# Design of Power Electronics Reliability:

## *A New, Interdisciplinary Approach*

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# Acknowledgements



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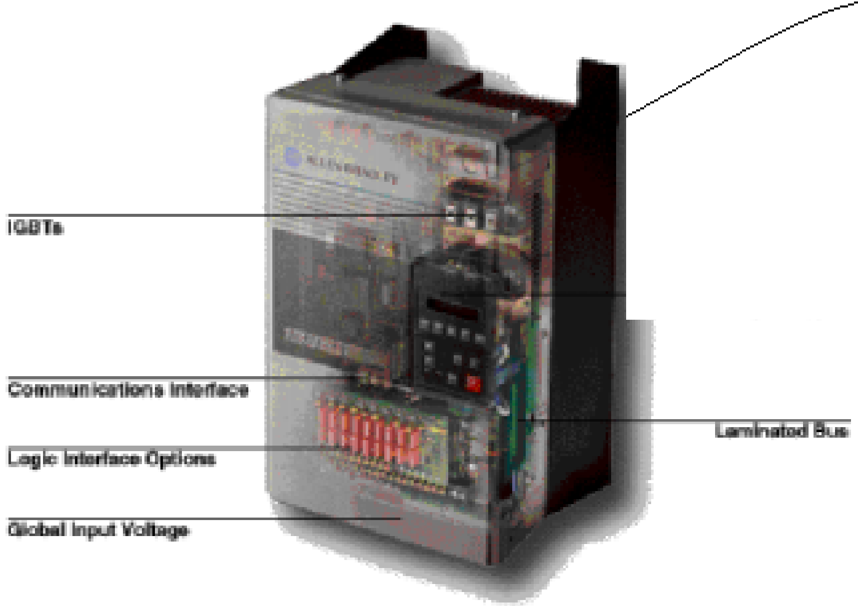
**Dr. Jun He,** ***Packaging and Interconnect Department, Intel***

**Mr. Bruce Beihoff,**
***Manager, Solid State Power Assembly Laboratory, RA***

# Variable Speed Drive & Motor
# *Automation System*



**Variable Speed Drive**




***Performance Metrics:***
- ***Power Density***
- ***Cost***
- ***Reliability***

**AC Motor**

**Converts AC power (<u>fixed</u> frequency, voltage) to AC Power (<u>variable</u> frequency, current, and voltage)**

**Enables exact control of speed (RPM) and torque of *motors***

**Motors *become controlled electromechanical energy converters*.**

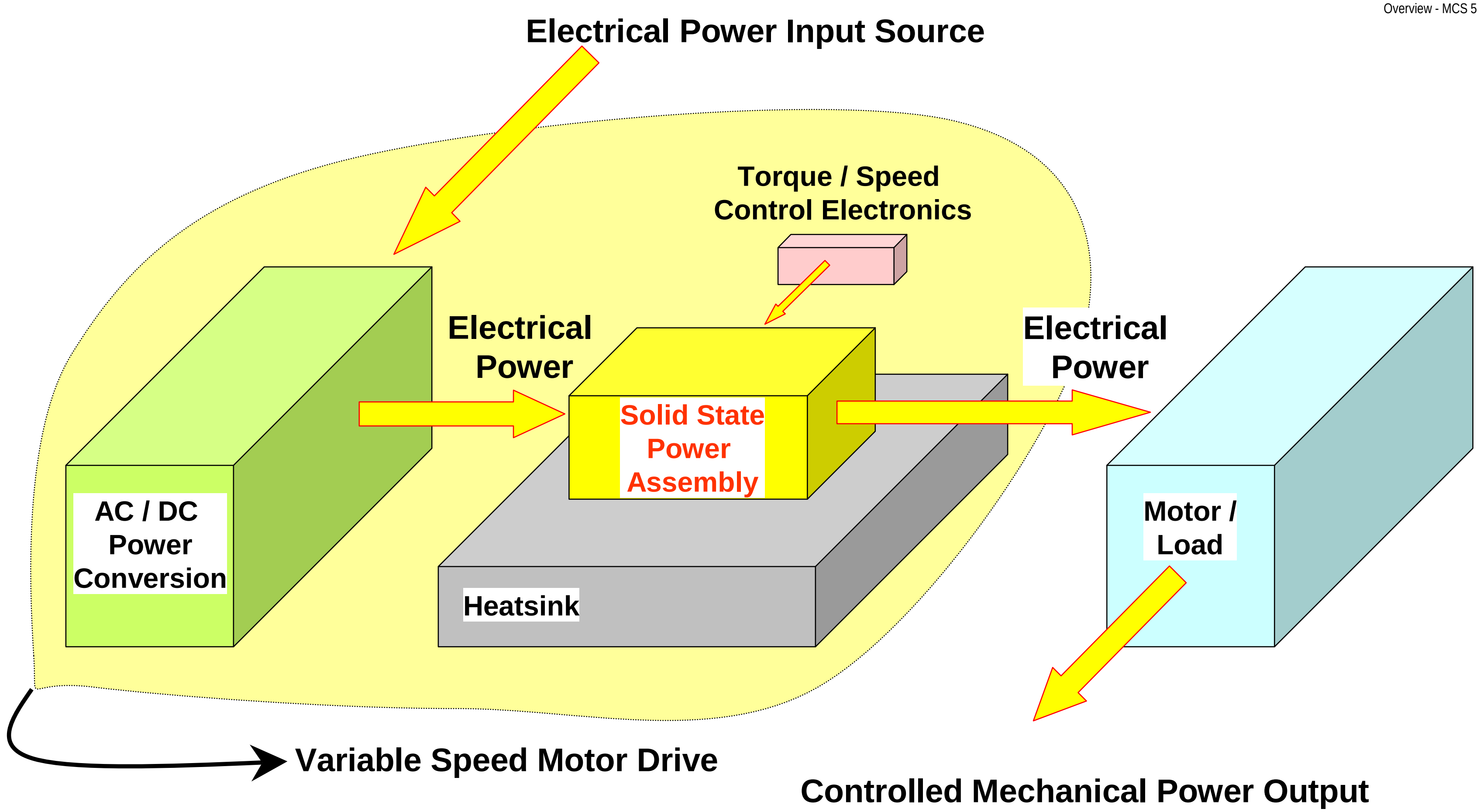
# Variable Speed Drive and Motor Applications



- Factory assembly lines
- Heating, ventilation and air-conditioning
- Refrigeration
- Disc drives / digital storage
- Electric / hybrid vehicles - commercial and military
- Rail transport
- Elevators
- Actuation of e.g., military aircraft controls, ship controls
- *Practically anything that moves!*

