Presented by:
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at

Using Simulation to Estimate MOSFET Junction Temperature in a Circuit Application

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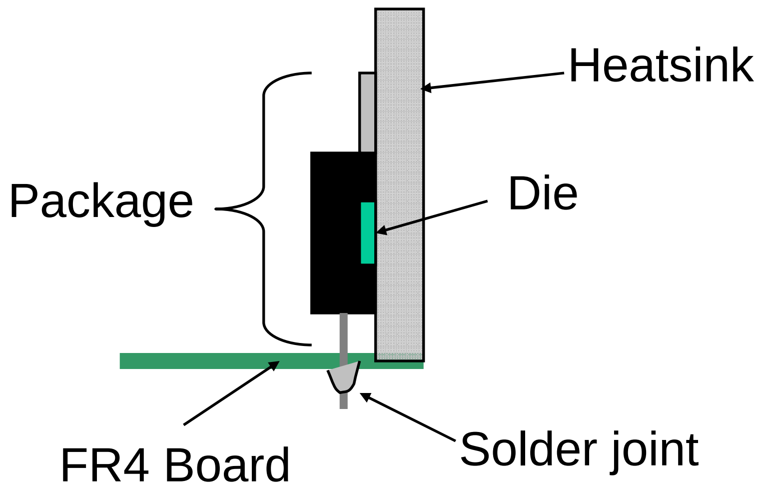
Agenda

- Definition of Electro-Thermal Simulation
- Simulation Tools and Methods
- Methods of Estimating Die Temperature
- Creating Quasi-Dynamic MOSFET Model
- Model Generation
- Example Application
- Conclusion

Electro-Thermal Simulation

- Purpose of Electro-Thermal Simulation is to predict MOSFET junction for a given application.



Electro-Thermal Simulation

- Applications
  - Solenoid drivers
  - Motor drive
  - Lighting ballast
  - DC/DC converters
  - Switch model power supplies
  - Class D amplifiers

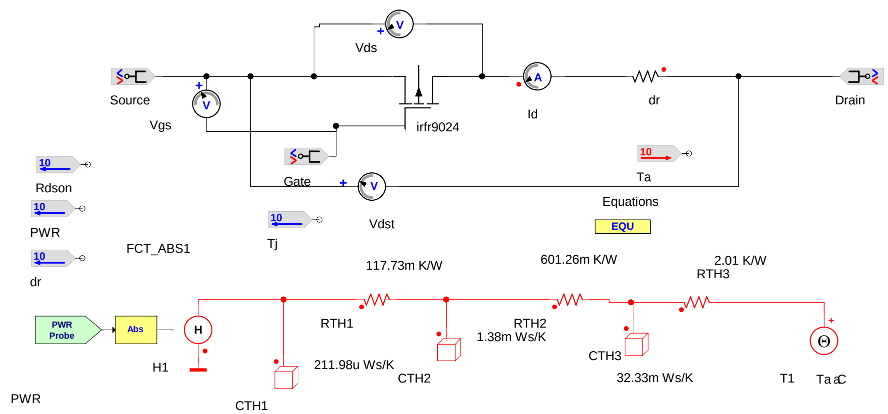
Simulation Tools and Methods

- Tools
  - Simplorer (Ansoft) - Circuit/System simulator with VHDL-AMS hardware description language
  - Saber (Synopsis) - Circuit/System simulator with VHDL-AMS and MAST hardware description languages
  - Spector (Cadence) - Circuit/System simulator with Verilog-A hardware description language
  - PSPICE (Cadence) – Defacto standard in circuit simulation.

