FOURTEENTH ANNUAL
BiTS 2013
Burn-in & Test Strategies Workshop™
Archive
TechTalk

THERMAL AND MECHANICAL CHALLENGES FOR TEST HANDLERS

by

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__Delta Design's Jerry Tustaniwskyj, Ph.D. talks tech__ about test handlers, addressing a number of challenges related to testing today's high-performance IC devices such as multi-chip modules, 3-D packages, and lapped silicon with thinned substrates. With "Thermal and Mechanical Challenges for Test Handlers", he zeroes in on thermal control of the DUT, the need for robust pick-and-place systems, and the importance of vision systems. Additionally, there will be a brief discussion on requirements for testing MEMS devices, where in addition to electrical test, physical excitation of the device is required.

ABSTRACT

IC **devices continue to evolve** with higher functionality and lower cost. This higher functionality means that the device circuit density is increased as is the corresponding number of IO's. The overall size of these devices is decreasing in order to improve performance and be useable in applications with minimal space such as mobile phones or tablets. These devices include multi-chip modules, 3-D packages, lapped silicon with thinned substrates, etc. In order to continue to drive device costs lower, these more complex devices cannot increase test time, resulting in a real push to increase the parallelism of test. Unique new challenges exist for test handlers with these devices during functional test as well as for other test processes such as burn-in or system level test.

This seminar addresses a number of challenges related to testing these devices. These challenges include purely mechanical issues as well thermal. We discuss the need for more robust pick and place processes along with the precision alignment of the device under test (DUT) to the contact pins. The use and advances of vision systems are described. Their benefit is not only in device alignment, but also for process control and diagnostics. We review the material property and thermal expansion issues related to testing at extreme temperatures (tri-temp).

A considerable portion of the seminar is dedicated to thermal control of the DUT. Traditional methods need to be modified in order to control device temperature with the new packaging technologies. We discuss the thermal challenges of designing highly parallel passive systems along with active thermal control for each DUT. Cost versus performance tradeoffs are addressed for both low and high power dissipating devices as well as the pros and cons of air, liquid, phase change, and thermoelectric cooling systems.

We also have included a brief discussion on requirements for testing MEMS devices, where in addition to electrical test, physical excitation of the device is required.

Thermal and Mechanical Challenges for Test Handlers

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Cohu Semiconductor Equipment Group

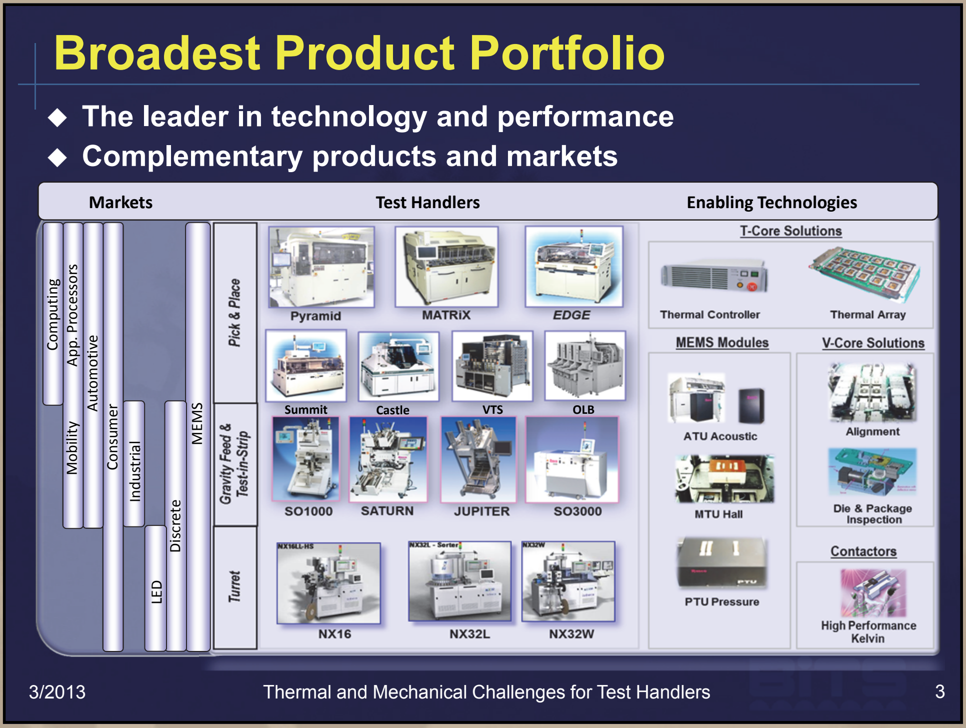
- Cohu Semiconductor Equipment Group is the leader in the Handler Market, offering pick & place, gravity, test-in-strip, turret, MEMS, thermal subsystems and contactors
- Three businesses developing and marketing products
- Global Customer Support and Operations

COHU, inc. Semiconductor Equipment Group

COHU
SEMICONDUCTOR EQUIPMENT GROUP

Delta Design, A Cohu Company: #1 in Pick&Place Handlers and Thermal Subsystems
ismeca, A Cohu Company: #1 in Turret Handlers and Backend Finishing
Rasco, A Cohu Company: #2 in MEMS, Gravity-Feed and Strip Handlers

Global Customer Support
Global Operations



Broadest Product Portfolio

- The leader in technology and performance
- Complementary products and markets

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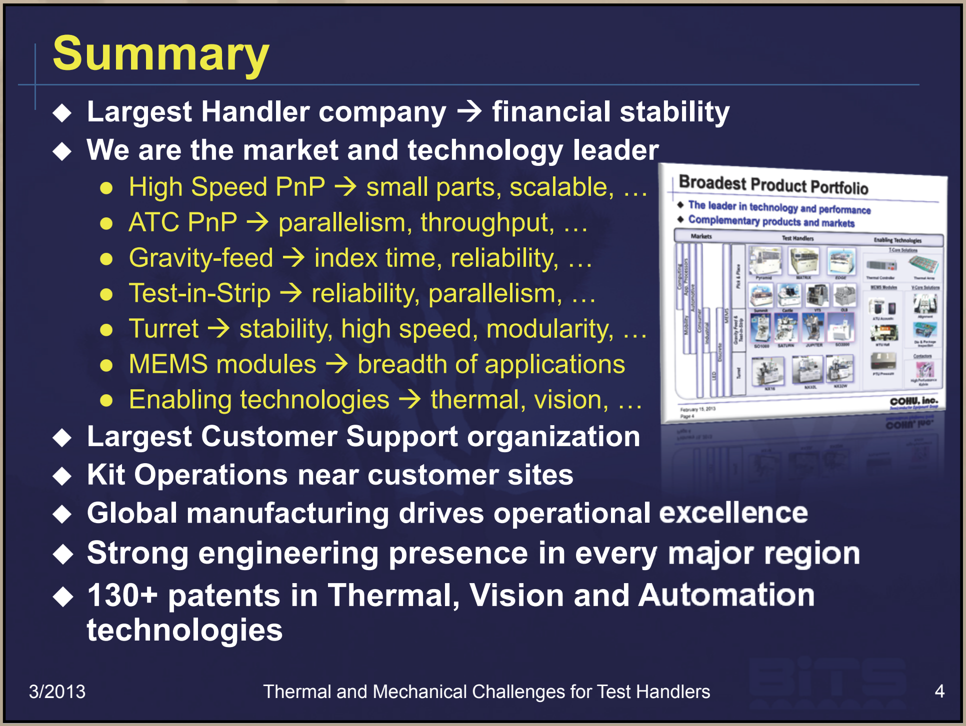

Summary

- Largest Handler company → financial stability
- We are the market and technology leader
  - High Speed PnP → small parts, scalable, …
  - ATC PnP → parallelism, throughput, …
  - Gravity-feed → index time, reliability, …
  - Test-in-Strip → reliability, parallelism, …
  - Turret → stability, high speed, modularity, …
  - MEMS modules → breadth of applications
  - Enabling technologies → thermal, vision, …
- Largest Customer Support organization
- Kit Operations near customer sites
- Global manufacturing drives operational excellence
- Strong engineering presence in every major region
- 130+ patents in Thermal, Vision and Automation technologies

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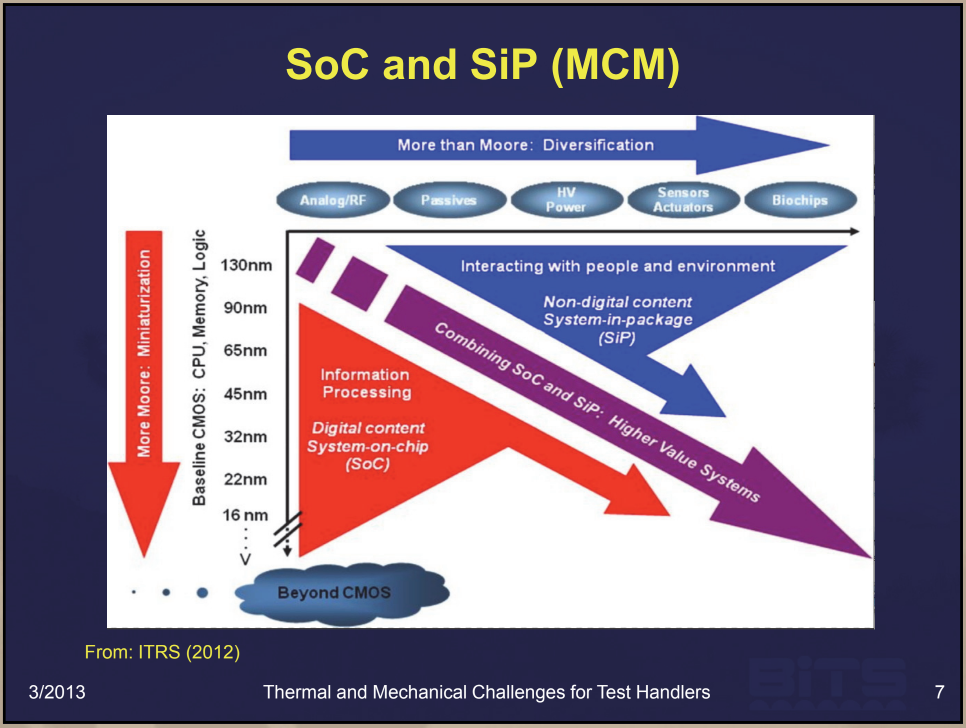
Content

- Typical challenges for handlers
- Semiconductor trends
- Mechanical issues
- Thermo-mechanical issues
- Vision systems
- Thermal Issues
- MEMS systems

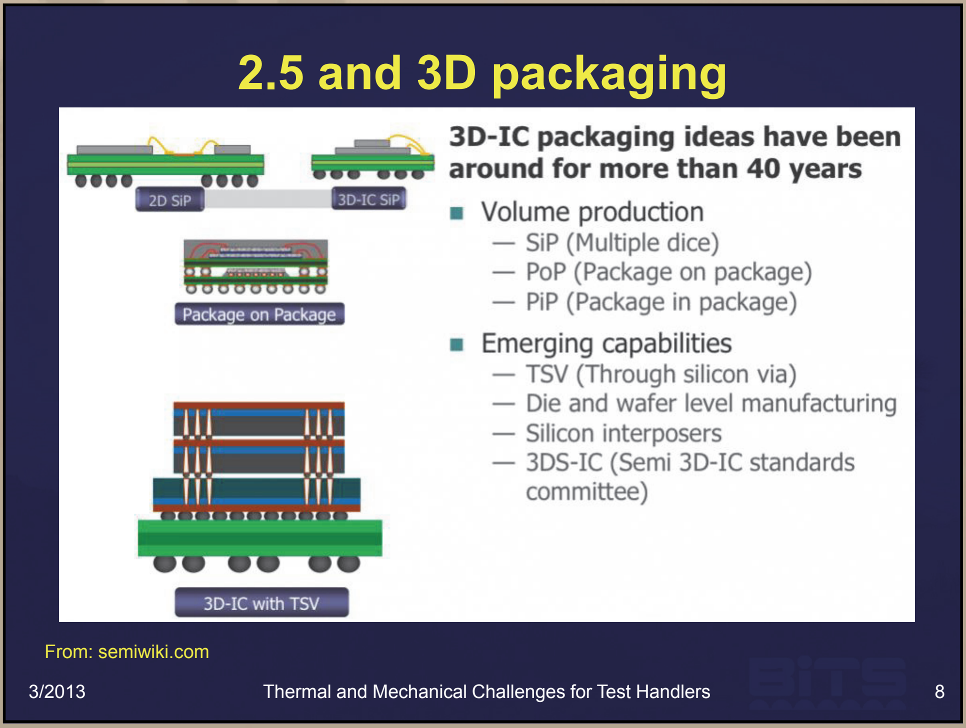
Typical handler requirements

- High throughput
  - Low index time
  - High parallelism
- Wide temperature range
  - -60° C to 160° C
- Insertion accuracy
- Controlled insertion force
- Accurate temperature control
- Configurability
- Reliability
- Cost of ownership



SoC and SiP (MCM)

From: ITRS (2012)



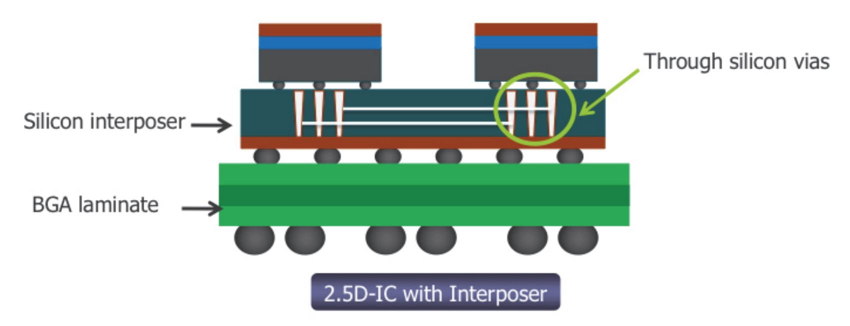
2.5 and 3D packaging

3D-IC packaging ideas have been around for more than 40 years

- Volume production
  - SiP (Multiple dice)
  - PoP (Package on package)
  - PiP (Package in package)
- Emerging capabilities
  - TSV (Through silicon via)
  - Die and wafer level manufacturing
  - Silicon interposers
  - 3DS-IC (Semi 3D-IC standards committee)

From: semiwiki.com

2.5D packaging



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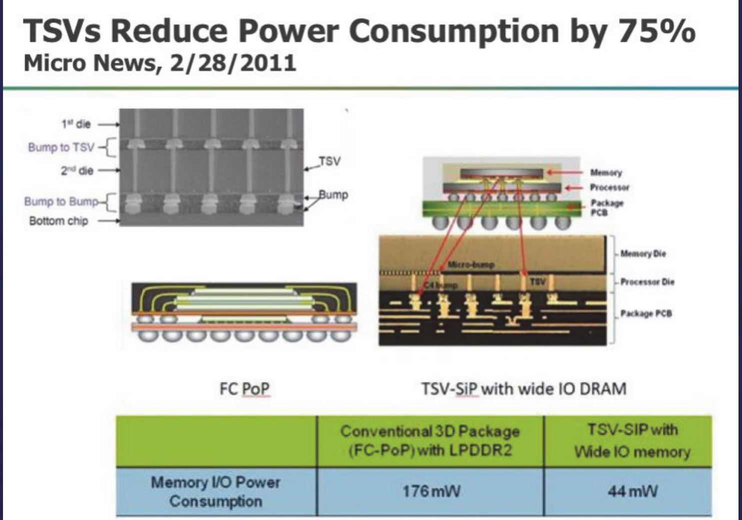
3D packaging



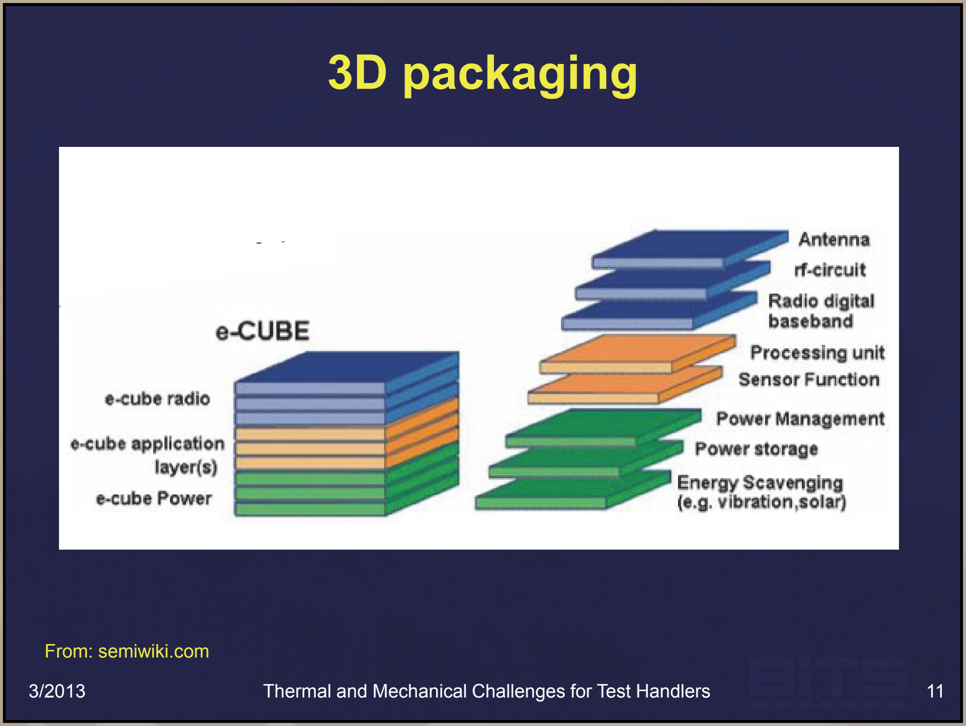
TSVs Reduce Power Consumption by 75%
Micro News, 2/28/2011

FC PoP

TSV-SiP with wide IO DRAM

	Conventional 3D Package (FC-PoP) with LPDDR2	TSV-SIP with Wide IO memory
Memory I/O Power Consumption	176 mW	44 mW

From: semiwiki.com



3D packaging

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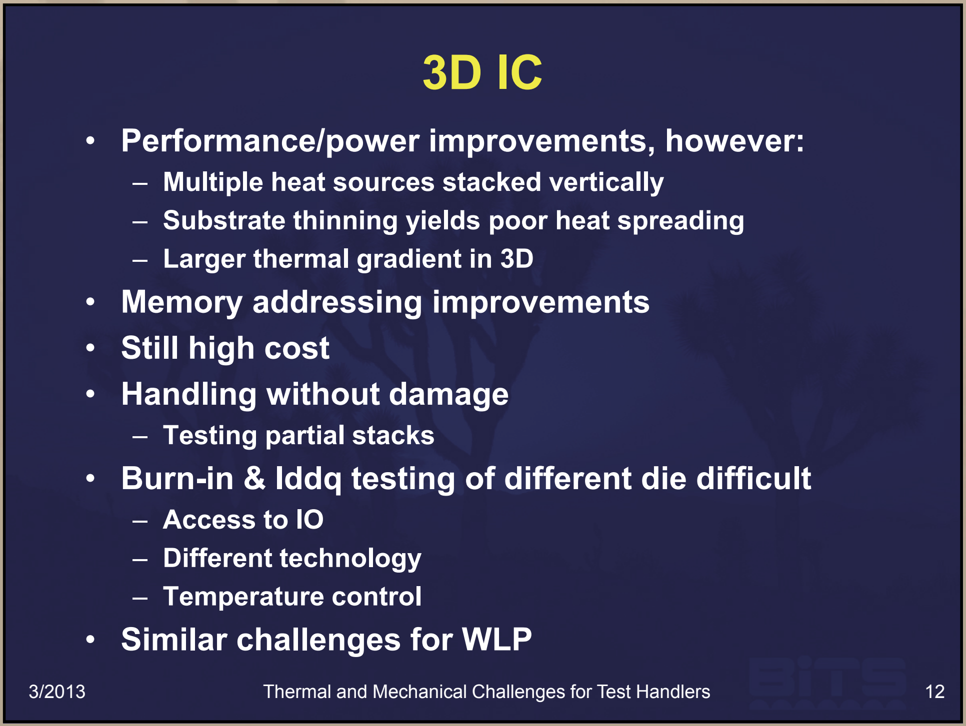
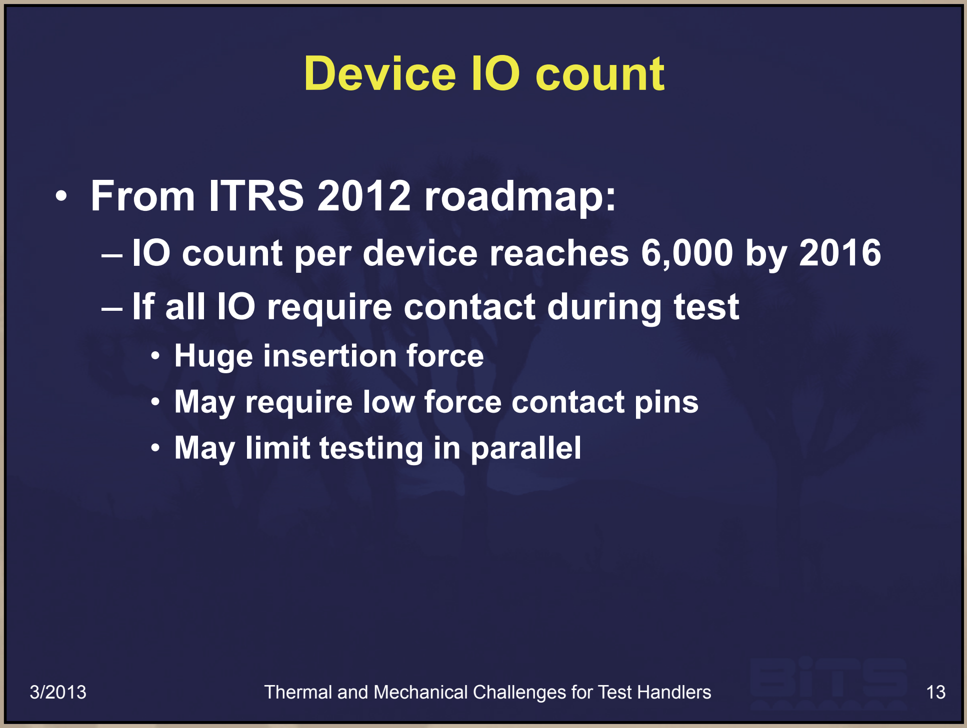