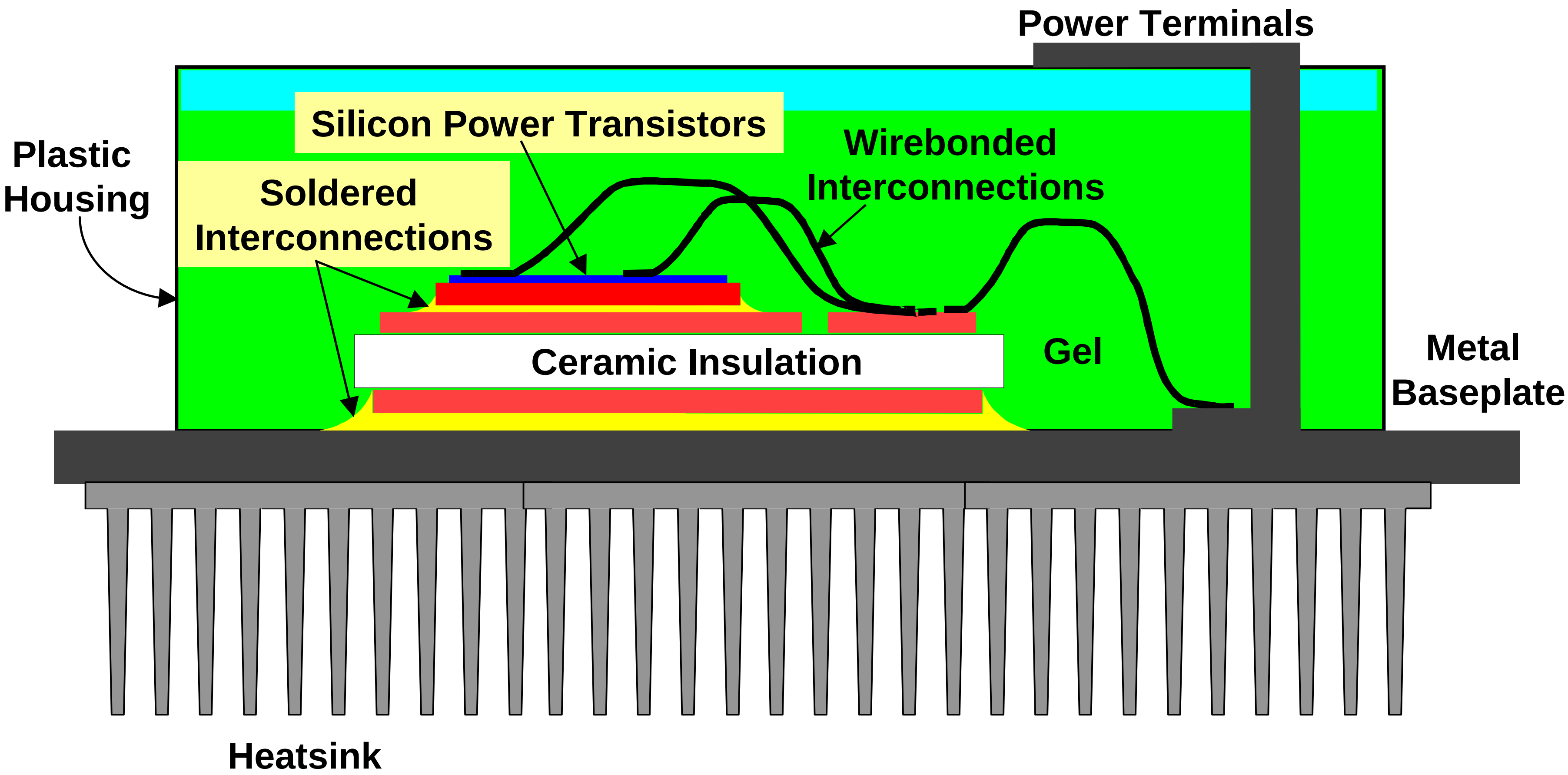
# Variable Speed Motor Drive Block Diagram