Simulation Tools and Methods

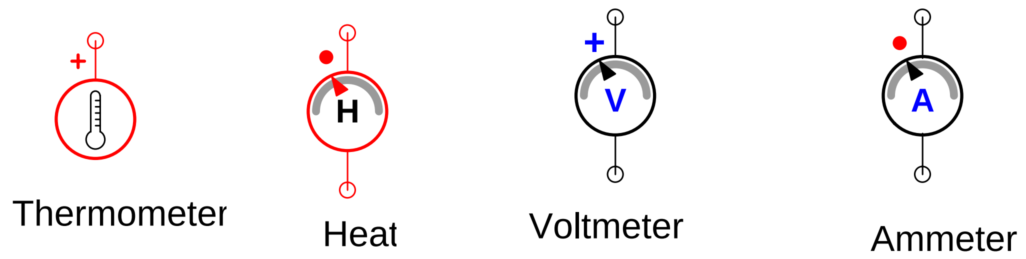
- Method
  - ❑ Implementing model in the hardware description language
  - ❑ Implementing model using equations and macro modeling

```
library ieee;  use ieee.std_logic_1164.all;
use ieee.electrical_systems.all;

entity comparator is
  port ( terminal a : electrical;
         signal d : out std_ulogic );
end entity comparator;

----------------------------------------------------------------

architecture ideal of comparator is
  constant ref_voltage : real := 5.0;
  quantity vin across a;
begin

  comparator_behavior : process is
  begin
    if vin > ref_voltage / 2.0 then
      d <= '1' after 5 ns;
    else
      d <= '0' after 5 ns;
    end if;
    wait on vin'above(ref_voltage / 2.0);
  end process comparator_behavior;

end architecture ideal;
```



Simulation Tools and Methods

- Quasi-Dynamic MOSFET model implementation
  - ❑ Macro modeling with use of linking equations
  - ❑ Using a multi domain simulator that allows for Electro-Thermal simulation.
    - Volts and Amps
    - Heat flow (Watts) and temperature



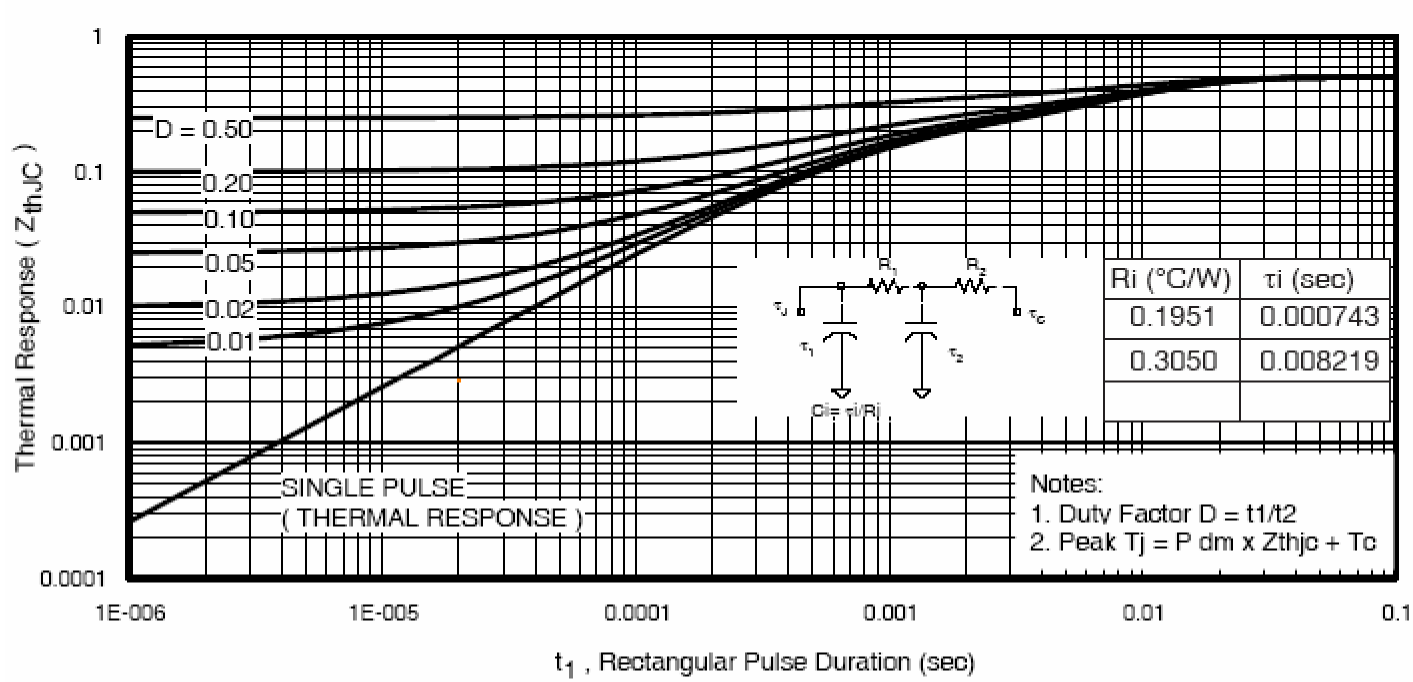
Methods of Estimating Die Temperature

- Methods of estimating MOSFET die junction temperature
  - ❑ Equation based + Thermal Impedance curve

$$P = I * V * D$$

Where:
I = average current during the conduction cycle
V = equivalent voltage across the device during the conduction cycle
D = duty cycle

