AN 5945

IGBT Module Reliability

Application Note

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INTRODUCTION:

Dynex Semiconductor products are used in a variety of power electronics systems such as power generation and distribution systems, marine and rail propulsion drives and auxiliaries, induction heating, industrial motor drives and power supplies.

This document describes both the process and analytical methodology that is used to both deliver and quantify product reliability.

An understanding and commitment to such a methodology is essential for Customer confidence in an age of continuously improving technologies required to meet the ever increasing harsh environments and Governmental legislation for environmentally friendly product.

IGBT MODULE

Fig. 1 illustrates the basic components and the construction of the IGBT module. IGBT and FRD (Fast Recovery Diode) chips are mounted on one side of the AlN (Aluminium-Nitride) or alumina DCB (Direct Copper Bonded) substrate using lead free solder. The DCB is also soldered to the copper or Aluminium-Silicon-Carbide (AlSiC) metal matrix composite base plate. The substrate provides electrical isolation to the base plate while the base plate provides the thermal path to the external heatsink. The electrical connections are provided by the heavy wire-bonds and the copper bus-bars. A coating of a special polymer is sometimes used over the wire bonds to enhance the power cycling capability. The module assembly is then enclosed in a plastic housing. The inside of the module is filled with silicone gel to provide electrical insulation and also overfill of epoxy resin to provide rigidity.

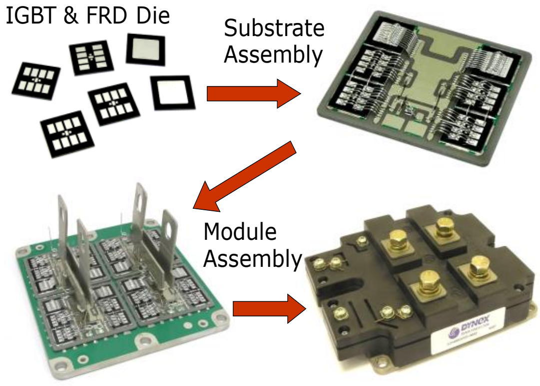

Fig. 1 Construction of IGBT module

Owing to the complexity in construction, the overall reliability of the module depends on the individual components, their material properties, and their interactions with external and internal stresses.

THE CONCEPT OF RELIABILITY

Reliability is a design engineering discipline, which applies scientific knowledge to assure a product will perform its intended function for the required duration within a given environment. This includes designing in the ability to maintain, test and support the product throughout its total life cycle.

As a summary statement, reliability is defined as the probability that a product will perform a required function, under the stated conditions, in a defined environment for a stated period of time. The fundamental understanding of a reliability of any product requires a basic understanding of failure mechanisms and how the failure rate is determined.

FAILURE MECHANISMS

The IGBT module failures can be classified into two main categories namely

- The random failures
- The wear-out failures

Random failures:

These failures are caused by external accidental event such as particle radiation, voltage transients, and damage by service actions leading to momentary over-stress. This type of failure is not related to the length of service or the age of the device. Figure 2 shows a typical failure site due to cosmic ray activity.

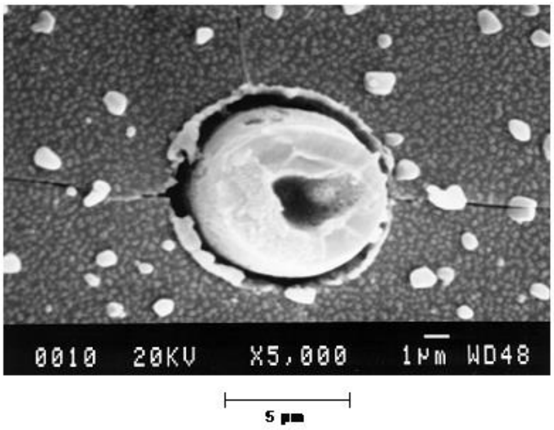

Fig.2 Burn out as a result of a neutron impact

Wear-out failures:

These types of failures are attributed to the accumulation of incremental physical damage under the operating load (stress) conditions altering the device properties beyond the functional limit. Some examples of wear out failures are the gate oxide breakdown, passivation failure at the blocking junction, dielectric failure of the insulating material, wire bond cracking, and delamination of solder joints. Each and every one of the packaging component is subject to wear out and needs to be considered collectively when predicting life of the whole device. Figures 3-5 show a selection of such wear out mechanisms.

