Failure Mechanisms of Insulated Gate Bipolar Transistors (IGBTs)

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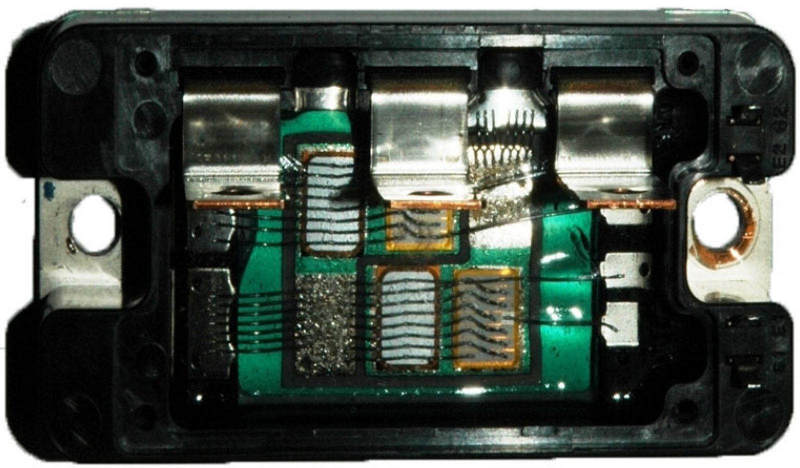
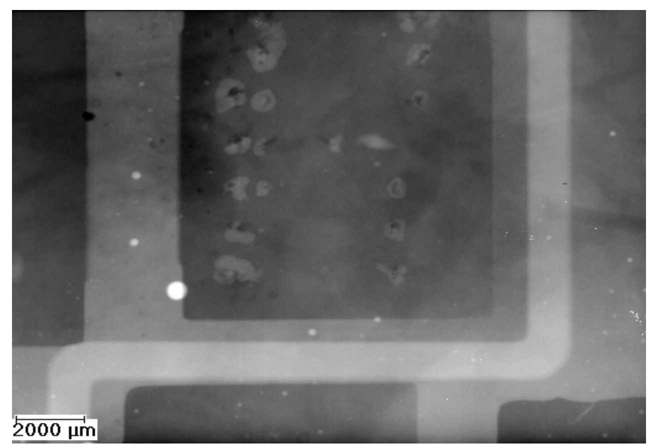




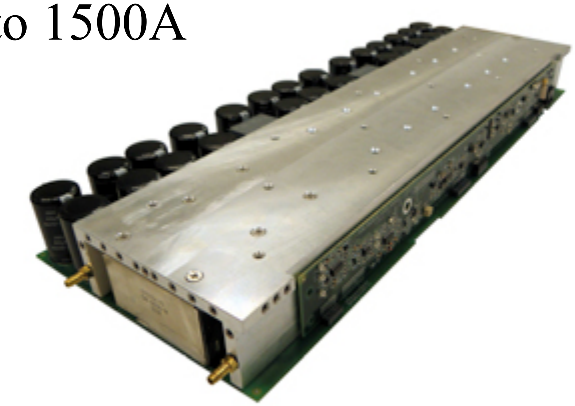
CALCE Introduction

- The Center for Advanced Life Cycle Engineering (CALCE) formally started in 1984, as a NSF Center of Excellence in systems reliability.
- One of the world's most advanced and comprehensive testing and failure analysis laboratories
- Funded at $6M by over 150 of the world's leading companies
- Supported by over 100 faculty, visiting scientists and research assistants
- Received NSF Innovation Award and NDIA Systems Engineering Excellence Award in 2009 and IEEE Standards Education Award in 2013.

IGBT Applications

- Need for more compact power converters achieved through faster device switching
- IGBTs are the ideal choice with switching frequencies of 1kHz-150kHz and current handling of up to 1500A