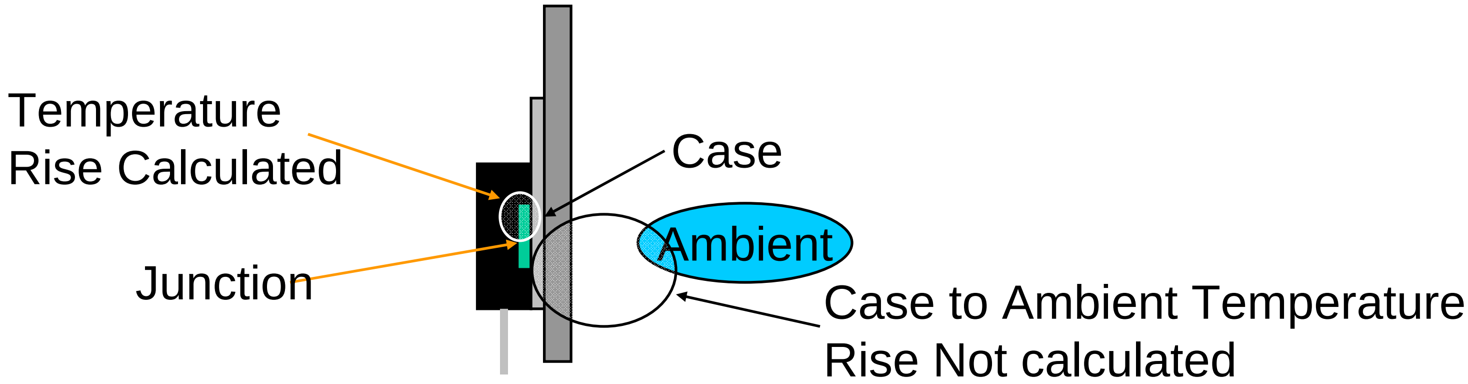
Methods of Estimating Die Temperature



- Use Power calculated with P=I*V*D
- Use pulse width and duty cycle to determine Zth (thermal impedance) from device thermal impedance curve
- Temperature rise (ΔTjunction)= Zth * P

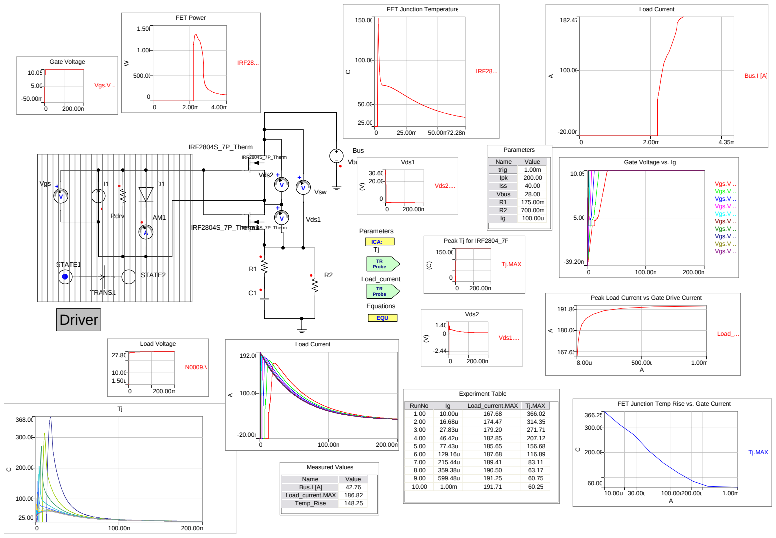
Methods of Estimating Die Temperature

- Limitations of the equation based junction temperature estimate
  - Only temperature rise from junction to case is taken into account. Neglects case to ambient temperature rise.
  - Assumes the power pulse is an ideal square edged pulse train.
  - It does not allow for transient thermal response.