3D IC

- Performance/power improvements, however:
  - Multiple heat sources stacked vertically
  - Substrate thinning yields poor heat spreading
  - Larger thermal gradient in 3D
- Memory addressing improvements
- Still high cost
- Handling without damage
  - Testing partial stacks
- Burn-in & Iddq testing of different die difficult
  - Access to IO
  - Different technology
  - Temperature control
- Similar challenges for WLP



Device IO count

- From ITRS 2012 roadmap:
  - IO count per device reaches 6,000 by 2016
  - If all IO require contact during test
    - Huge insertion force
    - May require low force contact pins
    - May limit testing in parallel

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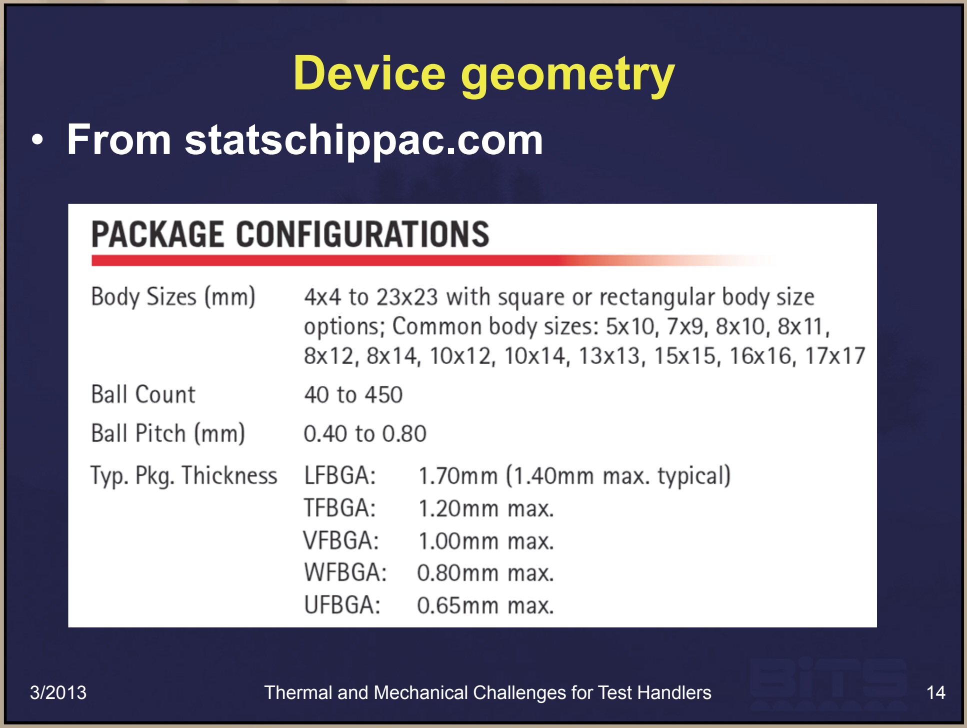

Device geometry

- From statschippac.com

PACKAGE CONFIGURATIONS

Body Sizes (mm)	4x4 to 23x23 with square or rectangular body size options; Common body sizes: 5x10, 7x9, 8x10, 8x11, 8x12, 8x14, 10x12, 10x14, 13x13, 15x15, 16x16, 17x17	
Ball Count	40 to 450	
Ball Pitch (mm)	0.40 to 0.80	
Typ. Pkg. Thickness	LFBGA:	1.70mm (1.40mm max. typical)
	TFBGA:	1.20mm max.
	VFBGA:	1.00mm max.
	WFBGA:	0.80mm max.
	UFBGA:	0.65mm max.

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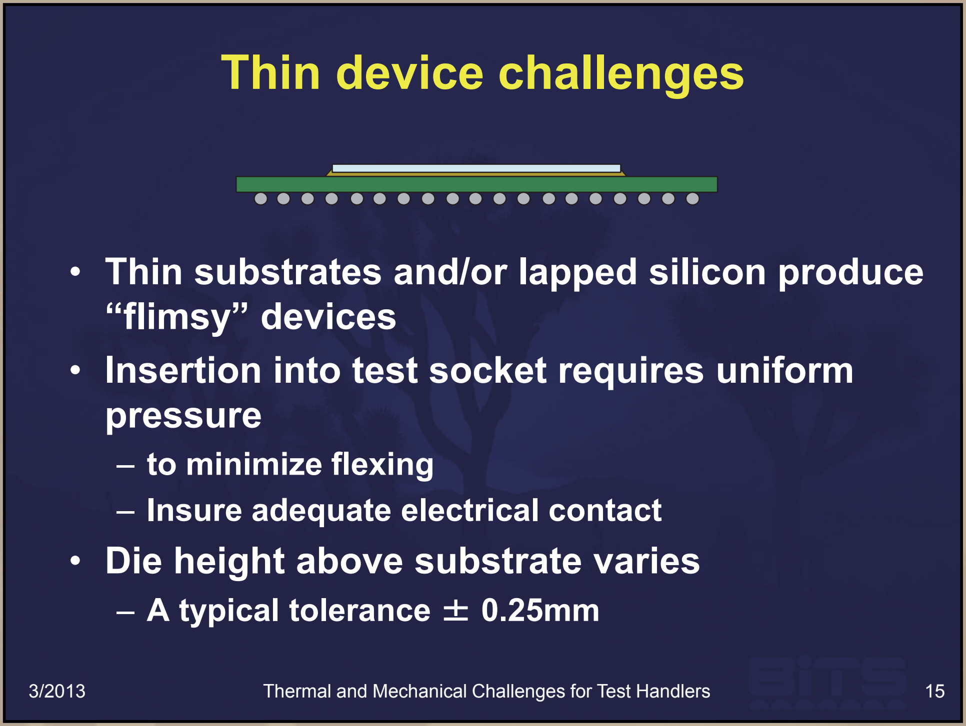

Thin device challenges

- Thin substrates and/or lapped silicon produce "flimsy" devices
- Insertion into test socket requires uniform pressure
  - to minimize flexing
  - Insure adequate electrical contact
- Die height above substrate varies
  - A typical tolerance ± 0.25mm

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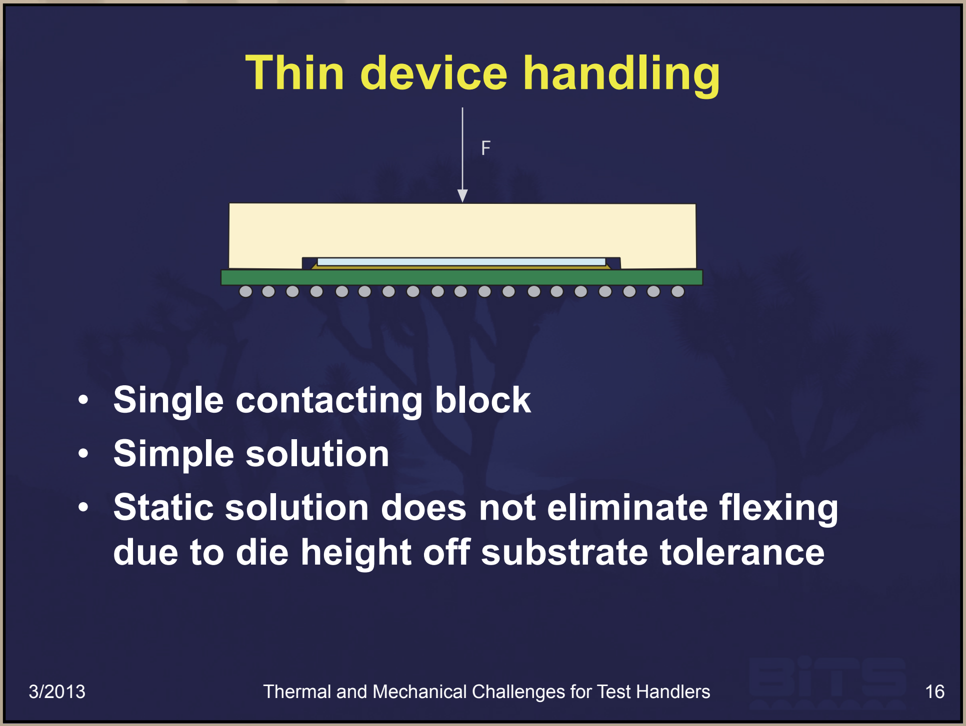

Thin device handling

- Single contacting block
- Simple solution
- Static solution does not eliminate flexing due to die height off substrate tolerance

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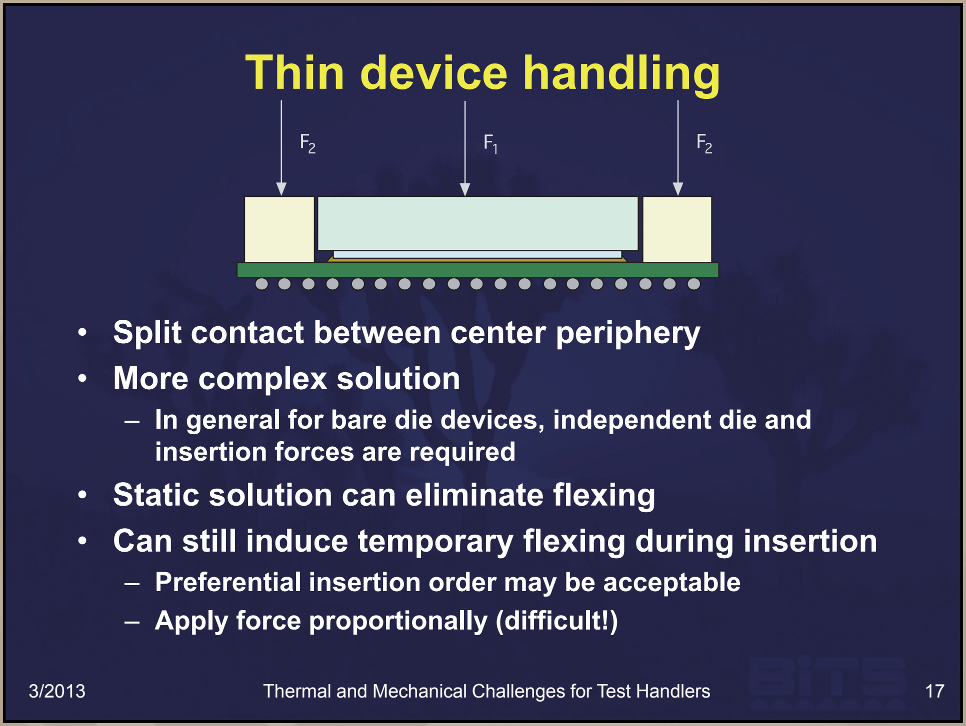

Thin device handling

- Split contact between center periphery
- More complex solution
  - In general for bare die devices, independent die and insertion forces are required
- Static solution can eliminate flexing
- Can still induce temporary flexing during insertion
  - Preferential insertion order may be acceptable
  - Apply force proportionally (difficult!)

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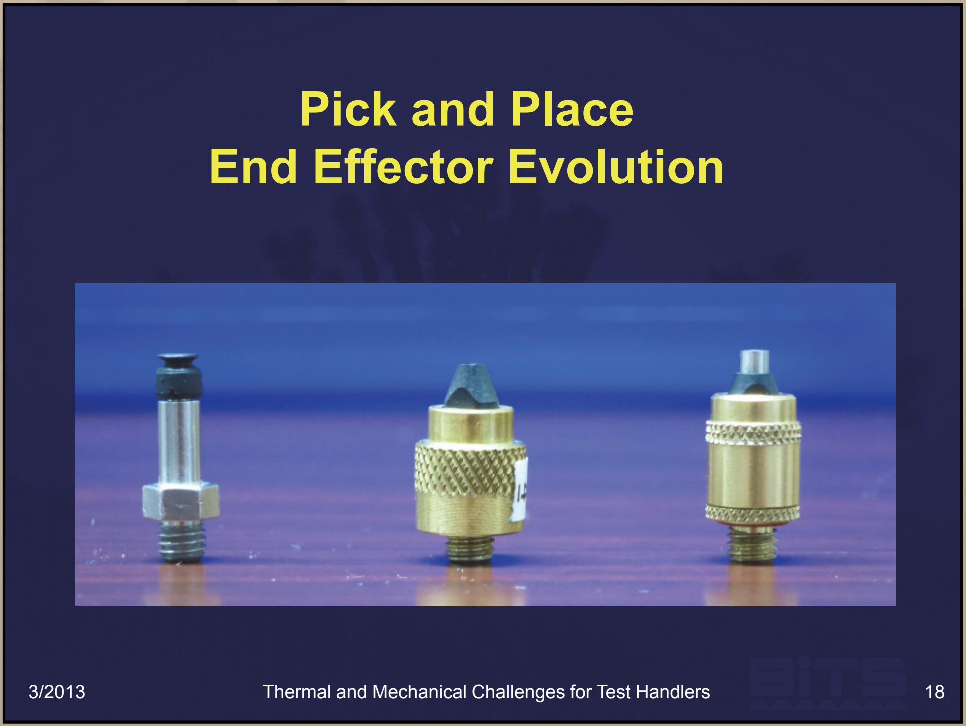

Pick and Place
End Effector Evolution

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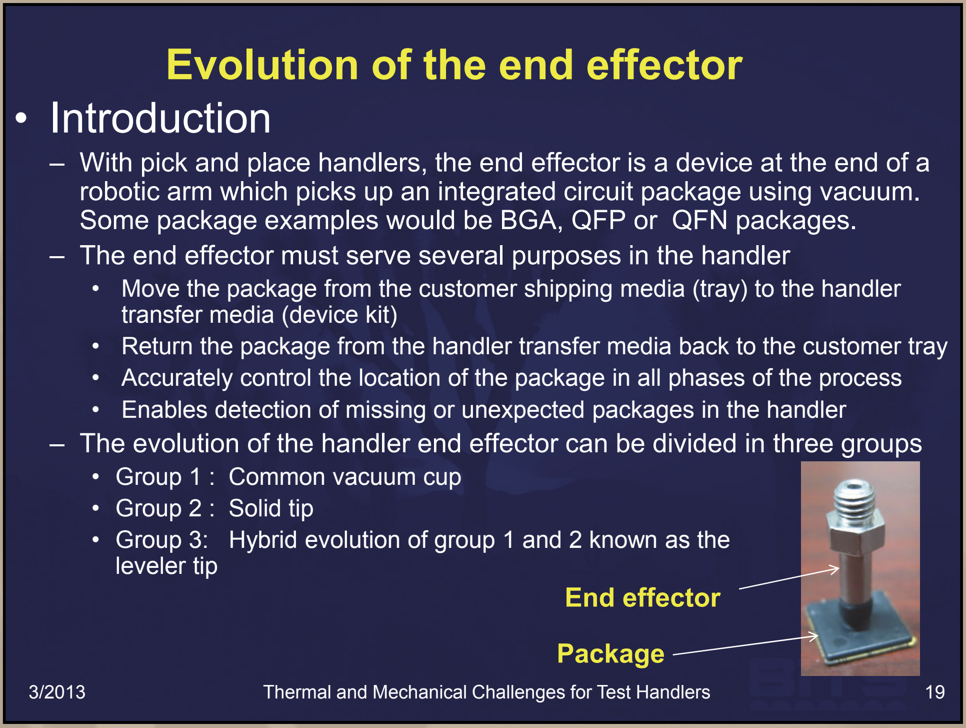
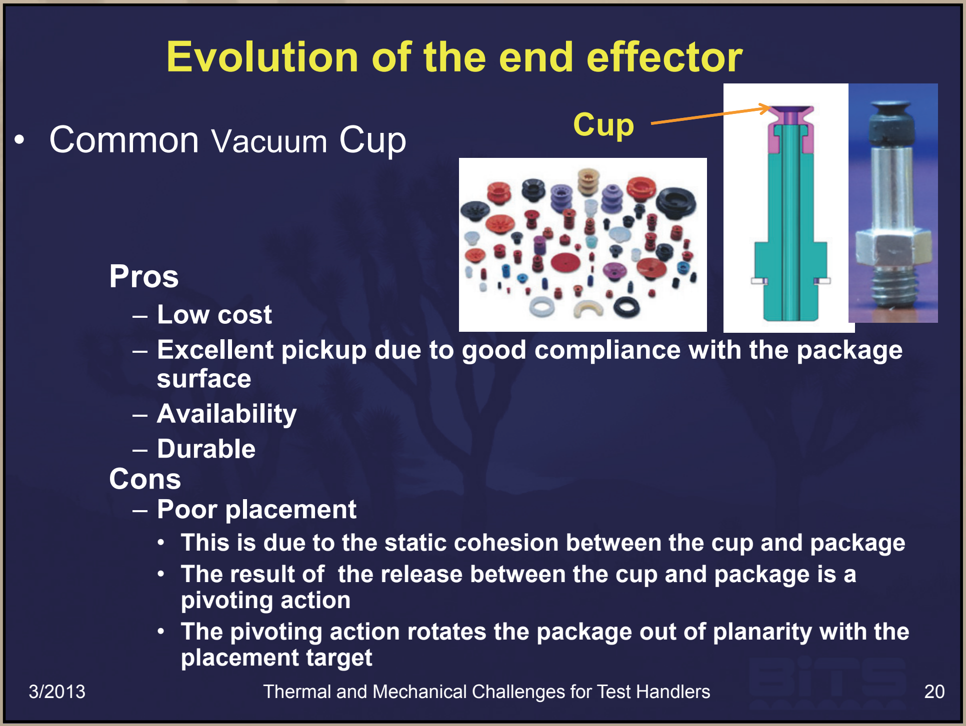


Evolution of the end effector

- Introduction
  - With pick and place handlers, the end effector is a device at the end of a robotic arm which picks up an integrated circuit package using vacuum. Some package examples would be BGA, QFP or QFN packages.
  - The end effector must serve several purposes in the handler
    - Move the package from the customer shipping media (tray) to the handler transfer media (device kit)
    - Return the package from the handler transfer media back to the customer tray
    - Accurately control the location of the package in all phases of the process
    - Enables detection of missing or unexpected packages in the handler
  - The evolution of the handler end effector can be divided in three groups
    - Group 1 : Common vacuum cup
    - Group 2 : Solid tip
    - Group 3: Hybrid evolution of group 1 and 2 known as the leveler tip