# The “Heart” of the Motor Drive:
# *The Solid-State Power Assembly*

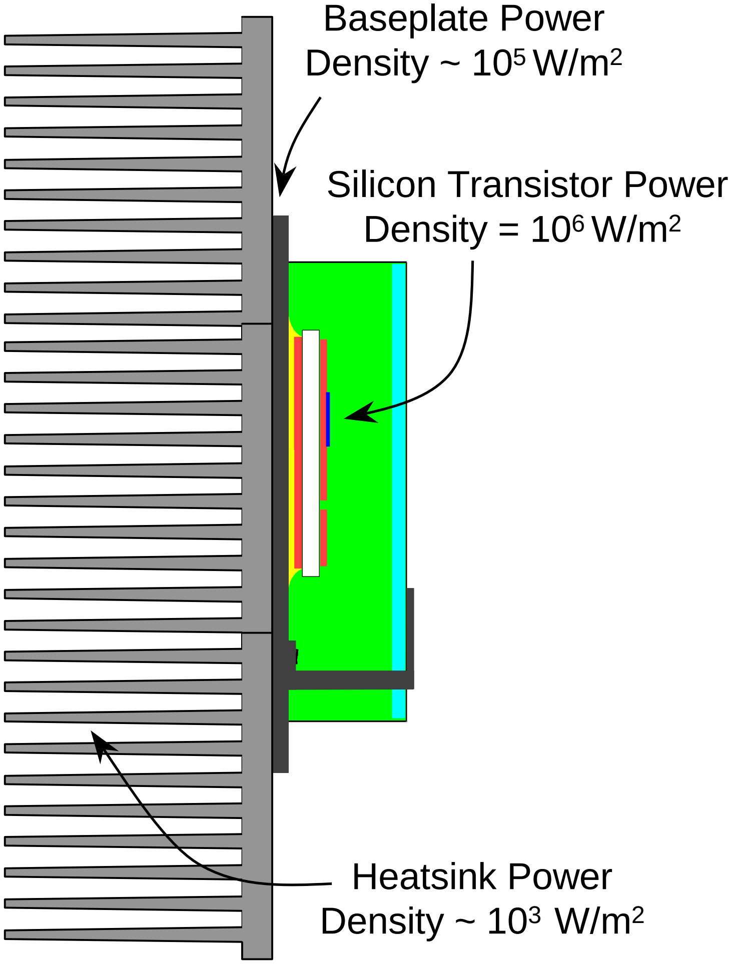


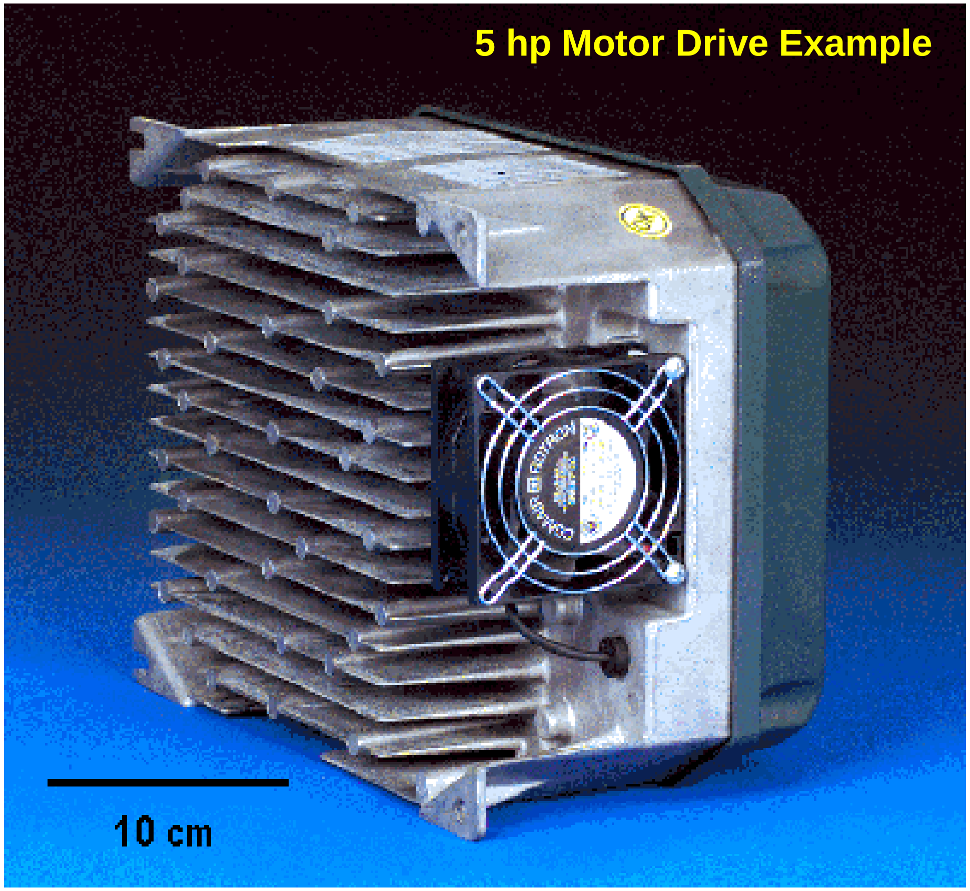



***Schematic Cross Section of Typical Solid State Power Assembly***

# Thermal Management Goal: Decrease Power Density Between Device & Heatsink

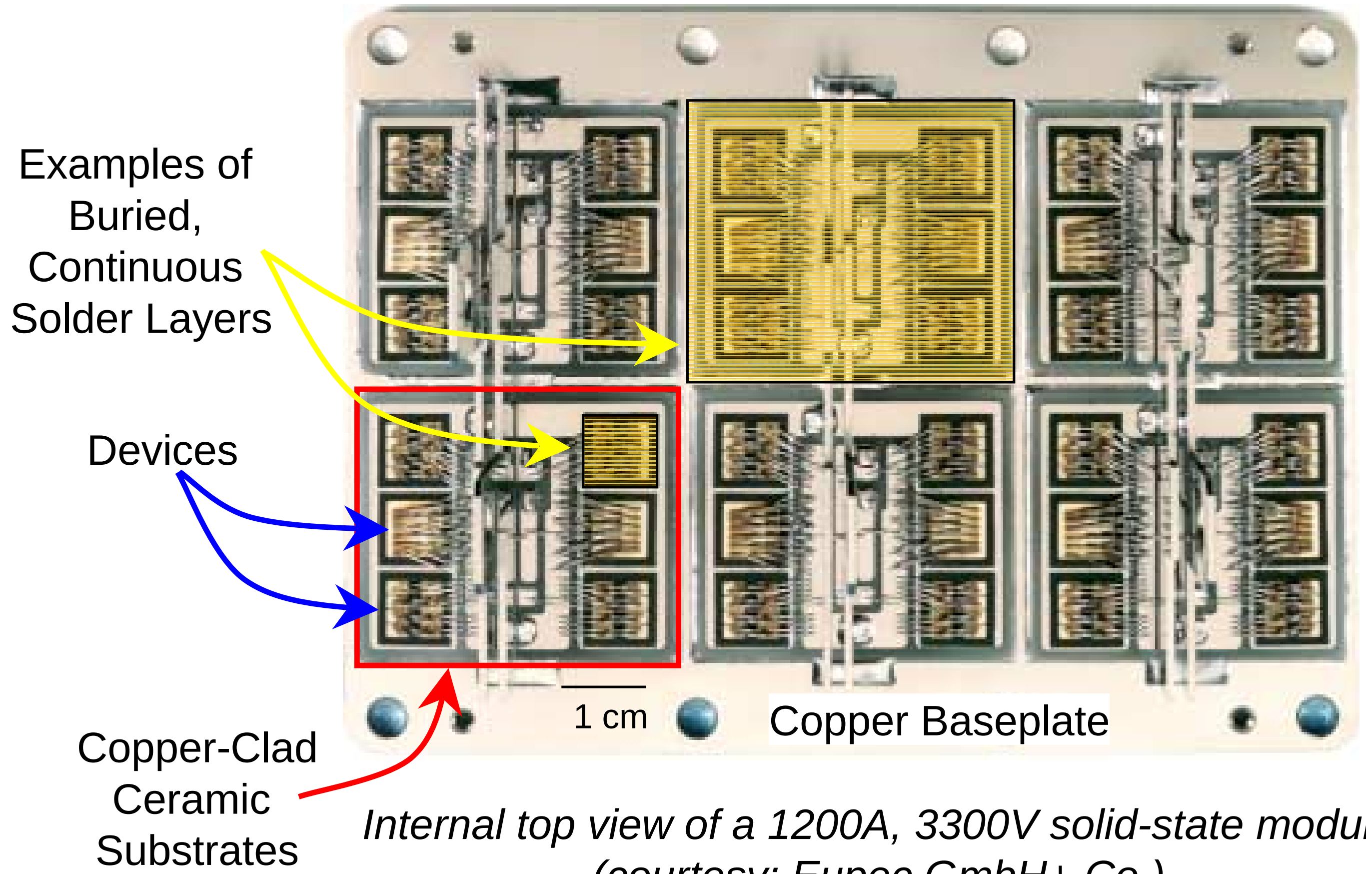




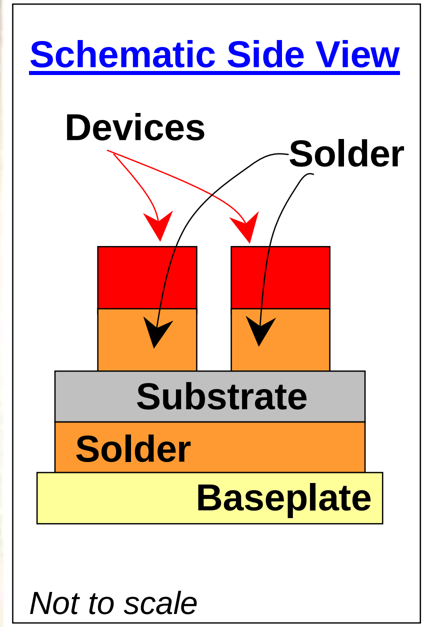



# Thin, Large Area Solder Joints Unique to Solid-State Power Assemblies



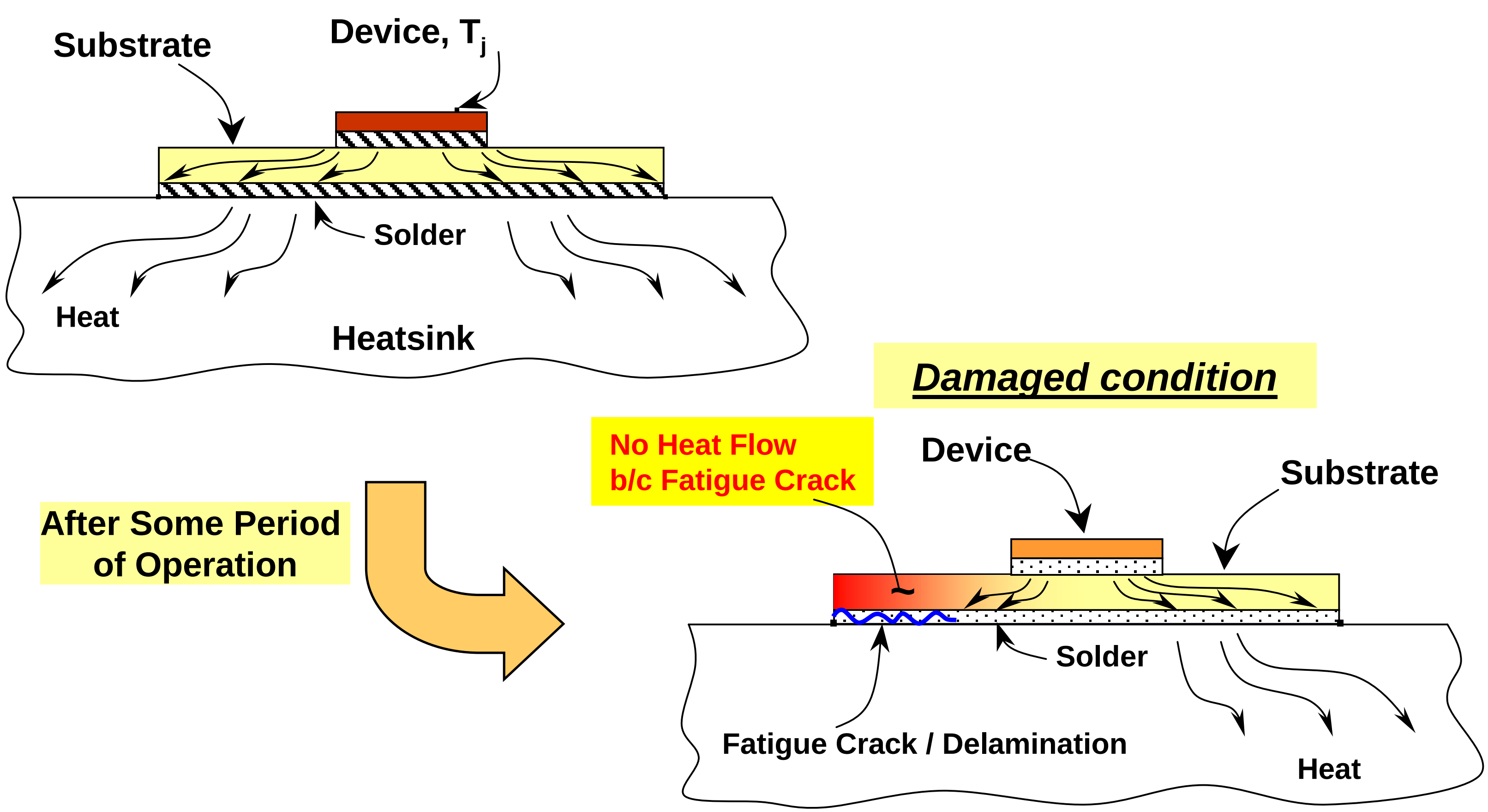



*Internal top view of a 1200A, 3300V solid-state module (courtesy: Eupec GmbH+ Co.)*



