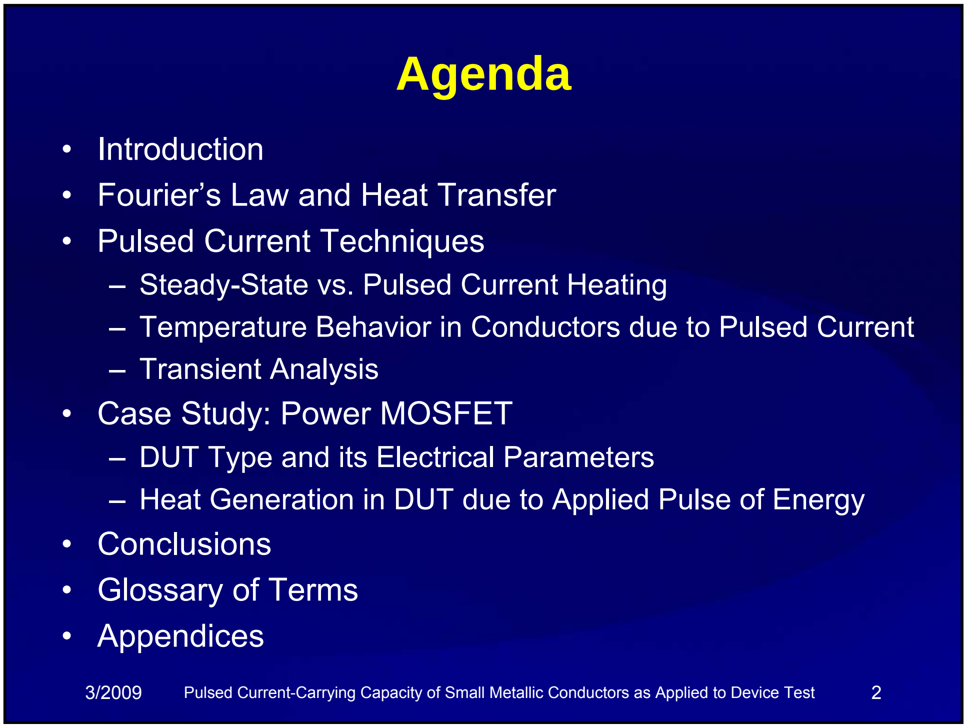
Pulsed Current-Carrying Capacity of Small Metallic Conductors as Applied to Device Test

Harlan Faller, P.E.
Johnstech International

2009 BiTS Workshop
March 8 - 11, 2009

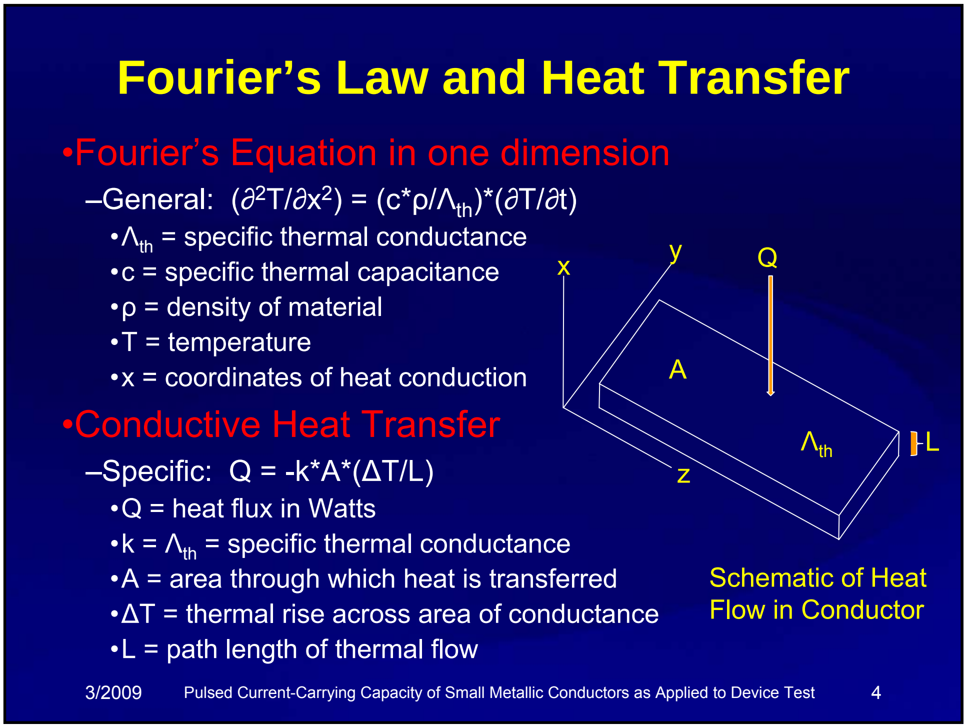


Agenda

- Introduction
- Fourier’s Law and Heat Transfer
- Pulsed Current Techniques
  - Steady-State vs. Pulsed Current Heating
  - Temperature Behavior in Conductors due to Pulsed Current
  - Transient Analysis
- Case Study: Power MOSFET
  - DUT Type and its Electrical Parameters
  - Heat Generation in DUT due to Applied Pulse of Energy
- Conclusions
- Glossary of Terms
- Appendices

Introduction

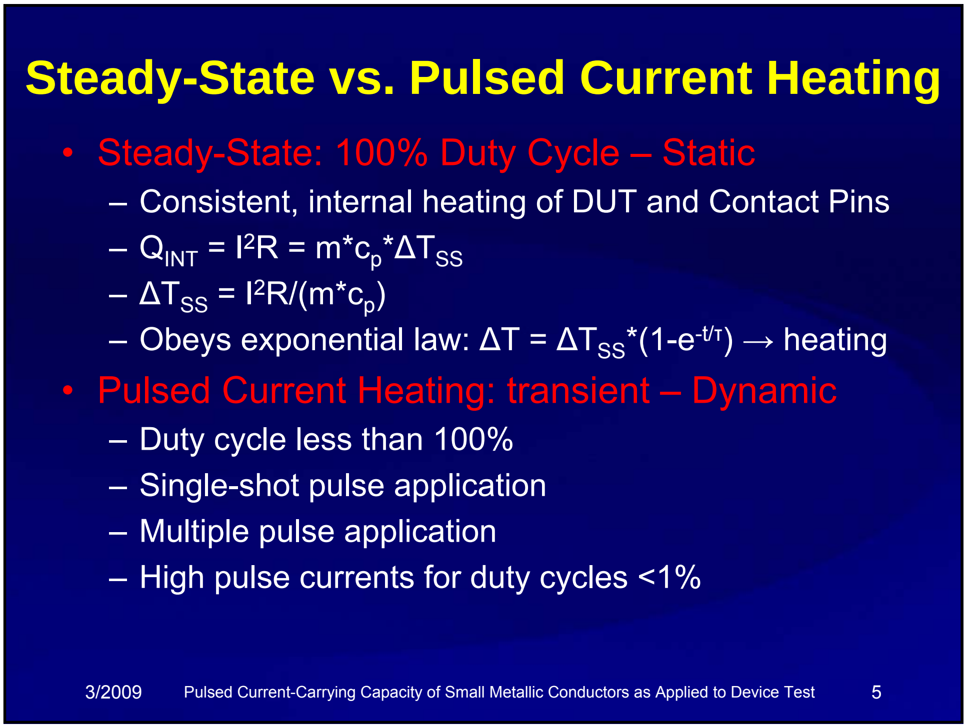
- Objective of this Presentation:
  - To demonstrate Pulsed Current Thermal Techniques as applied to Electrical Conductors and Device Test
- Goal:
  - To provide a set of Guidelines to Users of the Methodology presented herein
- Future Work:
  - Expand on these Guidelines