Induction Heating Units



Power Converters

Electric Cars

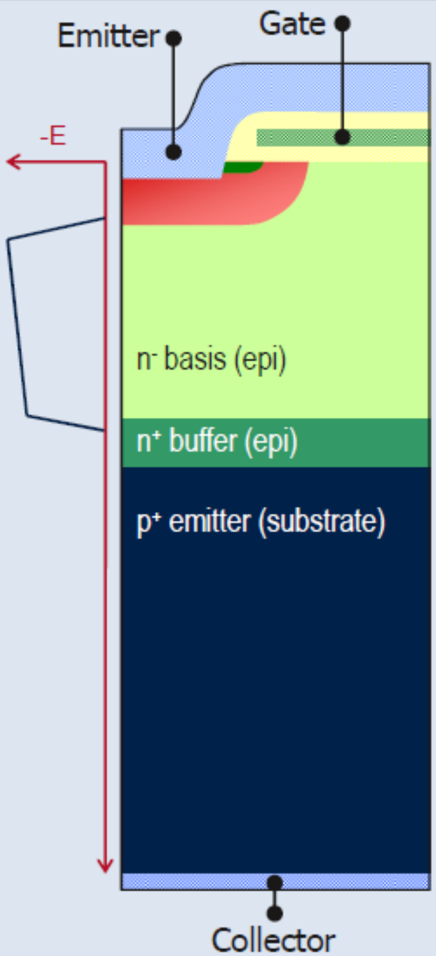
Electric Trains

Uninterruptible Power Supplies

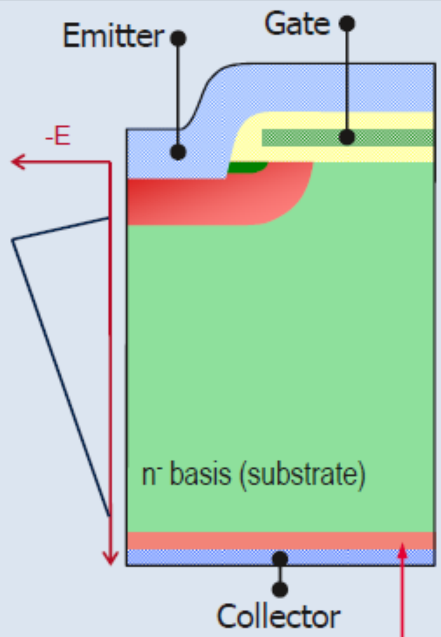
Wind Turbines

IGBT Technologies

Punch Through



Non Punch Through



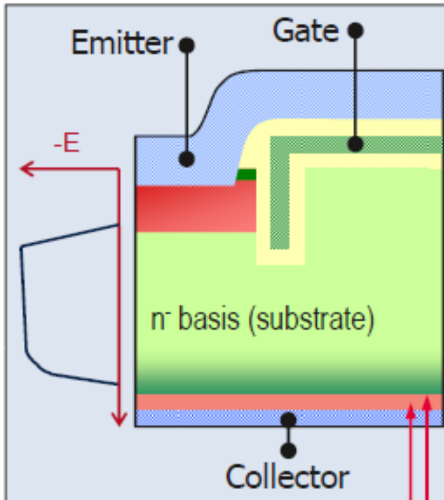
Advantage

- Implanted back-emitter better adjustable

Performance

- Lower switching losses
- Higher switching robustness

Trench + Field-Stop



Advantage

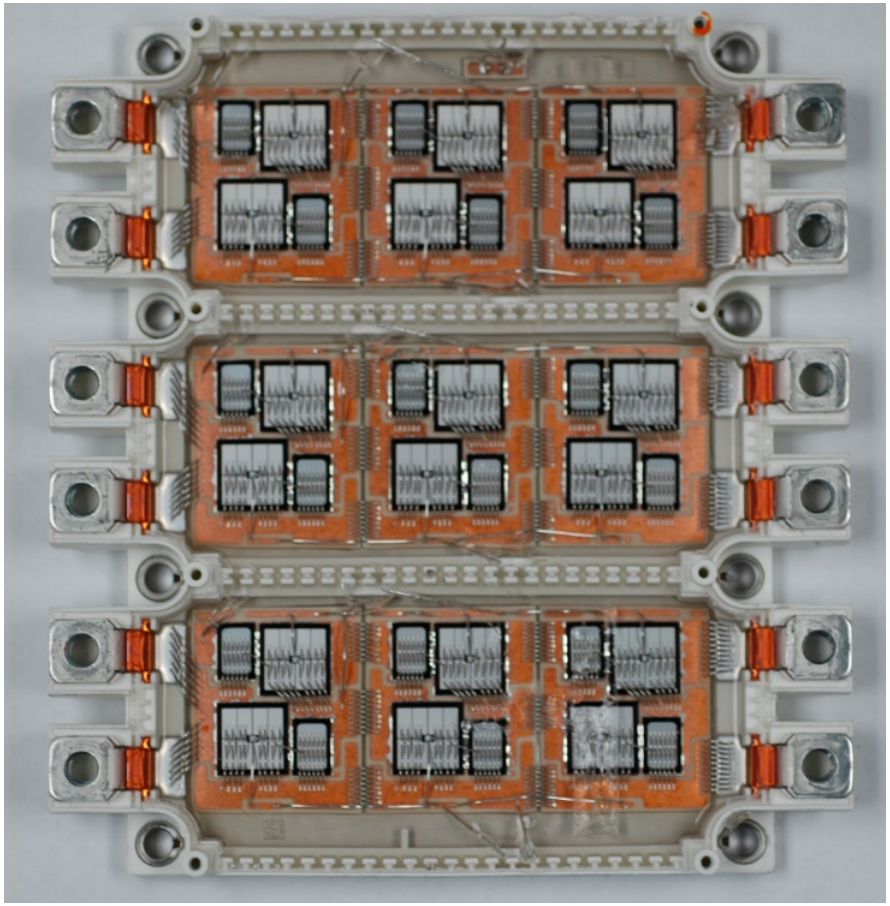
- Implanted backs-emitter
- Implanted field stop enables thinner base region

Performance

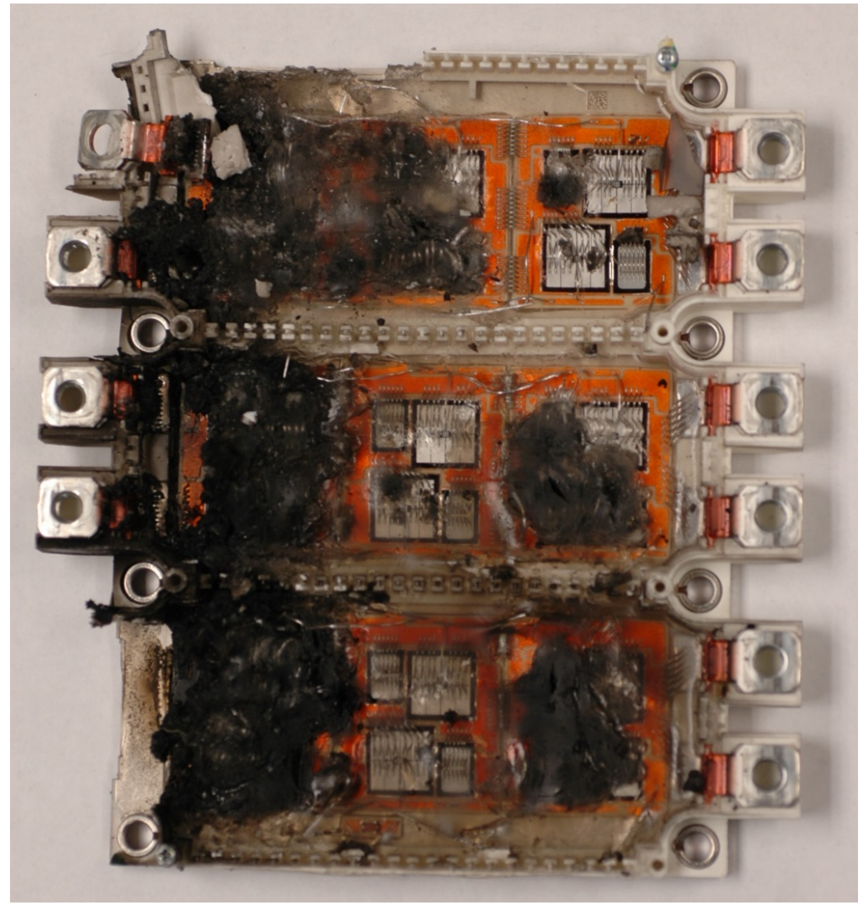
- Lower V_{CEsat}
- Lower switching losses
- Robustness like NPT

