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AN6442
IGBT Module Failure Mechanisms
Application Note

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***Abstract*—This work investigates the failure mechanisms of Insulated Gate Bipolar Transistor (IGBT) modules, with a particular emphasis on understanding how overstress and wear-out malfunctions contribute to their degradation. The primary objective is to educate users about the various failure mechanisms that can affect IGBT modules. Moreover, the work introduces a basic approach for diagnosing the causes of these failures and outlines several design and operational tactics that can be employed to reduce the likelihood of such failures occurring.**

1 Introduction

According to field experience, power electronics converters are considered a weak link that has significant influence on overall electrical system reliability. Semiconductor switches are one of the most vulnerable components of the power electronics converters. As a result, the power switches such as IGBT modules may not satisfy their specified target lifetime and fail to continue operation due to different reasons.

Wire bonded IGBT modules are a common package type widely used in industrial and transportation traction applications. As presented in **Figure 1**, a wire bonded IGBT module consists of several layers, each made from different materials serving specific functions. The silicon chip is soldered onto a direct copper bonded (DCB) ceramic substrate. The top copper layer forms the electrical connections to the silicon chips, while the bottom copper layer of the DCB serves as the connection to the module's baseplate, facilitating heat transfer to the cooling system. The ceramic layer between the copper sheets provides electrical insulation between the silicon chip and the baseplate, while it transfers the heat from

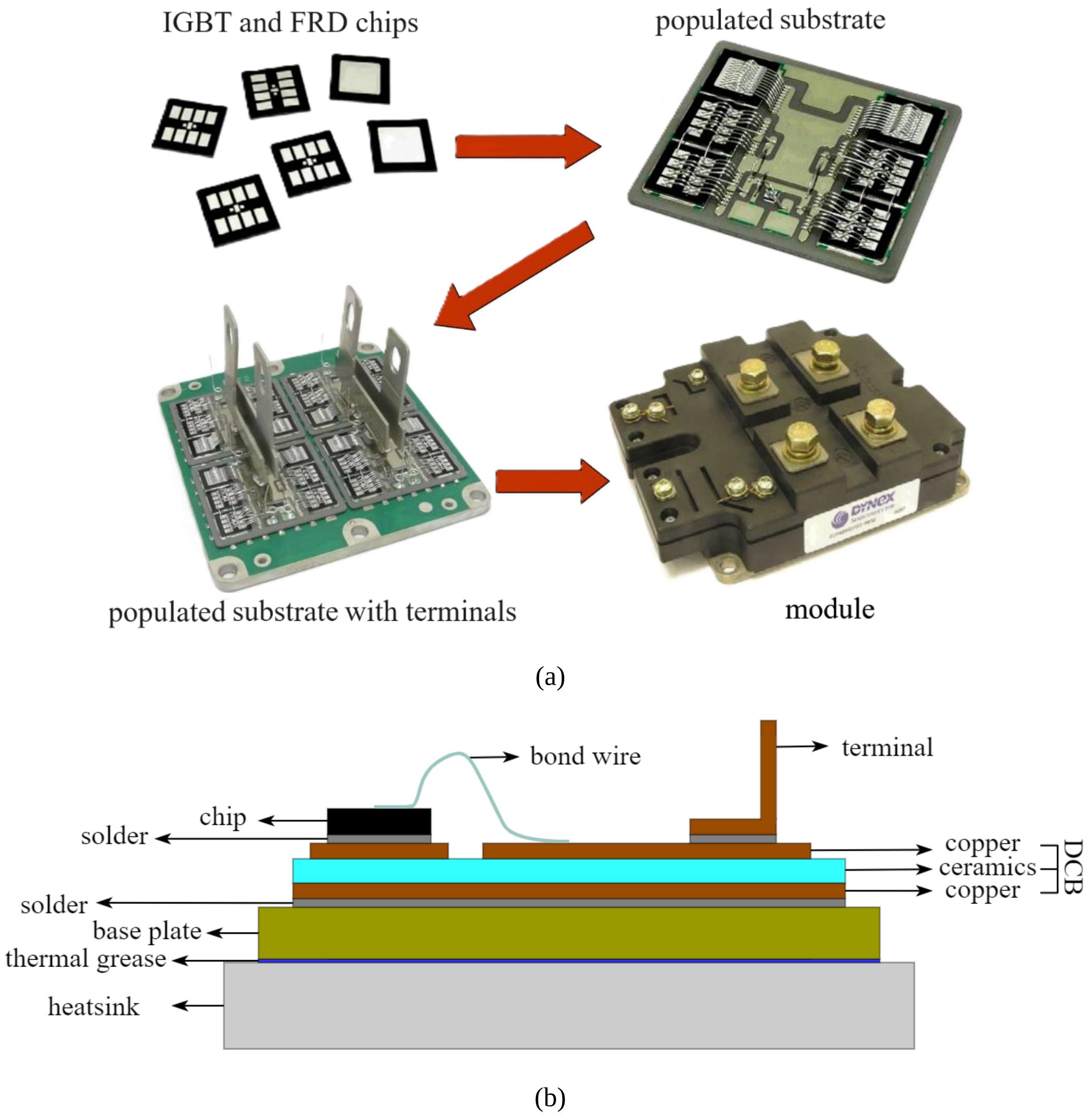


Figure 1. Wire bonded IGBT and fast recovery diode (FRD) module package. (a) A visual representation of the assembly process. (b) A cross-sectional diagram of the IGBT side.

the chip to the baseplate. Aluminium (or gold) bond wires are used for making additional electrical connections between the chip and other components on the substrate. The module assembly is completed with a baseplate, typically made of AlSiC, acting as a heat sink. This baseplate plays a crucial role in transferring heat from the chip to the cooling system, ensuring effective dissipation of heat to maintain optimal operating temperatures.