End effector

Package



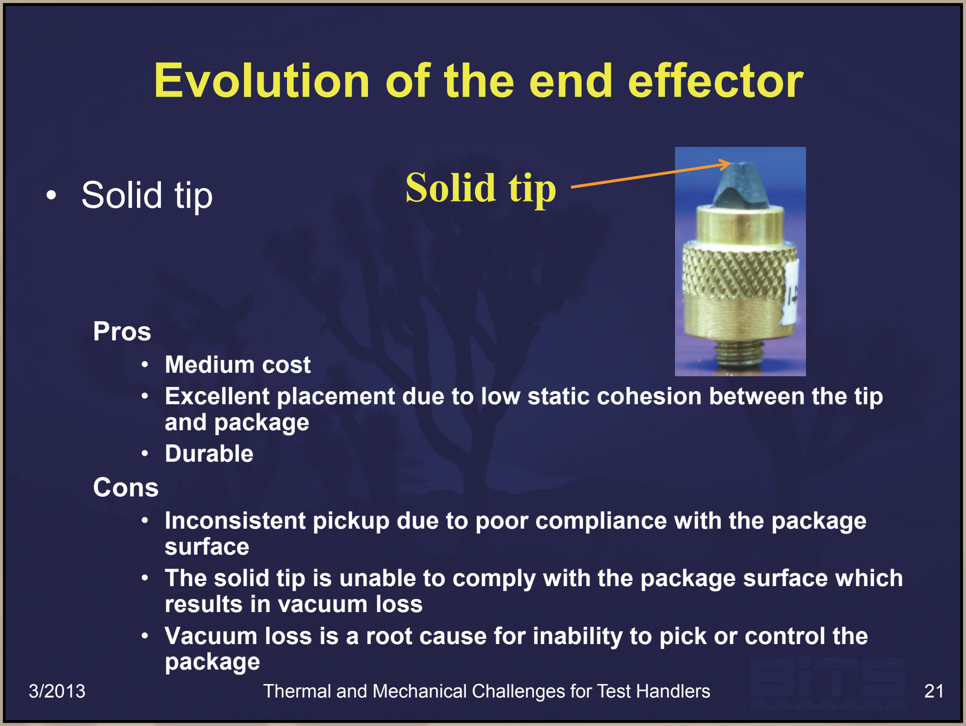
Evolution of the end effector

- Common Vacuum Cup

Cup

Pros
- Low cost
- Excellent pickup due to good compliance with the package surface
- Availability
- Durable

Cons
- Poor placement
  - This is due to the static cohesion between the cup and package
  - The result of the release between the cup and package is a pivoting action
  - The pivoting action rotates the package out of planarity with the placement target



Evolution of the end effector

- Solid tip

Solid tip

Pros

- **Medium cost**
- **Excellent placement due to low static cohesion between the tip and package**
- **Durable**

Cons

- **Inconsistent pickup due to poor compliance with the package surface**
- **The solid tip is unable to comply with the package surface which results in vacuum loss**
- **Vacuum loss is a root cause for inability to pick or control the package**

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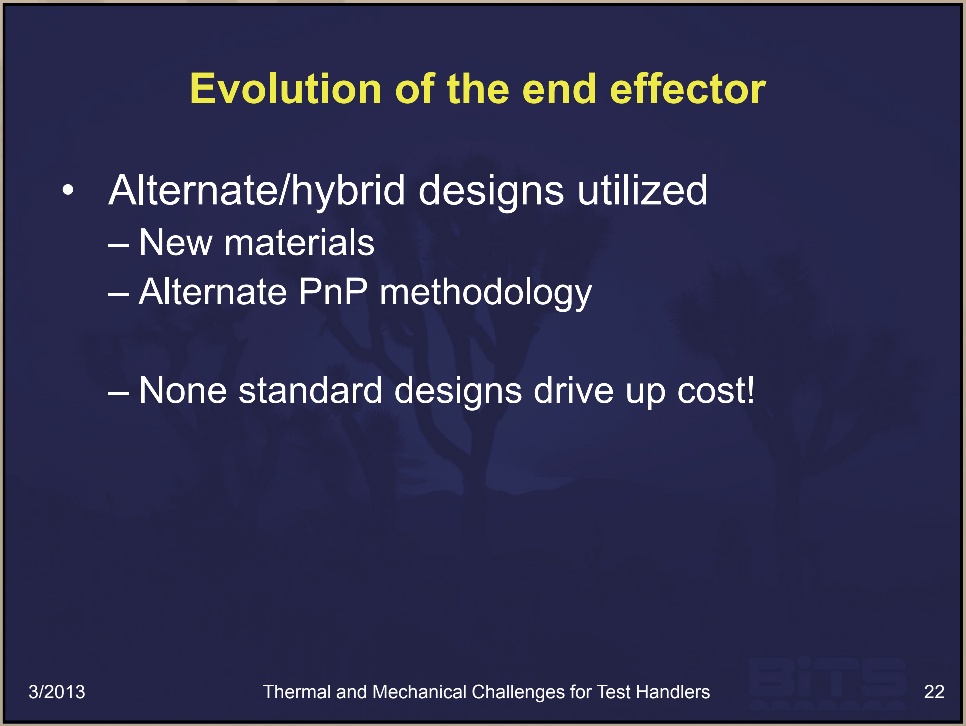

Evolution of the end effector

- Alternate/hybrid designs utilized
  - – New materials
  - – Alternate PnP methodology

  - – None standard designs drive up cost!

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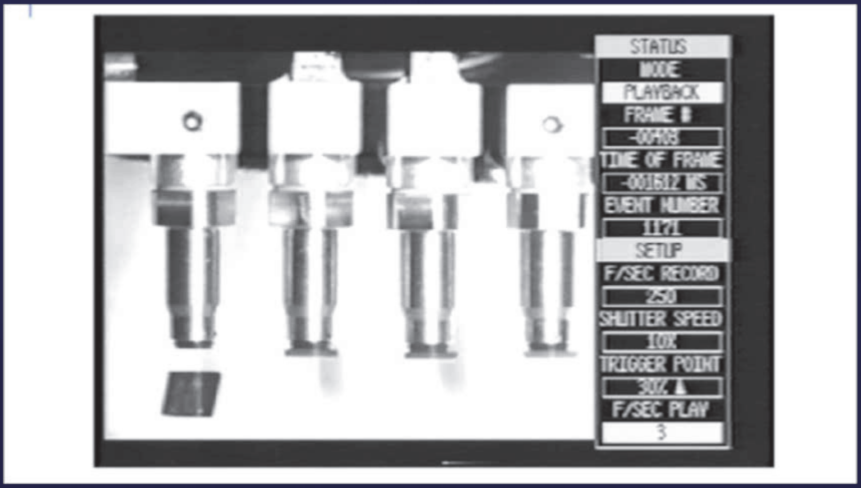
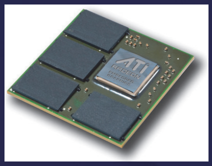
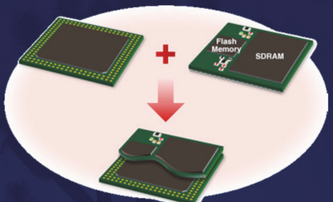
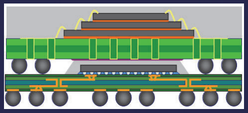
Evolution of the end effector

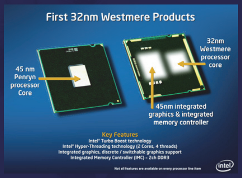


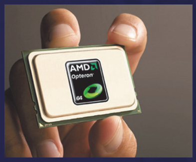
Multi-chip modules

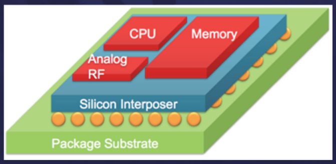


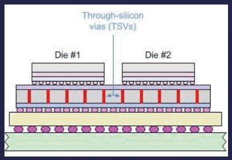


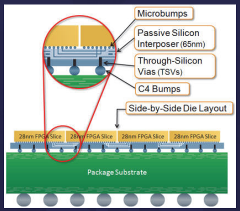


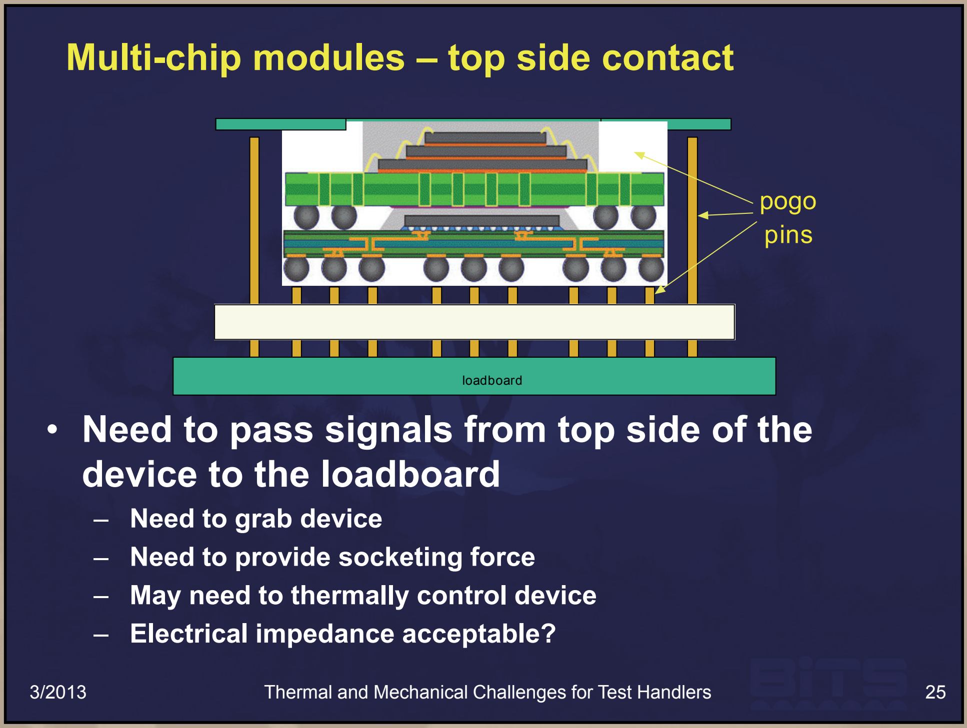












Multi-chip modules – top side contact

- Need to pass signals from top side of the device to the loadboard
  - Need to grab device
  - Need to provide socketing force
  - May need to thermally control device
  - Electrical impedance acceptable?

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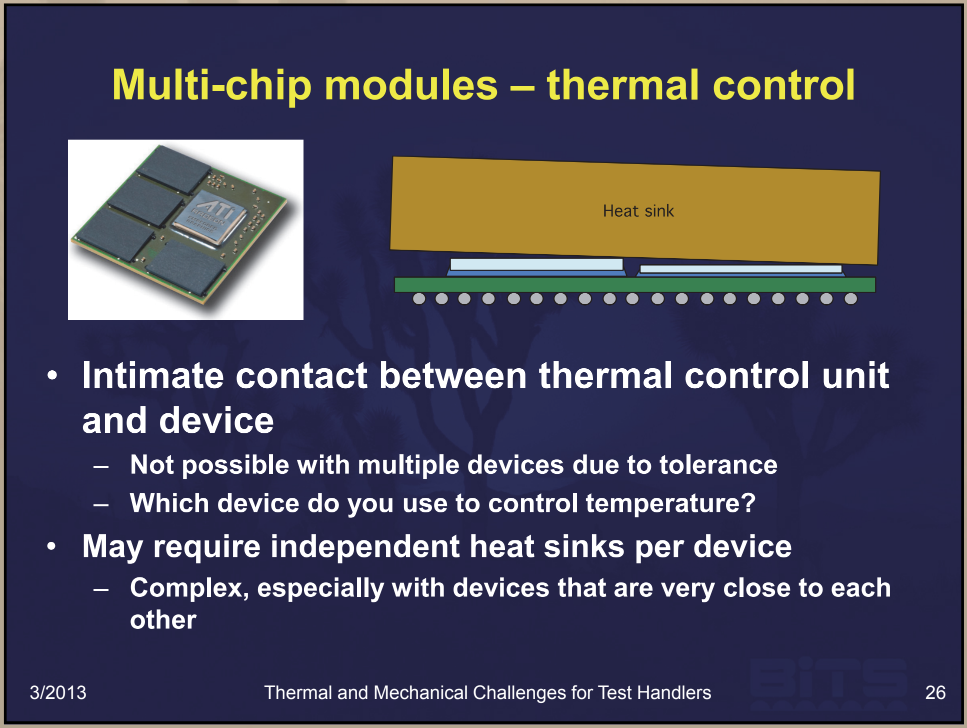

Multi-chip modules – thermal control

- Intimate contact between thermal control unit and device
  - Not possible with multiple devices due to tolerance
  - Which device do you use to control temperature?
- May require independent heat sinks per device
  - Complex, especially with devices that are very close to each other

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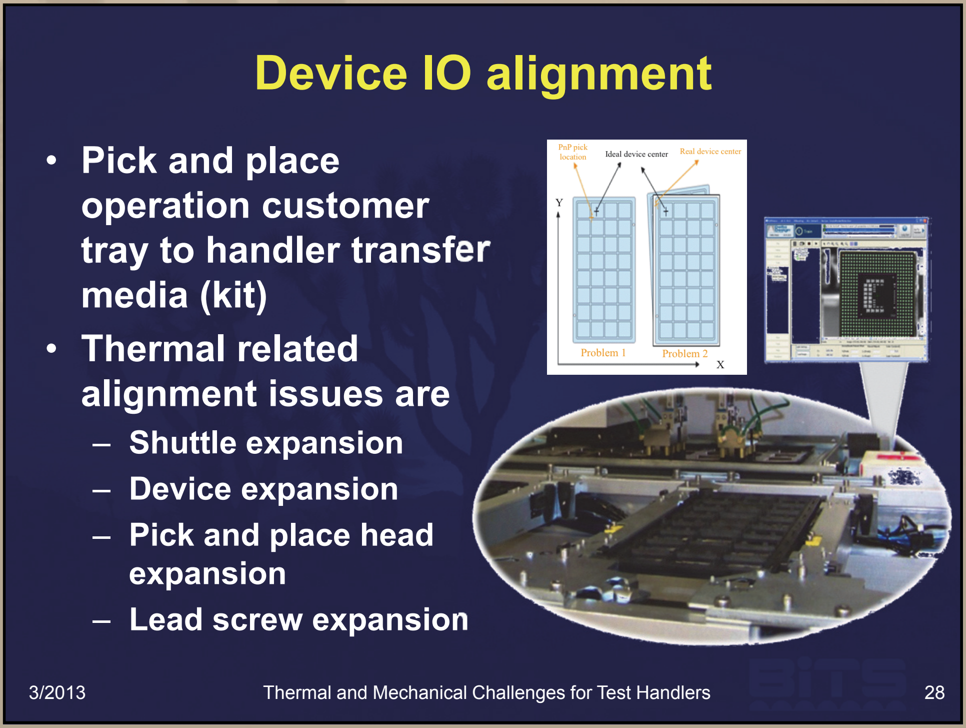
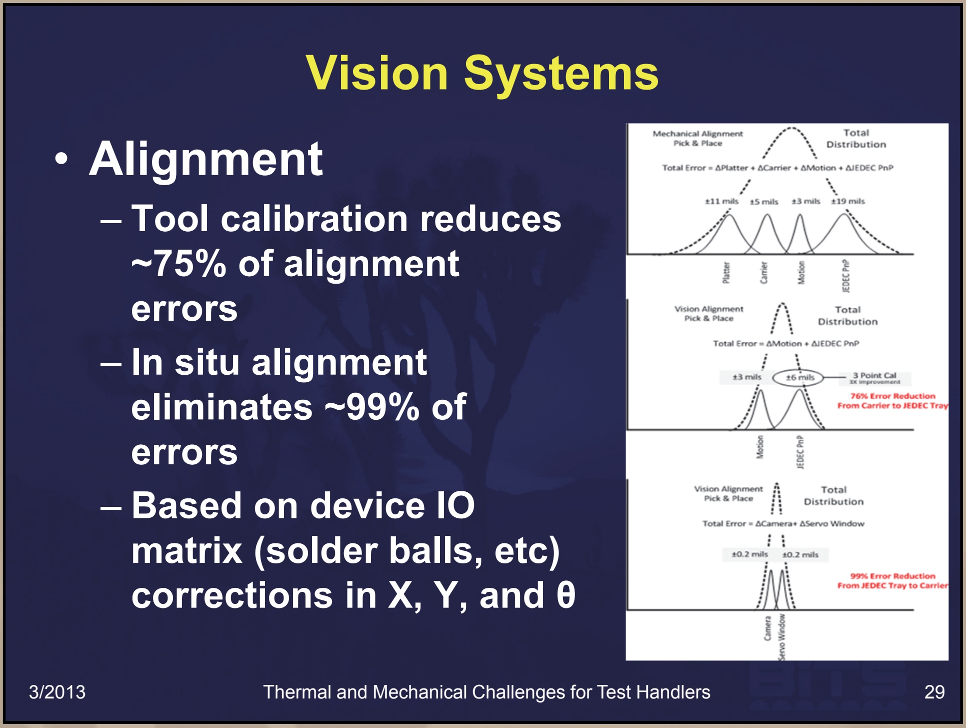
Device pick up

- Keep out zones (KOZ) increasing
  - Multiple devices (passive and active)
  - Area needed for thermal contact
  - ☙ ➔ vacuum cups not a viable option
- Requires new method for PnP step



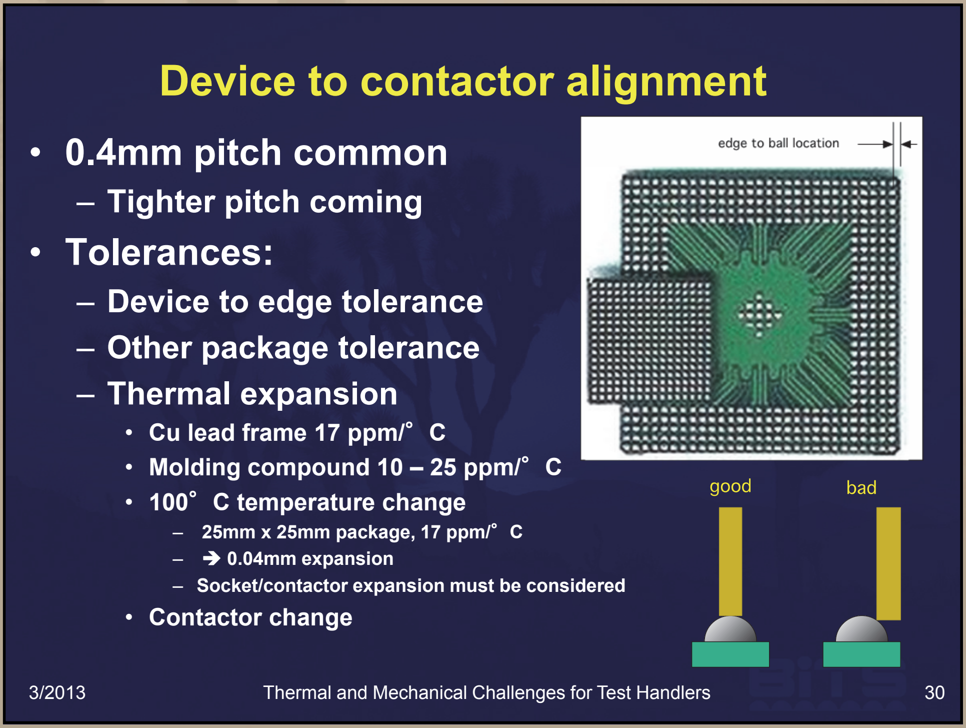
Device IO alignment

- Pick and place operation customer tray to handler transfer media (kit)
- Thermal related alignment issues are
  - Shuttle expansion
  - Device expansion
  - Pick and place head expansion
  - Lead screw expansion



