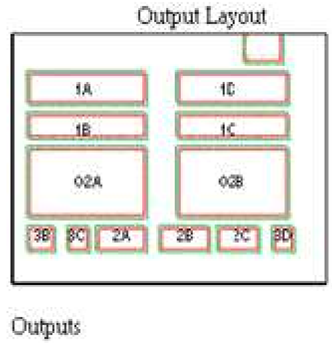
3D Transient Temperature Rise Interactions in DMOS

http://www.leapcad.com/Other_Tech/IC_DMOS_3D_Transient_Temperature_-_Greens.mcd

Problem:
Determine the transient temperature rises of an Power Integrated Circuit for multiple rectangular DMOS (two dimensional surface heat sources) from some ambient temperature, Tambient.



Solution:
The method is to create Rectangular Green's Functions for an array of rectangular DMOS outputs.

Given Parameters:
The Area of the die, A. The die and pedestal thickness.
Specifications for each output are vectors that define: Peak power (watts) and fall time (us) for the power transient.
The functional form for these power transients.

The dimensions of the outputs are the width,w and the height, h of the DMOS. Location on the DMOS on the die are given in terms of the x and y spacing between outputs, gx and gy. The variables gx and gy are used to replicate the same size outputs separated by gx and gy.

The Greens functions are expressed in terms of x and y coordinates of the left right edge of the DMOS, Lx and Ly. Lx and Ly can be composed from combinations of width, heights and spacings.

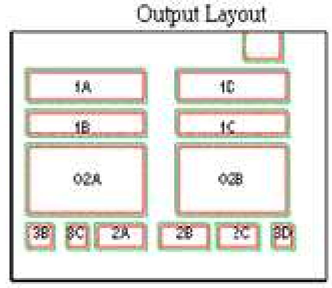
The nonlinearity of the heat conductivity is compensated by a Kirchoff transformation.

The final solution is to sum and plot the 2D thermal responses of the individual DMOS.

3D Transient Temperature Rise Interactions in DMOS

[3D Transient Temp - Greens DMOS.MCD] $Area_{dmos} := 1211 \cdot mil^2$

Output Layout



Outputs

Arrays: DMOS Power and Layout Coordinates:

Peak Snub Power (Ppk), Fall Time (Tf), Time End (us), Rds_O2A.
Layout width (w), spacing (g), heigth (h), rectangle Lx, Ly edge,

Peak Snub,Ppk:3B,O2A,1B,1A 3D,O2B,1C,1D 3C,2A,2B,2C,DMOS

$Ppk := (5\ \ 0\ \ 33\ \ 33\ \ 10\ \ 0\ \ 53.7\ \ 33\ \ 9\ \ 11\ \ 10\ \ 9\ \ 35.6)^T \cdot watt$

$T_{fs} := (2.2\ \ 2.7\ \ 2.7\ \ 2.7\ \ 2.7\ \ 0.88\ \ 1.8\ \ 2\ \ 2\ \ 2\ \ 2\ \ 2\ \ 2)^T \cdot 10^{-3}$

$T_{amb} := 137$ $time_{end\mu s} := 200$ $Rds\_O2A := 0.1$ $T_{dly} := 110 \cdot 10^{-6}$

Check ΔT with Output6

$w_{12} := \sqrt{Area_{dmos}}$ $gx_{12} := 0 \cdot mil$ $Lx_{12} := 190 \cdot mil$

$h_{12} := \sqrt{Area_{dmos}}$ $gy_{12} := 5.3 \cdot mil$ $Ly_{12} := 146.3 \cdot mil$ $A_{die} := 140 \cdot 160 mil^2$

Left Outputs Layout

3B:	$w_0 := 21.1 \cdot mil$	$gx_0 := 0 \cdot mil$	$Lx_0 := gx_0$	$h_0 := 22 \cdot mil$	$gy_0 := 5.8 \cdot mil$	$Ly_0 := gy_0$
02A:	$w_1 := 103 \cdot mil$	$gx_1 := 0 \cdot mil$	$Lx_1 := gx_1$	$h_1 := 54.3 \cdot mil$	$gy_1 := 33 \cdot mil$	$Ly_1 := gy_1$
1B:	$w_2 := w_1$	$gx_2 := 0 \cdot mil$	$Lx_2 := gx_2$	$h_2 := 22.6 \cdot mil$	$gy_2 := 3.2 \cdot mil$	$Ly_2 := Ly_1 + h_1 + gy_2$
1A:	$w_3 := w_1$	$gx_3 := 0 \cdot mil$	$Lx_3 := gx_3$	$h_3 := 22.6 \cdot mil$	$gy_3 := 5.3 \cdot mil$	$Ly_3 := Ly_2 + h_2 + gy_3$