Fourier's Law and Heat Transfer

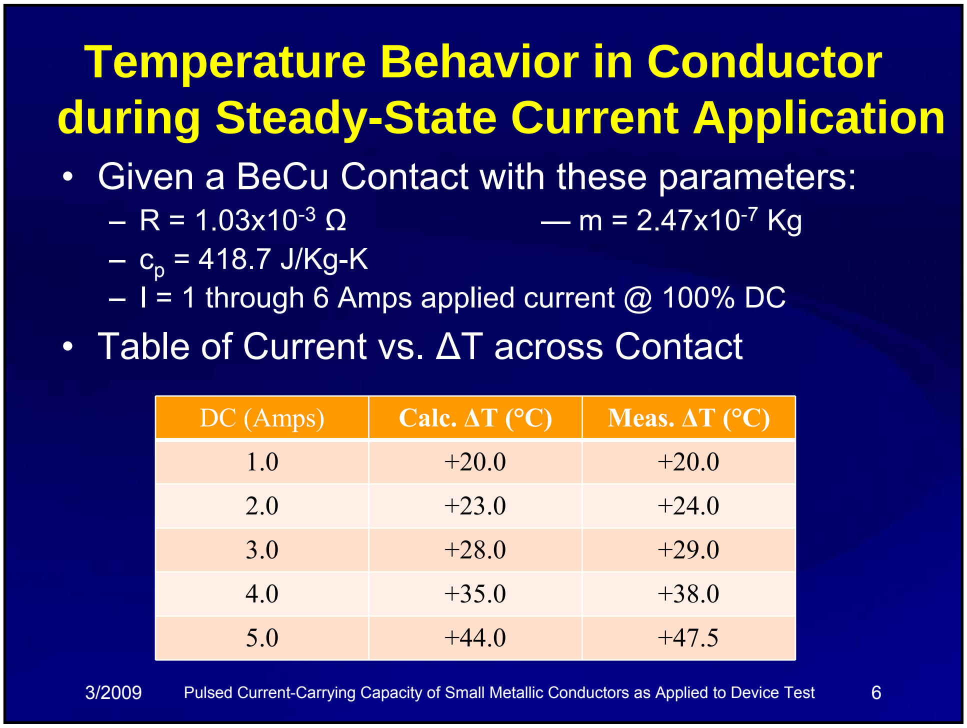
- Fourier's Equation in one dimension
  - General: $(\partial^2 T/\partial x^2) = (c*\rho/\Lambda_{th})*(\partial T/\partial t)$
    - Λ_{th} = specific thermal conductance
    - c = specific thermal capacitance
    - ρ = density of material
    - T = temperature
    - x = coordinates of heat conduction
- Conductive Heat Transfer
  - Specific: $Q = -k*A*(\Delta T/L)$
    - Q = heat flux in Watts
    - $k = \Lambda_{th}$ = specific thermal conductance
    - A = area through which heat is transferred
    - ΔT = thermal rise across area of conductance
    - L = path length of thermal flow

Schematic of Heat Flow in Conductor



Steady-State vs. Pulsed Current Heating

- Steady-State: 100% Duty Cycle – Static
  - Consistent, internal heating of DUT and Contact Pins
  - $Q_{INT} = I^2R = m*c_p*\Delta T_{SS}$
  - $\Delta T_{SS} = I^2R/(m*c_p)$
  - Obeys exponential law: $\Delta T = \Delta T_{SS}*(1-e^{-t/\tau})$ → heating
- Pulsed Current Heating: transient – Dynamic
  - Duty cycle less than 100%
  - Single-shot pulse application
  - Multiple pulse application
  - High pulse currents for duty cycles <1%



Temperature Behavior in Conductor during Steady-State Current Application

- Given a BeCu Contact with these parameters:
  - $R = 1.03 \times 10^{-3}\ \Omega$ — $m = 2.47 \times 10^{-7}$ Kg
  - $c_p = 418.7$ J/Kg-K
  - I = 1 through 6 Amps applied current @ 100% DC
- Table of Current vs. ΔT across Contact

DC (Amps)	Calc. ΔT (°C)	Meas. ΔT (°C)
1.0	+20.0	+20.0
2.0	+23.0	+24.0
3.0	+28.0	+29.0
4.0	+35.0	+38.0
5.0	+44.0	+47.5

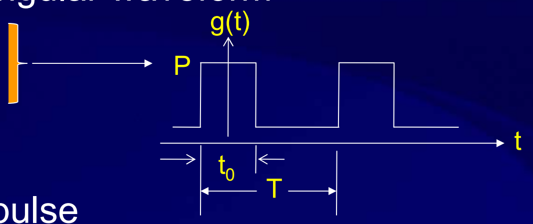
Temperature Behavior in Conductor During Pulse Current Application

- Heating of bond wires ≈ transient heating of one-dimensional slab with a step change in energy generation rate
- CCC* in wire follows same analysis as used for P-C conductors or wire-wrap interconnections

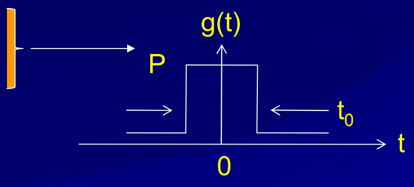
*CCC = Current-Carrying Capacity (Amps)

Temperature Behavior in Conductor During Pulse Current Application

- For a pulsed rectangular waveform
  - $P_{AV} = P * (t_0/T)$
  - $P_{RMS} = P * (t_0/T)^{1/2}$



- For a rectangular pulse
  - $g(t) = P$ for $(-t_0/2) < t < t_0/2)$
    $= 0$ otherwise