The IGBT module failures can result from three main failure categories, namely early failures, random (overstress) failures and wear-out (long-term) failures [1], [2].

Early failures are often attributed to defects introduced during the manufacturing process, material impurities, or design flaws. To address early failures, Dynex undertakes rigorous testing and quality assurance processes during production. Additionally, proper handling, installation, and initial operation practices can help mitigate the risk of early failures. This application note does not discuss early failures and operates under the assumption that the module is free from defects.

Unexpected overvoltage, overcurrent, system transients and system faults are main reasons for random failures, while thermal stresses coupled mechanical vibrations and humidity are the main causes for long-term failures. The random and wear-out failures are the main focus of this application note and are discussed in detail.

In general, IGBT module failure modes can be classified as open-circuit failure, short-circuit failure and parameter drift failure. Parameter drift occurs as a part degrades and the electrical characteristics such as collector-emitter voltage drift from the acceptable operating range due to the accumulation of damage within a device or module.

A failure mechanism is the underlying process that causes the degradation or failure of an IGBT module, leading directly to a failure mode, which is the observable manifestation of that mechanism. It is essential to pinpoint the root cause of each failure mechanism too, as understanding these origins is key to effectively slowing down or preventing their progression. Therefore, recently, a lot of research on failure mechanisms of IGBT modules has been done.

In the next section, some troubleshooting tables are provided. They are designed to assist in identifying the mechanism behind a failure and its root cause. Furthermore, all failure mechanisms mentioned in the tables are thoroughly explained in section 3.

Should the root cause of the failure remain unclear after consulting this application note, we encourage you to provide essential information along with the failed module. Our engineers at Dynex will then conduct a thorough and in-depth failure analysis, which will aid in the accurate identification of the cause of the failure. However, it is often impossible to determine the root cause of the failure due to the presence of stored energy in the failed power system. If a failure occurs, the stored energy is deposited into the module causing further damage, which can overwrite and mask the original root cause.

2 Troubleshooting

If a module fails to function before reaching its expected lifespan, especially if the discrepancy is substantial, it is crucial to determine the cause of this premature failure prior to replacing it with a new module. This pre-emptive measure helps to prevent further failures within the system. To assist in identifying the cause of a failure, **Tables 1-4** and the information provided in section 3 can be suitable resources.

An IGBT module may fail due to damage to the chip or any other components within its package. Therefore, after experiencing a failure, it is essential to carefully disassemble the module for a thorough inspection to determine which specific parts have been damaged.

2.1 Chip destruction

IGBT modules’ chip can fail due to exceeding the reverse bias of its Safe Operating Area (SOA), gate driver malfunction, and overheating. Each of these overstress failure mechanisms can result from other failures in the system, as presented in **Table 1** and **Table 2**.

There are other failure mechanisms for the chip that do not directly result from voltage/current abnormalities within the converter circuit. These types of failures which are mainly wear-out failure are often subtle and difficult to diagnose, typically requiring specialised tools to internally examine the module package and monitor its characteristics. These failures are summarised in **Table 3** and discussed in section 3. Dynex strives to reduce the likelihood of these failures to enhance the longevity of their products.

2.2 Package’s components destruction

Package components, including the housing, insulation gel, bond wires, solder layer, DCB substrate, baseplate, and terminals, can be damaged for various reasons. **Table 4** summarises the different failure mechanisms that can lead to the deterioration of these components. It's important to note that some of these issues may not be easily detectable, often requiring advanced technological methods for proper diagnosis and could be very time-consuming.

Table 1. Chip destruction: exceeding SOA and gate driver malfunction.

Failure mechanism	Root of the failure mechanism	System failure	Check point
Overvoltage (collector-emitter)	Excessive input voltage	A faulty input voltage may cause collector-emitter voltage to exceed its maximum limit.	Check the input voltage and overvoltage protection system.
	Excessive voltage spike during turn-off process	Snubber systems malfunction.	Check the voltage level during turn-off process. Check the turn-off current slope for gate driver and snubber integrity. Review the snubber circuit design. Check overvoltage level post overcurrent protection activation. Check overvoltage protection system.
		Gate driver malfunction can lead to excessive turn-off current slope, dI/dt.	
		Activating overcurrent protection may cause a swift current drop.	
		Excessive overvoltage due to reverse recovery of the diode.	
	Motor regenerative operation	During motor regenerative operation, the motor acts as a generator. This can result in a voltage increase in the system.	Check the collector-emitter voltage during motor regenerative operation. Check overvoltage protection system.
	Gate signal interruption	Interrupted gate signals creating brief off periods within each on cycle (i.e., presence of very short off period during on period in each switching pulse) can induce voltage spikes across the switch.	Check for the gate signal interruption which may result from faulty pulse signals or electro-magnetic interference.
	Inappropriate series connection	Improper voltage balancing in a series connection of IGBT modules can lead to an overvoltage condition in one of the modules.	Examine the balancing circuit and ensure that IGBTs with similar static and dynamic characteristics are utilised in series configurations.
Overvoltage ((gate-emitter)	Oscillation	Oscillations in gate-emitter voltage, possibly caused by long gate wiring, electromagnetic interference, or defective component (e.g., capacitors), can surpass the maximum gate-emitter voltage.	Ensure to verify the gate-emitter voltage, assess the parasitic inductance, and evaluate the condition of other components.
	High voltage source	A faulty gate driver's power supply can lead to exceeding maximum gate-emitter voltage.	
	Excessive voltage spike across gate	High parasitic inductance in the gate driver circuit or fast gate current slope can cause voltage spike across the gate-emitter	

Table 2. Chip destruction: overheating.