Methods of Estimating Die Temperature

- **Simulator based MOSFET junction temperature estimate**
  - **Uses circuit simulation to calculate junction temperature in an application**
  - **The circuit can be arbitrary**
  - **Transient thermal response is calculated**
  - **Component parameters change with temperature**



Methods of Estimating Die Temperature

- Assumptions made for junction temperature estimates using simulation
  - No other source of heat considered (Temperature rise due to self heating only)
  - Only MOSFET $R_{DS(on)}$ and threshold voltage changes with temperature
  - Since simulation solves Ordinary Differential the junction is assumed to be a point source of heat.

Creating Quasi-Dynamic Thermal MOSFET Model

- Gathering information:
  - ❑ 25C Spice Model of MOSFET
  - ❑ Datasheet information
    - $R_{DS(on)}$ vs. Temperature curve
    - Thermal Impedance Curve with thermal RC ladder network

.SUBCKT irf1404 1 2 3 * SPICE3 MODEL WITH THERMAL RC NETWORK ************************************** * Model Generated by MODPEX * *Copyright(c) Symmetry Design Systems* * All Rights Reserved * * UNPUBLISHED LICENSED SOFTWARE * * Contains Proprietary Information * * Which is The Property of * * SYMMETRY OR ITS LICENSORS * *Commercial Use or Resale Restricted * * by Symmetry License Agreement * ************************************** * Model generated on April 2, 01 * MODEL FORMAT: SPICE3 * Symmetry POWER MOS Model (Version 1.0) * External Node Designations * Node 1 -> Drain * Node 2 -> Gate * Node 3 -> Source M1 9 7 8 8 MM L=100u W=100u .MODEL MM NMOS LEVEL=1 IS=1e-32 +VTO=3.74133 LAMBDA=0.00250986 KP=514.947 +CGSO=7.17952e-05 CGDO=1.60578e-08 RS 8 3 0.00282867 D1 3 1 MD .MODEL MD D IS=1.89845e-10 RS=0.00218742 N=1.20398 BV=40 +IBV=0.00025 EG=1.2 XTI=1.85712 TT=2.00014e-05 +CJO=5.42237e-09 VJ=2.67939 M=0.566441 FC=0.1

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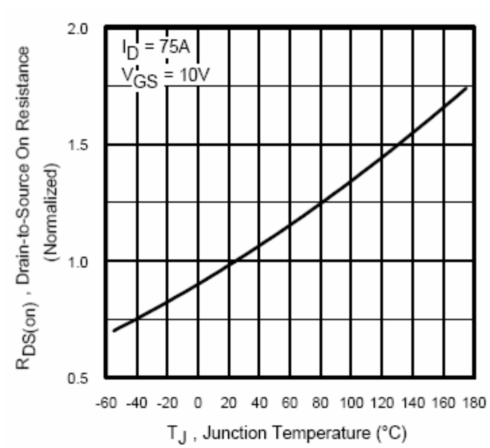
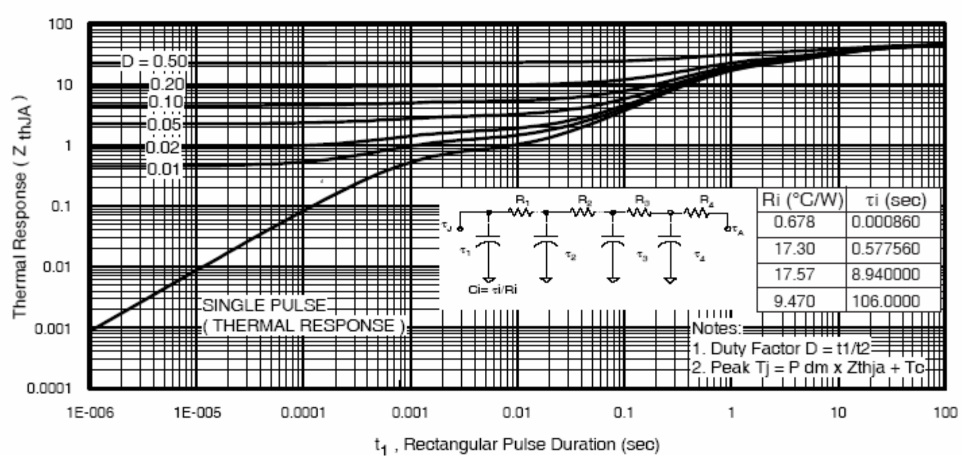
=0
e-09
)2 *
TT=0
S=1e-
'FI2 4
L 7 9
TT=0
D3 D

