Achieving Electrothermal Stability in Interconnect Metal During ESD Pulses

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Outline

- Partitioned wires as a heating slab
  - More surface/volume than ever
  - Neighboring metal is a heat sink
  - 1-dimensional R-C transmission line models for thermal behavior
- Feedback model for metal heating
  - Self-consistent T(t) expression
    - From metal tempco and thermal Ohm's Law; $T(s)=P(s)Z(s)$
  - Positive (tempco) and negative (electrical circuit, e.g., TLP) feedback
- Thermal impulse response $Z(s)\Leftrightarrow Z(t)$
  - **Pre-silicon:** finite element modeling
    - Also thermal circuit models and known limiting conditions
  - **Post-silicon:** Transmission Line Pulse (TLP) measurements
    - Derive Z(s) from $T(s)=P(s)Z(s)$, having measured T(t) and P(t)
      - Pole-zero expression for complex thermal impedance
        - Corresponds to 5-element R-C model
- ESD predictions in Excel using Z(t) and convolution software
  - Convolve $Z(t)*P(t)$ for HBM and CDM ESD conditions
    - Obtain complete T(t) waveform from feedback equation and check for melting

Metal Self-Heating Test Pattern

heat flow for
1-D heat slab:

$$\frac{\partial^2 V}{\partial x^2} = RC\frac{\partial V}{\partial t}$$

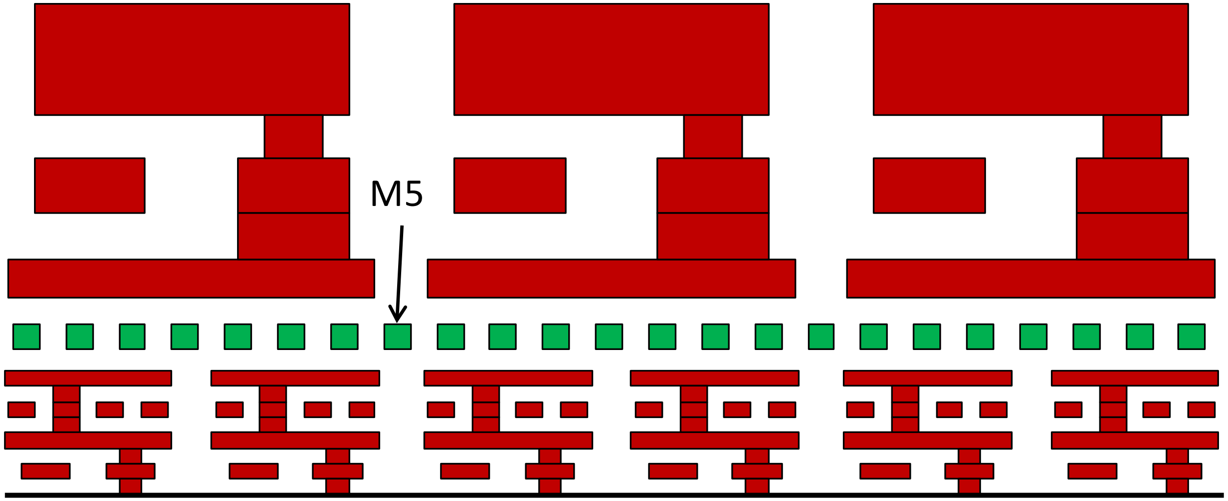
T-line
parameters:

$$Z_{th} = \frac{1}{\sqrt{sK\rho Cp}}$$

$$\gamma_{th} = \sqrt{\frac{s\rho Cp}{K}}$$

$s=\sigma+j\omega$

K=thermal conductivity
Cp=heat capacity
ρ=mass density

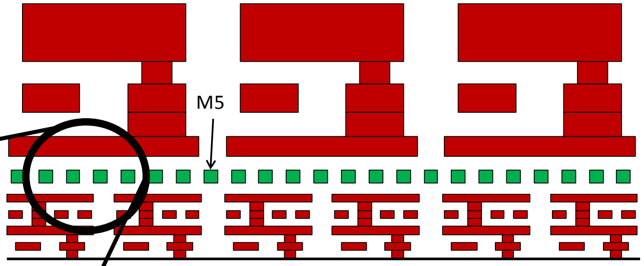


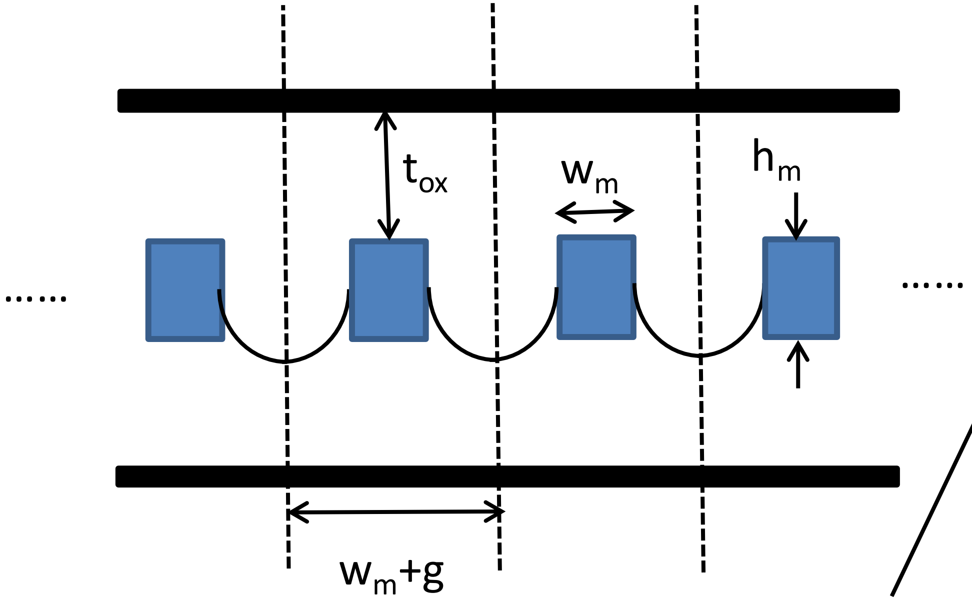
1 μm^2 metal cross section; electrical current through M5

Electrical: Thermal:
Volts ⇒ °C, temperature (usually a ΔT from room T)
Amps ⇒ Watts
Coulombs ⇒ Joules
Ohms ⇒ thermal impedance °C/W
Farads ⇒ Joules/°C

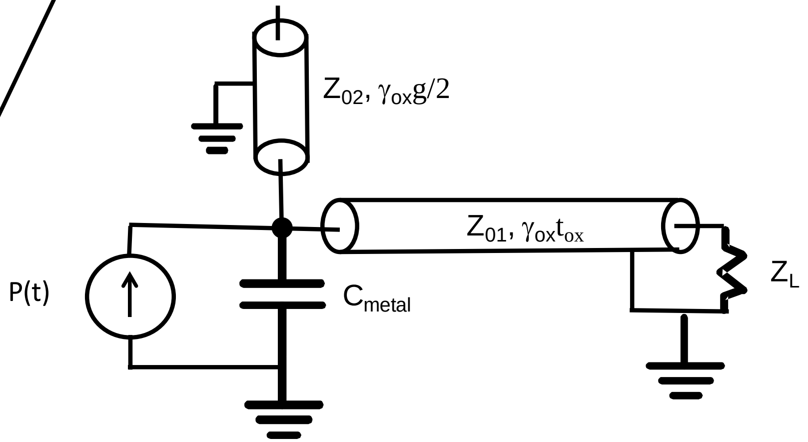
Wires Embedded in ILD Oxide

Thermal Ohm's Law:
$T(s)=P(s)Z(s)$





Thermal circuit model:



Pattern C as shown
Pattern D is wider, $g_D=2g_C$

Note open circuit b.c.

Thermal Feedback Model

metal resistance $R(t) = R_0(1+\alpha T(t))$ α = metal tempco=0.0025/°C for Cu

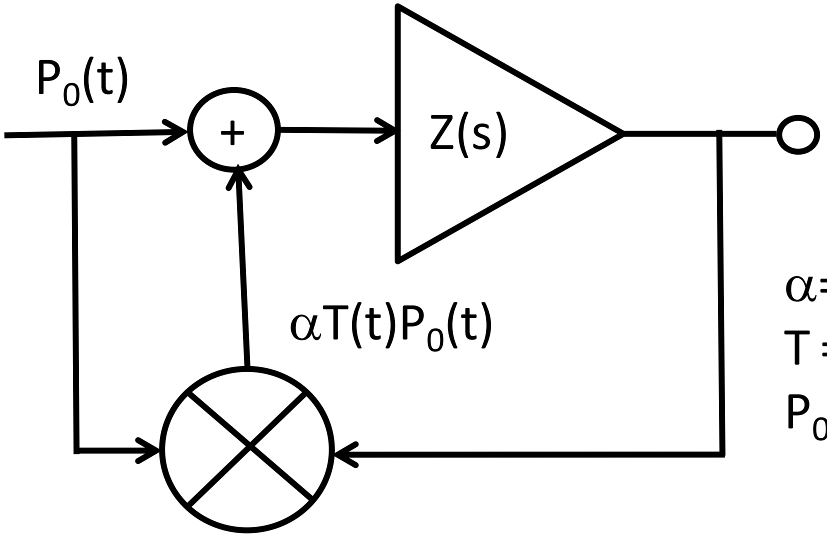
$$T(t) = P_0(t) * Z(t) + \alpha[T(t)P_0(t)] * Z(t)$$ thermal Ohm's Law

or $$T(t) = \frac{P_0(t) * Z(t)}{1-\alpha\frac{[T(t)P_0(t)] * Z(t)}{T(t)}}$$

$$P_0(t) * Z(t) = \int_0^t P_0(t-\tau)Z(\tau)d\tau \Leftrightarrow P_0(s)Z(s)$$

Solve implicit equation for T(t)