Source: Infineon

Failed Wind Turbine IGBT Module



Unused IGBT

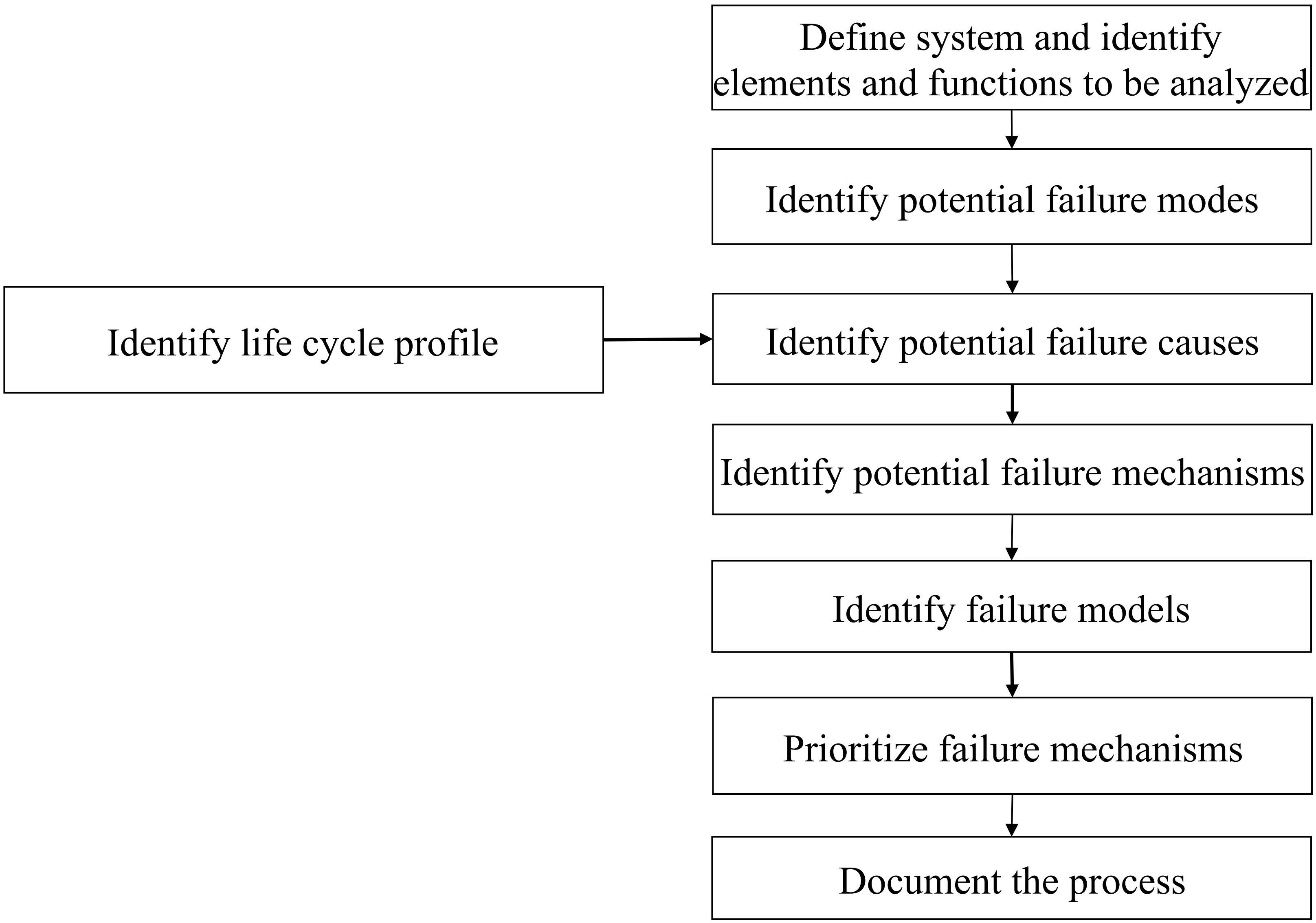


Failed IGBT which experienced a thermal runaway, burning the module

Steps in Reliability Evaluation

- Quantify the life cycle conditions
- Failure Modes, Mechanisms, and Effects Analysis (FMMEA) > reliability analysis, assess design tradeoffs and revise/update design
- Part, material and supplier selection
- Virtual qualification (VQ), including stress and thermal analysis

FMMEA Methodology



IGBT Failure Modes and Mechanisms

- Failure modes in an IGBT are simple at top level:
  - Short circuit
  - Open circuit
  - Parameter drift
- Parameter drift occurs as a part degrades and the electrical characteristics such as $V_{CE(ON)}$ or I_{CE} drift from the acceptable operating range due to the accumulation of damage within a device or module

Failure Modes and Mechanisms

Potential Failure Modes (Sites)	Potential Failure Causes	Potential Failure Mechanisms (Parameters affected)
Short circuit, loss of gate control, increased leakage current (Oxide)	High temperature, high electric field, overvoltage	Time dependent dielectric breakdown ($V_{th,}$ g_m)
Loss of gate control, device burn-out (Silicon die)	High electric field, overvoltage, ionizing radiation	Latch-up ($V_{CE(ON)}$)
High leakage currents (Oxide, Oxide/Substrate Interface)	Overvoltage, high current densities	Hot electrons (V_{th}, g_m)
Open Circuit (Bond Wire)	High temperature, high current densities	Bond Wire Cracking, Lift Off ($V_{CE(ON)}$)
Open Circuit (Die Attach)	High temperature, high current densities	Voiding, Delamination of Die Attach ($V_{CE(ON)}$)

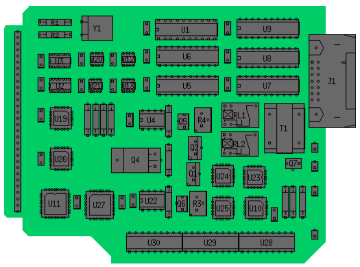
Examples of Failure Models

Failure Mechanism	Failure Sites	Failure Causes	Failure Models
Fatigue	Die attach, Wirebond/TAB, Solder leads, Bond pads, Traces, Vias/PTHs, Interfaces	Cyclic Deformations (Δ T, Δ H, Δ V)	Nonlinear Power Law (Coffin-Manson)
Corrosion	Metallizations	M, ΔV, T, chemical	Eyring (Howard)
Electromigration	Metallizations	T, J	Eyring (Black)
Conductive Filament Formation	Between Metallizations	M, ΛV	Power Law (Rudra)
Stress Driven Diffusion Voiding	Metal Traces	σ, T	Eyring (Okabayashi)
Time Dependent Dielectric Breakdown	Dielectric layers	V, T	Arrhenius (Fowler-Nordheim)

Δ:	Cyclic range	V:	Voltage
Λ:	gradient	M:	Moisture
T:	Temperature	J:	Current density
H:	Humidity	σ:	Stress

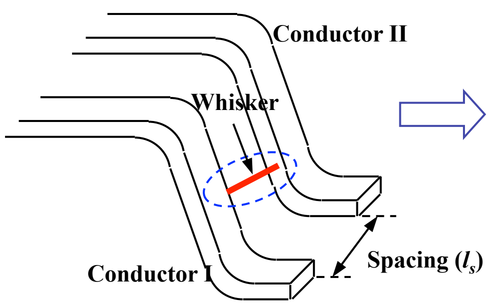
CALCE Simulation Assisted Reliability Assessment (SARA®) Software

http://www.calce.umd.edu/software

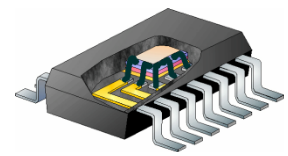


calcePWA
Circuit Card Assemblies

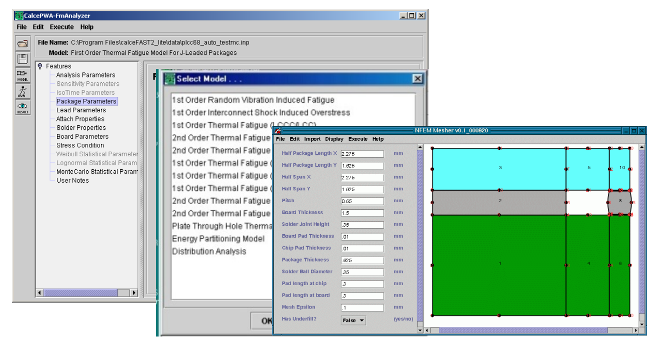
Thermal Analysis
Vibrational Analysis
Shock Analysis
Failure Analysis



calceTinWhisker FailureRiskCalculator



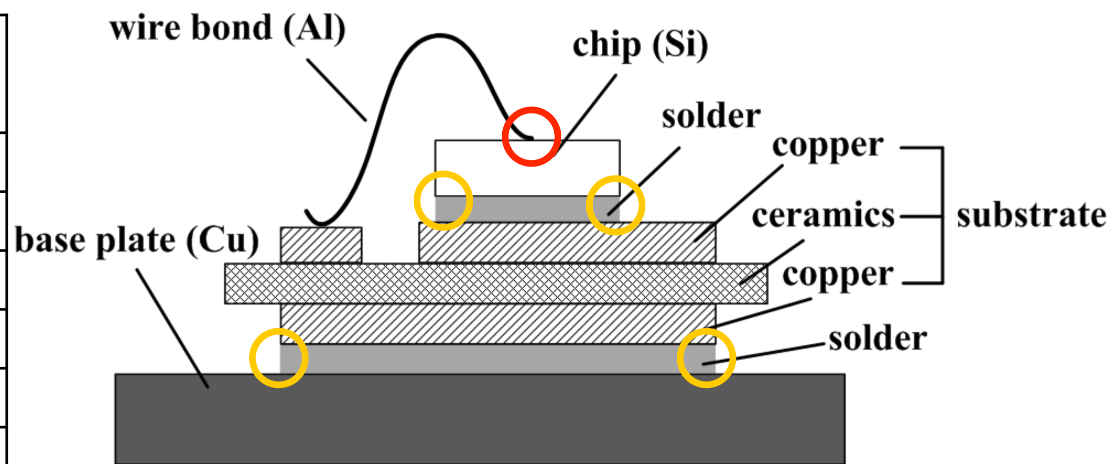
calceEP
Device andPackage
Failure Analysis