Right Outputs Layout

3D:	$w_4 := 21.1 \cdot mil$	$gx_4 := 22.9 \cdot mil$	$Lx_4 := 211.9 \cdot mil$	$h_4 := 22 \cdot mil$	$gy_4 := 5.8 \cdot mil$	$Ly_4 := gy_4$
02B:	$w_5 := 103 \cdot mil$	$gx_5 := 22.9 \cdot mil$	$Lx_5 := Lx_1 + w_1 + gx_5$	$h_5 := 54.3 \cdot mil$	$gy_5 := 33 \cdot mil$	$Ly_5 := gy_5$
1C:	$w_6 := w_1$	$gx_6 := 22.9 \cdot mil$	$Lx_6 := Lx_2 + w_2 + gx_6$	$h_6 := 22.6 \cdot mil$	$gy_6 := 3.2 \cdot mil$	$Ly_6 := Ly_5 + h_5 + gy_6$
1D:	$w_7 := w_1$	$gx_7 := 22.9 \cdot mil$	$Lx_7 := Lx_3 + w_3 + gx_7$	$h_7 := 22.6 \cdot mil$	$gy_7 := 5.3 \cdot mil$	$Ly_7 := Ly_6 + h_6 + gy_7$

Mid Bottom Outputs Layout

3C	$w_8 := 23 \cdot mil$	$gx_8 := 0 \cdot mil$	$Lx_8 := 31.2 \cdot mil$	$h_8 := 22 \cdot mil$	$gy_8 := 5.8 \cdot mil$	$Ly_8 := 5.8 \cdot mil$
2A	$w_9 := 46 \cdot mil$	$gx_9 := 0 \cdot mil$	$Lx_9 := 58.6 \cdot mil$	$h_9 := 22 \cdot mil$	$gy_9 := 5.8 \cdot mil$	$Ly_9 := 5.8 \cdot mil$
2B	$w_{10} := 46 \cdot mil$	$gx_{10} := 0 \cdot mil$	$Lx_{10} := 111.3 \cdot mil$	$h_{10} := 22.7 \cdot mil$	$gy_{10} := 5.8 \cdot mil$	$Ly_{10} := 5.8 \cdot mil$
2C	$w_{11} := 42.3 \cdot mil$	$gx_{11} := 0 \cdot mil$	$Lx_{11} := 161.6 \cdot mil$	$h_{11} := 22.7 \cdot mi$	$g_{11} := 5.8 \cdot mil$	$Ly_{11} := 5.1 \cdot mil$

Material Constants: Silicon, Aluminum, Pedestal

Thermal Conductivities Heat Capacity, cp, Thermal Diffusivity, D

$cond\_silicon_{avg} := 0.8 \cdot \frac{watt}{cm}$ $k := cond\_silicon_{avg}$ $z_j := 1.55 \cdot \mu m$ $cond\_si\_500C := 0.41 \cdot watt \cdot cm^{-1}$

$cp\_si := 1.9 \cdot watt \cdot sec \cdot cm^{-3}$ $Ksi := 0.87 \cdot cm^2 \cdot sec^{-1}$ $c\_ped := 1.5 \cdot cp\_si$ $T_{ambK} := T_{amb} + 273$

Metal Parameters: Aluminum characteristic thermal length, λ ~ 25 - 200um. Lines > λ are thermally "long".