# Solder Joint Cracking/Delamination Raises Package Thermal Resistance

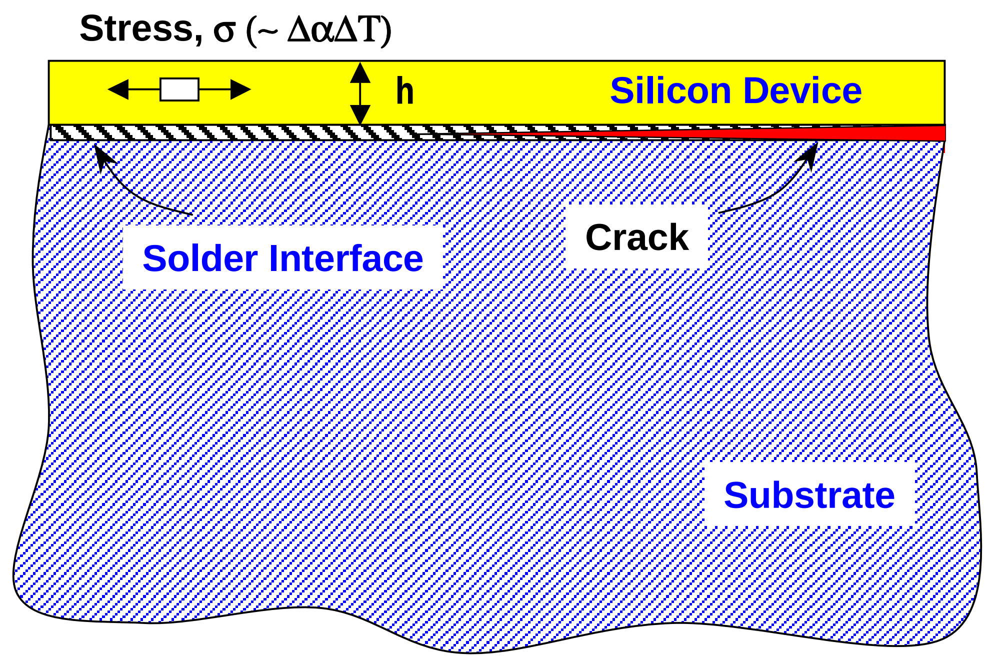
***Pristine condition***



# Driving Force for Delamination: Mechanical Strain Energy Release Rate, $G_I$



$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} = G_I$$

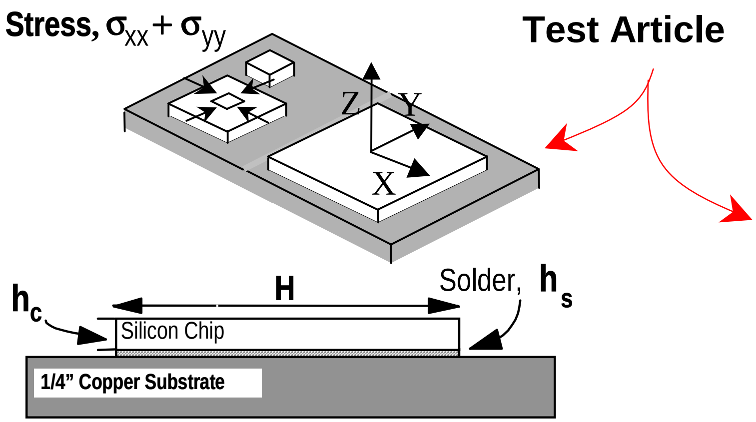


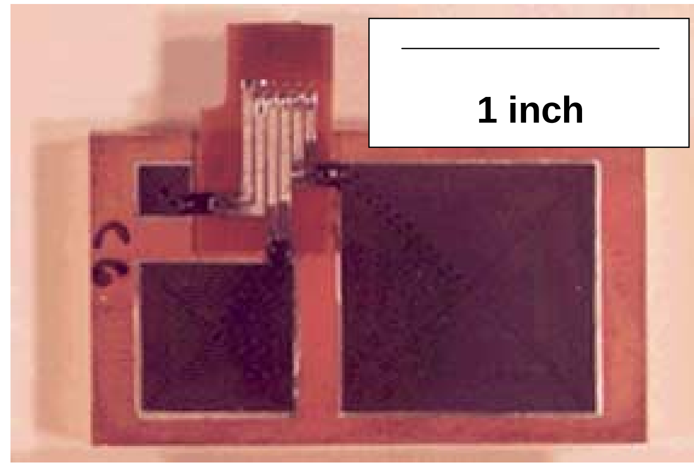

Z ~ 0.3 for this geometry
E = Young's modulus
$\nu$ = Poisson's ratio
$\sigma$ = In-plane mechanical stress
h = Top layer thickness
$G_I$ = Applied strain energy release rate
$\Delta\alpha$ = Coefficient of thermal expansion mismatch
$\Delta T$ = Range of temperature excursion

***Mechanical strain energy release rate, $G_I$, is the "applied load"***

# Experimental Methodology: *Materials and Architectures*






Three silicon device sizes:

| | |
|---|---|
| Small: | 0.2" square |
| Medium: | 0.6" square |
| Large: | 1.0" square |

Four solder compositions:

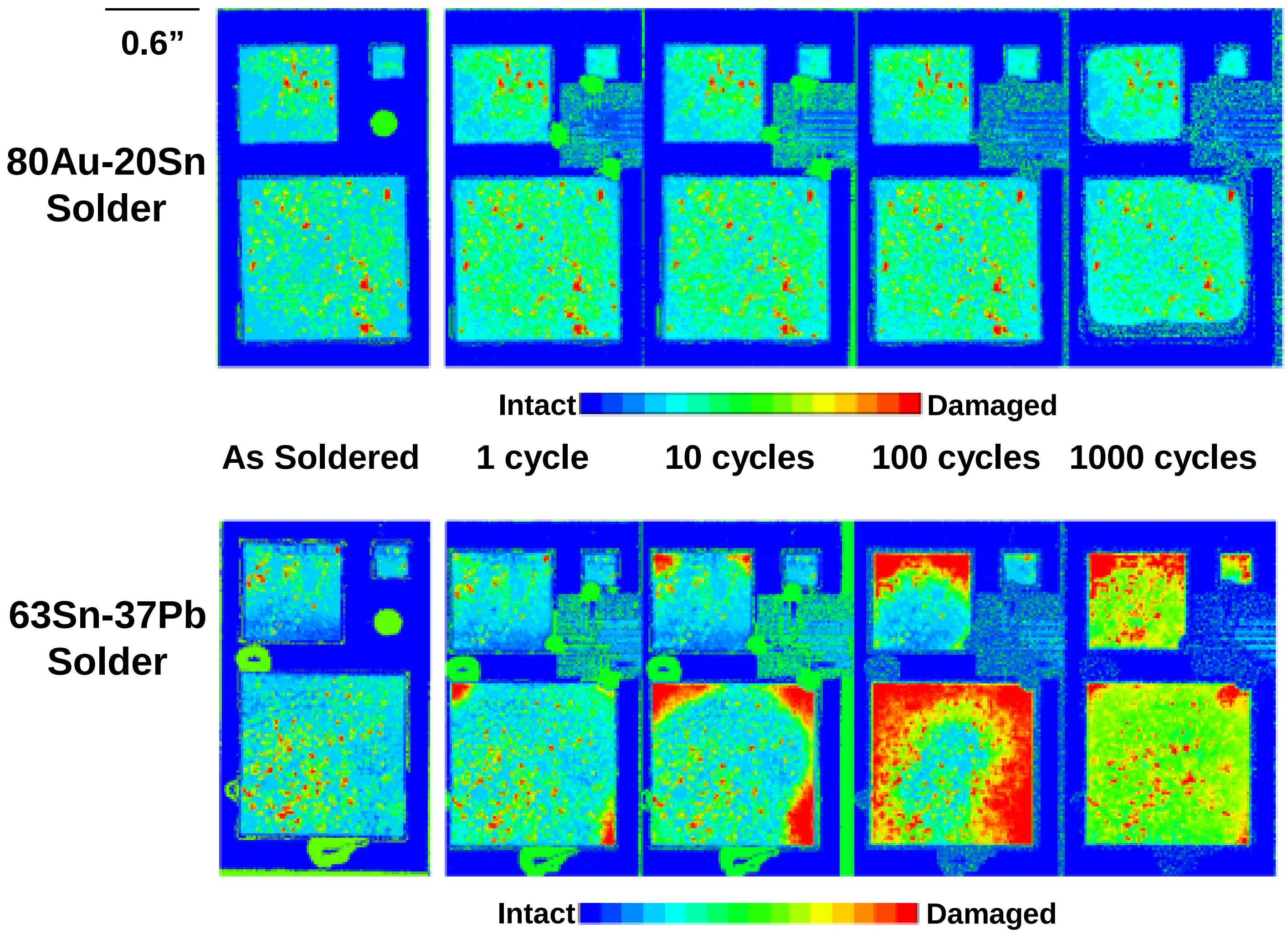
- 97.5Pb/1.5Ag/1.0Sn ($T_m$=309°C)
- 80Au/20Sn($T_m$=280°C)
- 96.5Sn/3.5Ag($T_m$=221°C)
- 63Sn/37Pb($T_m$=183°C)