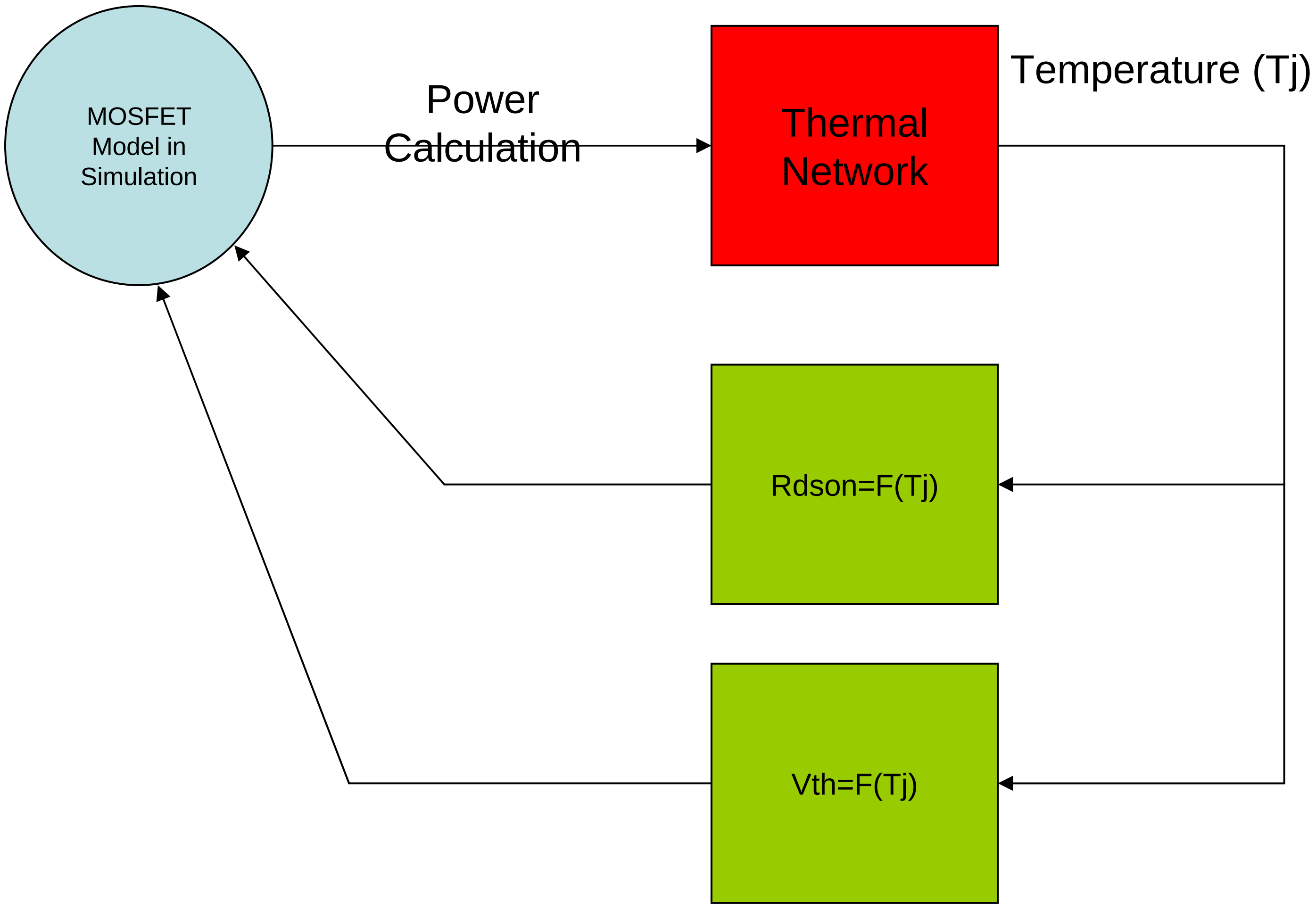




Creating Quasi-Dynamic Thermal MOSFET Model

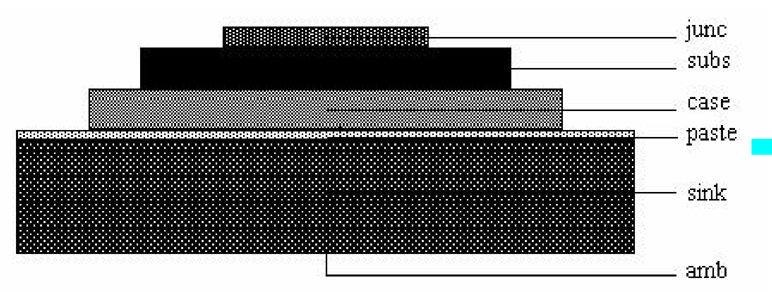
- 25C Spice Model
  - Characterized to the datasheet
  - Does not change performance characteristics as power is calculated
  - Used as base model for Quasi-Dynamic MOSFET model