$cp\_al := 0.637 \cdot cal \cdot cm^{-3}$ $k_{al} := 3.98 \cdot \frac{watt}{}$ $th_{al} := 2 \cdot mil$ $\lambda_{therm\_al} := 100 \cdot \mu m$

$\rho m\_al := 2.7 \cdot g \cdot cm^{-3}$ $C\theta_{al} := \overrightarrow{\left(cp\_al \cdot w \cdot \frac{h}{2} \cdot th_{al}\right)}$ $R\theta_{al} := \overrightarrow{\left[\lambda_{therm\_al} \cdot \left(k_{al} \cdot w \cdot th_{al}\right)^{-1}\right]}$ $\tau_{\theta\_al} := \overrightarrow{\left(R\theta_{al} \cdot C\theta_{al}\right)}$

$K_{300} := 1.42 \cdot \frac{watt}{cm}$ $k_{tong}(T) := 1.5486 \cdot \left(\frac{T}{300}\right)^{\frac{-4}{3}} \cdot \frac{watt}{cm}$ $\rho Cp(T) := 1.574 \cdot \left(\frac{T}{300}\right)^{0.1} \cdot \frac{joule}{cm^3}$

$D_{siavg} := \frac{cond\_silicon_{avg}}{cp\_si}$ $D_{si} := \frac{k_{tong}\left(T_{ambK}\right)}{\rho Cp\left(T_{ambK}\right)}$ $k_{ped} := 2 \cdot \frac{watt}{cm}$ $DTDo(Tk) := \left(\frac{Tk}{T_{ambK}}\right)^{\frac{-4}{3} - 0.1} \cdot \frac{cm^2}{sec}$

$cp_{LaRosa} := 1.638 \cdot watt \cdot sec \cdot cm^{-}$ $S_{LaRosa}(T) := cp_{LaRosa} \cdot \left[1 + 1.106 \cdot 10^{-3} \cdot (T - 300) - 1.33 \cdot 10^{-6} \cdot (T - 300)^2\right]$

One Dimensional Thermal Impedance Vector Function, Zθ, for Die Mount and Pedestal. Device Power Waveforms

$th_{die} := 14 \cdot mil \quad A_{dmos} := h_1 \cdot w_1 \quad R\theta_{die} := \frac{th_{die}}{k_{tong}(T_{ambK}) \cdot A_{dmos} \cdot 1.4} \quad C\theta_{die} := S_{LaRosa}(T_{ambK}) \cdot th_{die} \left(\frac{A_{dmos} + A_{die}}{2} \right.$

$th_{ped} := 50 \cdot mil \quad R\theta_{ped} := th_{ped} \cdot (k_{ped} \cdot 3A_{die})^{-1} \quad C\theta_{ped} := c\_ped \cdot th_{ped} \cdot 3A_{die}$

$Z\theta_{die}(t) := R\theta_{die} \cdot \left(1 - e^{\frac{-t \cdot sec}{R\theta_{die} \cdot C\theta_{d}}} \right. \quad Z\theta_{ped}(t) := R\theta_{ped} \cdot \left(1 - e^{\frac{-t \cdot sec}{R\theta_{ped} \cdot C\theta_{ped}}} \right) \quad Z\theta_{al}(t) := \overrightarrow{\left[R\theta_{al} \cdot \left(1 - e^{\frac{-t \cdot sec}{\tau_{\theta\_al}}} \right) \right]}$

$$Z\theta_{pkg}(t) := Z\theta_{die}(t) + Z\theta_{ped}(t)$$

DMOS Output 6 Load Waveforms and DMOS Case 11 from FE Simulation

$T_{snub} :=$ READPRN("Snub33W.TWP") $P_{snub} :=$ READPRN("SnubPwr.prn") $P_{1C} :=$ READPRN("DMOS1C-Case11.dat")

$P_{pk} := \left(P_{snub}^{\langle 1 \rangle} \right)_3 \cdot watt \quad P_{tri}(t, n) := \Phi(t - T_{dly}) \cdot \left(1 - \frac{t - T_{dly}}{T_{fs_n}} \right) \quad N := 30 \quad i := 0 .. 26 \quad n := 0 .. N \quad tt_n := \frac{P_{snub_{12,0}} \cdot n}{N}$

$P_{htr}(t) := \left[(8 - 4.5) \cdot \exp\left(\frac{-t}{2 \cdot 0.001} \right) + 4.5 \right]^2 \cdot Rds\_O2A \cdot watt \quad P_{load}(t, n) := Ppk_n \cdot P_{tri}(t, n) + \left(\overrightarrow{(\neg Ppk)} \right)_n \cdot P_{htr}(t)$