Three substrate coefficients of thermal expansion (CTE)

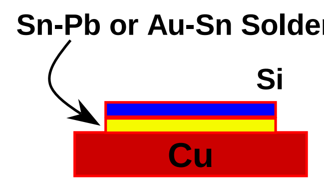
| | |
|---|---|
| Low: | Kovar (~ 6 ppm/°C) |
| Medium: | mild steel (~12 ppm/°C) |
| High: | copper (~17 ppm/°C) |

# Different Solders Exhibit Large Differences in Delamination






Δα = 14.1 ppm /ºC



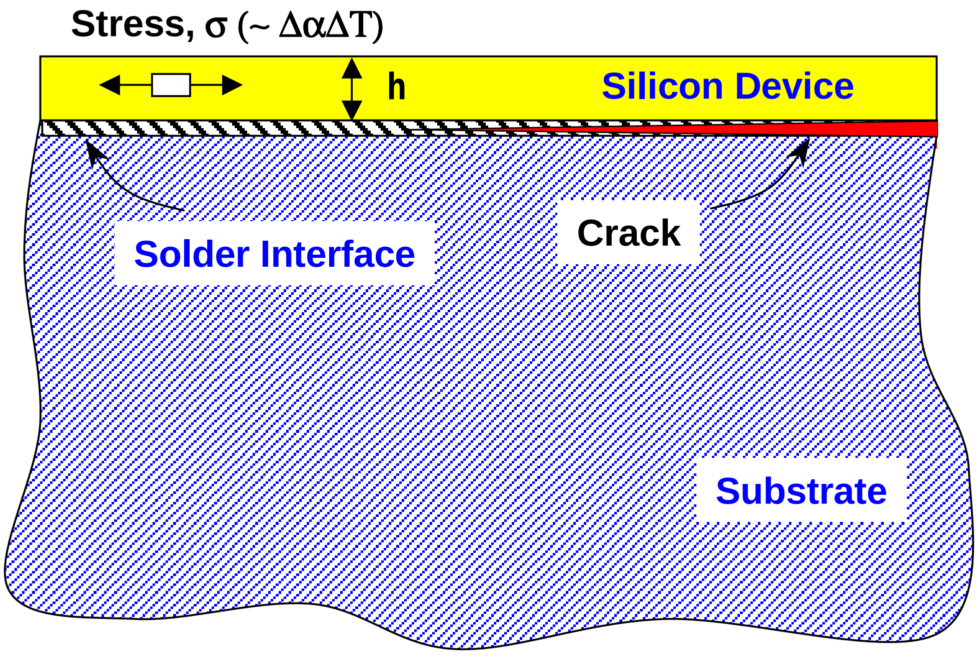

Δα = 14.1 ppm /ºC

*Ultrasonic Acoustic Micrographs*

# Recall: Driving Force for Delamination, $G_I$



$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} = G_I$$




$Z \sim 0.3$ for this geometry
E = Young's modulus
$\nu$ = Poisson's ratio
$\sigma$ = In-plane mechanical stress
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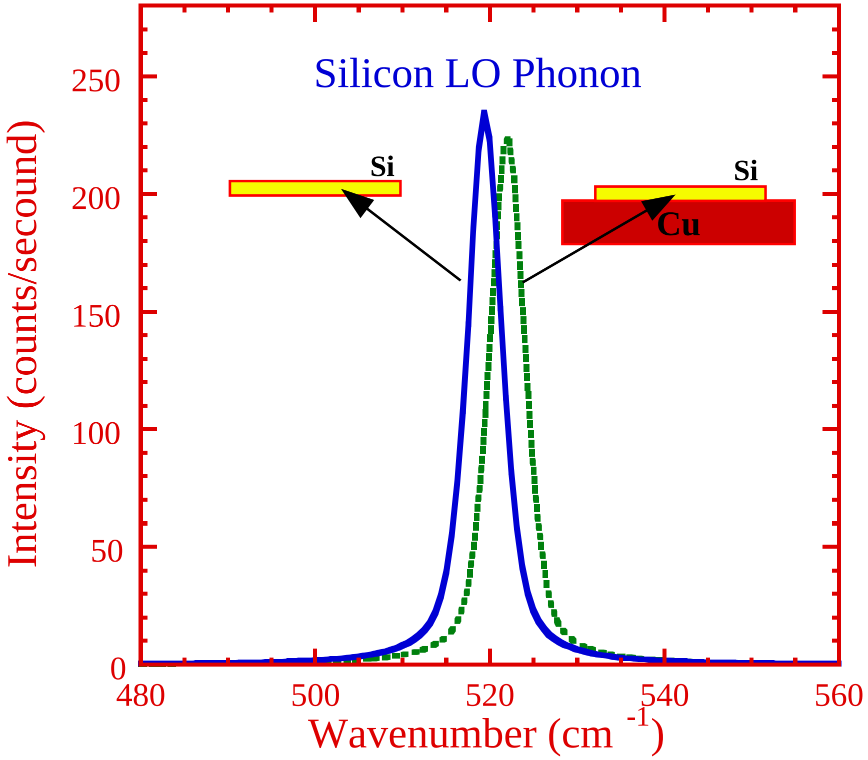
$G_I$ = Applied strain energy release rate
$\Delta\alpha$ = Coefficient of thermal expansion mismatch
$\Delta T$ = Range of temperature excursion

***Greater Damage Suggests Higher Stress and Higher $G_I$…..Right?***

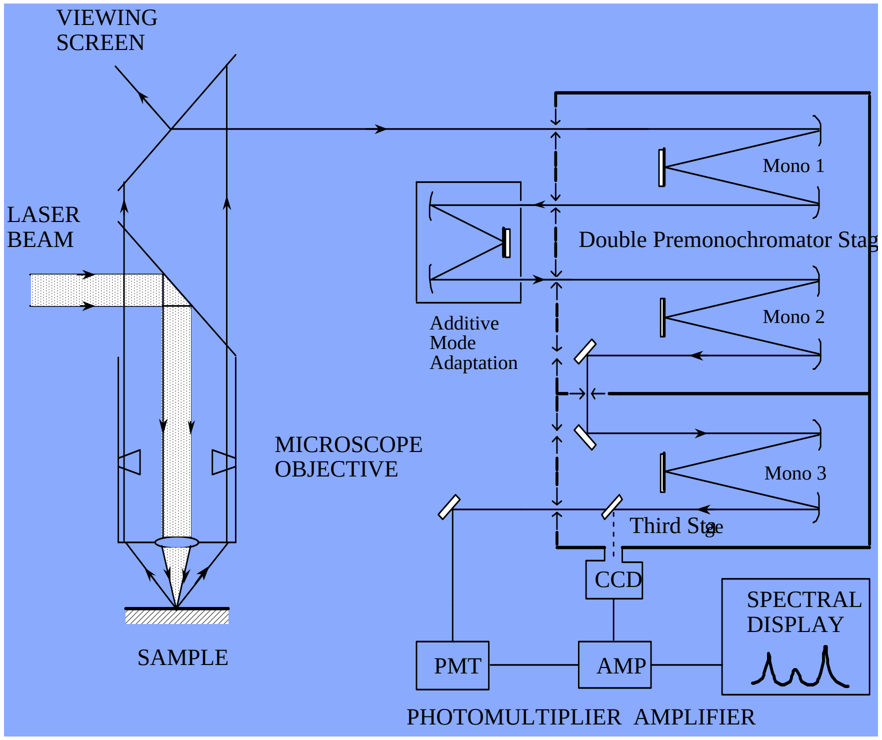
# Piezospectroscopy:
# Stress Mapping through Raman Spectroscopy



