 675K	4200-SCS	
MDC Mercury probe	J Bay	2	4 inch	yes	N/A	4200-SCS, Keysight 4990A	CV characterization of non contact sample
MM 6000 Cleanroom DC Probe station	Q Bay	4	4 inch	yes	N/A	4200-SCS	Cleanroom probe station
MM 6000 DC probe station	J Bay	4	4 inch	yes	N/A	4200-SCS, Keysight 4990A	
MM 8860 semi-automatic DC probe station	J Bay	4	8 inch	yes	-65 to +400 C	4200-SCS	Semi- Automatic Probe Station.
MMR H-50 Hall Effect station	1217						INACTIVE
Oxford Triton Dilution Refrigerator	F Bay						Not on recharge
Quantum Design DynaCool PPMS	1157	12	10mm		1.8 – 400 K	QD – ETO QD – Bridge	B= 9 tesla; Feedthru for any rack electronics
Quantum Design MPMS-3 SQUID Magnetometer	1157	8	5mm		1.8 – 400 K		B = 7 tesla; Feedthru for any rack electronics
Suss PLV50 DC probe station	1089	4	4 inch			4200-SCS	Feedthru for any electronics. LDV compatible

Jandel 4-point probe





Tool Name : Jandel 4-point probe
Location: 2100-J
Owner: Nithin Raghunathan

- Jandel 4-point Probe
  - 1.00 mm probe spacing
  - Loads: 30-60 g
  - Tungsten Carbide Tips
  - Fast measurements
  - **Sheet resistance**
  - Alternate to Van Der Pauw measurements for bulk materials

Probe Stations

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

- 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

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 .

Micromanipulator 8860– Semi Automatic probe station

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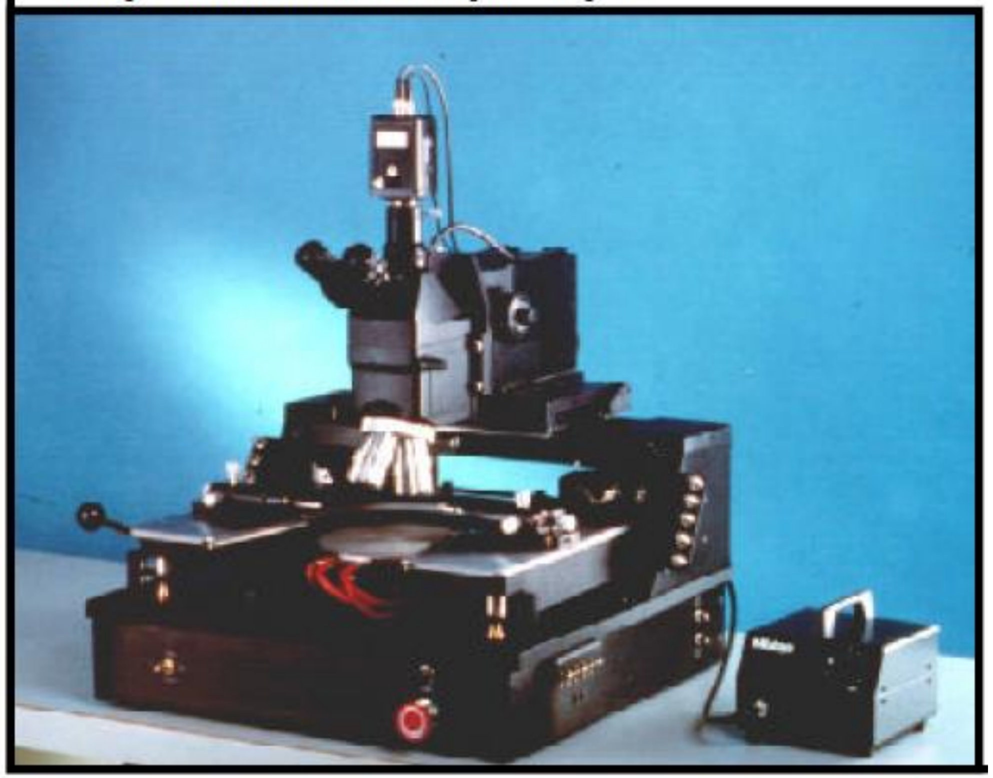
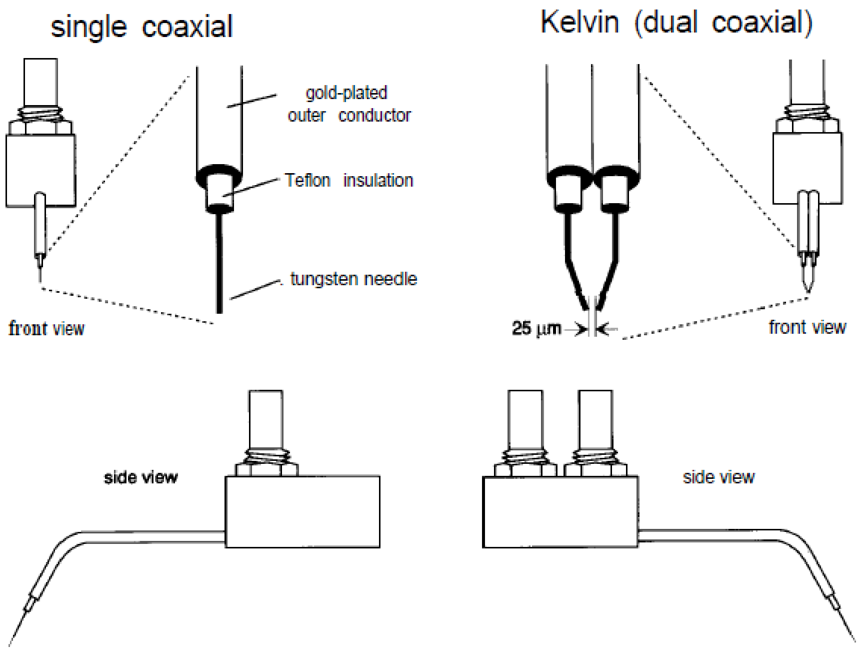
8860 probe station shown with optional optics.



- Features
  - Available at Birck
  - Semi-automatic
    - Stage X-Y & Z control
    - 0.1 um resolution
  - Ideal for C-V measurements
  - H1000 Thermal Chuck
    - -65 ^{o}C to 400 ^{o}C
  - Computer controlled
    - Enables Keithley SCS integration
    - Allows complex test routines
  - Equivalent system value: $145K

- Necessary for operation
  - $50K controller board upgrade
  - Necessary for operation (since computer is no longer supported)

Kelvin Probing



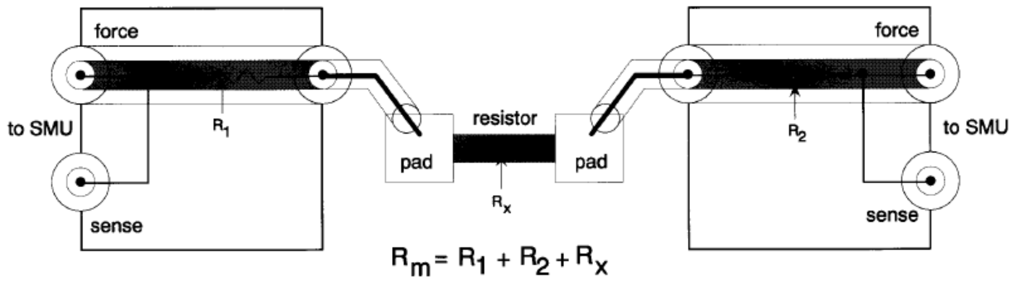
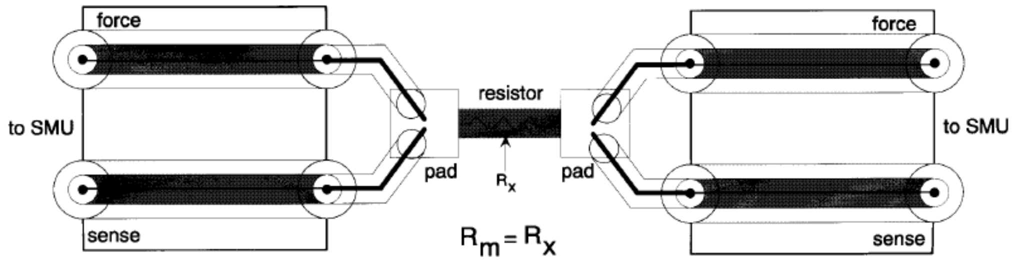


Figure 34. Non-Kelvin example.



- Compensates for parasitic resistances
- Low-level I/V measurements can be made.
- Compatible with Keithley 4200SCS
- Values measured with a Kelvin probe are more accurate

Kelvin probes offer lower noise measurements

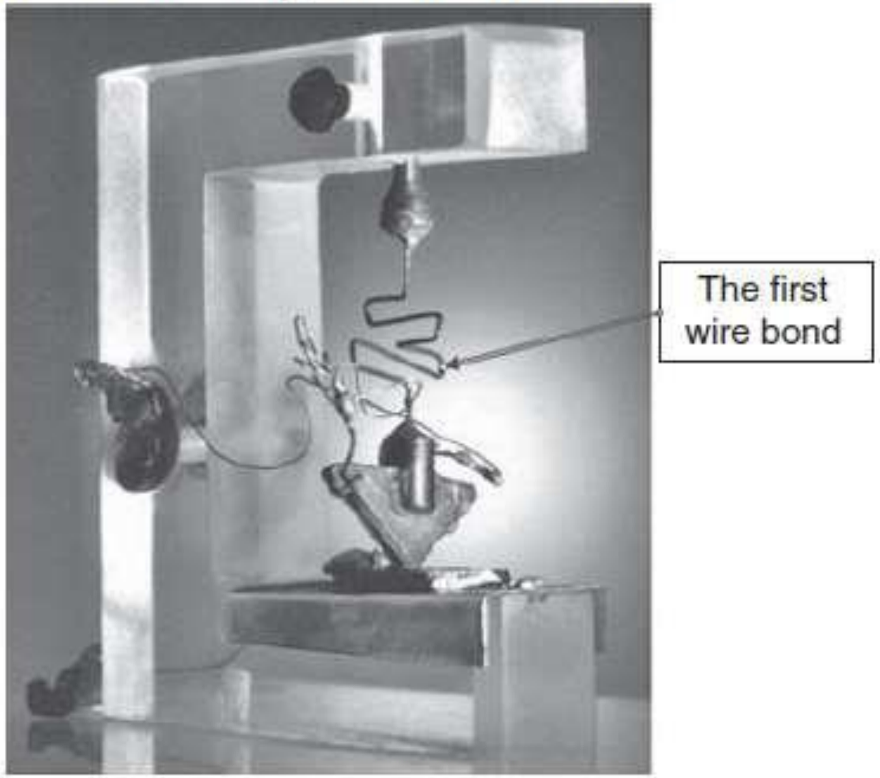
Courtesy of Cascade Microtech

WIREBONDING

Introduction

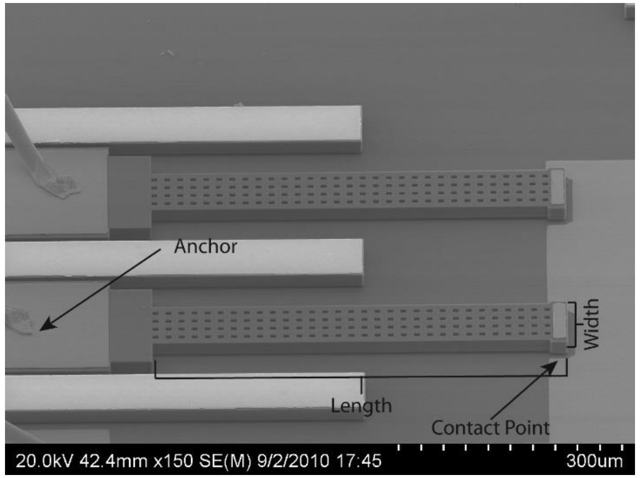
World's first wire bond!