Failure mechanism	Root of the failure mechanism	System failure	Check point
Overheating from significant overcurrent	Fault	Overcurrent, caused by overload, IGBT short-circuit, arm short-circuit, output short-circuit, or ground fault, increases losses and heat generation.	Inspect load current, ground wiring, power circuit wiring, overcurrent protection, and device's overcurrent tolerance.
Overheating from increased losses	Collector-emitter voltage increase	Low gate-emitter voltage can increase collector-emitter voltage, leading to more conduction losses and heat generation.	Check gate-emitter voltage and assess collector-emitter voltage.
	Overcurrent due to micro shoot-through	Inadequate deadtime, self-turn-on from collector-gate capacitance, high noise, malfunctions in gate drivers, or logic circuits can cause arm micro shoot-through, increasing losses and heat generation.	Check the gate driver circuit, ensure the turn-off period and deadtime match, and assess for any occurrences of self-turn-on.
	Switching losses increase	Increased switching losses, potentially caused by higher switching frequency, gate resistance rise, gate-emitter voltage deviations, high snubber discharge current, or insufficient deadtime, can lead to elevated heat generation.	Examine the frequency, voltage, and deadtime of gate driver pulses, measure gate resistance, and evaluate the snubber design and its circuitry.
	Inappropriate parallel connection	Inadequate current balancing can lead to disproportionate losses in one of the modules, potentially resulting in its failure.	Examine the balancing circuit and ensure that IGBTs with similar static and dynamic characteristics are utilised in parallel configurations.
	Driving with gate open circuit	When a voltage is applied across the collector-emitter while the gate is in an open circuit condition, the gate-emitter capacitance can become charged, potentially leading to a high current flow due to a short circuit.	Ensure to verify the gate-emitter voltage and confirm that the gate-emitter is short-circuit when measuring the collector-emitter leakage current.
Overheating from heat dissipation malfunction	High thermal resistance of thermal interface layer	Improper mounting of the IGBT module, caused by insufficient tightening, low-quality or inadequate thermal grease, or excessive heatsink warpage, can lead to higher thermal resistance, reducing heat dissipation and raising the device's temperature.	Review and check mounting-down of the module. Please refer to AN4505 for guidance on mounting of Dynex HV IGBT modules.
	Abnormal rise in ambient temperature	Excessively high ambient temperatures can push the IGBT module's junction temperature beyond its maximum allowable limit and intensify thermal stress on the components.	Enhance the cooling system to handle significant increases from normal ambient temperatures and ensure the abnormal case temperature protection system is functioning properly.
	Cooling system malfunction	A malfunctioning cooling system, resulting in reduced heat dissipation, reduces the device's ability to expel generated heat, leading to a further rise in device temperature.	Inspect the cooling system and abnormal case temperature protection. Assess the module's placement for optimal airflow. Examine the heatsink for any damage or dust accumulation and grease build-up (clogging). Examine the cooling fan speed. If liquid-cooling systems are used, ensure the flow rate through these is high enough, and inspect the coolant for any degradation.

Table 3. Chip destruction: other failure mechanisms.

Failure mechanism	Root of the failure mechanism	System failure	Check point
Cosmic ray radiation	External radiation	Cosmic ray radiation can generate secondary particles via reactions in the atmosphere. These secondary particles can create charge carriers in the semiconductor material, leading to unintended conduction or breakdown, disrupting the normal operation of the IGBT.	Attributing device failures to cosmic rays is complex due to their random and infrequent nature. The emphasis is typically on spotting trends or vulnerabilities that imply cosmic rays as a likely factor.
Time dependent dielectric breakdown (TDDB)	Degradation of insulating materials over time	TDDB is a failure mechanism associated with the degradation of insulating materials over time due to the application of a voltage across gate-emitter.	Perform a thorough electrical test to detect any unusual gate leakage currents, gate voltage blocking capability or time-constant for gate-emitter charging, and carefully inspect for cracks or conductive paths that may have developed in gate oxide layer.
Static electricity	Static electricity charge or discharge	Applied static electricity may lead to overvoltage across gate-emitter or penetrate in gate oxide layer and alter its characteristics.	Check measures against static electricity.
Electro-chemical migration (ECM)	Migration of metal ions across insulating materials	ECM in an IGBT module refers to a phenomenon where metal ions migrate across insulating materials under the influence of an electric field, leading to the formation of conductive paths. This migration can result in electrical shorts and ultimately cause the failure of the IGBT module. High temperature and humidity can accelerate ECM.	Utilise specialised tools like microscopes to identify signs of ECM, and meticulously inspect packaging and encapsulation materials for any damage or wear that may have allowed moisture penetration, potentially causing ECM. Perform a thorough electrical test to detect any unusual leakage currents or voltage blocking capability.
Metallisation reconstruction	Thermal cycling	Restructuring of the metal layers within the device, often caused by thermal cycling, leading to performance degradation or failure.	Inspect the metallisation layer using high-resolution tools like microscopes for complete examination. Perform a thorough electrical test to detect any unusual electrical resistance.

Table 4. Package’s components destruction.