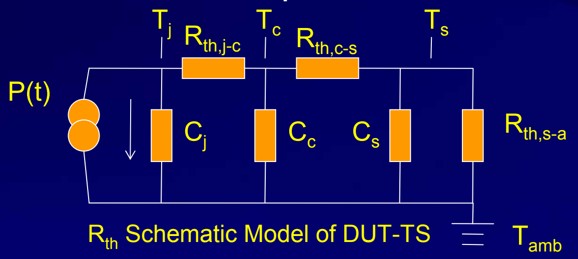


Temperature Behavior in Conductor During Pulse Current Application

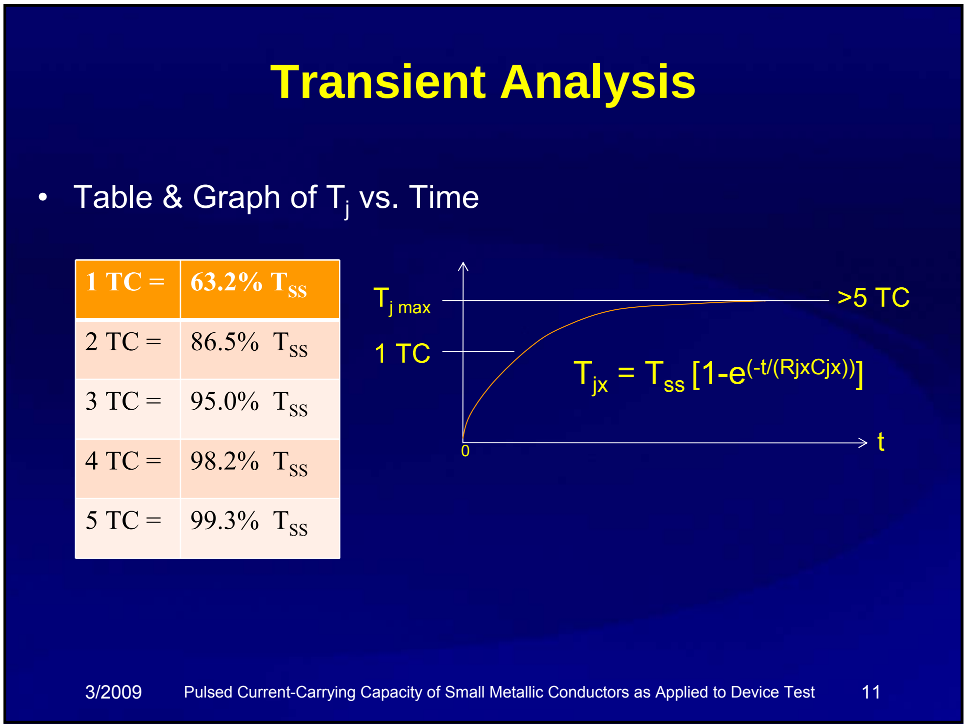
- Given a BeCu Contact with these parameters:
  - $R = 1\text{x}10^{-3}\ \Omega$ $m = 1\text{x}10^{-7}$ Kg
  - $P = 1\text{x}10^{-3}$ Watts $c_p = 400$ J/Kg-K
  - Conditions: Contact is a “free body” suspended in air
- At a current of 1 amp @ 100% duty cycle ($t_0/T = 1$)
  - $Q_{int} = I^2R = m^* C_p{}^*\Delta T$
  - $\Delta T = (1^2 * 1\text{x}10^{-3})/(1\text{x}10^{-7} * 400) = 25°\text{C} \uparrow$
- If duty cycle = 50% ($t_0/T = 0.5$) and peak power remains the same…
  - I = 0.707 amps
  - $\Delta T = (0.707^2 * 1\text{x}10^{-3})/(1\text{x}10^{-7} * 400) = 12.5°\text{C} \uparrow$
  - Thus halving the duty cycle, halved the temperature rise

Transient Analysis

- Transient heating of DUT with 100% duty cycle current pulse
- DUT thermal resistance equivalent circuit diagram



- $T_j = T_{SS}{}^*[1-\exp(-t/(R_{th,x}{}^*C_{th,x}))]$
- $R_{th,x}$ = relative thermal resistance
- $R_{th,x}{}^* C_{th,x}$ = time constant (τ)
- t = time (sec)
- $C_{th,x}$ = relative thermal capacitance

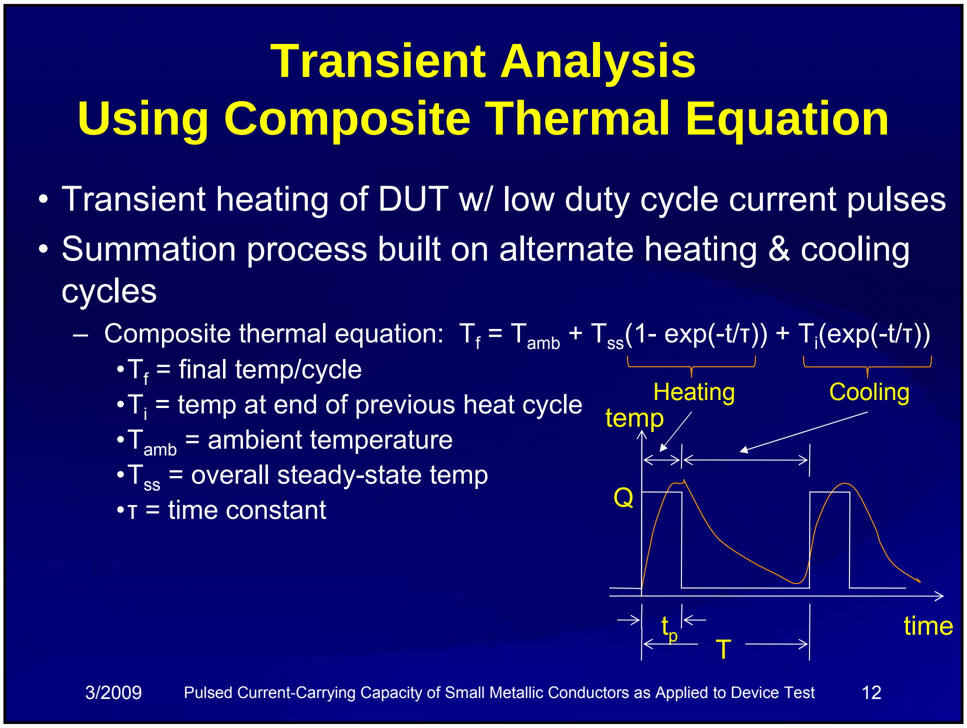


Transient Analysis

- Table & Graph of T_j vs. Time

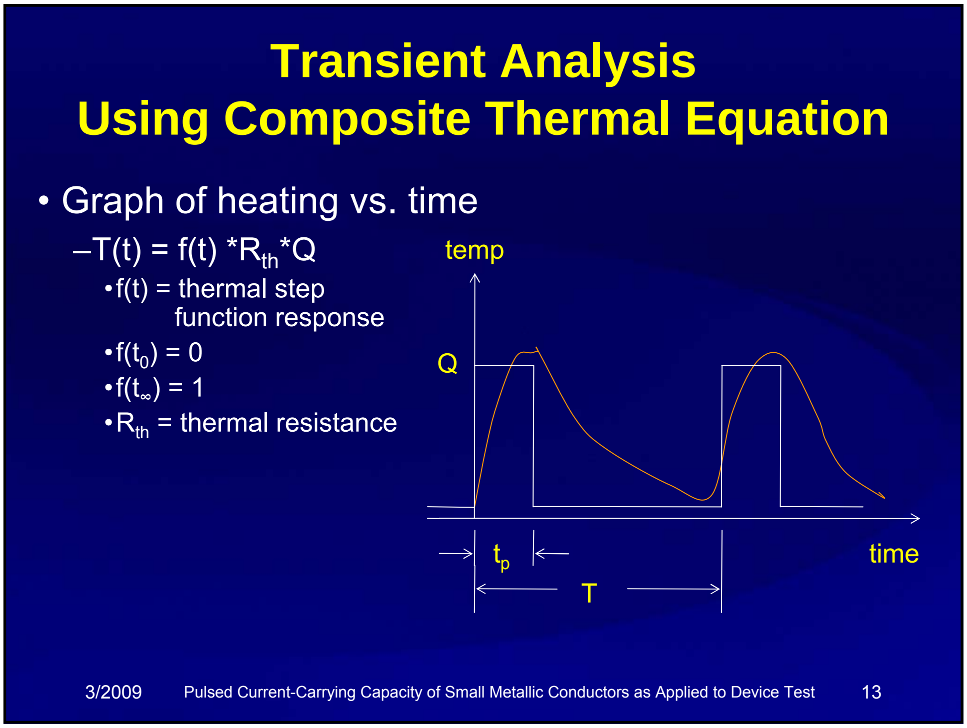
1 TC =	63.2% T_{SS}
2 TC =	86.5% T_{SS}
3 TC =	95.0% T_{SS}
4 TC =	98.2% T_{SS}
5 TC =	99.3% T_{SS}

$T_{jx} = T_{ss}\,[1-e^{(-t/(RjxCjx))}]$



Transient Analysis
Using Composite Thermal Equation

- Transient heating of DUT w/ low duty cycle current pulses
- Summation process built on alternate heating & cooling cycles
  - Composite thermal equation: $T_f = T_{amb} + \underbrace{T_{ss}(1- \exp(-t/\tau))}_{\text{Heating}} + \underbrace{T_i(\exp(-t/\tau))}_{\text{Cooling}}$
    - •T_f = final temp/cycle
    - •T_i = temp at end of previous heat cycle
    - •T_{amb} = ambient temperature
    - •T_{ss} = overall steady-state temp
    - •τ = time constant