Solution for Green's Function to Transient Temperature Equation for Rectangle

Surface Source Model Predicts higher temp and faster transients.
For x, sources have edge Lox and width W. For y, Loy and height H.

$$G(x, L_{ox}, W, y, L_{oy}, H, \tau) := \frac{1}{4 \cdot W \cdot H} \cdot \left(erf\left(\frac{-L_{ox} + x \cdot mil}{2 \cdot \sqrt{D_{si} \cdot \tau \cdot sec}} \right) + erf\left(\frac{L_{ox} + W - x \cdot mil}{2 \cdot \sqrt{D_{si} \cdot \tau \cdot sec}} \right) \right) \cdot \left(erf\left(\frac{-L_{oy} + y \cdot mil}{2 \cdot \sqrt{D_{si} \cdot \tau \cdot sec}} \right) + erf\left(\frac{L_{oy} + H - y \cdot mil}{2 \cdot \sqrt{D_{si} \cdot \tau \cdot sec}} \right) \right)$$

$a := w_{12} \quad b := h_{12} \quad G_{S6}(x, y, \tau) := G\left(x, L_{x_{12}}, a, y, L_{y_{12}}, b, \tau\right) \quad PSources(x, y, t, \tau) := P_{pk} \cdot P_{tri}(t, 12) \cdot G_{S6}(x, y, t - \tau)$

Greens Transient Temperature Rise for Sources, ΔTo

$ISqk\rho Cp := \left(\sqrt{\pi \cdot k_{tong}(T_{ambK}) \cdot \rho Cp(T_{ambK})} \right)^{-1} \quad ISqk\rho Cp := \left(\sqrt{\pi \cdot k_{tong}(T_{ambK}) \cdot \rho Cp(273 + 180)} \right)^{-1}$

$$\Delta T_{OS}(x, y, z, t) := ISqk\rho Cp \cdot \int_0^t [(t - \tau) \cdot sec]^{\frac{-1}{2}} \cdot \frac{1}{2} \cdot \left[\exp\left[\frac{-(z \cdot mil - z_j)^2}{4 \cdot D_{si} \cdot (t - \tau) \cdot sec} \right] + \exp\left[\frac{-(z \cdot mil + z_j)^2}{4 \cdot D_{si} \cdot (t - \tau) \cdot sec} \right] \right] \cdot PSources(x, y, t, \tau) \, d\tau \cdot sec$$

$$\Delta T_o(x, L_x, W, y, L_y, H, z, t, n) := ISqk\rho Cp \cdot \int_0^t \frac{\frac{1}{2} \cdot \left[\exp\left[\frac{-(z \cdot mil - z_j)^2}{4 \cdot D_{si} \cdot (t - \tau) \cdot sec} \right] + \exp\left[\frac{-(z \cdot mil + z_j)^2}{4 \cdot D_{si} \cdot (t - \tau) \cdot sec} \right] \right]}{[(t - \tau) \cdot sec]^{\frac{1}{2}}} \cdot P_{load}(t, n) \cdot G(x, L_x, W, y,$$

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$$\Delta T_o(x, L_x, W, y, L_y, H, z, t, n) := ISqk\rho Cp \cdot \int_0^t \frac{\frac{1}{2} \cdot \left[\exp\left[\frac{-(z \cdot mil - z_j)^2}{4 \cdot D_{si}(t - \tau) \cdot sec} \right] + \exp\left[\frac{-(z \cdot mil + z_j)^2}{4 \cdot D_{si}(t - \tau) \cdot sec} \right] \right]}{[(t - \tau) \cdot sec]^{\frac{1}{2}}} \cdot P_{load}(t, n) \cdot G(x, L_x, W, y, L_y, H, t - \tau) \, d\tau \cdot sec$$

Remove Heat Equation Nonlinearity from Temperature Dependence of Conductivity
Kirchhoff Transformation: K, D must have value at Tamb

Tk Kirch is the Inverse of Θ, the Integral Transform of Conductivity, λsi(T)

$$\lambda_{Si}(T) := K_{300}\cdot\left(\frac{300}{T}\right)^{\frac{4}{3}} \qquad \Theta = T_s + \frac{1}{\lambda_s}\cdot\int_{Ts}^{T}\lambda(T)\,dT \qquad Tk_{Kirch34}(\Theta, T_o) := \frac{27\cdot T_o^{\,4}}{(4\cdot T_o - \Theta)^3}$$