calceFAST
Failure Assessment Software Toolkit

Thermally-Induced Stresses in IGBT

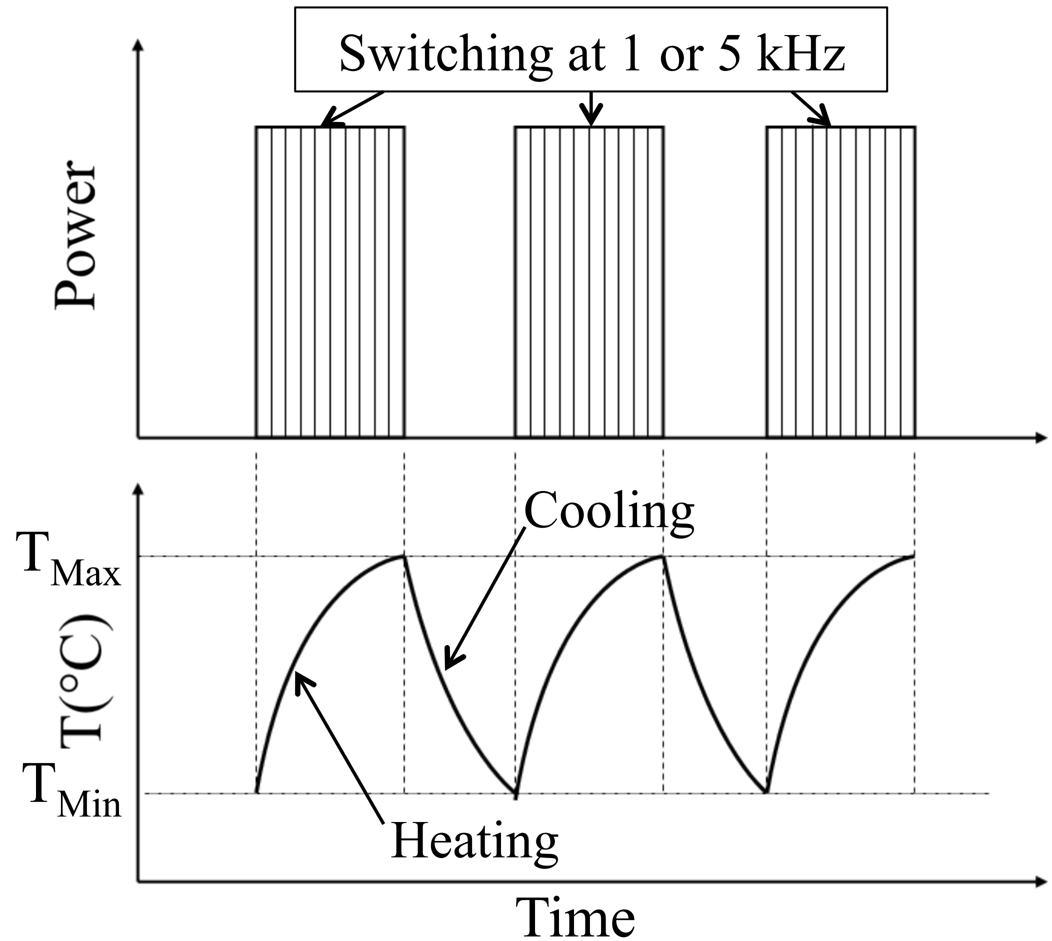
Material	CTE (10^{-6} K^{-1})	Conductivity ($W\ m^{-1}\ K^{-1}$)
Al_2O_3	6.8	24
AlN	4.7	170
Si_3N_4	2.7	60
BeO	9	250
Al	23.5	237
Cu	17.5	394
Mo	5.1	138
Si	2.6	148
AlSiC	7.5	200



- Bond Wire Fatigue
- Solder Joint Fatigue

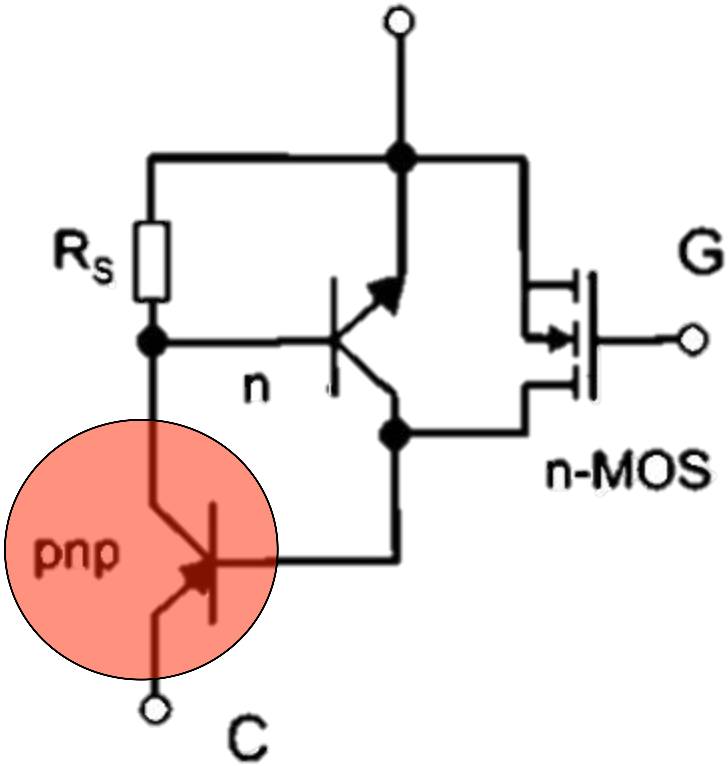
IGBT Power Cycling Experiment

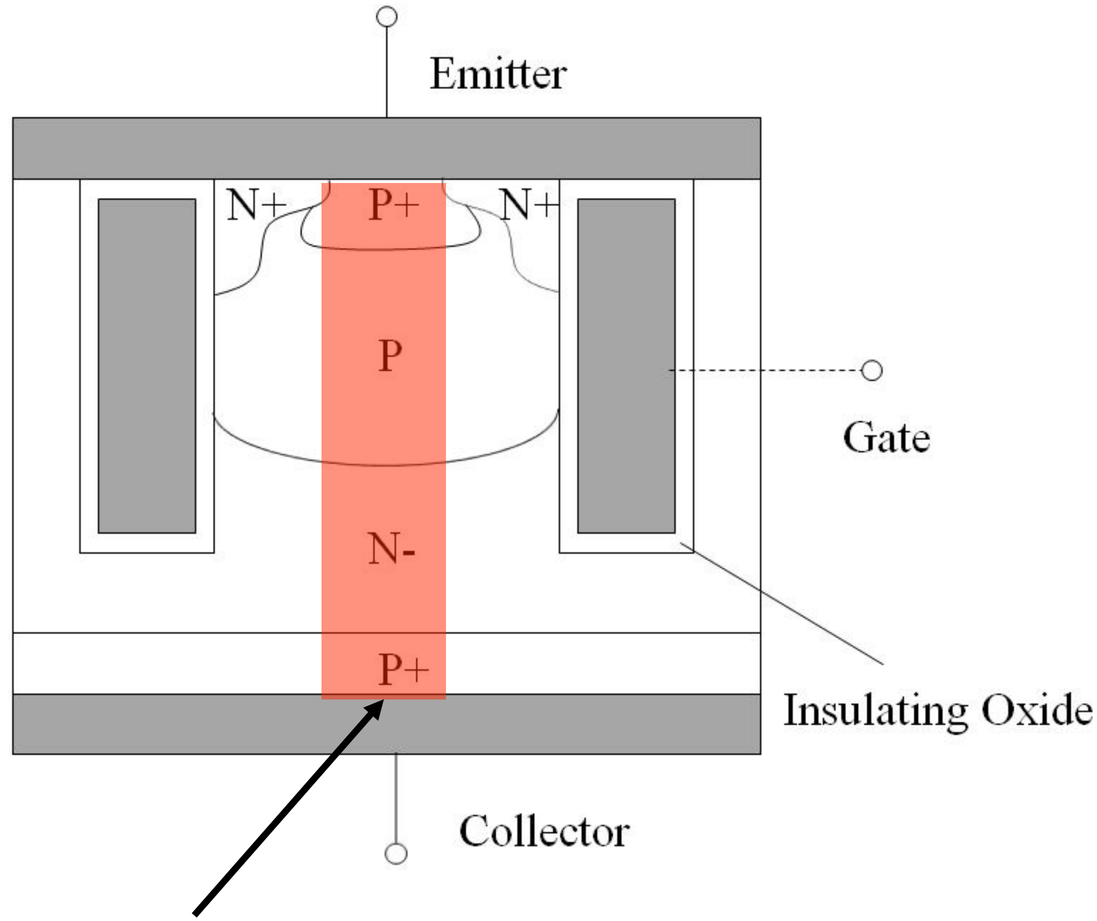
- IGBT samples were power cycled between specified temperatures T_{Min} and T_{Max}. The devices were switched at 1 or 5 kHz. Cooling was carried out passively by exposure to ambient temperature.
- This 'power' (thermal) cycling was repeated until failure occurred by latchup or by failure to "turn on".