- **Stress-Sensitive Raman Peaks**

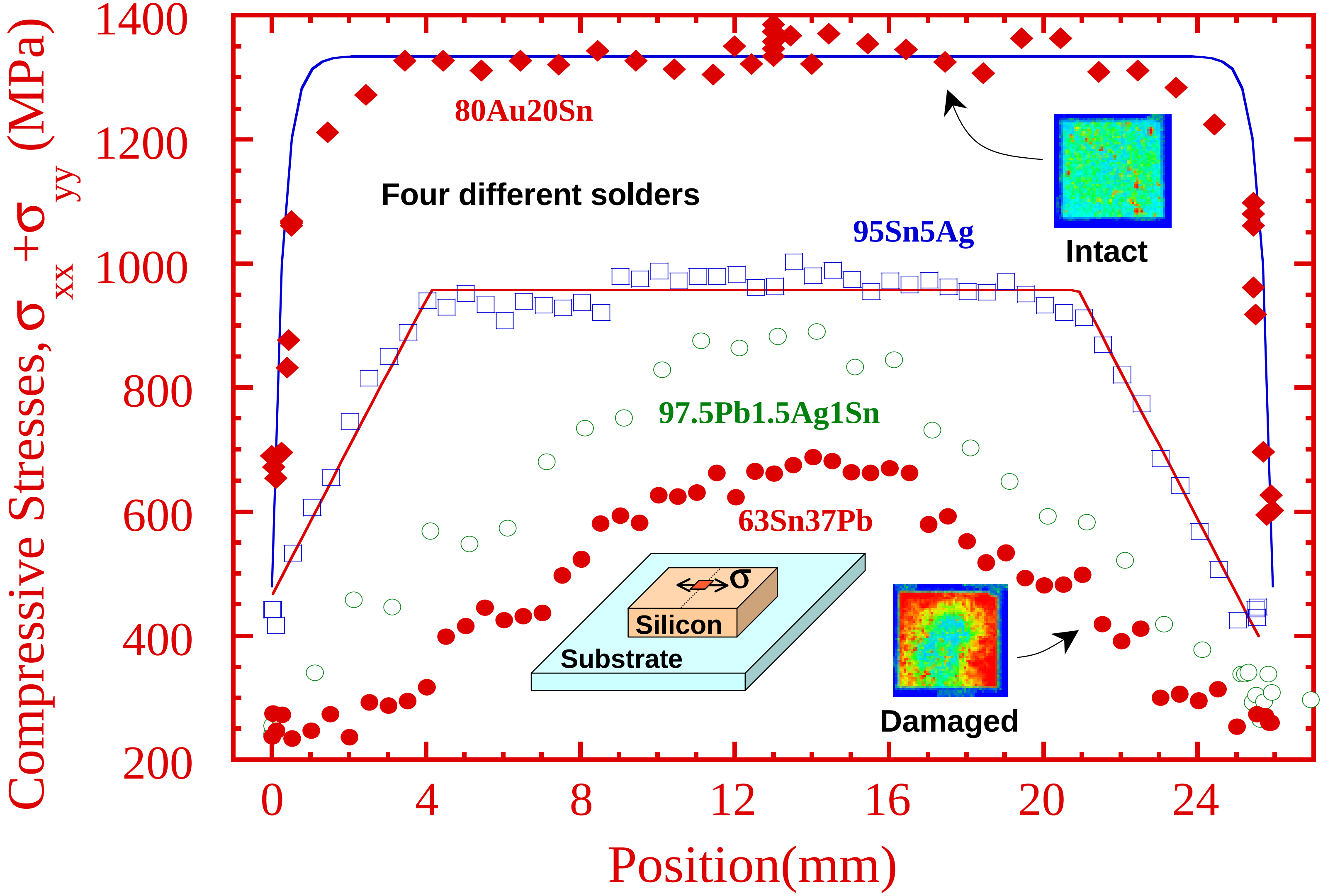



- **Raman Probe Optical Path**



# Solder Damage Depends on *both* Stress *and* Material Resistance



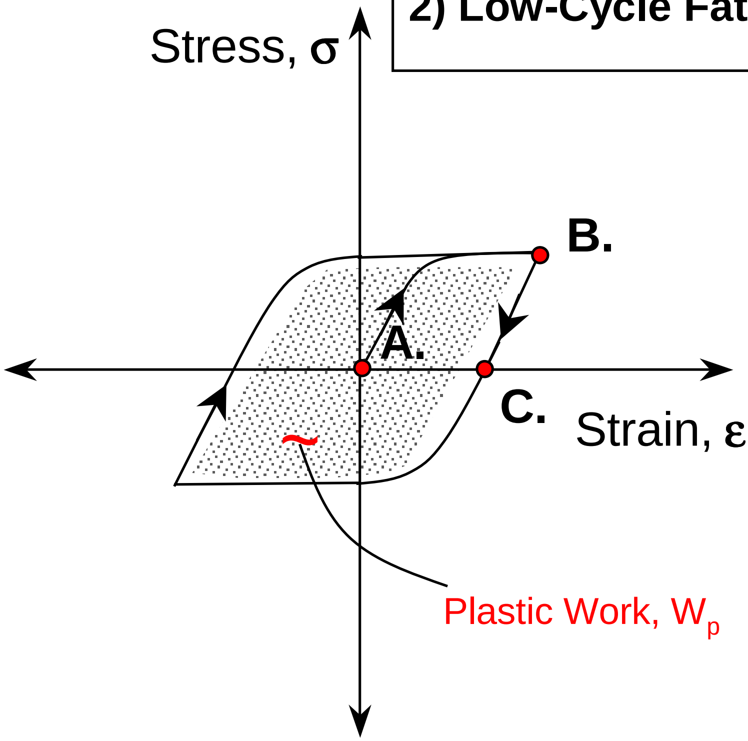


# Material Resistance, $G_{Ic}$, Depends on Degree of Cyclic Plastic Work, $W_p$

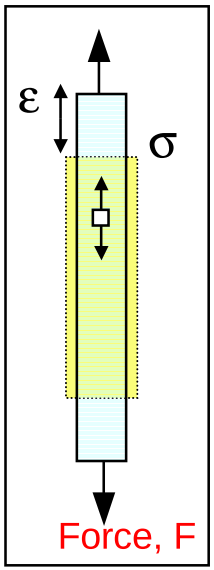


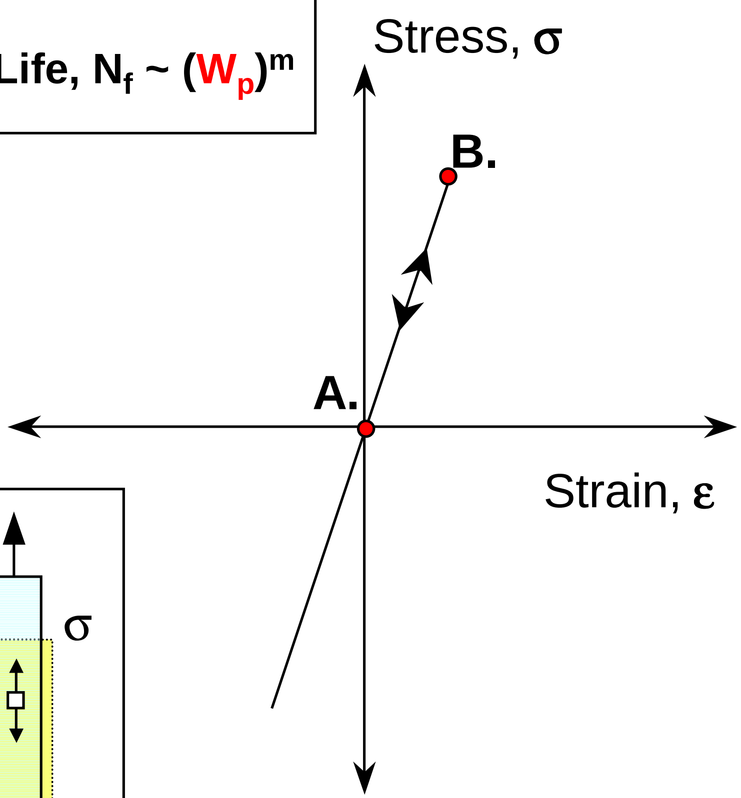
1) **Plastic Work, $W_p = \int \sigma \, d\varepsilon_p$**