Calculate Temperature versus Time. Find Peak Temp at Given Output

Evaluation Times: $rt := 0..\ 60 \quad Time_{rt} := \frac{15\cdot time_{end\mu s}}{700\cdot 10^6}\cdot rt \quad Time_0 := 10^{-9}$

$$T_{MDj_{rt}} := \sum_{n=6}^{6}\Delta T_o\left(\frac{L_{x_n}}{mil} + \frac{w_n}{2\cdot mil}, L_{x_n}, w_n, \frac{L_{y_n}}{mil} + \frac{h_n}{2\cdot mil}, L_{y_n}, h_n, 0, Time_{rt}, n\right)$$

$$T_{MDKj_{rt}} := \left(Tk_{Kirch34}\left(T_{MDj_{rt}} + T_{ambK}, T_{ambK}\right) - 273\right) \quad \max(T_{MDKj}) = 192.436$$

$$\text{match}(\max(T_{MDKj}), T_{MDKj}) = (13)$$

Check DMOS Output 6

Corrected Transient Temperature at midpoints, eg. DMOS Out 6, Q=12 or DMOS 1C, Q=6 $Q := 6$

$$T_{DKjs_{rt}} := \left(Tk_{Kirch34}\left(\Delta T_o\left(\frac{L_{x_Q}}{mil} + \frac{w_Q}{2\cdot mil}, L_{x_Q}, w_Q, \frac{L_{y_Q}}{mil} + \frac{h_Q}{2\cdot mil}, L_{y_Q}, h_Q, 0, Time_{rt}, Q\right) + T_{ambK}, T_{ambK}\right) - 273\right)$$

$$\max(T_{DKjs}) = 192.436$$

Compensate for Thermal Effects of Metal Runners with 1 D Thermal Impedance, Zθal for Output Q

$$\Delta Tal(\Delta T, P, Z\theta) := \Delta T\cdot\left[1 + \frac{\Delta T}{(P\cdot Z\theta)}\right]^{-1} \qquad \Delta T_{al_{rt}} := \Delta Tal\left(T_{DKjs_{rt}} - T_{amb}, P_{pk}\cdot P_{tri}(Time_{rt}, Q), Z\theta_{al}(Time_{rt})_Q\right)$$

$$T_{DKjM_{rt}} := \Delta T_{al_{rt}} + T_{amb} \qquad P_{tot_{rt}} := \sum_{n=1}^{11} Ppk_n\cdot P_{tri}(Time_{rt}, n) \qquad \max(T_{DKjM}) = 162.978$$

$$T_{3DK_{rt}} := T_{DKjM_{rt}} + P_{tot_{rt}} Z\theta_{ped}(Time_{rt}) \qquad \max(P_{tot}) = 199.955\,\text{watt} \qquad \max(T_{3DK}) = 163.476$$

Remove Heat Equation Time Nonlinearity from Temperature Dependece of Diffusivity
Time Variable, ζ, Transformation for Diffusivity
"E-T Device and Ckt Sim with thermal nonlinearity" Batty and Snowden

$$\zeta_{rt} := \int_0^{Time_{rt}}\left(\frac{\Delta T_o\left(\frac{L_{x_Q}}{mil} + \frac{w_Q}{2\cdot mil}, L_{x_Q}, w_Q, \frac{L_{y_Q}}{mil} + \frac{h_Q}{2\cdot mil}, L_{y_Q}, h_Q, 0, Time_{rt}, Q\right) + T_{ambK}}{T_{ambK}}\right)^{-1.35} dt$$

Above ΔTime Solution is the ξ domain from 0 to "time_end = 0.04" sec.