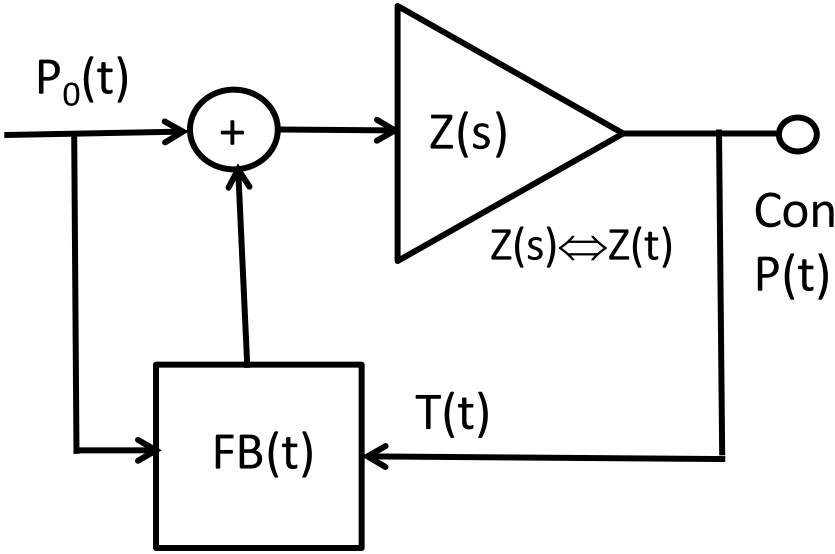
For "current" source $P_0(t)$:



P(s)Z(s)=T(s)

α= metal tempco
T = temp ("voltage")
$P_0 = I^2R_0$ in ("current")

General Feedback Network



$P_0(t)$

+

Z(s)

Z(s)⇔Z(t)

T(t)

FB(t)

Convolve
P(t)*Z(t)=T(t)

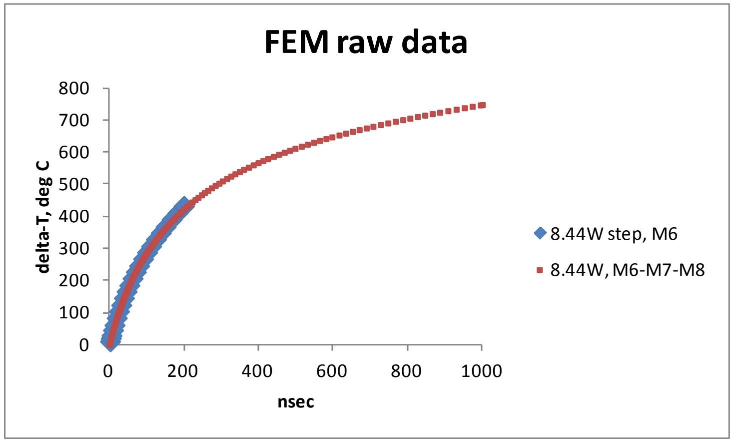
- Current source produces positive feedback
- Voltage source produces negative feedback

For TLP:

$$P_0(t) = P_0 = \frac{V_0^2 R_0}{(R_0+50)^2} \qquad FB(t) = P_0\left[\left(\frac{1+\alpha T(t)}{\left(1+\frac{\alpha R_0 T(t)}{R_0+50}\right)^2}\right)-1\right]$$

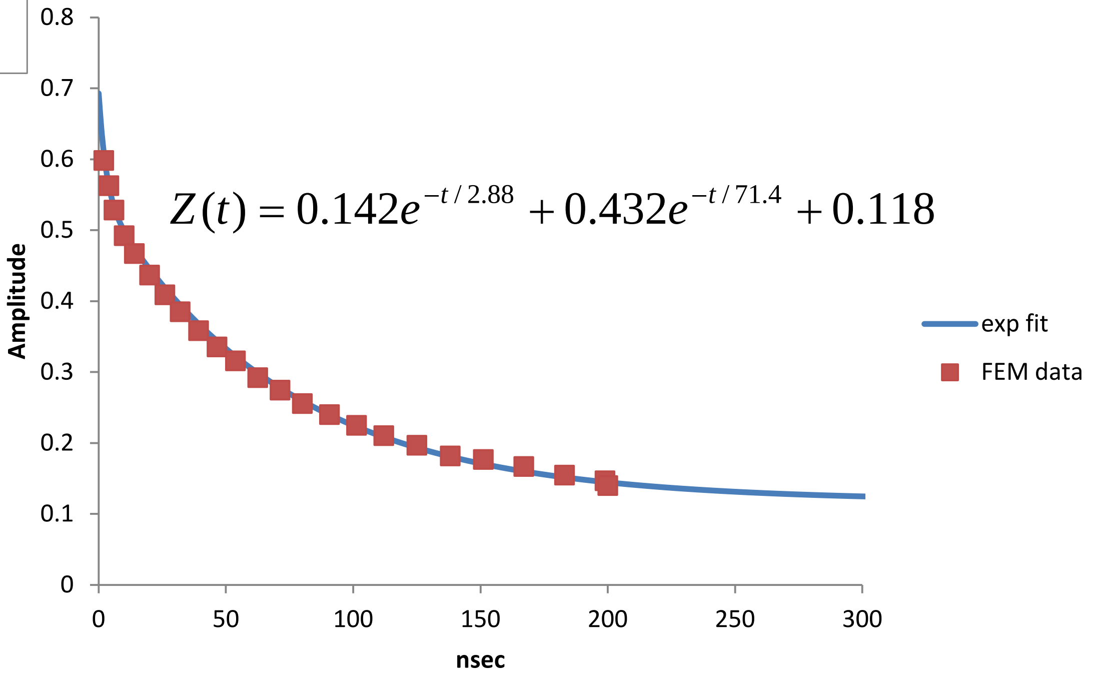
- Because of source resistance $Z_s=50\Omega$, TLP introduces negative feedback, and when $R(t)>50\ \Omega$, it becomes net negative

Z(t) from Finite Element Modeling



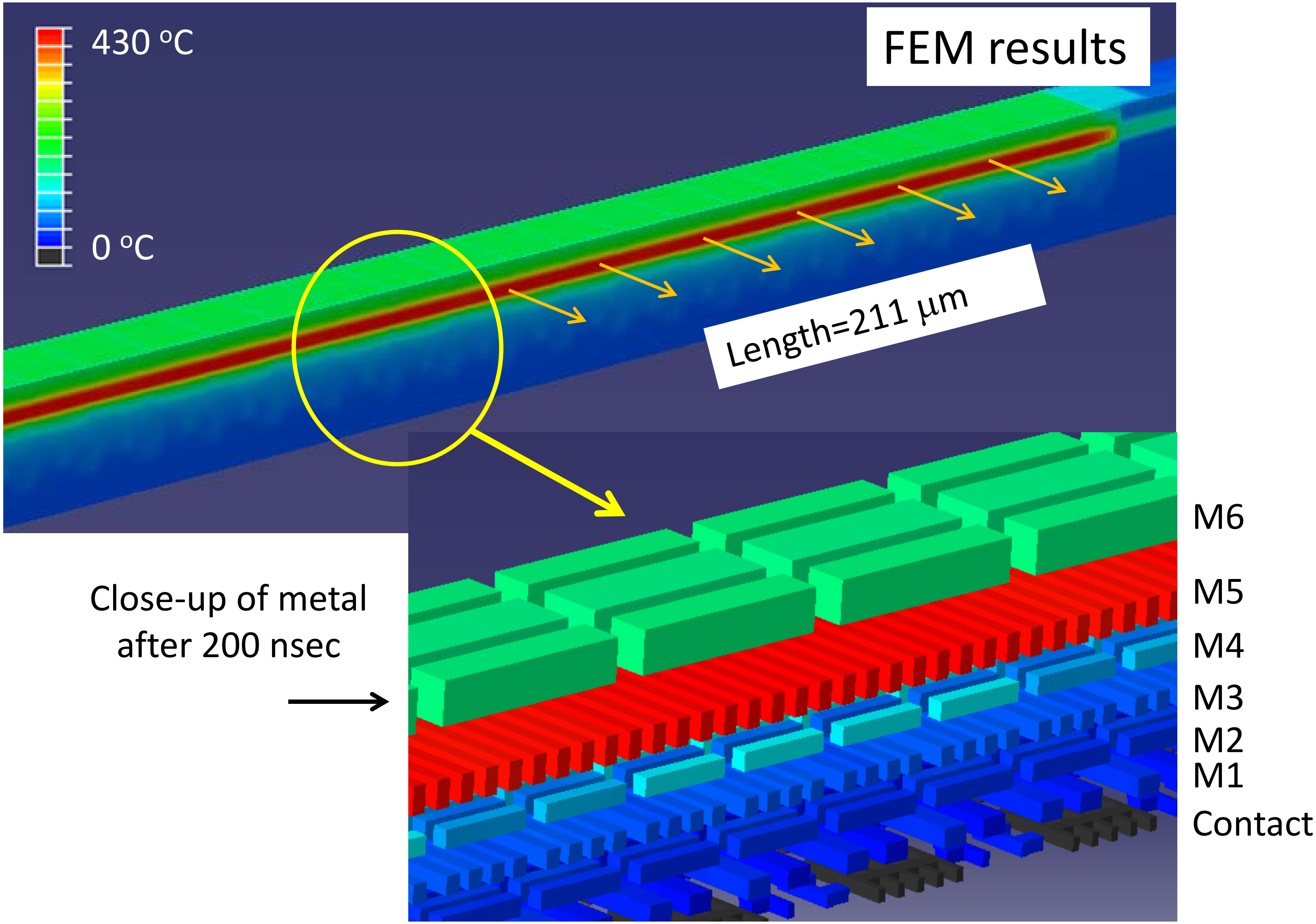
Step response gives thermal impulse response Z(t)