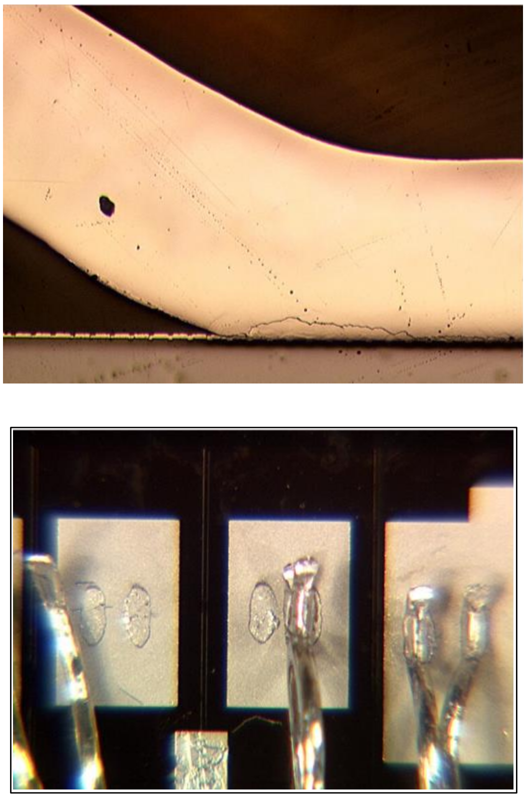

Fig.3 Wire-bond cracking and ultimate lift-off as results of thermo-mechanical fatigue during power cycling

PREDICTIVE RELIABILITY

The overall reliability of a system consisting of many active and passive components is estimated using individual failure rate of each component. The failure rate is used to estimate the MTBF (Mean time between failures) of a component. In a repairable system the MTBF is useful in organising a repair/maintenance schedule for the system. The unit of failure rate is FIT (1 FIT = 10^{-9} /h).

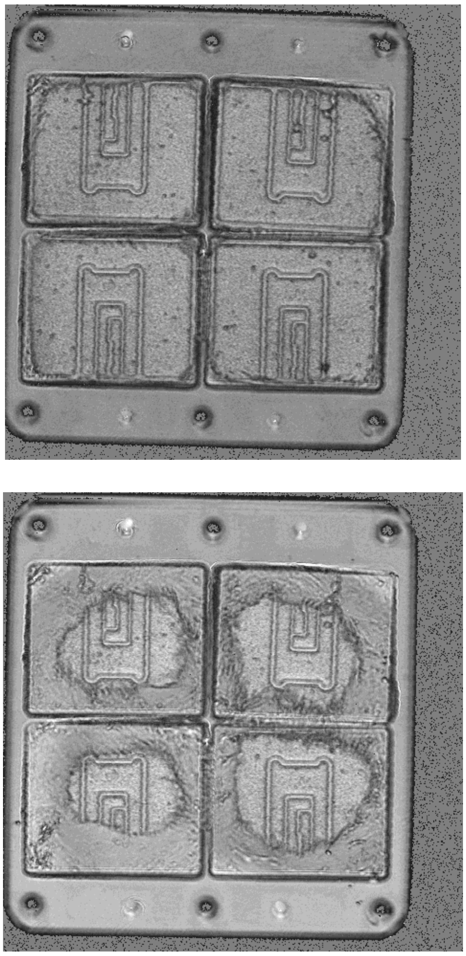

Fig. 4 Progressive cracking in substrate-base plate solder during temperature cycling

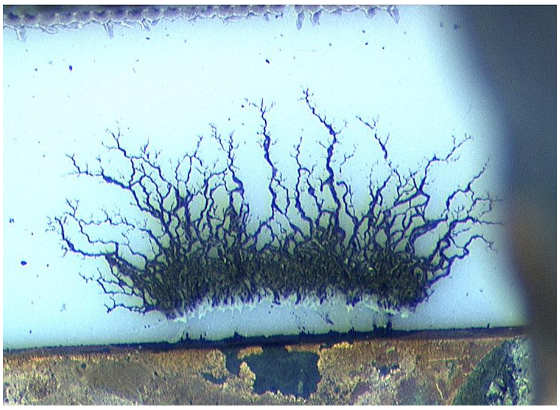

Fig. 5 Electrical breakdown at gel-ceramic interface (“treeing”).

There are several methods of evaluating the failure rate of the semiconductor devices.