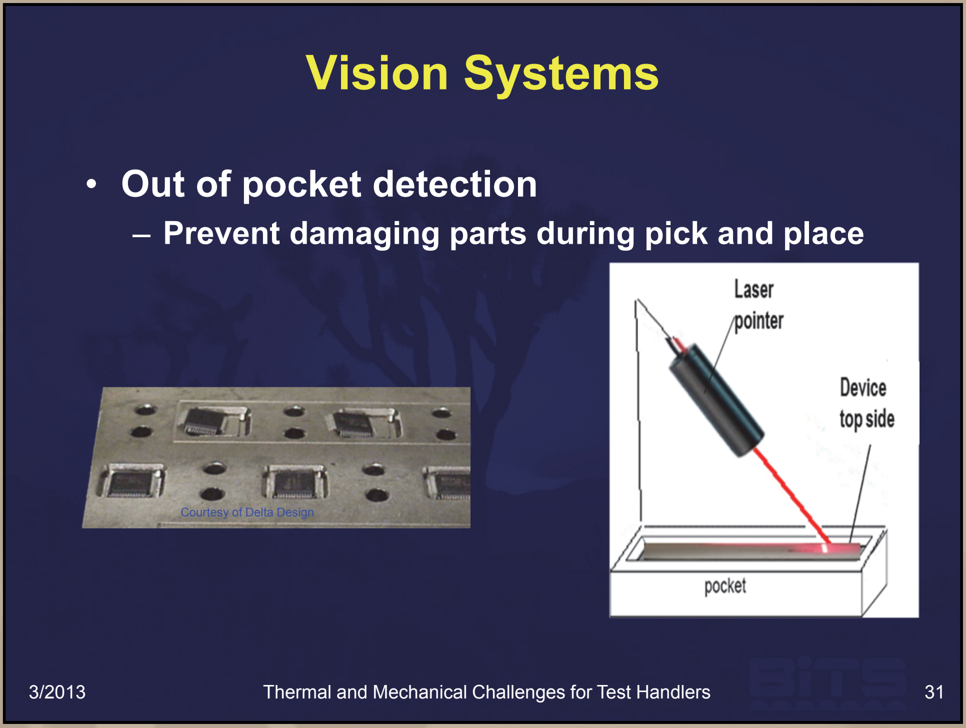
Vision Systems

- Alignment
  - Tool calibration reduces ~75% of alignment errors
  - In situ alignment eliminates ~99% of errors
  - Based on device IO matrix (solder balls, etc) corrections in X, Y, and θ



Device to contactor alignment

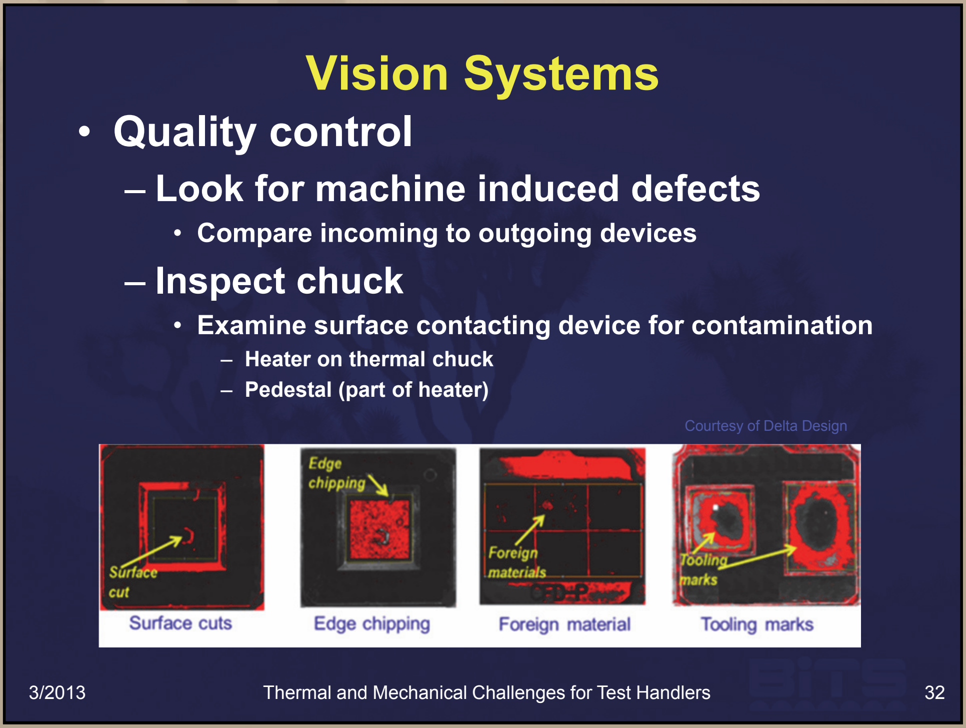
- 0.4mm pitch common
  - Tighter pitch coming
- Tolerances:
  - Device to edge tolerance
  - Other package tolerance
  - Thermal expansion
    - Cu lead frame 17 ppm/° C
    - Molding compound 10 – 25 ppm/° C
    - 100° C temperature change
      - 25mm x 25mm package, 17 ppm/° C
      - ➔ 0.04mm expansion
      - Socket/contactor expansion must be considered
    - Contactor change



Vision Systems

- Out of pocket detection
  - Prevent damaging parts during pick and place

Courtesy of Delta Design



Vision Systems

- Quality control
  - Look for machine induced defects
    - Compare incoming to outgoing devices
  - Inspect chuck
    - Examine surface contacting device for contamination
      - Heater on thermal chuck
      - Pedestal (part of heater)

Courtesy of Delta Design

Surface cuts | Edge chipping | Foreign material | Tooling marks

Vision Systems

- Quality control
  - –Inspect top side of device for defects
    - Crack detection
    - Foreign matter
    - Edge chipping
    - Stains (example: fingerprint)

Cracks

Edge chips

Stains

FM Contamination

Courtesy of Delta Design

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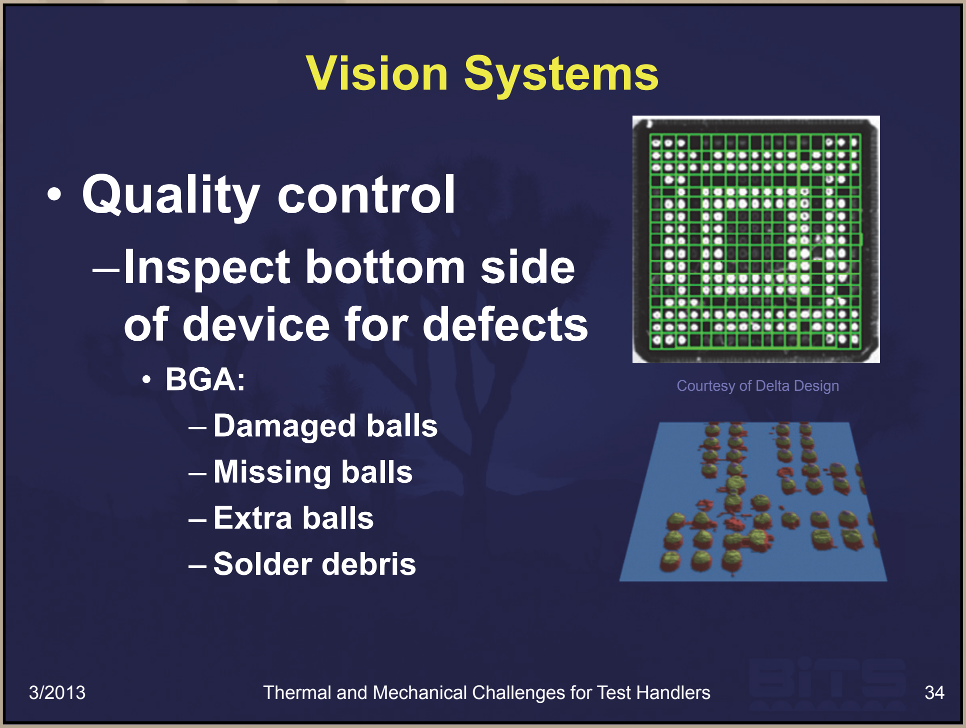

Vision Systems

- Quality control
  - –Inspect bottom side of device for defects
    - BGA:
      - – Damaged balls
      - – Missing balls
      - – Extra balls
      - – Solder debris

Courtesy of Delta Design

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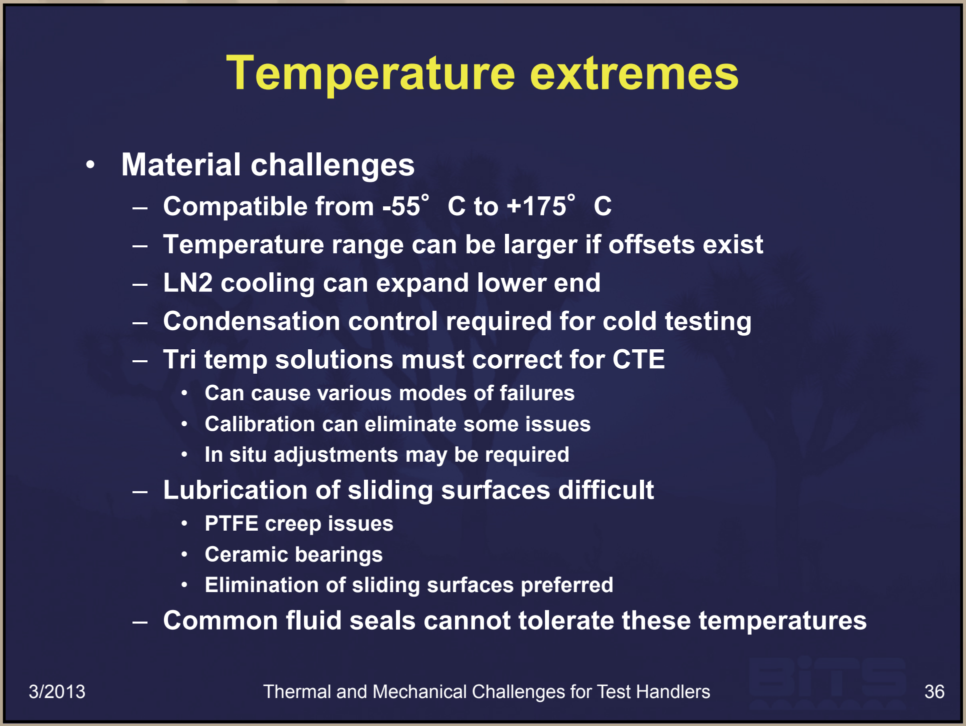
Vision Systems

- **Quality control bottom side:**
  - PGA:
    - Bent pin
  - LGA:
    - Contamination
  - QFP:
    - Bent lead
  - QFN:
    - Damaged pad

Courtesy of Delta Design



Temperature extremes

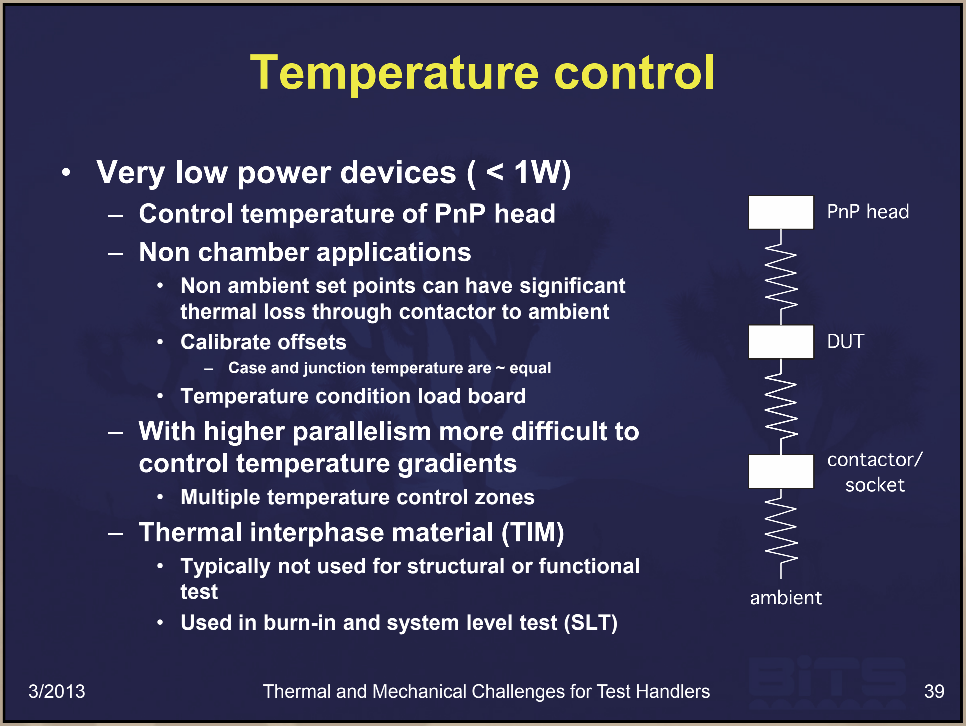
- Material challenges
  - Compatible from -55° C to +175° C
  - Temperature range can be larger if offsets exist
  - LN2 cooling can expand lower end
  - Condensation control required for cold testing
  - Tri temp solutions must correct for CTE
    - Can cause various modes of failures
    - Calibration can eliminate some issues
    - In situ adjustments may be required
  - Lubrication of sliding surfaces difficult
    - PTFE creep issues
    - Ceramic bearings
    - Elimination of sliding surfaces preferred
  - Common fluid seals cannot tolerate these temperatures

Temperature control

- Functional or structural test
  - Short test time and single temperature
- System level test (SLT)
  - Moderate test time and multiple temperatures
- Burn-in (BI)
  - Relatively long test time and single (hot) temperature

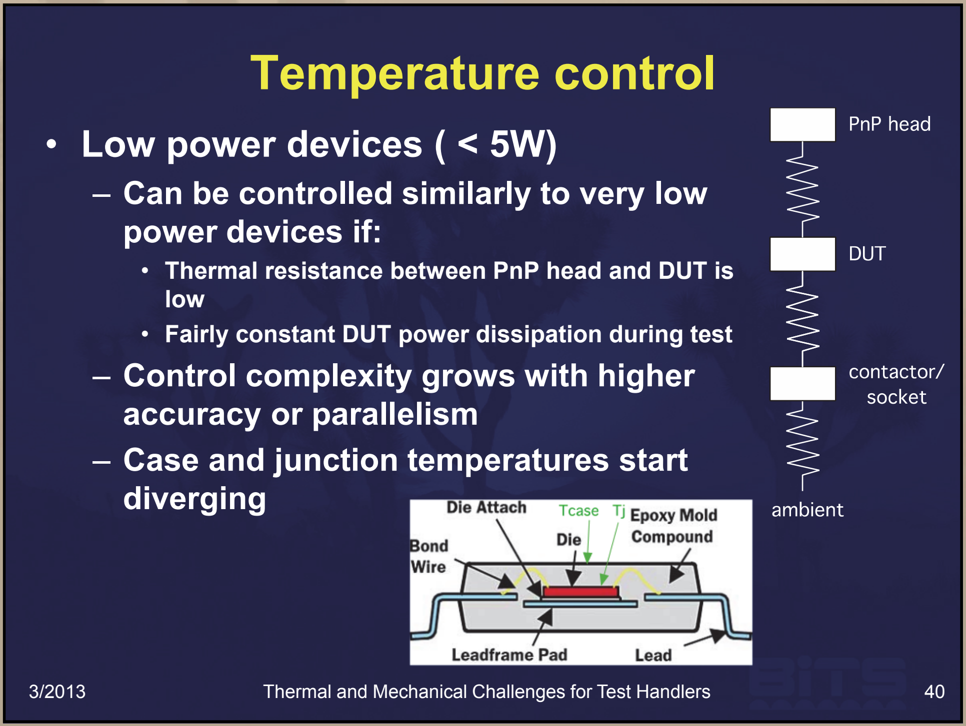
Temperature control

- Heating
  - Direct with electric heaters
  - Heated fluids
  - Thermoelectric modules
- Cooling
  - Air, natural and forced convection
  - Liquid
  - Thermoelectric modules
  - Phase change
    - Single phase refrigeration
    - Two stage refrigeration (< -30° C)
    - Liquid nitrogen (LN2)



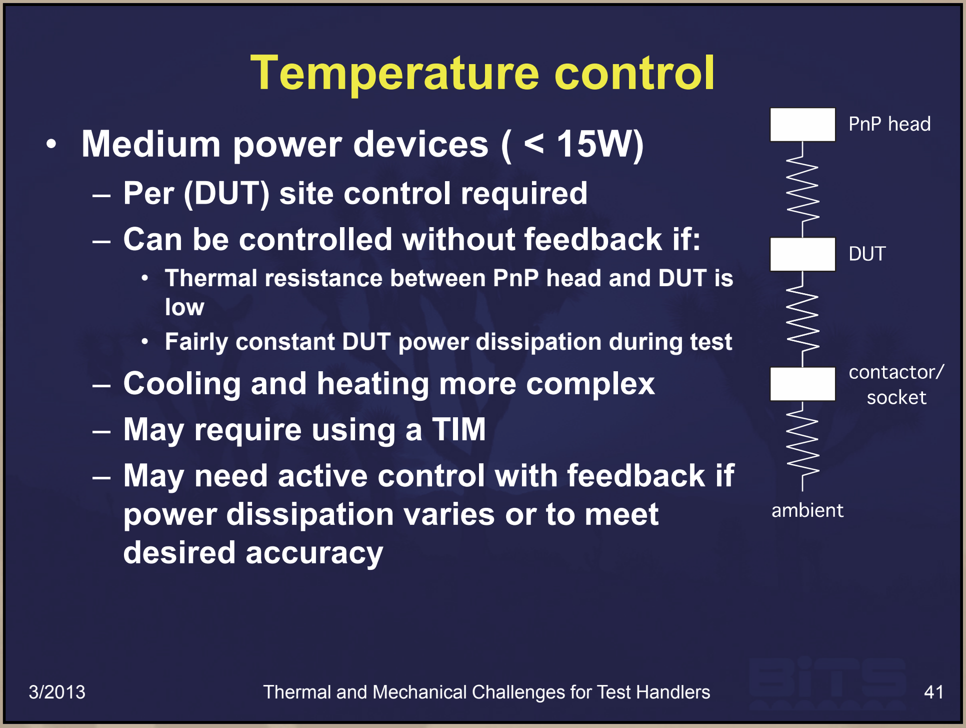
Temperature control

- Very low power devices (< 1W)
  - Control temperature of PnP head
  - Non chamber applications
    - Non ambient set points can have significant thermal loss through contactor to ambient
    - Calibrate offsets
      - Case and junction temperature are ~ equal
    - Temperature condition load board
  - With higher parallelism more difficult to control temperature gradients
    - Multiple temperature control zones
  - Thermal interphase material (TIM)
    - Typically not used for structural or functional test
    - Used in burn-in and system level test (SLT)



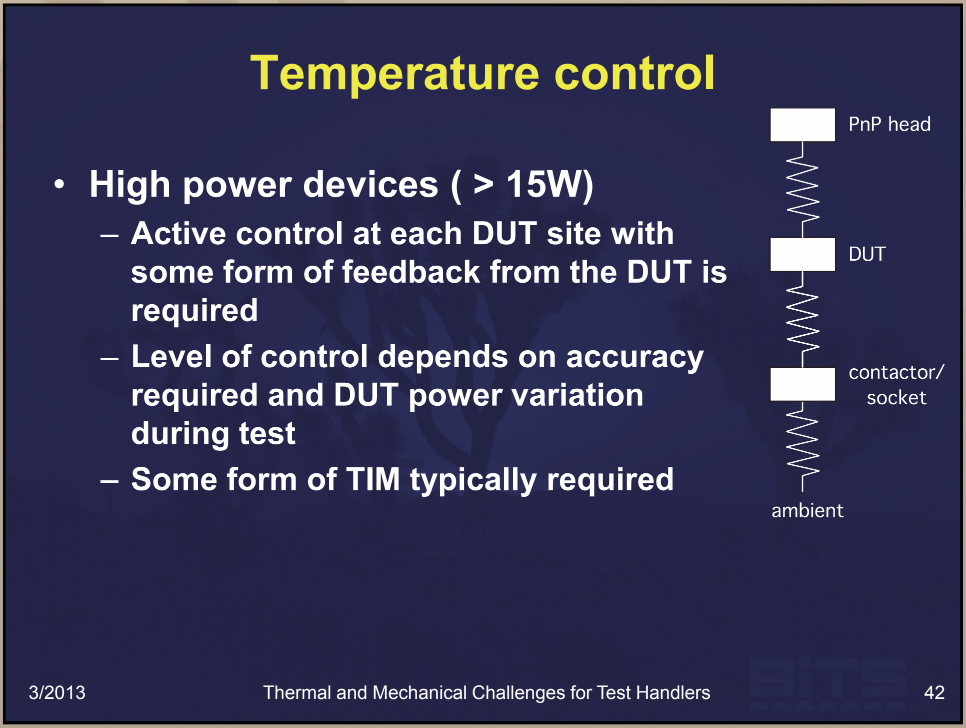
Temperature control

- Low power devices (< 5W)
  - Can be controlled similarly to very low power devices if:
    - Thermal resistance between PnP head and DUT is low
    - Fairly constant DUT power dissipation during test
  - Control complexity grows with higher accuracy or parallelism
  - Case and junction temperatures start diverging



