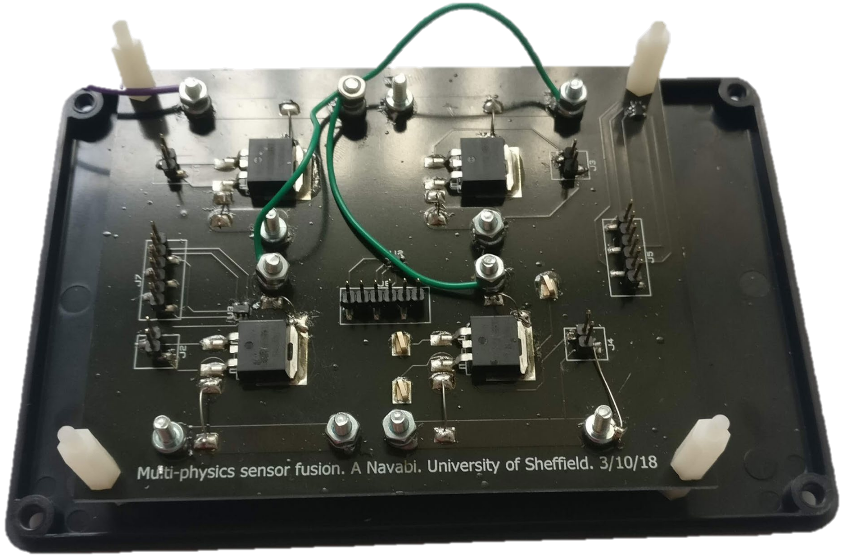
Thermal Modelling & Temperature Prediction of a Power Module Mounted on an IMS PCB

BENJAMIN GRIFFITHS

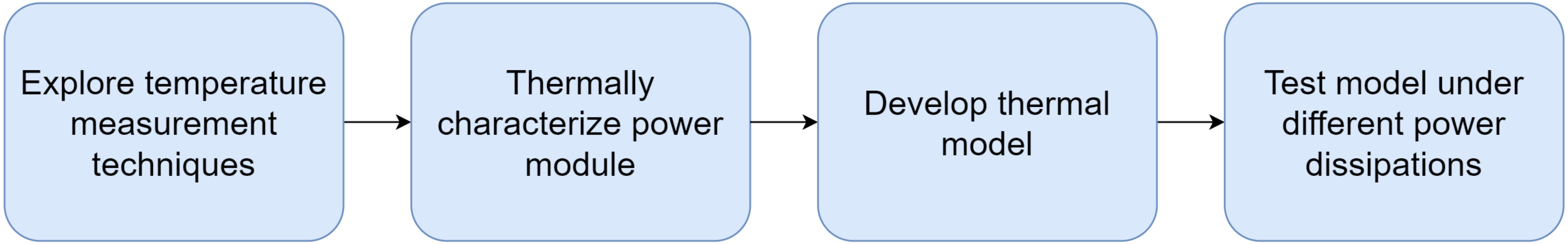
My Project

- Connected to a current ‘Multi Physics Sensor Fusion’ research project between several universities.
- Developed a thermal model for a simple power module mounted on an insulated metal substrate (IMS) PCB.
- Model can predict temperatures of all devices for any given power dissipation in any device combination.



- Rise in development of electric vehicles.
- Increasing demand for power electronics with greater power capabilities with smaller physical footprints.
- Complicates thermal management:
  - Devices close together – thermal cross coupling.
  - High operating temperatures.
  - Rapid thermal cycling.
  - Mechanical stress.
  - Cracked solder joints.
  - Bond wire lift off.
- Thermal model can be used in conjunction with degradation model.

Project Components



Explore temperature measurement techniques

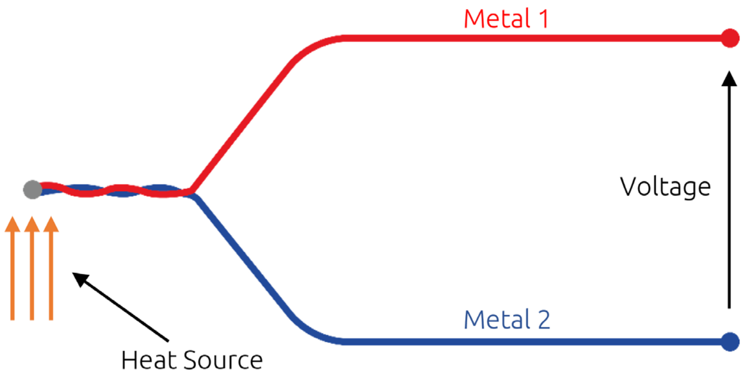
Thermally characterize power module

Develop thermal model

Test model under different power dissipations

Theory: Temperature Measurement

- **External:** Thermocouples
  - Fast response time.
  - Inexpensive and widely available.
  - Require complex electronics.
  - Additional thermal impedance between case and semiconductor die – time delay.



- **Internal:** Electro-thermal relationships
  - Takes advantage of intrinsic features in devices structure.
  - MOSFET: Anti-parallel diode / body diode.
  - If current is constant, temperature is function of diode voltage.

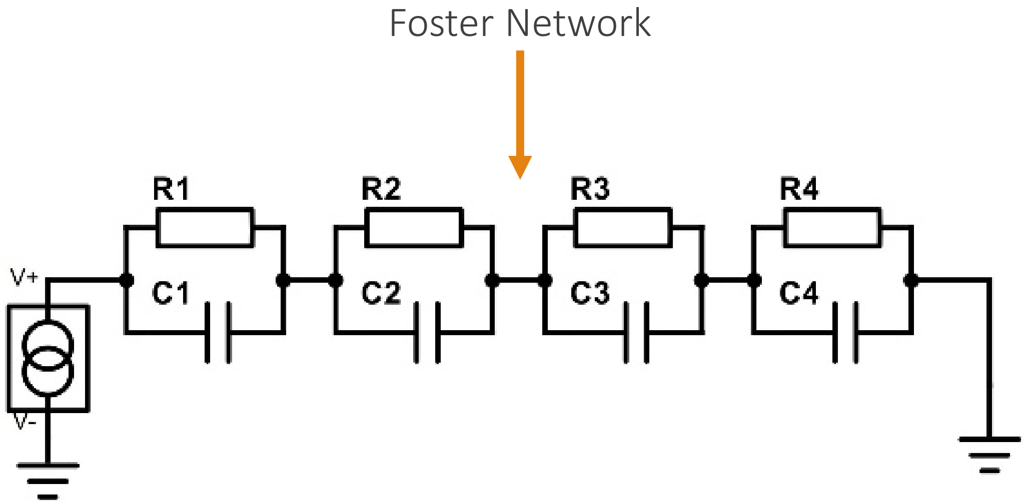
$$V_d = \frac{kT}{e} \ln\left(\frac{I}{I_s} - 1\right)$$

  - Direct die temperature measurement.
  - Linear relationship over range of interest (30°C - 120°C)

$$V_d = m \cdot T_j + V_0$$

Theory: RC Thermal Model

- Conventionally, thermal resistance used to calculate heatsink value.
- Does not describe transient behaviour – capacitors added to produce complex thermal impedance.
- Modelled in RC network form – computationally lightweight/LTSpice
- **Foster Network:**
  - R and C values found from system step response.
  - Time constants of each section found from fitting step response to multi-term exponential equation.