2) **Low-Cycle Fatigue Life, $N_f \sim (W_p)^m$**




***Plastic Response***



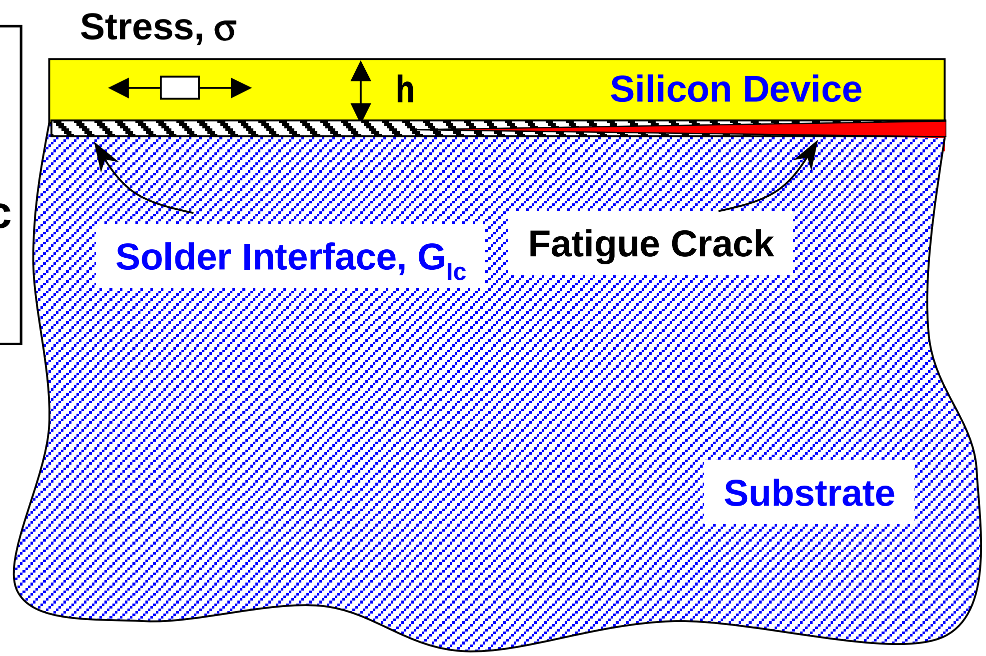

***Elastic Response***

( $W_p \sim 0$ )

# Delamination Only Occurs of $G_I$ is Greater than $G_{Ic}$



$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} = G_I \textit{ vs. } G_{Ic}$$



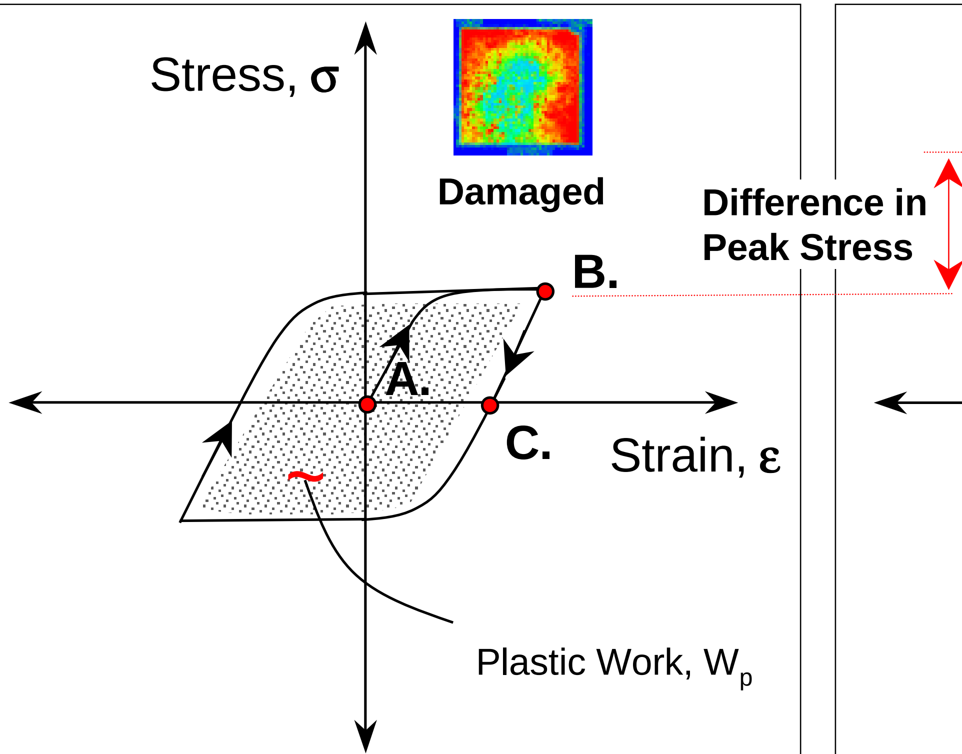

Z ~ 0.3 for this geometry
E = Young's modulus
ν = Poisson's ratio
σ = In-plane mechanical stress
h = Top layer thickness
$G_{Ic}$ = Critical $G_I$ for fracture