Linearize and then get solution in terms of time ζ, i.e. given a ζ sample from the transformed temperature solution, find the corresponding inverse Time value of real time. Matrix solution points, T3D and Time goes into above. Need to get inverse of transform, i.e. in terms of the above integral, want Ratio matrix, RT2ζ, to get inverse. Then real time equals ζ times T/ζ equals T.

$$RT2\zeta F(t) := \text{linterp}(\zeta, Time, t) \qquad Time\zeta_{rt} := RT2\zeta F(Time_{rt})$$

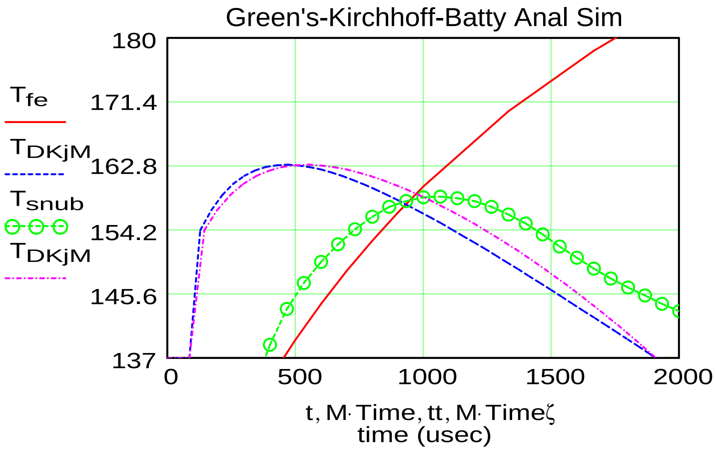
FE VERSUS ANALYTIC 3D: SIMULATION DMOS OUTPUT 6 AT 24W WITH A PEDESTAL TEMP OF 115C

$T5 := READPRN("TT24WH\sim 1.prn")$

$M := 10^6$

Time	Max Temp	Bump Temp	TSD Temp
$t := M \cdot T5^{\langle 0 \rangle}$	$T_{fe} := T5^{\langle 1 \rangle}$	$T_{bmp} := T5^{\langle 4 \rangle}$	$T_{sen} := T5^{\langle 5 \rangle}$

DMOS Out 6 FE 24W Short and Snub vs Greens ZMetal Snub



$nax(T_{DKjM}) = 162.978$

$R_{pk} := match(max(T_{3DK}), T_{3DK})$

$R_{pk} = (11)$

$\mathrm{ok}\zeta := 1000\, Time\zeta_{(R_{pk_0})}$ ■

$\mathrm{ok}\zeta =$ ■

$\mathrm{ok} := 1000\, Time_{(R_{pk_0})}$

$R_{pk3} := match(max(T_{MDKj}), T_{MDKj})$

$tpk3 := 1000 \cdot Time_{(R_{pk3_0})}$ ‹ (msec)

$tpk3 = 0.557$

Plot Spatial Thermal Response for DMOS Outputs at O2A Temp Peak

$r := 0..55$ $\quad rr := 0..37$ $\quad X_r := -10 + 5\cdot(r-1)$ $\quad Y_{rr} := -10 + 5\cdot(rr-1)$

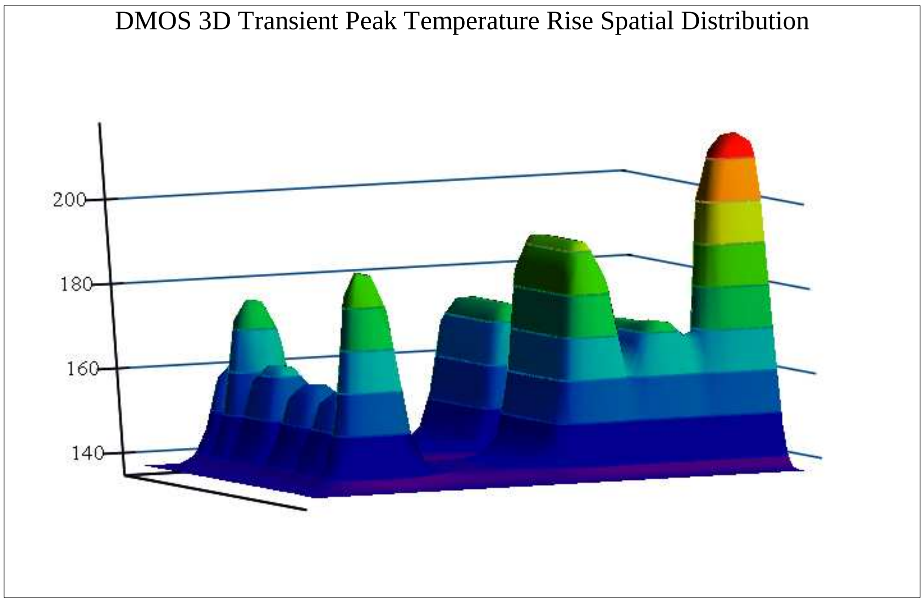
$$T_{XYj_{r,rr}} := \sum_{n=0}^{12} \Delta T_o\left(X_r, L_{x_n}, w_n, Y_{rr}, L_{y_n}, h_n, 0, tpk3\cdot10^{-3}, n\right) \quad pk3 = 0.557$$