Creating Quasi-Dynamic Thermal MOSFET Model

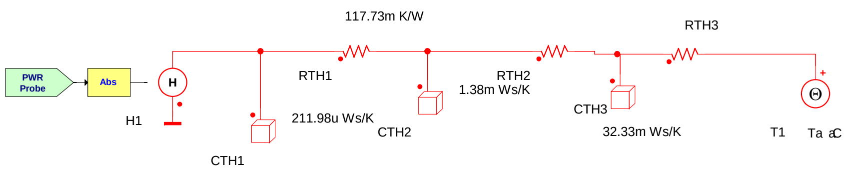


Model Generation

- Ladder Network
  - A thermal RC network used to model the dynamic thermal behavior of the package + mounting system.



Package + Mounting



Equivalent RC Ladder Network

The ladder network can be synthesized from the thermal impedance curve or is given by the MOSFET manufacturer

Model Generation

- Tying the thermal model to the 25C Spice model
  - Create the equation that represents $R_{DS(on)}$ vs. temperature

$$\frac{dRdson(Tj)}{dTj} = Rdson(25C)*(2*a*Tj+b)$$

$$dRdson = Rdson(25C)*(2*a*Tj+b)*(Tj-25)$$

← This expression gets implemented in the model

Note: a, b and c are calculated via a curve fitting routine.
The Rdson vs Temperature curve is assumed to be quadratic.

Model Generation

- Create the voltage source that represents the temperature dependence of Vth (threshold voltage)

$$Vth(Tj) = -0.007 * (Tj - 25) \longrightarrow \text{Expression used in model.}$$

The voltage source is in series with the MOSFETs gate.

Model Generation

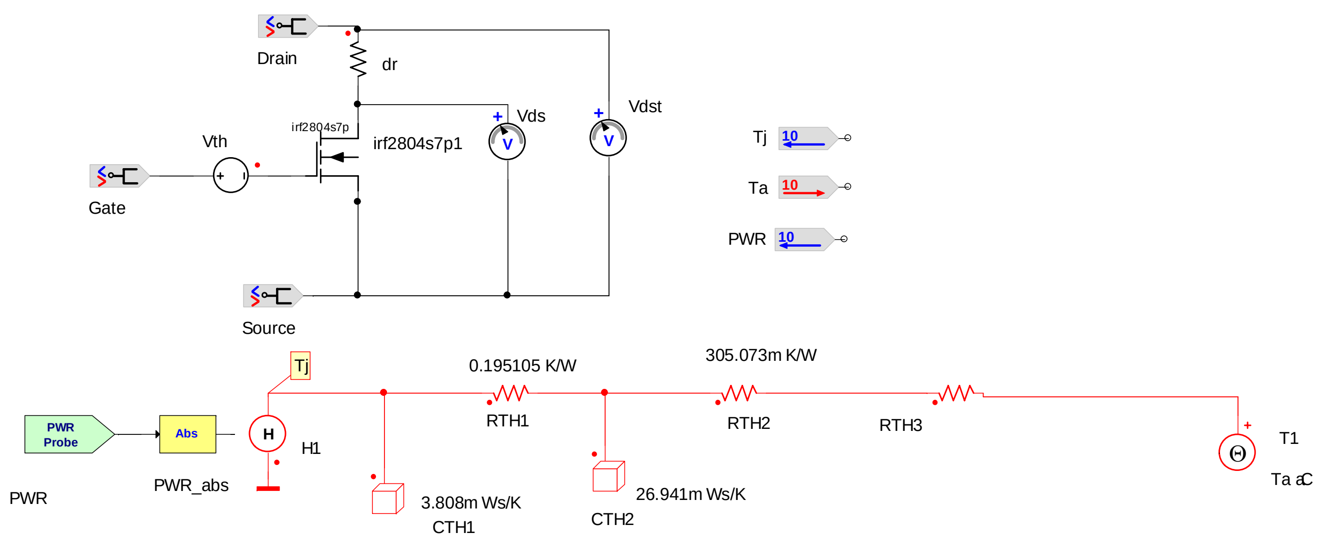
- Calculating the power in the MOSFET for use in the thermal network.

$$P = Id * Vds$$

This calculated power is the source for the thermal network.