Power cycling illustration

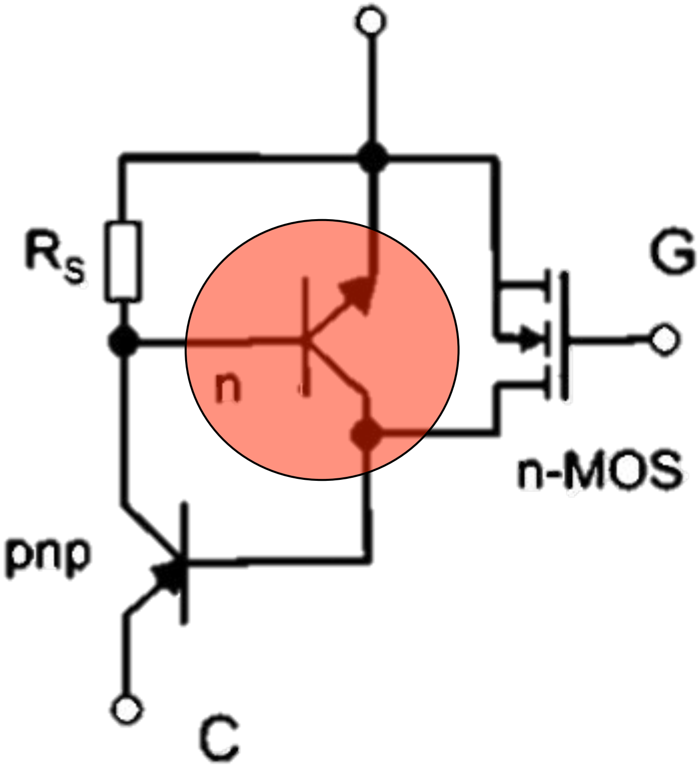
Parasitic Thyristor in IGBT Structure

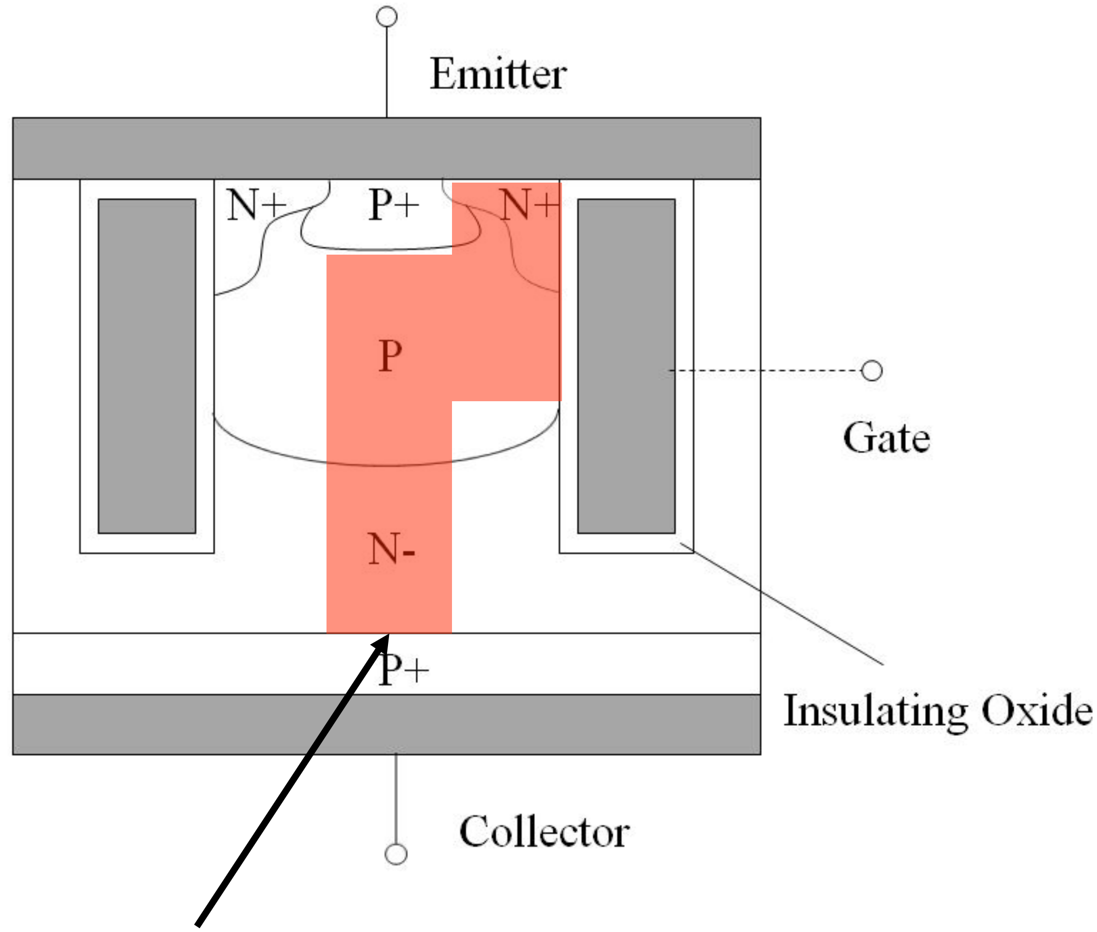




Internal PNP Bipolar Transistor

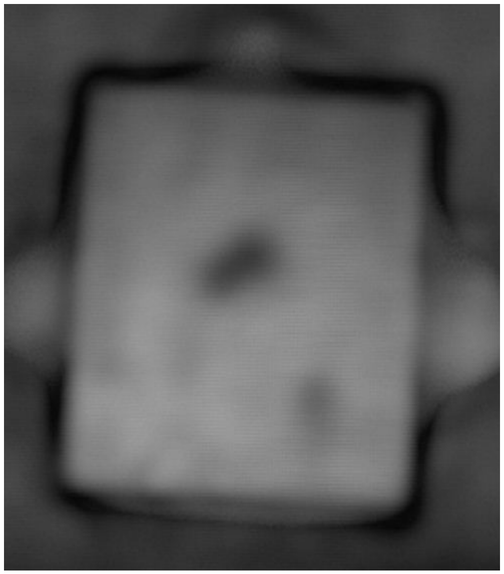
Parasitic Thyristor in IGBT Structure

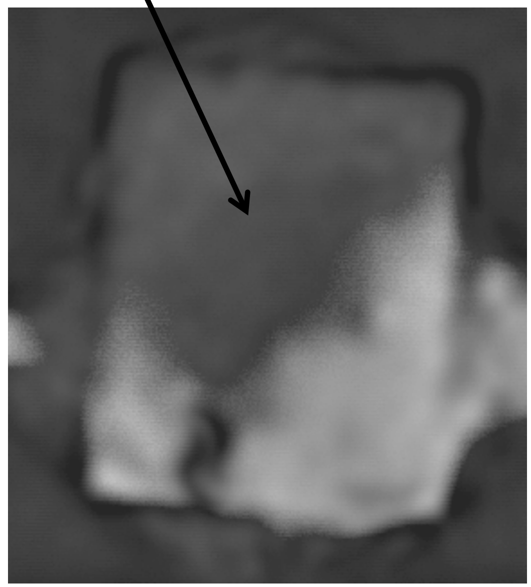




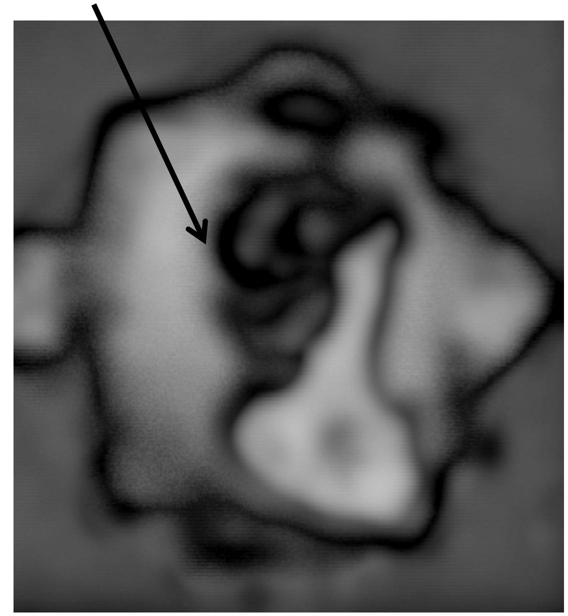
Parasitic NPN Bipolar Transistor

Die Attach Acoustic Scan Images


New IGBT sample.



Failure to turn on after 3126 power cycles, ΔT = 75°C. Die attach shows delamination.

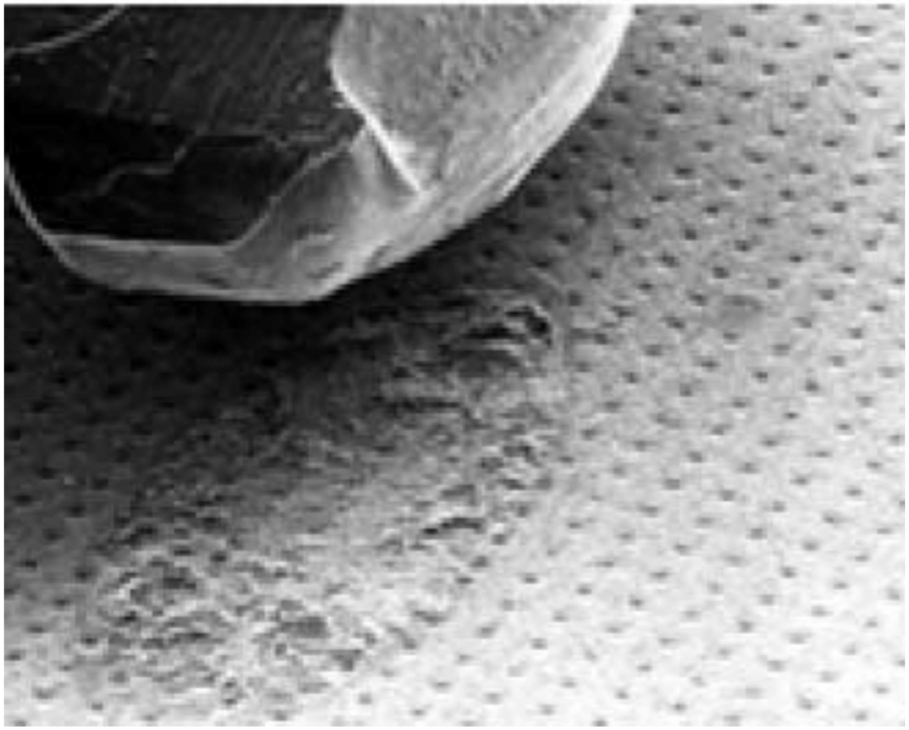