Transient Analysis
Using Composite Thermal Equation

- Graph of heating vs. time
  - –$T(t) = f(t) * R_{th} * Q$
    - $f(t)$ = thermal step function response
    - $f(t_0) = 0$
    - $f(t_\infty) = 1$
    - R_{th} = thermal resistance

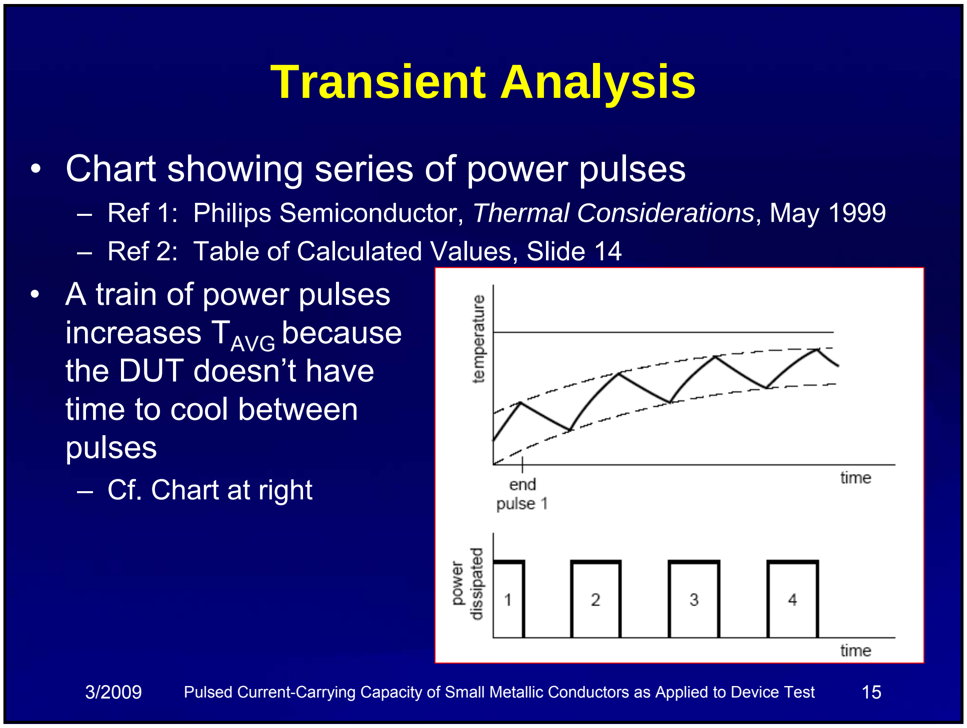
Transient Analysis
using Composite Thermal Equation

- A 10 Hertz square wave (P_{AVG} = 1W) is applied to a DUT and cycled 5 times. What is the temperature of the die?

T_{amb} = +30°C R_{th} = 10°C/W T_{ss} = +60°C
C_{th} = 0.01W-sec/°C $T_{ON} = T_{OFF}$ = 0.05 sec TC = 0.10 sec

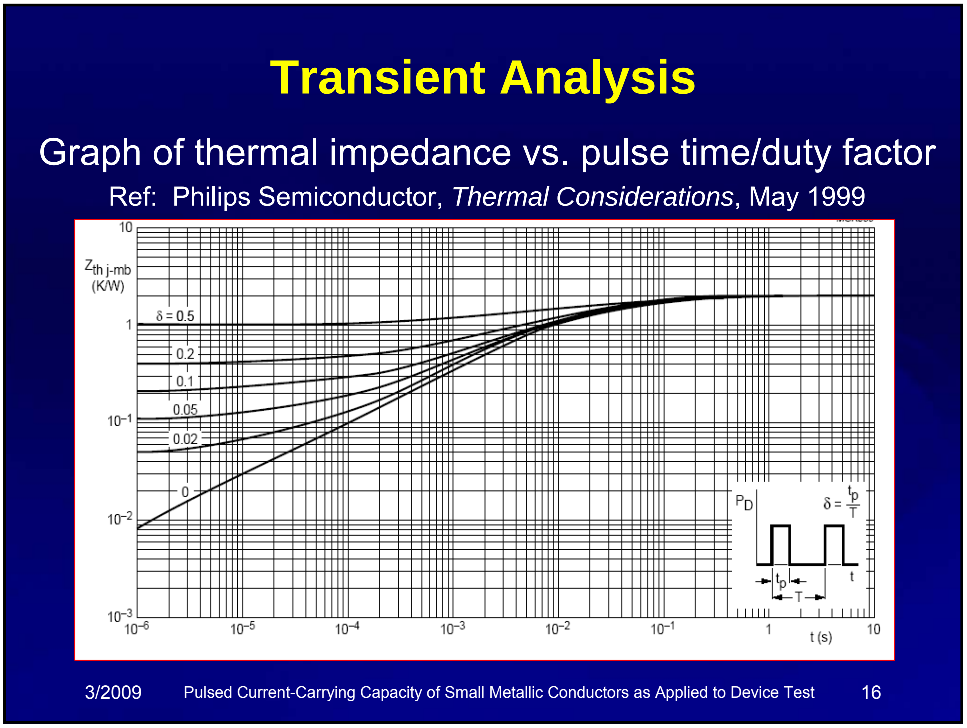
Table of Calculated Values

T_1	**60*(1-exp(-0.05/0.10))**	**= 23.6°C**	**Heating**	
T_2	**23.6*(exp(-0.5))**	**= 14.3°C**	**Cooling**	
T_3	**14.3 + 60*(1-exp(-0.05/0.10))**	**= 37.9°C**	**Heating**	**TC1**
T_4	**37.9*(exp(-0.5))**	**= 23.0°C**	**Cooling**	
T_5	**23.0 + 60*(1-exp(-0.05/0.10))**	**= 46.6°C**	**Heating**	
T_6	**46.6*(exp(-0.5))**	**= 28.3°C**	**Cooling**	
T_7	**28.3 + 60*(1-exp(-0.05/0.10))**	**= 51.9°C**	**Heating**	**TC2**
T_8	**51.9*(exp(-0.5))**	**= 31.5°C**	**Cooling**	
T_9	**31.5 + 60*(1-exp(-0.05/0.10))**	**= 55.1°C**	**Heating**	**~TC3**
T_{10}	**55.1*(exp(-0.5))**	**= 33.4°C**	**Cooling**	



Transient Analysis

- Chart showing series of power pulses
  - Ref 1: Philips Semiconductor, *Thermal Considerations*, May 1999
  - Ref 2: Table of Calculated Values, Slide 14
- A train of power pulses increases T_{AVG} because the DUT doesn't have time to cool between pulses
  - Cf. Chart at right