differentiate and normalize



$$Z(t) = 0.142e^{-t/2.88} + 0.432e^{-t/71.4} + 0.118$$

Final offset (0.118) substitutes for LONG (250 nsec, 1 μsec) time constant terms

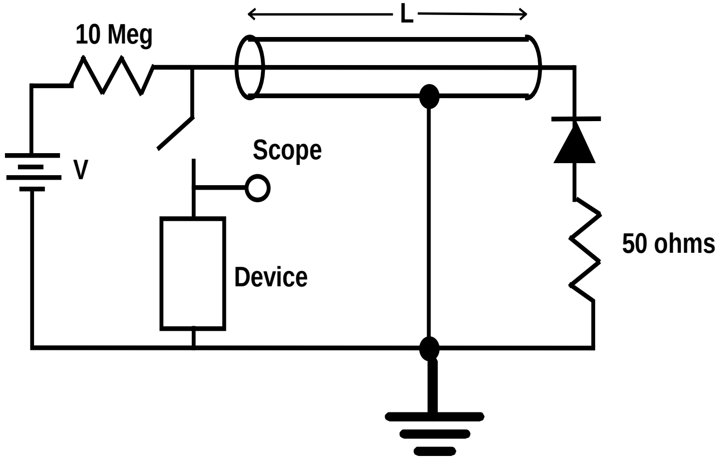


Close-up of metal after 200 nsec →

Transmission Line Pulsing (TLP)

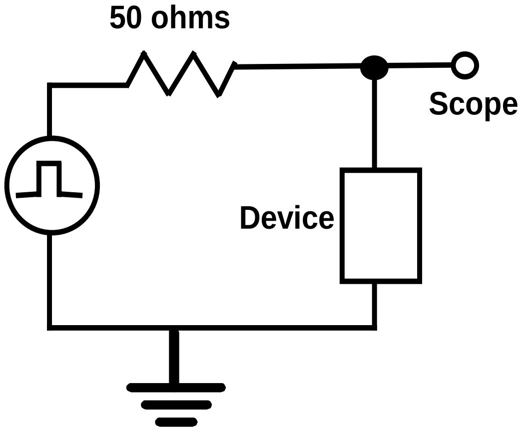
- Transmission line pulsing generates brief, high current (several ampere) pulses; same current/time scale as ESD

Setup:



- Equivalent circuit

(R_{device}<50 Ω):

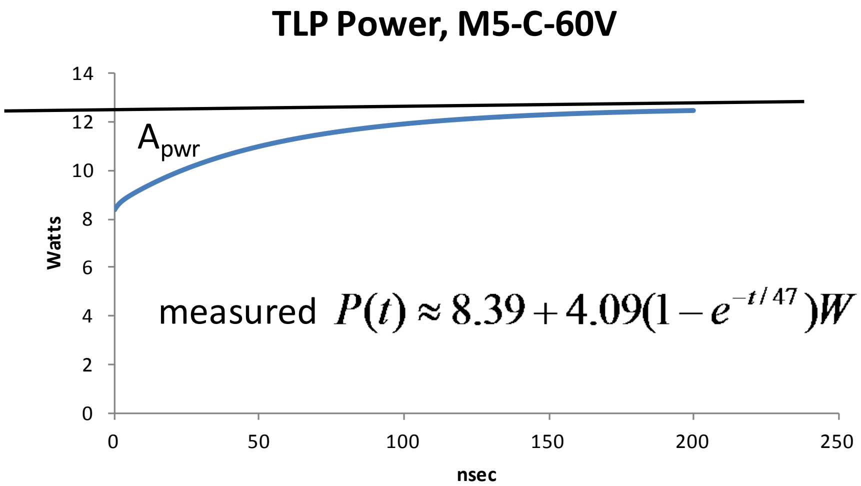


$I_{device}=(V-V_{device})/50$

t_{pulse} = 2L/c, c=20 cm/nsec

Apply to metal lines and use Cu tempco (α=0.0025) for *in-situ* T measurement

TLP data



measured $P(t) \approx 8.39 + 4.09(1 - e^{-t/47})W$

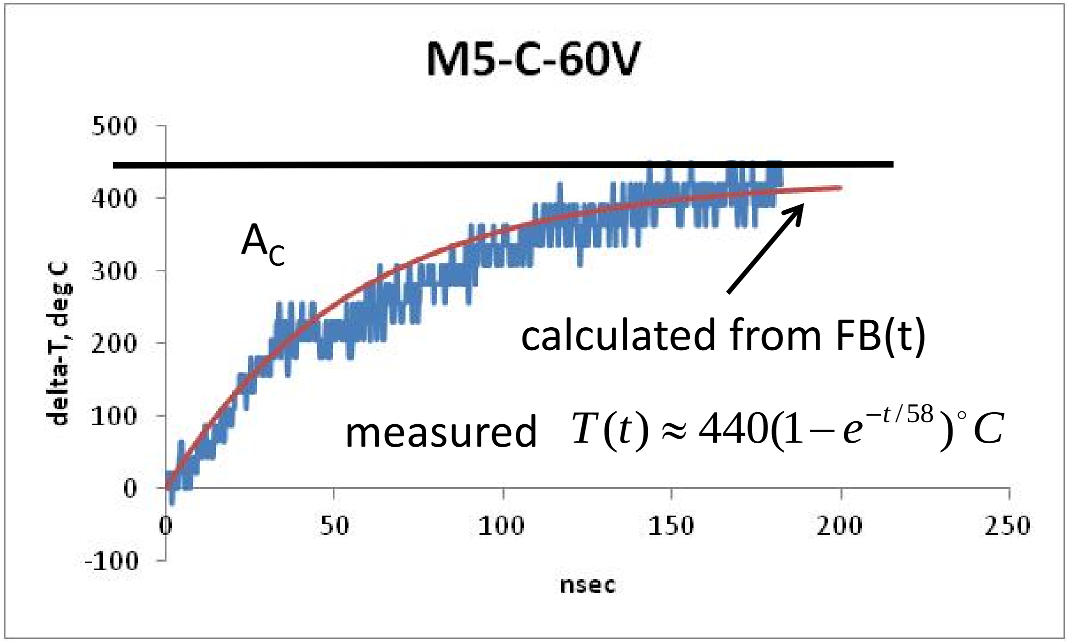
Pattern C, 60V

$$P(s) = \frac{8.39W}{s} + \frac{4.09W}{s(1+47s)}$$

normalized A_c, A_{pwr} give time constants

$$T(s) = \frac{440^\circ C}{s(1+58s)}$$

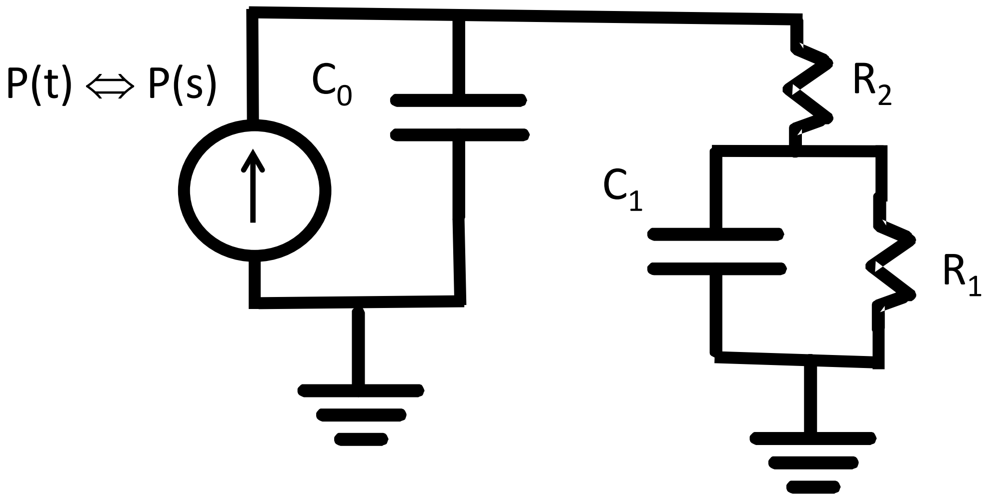
$$\boxed{Z(s) = \frac{T(s)}{P(s)}}$$



calculated from FB(t)

measured $T(t) \approx 440(1 - e^{-t/58})^\circ C$

Thermal Impedance



C_0 = 1.1 nJ/°C (metal + oxide)
R_2 = 32.7 °C/W (oxide)
C_1 = 20 nJ/°C
R_1 = 2.52 °C/W