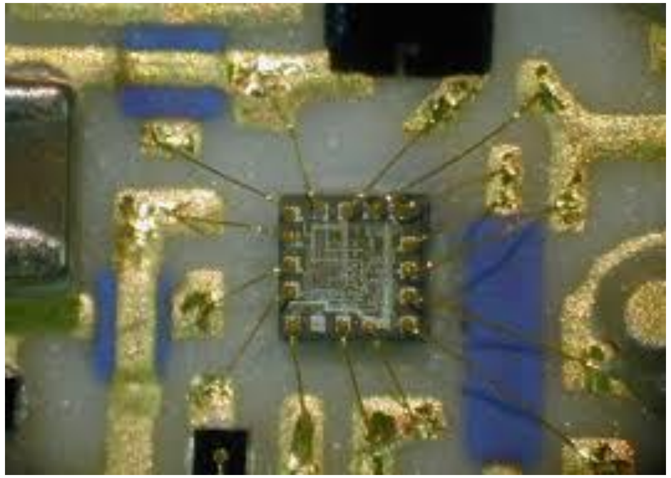
Note the manually attached wire bonds

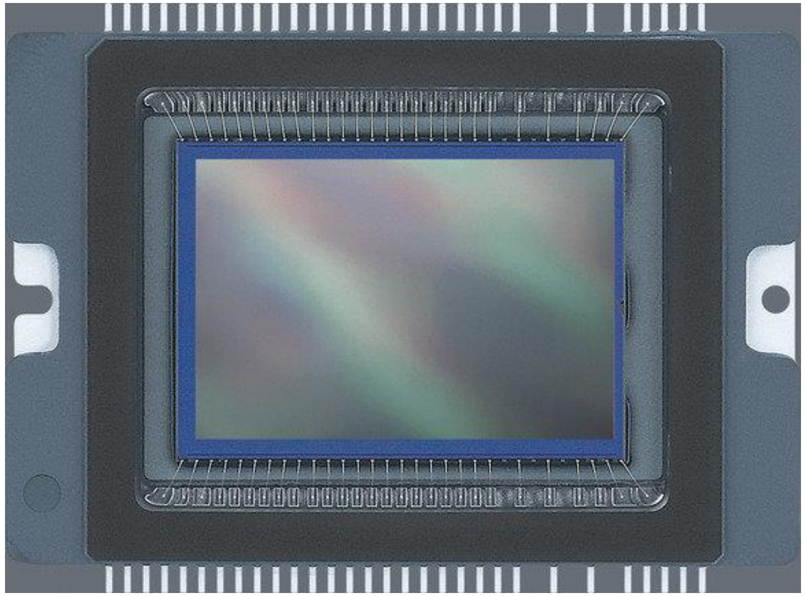


- Good electrical measurements need good contacts
- Wire bonding is the method of making interconnections between an integrated circuit (IC), printed circuit board (PCB), electronics or other semiconductor device and its packaging. (Wiki)

General Info





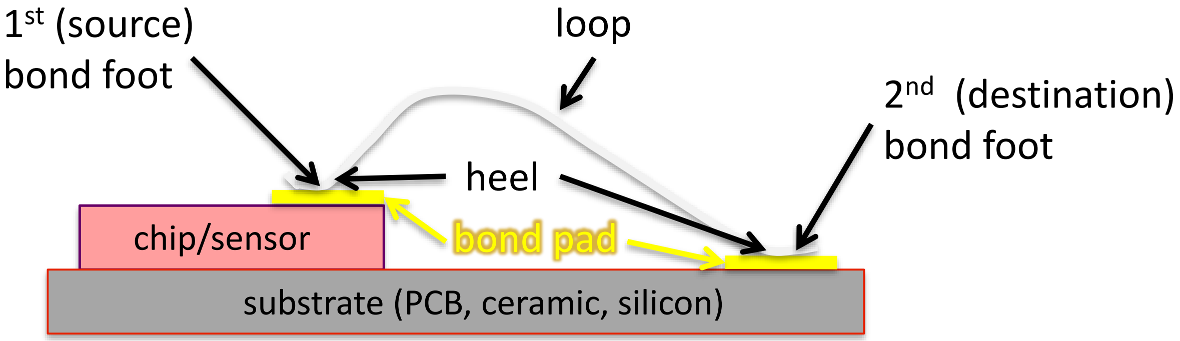


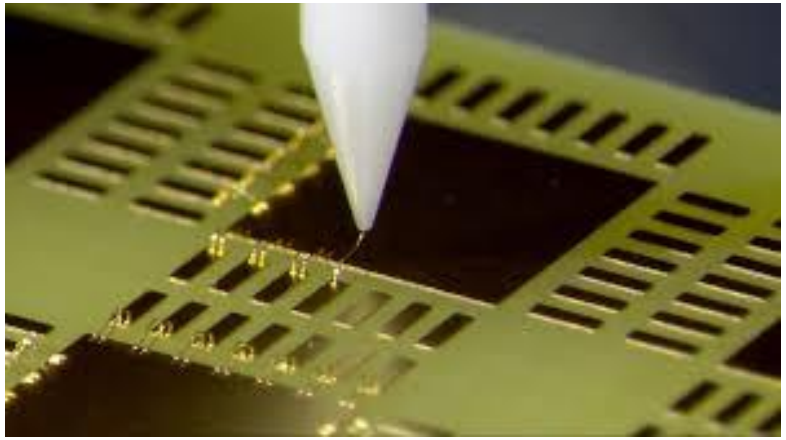
- Applications
  - Optical Sensors (Phone cameras)
  - DIP packages
  - PPMS stage
- Typically two types of bonding processes
  - Wedge bonding
    - Ultrasonic
    - Thermosonic
    - Thermocompression
  - Ball Bonding
    - Thermosonic

<u>Wirebonds are the standard for packaged semiconductor devices and measurements</u>

General Info

Some terminology:





Some bonding reference links:

2003 Bond Workshop at CERN: http://ssd-rd.web.cern.ch/ssd-rd/bond/default.htm

CERN Bondlab: http://bondlab-qa.web.cern.ch/bondlab-qa/Bondlab_Home.html

Our bonding tips: http://bondlab-qa.web.cern.ch/bondlab-qa/Recommendations.html

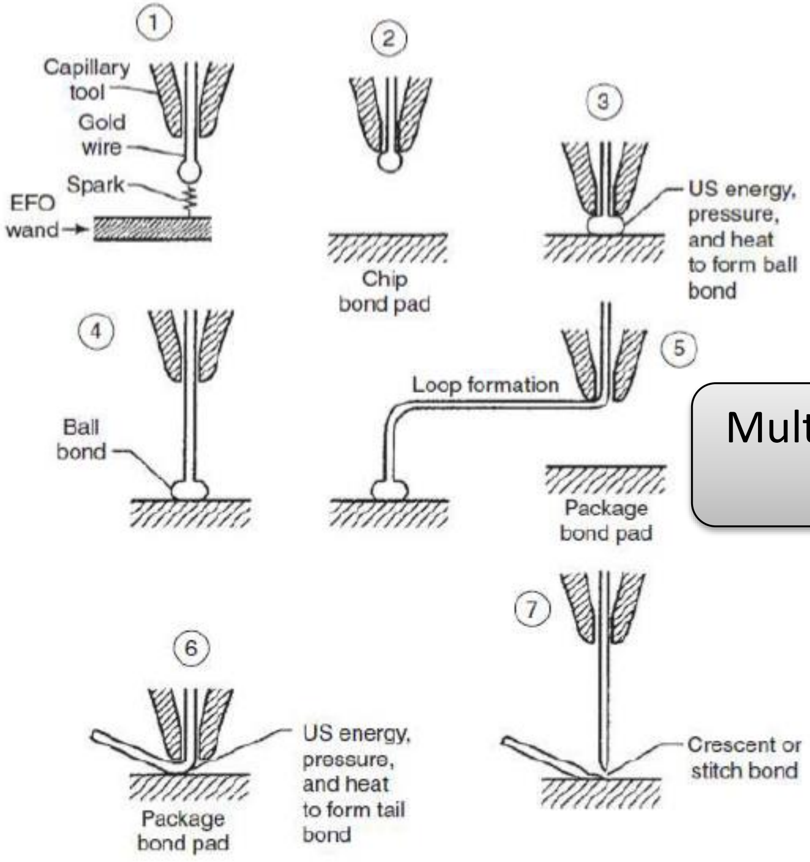
An excellent web resource (bonding and packaging): http://extra.ivf.se/ngl/

The “Bible”:

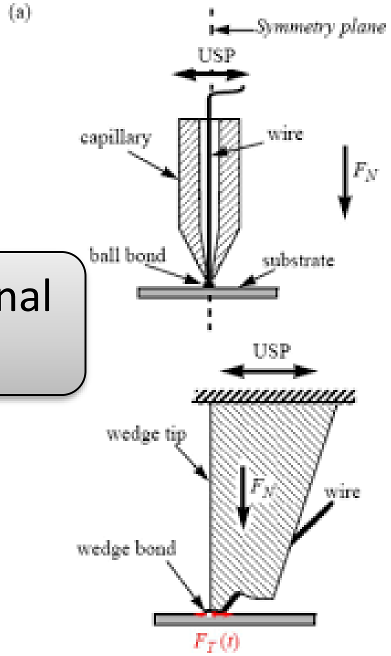
Harman, G., *Wire Bonding In Microelectronics*, McGraw-Hill, 2010 ISBN 0071476237