Theory: RC Thermal Model

- Step response found by applying step change in power dissipation and observing the temperature rise.
- Converted into a transient thermal impedance curve.

$$Z_{TH}(t) = \frac{T_j(t) - T_a(t)}{P}$$

- Fitted to multi-term exponential curve.
- RC values extracted.

$$Z_{TH}(t) = \sum_{n=1}^{N} R_n \left[(1 - \exp\left(-\frac{t}{R_n C_n}\right)\right]$$

- Transfer function of network derived.

$$Z_{TH}(s) = \frac{R_1}{1 + sR_1C_1} + \frac{R_2}{1 + sR_2C_2}$$

- Total junction temperature elevation due to both self heating and thermal cross coupling.

- Linear superposition of contributions from heat sources.

Self heating

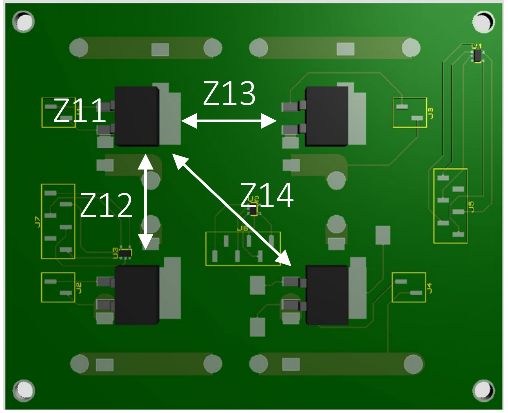
Cross coupling

$$\begin{bmatrix}T_{j1}\\T_{j2}\\T_{j3}\\T_{j4}\end{bmatrix} = \begin{bmatrix}T_a\\T_a\\T_a\\T_a\end{bmatrix} + \left(\begin{bmatrix}Z_{11} & Z_{12} & Z_{13} & Z_{14}\\Z_{21} & Z_{22} & Z_{23} & Z_{24}\\Z_{31} & Z_{32} & Z_{33} & Z_{34}\\Z_{41} & Z_{42} & Z_{43} & Z_{44}\end{bmatrix} \times \begin{bmatrix}P_1\\P_2\\P_3\\P_4\end{bmatrix}\right)$$

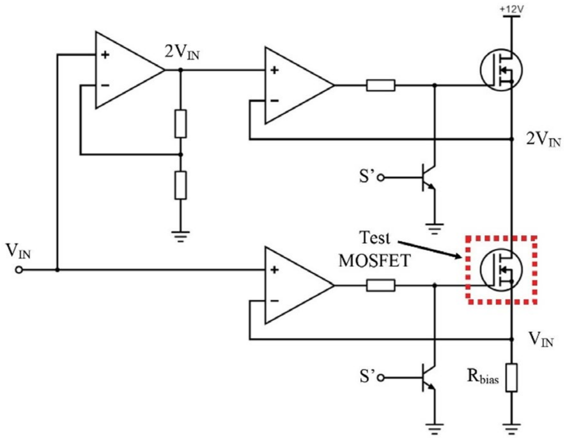
Self heating contribution

Cross coupling contributions

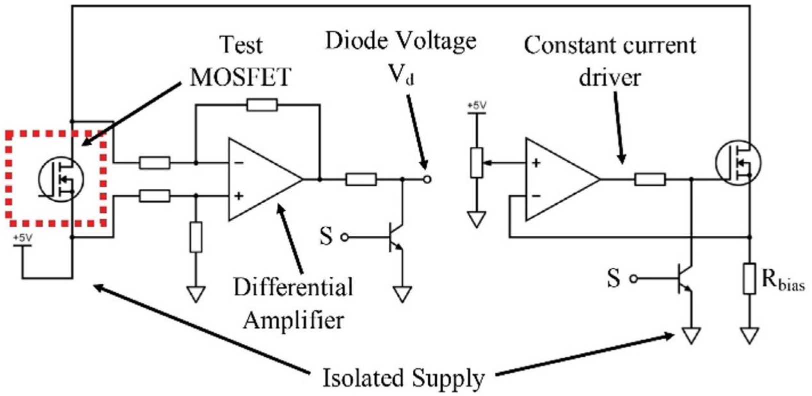
$$T_{j1} = T_a + P_1Z_{11} + P_2Z_{12} + P_3Z_{13} + P_4Z_{14}$$