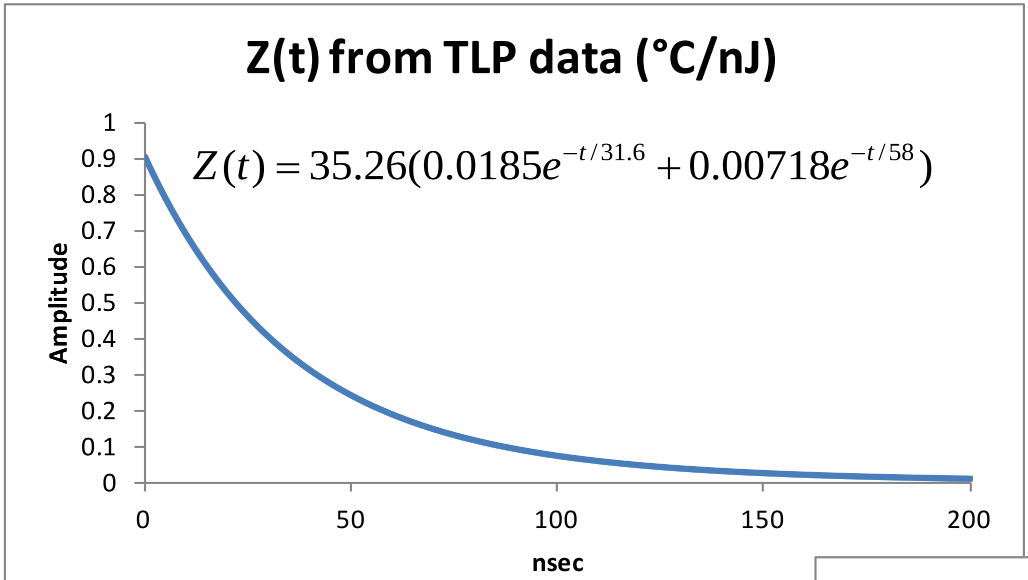
Values for Pattern C, 60V
from slide 10

$$Z(s) = \frac{(R_1 + R_2)(1 + R_1 \| R_2 C_1 s)}{1 + (R_1 C_1 + (R_1 + R_2) C_0) s + R_1 R_2 C_1 C_0 s^2}$$

$$P_0 = \frac{V_0^2 R_0}{(50 + R_0)^2}$$ for TLP

- Z(s) from slide 10 has 2 poles and 1 zero; 5-element RC network
- For TLP, temp should flatten out at $P_{final}(R_1+R_2) = P_{final}Z_0 = T_{final}$

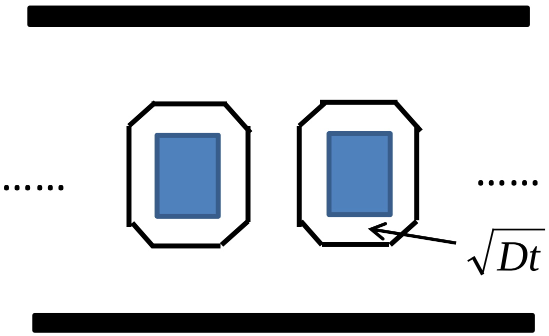
Thermal Impulse Response

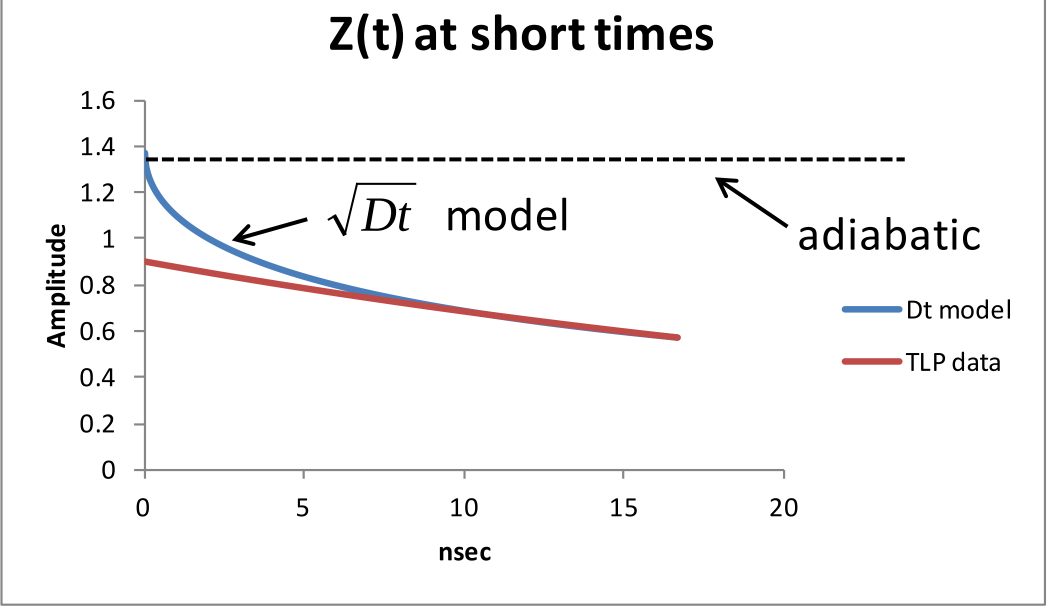


from $Z(s) = 35.26\dfrac{1+47s}{(1+31.6s)(1+58s)}$ °C/W

$$= \frac{T(s)}{P(s)}$$

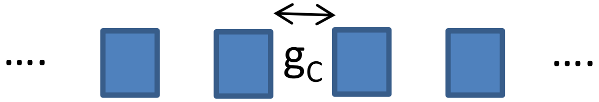
thermal sheath for short time:

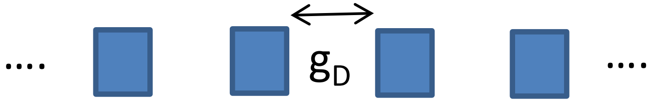


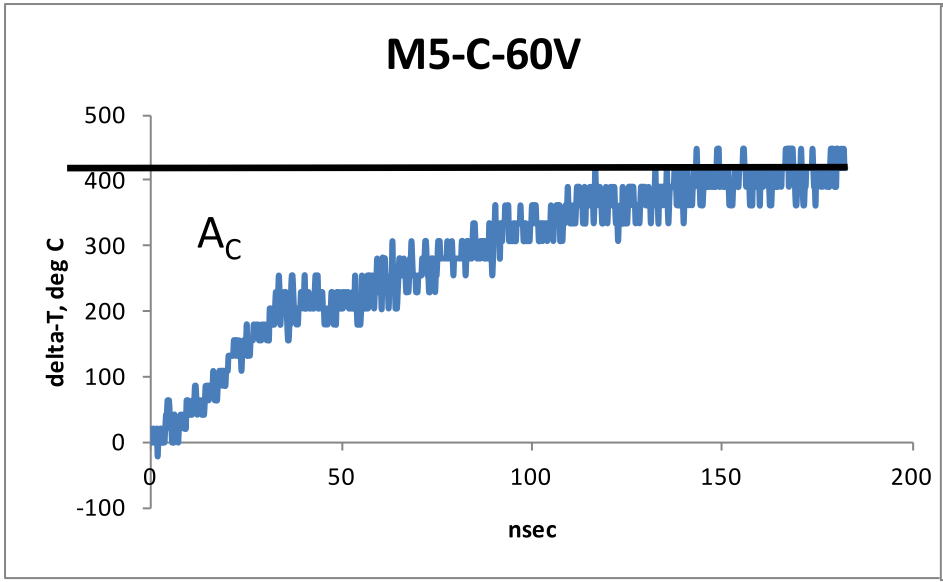


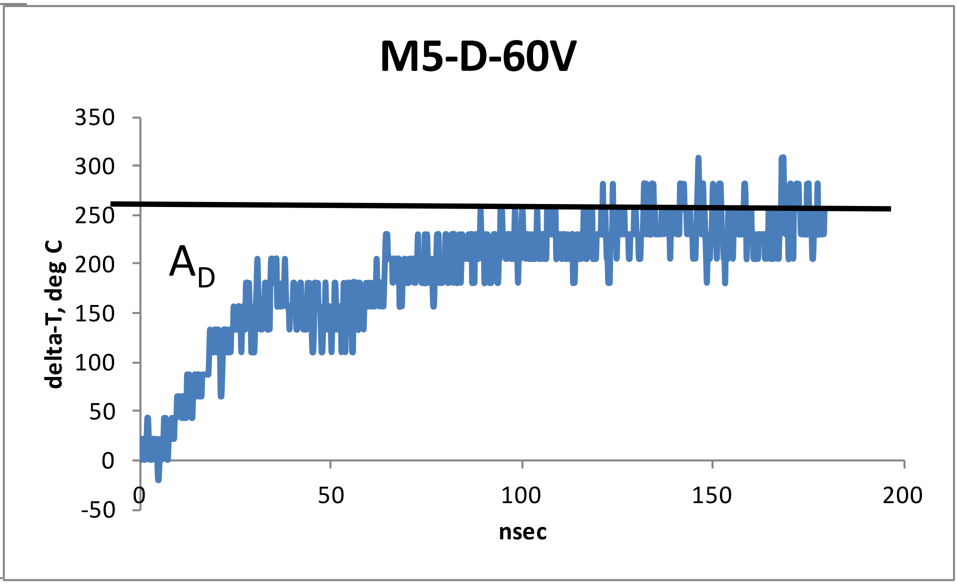
adiabatic limit is from Cu line heat capacity; 1.37 °C/nJ