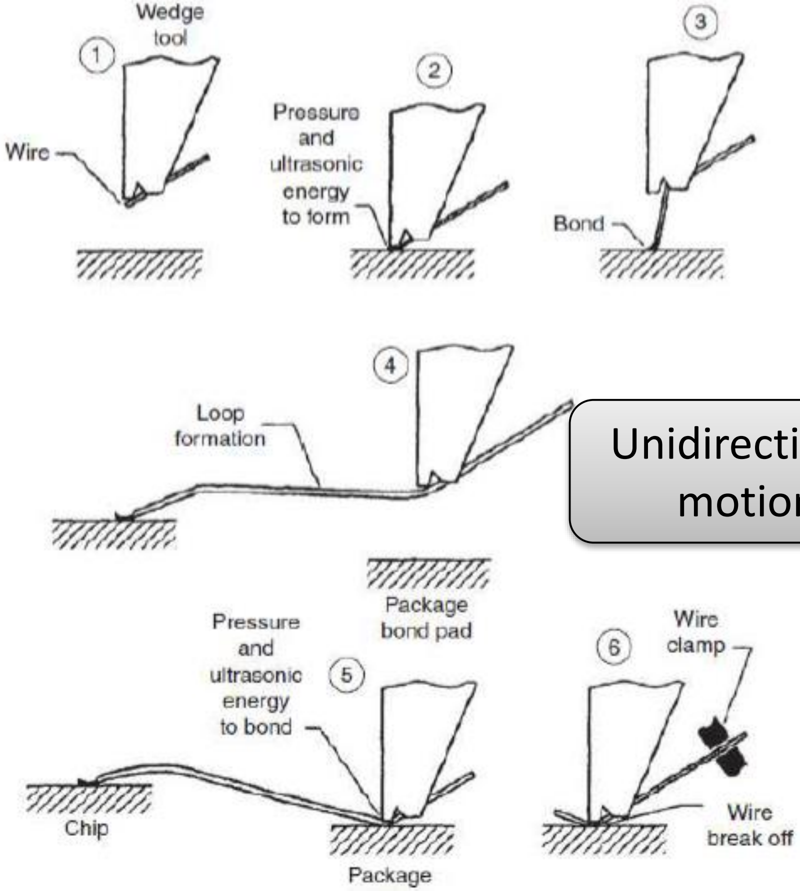
Courtesy of Workshop on Quality Issues in Current and Future Silicon Detectors

Ball Bonding Vs Wedge Bonding



Multidirectional motion



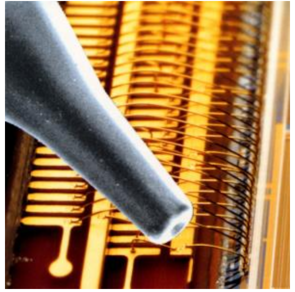
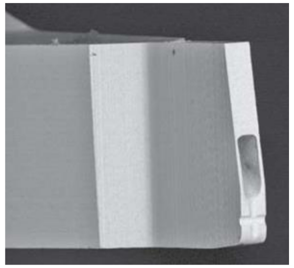
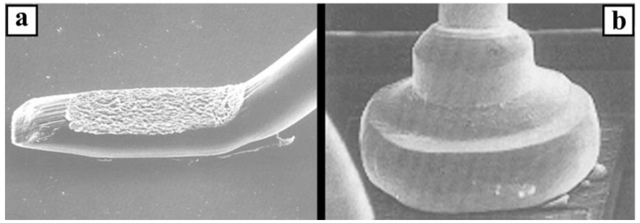
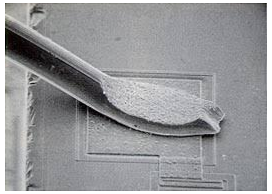


Unidirectional motion

Process is very similar to knitting/stitching

<u>Type of bonding affect range of motion in the bonding process</u>

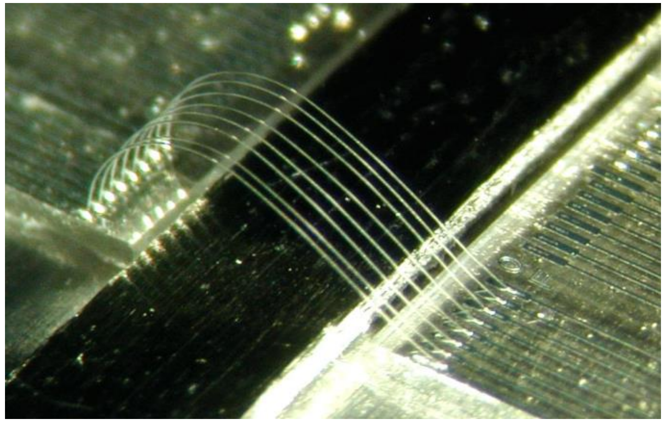
Bonding Comparisons

Technique	Ball Bond	Wedge Bond
Process	TC, TS	TS, US
Tool	Capillary 	Wedge 
Bond Foot		
Wire	Au	Al, Au
PAD	Al, Au, Cu (not preferred)	Al, Au
Speed	<20/s	<4/s

Wedge bonding Vs Gold Bonding

Why aluminium wedge over gold ball ?

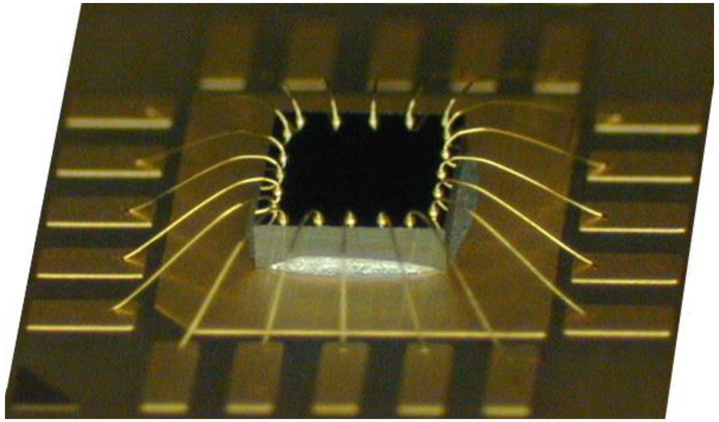
Aluminium wedge ultrasonic



Room temperature process
More control (larger parameter window)
Better at fine pitch
Excellent reliability on Al bond pads
Good reliability on PCB Bond Pands
Bonding is always done in a single directions

Similar Advantages are seen in Gold Wedge Bonding

Gold ball thermosonic (industry standard)

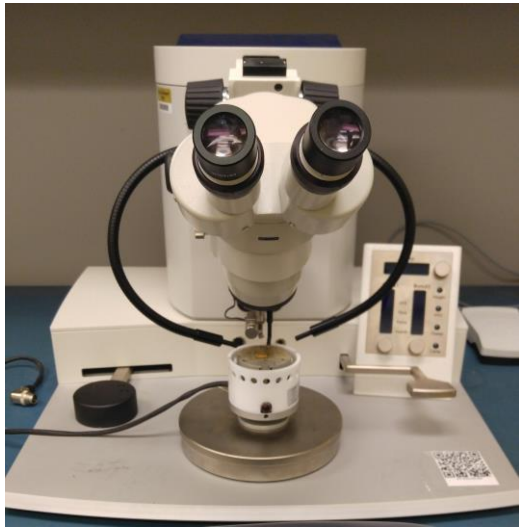


Needs heating of substrate (>150°C)
Smaller parameter window
Almost as good at fine pitch
Good reliability on Al bond pads
Problematic on PCB bonds
Allows for multidirectional boning
Higher Bond Strength

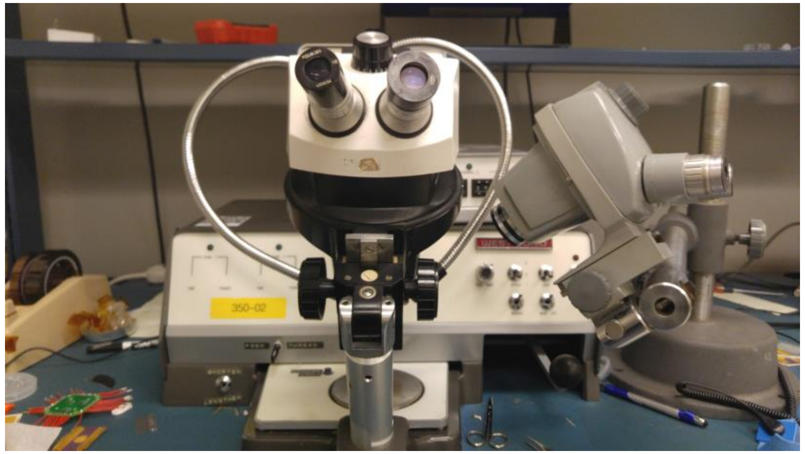
Used in ~90% of industrial packaged chips but copper wire use increasing

Choose the bonding process best for your sample

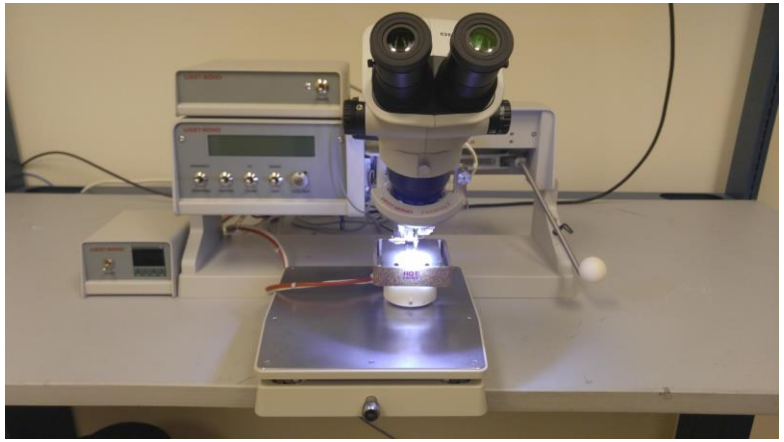
Wire bonding Capabilities at Birck



JFP Wire Bonder



Westbond 7400A



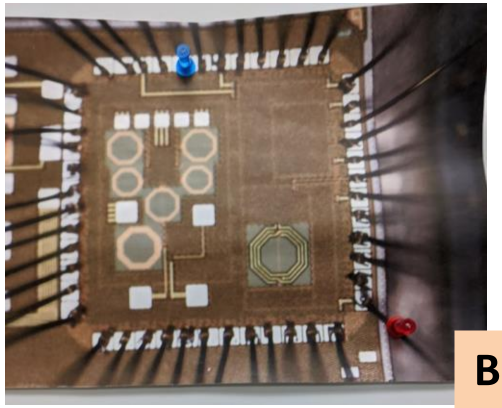
Westbond 7476E

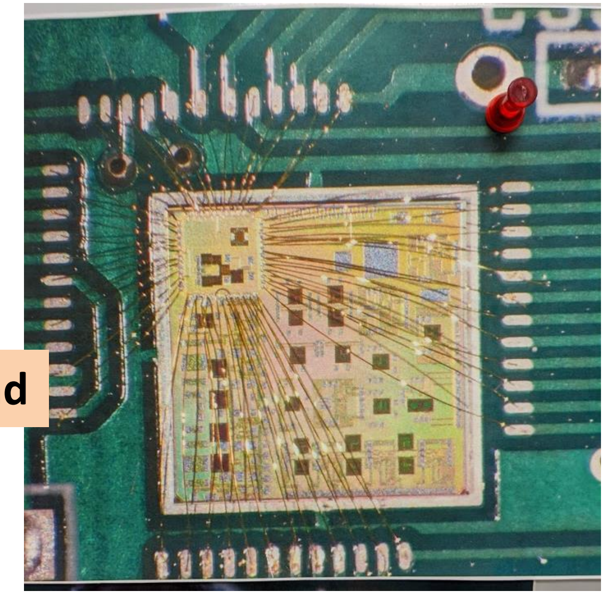
- JFP Wire Bonder:
    - Ball Bonder, Wedge Bonder (with conversion)
    - Heated Stage