Transient Analysis

Graph of thermal impedance vs. pulse time/duty factor

Ref: Philips Semiconductor, *Thermal Considerations*, May 1999

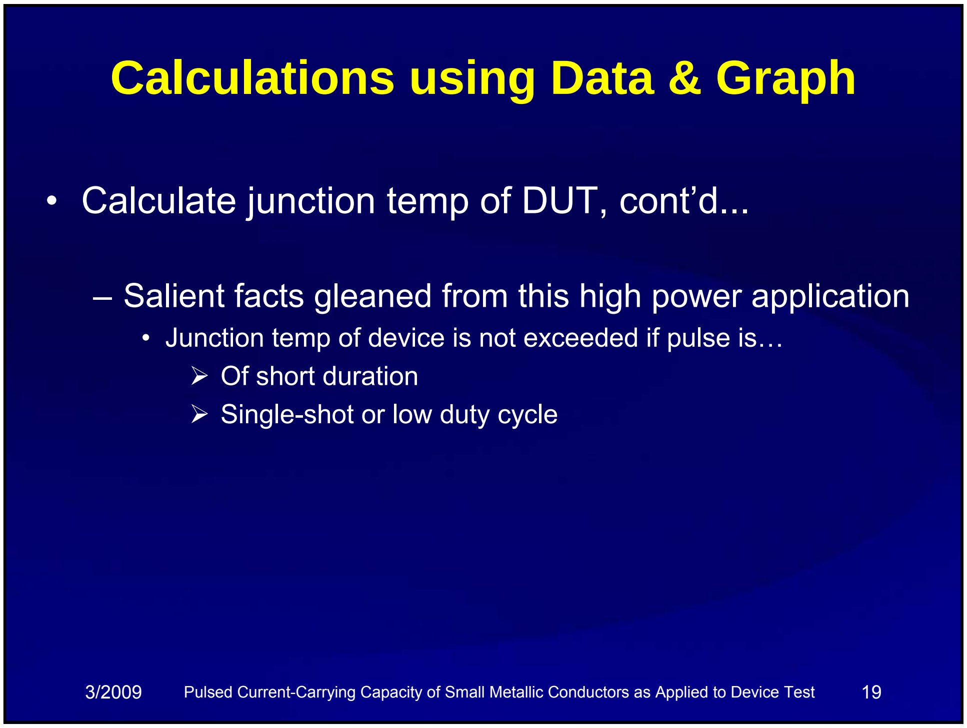
Transient Analysis

Things to consider when using Graph on previous slide

- If pulse time is very short:
  - Power dissipated doesn't have a limiting action
  - Pulse current and maximum voltage form the only limits
- A train of power pulses increases T_{AVG} :
  - DUT doesn't have time to cool between pulses
- Short pulses at low frequencies:
  - Lower the final temperature that the DUT junction reaches
- Peak junction temp usually occurs at end of applied pulse:
  - Its calculation will involve transient thermal impedance
- Avg. junction temp is calculated (if applicable) by using avg. power dissipation and the DC thermal resistance

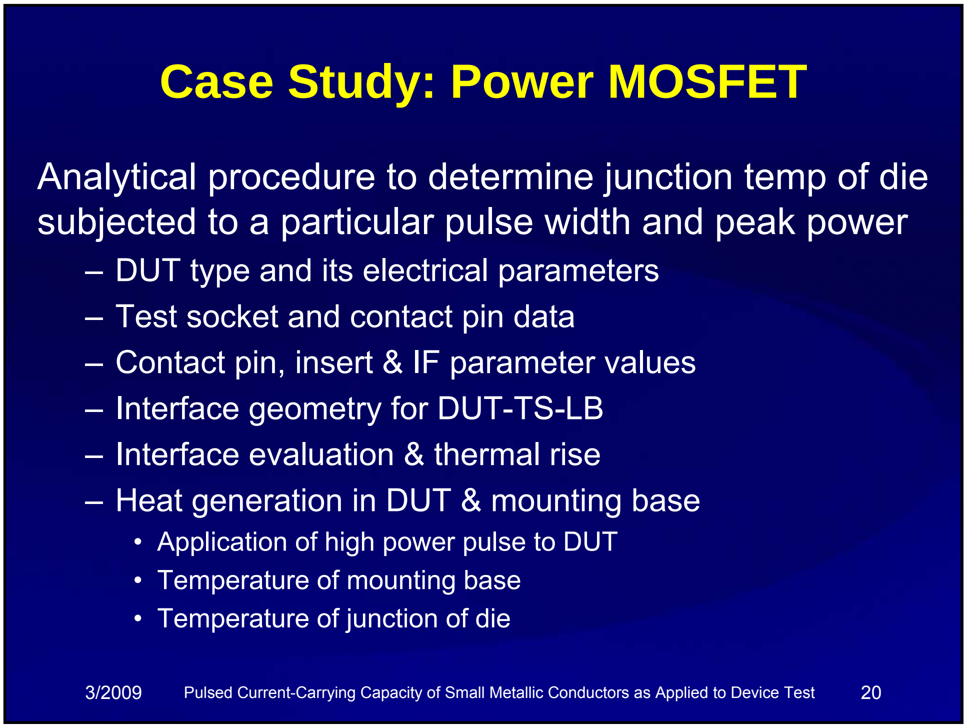
Calculations using Data & Graph

- Calculate junction temp of DUT
  - Use a single-shot pulse
    - Peak current and voltage = 50 amps @ 20VDC for 100 microseconds
    - Pulse repeated after 20 seconds (Duty Cycle, $\delta \sim 0$)
    - $P_p = I^*E = 50*20 = 1000$ Watts
    - $T_{mb} = +30°C$
  - Use transient analysis for short duration pulse
    - $Z_{th,j\text{-}mb} = 1.8\text{x}10^{-2}$ K/W (from graph on slide 16)
    - $\Delta T_{j\text{-}mb} = P^*Z_{thj\text{-}mb} = 1\text{x}10^3 \text{ x } 1.8\text{x}10^{-2} = 18°C$
    - $T_{j\text{-}peak} = T_{mb} + \Delta T_{j\text{-}mb} = 30 + 18 = +48°C$



Calculations using Data & Graph

- Calculate junction temp of DUT, cont'd...
  - Salient facts gleaned from this high power application
    - Junction temp of device is not exceeded if pulse is…
      - ➢ Of short duration
      - ➢ Single-shot or low duty cycle



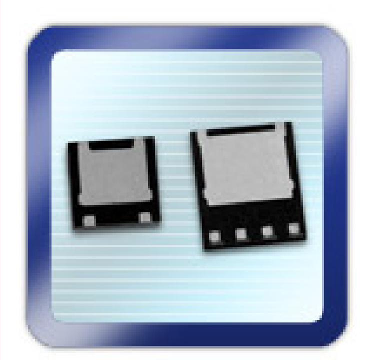
Case Study: Power MOSFET

Analytical procedure to determine junction temp of die subjected to a particular pulse width and peak power

- – DUT type and its electrical parameters
- – Test socket and contact pin data
- – Contact pin, insert & IF parameter values
- – Interface geometry for DUT-TS-LB
- – Interface evaluation & thermal rise
- – Heat generation in DUT & mounting base
  - Application of high power pulse to DUT
  - Temperature of mounting base
  - Temperature of junction of die

DUT Type and Electrical Parameters

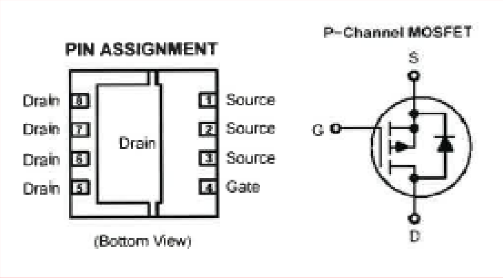
- Package size: 3.3 x 3.3 mm, 0.65mm pitch, 8 pads
- Electrical parameters
  - V_{IN} =20V, max.
  - I_{IN} = 40 A, max.
  - Specific heat ~ 200J/Kg-K
  - Mass ~ $1x10^{-4}$ Kg
  - Electrical resistivity (R_e) ~ $1x10^{-2}$ Ω
- Other
  - $R_{th, j-c}$ = 2.4°C/W
  - $C_{th, j-c}$ = 0.1W-sec/°C
  - $J_{T,max}$ = +175°C
  - P_{DISS} (<10sec) = 3.8W