Model Generation

- Putting it together



Equations

EQU

dt:=Tj.T-Ta

Tj:=Tj.T-273.15

if(Vds.V<0.1) {Rdson25:=abs(Vds.V/dr.I)} else {dr:=1m}

if(Vds.V<0.1) {dr:=(7.41u*Tj+3.519m)*dt*Rdson25} else {dr:=1u}

PWR:=PWR_abs.VAL

Vth:=-7m*(Tj-25)

Model Generation

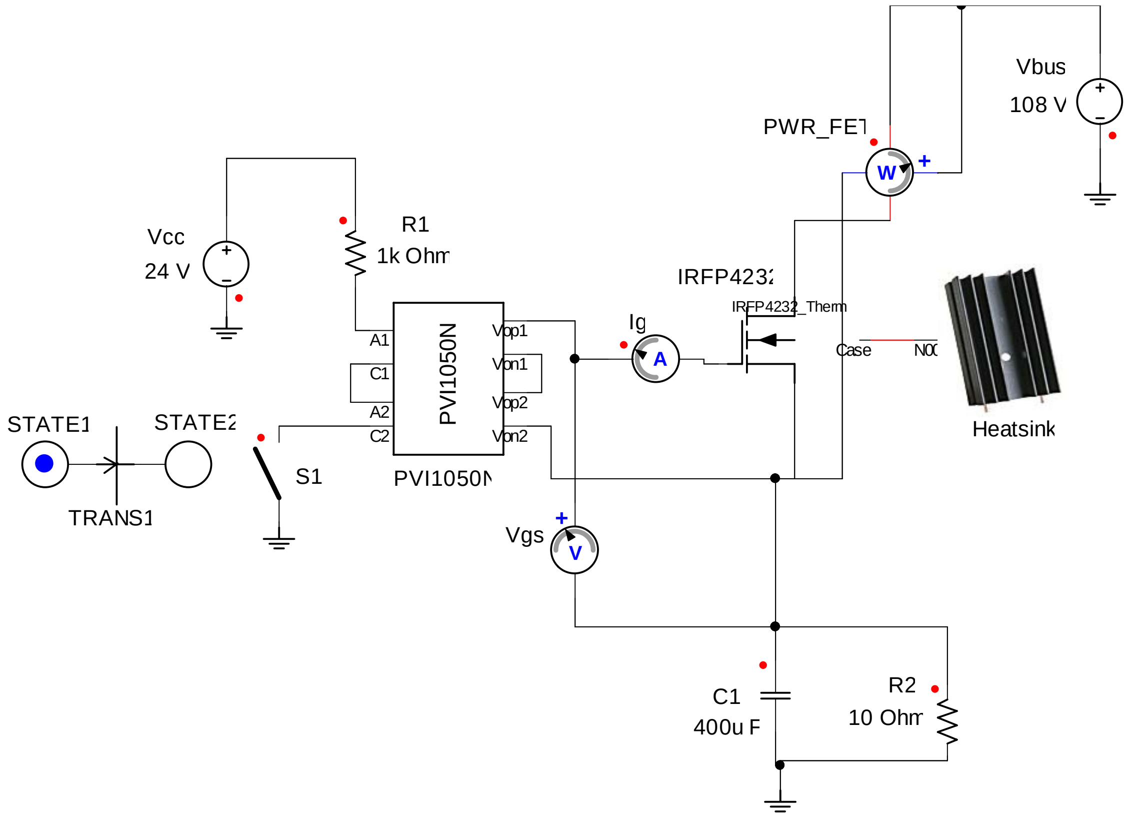
- Final model
  - 25C Spice model
  - Added voltage source Vth in gate implements Vth(Tj)
  - dr implements
  - Vds and the current in dr are used to calculate $R_{DS(on)}$ 25C
  - Vdst and the current in dr is used to calculate the total power
  - PWR_abs is used to insure that the thermal network is driven with positive power.