- Westbond 7400A
    - Wedge Bonder

- Westbond 7476E
    - Wedge Bonder
    - Flexible Workpiece

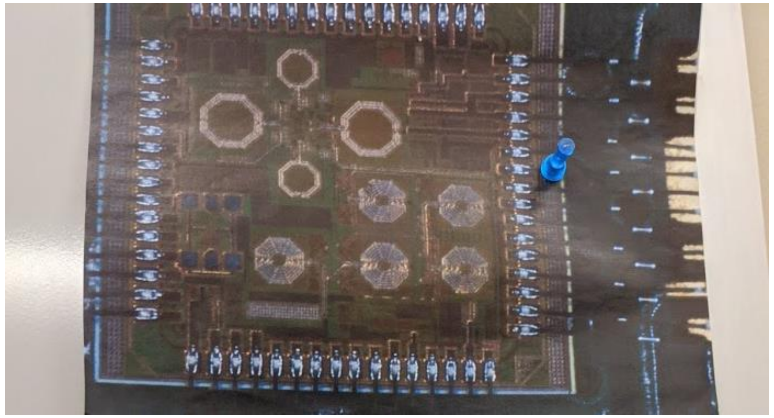
What's wrong with these pictures ?

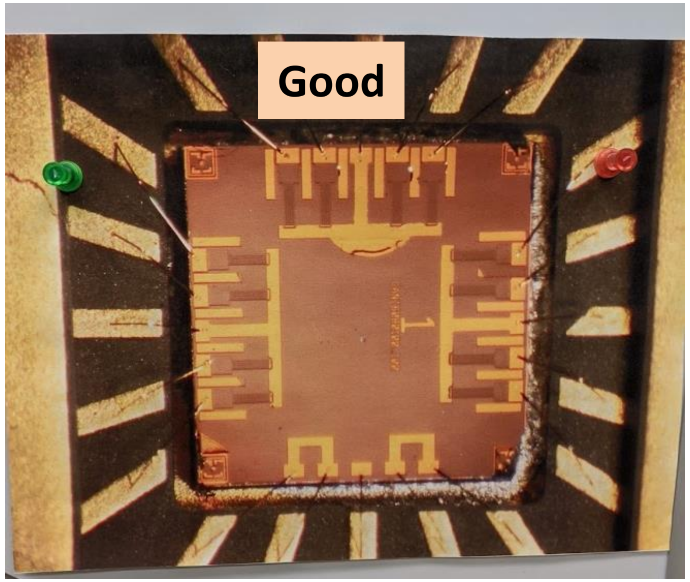




Bad

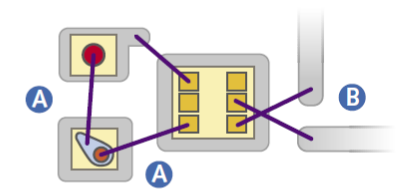
- Long wirebonds
- Incorrect bonding pad placement
- Crossing Wire bonds





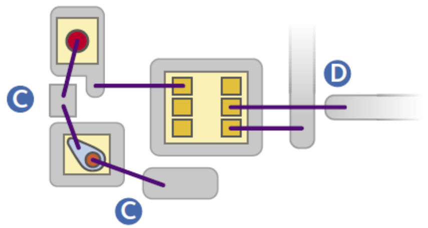
Good

General Do's & Don't



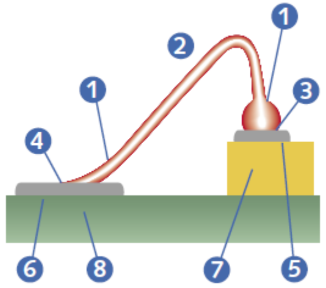
Poor bonding practice

- Ⓐ Die-to-die bonds
- Ⓑ Crossed wire bonds



Good bonding practice

- Ⓒ Extra pad to avoid die-to-die bonds
- Ⓓ Rearrange pads to avoid crossed wire bonds



1. Wire break at neckdown point
2. Wire break at point other than at neckdown
3. Failure in bond at die (wire/pad interface)
4. Failure in bond at substrate (wire/pad interface)
5. Lifted metallization from die pad
6. Lifted metallization from substrate pad
7. Die fracture
8. Substrate fracture

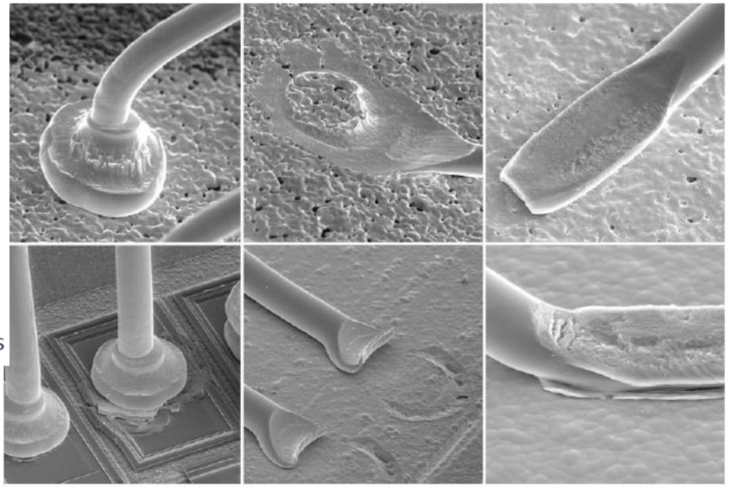
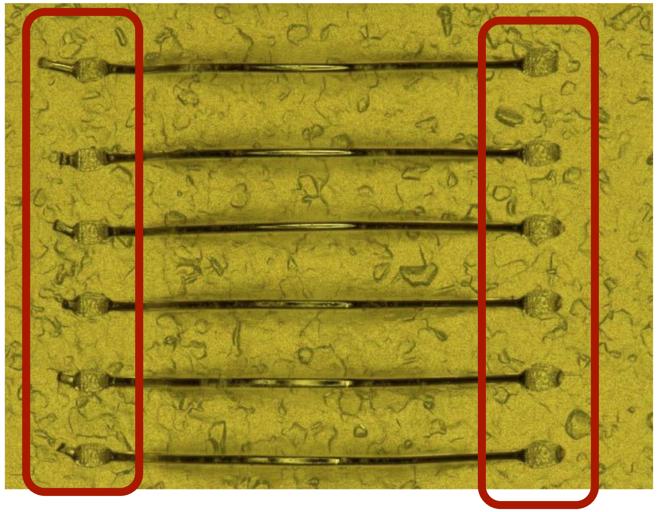
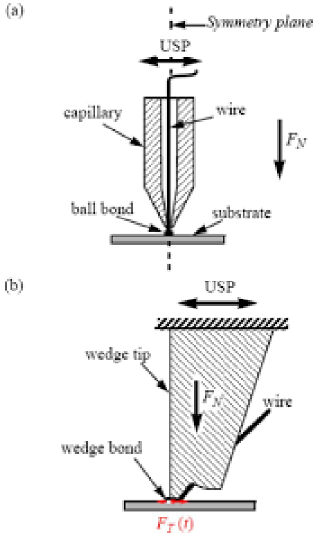


FIGURE 1. Top row (l-r) – Examples of typical ball, stitch, and wedge bonds formed using 0.001-in. Au wire. Bottom row (l-r) – examples of typical failures, including cratering, poor heel stick, and heel cracking.



Inconsistent Tails

Overbonding



Courtesy of Martek Components

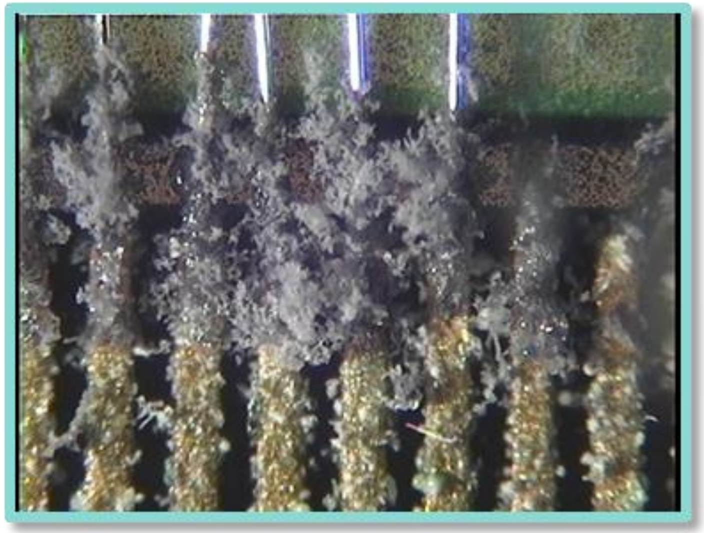
- ➢ Most issues avoided by good design
  - Have short wire bonds. i.e. 1st and 2nd bond pads close to each other
  - Avoid excessive force
  - Smashed bond usually indicate excessive force
    - Clean pads (Helps tremendously!)
- ➢ Wirebonding is an art
  - Irregular process parameters will cause damage to your samples

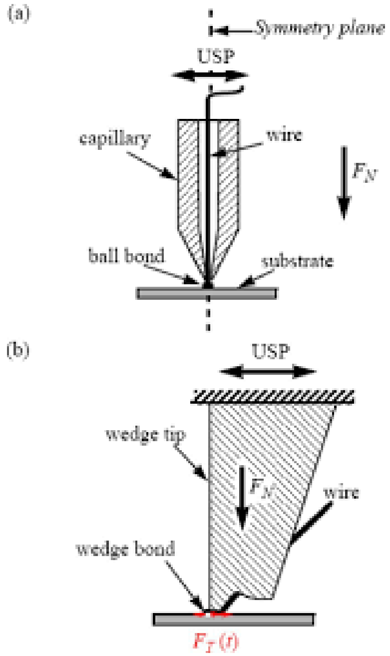
<u>Good design and forethought can save headaches later</u>