**$G_{Ic}$ is Intrinsic Material Property - $G_I$ is Applied Load**

# Thus, Fatigue Life Depends on Response of Solder Material <u>as Compared to</u> $G_I$

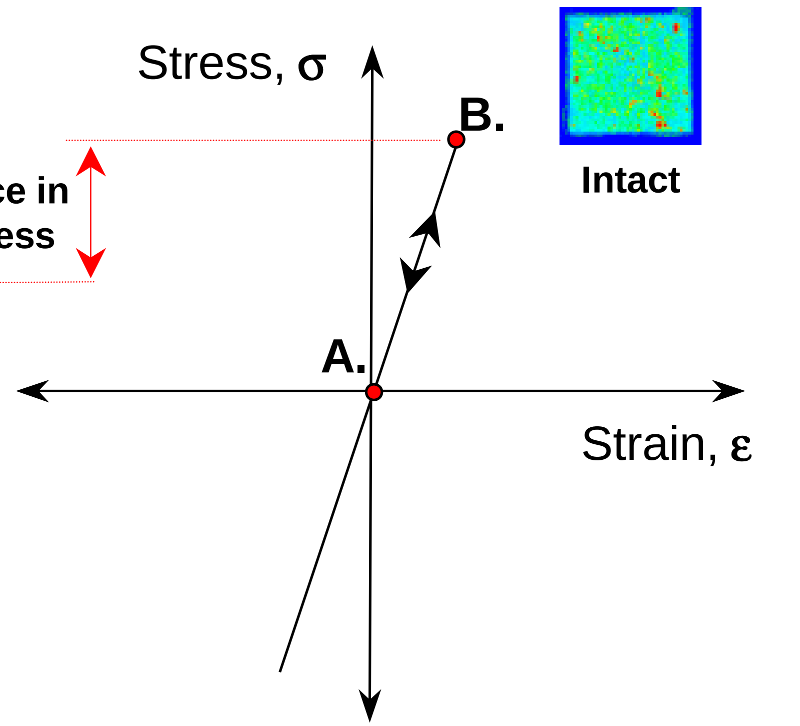


***Different Physical Damage Mechanisms Operate in Different Solders!***




**Plastic Response:**
**Low Stress (Low $G_I$),**
**BUT ( $W_p >> 0$ ),**
**so Low $G_{Ic}$ (Crack *Resistance*)**

***$G_I$ Exceeds $G_{Ic}$***



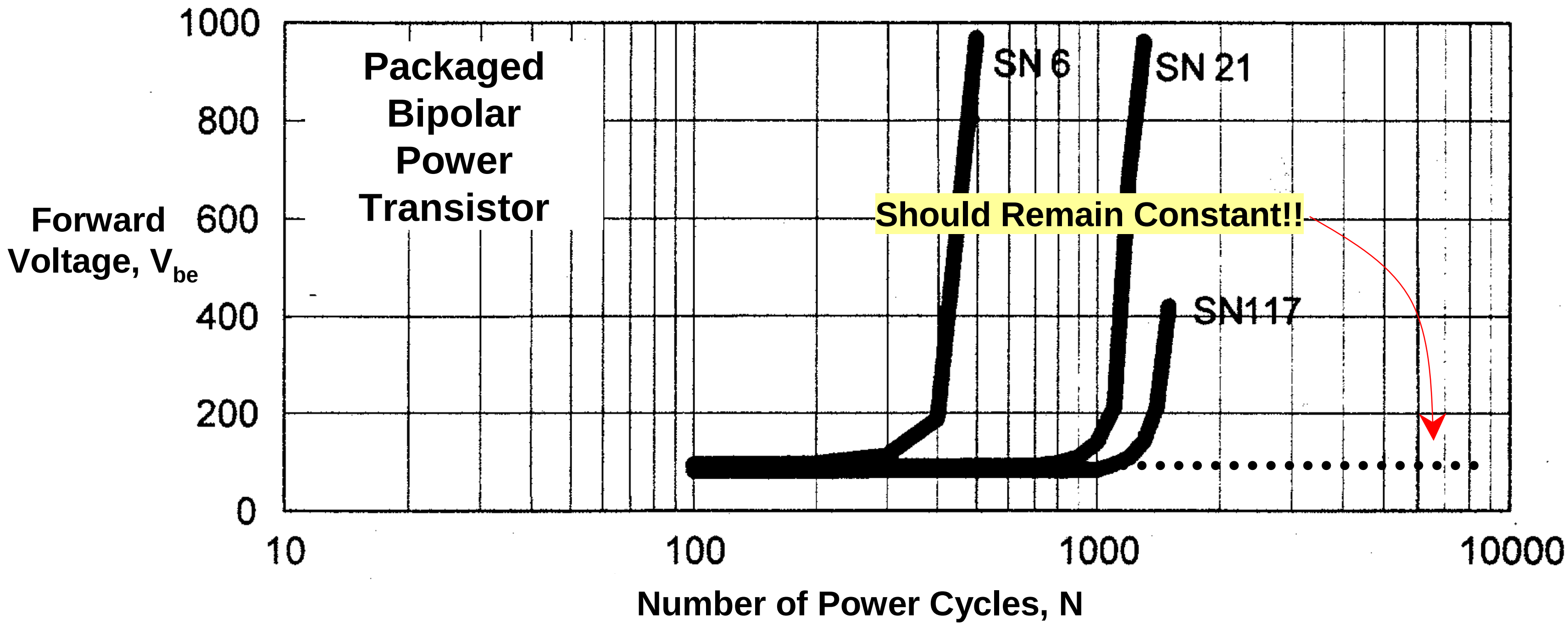

**Elastic Response:**
**High Stress ( High $G_I$)**
**BUT ( $W_p \sim 0$ )**
**so High $G_{ic}$ (Crack *Resistance*)**

***$G_I$ Is Less Than $G_{Ic}$***

# Back to Our Problem:
# *Unpredictable Performance Changes!*



*Large Electrical Deviations May Occur During Operation*

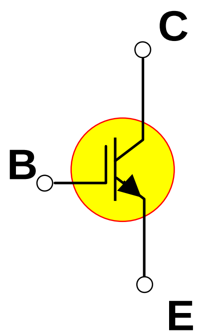



***Now we can apply our detailed knowledge of thermomechanical stress and response of solder***

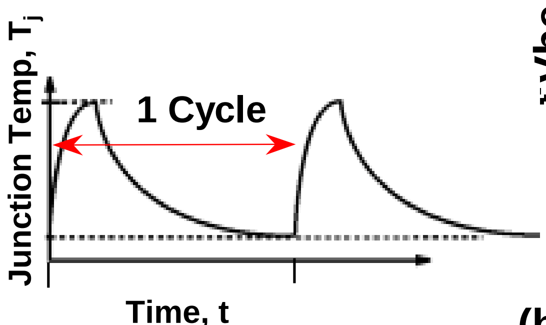
**(Evans and Evans, IEEE Trans. Comp. Pack., Mfg. Tech., Part A, v. 21 no. 3 pp. 459 - 468, 1998)**

# Predicted Electronic Parameter Shift Correlates with Experimental Data

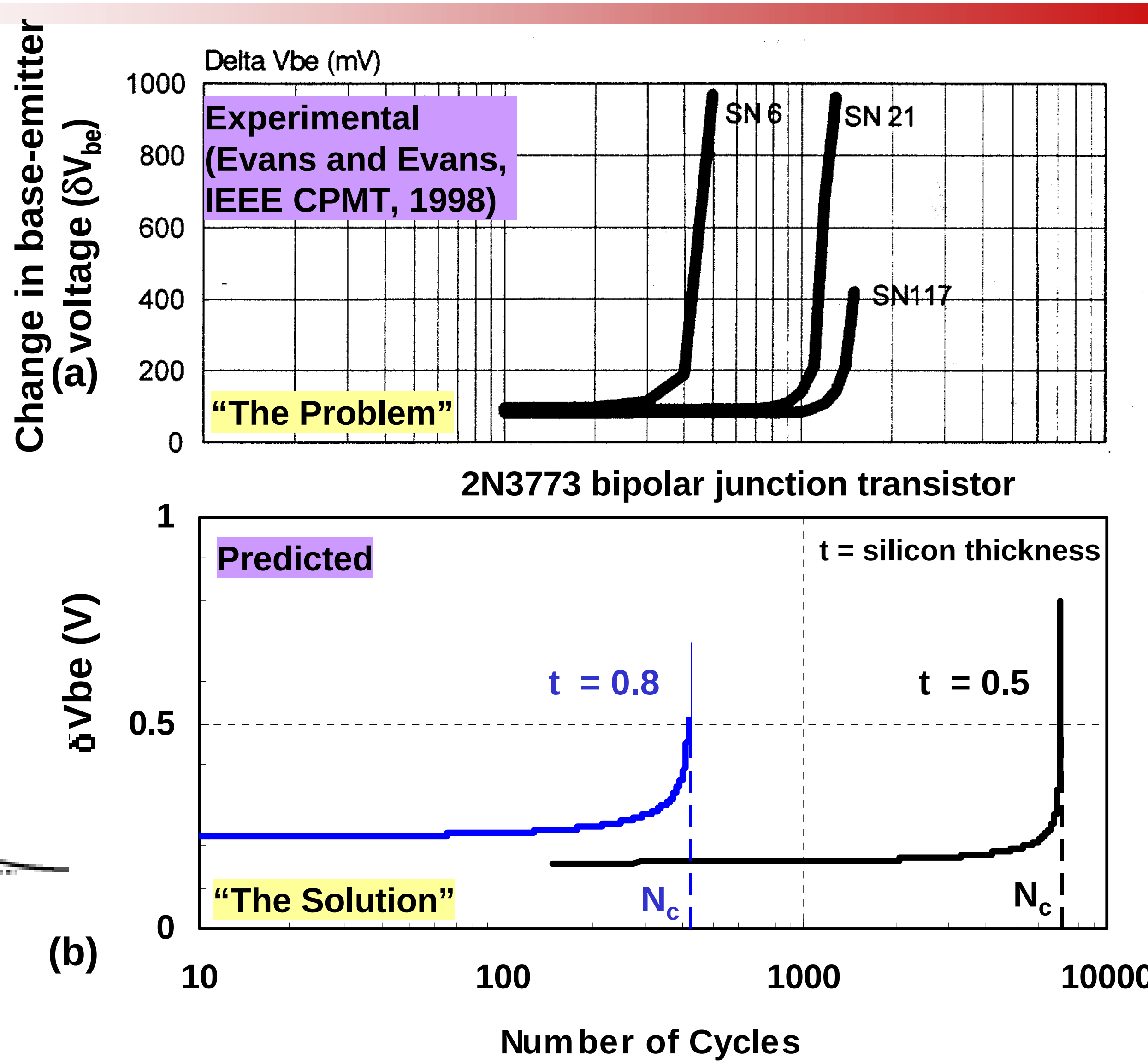
**2N3773 npn bipolar**
$I_C$ = 1.5 A
$V_{CE}$ = 100 V
$P_D$ = 150 W




Bipolar Transistor




(b)



# Conclusions



- **Power Electronics Packaging Demands Highly <u>Interdisciplinary Analyses, Experiments & Knowledge</u>**

- **<u>New Methodology</u> Developed to Quantitatively Assess Device/Circuit/System Interactions Resulting from Degradation**

- **Rigorous, <u>Physics-Based Coupling</u> of Electronics / Mechanics / Materials / Heat Transfer**

- **<u>Interfaces</u> are Crucial**

- **Expanding Approach to Explore <u>Biomechanics</u>, <u>Biomaterials</u> Applications and Interactions**