Method: Circuit



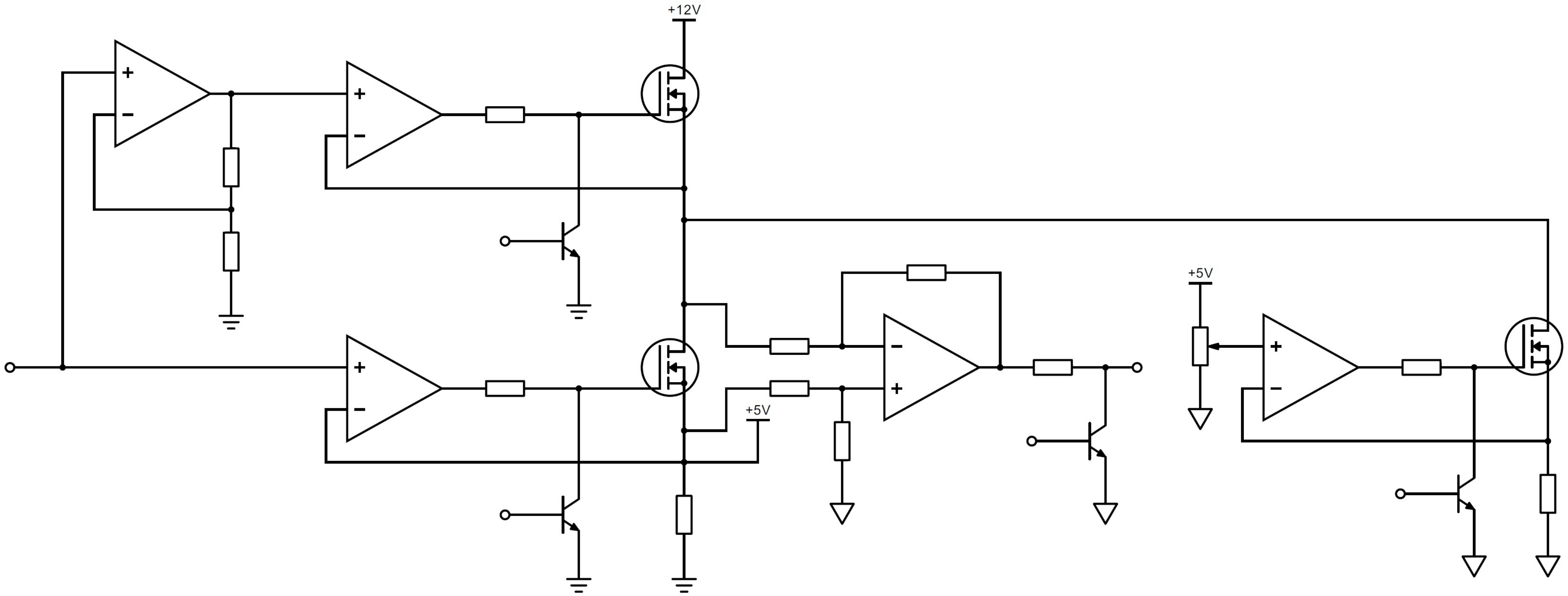
- Needed a circuit capable of precisely controlling the power dissipation in a device.
- Vin maintained across Rbias, 2Vin maintained across test MOSFET.
- Hence Vin also maintained across test MOSFET.
- Current set by Rbias.
- Dissipation in resistor equal to dissipation in test MOSFET.



- Needed circuit to measure body diode voltage.
- Gate of MOSFET grounded so current only flows through body diode.
- Constant current driver forward biases body diode with ~5mA – Develops voltage between source and drain.
- Differential amplifier outputs diode voltage into ADC.

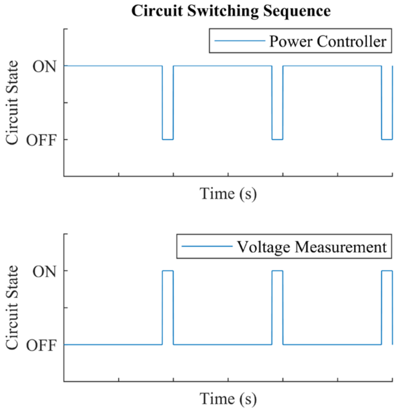
Method: Combined Circuit

- Voltage measurement circuit operates on an isolated supply since it has to reverse bias the MOSFET.

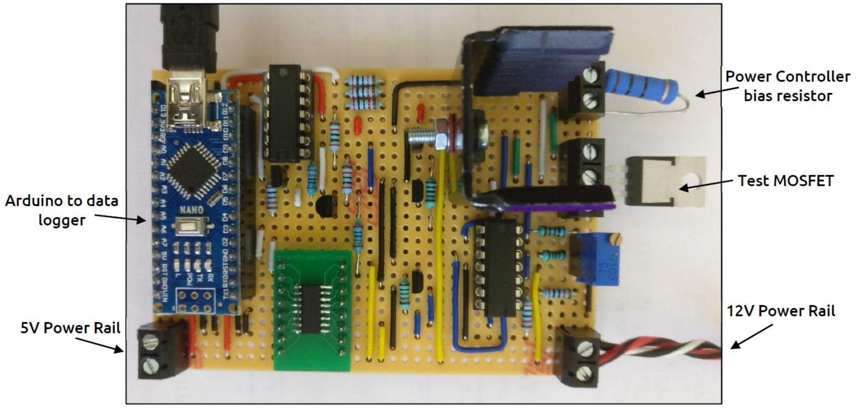


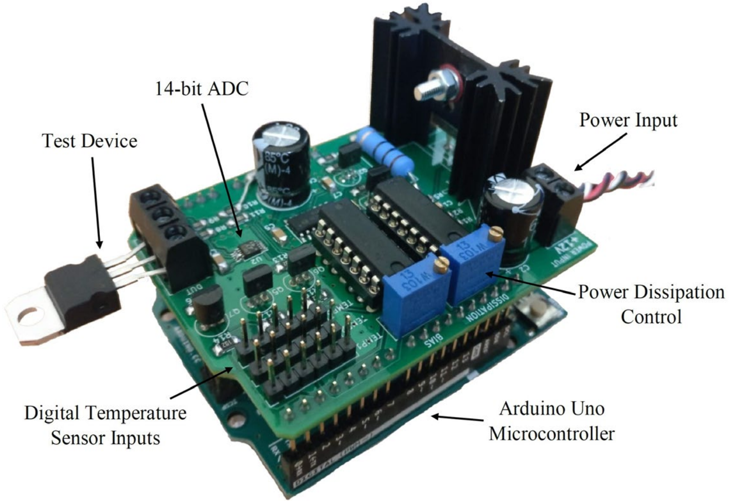
Method: Simultaneous Operation

- Both circuits cannot operate simultaneously.