Other Considerations

Bonding Pads

- Items to consider
  - Bonding Pad
    - Materials: Gold (Preferred), Copper (less preferred)
    - Thickness: 100 nm, Width : 50 µm (min)
    - **Cleanliness**
  - Bonding Parameters
    - Ultrasonic Power
    - Temperature
    - Bond Force
    - Time

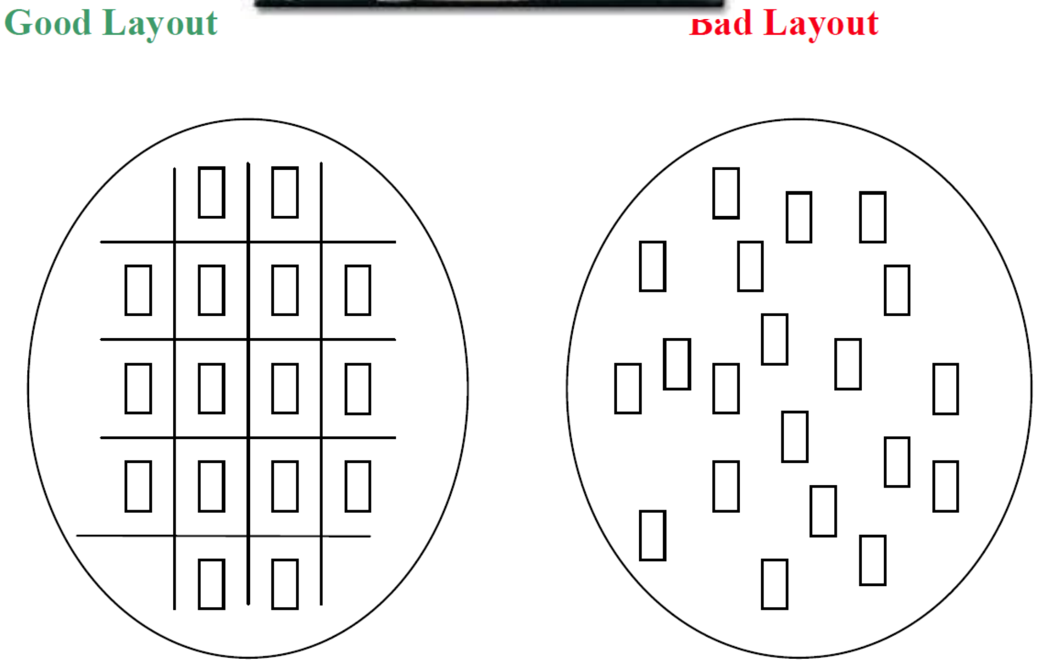




<u>Know these values for your samples</u>

Dicing Considerations

- ➢ Wafer Saw can cut only in a straight line
- ➢ Layout affect how fast you can cut the wafer
- ➢ Dicing Streets
  - Well defined with optical marks
    - Faster processing
    - Easier microscope alignment
  - Typical 100um for Nickel Blades
    - Silicon Dicing
  - 300-500um for Resin Blade
    - Glass
    - Silicon Carbide etc
  - Substrate Mounting
    - UV Tape (white)
    - Tacky Tape (Blue)

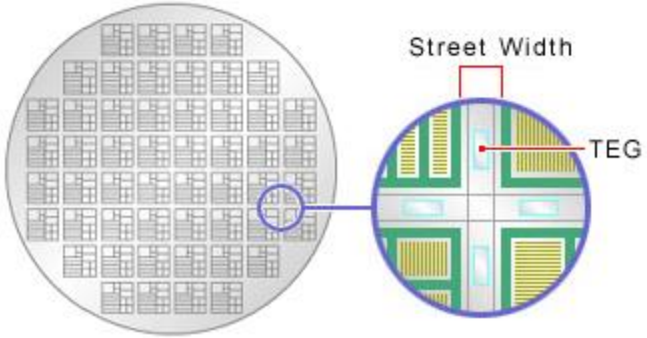


<u>Good design can once again prevent headaches later</u>

<u>Use the right blades for the right substrates!</u>

Dicing Tools – DiscoDAD 641

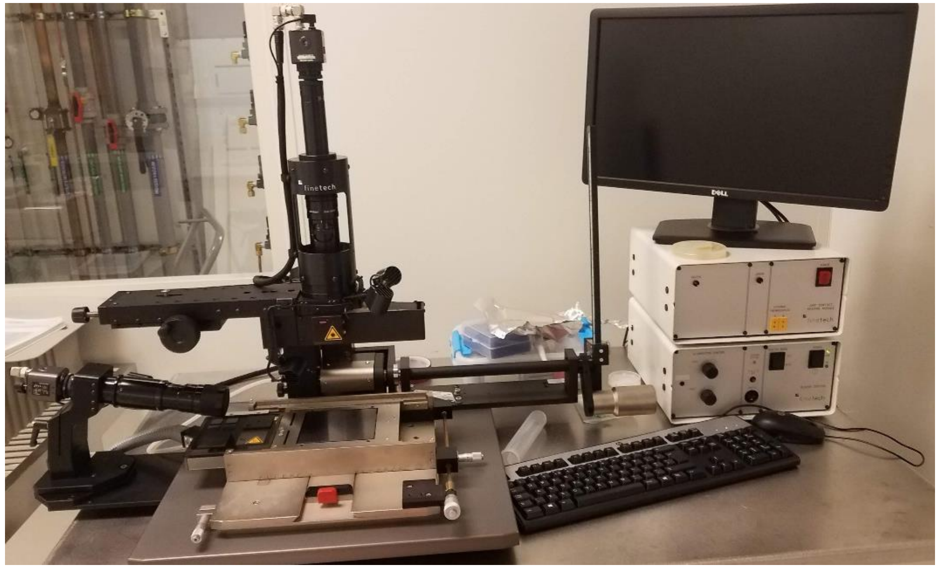
- Fully automatic dicing Saw
- Can handle up to 8 inch wafers.
- Also capable of dicing 0.1 um streets.
- Capable of asymmetric dicing.
  - i.e. the samples can have different spacings in each axis.
  - Can also perform angular cuts
- **Fully automatic dicing**
  - Cuts performed based on program parameters.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

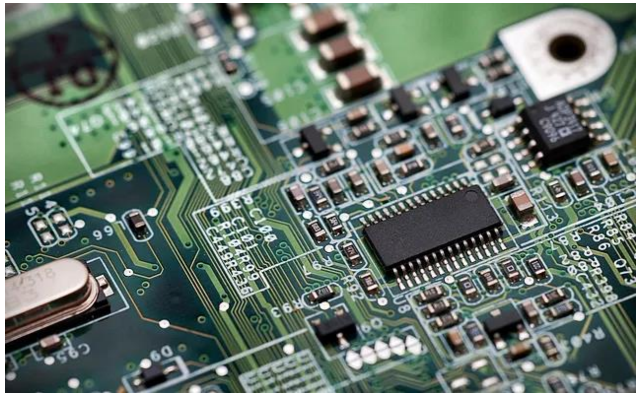


Tool name: DiscoDAD 641
Location: 2nd floor galley
Owner: Timothy Miller

PACKAGING TOOLS

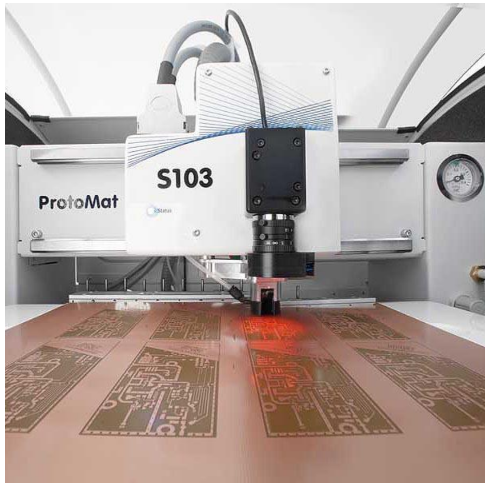
Pick and Place

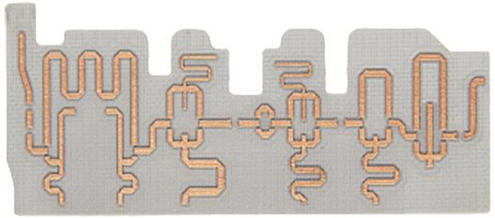




- Prototyping Pick and place system
- Die bonding capabilities
- Optical overlay alignment
  - Vision alignment system (VAS)
- Force
  - 0.1N to 700 N
- Thermal bonding capable
- Can be used to align chip-scale packages
- Assemble printed circuit boards