Failure mechanism	Root of the failure mechanism	System failure	Check point
Mechanical stress	External force	Stress exerted on the housing and terminals from incidents such as dropping or collision can lead to cracks in various components, or potentially cause internal short- or open-circuit.	Inspect the conditions of both transportation and operational areas. Additionally, examine the module for any internal and external cracks in an of the components. Check abnormal temperature protection system. Finally, evaluate the vibration conditions to ensure stability.
	Thermal shock	Sudden temperature fluctuations, caused by cooling system failures or substantial overcurrent, can lead to internal mechanical stress due to differential expansion of components. This stress may result in cracks in bond wires, solder layers, insulation gel, housing or even chip.	
Vibration	Vibration	Excessive vibration during production, transportation or operation, especially in traction applications, can subject the package components to additional mechanical stress. This increased stress may lead to cracking, particularly in the solder layer and bond wires. Furthermore, such vibrations can also loosen screws essential for mounting the module.	
Overheating	Increased heat generation	Heat losses from the chip and conductors are initially dissipated to the package components. If the cooling system's heat dissipation is inadequate due to its malfunction or increased losses, local hot spots can develop, potentially leading to the deterioration of the nearby components. See also Table 2.	Same as Table 2. Additionally, examine the module for any internal and external cracks/melting in any of package’s components.
	Cooling system malfunction		
Bond wire and solder layer fatigue	Temperature cycling	Because of different coefficients of thermal expansion between the package materials, temperature cycling inside the package results in thermomechanical fatigue.	Inspect the module thoroughly for any internal or external cracks, particularly in the bond wires and solder layers. Additionally, reassess the design to achieve reduced temperature fluctuations during each operating cycle and enhance the effectivity of the cooling system.
Solder layer creep	Temperature cycling duration	The constant application of high temperatures can induce time-dependent deformation in solder joints.	
Flashovers	Humidity and pollution	Salt traces and other conductive formations on IGBT module terminals and gate driver boards may cause flashovers and improper operation of gate driver.	Ensure to regularly assess the operating environment and avoid exposing the device to humid and polluted conditions. Additionally, inspect the package for any signs of corrosion, both internally and externally. Perform a thorough electrical test to detect any unusual leakage currents, and electrical/thermal resistance.
Corrosion	Humidity and pollution	Corrosion can alter the material's properties, leading to change of module’s characteristics, and it can also accelerate the formation of cracks in internal and external package’s components.	
Aging	Insulation material deterioration	Deterioration of insulation materials, resulting from a combination of thermal, electrical, and environmental stresses, is an inevitable process. The best approach is to maintain the device in optimal operating condition and design it to function at lower temperatures with lower temperature cycling, as these measures can help mitigate potential issues.	Check how old the module is. Check the partial discharge. Inspect the insulation gel for any physical alterations and perform electrical testing such voltage blocking capability and material dielectric constant to assess its integrity. Check the insulation material lifespan.
	Long-term operating applications	Prolonged exposure to voltage, especially under conditions of high temperature or/and humidity (temperature humidity bias), can significantly shorten the lifespan of the device since it accelerates other failure mechanisms.	Check the device lifespan for long-term voltage application.
	Storage in abnormal conditions	Storing the device for extended periods, particularly in environments with extremely high or low temperatures, high humidity or corrosive gas atmosphere, and dusty environment can notably decrease the device's lifespan.	Check the device’s guidance for storage.
Electro-migration	Migration of metal atoms	Metal atoms migrate in the direction of electron flow, leading to the progressive thinning and eventual breaking of conductive paths.	Inspect the module thoroughly for any cracks or loss of thickness in the bond wires and solder layers. Perform a thorough electrical test to detect any unusual electrical resistance.

3 IGBT modules failure mechanisms

IGBT module failure mechanisms are mainly classified into chip-level failure and package level failure. Generally, overstress may cause IGBT chip failure while package failure is usually caused by multiple factors and is closely related to the internal structure [1], [2], [3], [4], [5], [6].

3.1 IGBT module chip related failure mechanisms

Overstress failure mechanisms are mainly due to events such as gate overvoltage, collector-emitter overvoltage, overcurrent, latch-up, and burnout due to cosmic rays. On the other side, the most common IGBT chip wear-out failure mechanisms are time dependent dielectric breakdown, static electricity charge-discharge, hot carrier injection, electro-chemical migration, and metallisation reconstruction. In addition, thermal issues compromise both short-term and long-term reliability of IGBT modules depending on their magnitude.

3.1.1 Overvoltage

Collector-emitter overvoltage may take place due to many reasons such as input voltage surges, control signal anomalies, voltage spike during turn-off process and unexpected load condition. Gate overvoltage may happen due to external surge, gate driver anomalies, voltage spike due to parasitic inductance, and gate circuit oscillation. The overvoltage may lead to different breakdowns, which are presented below.

3.1.1.1 IGBT cell breakdown

High voltage spikes induced by high falling rate of collector-emitter current and stray inductance can destroy an IGBT cell during turn-off, especially under repetitive spikes. Due to the high turn-off voltage spike, electric field can reach the critical field and break down one or more IGBT cells initially, leading to high leakage current as well as high local temperature. Subsequently, the heat-flux radially diffuses from the overheated region to the neighbouring cells, eventually resulting in catastrophic failure.

The high voltage breakdown can also happen due to high value of collector-emitter voltage. It results into rapid destruction followed by a surge of current during turn on of the device.

3.1.1.2 Oxide layer breakdown

IGBTs have a gate oxide layer that insulates the gate terminal from the emitter and collector regions. Exceeding the specified maximum gate-emitter voltage, can lead to the breakdown of this oxide layer, causing a short circuit between the gate and emitter. This breakdown can be destructive and may result in permanent damage to the IGBT.

3.1.1.3 Avalanche breakdown

High values of collector-emitter voltage can also lead to excessive electric fields within the device, potentially triggering avalanche breakdown. This can result in uncontrolled and damaging current flow. Therefore, it is critical to clamp the collector-emitter voltage during switching transients.

3.1.2 Overheating from increased losses

Increased switching and conduction losses can result in increased heat generation, pushing the junction temperature of the devices beyond their tolerance levels, potentially damaging the chip.