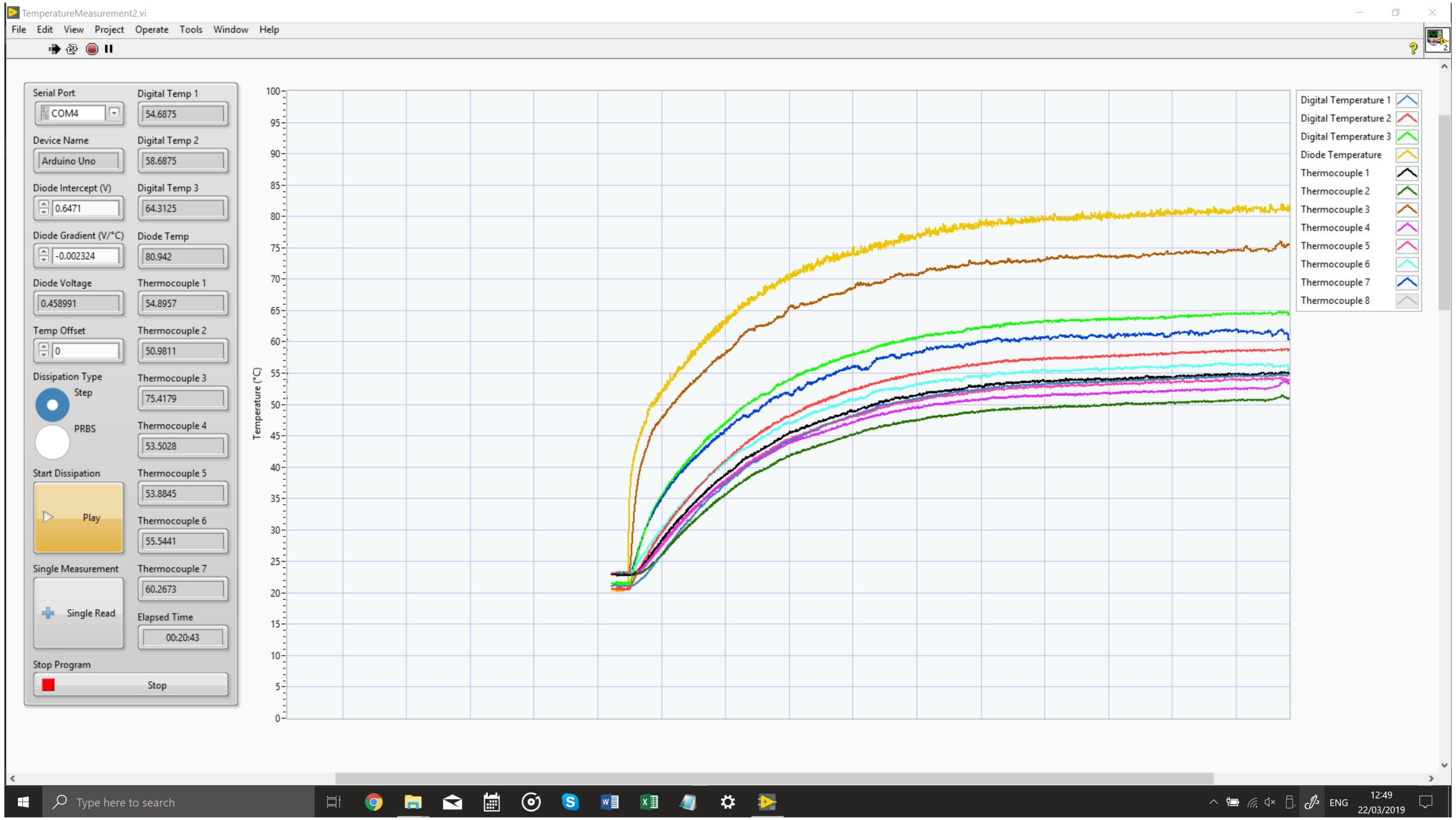


- PWM style switching scheme used to rapidly switch between circuits.
- Circuit designed onto Arduino Uno 'shield'.
- Arduino communicates to data acquisition program.





Method: Data Acquisition Program



Serial Port: COM4

Device Name: Arduino Uno

Diode Intercept (V): 0.6471

Diode Gradient (V/°C): -0.002324

Diode Voltage: 0.458991

Temp Offset: 0

Dissipation Type: ● Step ○ PRBS

Digital Temp 1: 54.6875

Digital Temp 2: 58.6875

Digital Temp 3: 64.3125

Diode Temp: 80.942

Thermocouple 1: 54.8957

Thermocouple 2: 50.9811

Thermocouple 3: 75.4179

Thermocouple 4: 53.5028

Thermocouple 5: 53.8845

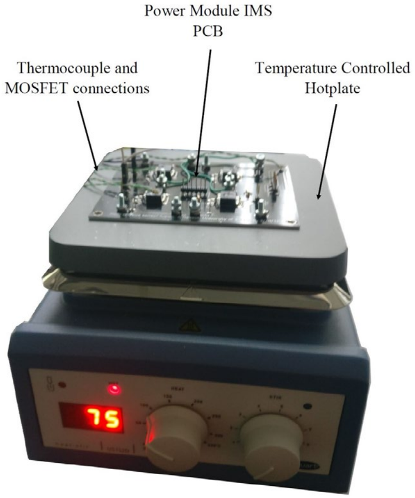
Thermocouple 6: 55.5441

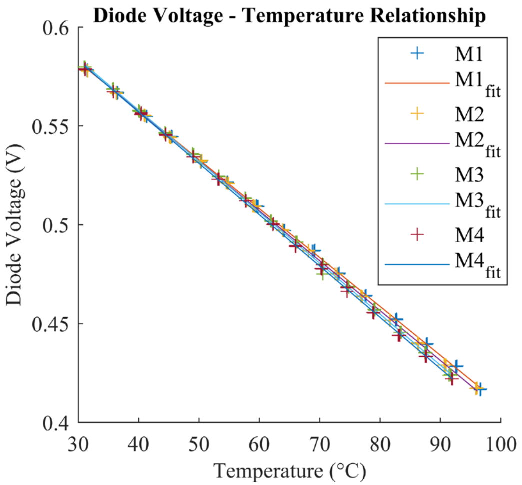
Thermocouple 7: 60.2673

Elapsed Time: 00:20:43

- Designed a LabVIEW program.
- Controls circuit functions.
- Extracts diode voltage and SPI digital temperature sensor measurements through Arduino Uno.
- Extracts thermocouple readings from LabJack U6 ADC.
- Records all temperature measurements to excel spreadsheet for further processing.
- Automatic switching between dissipation and measurement functions.