PCB Milling Tool and Plater : LPKF S103





- 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

RESEARCH APPLICATION: HIGH-G SWITCHES

Digital Accelerometer Concept

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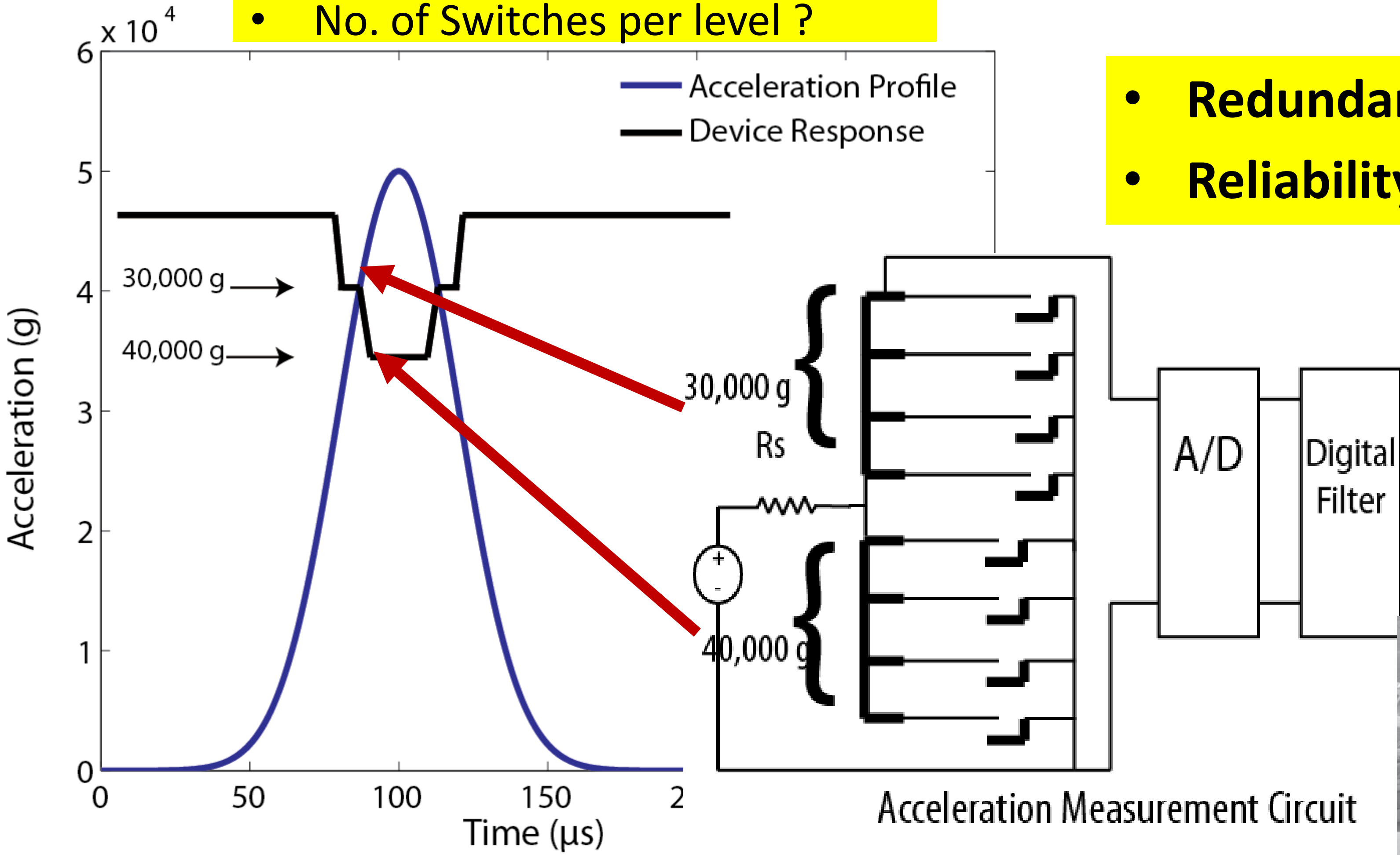
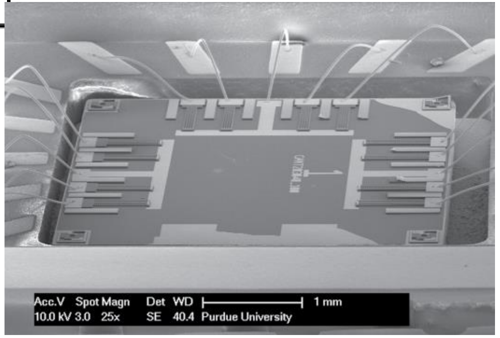
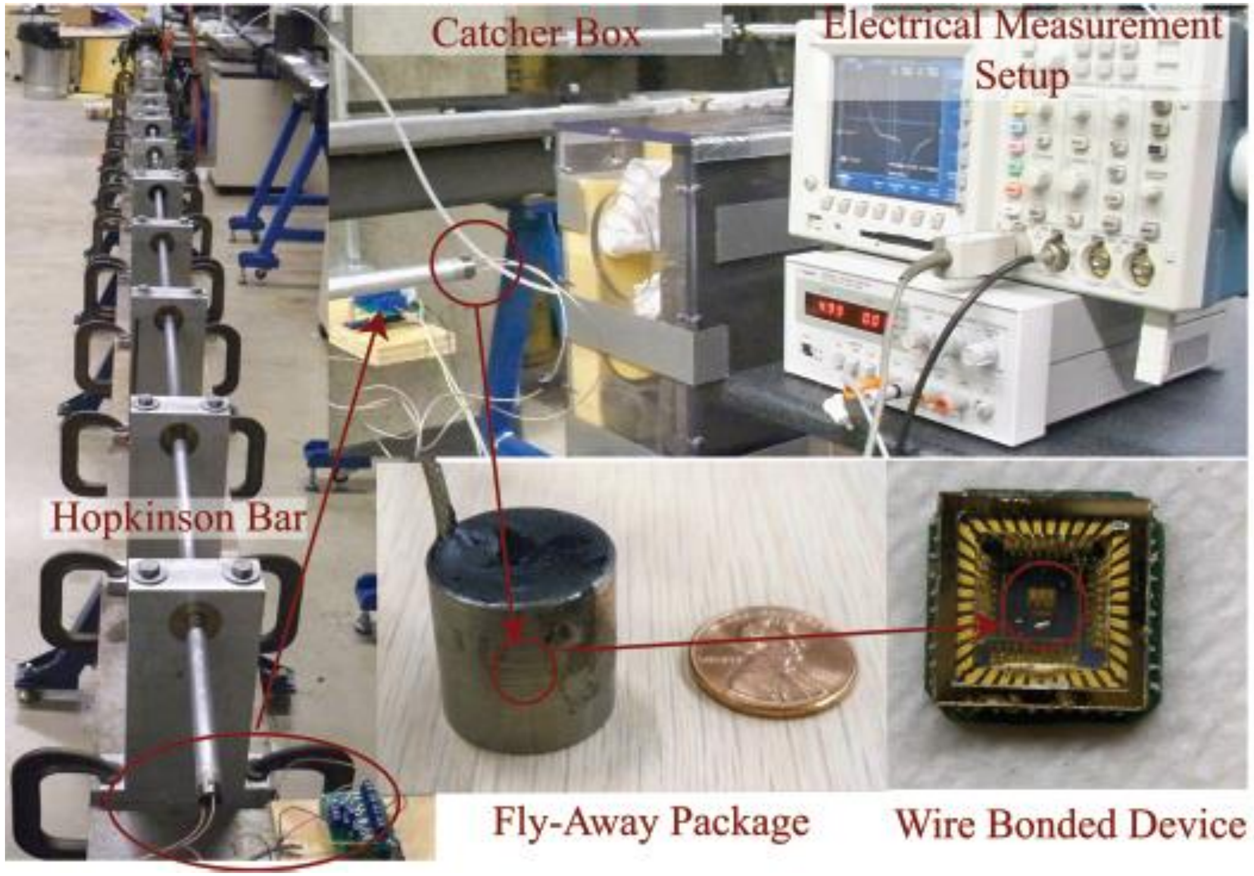
- No. of levels ?
- No. of Switches per level ?

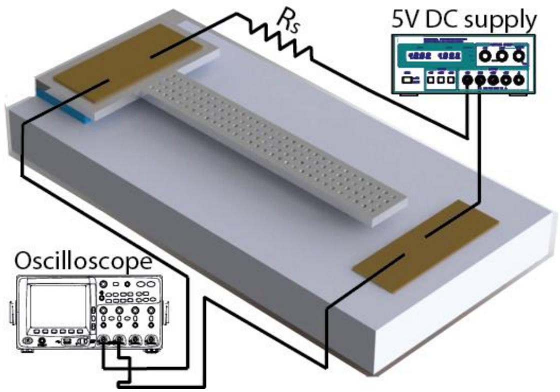


- **Redundancy**
- **Reliability**

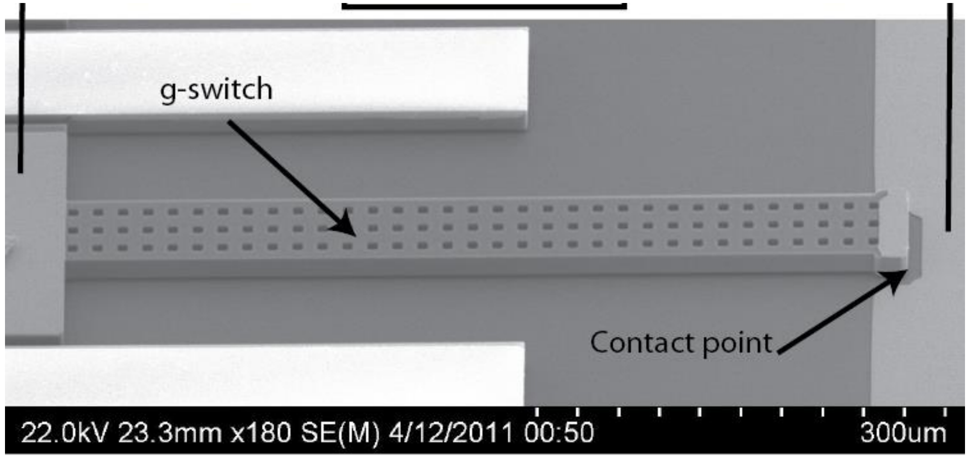


Measurement Setup





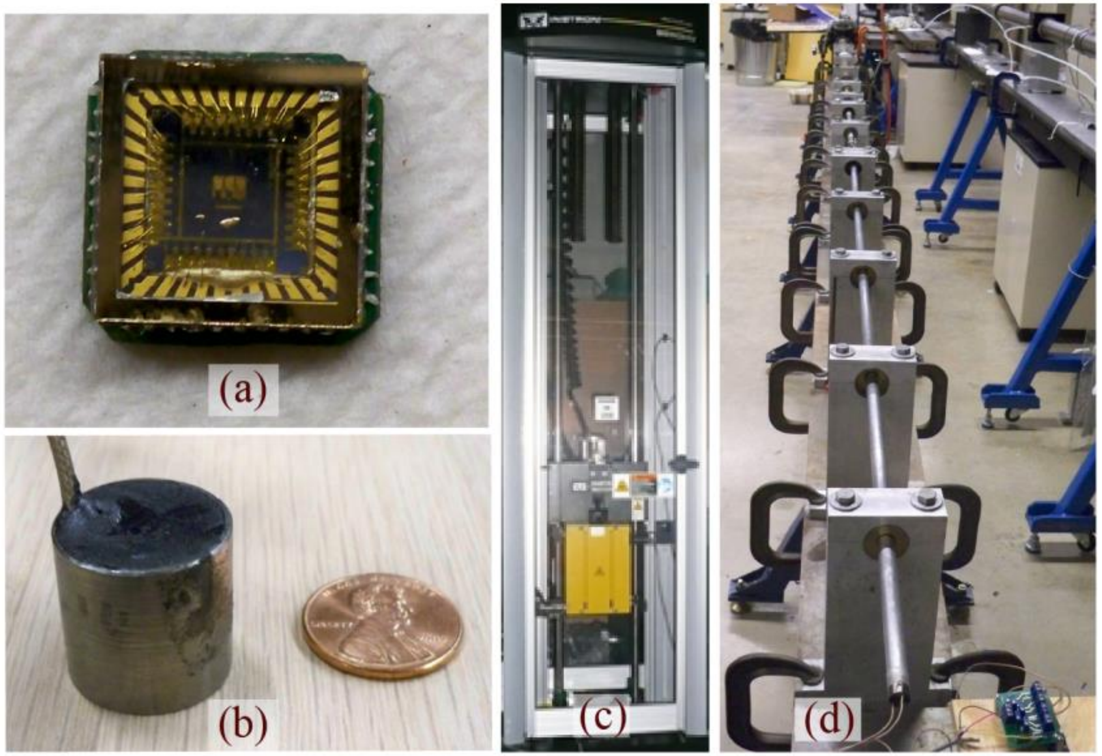
Electrical Setup



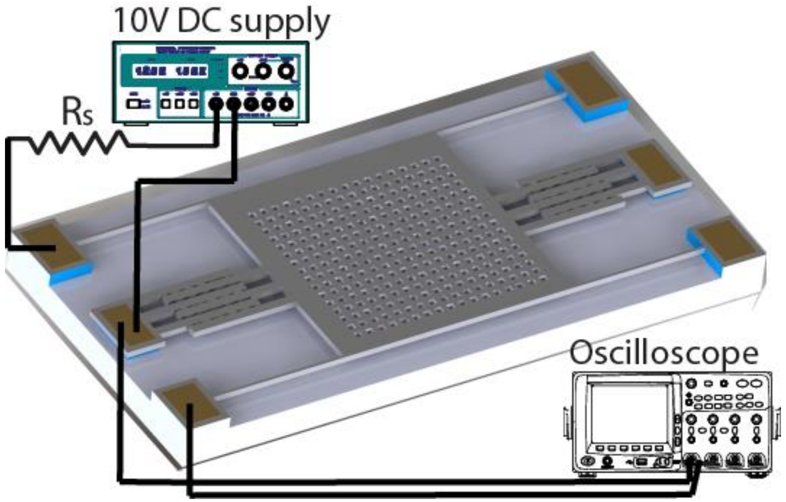
Key Features:

- Quicker disconnects and reconnect
- Faster measurements

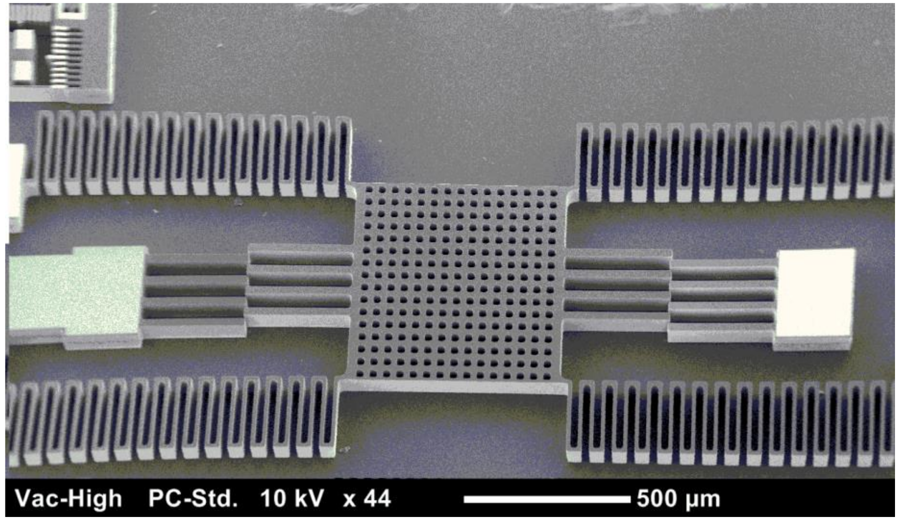
Setup Overview



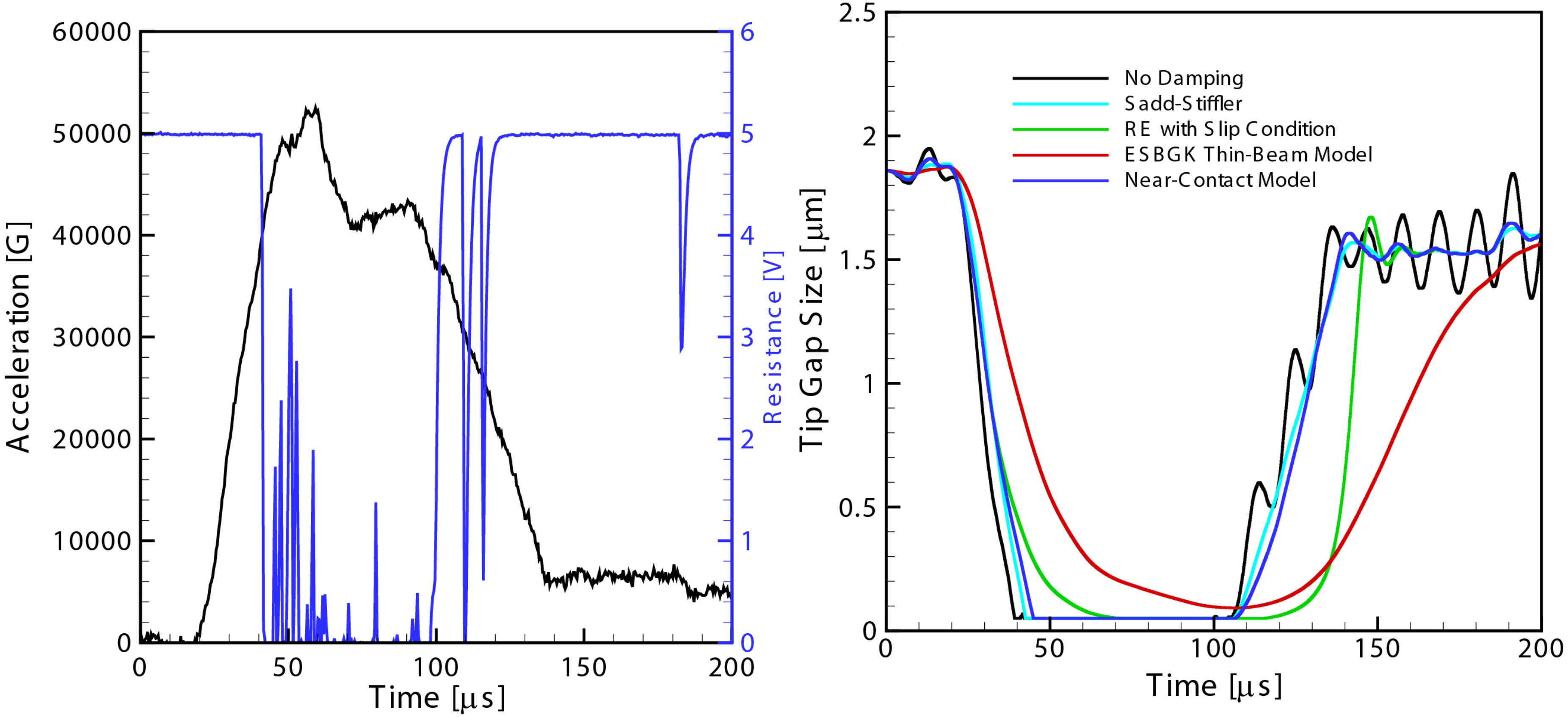
- Similar packaging process as high-g switch
- Low-g tests: Instron Dynatup 9250 HV drop tower courtesy of Prof Chen’s group.
- Acceleration measured using Endevco 7270-2K
- Testing Process:
  - Low-g test → High-g tests → Low-g tests