While switching losses may increase due to gate-driver or control system malfunction, it usually doesn't result in sudden chip failure unless there is a significant alteration in gate-emitter voltage pulses. Likewise, increased conduction losses resulting from reasons mentioned in **Table 2** do not typically lead to sudden device failure. However, this failure mechanism is still categorised as random failure since it significantly reduces the device's lifespan and is not normally expected to occur.

3.1.3 Overheating from significant overcurrent

Significant overcurrent can result from internal or external faults, improper control actions, or unexpected load events, and its effect is often sudden and leads to thermal runaway, defined in section 3.2.1. Overheating from significant overcurrent failure mechanism can be categorised into the following types.

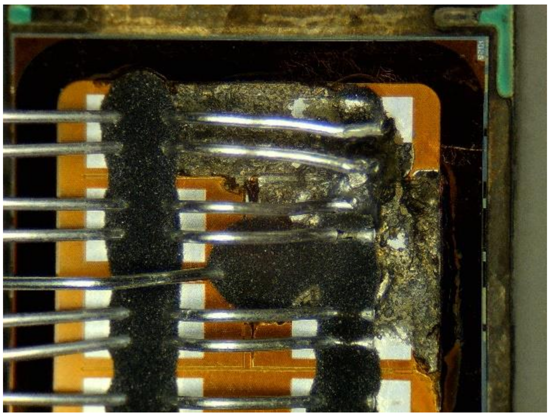


Figure 2. Overcurrent failure.

3.1.3.1 Energy shock

The high-power dissipation within a short time is defined as energy shock. Under the action of overcurrent stress which can lead to energy shock, hot spots are formed locally in the IGBT package’s components. When the local temperature is too high, it can damage the chip and other package components such as bond wires, ultimately resulting in device failure. **Figure 2** shows large melting spots in metallisation localised next to bond wires caused by significant overcurrent.

3.1.3.2 Second breakdown

The occurrence of overcurrent conditions in an IGBT can escalate the risk of second breakdown. Heightened current levels may lead to localised stress concentrations within the device. These areas of concentrated stress can compromise the IGBT's voltage-blocking capability and further increase the current flow through these stressed regions. This can result in additional heating and, eventually, the destruction of the device.

3.1.3.3 Latch-up

Latch-up is a condition where the collector current can no longer be controlled by the gate voltage. Latch-up happens when the parasitic internal NPNP thyristor of an IGBT turns on which could be due to high collector-emitter current, high off-state collector-emitter voltage or fast reduction of gate voltage. This type of event can occur due to excessive temperatures seen during high current conduction.

3.1.4 Cosmic ray radiation

In normal use, devices are subject to naturally occurring external radiation, and when energetic particles generated in the upper atmosphere due to Cosmic Rays from space pass through a semiconductor device, they can collide with silicon atoms. This can create electron-hole pairs which may be multiplied many times through impact ionisation. The generation of these free charge carriers can lead to current pulses within the semiconductor material. These current pulses can potentially disrupt the normal operation of the semiconductor device, leading to permanent damage to the chip. **Figure 3** shows a typical failure site due to cosmic ray.

Cosmic ray radiation failure is a significant concern in high-altitude and space applications, where the intensity of cosmic rays is much higher than at the Earth's surface [7].

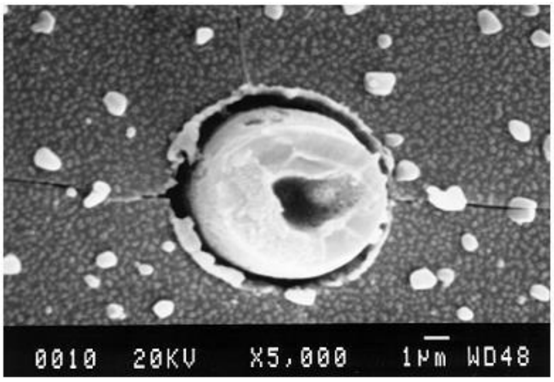


Figure 3. Burn out as a result of a neutron impact.

3.1.5 Overheating from heat dissipation malfunction

High temperature can lead to destruction of the chip due to variation of Temperature Sensitive Electrical Parameters (TSEP). For example, threshold voltage, V_{th}, which generally reduces with increasing temperature. If the V_{th} fall below the built-in voltage, V_{bi}, of the junction then a latch-up type fail can be seen. Furthermore, the maximum temperature that the chip can tolerate is limited by the Intrinsic Temperature. Above the intrinsic temperature current filamentation & failure can be expected. Improper operation of the cooling system, degradation of the Thermal Interface Material (TIM) via pump-out, and abnormal high ambient temperature can lead to high junction temperature of the IGBT.

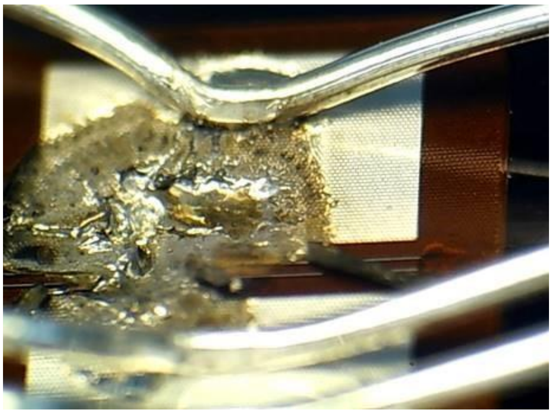


Figure 4. Thermal excitation failure.

A key contributor to temperature rise is a TIM with raised thermal resistance, often due to improper mounting or the use of substandard thermal grease. Such conditions may subsequently lead to localised overheating within the material stack, potentially resulting in premature module failure. **Figure 4** shows melting of chip metallisation and die-attach solder due to high temperature.

