Thermal Transient Testing of Semiconductor Components - Fundamentals
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Topics

- Introduction to Thermal Transient Testing
- Structure Functions
- Thermal model calibration value, reasons and method
- Power cycling testing for lifetime estimation
- Summary and Q&A
Airbus, Rolls-Royce & Siemens team up for electric future

All indications suggest that we are on the cusp of a revolution in the aerospace and aviation industries

- Roland Berger

Start-ups Propelling the Electrification of Air Transport
Developments in electrical aircraft propulsion by type of company and geographical origin*

- 46% Start-ups & independents
- 18% Big aerospace company
- 5% Motor manufacturers
- 31% Other aerospace company

* Includes more than 70 programmes with first flight dates ranging from 2006–2030

Source: Roland Berger
Thermal challenges in the semiconductor industry are important:

**Influence Reliability:** High temperature will inevitably cause device/system failure

**Improve Performance:** Low temperature electronics may be more efficient (LED-s, IC-s)

**Decrease system cost:** Proper testing can help avoid thermal over-design, reducing weight and cost
Traditional Temperature Test Methods

- Only surface temperature (Thermocouples, IR camera)
- Effect by thermocouple itself or surface, emissivity and absorptivity.

How do you know the real junction temperature ($T_j$)?
How Do We Know \( \Delta T_j \) 

• The forward voltage of a PN junction under forced current condition can be used as a very accurate thermometer

• The change of the forward voltage (TSP – temperature sensitive parameter) should be carefully calibrated against the change of the temperature (see JEDEC JESD51-1 and MIL-STD-750D)
  – In the calibration process the \( S_{VF} \) temperature sensitivity of the forward voltage is obtained

\[
\Delta T = \Delta V_F \cdot K
\]
Thermal Transient Test Workflow

1. Find the TSP

2. Calibrate

3a. Power Step

3b. Record

4. Analyze

I_{sense} \rightarrow V_{sense}

\[ y = -0.001484x + 2.725130 \]

2.700V
2.680V
2.660V
2.640V
2.620V
2.600V
2.580V

00.0°C
50.0°C
100.0°C

1. Find the TSP

2. Calibrate

3a. Power Step

3b. Record

4. Analyze

\[ T(t) \]

\[ P(t) \]

\[ I_{power} \]
Each section of the Structure Function path represents physical objects the heat encounters. There is a correlation between physical objects and sections of the RC path.
Introduction to Structure Functions

Through numerical manipulations, we can work out what thermal structure would have this effect! The thermal structure will be a manifestation of thermal R’s and C’s.

If the $T$ response to the $P$ excitation is known:

$$W(t) = T(t) \otimes^{-1} P(t)$$

$\otimes^{-1}$ = deconvolution (to be calculated numerically)
Consider a Cu rod of 1x1mm² cross-sectional area
- Rod 1: 100mm (λ, Cᵥ)
- Rod 2: 40mm (λ, Cᵥ), 20mm (λ, 2xCᵥ), 40mm (λ, Cᵥ)

\[ T \approx 250 \text{K/W} \]
• The same results in structure functions:
Structure Function of a Power MOSFET

![Diagram showing structure function of a Power MOSFET with labeled parts 1 to 5.](image)

T3Ster Master: cumulative structure function(s)

- ![Graph showing cumulative structure function with data points and labels 1 to 5.](image)
Applications of the Structure Function

**Measurement**

Obtain accurate and detailed component thermal metrics. A simple change to the environment reveals the package. (JEDEC Standard JEDEC Standard JESD51-14)

**Calibration**

Quantitatively measure changes in structure through cycling. Degradation of the die attach can be observed and measured throughout the test.

**Reliability**

Identify quality issues for incoming/outgoing devices. Here the vendor made an unannounced change to the die size and T3STER detected it.

**Quality**

Utilize a combination of measurement and simulation to create extremely accurate thermal models.
How Simulation and Test Support Each Other

Real package

Model to validate

Thermal CFD

Thermal transient measurement

Simulated thermal transient

STF creation

Structure functions for structural analysis and validation of detailed models

Validated detailed model

Test based compact mode

SIMULATOR

From FEM simulation

Thermal Transient Test

CFD simulation
Dual Sided IGBT Package

- The internal layout of the package is asymmetrical.
- The package had a lower thermal resistance for the top half of the package compared to the bottom half.
Experimental Temperature Results
3D Simulation Model Calibration Results

• The Structure Function graph on the right shows the initial (uncalibrated) and final (calibrated) results from the simulation model, in comparison to the measured results (blue line) obtained by thermal transient testing.

• Thermal conductivity coefficients and interfacial thermal resistance values were aligned.

• When calibrated, the 3D CFD model of the IGBT will behave in the same way as the actual package, including its transient heating and cooling characteristics.
Traditional Power Cycling Processes

- Traditional Process:
  - Run set number of power cycles
  - Take to lab and test for failure
  - Repeat power cycling/lab testing cycle until failure
  - Take to lab and determine reason for failure

Issues:
- Repetitive cycle/lab test process = long times
- No “real time” indication of failure in progress – only post mortem
- Failure cause requires lab analysis – typically internal to package

How about combining cycling and analysis to a single test set-up?
How about automating the workflow?
- Simulation of the power cycling process on an IGBT, illustrated in Simcenter Flotherm
  - High internal temperature gradients highlight areas more likely to fail
Continuous degradation of the die-attach layer can be observed after ~10,000 to 15,000 cycles.
Assessing Field Reliability

• Damage models developed based on active power cycling test results: \( N_f = f_n(\Delta T, T_m) \)

• Rainflow-counting algorithm processes 3D Thermal CFD drive cycle temperature swings:

Results predict onset and rate of wear out:
Thermal transient testing is an accurate way to characterize power electronics

Structure functions will help you
- understand package properties and the effect of external cooling solutions
- serve a perfect reference for calibrating CFD thermal models

You can measure cycle number to failure data as well as understand the degradation process

You can use test and simulation to estimate mission profile based lifetime