Temperature control

- **Medium power devices (< 15W)**
  - – Per (DUT) site control required
  - – Can be controlled without feedback if:
    - Thermal resistance between PnP head and DUT is low
    - Fairly constant DUT power dissipation during test
  - – Cooling and heating more complex
  - – May require using a TIM
  - – May need active control with feedback if power dissipation varies or to meet desired accuracy

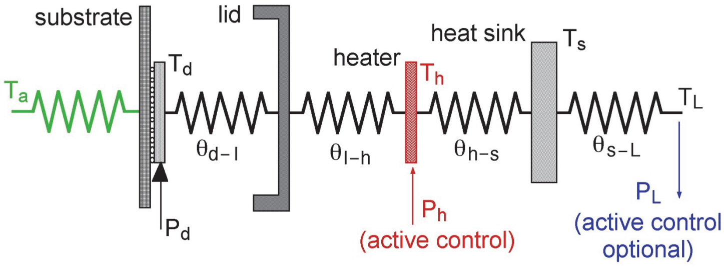


Temperature control

- **High power devices (> 15W)**
  - – Active control at each DUT site with some form of feedback from the DUT is required
  - – Level of control depends on accuracy required and DUT power variation during test
  - – Some form of TIM typically required

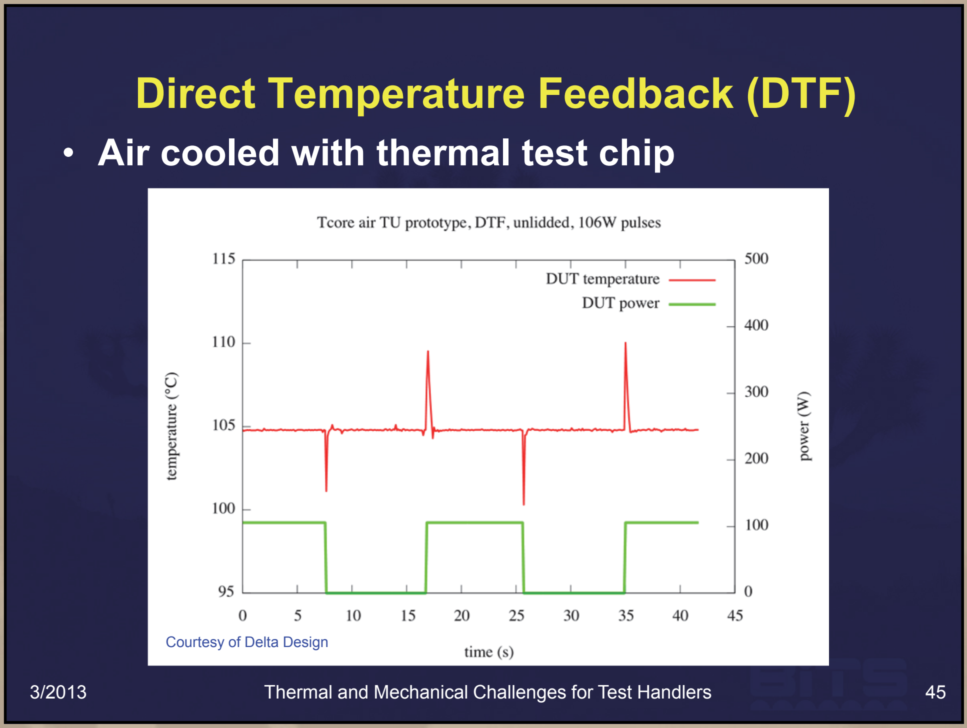
Temperature control

- **Active cooling technology** (Delta Design patent)
  - **Air Liquid, or phase change (refrigeration)**
  - **Low mass, highly conductive heater**
    - **Heater provides very fast dynamic response**
  - **Slower response with variable coolant flow**
    - **Extends range and improves efficiency**
  - **Temperature control with or without DUT thermal sensor**



Direct Temperature Feedback (DTF)

- Control with DUT temperature sensor(s) present
  - Typically diode or RTD on chip
  - Theoretically more accurate and more stable
  - Sensor output varies with manufacturing tolerances
    - In-situ calibration with heater eliminates error
    - Use saturation current cancellation technique
  - Sensor location may not be optimal
    - Non uniform power dissipation
    - Large temperature gradients across chip
  - Digital sensors beginning to appear
    - Access available between subtests
    - No feedback without DUT power



Direct Temperature Feedback (DTF)

- Air cooled with thermal test chip

Courtesy of Delta Design

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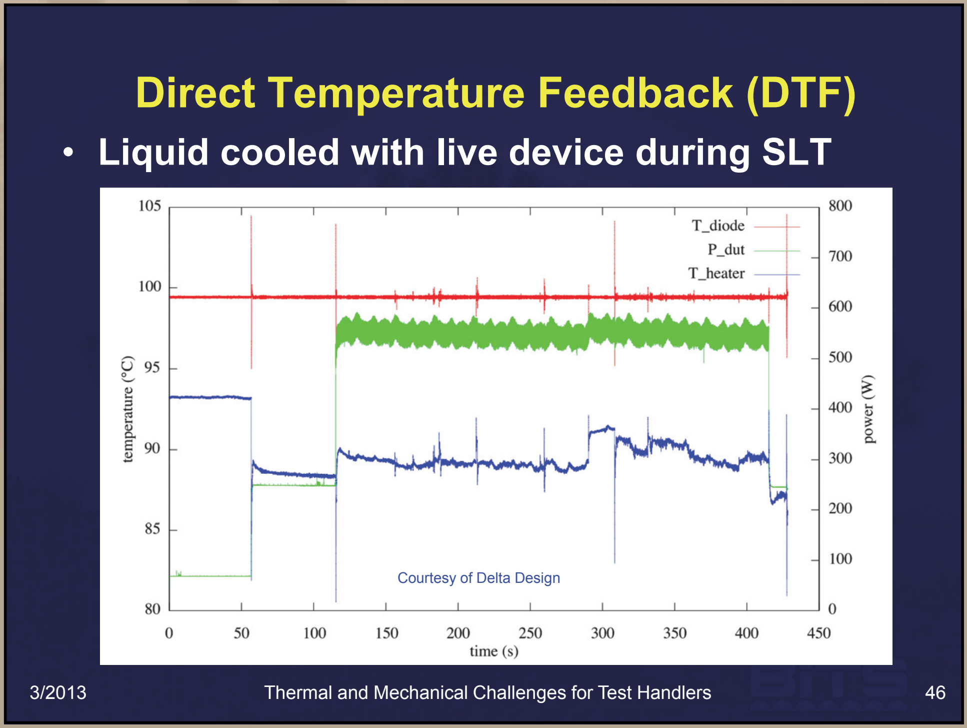

Direct Temperature Feedback (DTF)

- Liquid cooled with live device during SLT

Courtesy of Delta Design

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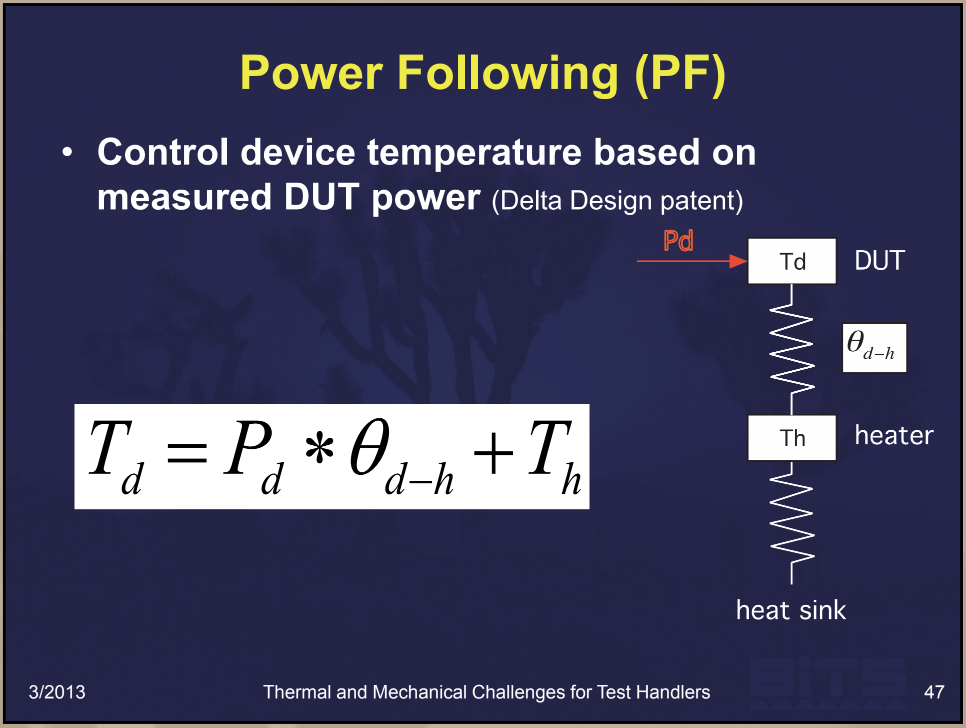

Power Following (PF)

- **Control device temperature based on measured DUT power** (Delta Design patent)

$$T_d = P_d * \theta_{d-h} + T_h$$

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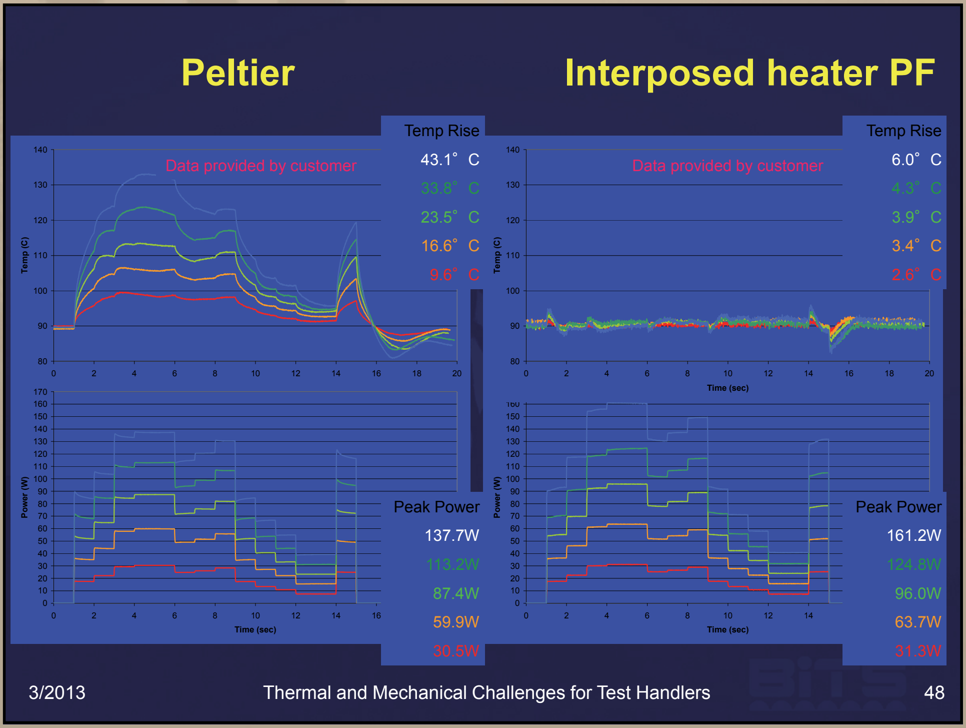

Peltier

Interposed heater PF

Peltier:

Temp Rise
43.1° C
33.8° C
23.5° C
16.6° C
9.6° C

Peak Power
137.7W
113.2W
87.4W
59.9W
30.5W

Interposed heater PF:

Temp Rise
6.0° C
4.3° C
3.9° C
3.4° C
2.6° C

Peak Power
161.2W
124.8W
96.0W
63.7W
31.3W

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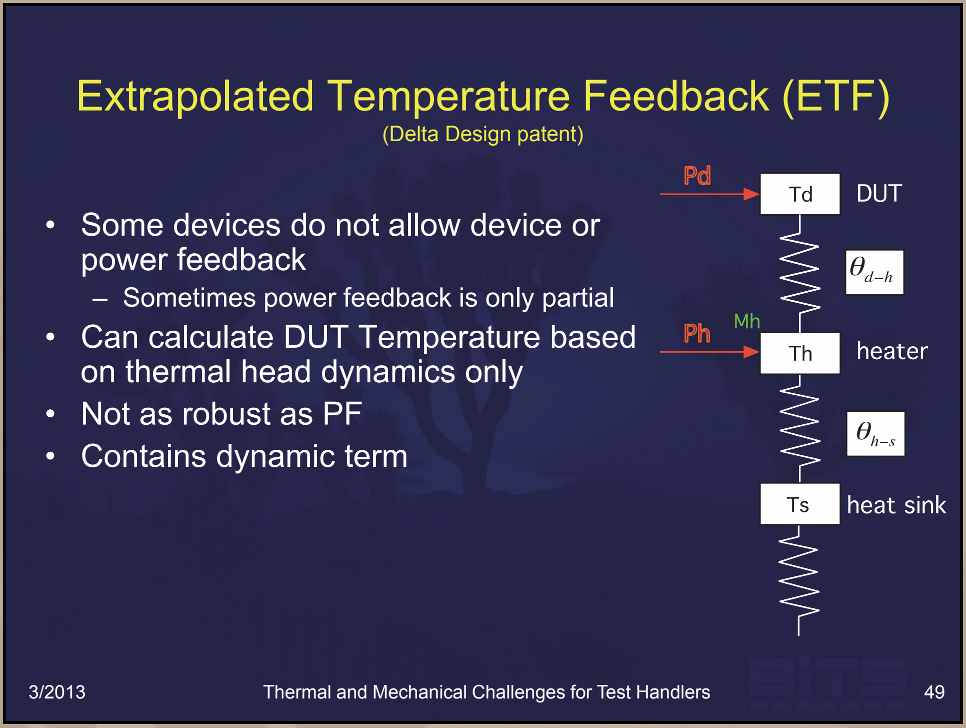

Extrapolated Temperature Feedback (ETF)

(Delta Design patent)

- Some devices do not allow device or power feedback
  - Sometimes power feedback is only partial
- Can calculate DUT Temperature based on thermal head dynamics only
- Not as robust as PF
- Contains dynamic term

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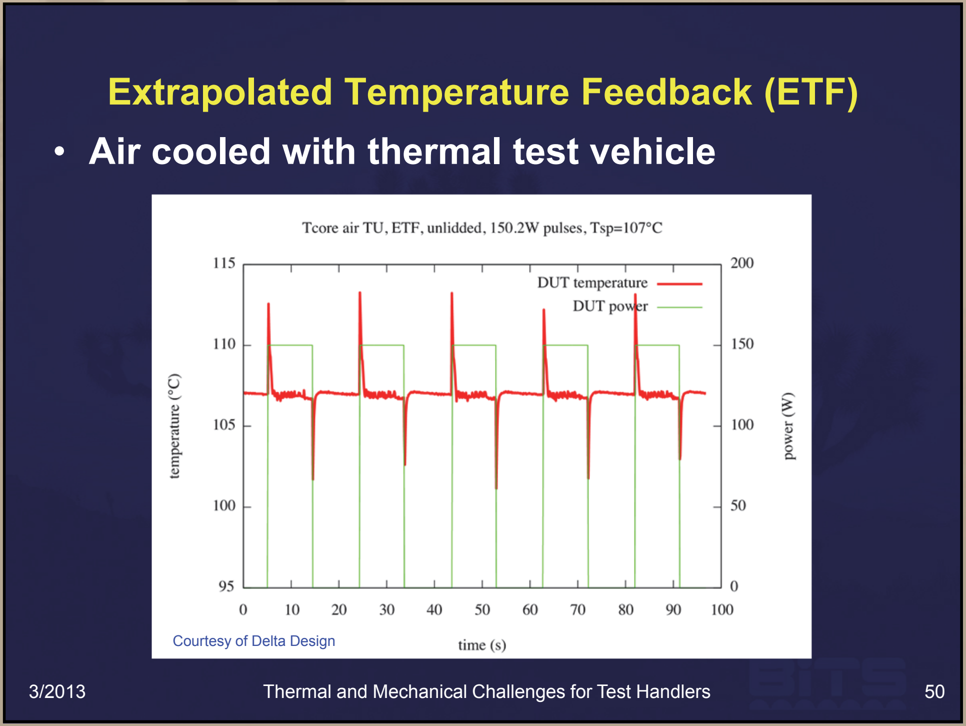

Extrapolated Temperature Feedback (ETF)

- **Air cooled with thermal test vehicle**

Courtesy of Delta Design

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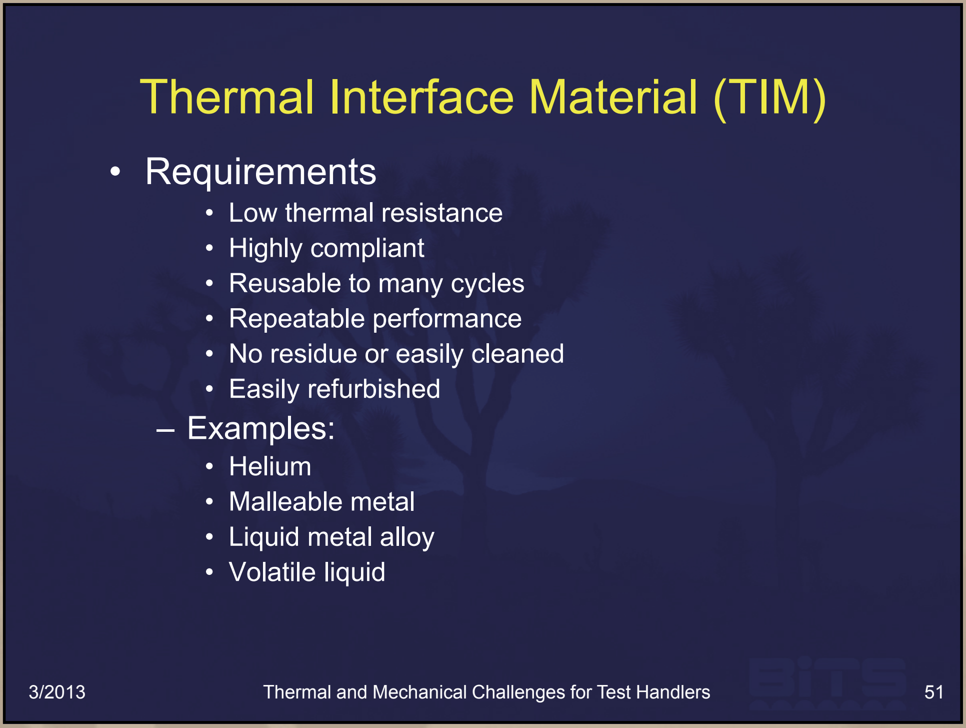
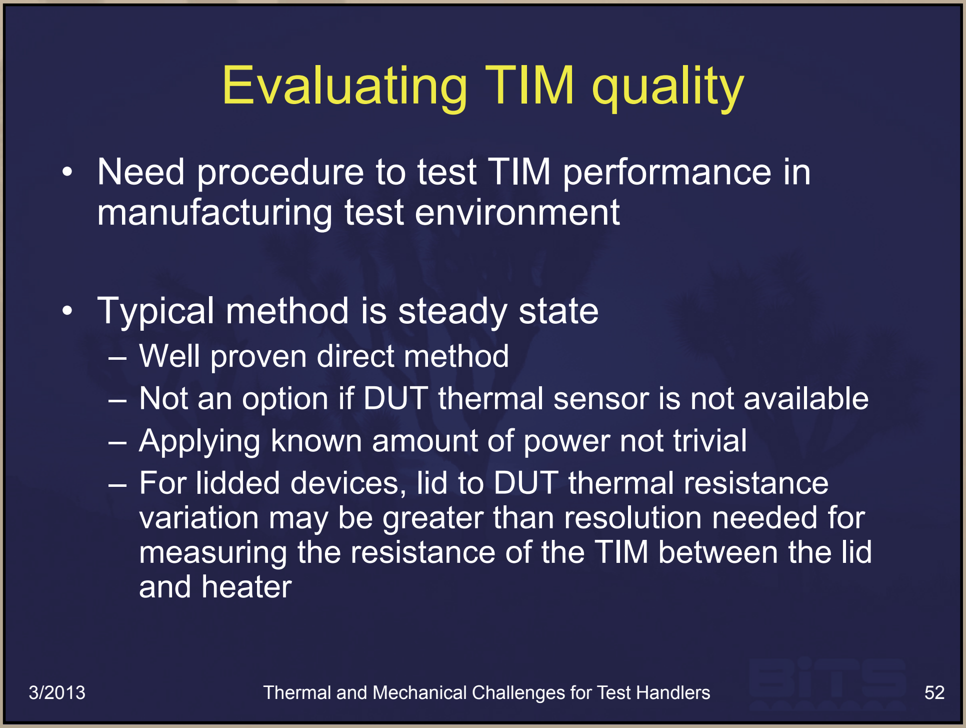