TLP on Patterns C and D, 60V, 1 μm² cross-section









Pattern C width = X

T_{final} = 440 °C (“volts”)

Z_{0C} = 35.26 °C/W (“ohms”)

P_0= 8.24W, P_{final}=12.16W

A_C (normalized) = 58 nsec

α= 0.0025

Pattern D width = 1.48X (g_D=2g_C)

T_{final} = 225 °C (“volts”)

Z_{0D} = 23.2 °C/W (“ohms”)

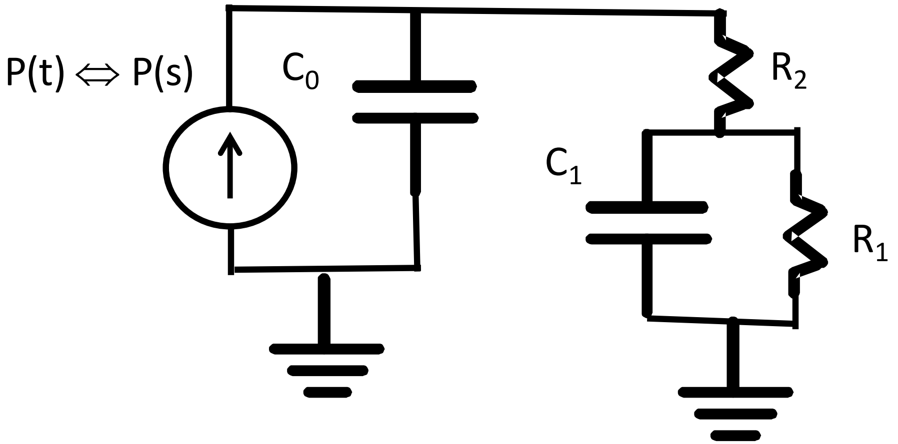
P_0= 8.24W, P_{final}=10.99W

A_D (normalized) = 46 nsec

Thermal Circuit Elements

Pattern	TLP Volts	C_0	R_2	R_1	C_1	T_{final}
C	60	1.1 nF	32.7Ω	2.52Ω	20 nF	440 °C
C	70	1.09 nF	33.9Ω	2.84Ω	21.7 nF	645 °C
D	60	1.53 nF	21.9Ω	1.33Ω	29.5 nF	225 °C

from TLP data



$\Omega \Rightarrow$ °C/W

nF $\Rightarrow$ nJ/°C

Trend for wider Pattern D ($g_D=2g_C$) is as expected

Stability Criterion, Step Current

Eq. (10), steady state:

$$T_{final} = P_{final} Z_{0th} = \frac{P_0 Z_{0th}}{1 - \alpha P_0 Z_{0th}}$$

$$\boxed{\begin{array}{ll} J = \dfrac{i}{\ell W} & R_{el} = \rho_0 \dfrac{z}{\ell W} \\ \multicolumn{2}{l}{P_0 = i^2 R_{el} = \dfrac{J^2 \rho_0 z \ell^2 W^2}{\ell W} = J^2 \rho_0 z \ell W} \end{array}}$$

electrical

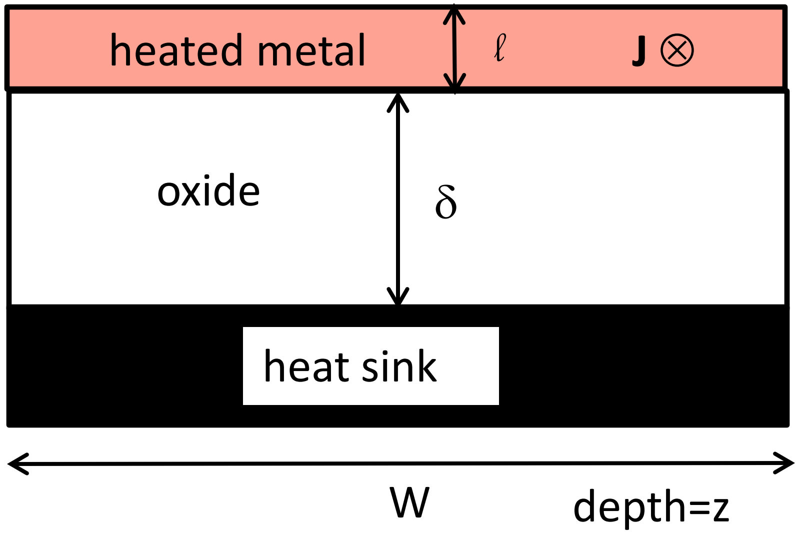
$$\boxed{Z_{0th} = \frac{1}{K_{ox}} \frac{\delta}{zW}}$$

thermal

T_{final} is finite unless

$$\alpha P_0 Z_{0th} > 1$$

or $$\boxed{\frac{\alpha J^2 \rho_0 \delta \ell}{K_{ox}} > 1}$$



D.G. Pierce (1982) derived the same condition for "unbounded" solutions: →

$$\boxed{J^2 > \frac{K_{ox}}{\alpha \rho_0 \delta \ell}}$$

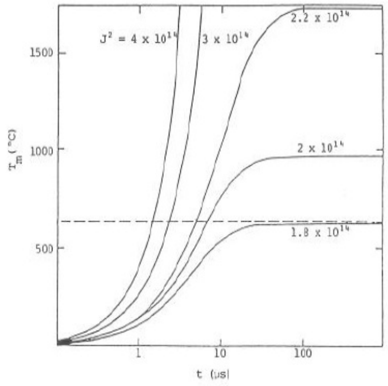
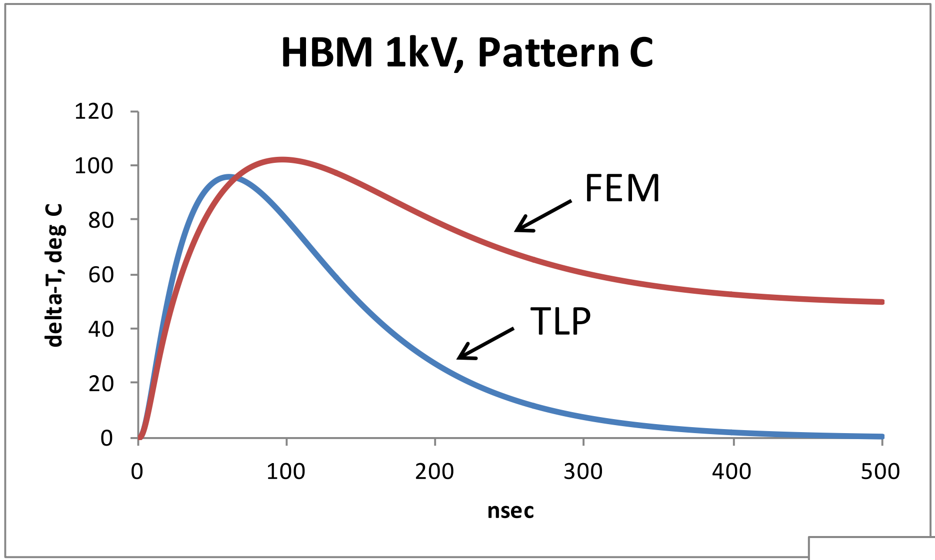


Figure 4. Temperature Versus Time for Aluminum Metallization

Pierce, EOS/ESD 1982

HBM Temperature Waveforms



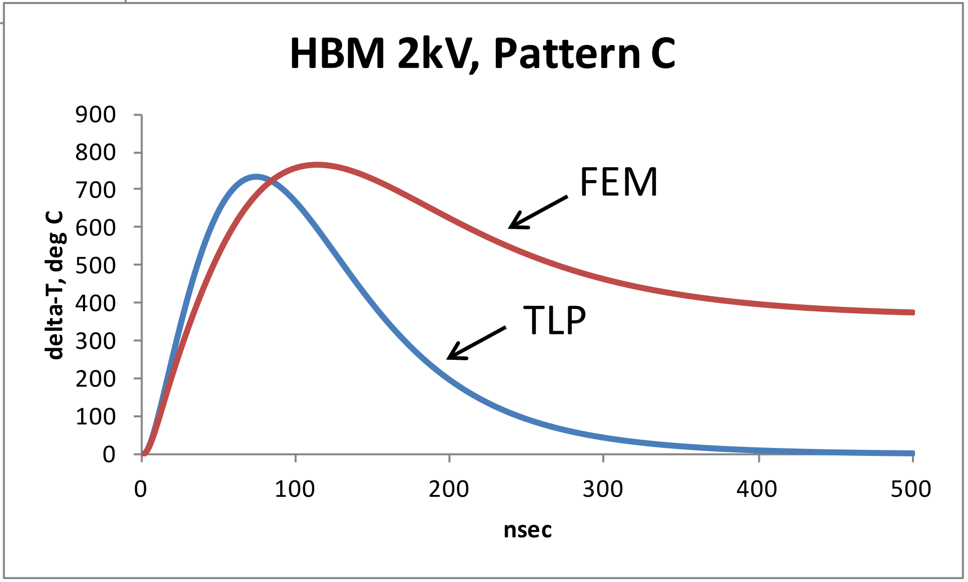
Convolve Z(t) with Human Body Model $P_0(t)$ function and solve feedback equation for self-consistent T(t) in Excel