Failure by latchup after 1010 power cycles, ΔT = 100°C. Melting T of die attach = 233°C*.

*Specification sheet for Sn65Ag25Sb10 solder from Indium Corp. Indalloy 209.

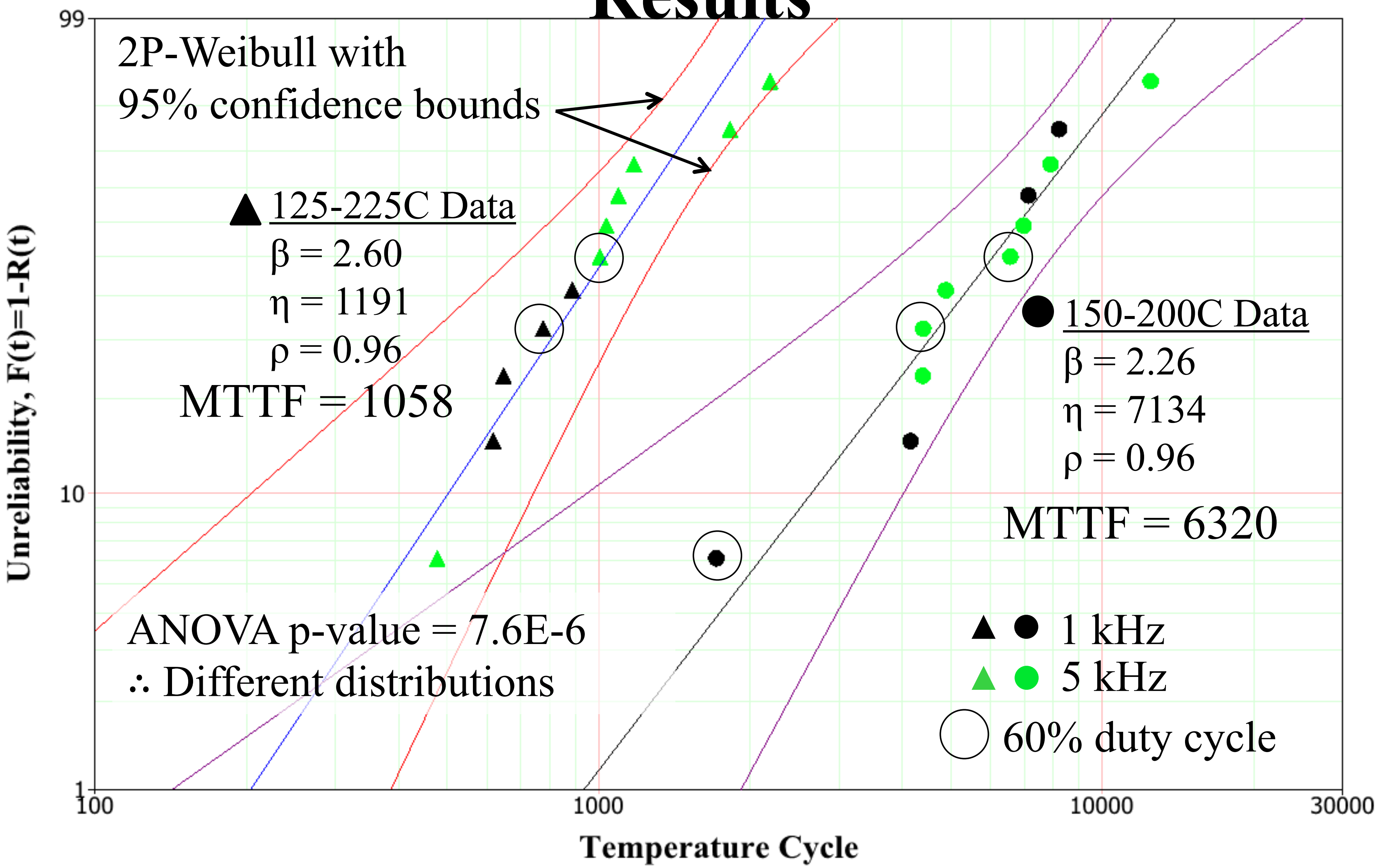
Bond Wire Failures

Bond Wire Cracking



Bond Wire Liftoff

Lifetime Statistics of Experimental Results



Prediction of Other Reliability Metrics

Temperature Range	MTTF (Cycles)	[B5%Life; B95%Life] (Cycles)
150-200°C	6320 cycles	[1922; 11,582]
125-225°C	1058 cycles	[381; 1815]

MTTF varies with loading conditions and from part to part. Predicting service life of an IGBT based on a population MTTF results in a high uncertainty.