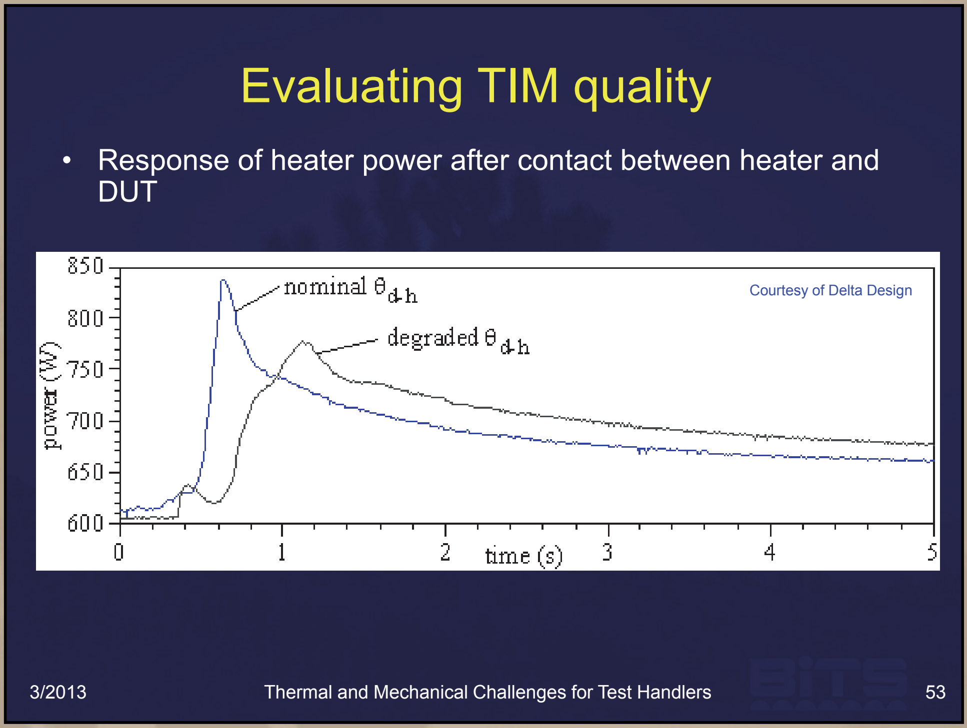
Thermal Interface Material (TIM)

- Requirements
    - Low thermal resistance
    - Highly compliant
    - Reusable to many cycles
    - Repeatable performance
    - No residue or easily cleaned
    - Easily refurbished
  - Examples:
    - Helium
    - Malleable metal
    - Liquid metal alloy
    - Volatile liquid



Evaluating TIM quality

- Need procedure to test TIM performance in manufacturing test environment
- Typical method is steady state
  - Well proven direct method
  - Not an option if DUT thermal sensor is not available
  - Applying known amount of power not trivial
  - For lidded devices, lid to DUT thermal resistance variation may be greater than resolution needed for measuring the resistance of the TIM between the lid and heater



Evaluating TIM quality

- Response of heater power after contact between heater and DUT

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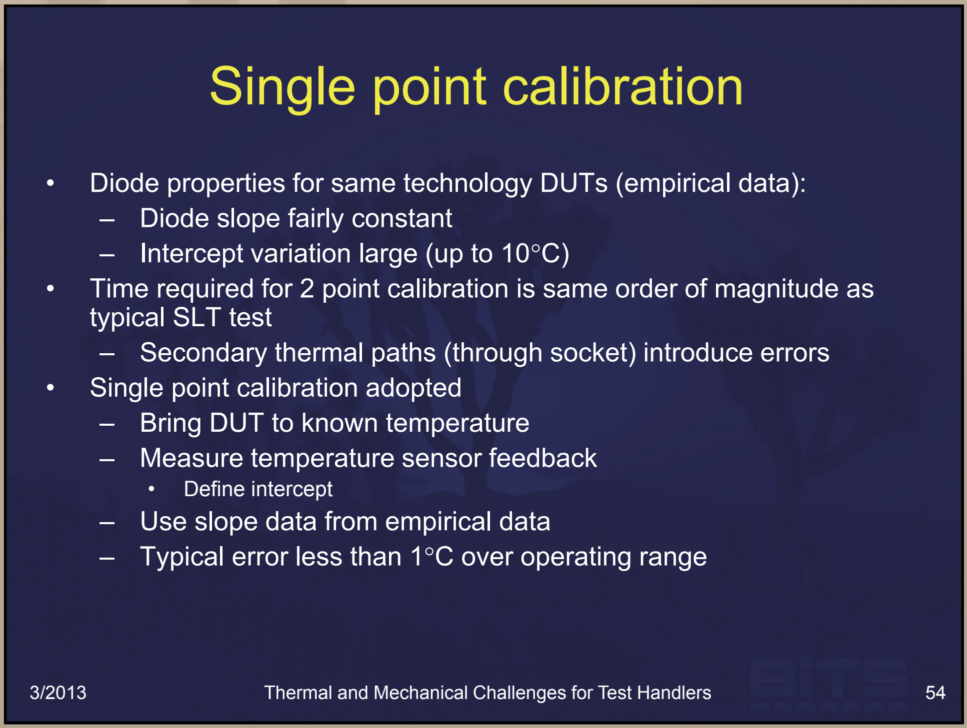

Single point calibration

- Diode properties for same technology DUTs (empirical data):
  - Diode slope fairly constant
  - Intercept variation large (up to 10°C)
- Time required for 2 point calibration is same order of magnitude as typical SLT test
  - Secondary thermal paths (through socket) introduce errors
- Single point calibration adopted
  - Bring DUT to known temperature
  - Measure temperature sensor feedback
    - Define intercept
  - Use slope data from empirical data
  - Typical error less than 1°C over operating range

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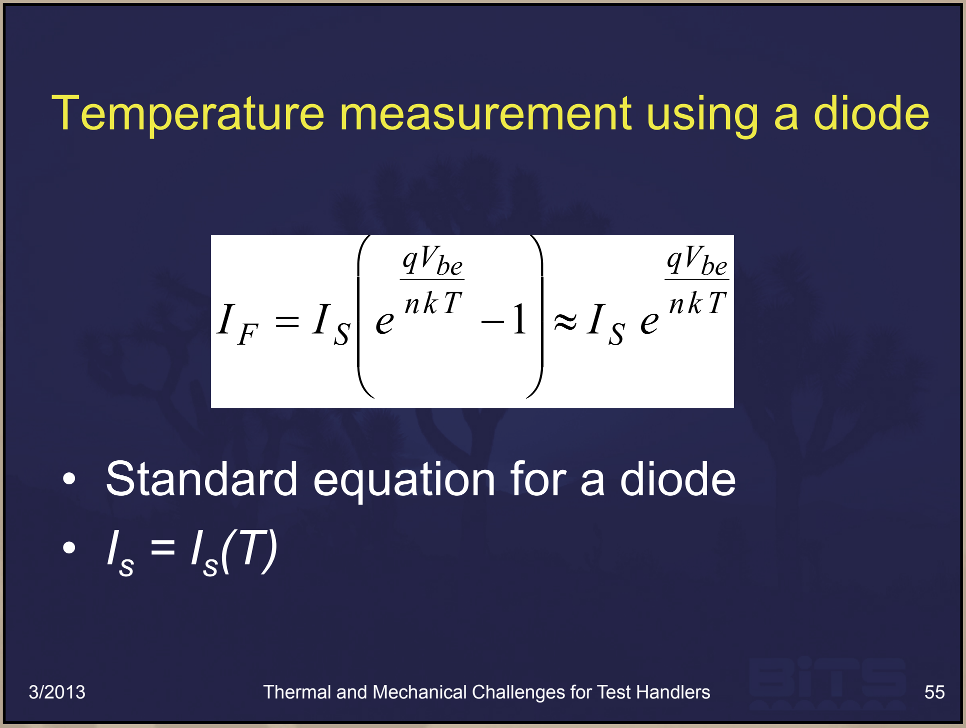
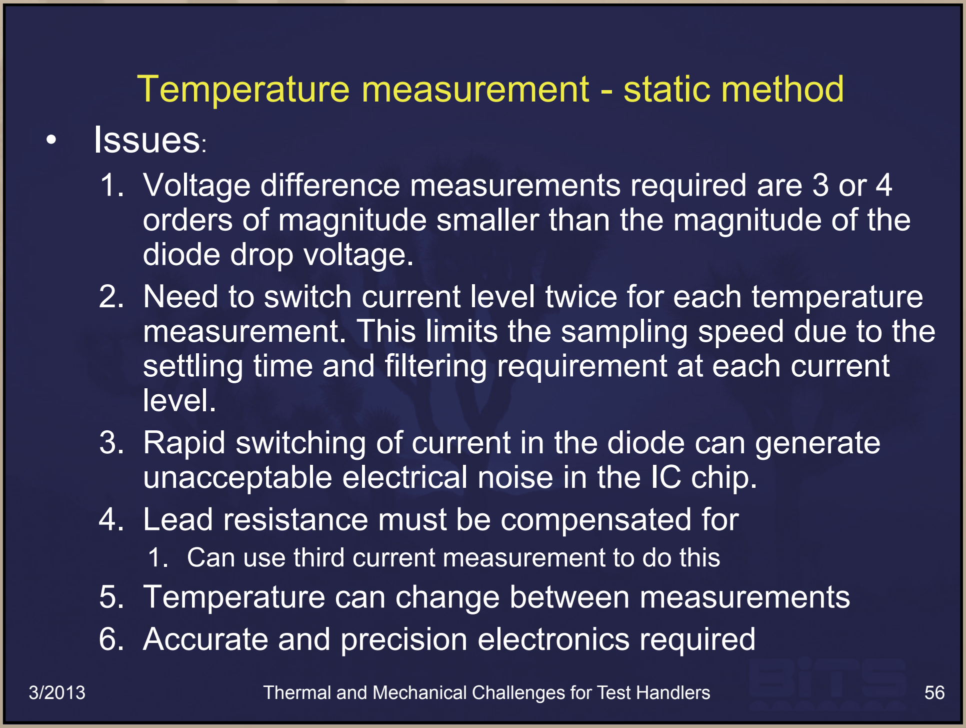


Temperature measurement using a diode

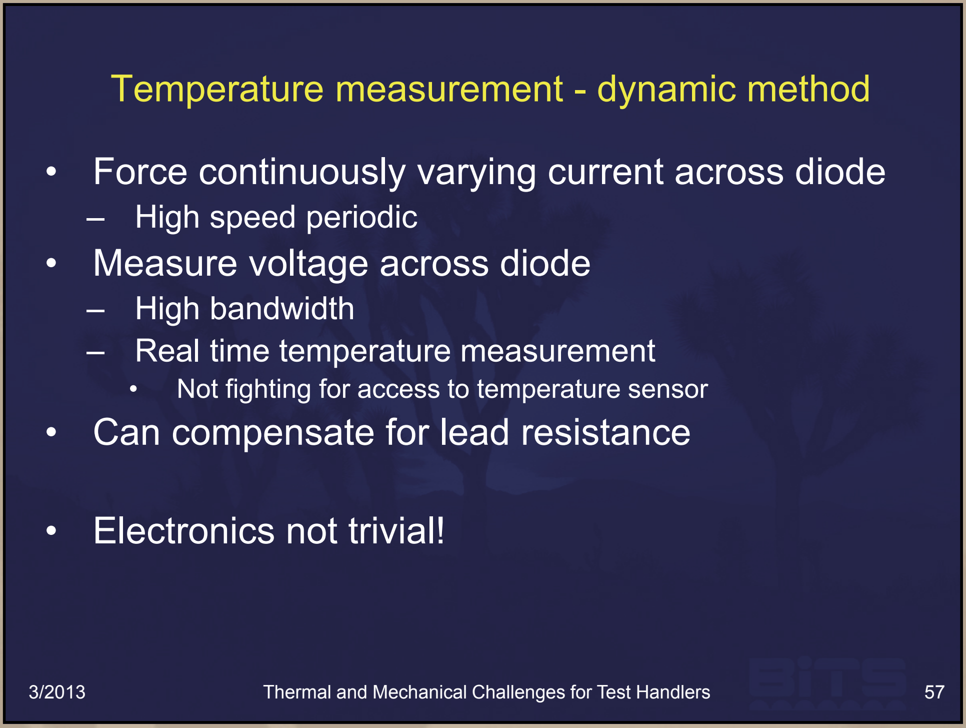
$$I_F = I_S\left(e^{\frac{qV_{be}}{nkT}} - 1\right) \approx I_S\, e^{\frac{qV_{be}}{nkT}}$$

- Standard equation for a diode
- $I_s = I_s(T)$



Temperature measurement - static method

- Issues:
  1. Voltage difference measurements required are 3 or 4 orders of magnitude smaller than the magnitude of the diode drop voltage.
  2. Need to switch current level twice for each temperature measurement. This limits the sampling speed due to the settling time and filtering requirement at each current level.
  3. Rapid switching of current in the diode can generate unacceptable electrical noise in the IC chip.
  4. Lead resistance must be compensated for
     1. Can use third current measurement to do this
  5. Temperature can change between measurements
  6. Accurate and precision electronics required



Temperature measurement - dynamic method

- Force continuously varying current across diode
  - High speed periodic
- Measure voltage across diode
  - High bandwidth
  - Real time temperature measurement
    - Not fighting for access to temperature sensor
- Can compensate for lead resistance

- Electronics not trivial!

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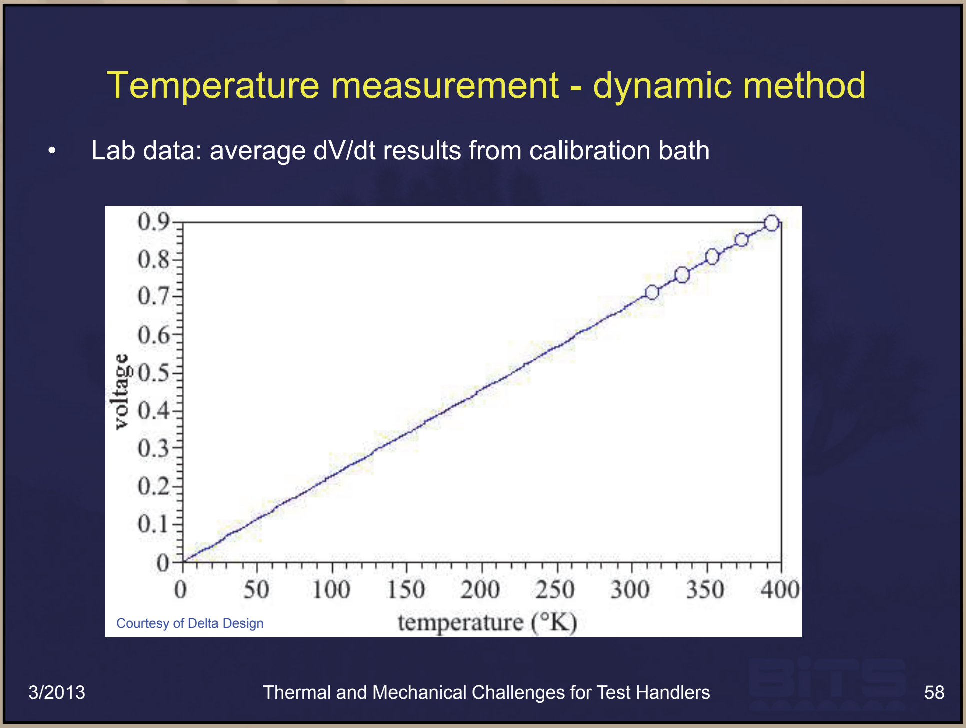

Temperature measurement - dynamic method

- Lab data: average dV/dt results from calibration bath

Courtesy of Delta Design

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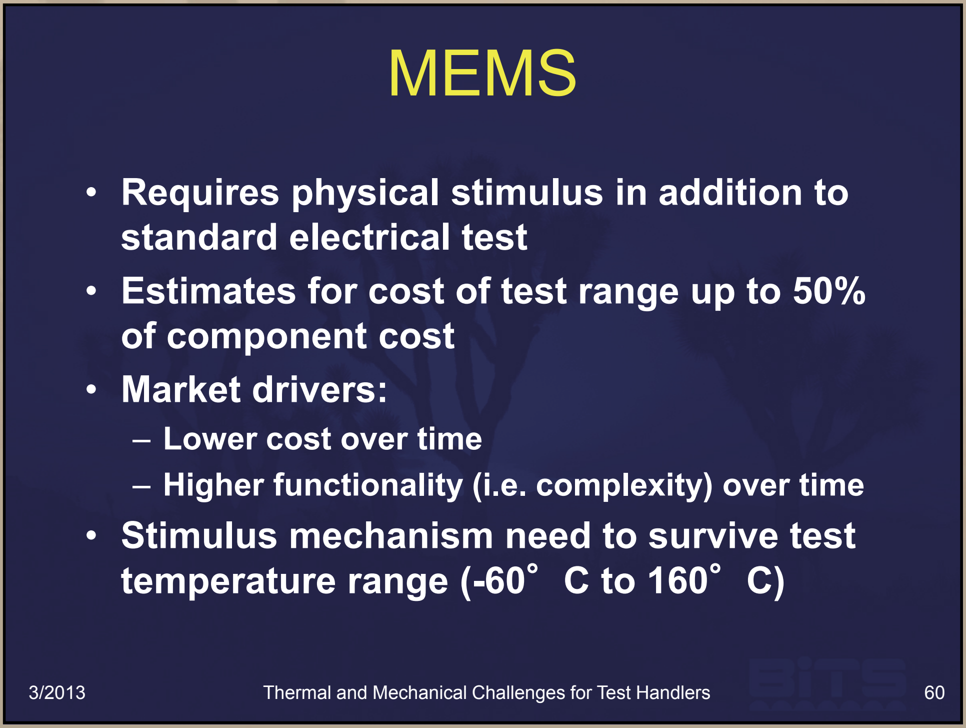
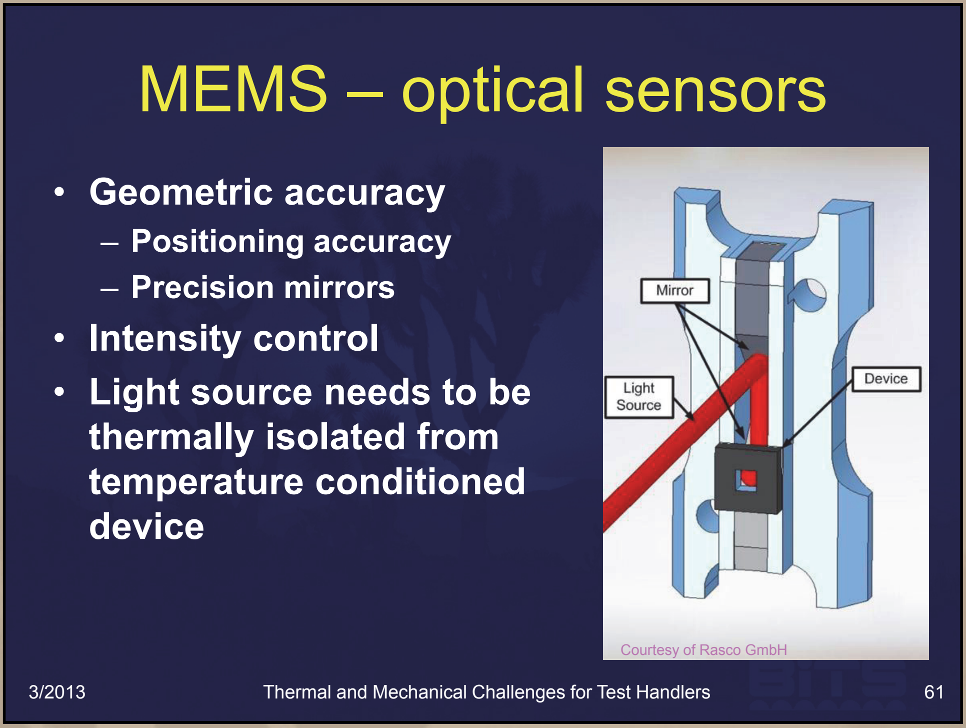
MEMS