Power QFN MOSFET
Courtesy: PSi Technologies

Test Socket and Contact Pin Data

- Contact Pins: AuNi-plated BeCu – 8 req'd.
- Ground/Thermal Insert: Copper
- Surface of DUT leads: Matte Tin or NiPdAu-plated
- Force of DUT against Contacts at I.F. ~65 grams/pin
- Typical Contactor pin-outs to pads of DUT
  - Source: 3 pins
  - Gate: 1 pin
  - Drain: 4 pins



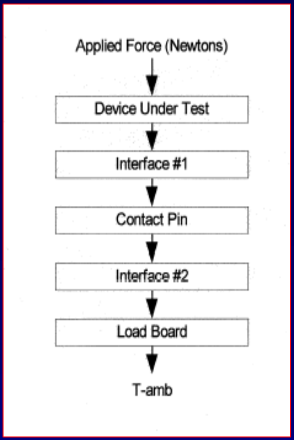
Contact Pin, Insert & IF Data

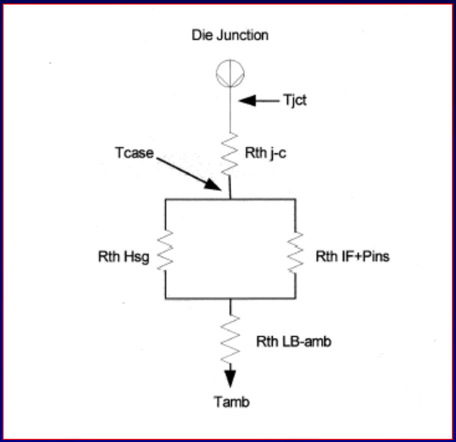
Calculated Contact Pin/Insert/IF values

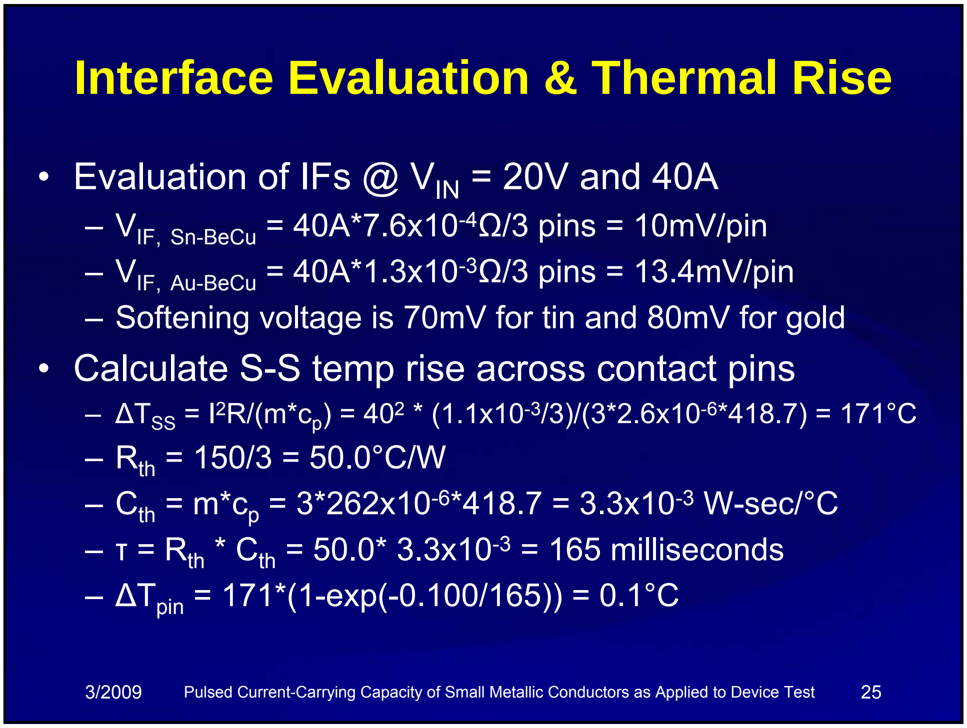
Parameter	Calc. Value
R_E (Contact Pin)	$7.0\mathrm{x}10^{-4}$ Ω/pin
R_E (IF)	$1.3\mathrm{x}10^{-3}$ Ω/IF
R_E (Contact Pin + IFs)	$3.3\mathrm{x}10^{-3}$ Ω
R_E (Copper Insert)	$2.6\mathrm{x}10^{-6}$ Ω
R_E (Copper Insert + IFs)	$3.9\mathrm{x}10^{-5}$ Ω
R_{TH} (Contact Pin)	142°C/W
R_{TH} (Contact Pin + IFs)	150°C/W
R_E (Copper Insert)	0.5°C/W
R_E (Copper Insert + IFs)	1.0°C/W