3.1.6 Time dependent dielectric breakdown (TDDB)

TDDB is a failure mechanism associated with the degradation of insulating materials over time due to the application of a high voltage. In an IGBT module, the gate oxide layer degrades as a result of excessive electric field in the material. If left unchecked, TDDB can ultimately result in the failure of the semiconductor device. The cumulative effects of increased leakage current, reduced breakdown voltage, and the eventual dielectric breakdown can render the device non-functional.

3.1.7 Static electricity

The electrostatic charge that accumulates can result in a very high voltage that can damage the gate oxide layer. This high voltage is due to the potential difference created by the separation of charges. When an operator handles the module in an environment with static electricity, the sudden, high voltage of an electrostatic discharge event is capable of breaking through the gate oxide layer. Although the module might appear to function normally post-discharge, such an incident can inflict latent damage that is challenging to detect. Subsequently, when the module is exposed to higher voltages, this pre-existing weakness can precipitate a gate-emitter short-circuit, leading to outright failure.

3.1.8 Hot carrier injection

At high electric fields, the phenomenon of hot carrier injection occurs when the energy of carriers (such as electrons or holes) surpasses the lattice potential barrier, leading to carrier injection into the gate oxide layer. This process can accumulate significant damage to the layer if allowed to continue for long periods. An IGBT is a device based on a MOS gate structure, and its gate oxide layer is typically thicker than a MOSFET. Hence, gate damage caused by hot carrier injection is less common, but it will lead to changes in the external characteristics of the IGBT, such as gate threshold voltage, transconductance, and leakage current, eventually leading to device failure.

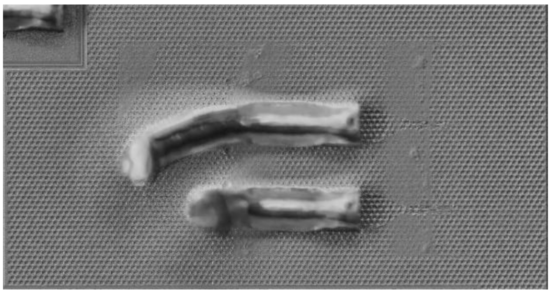
3.1.9 Electro-chemical migration

Electro-chemical migration in an IGBT module refers to a phenomenon where metal ions migrate across insulating materials under the influence of an electric field, leading to the formation of conductive filaments. This migration can result in electrical shorts many of which will fuse open-circuit due heating effect of fault current through the filament but ultimately can cause the failure of the IGBT module. For example, in humid environments, under high voltage and temperature, electro-chemical migration at chip passivation layer and terminal structure can cause an increase in leakage currents and gradual loss of blocking capability. Please refer to [8] for further information.

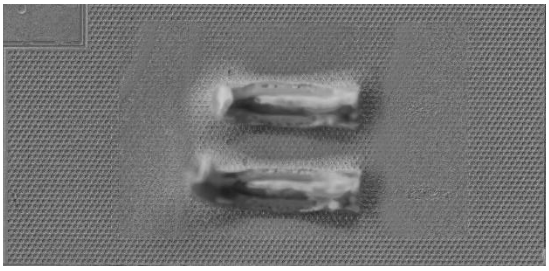
3.1.10 Metallisation reconstruction

In practice, the forward conduction current flowing through a controllable device, such as IGBT modules, causes the temperature to rise. Conversely, during the non-conduction period, the temperature decreases. Therefore, the power module is continually subjected to temperature changes during operational cycles.

Due to the temperature cycling, tensile or compressive forces are imposed on the thin metallisation layer, which typically is an aluminium metal applied on the chip surface. Stress arises from the difference between the thermal expansion of the chip and the metallisation layer. Under extreme conditions the metallisation layer may melt and resolidify due to localised temperature fluctuations; that is, the reconstruction phenomenon occurs. This impacts the function of the metallisation layer by reducing its ability to distribute the current across the whole chip.



(a)



(b)

Figure 5. Metallisation degradation failure. (a) Before. (b) After.

This increases the on-resistance of the IGBT module and indirectly increases the on-voltage drop of the IGBT. The power loss of the module will increase, and the junction temperature will also increase, which is not conducive to the reliable operation of the IGBT module. **Figure 5** shows metallisation degradation as a result of temperature cycling.

3.2 Package related failure mechanisms

Thermal shocks, mechanical shocks, and thermal runaways are the main causes of overstress package related failures. Typically, thermomechanical fatigue, thermomechanical creep, electro-migration and corrosion are the main causes of wear-out due to package related failures.

3.2.1 Package overheating

Overheating can significantly accelerate various failure mechanisms in electronic components, leading to a gradual degradation of their functionality or, in extreme cases, it can cause thermal runaway and their immediate destruction if temperatures exceed their specified limits. The rate at which these components degrade is directly proportional to the severity of the overheating. Higher temperatures typically result in more rapid deterioration.