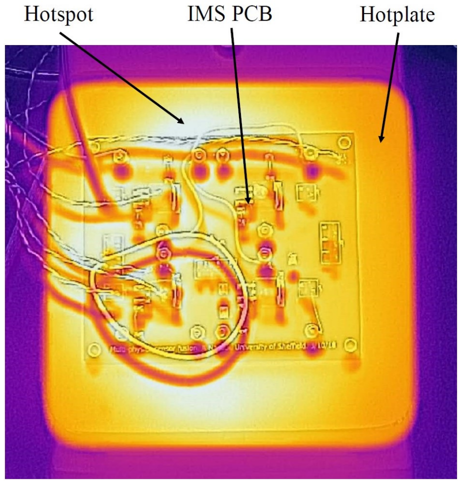
Method: Diode Voltage Calibration

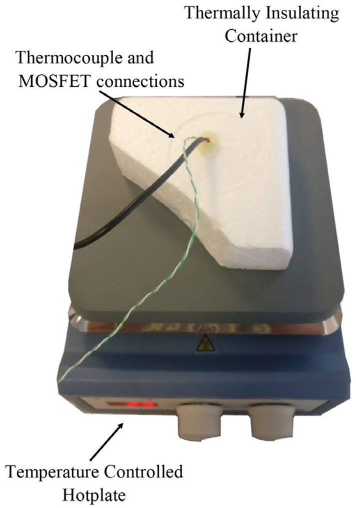




- IMS PCB placed onto temperature controlled hotplate.
- Diode voltage measured from 30°C - 100°C.

Device	Gradient (V/°C)	Intercept (V)
MOSFET 1	-0.002476	0.6567
MOSFET 2	-0.002524	0.6584
MOSFET 3	-0.002582	0.6613
MOSFET 4	-0.002597	0.6609



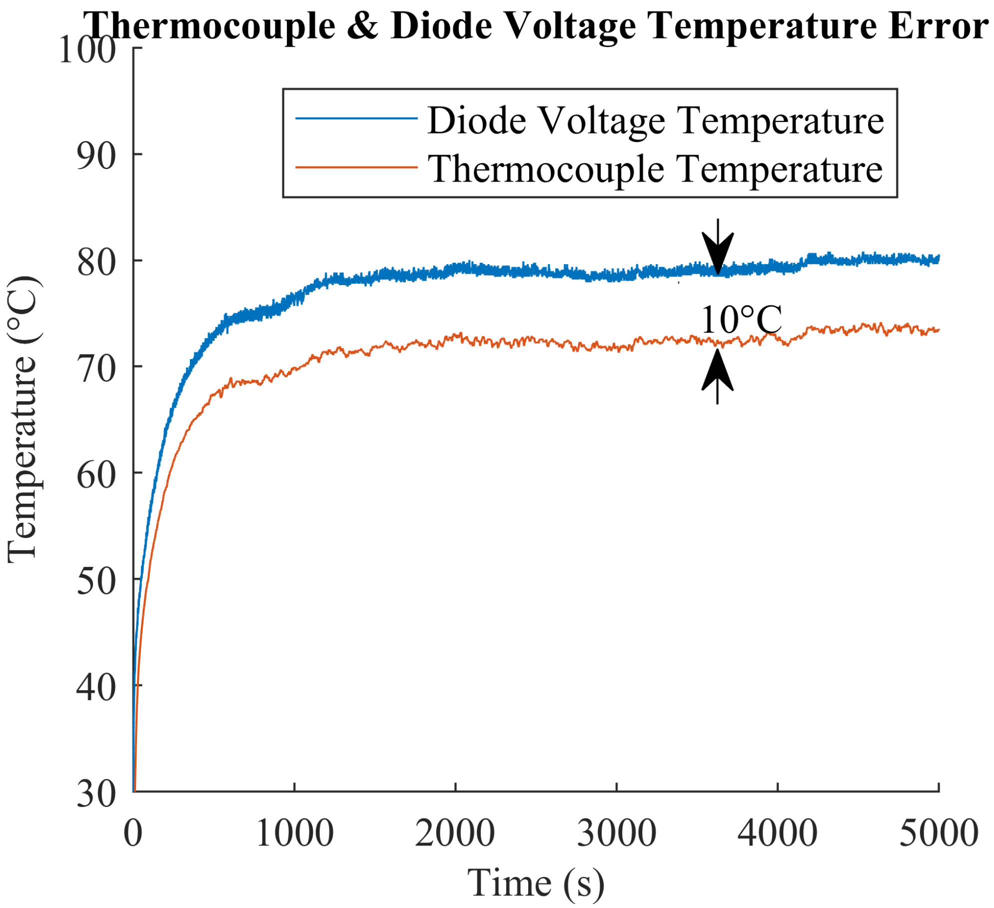


- Thermocouples did not reach temperature of semiconductor die.
- MOSFET suspended in thermally insulated container.
- Even heating by surrounding ambient air.

Gradient (V/°C)	Intercept (V)
-0.002324	0.6471

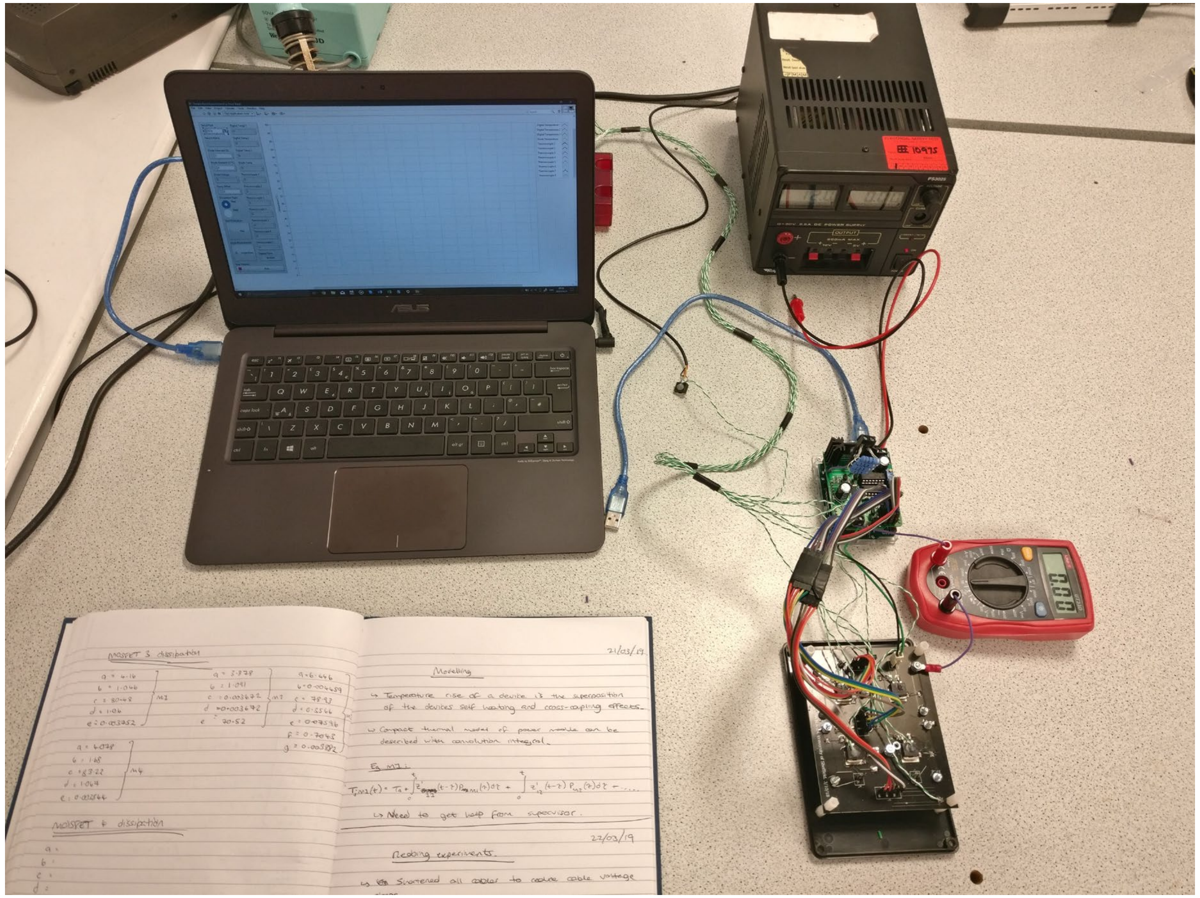
$$Temperature = \frac{V_{diode} - 0.6471}{-0.002324}$$