Microelectromechanical systems (MEMS)



MEMS

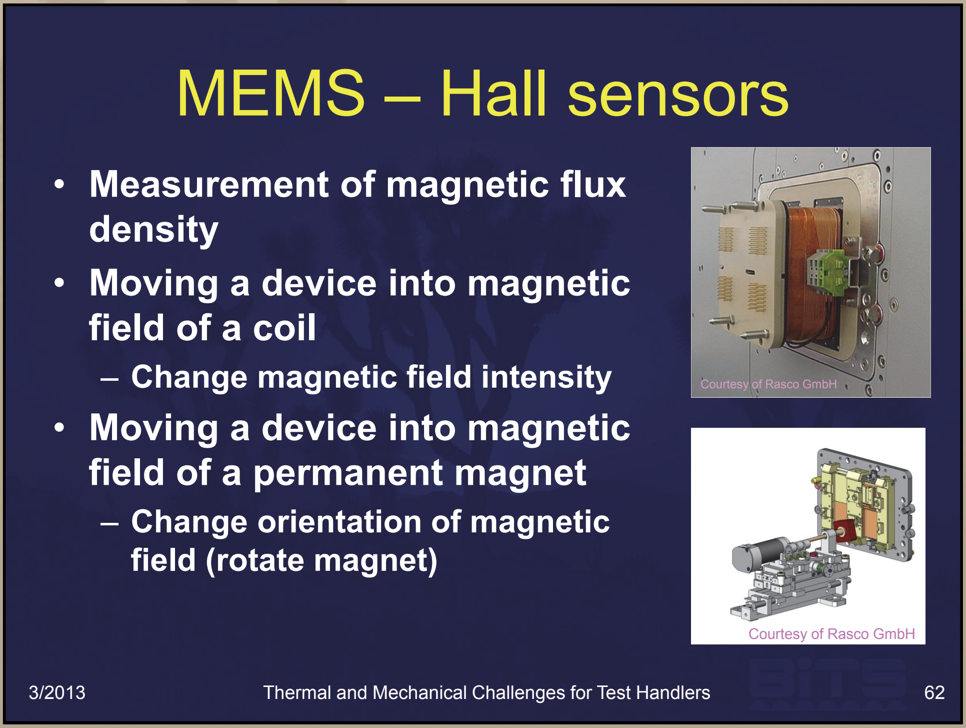
- Requires physical stimulus in addition to standard electrical test
- Estimates for cost of test range up to 50% of component cost
- Market drivers:
  - Lower cost over time
  - Higher functionality (i.e. complexity) over time
- Stimulus mechanism need to survive test temperature range (-60° C to 160° C)



MEMS – optical sensors

- Geometric accuracy
  - Positioning accuracy
  - Precision mirrors
- Intensity control
- Light source needs to be thermally isolated from temperature conditioned device

Courtesy of Rasco GmbH

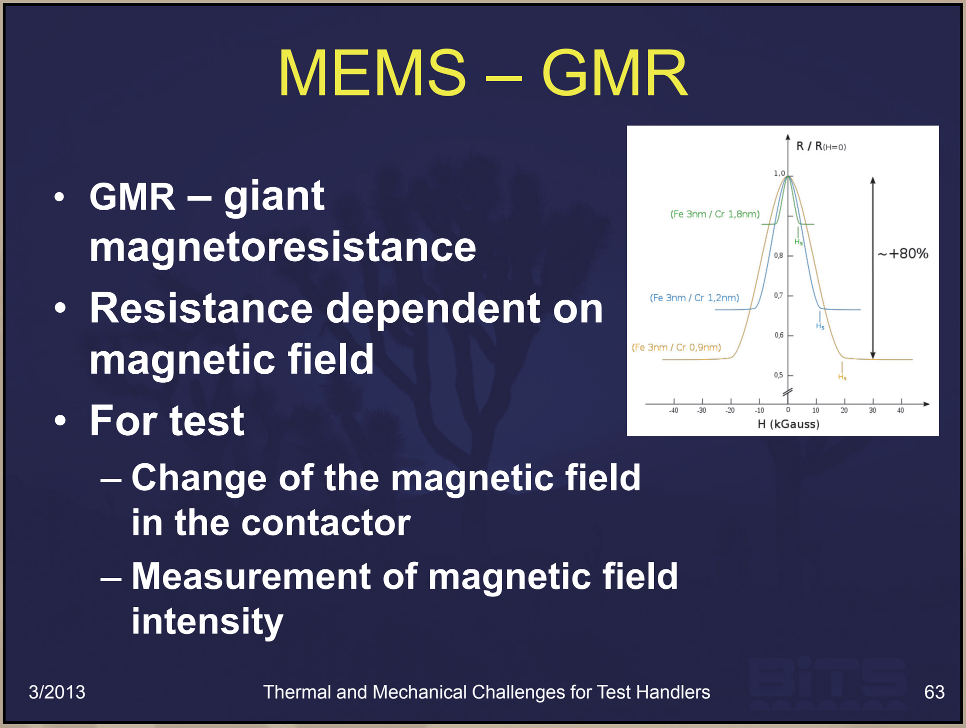


MEMS – Hall sensors

- Measurement of magnetic flux density
- Moving a device into magnetic field of a coil
  - Change magnetic field intensity
- Moving a device into magnetic field of a permanent magnet
  - Change orientation of magnetic field (rotate magnet)

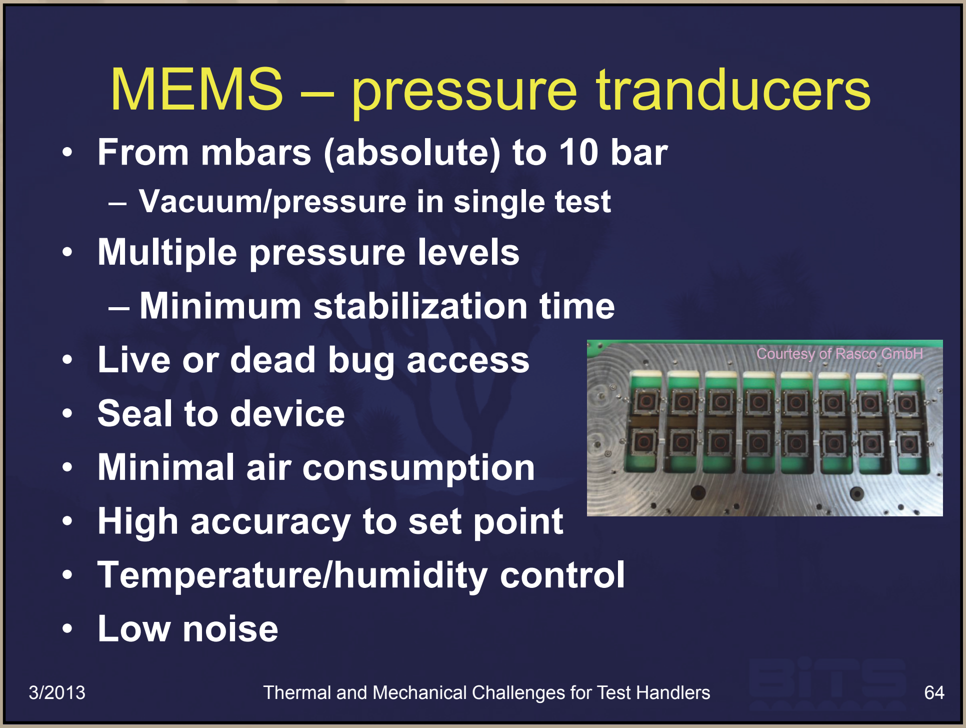
Courtesy of Rasco GmbH

Courtesy of Rasco GmbH



MEMS – GMR

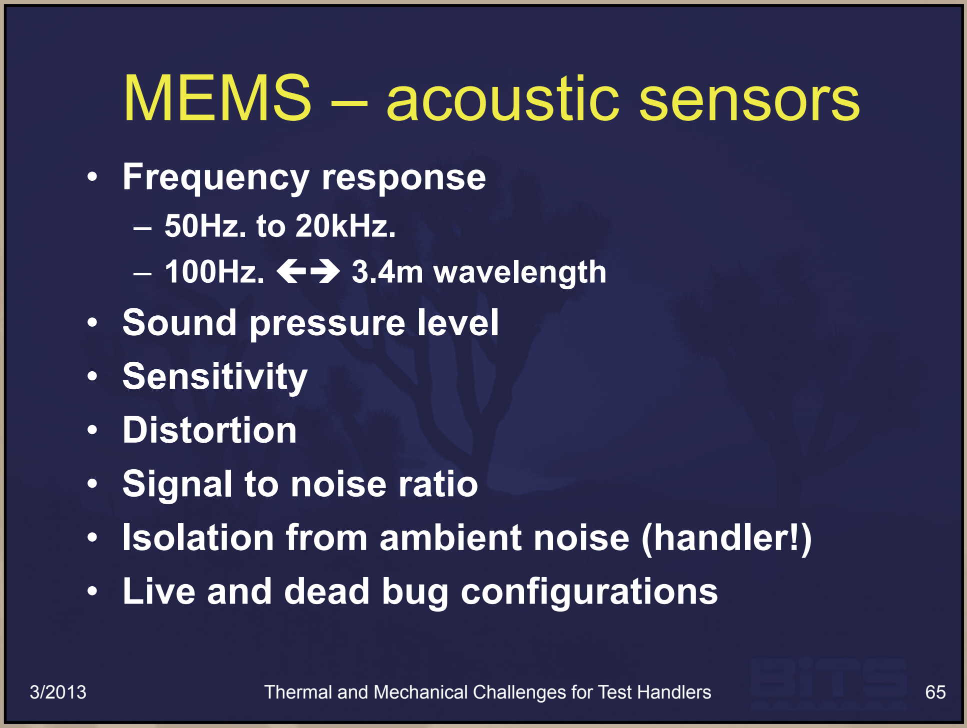
- GMR – giant magnetoresistance
- Resistance dependent on magnetic field
- For test
  - Change of the magnetic field in the contactor
  - Measurement of magnetic field intensity



MEMS – pressure tranducers

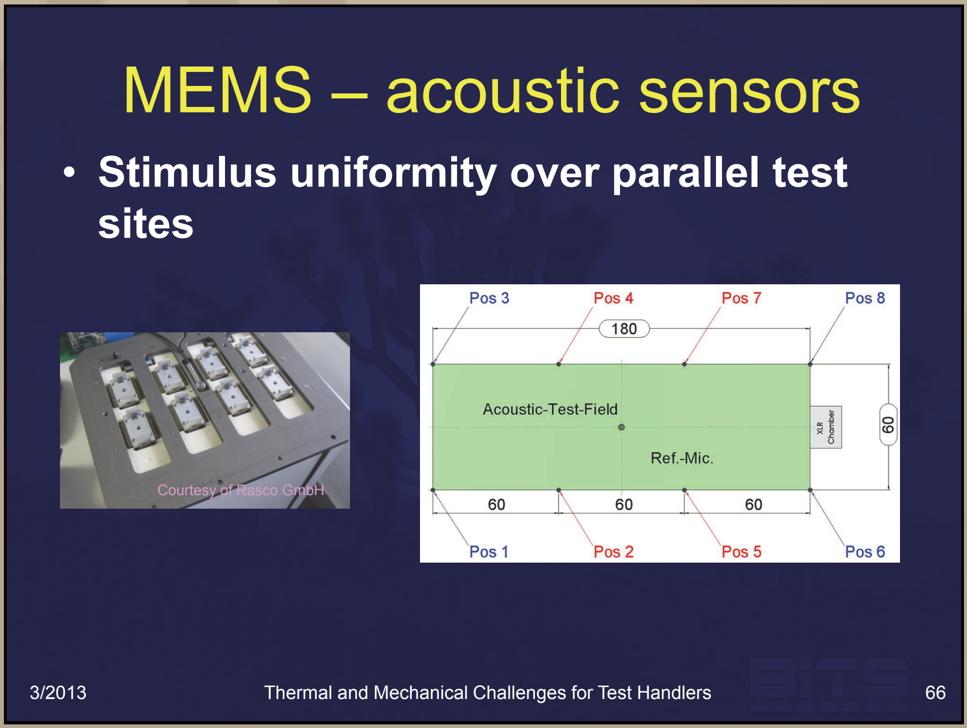
- From mbars (absolute) to 10 bar
  - Vacuum/pressure in single test
- Multiple pressure levels
  - Minimum stabilization time
- Live or dead bug access
- Seal to device
- Minimal air consumption
- High accuracy to set point
- Temperature/humidity control
- Low noise

Courtesy of Rasco GmbH



MEMS – acoustic sensors

- Frequency response
  - 50Hz. to 20kHz.
  - 100Hz. ←→ 3.4m wavelength
- Sound pressure level
- Sensitivity
- Distortion
- Signal to noise ratio
- Isolation from ambient noise (handler!)
- Live and dead bug configurations



MEMS – acoustic sensors

- Stimulus uniformity over parallel test sites

Courtesy of Rasco GmbH

MEMS – acoustic chamber

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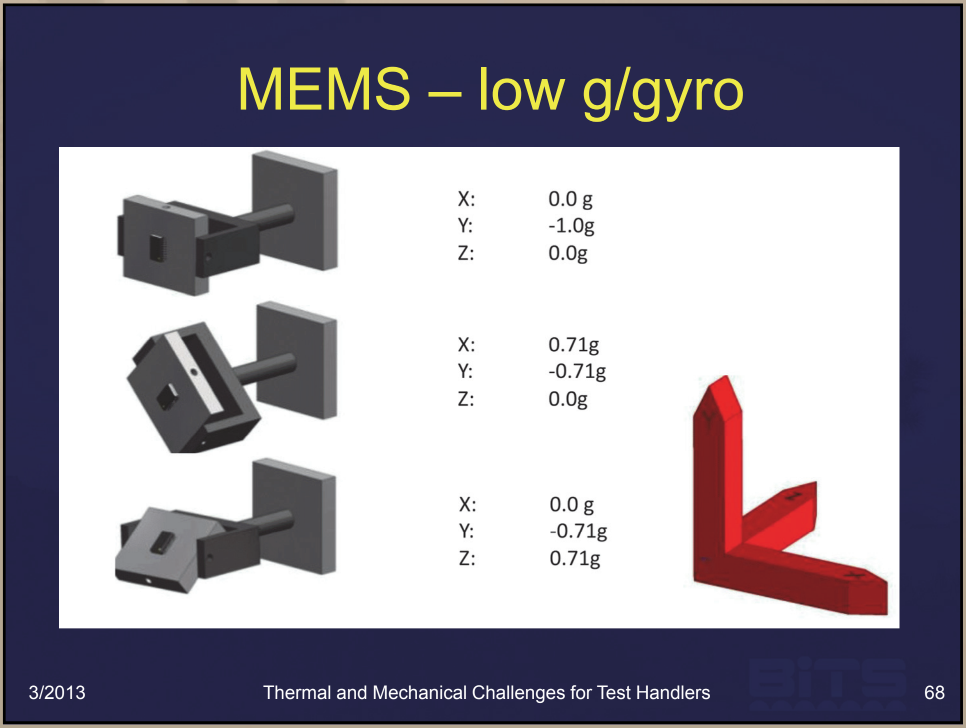

MEMS – low g/gyro

X: 0.0 g
Y: -1.0g
Z: 0.0g

X: 0.71g
Y: -0.71g
Z: 0.0g

X: 0.0 g
Y: -0.71g
Z: 0.71g

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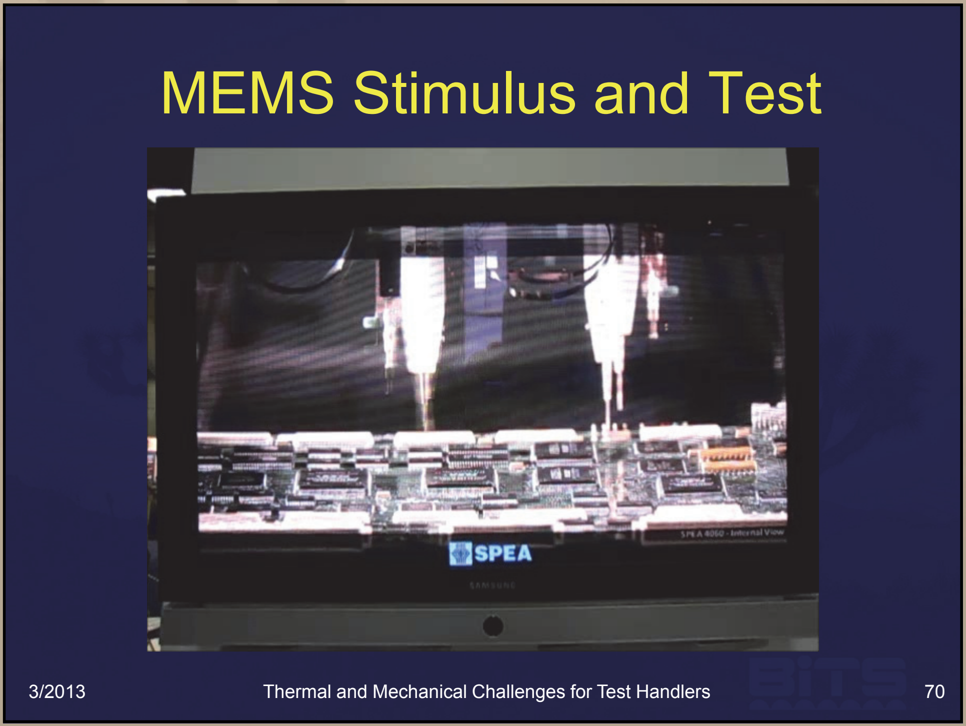
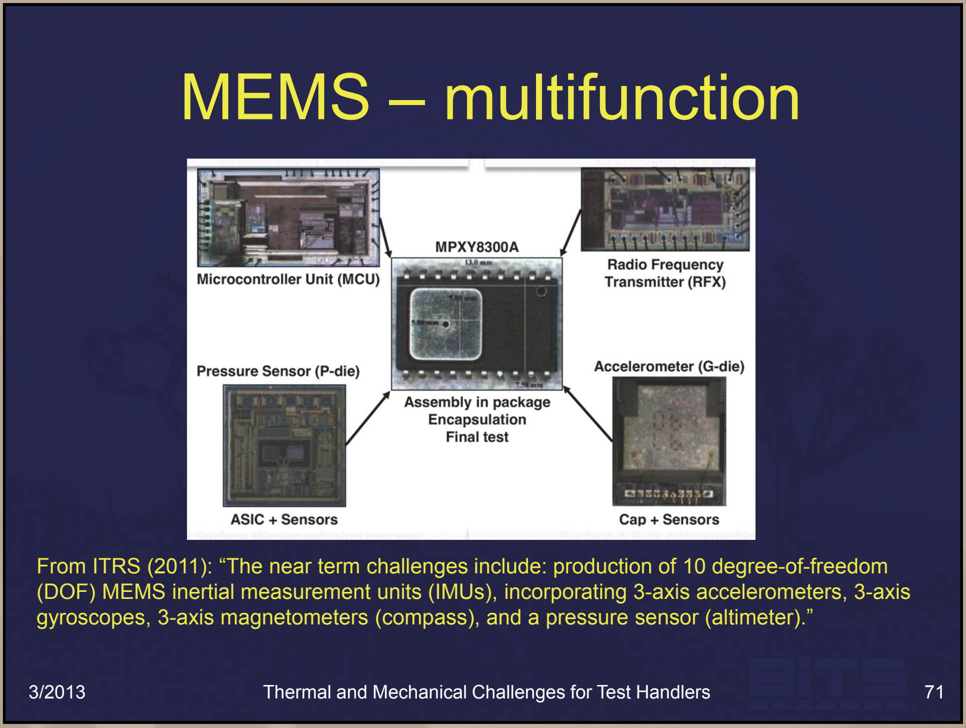
MEMS – low g/gyro