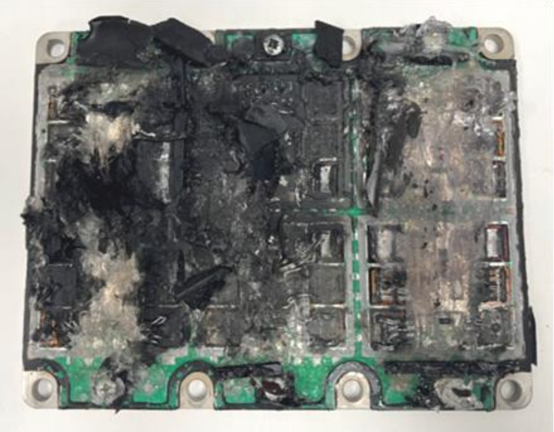


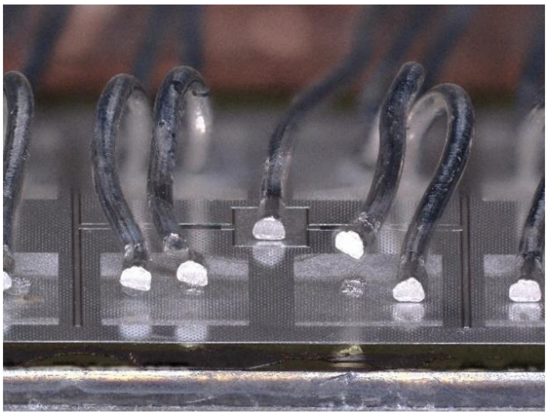
Figure 6. Thermal runaway failure.

Thermal runaway in an IGBT module occurs when the heat generated by the device exceeds the cooling system's capacity to dissipate it, leading to a self-reinforcing cycle of increasing temperature of the package. Failure in the cooling system or control system, overvoltage, and overcurrent (particularly short-circuit current) may lead the module to thermal runaway which can quickly destroy (melt) IGBT module’s components such as chip, bond wires and solder joints. **Figure 6** shows the extensive destruction of an IGBT module as a result of thermal runaway.

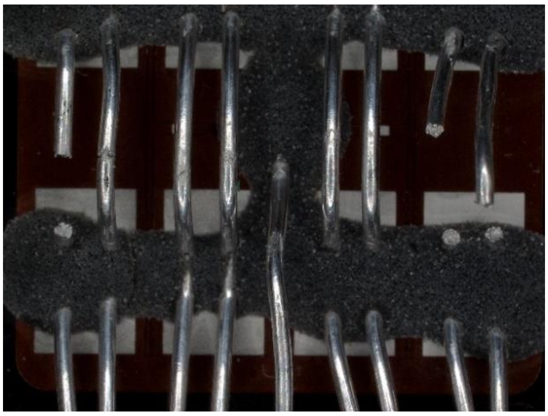
3.2.2 Mechanical stress

Mechanical shock (force) refers to the sudden and intense physical impact or vibration experienced by a device. It can pose a risk of failure in IGBT modules, which are sensitive electronic devices. Mechanical shock can occur during transportation, handling, assembly, or operation. In addition, mechanical shock can be caused by thermal shock which occurs when the device experiences rapid and severe temperature changes, typically from high to low temperatures or vice versa. This sudden thermal gradient can induce mechanical shock within the IGBT module due to different coefficients of expansion of the package materials.

Mechanical shock can lead to cracks and fractures of different package components such as solder joints, chips, bond wires, DCB, housing, and insulation.



(a)



(b)

Figure 7. Bond wire degradation due to thermo-mechanical fatigue. (a) Bond wire lift-off. (b) Bond wire heel cracks.

3.2.3 Bond wire fatigue

As previously mentioned, the IGBT module is continually subjected to temperature cycling, as the forward conduction current flowing through it causes the temperature to rise, and the current dropping to zero leads to a temperature decrease. Because of the different coefficients of expansion between the package materials, temperature cycling inside the package results in thermomechanical fatigue. Therefore, thermomechanical fatigue in an IGBT module occurs due to repeated cyclic loading during its operational cycles. As a result of thermomechanical fatigue, bond wire can crack, and lift-off as shown in **Figure 7**. Other factors, such as fluctuations in ambient temperature and vibration, can accelerate this failure process.

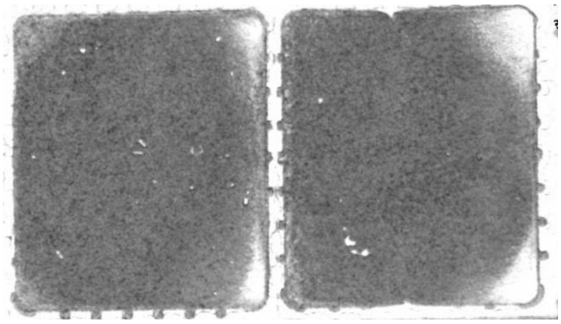


Figure 8. Solder layer delamination due to thermo-mechanical fatigue.

3.2.4 Solder layer fatigue and creep

An IGBT module in which solder has been used as an interconnect material consists of two parts: a chip to substrate solder layer and a substrate to baseplate solder layer. Owing to the diversity of packaging materials, the thermal expansion coefficients between layers are different. During operation, owing to constant temperature fluctuations, different mechanical stresses are generated on the different layers, which in turn leads to different degrees of deformation in each layer of the material. Compared to the other layer used in the module construction the solder is thinner and has a lower modulus of elasticity. Hence, the solder layer accumulates mechanical damage compared to the other layers making it susceptible to fatigue type failures.

Under cyclical thermal stress, the solder layer gradually develops cracks and voids, and eventually, solder layer delamination may occur [9] [10], as shown in **Figure 8**. Thermomechanical creep in an IGBT module is associated with prolonged exposure to increased temperatures during operation. The constant application of high temperatures can induce slow, time-dependent deformation in the materials, particularly in solder joints and other critical components. This deformation may lead to the gradual deterioration of the module’s structural integrity, impacting its overall performance and reliability.