Results: Diode Voltage Calibration



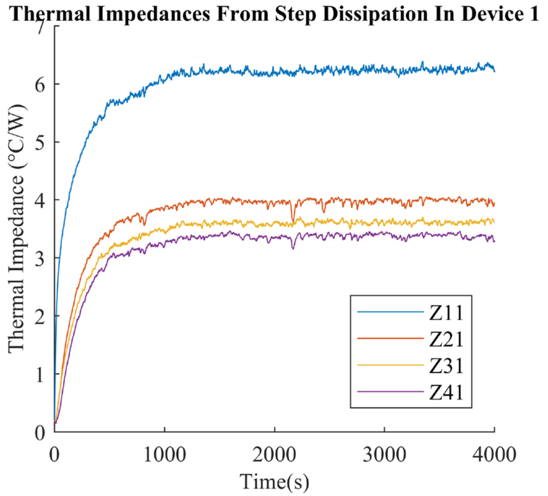
- Very low error at room temperature (<1°C).
- Approximately 10°C difference at equilibrium with 10W dissipation
- Caused by thermal impedance between semiconductor die and case.
- 1°C/W would cause a temperature drop of 10°C due to a dissipation of 10W.
- Highlights the uncertainty caused by external temperature measurement techniques.

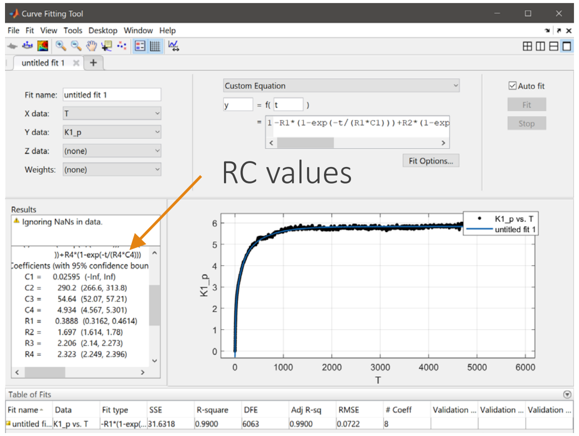
Method: Step Response



- Circuit only capable of measuring diode voltage of one device at a time.
- Thermocouples were used for the modelling process.
- Battery powered laptop used to achieve ground isolation between power controller and voltage measurement circuits.
- Performed 10W step power dissipation in each device in turn.
- Voltage at MOSFET terminals and current measured to calculate power.
- Measured and recorded temperature elevation of all devices.

Results: Step Response


Thermal Impedances From Step Dissipation In Device 1



Fit name: untitled fit 1

X data: T

Y data: K1_p

Z data: (none)

Weights: (none)

Custom Equation

y = f(t)

```
= -R1*(1-exp(-t/(R1*C1)))+R2*(1-exp
```

☑ Auto fit

RC values

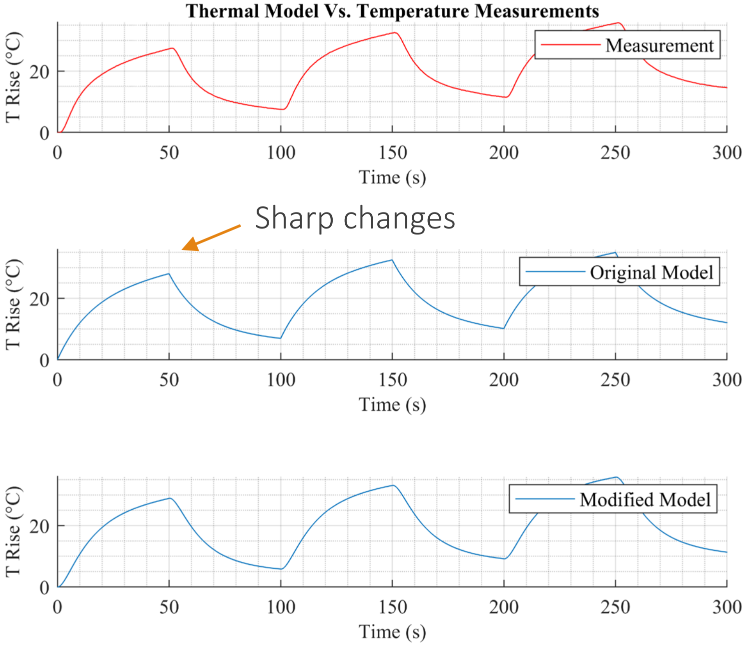
Results

Ignoring NaNs in data.

```
          ))+R4*(1-exp(-t/(R4*C4)))
Coefficients (with 95% confidence boun
    C1 =    0.02595  (-Inf, Inf)
    C2 =      290.2  (266.6, 313.8)
    C3 =      54.64  (52.07, 57.21)
    C4 =      4.934  (4.567, 5.301)
    R1 =     0.3888  (0.3162, 0.4614)
    R2 =      1.697  (1.614, 1.78)
    R3 =      2.206  (2.14, 2.273)
    R4 =      2.323  (2.249, 2.396)
```

Table of Fits

Fit name	Data	Fit type	SSE	R-square	DFE	Adj R-sq	RMSE	# Coeff	Validation ...	Validation ...	Validation ...
untitled fi...	K1_p vs. T	-R1*(1-exp(...	31.6318	0.9900	6063	0.9900	0.0722	8			


Thermal Model Vs. Temperature Measurements

Sharp changes

- Temperature curve converted into thermal impedance curve.
- Error possibly caused by to additional thermal impedances caused by mounting bolts and pin headers.
- Curve fit obtained for each curve.
- Through experimentation, four exponential terms were suitable to produce a precise curve fit.