T_{max} is similar despite the ultimately “capacitive” FEM Z(t)

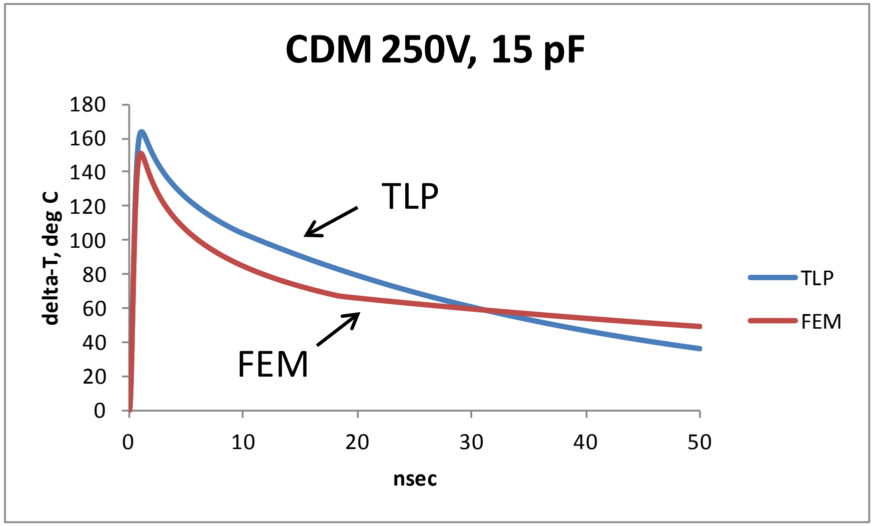
For 1kV HBM,

$$P_0(t) = \frac{1040}{201}\left[-2e^{-t/4} + e^{\frac{\sqrt{201}-15}{60}t} + e^{\frac{\sqrt{201}+15}{60}t}\right]$$

$P_{0\text{-}2kV}(t)=4P_{0\text{-}1kV}(t)$ but T_{max} is higher due to positive feedback effect



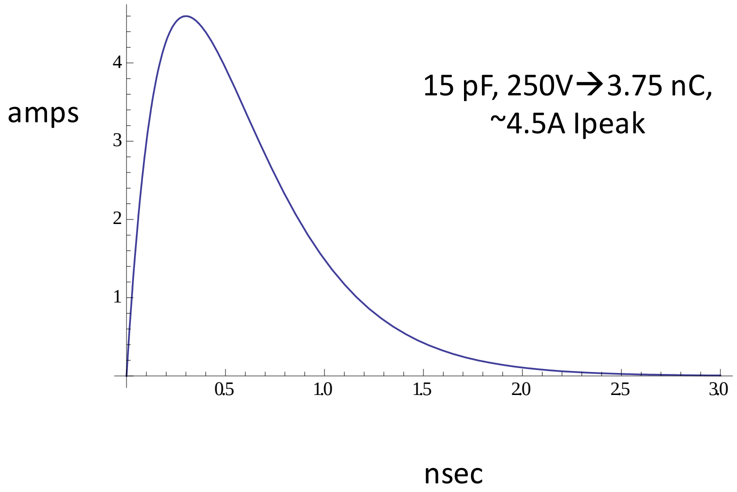
CDM Temperature Waveforms



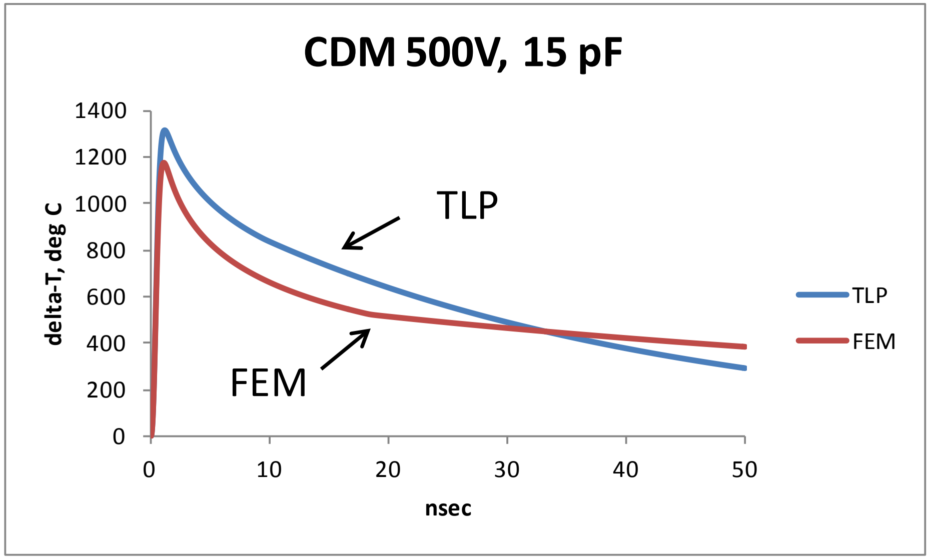
Using Z(t) for Pattern C, 1 μm^2 Cu
Excel calculations

At 500V (I_{peak}=9A), feedback pushes Cu metal temperature beyond the melting point (1085 °C) for a few nsec

CDM current waveform:



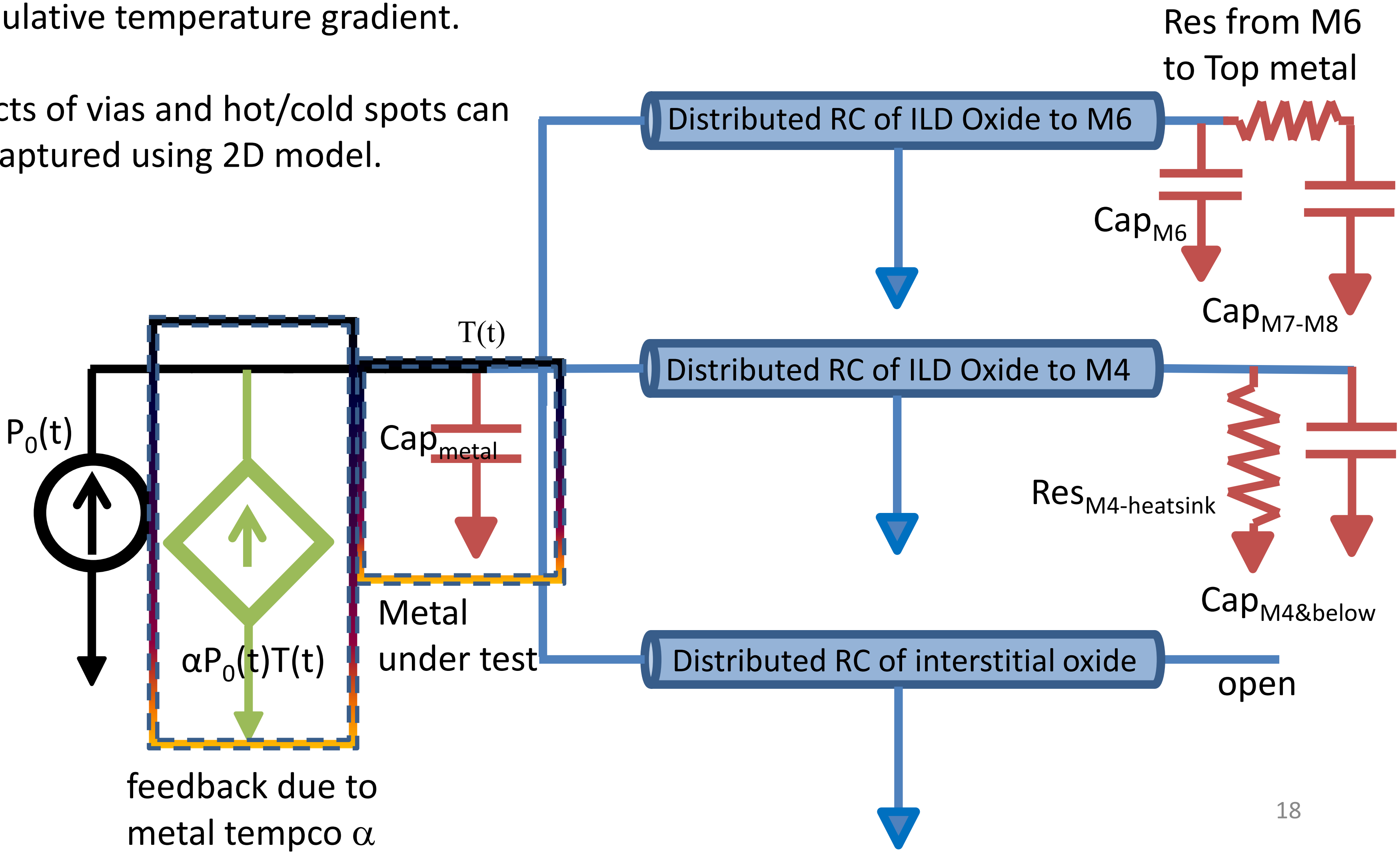
15 pF, 250V→3.75 nC,
~4.5A Ipeak



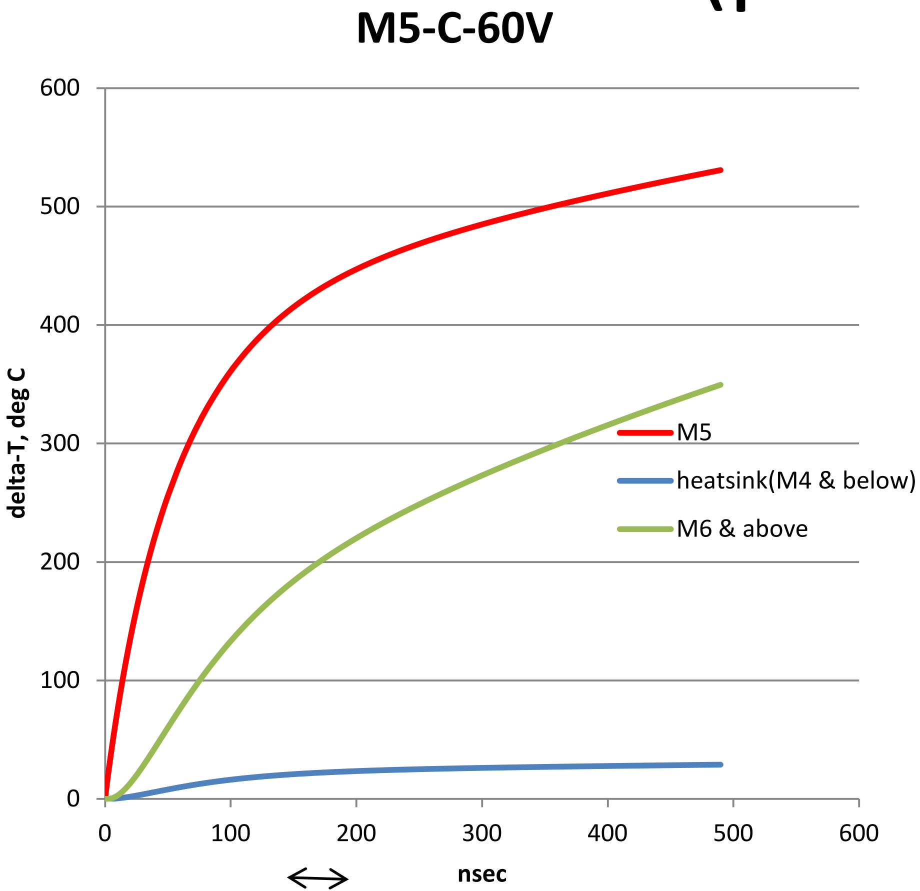
1D representation of heat flow

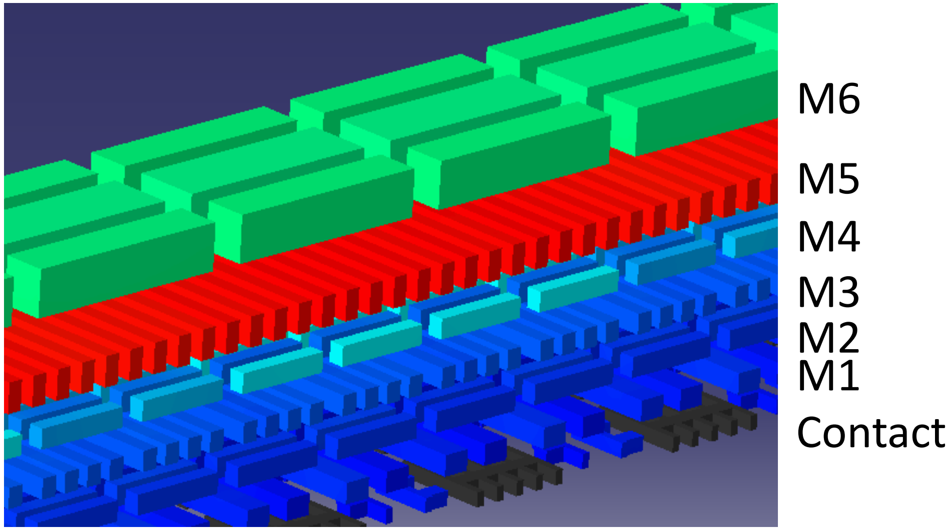
1D SPICE-like circuit model captures cumulative temperature gradient.

Effects of vias and hot/cold spots can be captured using 2D model.

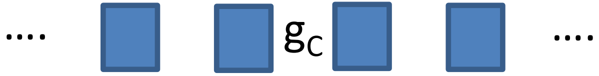


Results : FEM vs 1D model, step response (pattern C)





Close-up of metal after 200 nsec ↑

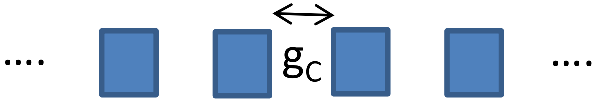


Pattern C width = X
Power: 8.44W

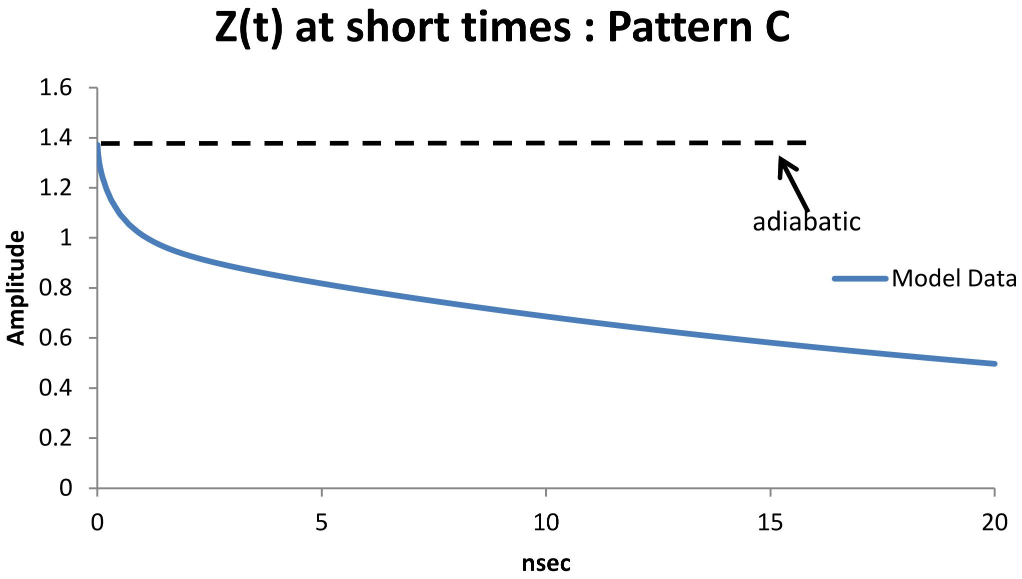
The temperature profile of M6 & above and M4 & below of the 1D model matches closely with FEM (see slide 7).

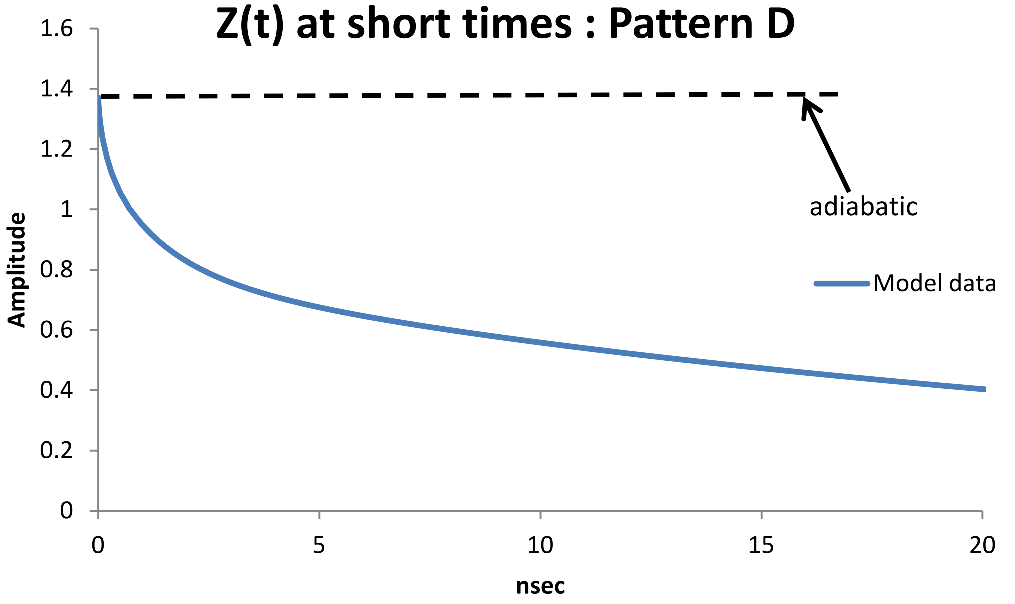
Impulse Response

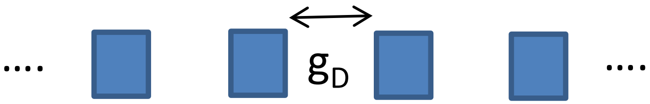
From SPICE-like circuit model, no feedback