Physics of Failure Based Lifetime Prediction

Temperature	PoF Lifetime Prediction	Experiment MTTF
150-200°C	15,300 cycles	6320 cycles
125-225°C	10,800 cycles	1058 cycles

- Thermo-mechanical fatigue due to variations of power dissipation has been identified as a failure mechanism of IGBT.
- Die attach fatigue failure model was used in the CalceFAST software. The model was based on the Suhir's interface stress equation coupled with the Coffin Manson equation.
  - Model inputs were: ΔT, cycling period, materials, and dimensions.
  - Failure criteria were based on separation of die attach material.
- This model does not represent latchup failures and the actual degradation involves intermetallic growth which changes the crack propagation due to brittle fracture.

Limitations of the Die Attach Method

- Die attach area reduction may not be linear as assumed since thermal stress is highest in the perimeter and reduces as cracks move toward the center of the die. Crack growth in the brittle intermetallic is not the same as the original material.
- Power dissipation changes with time as efficiency degrades.
- The latchup Tj is not always 255C due to difference in current density between operating conditions, metallization degradation, and chip manufacturing variations.
- The developed thermal stack model does not represent the actual thermal resistance network due to unknown spreading resistance, dissipation through the encapsulant and bond wires, and changing conductivity through the growing intermetallic.

MIL-217 Handbook: Reliability Prediction of Electronic Equipment

- MIL217 Handbook provides formulas to estimate failure rate of military electronic equipment. **Constant failure rate is assumed.**
- No formula was provided for IGBT, therefore a MOSFET and Bipolar Junction Transistor (BJT) was modeled in series to represent an IGBT.
- Failure rate is calculated by multiplying a base failure rate with several conditional factors. For example:

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E \text{ failures}/10^6 \text{ hours}$$

where λ_P = part failure rate

λ_b = base failure rate

π_T = temperature factor ← Temperature factor does not account for temperature cycling input.

λ_A = application factor

λ_Q = quality factor

π_E = environment factor

Comparison of MTTFs

Temperature Profile	MIL-HDBK-217	Die Attach Fatigue Model	Experimental Data 2P-Weibull
150-200°C	115,843 hours	15,300 cycles	18.7 hours (6320 cycles)
125-225°C	96,327 hours	10,800 cycles	12.2 hours (1058 cycles)

- MIL-HDBK-217 method does not account for temperature cycling loading and other relevant loading conditions.
- Die attach fatigue model provides a better estimate than the handbook. Improvement to the model includes obtaining material fatigue properties, incorporating intermetallic growth into the crack propagation, and estimation of junction temperature.
- Predicting lifetime using a population MTTF cannot account for variability from part to part.

Motivation for Health Monitoring Approach (for IGBT and System)

- Using MTTF to predict IGBT lifetime is not sufficient to avoid unexpected failures in the field due to the variability in prediction.
- Handbook approach ignores relevant loading conditions, device characteristics, and failure mechanisms leading to erroneous lifetime predictions.
- Physics-based lifetime prediction cannot avoid unexpected failures in the field due to variations from part to part and field loading conditions.
- An alternative approach to avoid failures is to monitor IGBT health individually under operation by using a data-driven method to analyze the operating data and detect for faulty conditions before failure occurs.

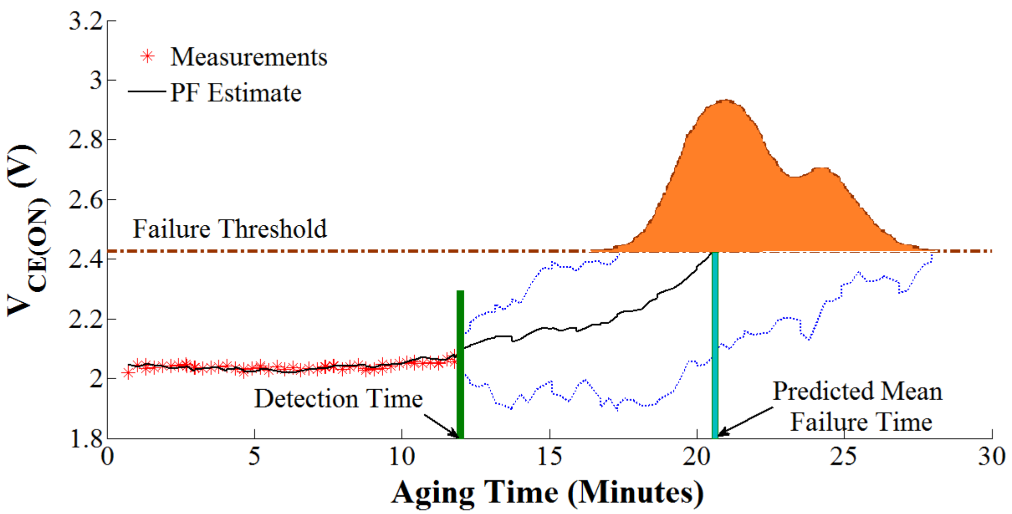
What We Need to Do?

- Relevant material properties for the critical failure mechanisms
- Ability to update the failure models quickly
- Modeling platforms for the units and components

- Life cycle condition information from monitoring
- Use of data for determination of anomaly at the level of interest
- Remaining useful life assessment ability

IGBT Prognostics

- Patil et. al. [9] IGBTs were monitored for V_{CE} and I_{CE} during continuous power cycling. Proposed a method to predict remaining useful life (RUL) of IGBT under power cycling by extrapolating V_{CE} curve to a failure threshold using particle filter
- Sutrisno et. al. [10] generated a K-Nearest Neighbor algorithm for fault detection of IGBTs under continuous power cycling conditions using monitored electrical characteristics such as V_{CE} and I_{CE} .

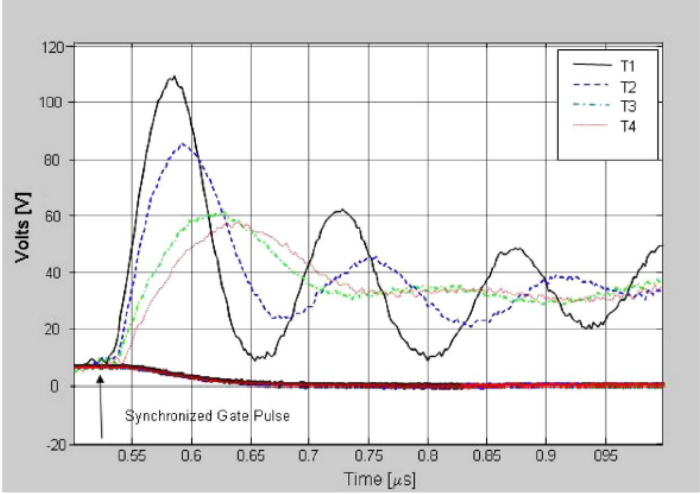


[9] N. Patil, “Prognostics of Insulated Gate Bipolar Transistors,” Ph. D. dissertation, Dept. Mech. Eng., University of Maryland, College Park, MD, 2011.