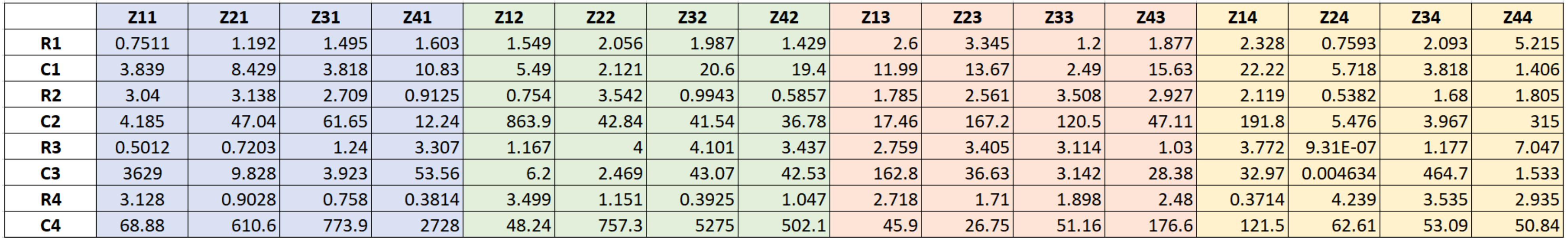
- First term made negative to account for non-instantaneous temperature rise.
- Improved resemblance to measured curve shape.

Results: Step Response

Model equation for each thermal path

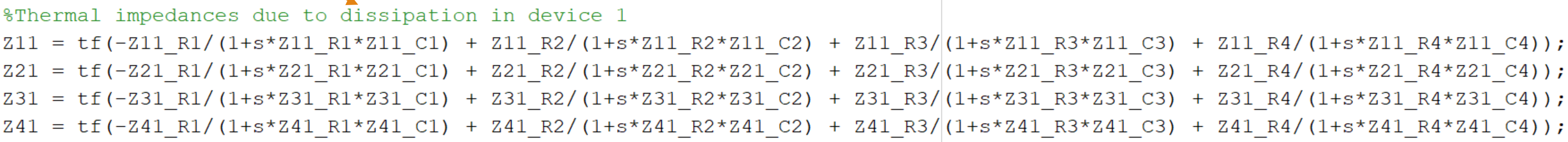
$$Z_{TH}(t) = -R_1\left[1 - exp\left(-\frac{t}{R_1C_1}\right)\right] + R_2\left[1 - exp\left(-\frac{t}{R_2C_2}\right)\right] + R_3\left[1 - exp\left(-\frac{t}{R_3C_3}\right)\right] + R_4\left[1 - exp\left(-\frac{t}{R_4C_4}\right)\right]$$

RC vales for each thermal path



	Z11	Z21	Z31	Z41	Z12	Z22	Z32	Z42	Z13	Z23	Z33	Z43	Z14	Z24	Z34	Z44
R1	0.7511	1.192	1.495	1.603	1.549	2.056	1.987	1.429	2.6	3.345	1.2	1.877	2.328	0.7593	2.093	5.215
C1	3.839	8.429	3.818	10.83	5.49	2.121	20.6	19.4	11.99	13.67	2.49	15.63	22.22	5.718	3.818	1.406
R2	3.04	3.138	2.709	0.9125	0.754	3.542	0.9943	0.5857	1.785	2.561	3.508	2.927	2.119	0.5382	1.68	1.805
C2	4.185	47.04	61.65	12.24	863.9	42.84	41.54	36.78	17.46	167.2	120.5	47.11	191.8	5.476	3.967	315
R3	0.5012	0.7203	1.24	3.307	1.167	4	4.101	3.437	2.759	3.405	3.114	1.03	3.772	9.31E-07	1.177	7.047
C3	3629	9.828	3.923	53.56	6.2	2.469	43.07	42.53	162.8	36.63	3.142	28.38	32.97	0.004634	464.7	1.533
R4	3.128	0.9028	0.758	0.3814	3.499	1.151	0.3925	1.047	2.718	1.71	1.898	2.48	0.3714	4.239	3.535	2.935
C4	68.88	610.6	773.9	2728	48.24	757.3	5275	502.1	45.9	26.75	51.16	176.6	121.5	62.61	53.09	50.84

Transfer function of each thermal impedance
entered into MATLAB using tf() command.



```
%Thermal impedances due to dissipation in device 1
Z11 = tf(-Z11_R1/(1+s*Z11_R1*Z11_C1) + Z11_R2/(1+s*Z11_R2*Z11_C2) + Z11_R3/(1+s*Z11_R3*Z11_C3) + Z11_R4/(1+s*Z11_R4*Z11_C4));
Z21 = tf(-Z21_R1/(1+s*Z21_R1*Z21_C1) + Z21_R2/(1+s*Z21_R2*Z21_C2) + Z21_R3/(1+s*Z21_R3*Z21_C3) + Z21_R4/(1+s*Z21_R4*Z21_C4));
Z31 = tf(-Z31_R1/(1+s*Z31_R1*Z31_C1) + Z31_R2/(1+s*Z31_R2*Z31_C2) + Z31_R3/(1+s*Z31_R3*Z31_C3) + Z31_R4/(1+s*Z31_R4*Z31_C4));
Z41 = tf(-Z41_R1/(1+s*Z41_R1*Z41_C1) + Z41_R2/(1+s*Z41_R2*Z41_C2) + Z41_R3/(1+s*Z41_R3*Z41_C3) + Z41_R4/(1+s*Z41_R4*Z41_C4));
```