Pattern C width = X


Z(t) at short times : Pattern C

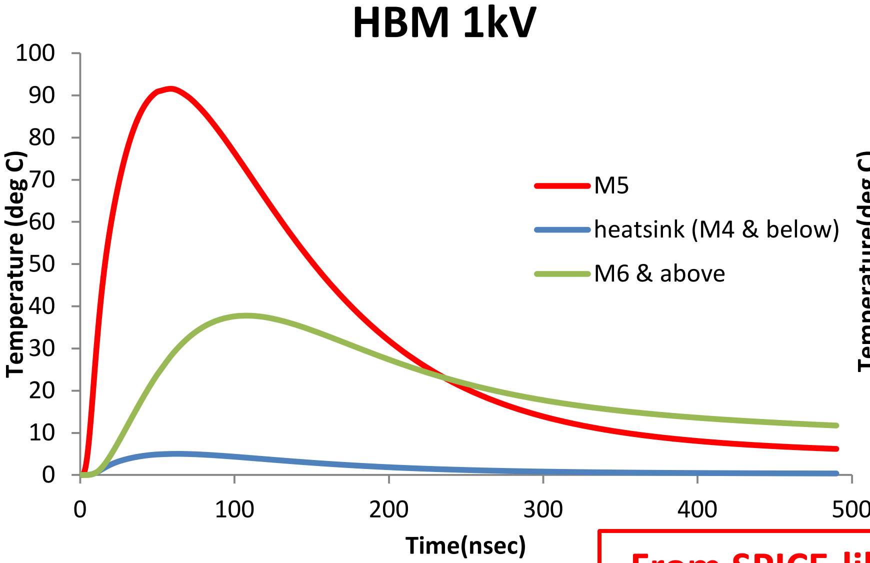

Z(t) at short times : Pattern D



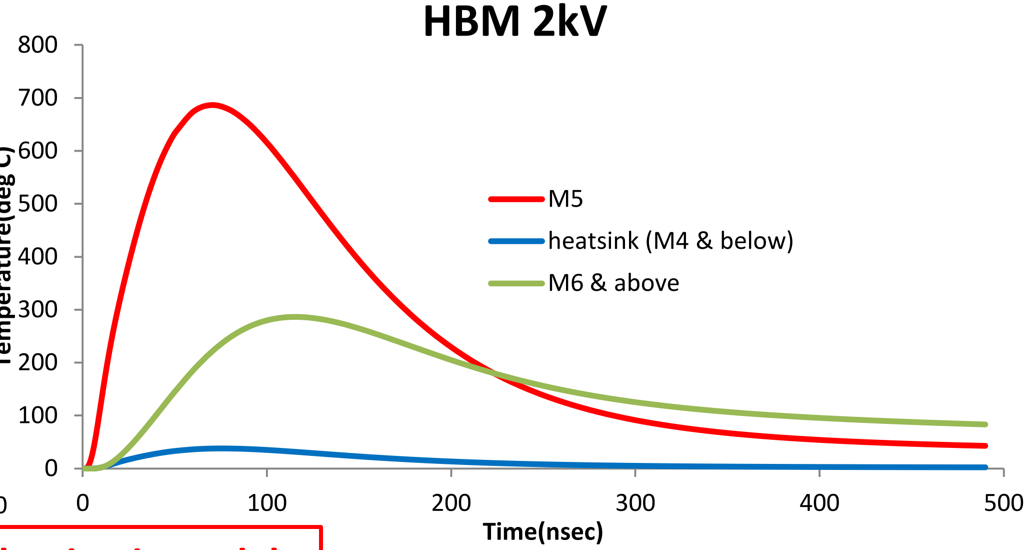
Pattern D width = 1.48X (g_D=2g_C)

See slide 7 for derivation from step

CDM & HBM response: Pattern C

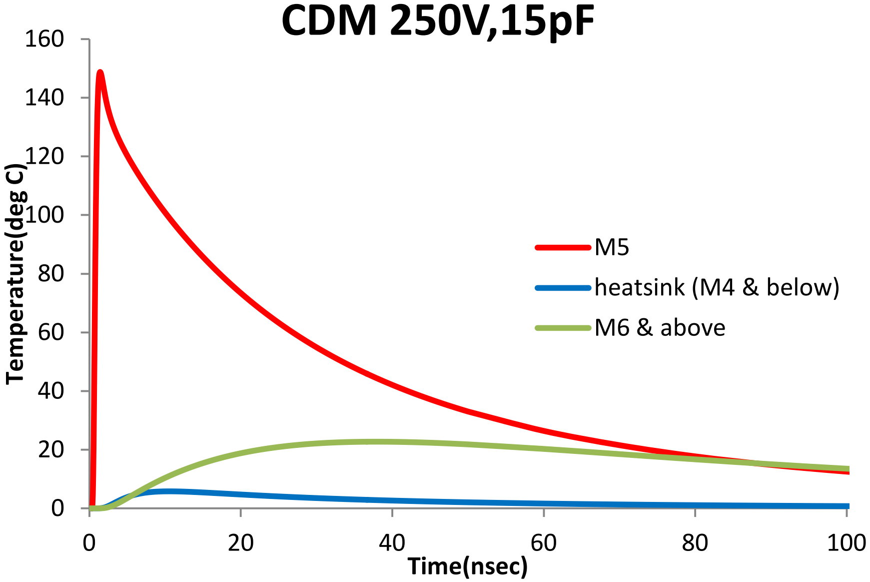


HBM 1kV

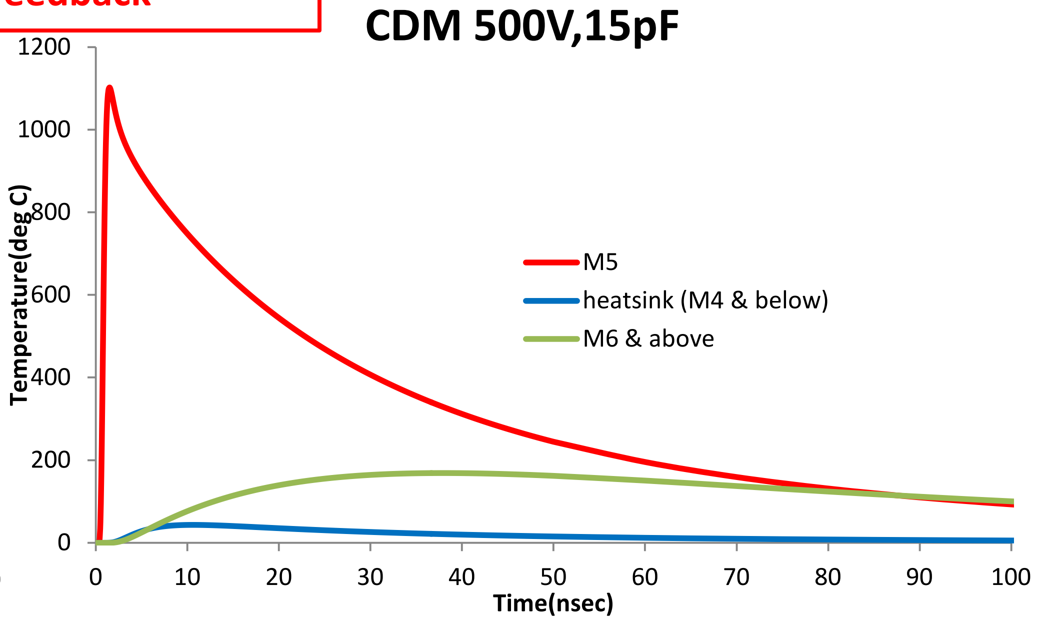


HBM 2kV

From SPICE-like circuit model, with feedback



CDM 250V,15pF



CDM 500V,15pF

Conclusions

- Feedback model for metal heating presented
    - Self-consistent T(t) expression from thermal Ohm's Law and α
        - Positive feedback from pure current source
        - Negative feedback from pure voltage source
            - Electrical source/load impedance determines net feedback
- Thermal impulse response $Z(s) \Leftrightarrow Z(t)$ is central to solving for T(t)
    - **Pre-silicon:** finite element modeling (FEM) or SPICE-like circuit model
        - Differentiate response to heat step to get Z(t)
    - **Post-silicon:** Transmission Line Pulse (TLP) measurements
        - Measure T(t) and input power P(t)
            - Maps to 5-element R-C model for each waveform
            - Add simple "heat sheath" model for $0<t<10$ nsec
                - Meshes nicely with TLP data
- ESD predictions in Excel using Z(t) and convolution software
    - Convolve Z(t)*P(t), solve for T(t) for HBM and CDM ESD conditions
        - 1 μm^2 Cu x-section gives $T_{max}<800^\circ C$ for 2kV HBM
        - But 500V CDM (7.5nC) melts Cu with $T_{max} \approx 1200\text{-}1300^\circ C$
            - Brief event; should re-solidify but with material changes
        - Strong effect of positive feedback seen for higher ESD voltages
    - SPICE-like circuit model agrees