DUT $R_{th,x}$ Geometry for DUT-TS-LB

Block and schematic diagrams of DUT $R_{th,x}$ geometry

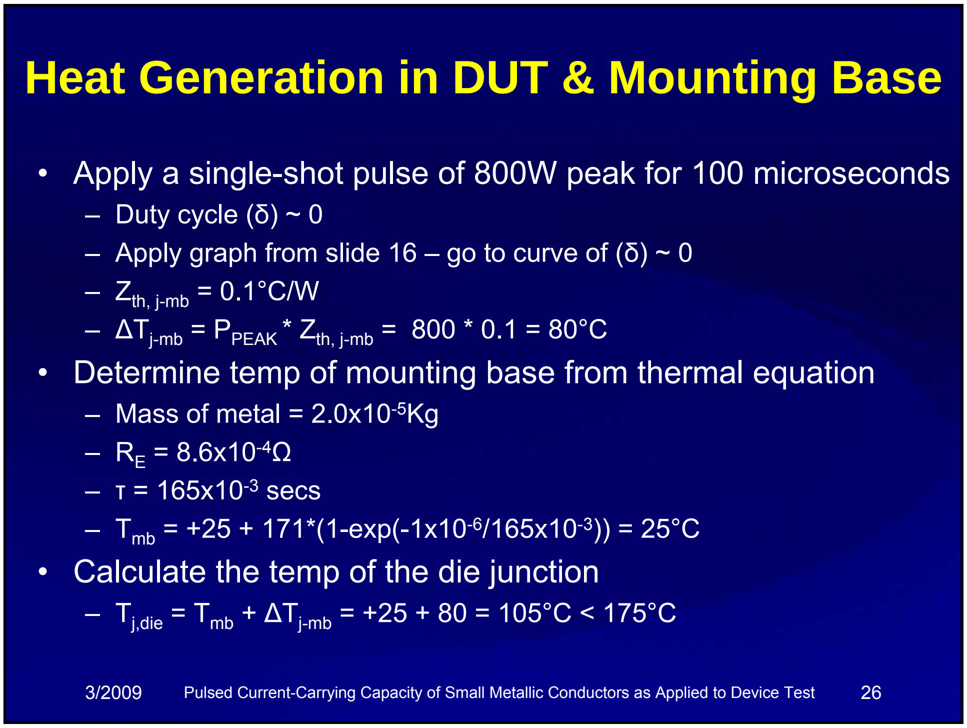






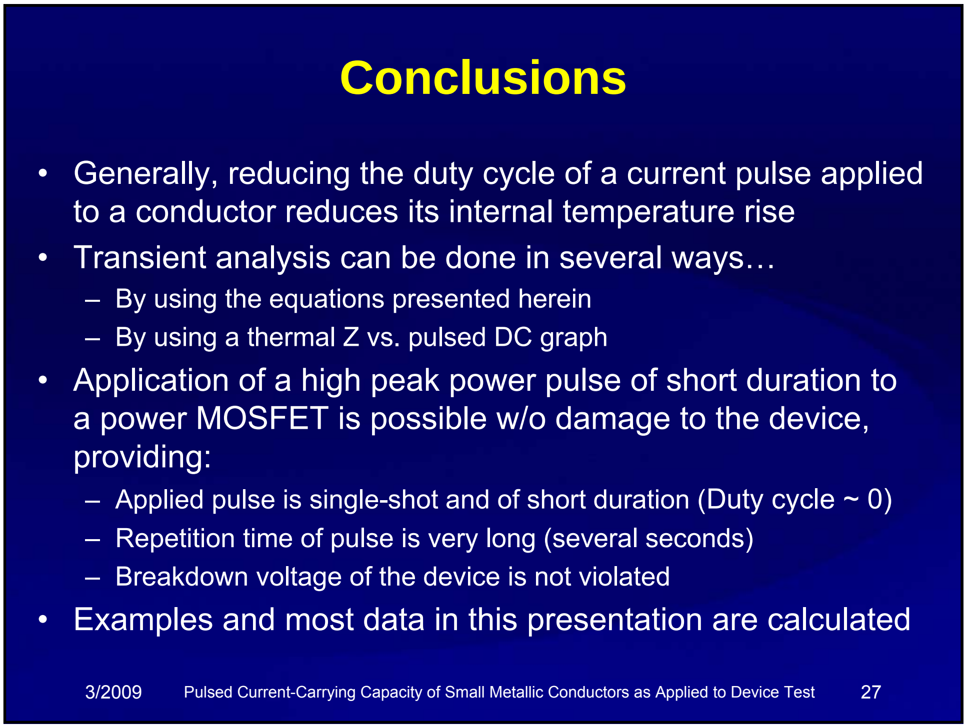
Interface Evaluation & Thermal Rise

- Evaluation of IFs @ V_{IN} = 20V and 40A
  - $V_{IF,\ Sn\text{-}BeCu} = 40A*7.6x10^{-4}\Omega/3$ pins = 10mV/pin
  - $V_{IF,\ Au\text{-}BeCu} = 40A*1.3x10^{-3}\Omega/3$ pins = 13.4mV/pin
  - Softening voltage is 70mV for tin and 80mV for gold
- Calculate S-S temp rise across contact pins
  - $\Delta T_{SS} = I^2R/(m*c_p) = 40^2 * (1.1x10^{-3}/3)/(3*2.6x10^{-6}*418.7) = 171°C$
  - $R_{th} = 150/3 = 50.0°C/W$
  - $C_{th} = m*c_p = 3*262x10^{-6}*418.7 = 3.3x10^{-3}$ W-sec/°C
  - $\tau = R_{th} * C_{th} = 50.0* 3.3x10^{-3} = 165$ milliseconds
  - $\Delta T_{pin} = 171*(1-\exp(-0.100/165)) = 0.1°C$



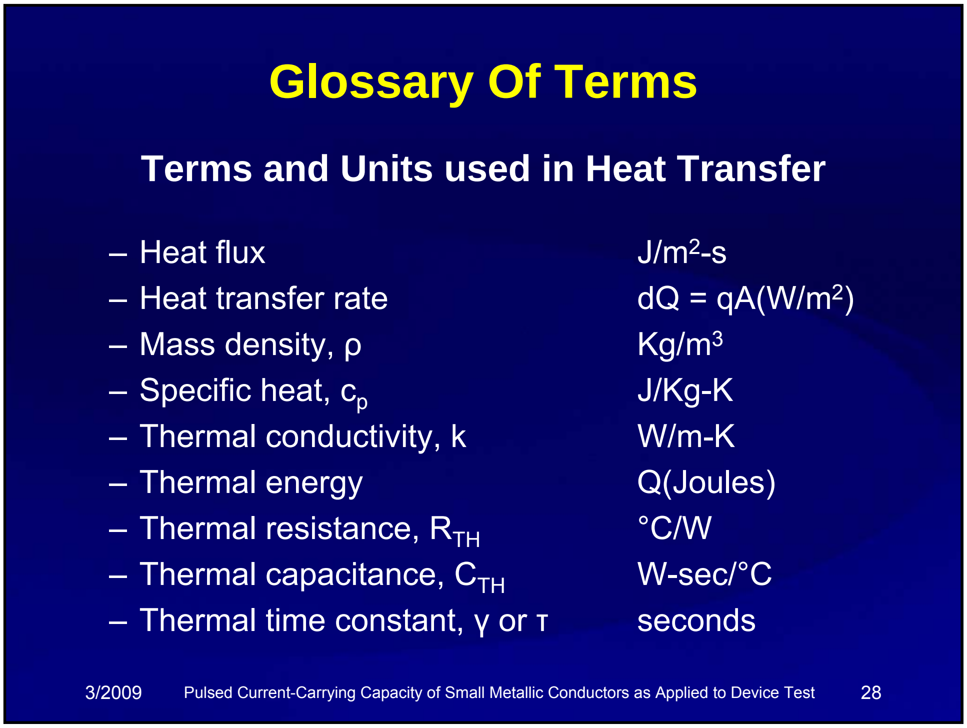
Heat Generation in DUT & Mounting Base

- Apply a single-shot pulse of 800W peak for 100 microseconds
  - Duty cycle (δ) ~ 0
  - Apply graph from slide 16 – go to curve of (δ) ~ 0
  - $Z_{th,\ j\text{-}mb} = 0.1°C/W$
  - $\Delta T_{j\text{-}mb} = P_{PEAK} * Z_{th,\ j\text{-}mb} = 800 * 0.1 = 80°C$
- Determine temp of mounting base from thermal equation
  - Mass of metal = $2.0x10^{-5}$Kg
  - $R_E = 8.6x10^{-4}\Omega$
  - $\tau = 165x10^{-3}$ secs
  - $T_{mb} = +25 + 171*(1-\exp(-1x10^{-6}/165x10^{-3})) = 25°C$
- Calculate the temp of the die junction
  - $T_{j,die} = T_{mb} + \Delta T_{j\text{-}mb} = +25 + 80 = 105°C < 175°C$



Conclusions

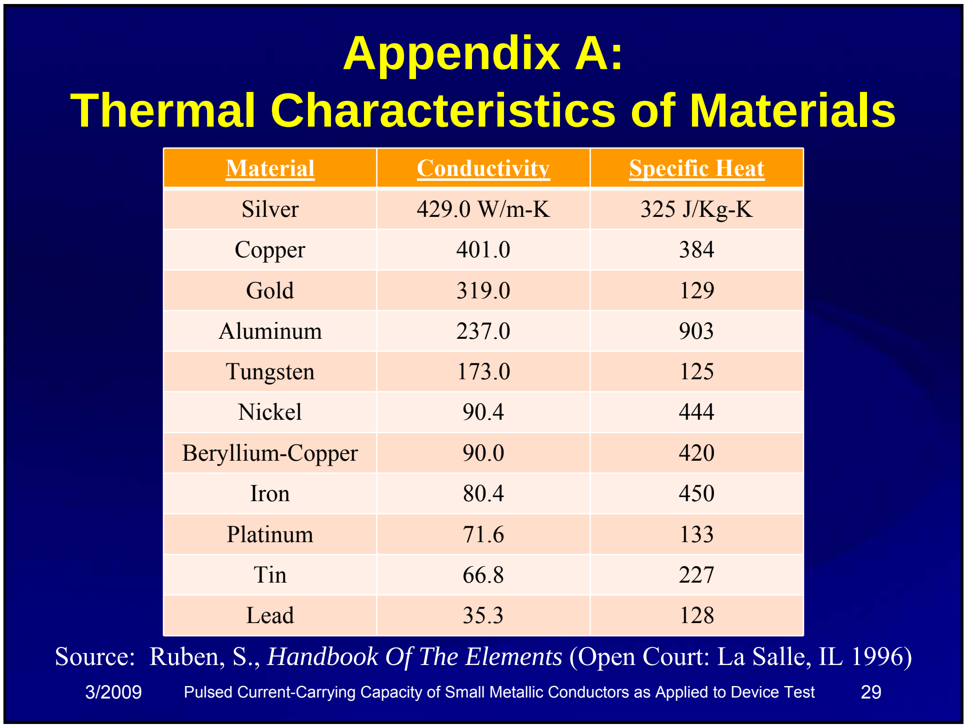
- Generally, reducing the duty cycle of a current pulse applied to a conductor reduces its internal temperature rise
- Transient analysis can be done in several ways…
  - By using the equations presented herein
  - By using a thermal Z vs. pulsed DC graph
- Application of a high peak power pulse of short duration to a power MOSFET is possible w/o damage to the device, providing:
  - Applied pulse is single-shot and of short duration (Duty cycle ~ 0)
  - Repetition time of pulse is very long (several seconds)
  - Breakdown voltage of the device is not violated
- Examples and most data in this presentation are calculated