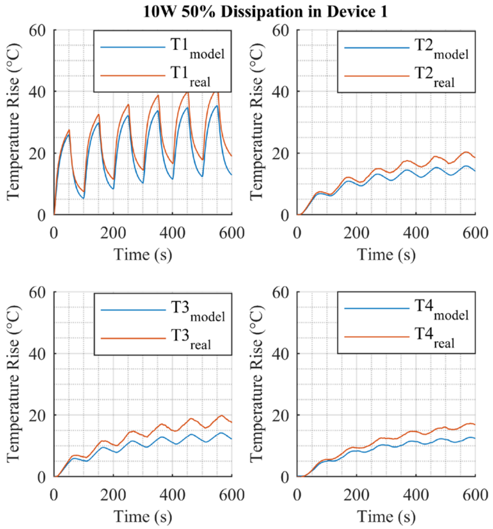
Results: Modelling

```
%Simulation time
t = 0:0.1:600;

%Dissipation Parameters
power = 10;
freq = 0.01;
duty = 50;

%Defines power dissipation in each device
P1 = power*(0.5*(square(2*pi*freq*t,duty)+1));
P2 = 0*t;
P3 = 0*t;
P4 = 0*t;

%Calculates temperatures of each devices due to dissipation in all devices.
T1 = lsim(Z11,P1,t) + lsim(Z12,P2,t) + lsim(Z13,P3,t) + lsim(Z14,P4,t);

T2 = lsim(Z21,P1,t) + lsim(Z22,P2,t) + lsim(Z23,P3,t) + lsim(Z24,P4,t);

T3 = lsim(Z31,P1,t) + lsim(Z32,P2,t) + lsim(Z33,P3,t) + lsim(Z34,P4,t);

T4 = lsim(Z41,P1,t) + lsim(Z42,P2,t) + lsim(Z43,P3,t) + lsim(Z44,P4,t);
```

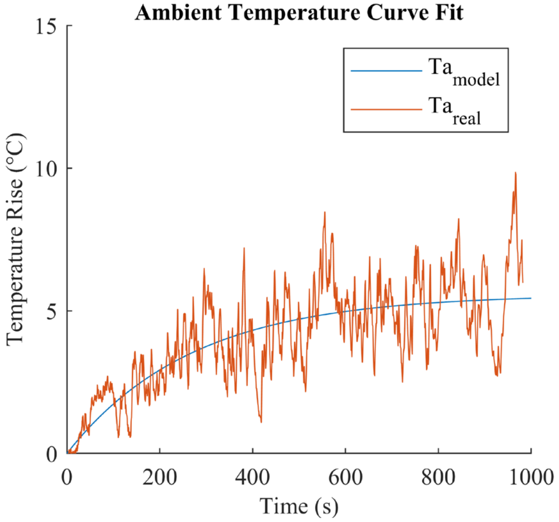
Dissipation parameters

Junction temperatures

- Square wave with variable frequency and duty cycle used to test model.
- Power dissipation defined for each device.
- `lsim(Z,P,t)` command used to extract temperature in time domain from transfer function.



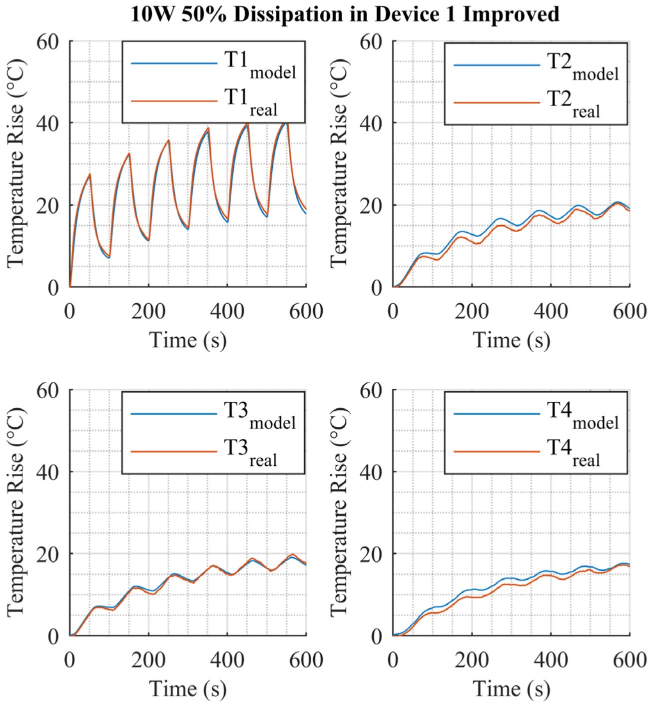
10W 50% Dissipation in Device 1

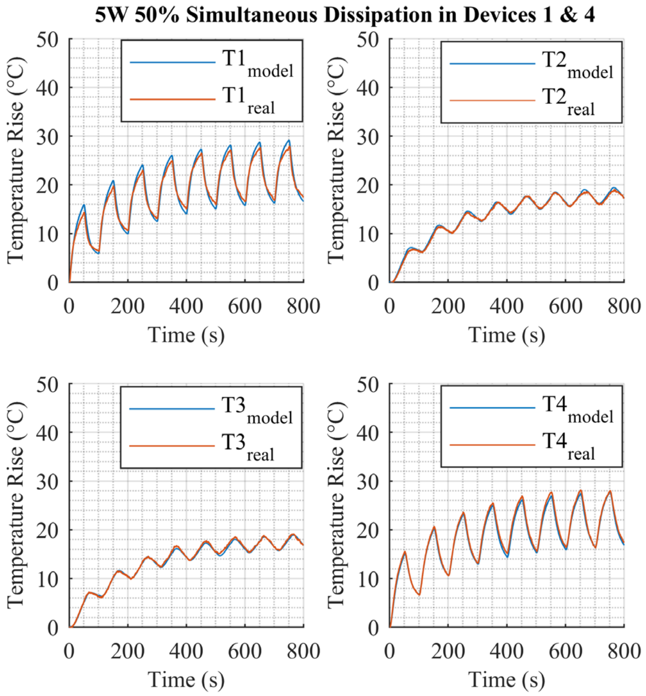


Ambient Temperature Curve Fit

- Large error between model and measurements.
- Caused by non-constant ambient air temperature.
- Experiment repeated with ambient air thermocouple.
- Ambient air model added to current model.

Results: Modelling





- Tested again at 100mHz with a 50% duty cycle.
- Improved accuracy of model compared to measured results.
- Highlights the effects of thermal cross coupling.

- 5W dissipation in device 1 & 4.
- Excellent agreement between model and measured data.

Conclusion

- Internal temperature measurement technique has been presented.
- Methodology to thermally characterise a board and produce a simple thermal model has been described.
- Model has been tested and compared to measured data – good correlation.

Thank you for listening…