$$T_{XYKj_{r,rr}} := \left(Tk_{Kirch34}\left(T_{XYj_{r,rr}} + T_{ambK}, T_{ambK}\right) - 273\right) \qquad \max\left(T_{MDKj}\right) = 192.436$$

$$T_{xy_{r,rr}} := Tk_{Kirch34}\left(\Delta T_{os}\left(X_r, Y_{rr}, 0, tpk3\cdot10^{-3}\right) + T_{ambK}, T_{ambK}\right) - 273$$

WRITEPRN("KTempXY00429s_DMOS") := T_{XYKj}

2 Dimensional Transient Temp Solution for Outputs (Peak Power, Fall Time) from Green's Function wtih Kirchoff

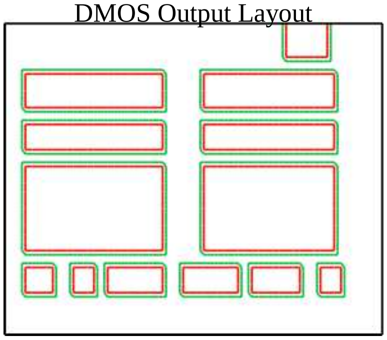


$\max\left(T_{XYKj}\right) = 215.793$

T_{XYKj}

$$PS(x,y,t) := \sum_{n=0}^{12} G\left(x, L_{x_n}, w_n, y, L_{y_n}, h_n, t\right) \quad Outputs_{r,rr} := \text{if}\left[PS\left(X_r, Y_{rr}, 10^{-20}\right) > \left(\frac{0.01}{mm}\right)^2, 1, 0\right]$$

DMOS Output Layout



Outputs

Find Peak Temp for Output 1B, ν $\quad \nu := 2$

$$Out_{r,rr} := w_\nu\cdot h_\nu\cdot G\left(X_r, L_{x_\nu}, w_\nu, Y_{rr}, L_{y_\nu}, h_\nu, 10^{-12}\right)$$

$$\max\left(\overrightarrow{\left(Out\cdot T_{XYKj}\right)}\right) = 173.962$$

What is max temp increase from other outputs?

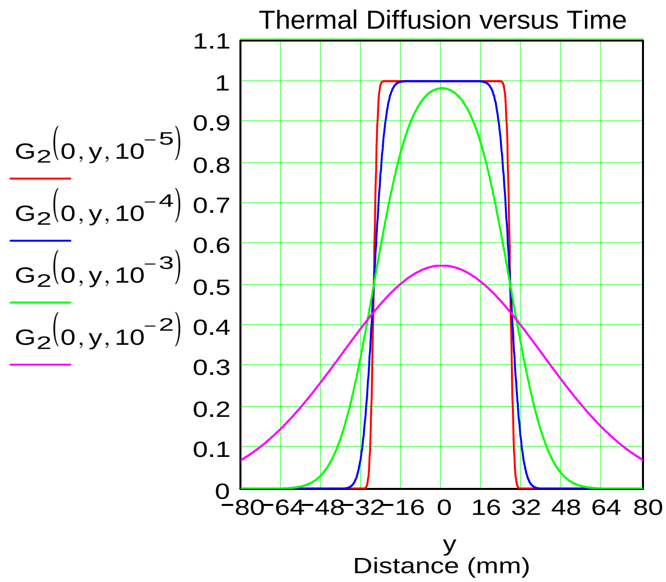
$$T_{XYj\nu_{r,rr}} := \Delta T_o\left(X_r, L_{x_\nu}, w_\nu, Y_{rr}, L_{y_\nu}, h_\nu, 10^{-12}, tpk3\cdot10^{-3}, \nu\right)$$

$$T_{XYKj\nu_{r,rr}} := \left(Tk_{Kirch34}\left(T_{XYj\nu_{r,rr}} + T_{ambK}, T_{ambK}\right) - 27\right.$$