Glossary Of Terms

Terms and Units used in Heat Transfer

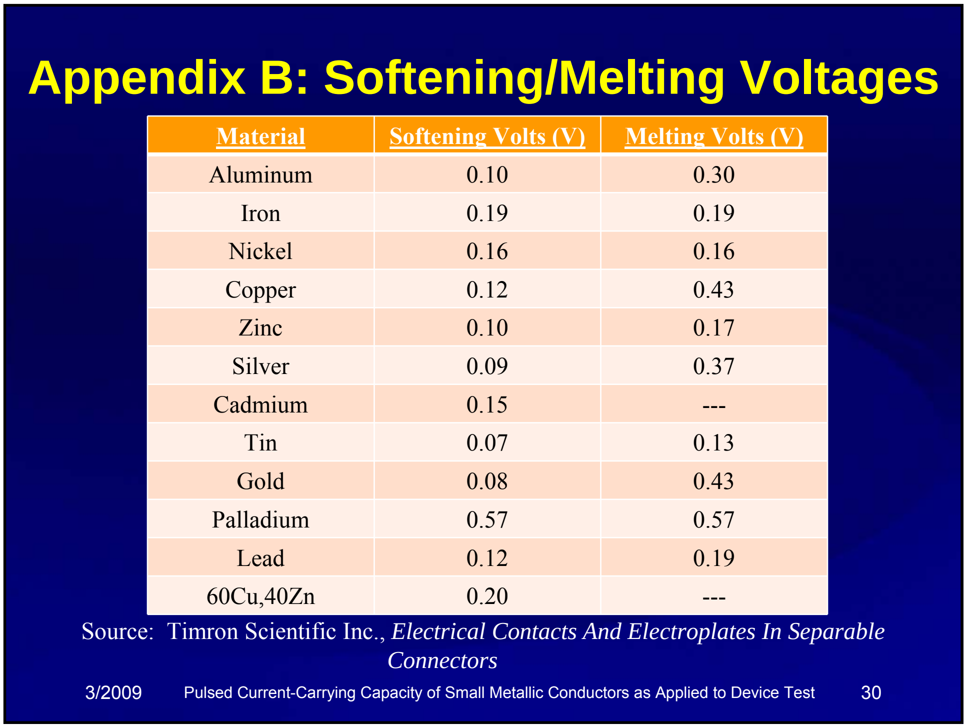
– Heat flux	J/m^2-s
– Heat transfer rate	dQ = qA(W/m^2)
– Mass density, ρ	Kg/m^3
– Specific heat, c_p	J/Kg-K
– Thermal conductivity, k	W/m-K
– Thermal energy	Q(Joules)
– Thermal resistance, R_{TH}	°C/W
– Thermal capacitance, C_{TH}	W-sec/°C
– Thermal time constant, γ or τ	seconds



Appendix A: Thermal Characteristics of Materials

Material	Conductivity	Specific Heat
Silver	429.0 W/m-K	325 J/Kg-K
Copper	401.0	384
Gold	319.0	129
Aluminum	237.0	903
Tungsten	173.0	125
Nickel	90.4	444
Beryllium-Copper	90.0	420
Iron	80.4	450
Platinum	71.6	133
Tin	66.8	227
Lead	35.3	128

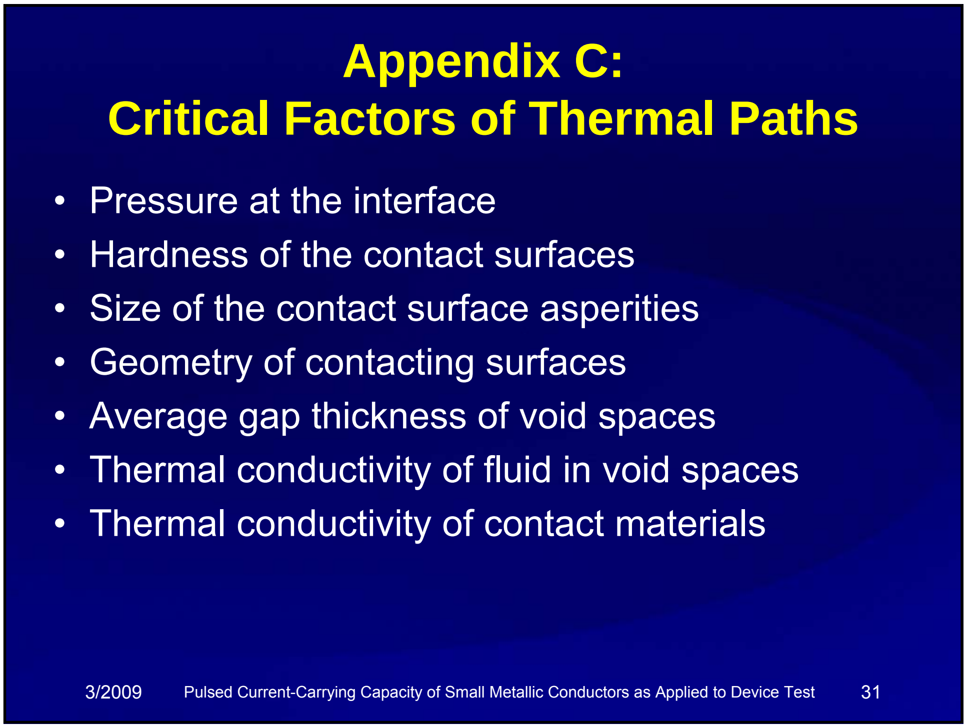
Source: Ruben, S., *Handbook Of The Elements* (Open Court: La Salle, IL 1996)



Appendix B: Softening/Melting Voltages

Material	Softening Volts (V)	Melting Volts (V)
Aluminum	0.10	0.30
Iron	0.19	0.19
Nickel	0.16	0.16
Copper	0.12	0.43
Zinc	0.10	0.17
Silver	0.09	0.37
Cadmium	0.15	---
Tin	0.07	0.13
Gold	0.08	0.43
Palladium	0.57	0.57
Lead	0.12	0.19
60Cu,40Zn	0.20	---

Source: Timron Scientific Inc., *Electrical Contacts And Electroplates In Separable Connectors*



Appendix C: Critical Factors of Thermal Paths

- Pressure at the interface
- Hardness of the contact surfaces
- Size of the contact surface asperities
- Geometry of contacting surfaces
- Average gap thickness of void spaces
- Thermal conductivity of fluid in void spaces
- Thermal conductivity of contact materials