3.2.5 Vibration

Constant vibrational stress can cause mechanical fatigue and eventual failure of bond wires and solder joints, essential for electrical continuity. In extreme circumstances it can also induce cracks in the semiconductor die or substrate, disrupt internal connections, and lead to the delamination of critical layers like die attach and encapsulants. Such effects compromise the structural integrity and electrical functionality of the module. Additionally, vibration can exacerbate pre-existing micro-defects, leading to accelerated degradation, and can cause misalignment of components like heat sinks, indirectly affecting thermal management. In scenarios with resonance, where the vibration frequency aligns with the natural frequency of components, the damage can be particularly severe due to the amplified stress.

3.2.6 Flashovers

Insufficient protection of the converter hardware against the environment, particularly in humid environment, leads to the build-up of salt traces and other conductive deposits on IGBT module casing and gate driver boards. They may cause flashovers and improper operation of gate driver that the device is not designed to handle.

3.2.7 Corrosion

The investigation of humidity related failure mechanism (HRFM) is of high importance for reliable operation of IGBTs [11]. In high-humidity and high-salt spray environments, external interface corrosion is a failure mechanism that cannot be ignored. The metal interface exposed to high salt spray and high humidity is the weakest link of the module, and its corrosion phenomenon can directly affect the electrical characteristics of the module. In addition, corrosion byproducts assisted by humidity may get into IGBT modules and react with the internals, resulting in long-term degradation. The manner in which corrosion occurs is highly dependent on the materials involved and the presence of contaminants. High levels of humidity and corrosive chemicals existing in many industrial applications (e.g., mining, cement, oil, gas, and marine) may result in corrosion of bond wires accelerating their mechanical degradation, and eventually leading to their rupture.

3.2.8 Aging

Insulation material aging in IGBT modules can occur over time due to various factors, and it can contribute to device failure. The insulation materials in IGBT modules are crucial for providing electrical isolation between different components and preventing unintended electrical paths. Aging of insulation materials can result from a combination of thermal, electrical, and environmental stresses. For example, partial discharges at the interface between the ceramic and metal layers produce small discharge activity, while the partial discharges at the metal edges might be in the range of a few nC, leading to the decomposition of silicone gel into gaseous products and reducing the insulating capability of the material. In addition, humidity severely degrades the insulation characteristics of the module encapsulation materials such as silicone gel, particularly at high temperature and long-term voltage application. **Figure 9** shows gas bubbles formation in silicone gel.

Storing IGBT modules for extended periods, especially in environments characterised by extremely high or low temperatures or high humidity, can markedly reduce their lifespan. Even though the IGBT modules are not operating, such conditions can still lead to thermal stress, material degradation, corrosion, and moisture-related damages, which are detrimental to the performance and reliability of the modules’ components.

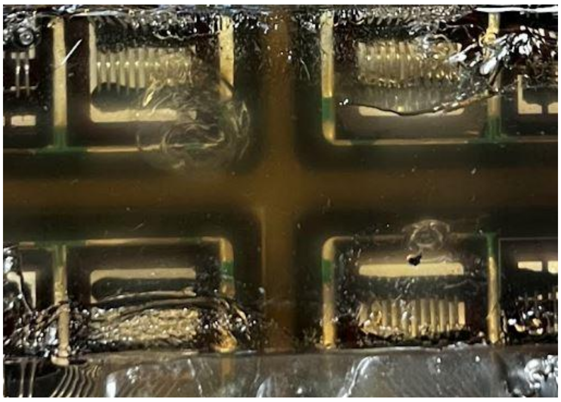


Figure 9. Gases bubbles in silicone gel due to surface corrosion.

3.2.9 Electro-migration

Electro-migration is the phenomenon where metal atoms migrate in the direction of electron flow, leading to the progressive thinning and eventual breaking of conductive paths. In an IGBT module, high electrical currents passing through the bond wires and metallisation layers can cause the movement of metal atoms due to electro-migration.

Table 5. IGBT modules' failure mechanisms.

Category	Site	Mechanism	Mode
Random	Chip	Overvoltage	• Short circuit (majority of cases) • Open circuit
		Overheating	
		Cosmic ray radiation	
	Package	Mechanical shock	• Open or short circuit • Melting and burnout
		Overheating	
Wear-out	Chip	TDDB	• Faults in gate drivers • Faults in switching • Reduced voltage blocking • Higher V_{CE} • Higher thermal/electrical resistance • Different gate-emitter charging time-constant
		Static electricity	
		Hot carrier injection	
		Electro-chemical migration	
		Metallisation reconstruction	
	Package	Bonding line fatigue	• Thermal issues • Leakage current issues • Reduced voltage blocking • Higher V_{CE} • Open circuit • Higher thermal/electrical resistance • Different partial discharging
		Solder layer fatigue and creep	
		Vibration	
		Flashovers	
		Corrosion	
		Aging	
		Electro-migration	

3.3 Interactions between failure modes

Excluding the early failures due to manufacturing and installation defects, the failure mechanisms are summarised in **Table 5**. In real case situation, failure mechanisms compete against and interact with each other to accelerate module degradation.

For example, solder degradation competes with bond wire degradation. The degradation of solder layer deteriorates the integrity of the thermal path causing an increase in thermal resistance. If the solder layer degradation dominates, the peak-to-peak fluctuation of the junction temperature will increase in a way that accelerates the degradation of the bond wire and accelerates the degradation of the solder as well. Failure mechanisms keep accelerating one another until the complete deterioration of the package.

For more details and images related to each failure mechanism and their interactions, please refer to sources [1]-[11].

4 IGBT modules failures diagnosis at Dynex

Should the cause of failure remain unclear after reviewing sections 1-3, the malfunctioning module may be returned to Dynex. Upon receipt, our team of engineers will perform a thorough failure analysis to determine the root cause of the issue.

If you have any suggestions for the cause of the failure or additional information that might aid in identifying the cause of the failure, please include them. Your insights could be invaluable in our analysis.

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