Example Application

- High side switch
- MOSFET being driven by a opto isolated drive
  - Very low drive current capability
- Load is capacitive
- Issue: How does driving this load effect the junction temperature of the MOSFET

Example Application

- Simulation Schematic

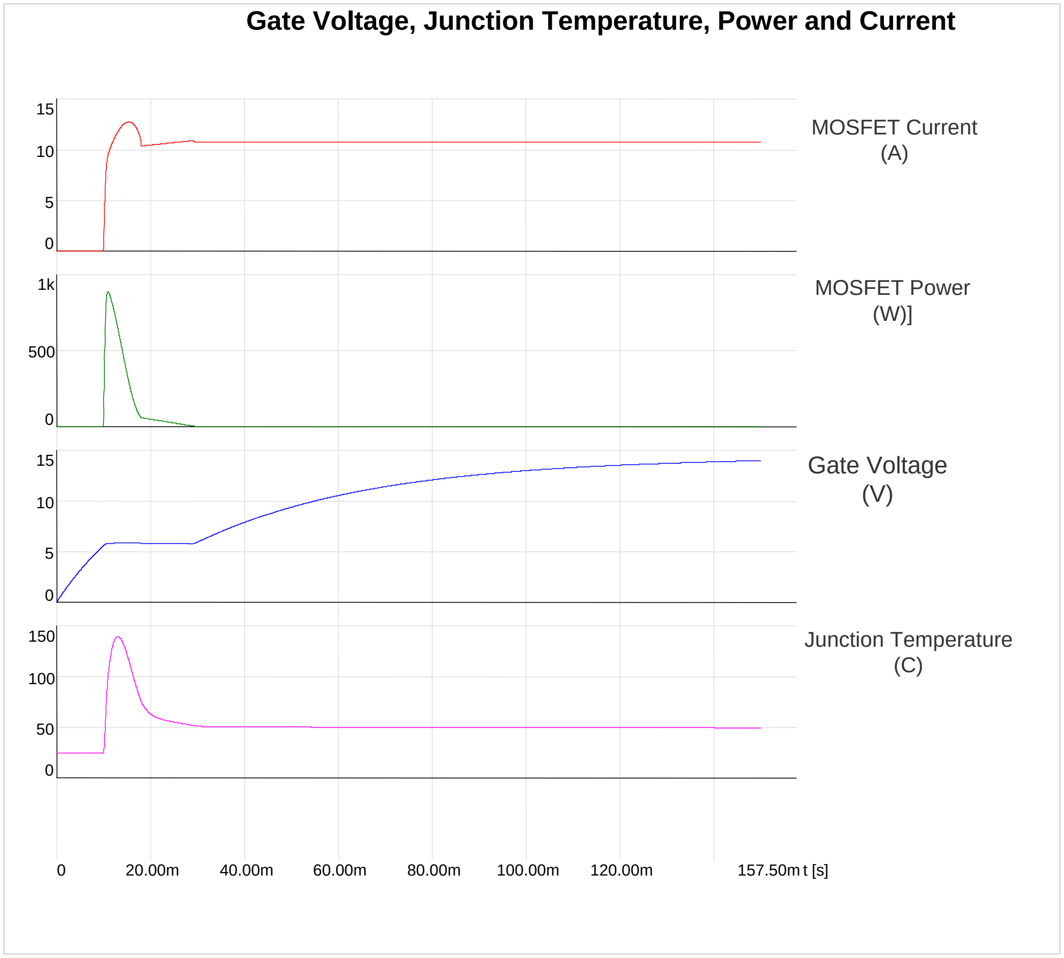


Example Application

- Assumptions
  - Tambient=25C
  - Heak sink is modeled as just a thermal resistor
  - C1 & R2 represent a load system i.e. power supply
  - Ig, Vgs, PWR_FET, States 1 & 2, Trans1 and S1 are measurements, input stimulus and ideal switch

Example Application

- Results



Conclusion

- Electro-Thermal simulation allows for analysis in both electrical and thermal domains
- Quasi-Dynamic Thermal MOSFET model allows for self-heating to alter $R_{DS(on)}$ and Vth during simulation as a function of temperature
- Quasi-Dynamic Thermal MOSFET Model generation is a data gathering task
- The example shows why it is difficult to switch a capacitive load with an opto-driver and a MOSFET due to the excessive junction temperature spike during turn-on.