- Static test
  - Measure low g by aligning to gravity
  - Can measure multiple axes
- Dynamic test
  - Values of g > 1
  - Gyro performance
- Connectivity to devices complex
- BIST available but requires more device area (higher cost)
  - Tradeoff: cost of test vs. extra area

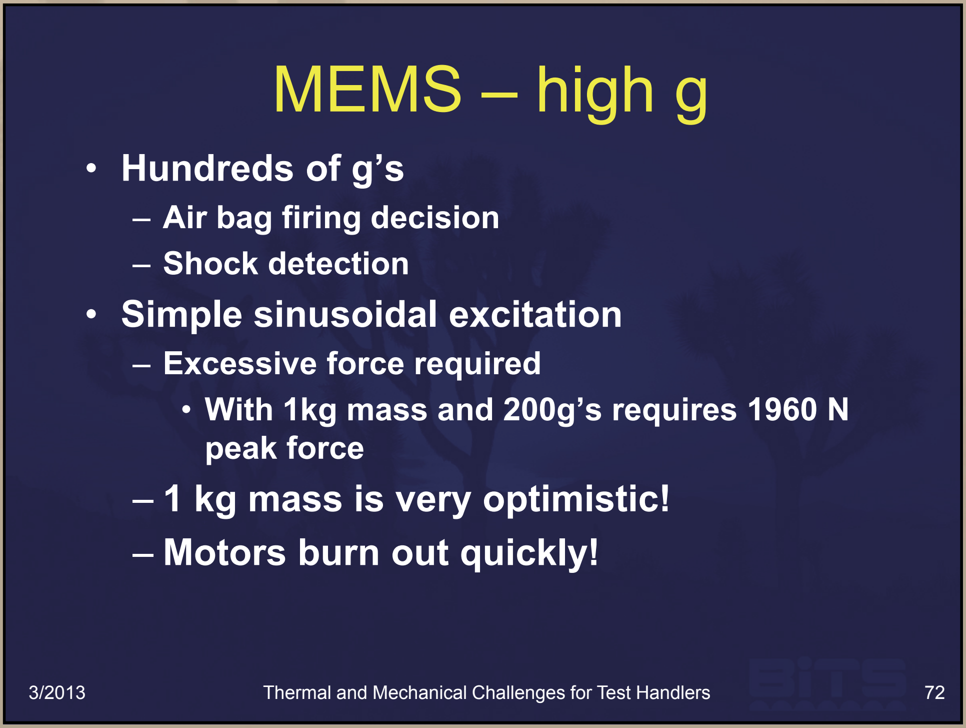


MEMS Stimulus and Test



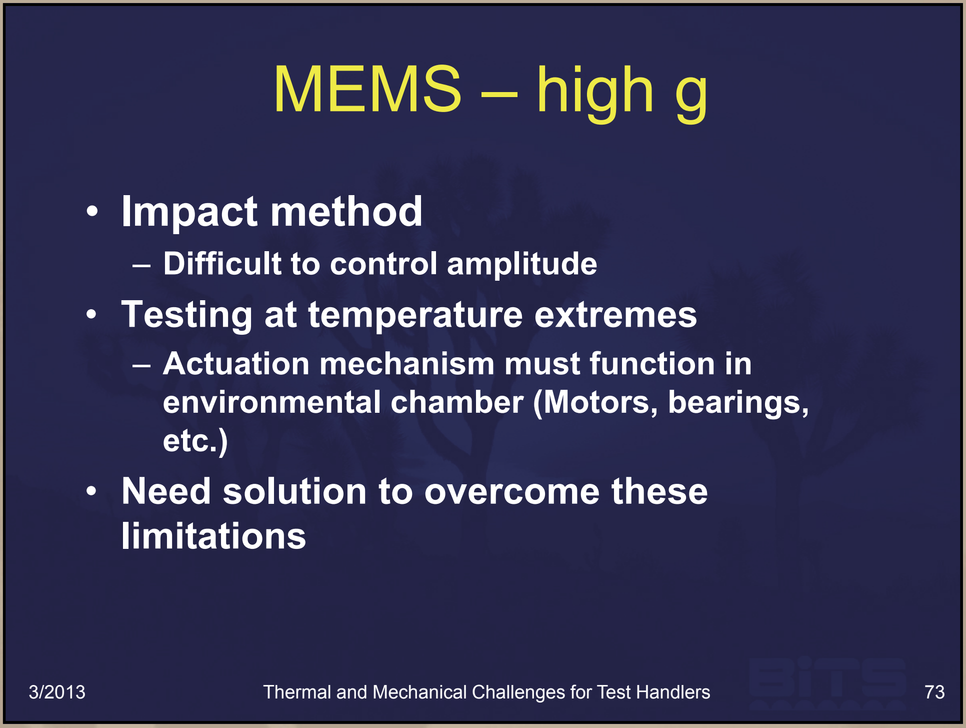
MEMS – multifunction

From ITRS (2011): "The near term challenges include: production of 10 degree-of-freedom (DOF) MEMS inertial measurement units (IMUs), incorporating 3-axis accelerometers, 3-axis gyroscopes, 3-axis magnetometers (compass), and a pressure sensor (altimeter)."



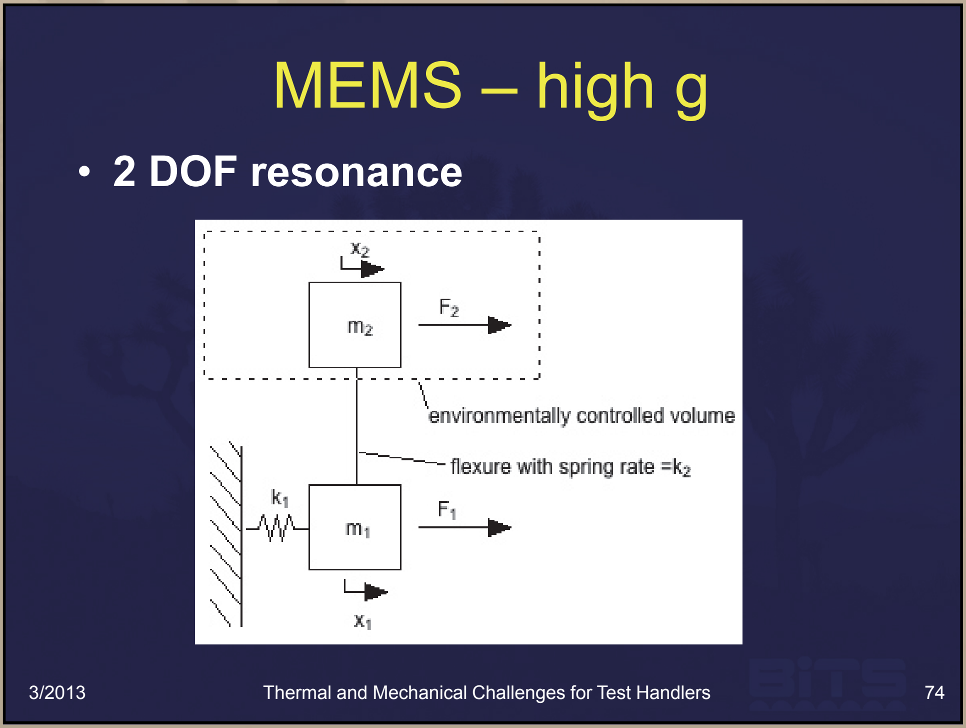
MEMS – high g

- Hundreds of g's
  - Air bag firing decision
  - Shock detection
- Simple sinusoidal excitation
  - Excessive force required
    - With 1kg mass and 200g's requires 1960 N peak force
  - 1 kg mass is very optimistic!
  - Motors burn out quickly!



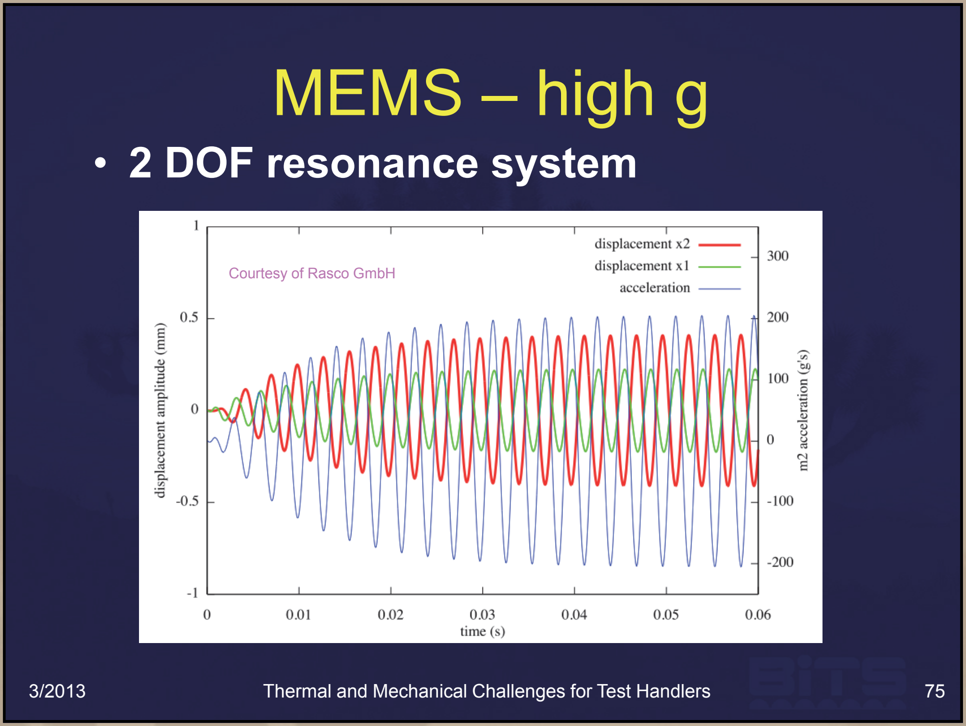
MEMS – high g

- Impact method
  - Difficult to control amplitude
- Testing at temperature extremes
  - Actuation mechanism must function in environmental chamber (Motors, bearings, etc.)
- Need solution to overcome these limitations



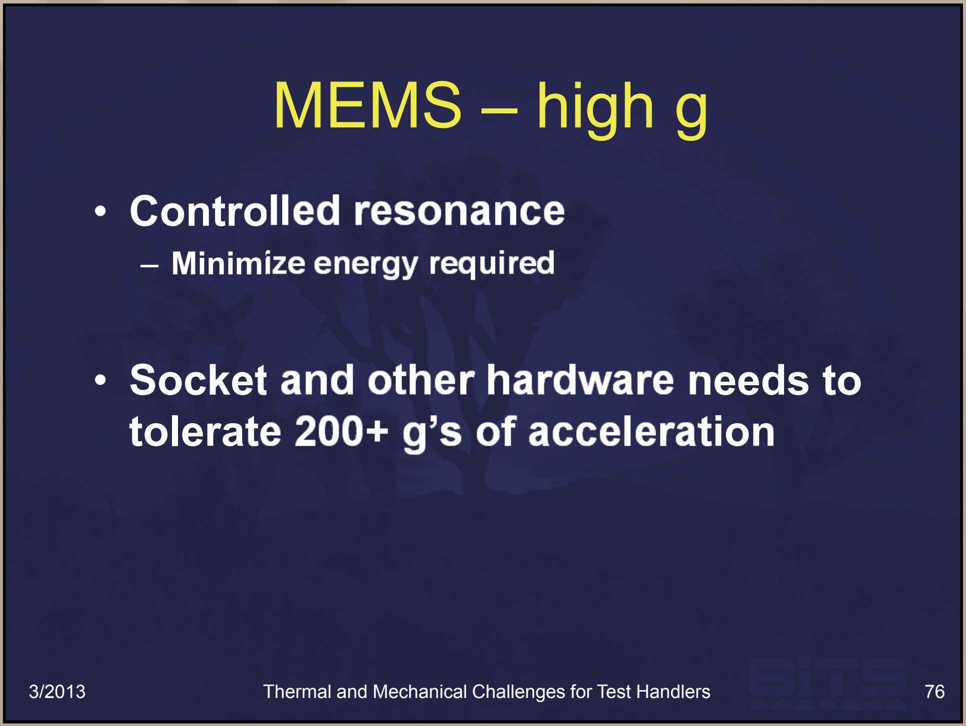
MEMS – high g

- 2 DOF resonance



MEMS – high g

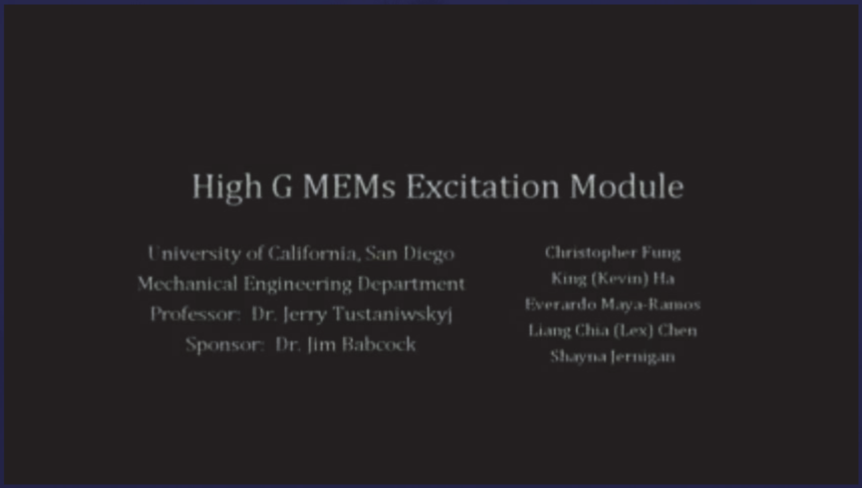
- 2 DOF resonance system



MEMS – high g

- Controlled resonance
  - Minimize energy required
- Socket and other hardware needs to tolerate 200+ g’s of acceleration

MEMS – high g



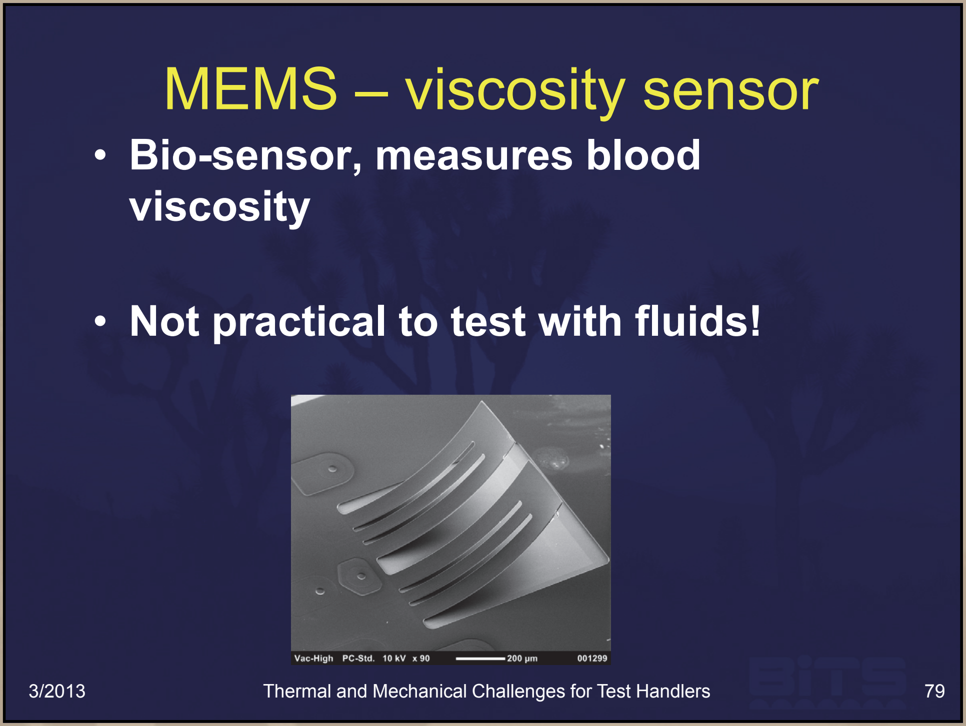
High G MEMs Excitation Module

University of California, San Diego
Mechanical Engineering Department
Professor: Dr. Jerry Tustaniwskyj
Sponsor: Dr. Jim Babcock

Christopher Fung
King (Kevin) Ha
Everardo Maya-Ramos
Liang Chia (Lex) Chen
Shayna Jernigan

MEMS – energy harvesting

- **Generates energy to power other sensors**
  - **Running sensors**
  - **GPS**
- **Must be exposed to vibratory motion for test**



MEMS – viscosity sensor

- **Bio-sensor, measures blood viscosity**
- **Not practical to test with fluids!**

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Cost of Ownership

- **Capital cost**
- **Facilities cost**
  - **Electrical**
  - **Compressed air**
  - **LN_2**
  - **Chilled water**
  - **Etc.**
- **Availability**
  - **MTBF**
  - **MTTR**
  - **repair cost**
- **Kit cost**
- **Fungibility**

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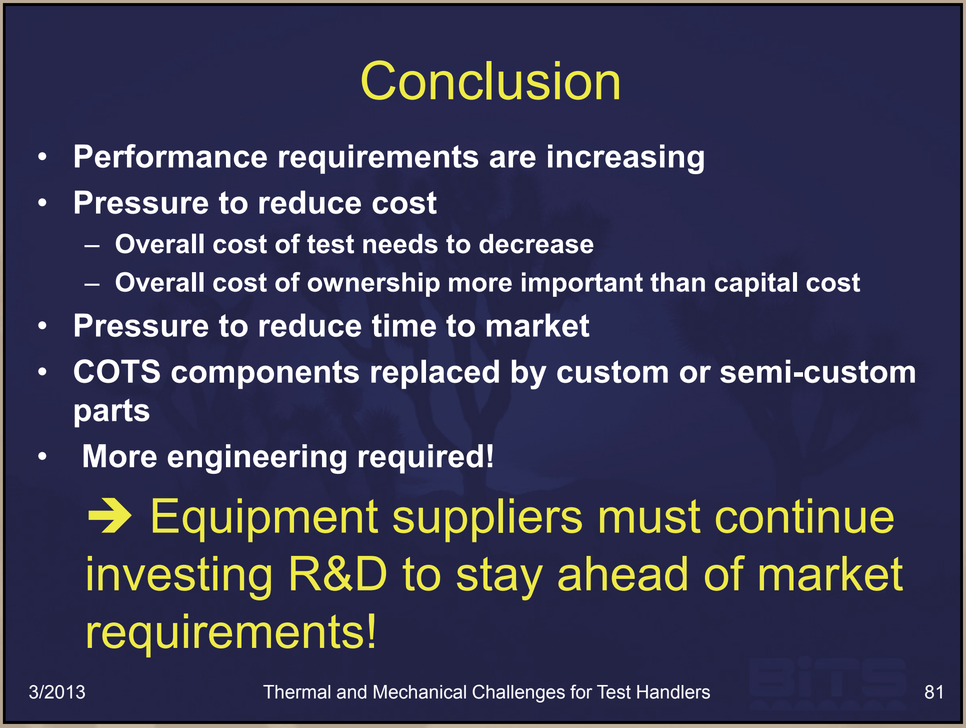

Conclusion

- Performance requirements are increasing
- Pressure to reduce cost
  - Overall cost of test needs to decrease
  - Overall cost of ownership more important than capital cost
- Pressure to reduce time to market
- COTS components replaced by custom or semi-custom parts
- More engineering required!

➔ Equipment suppliers must continue investing R&D to stay ahead of market requirements!