[10] E. Sutrisno, “Fault Detection and Prognostics of Insulated Gate Bipolar Transistor (IGBT) Using K-Nearest Neighbor Classification Algoritihm,” M.S. dissertation, Dept. Mech. Eng., University of Maryland, College Park, MD, 2013.

IGBT Prognostics

- Xiong et al. [11] proposed an online diagnostic and prognostic system to predict the potential failure of an automotive IGBT power module. A prognostic check-up routine was implemented that would be activated at a preset frequency and current during vehicle turn-on and turn-off.
- Ginart et al. [12] developed an online ringing characterization technique to diagnose IGBT faults in power drives. Analysis of the damping characteristic allowed the authors to identify failure mechanisms

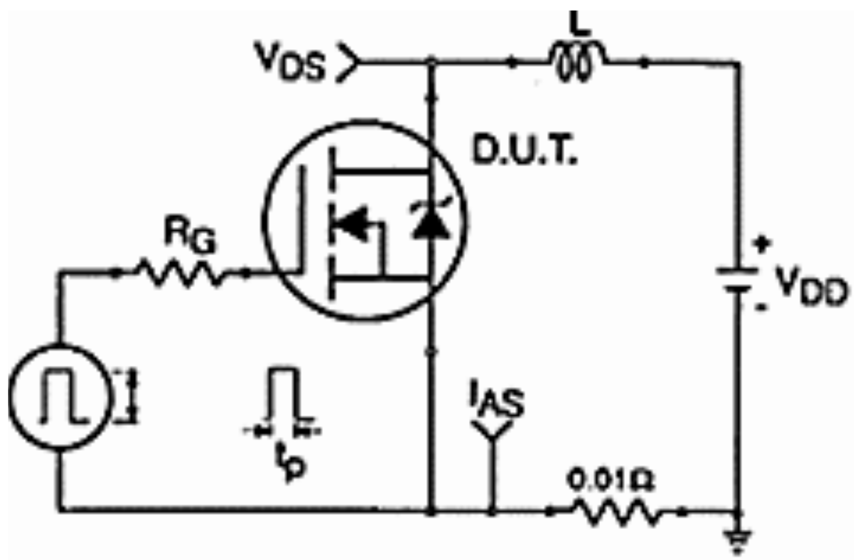


[11] Y. Xiong, Xu. Cheng, Z. Shen, C. Mi, H. Wu, and V. Garg, ―Prognostic and Warning System for Power-Electronic Modules in Electric, Hybrid Electric, and Fuel-Cell Vehicles,‖ IEEE Transactions on Industrial Electronics, Vol. 55, No. 6, pp. 2268-2276, 2008.

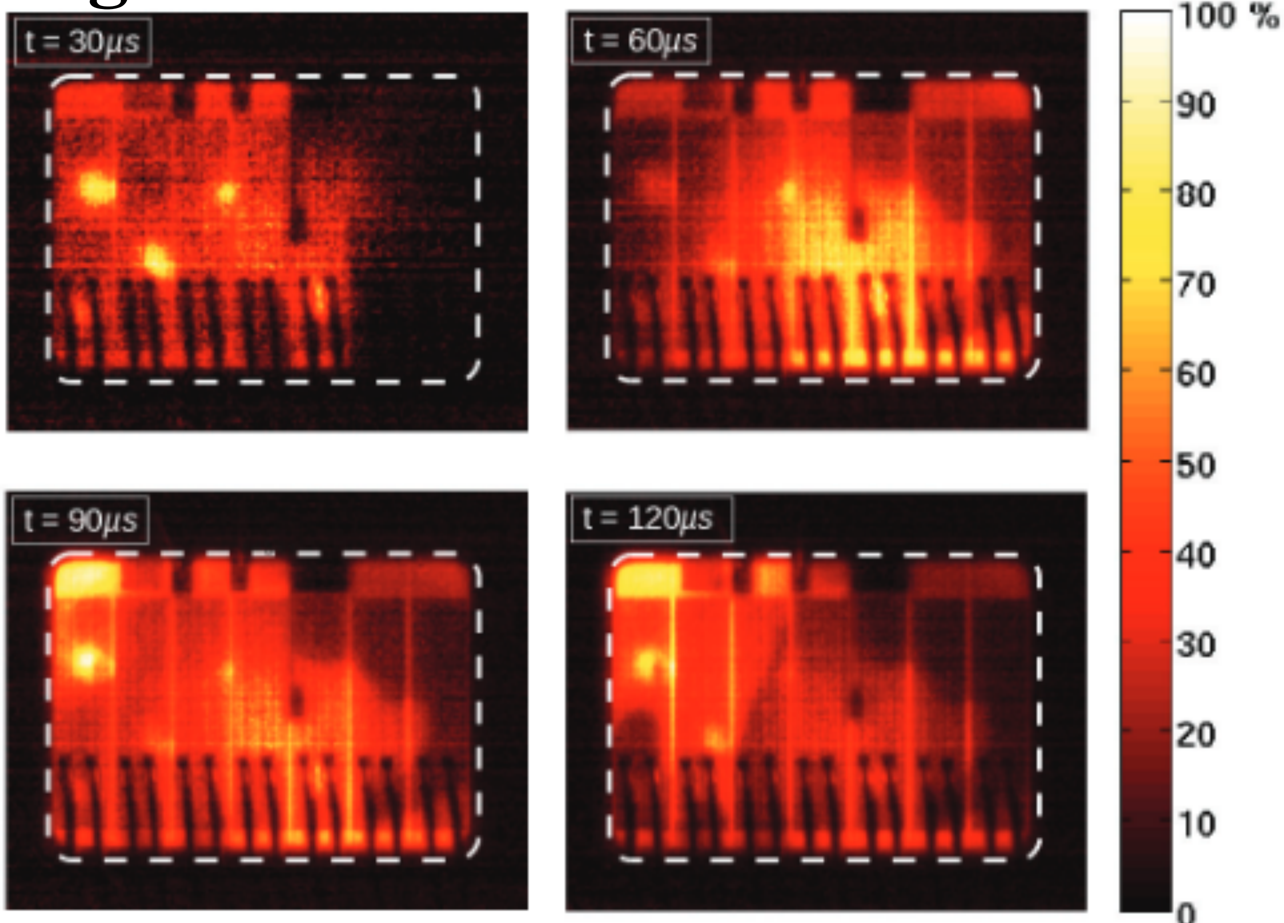
[12] A. Ginart, D. Brown, P. Kalgren and M. Roemer, ―Online Ringing Characterization as a Diagnostic Technique for IGBTs in Power Drives,‖ IEEE Transactions on Instrumentation and Measurement, Vol.58, No.7, pp.2290-2299, 2009.

Unclamped Inductive Switching (UIS) Current Imbalance

- IGBTs operated with inductive loads can experience voltages well above their breakdown rating if no voltage clamp is implemented
- Voiding and delamination caused by either aging or voiding leads to current imbalance within the IGBT cells, causing local heating



Heating within IGBT under UIS Conditions



Unstable behavior observed on die at nominal current localized heating [13]

[13] M. Riccio, A. Irace, G. Breglio, P. Spirito, E. Napoli, and Y. Mizuno, "Electro-thermal instability in multi-cellular Trench-IGBTs in avalanche condition: Experiments and simulations," in Proc. IEEE 23rd Int. Symp. Power Semiconductor Devices and ICs (ISPSD), May 23–26, 2011, pp. 124–127.

Dynamic Avalanche at Turn-off

- Similar to UIS conditions, dynamic avalanche can cause current imbalance between the cells of the IGBT
- Dynamic Avalanche can be self-induced if the gate resistance is too low causing high gate currents

Burned emitter contact pad for discrete IGBT