- Electrical Setup

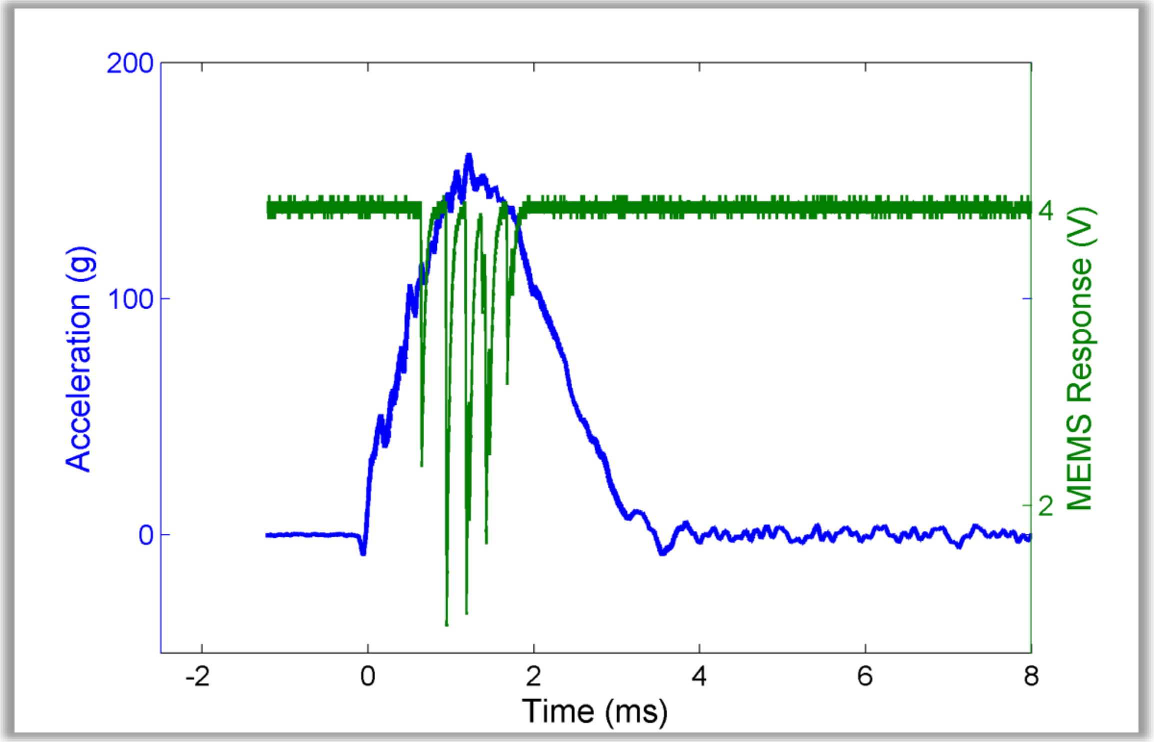


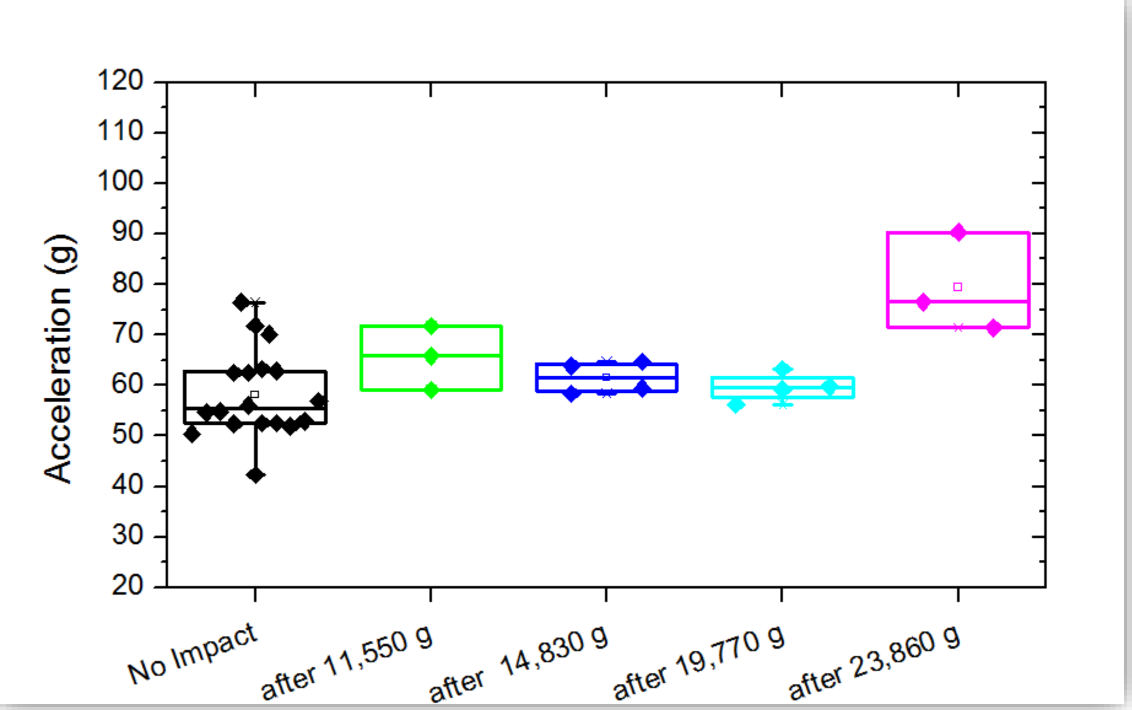
Measurements



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

Results





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

RESEARCH APPLICATIONS : 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

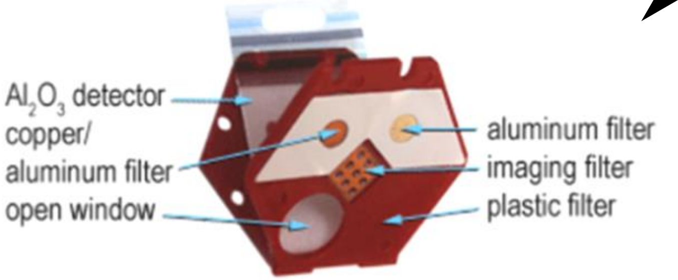
Examples of detector technologies

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

Courtesy of Harris Mousoulis

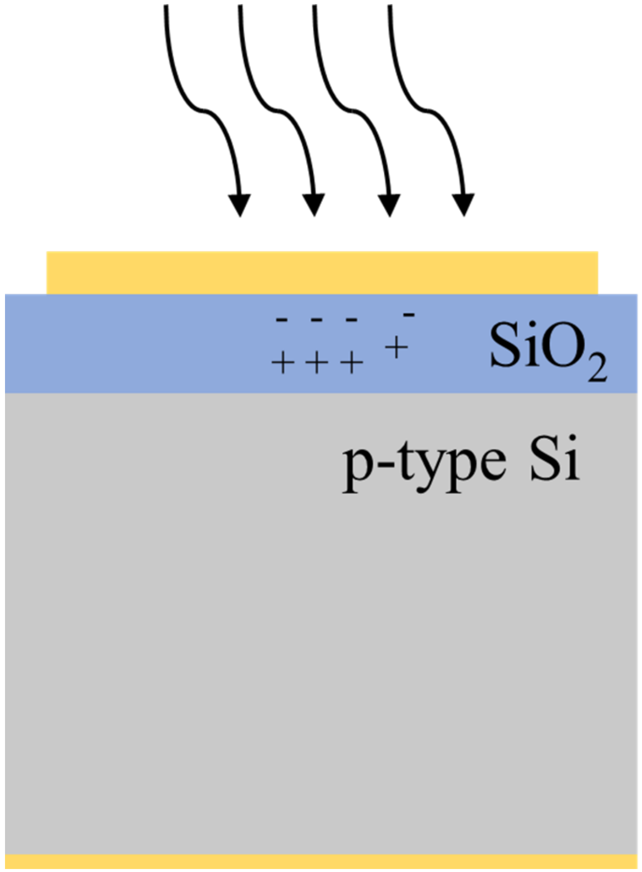
MOSCAP Sensor: 2D Geometry

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

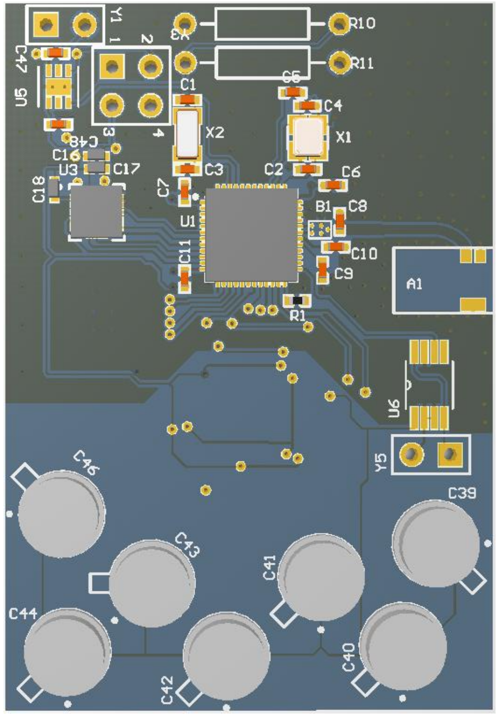


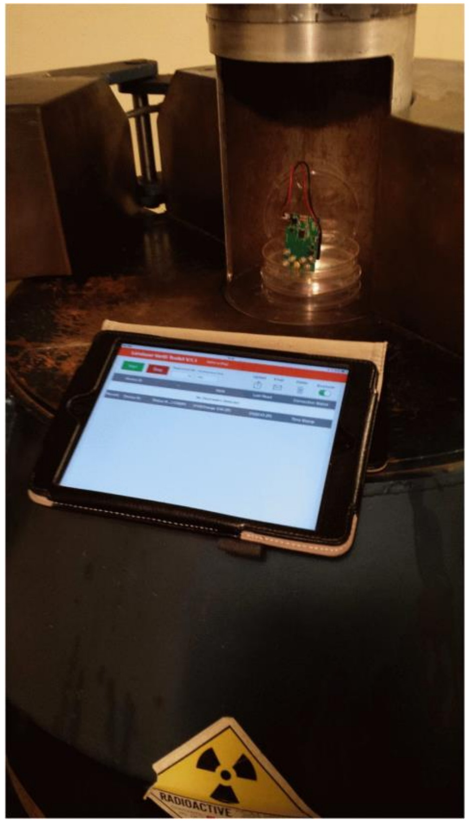
MOSCAP sensing principle [1]

[1] Scott et al., IEEE Sensors 2015

Courtesy of Harris Mousoulis

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

2/7/2020

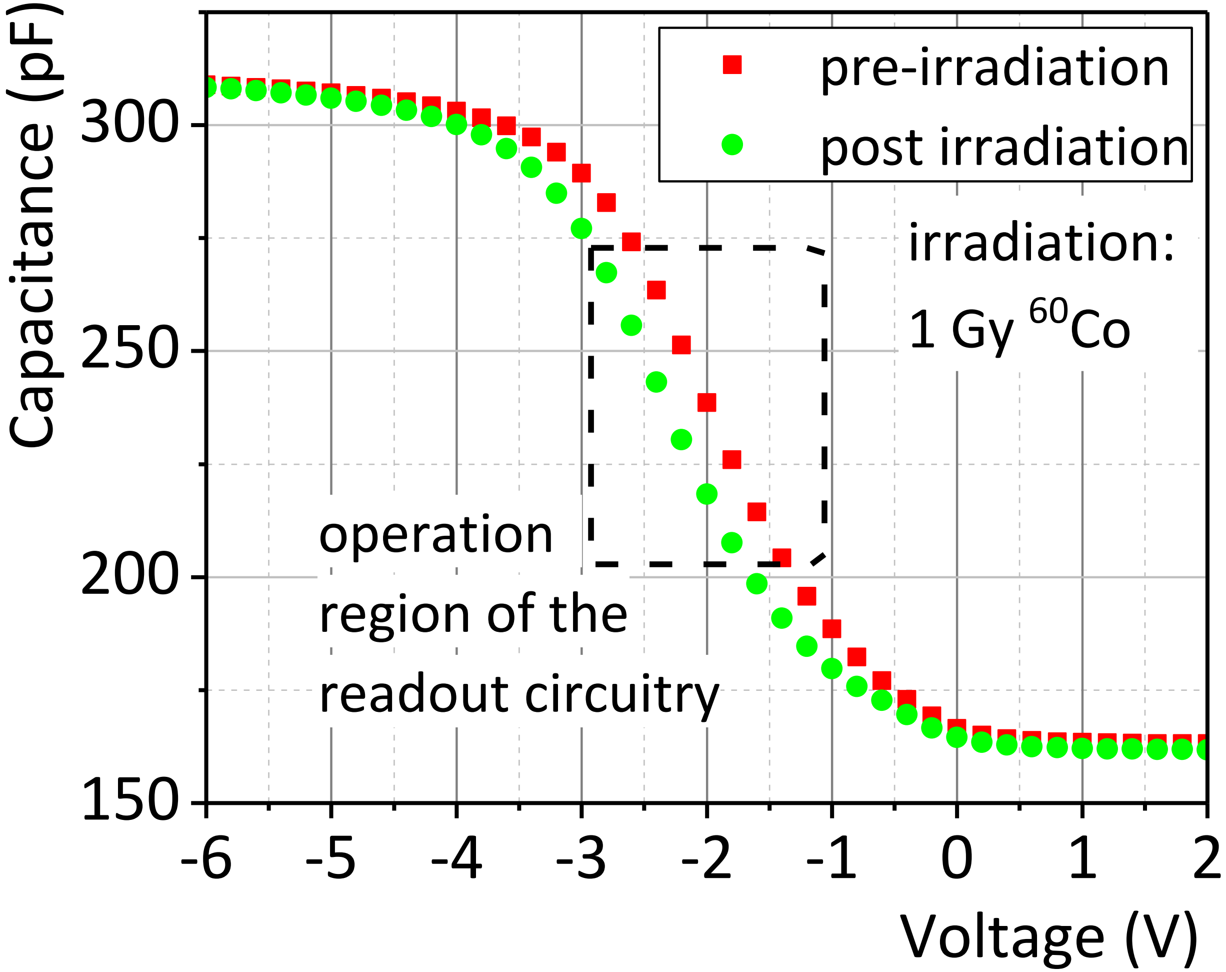
Courtesy of Harris Mousoulis

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

CV shift due to irradiation [1]



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

Summary

- Birck Nanotechnology Center
  - Wirebonding : General Guidelines
  - Characterization Capabilities.
  - Packaging Capabilities
- Applications in sensor research at Birck
  - High-g MEMS switches
  - Radiation dosimeters

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Thank You!