$\max\left(T_{XYKj\nu}\right) = 173.529 \qquad 166.277 - 165.775 = 0.502$

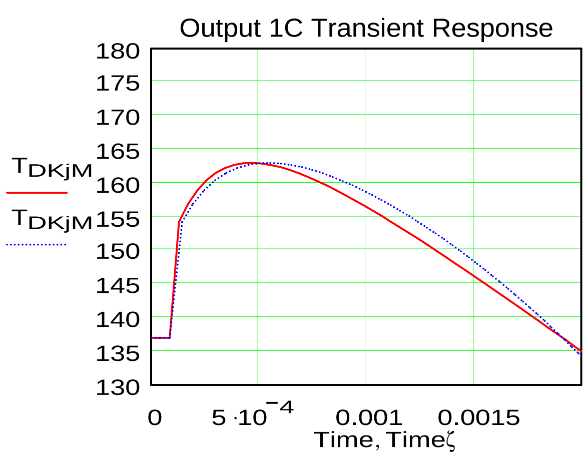
Thermal Diffusion With Time

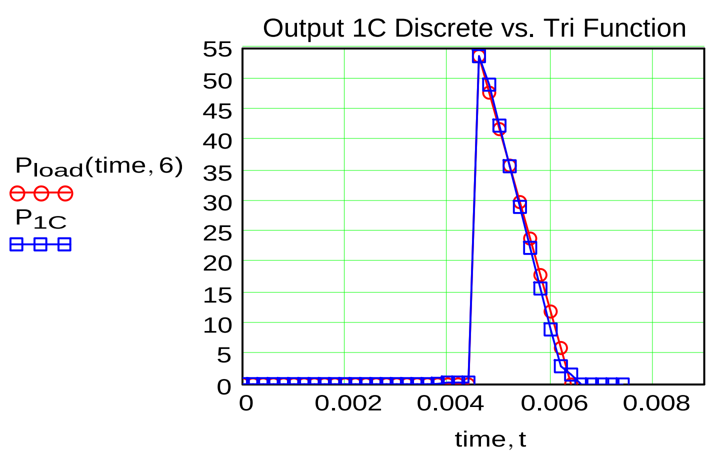
$$G_2(x,y,\tau) := \frac{1}{2}\cdot\left(\operatorname{erf}\left(\frac{\frac{h_1}{2}+y\cdot mil}{2\cdot\sqrt{D_{siavg}\cdot\tau\cdot sec}}\right)+\operatorname{erf}\left(\frac{\frac{h_1}{2}-y\cdot mil}{2\cdot\sqrt{D_{siavg}\cdot\tau\cdot sec}}\right)\right)$$



$rows(P_{1C}) = 38$ $\quad r := 0..37$ $\quad t_r := r\cdot 0.0002$ $\quad time := 0, 0.0002..0.009$ $\quad T_{dly} := 0.0046$

$$P_{tri}(t,n) := \Phi(t-T_{dly})\cdot\left(1-\frac{t-T_{dly}}{0.0018}\right) \qquad P_{load}(t,n) := Ppk_n\cdot P_{tri}(t,n)$$





$millihenry \equiv 10^{-3}\cdot henry$ $\quad usec \equiv 10^{-6}\cdot sec$ $\quad millisec \equiv 10^{-3}\cdot sec$ $\quad msec \equiv millisec$

$\mu ohm \equiv 0.000001\cdot ohm$ $\quad \mu F \equiv 0.000001\cdot farad$ $\quad \mu m \equiv 10^{-6}\cdot m$ $\quad nm \equiv 10^{-9}\cdot m$

$ms \equiv 10^{-3}\cdot sec$ $\quad mil \equiv 10^{-3}\cdot in$ $\quad mJ \equiv 10^{-3}\cdot joule$ $\quad \mu J \equiv 10^{-6}\cdot joule$

$A \equiv 10^{-8}\cdot cm$ $\quad \Omega \equiv ohm$

$L_y, H, t - \tau) \, d\tau \cdot sec$