- Qualification procedure
- Theoretical calculation
- Field failure experience
- Physics of failure method

Qualification procedure:

The principle behind this method is to qualify a product based on a test plan according to defined conditions such as international standards and or some reference test plan. The obvious advantages of this method are the same evaluation process for all companies in a same industry sector and no additional cost for study (test plan definition). The major disadvantage is that the test plan becomes obsolete when considering new technology. The test plan can be very general and not exactly adapted to the application (constraint choice)Table 2 shows an example of a standard qualification tests (based mainly on the IEC Standard) adopted by Dynex during the product release stage and the maintenance of the qualified product.

Theoretical calculations:

The traditional method of calculating failure rate uses an accelerated life testing of the device. The method involves testing devices from a random sample obtained from the parent population followed by a stress test, under accelerated conditions, to promote failures. The acceleration factor (AF) thus obtained is then extrapolated to end-use conditions by means of a predetermined statistical model to give an estimate of the failure rate in the field applications. For thermally/electrically activated failures, modified Arrhenius equation (1) is used in conjunction with Chi square statistical model equation (2).

$$AF = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right)\left(\frac{V_2}{V_1}\right)^{\beta} \qquad (1)$$

$$\lambda = \frac{\chi^2}{2T_D AF} \times 10^9\, FIT \qquad (2)$$

where

AF = acceleration factor

E_a = activation energy (eV)

k = Boltzmann-factor (J/K)

T_{use} = application temperature (°C)

T_{stress} = stress temperature (°C)

V_1 = application voltage

V_2 = test voltage

β = voltage stress factor

λ = failure rate (FIT)

χ^2 = Chi square confidence value

T_D = Total device hours

It is clear from the equation (2) that higher value of device hours (T_D) gives low value of failure rate. Hence in order to accumulate high number of device hours, large number of devices in test is required and or much longer time for the test. This form of statistics is acquired over a number of years of regular testing of the product. This process is illustrated in the Figure 6 for the gate-oxide failure rate. The unknown parameter in equation (1) is the activation energy (E_a). It is a constant in the Arrhenius equation and is related to the kinetics of the underlying physical process under temperature stress. This constant is experimentally determined.

For cyclic stress the Coffin Manson equation (3) is used. This model predicts the number of cycles to fail due to thermo-mechanical cyclic stress.

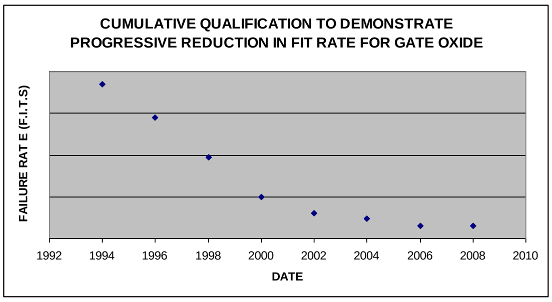

Fig. 6 IGBT gate-oxide failure rate

$$N = \left(\frac{A}{\Delta T_{j-c}}\right)^{B} \qquad (3)$$

where

ΔT_{j-c} = temperature difference, junction to case.

N = number of cycles to fail.

A = fitting parameter.

B = fitting parameter.

The parameters A and B are related to the geometry and the mechanical properties of the material and are experimentally derived. Figure 7 shows numbers of cycles to fail for wire bond wear-out for a number of power cycling conditions (ΔT). Note that no vertical scale is given for this graph because the values are not fixed but subject to statistical distribution.

Field failure experience:

This method involves collection and analysis of all field failures and also system integration. The advantage of this method is that it gives the best reliability evaluation.

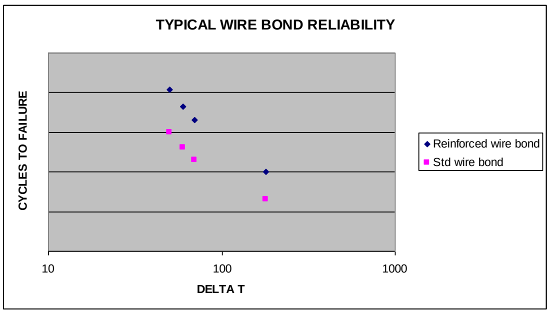

Fig.7 Cycles to fail for wire-bond wear-out

The main drawback is the difficulty in collecting data, and its integrity (use duration, failure context, quantity of parts used with reliable accuracy). Dynex do not subscribe to this method for calculation of failure rate.

Physics of failure method:

This is relatively a new approach to the design and development of a reliable product to prevent failure based on the knowledge of root cause failure processes. The concept is based on a good understanding of relationships between the requirements and the physical properties of the product and their variation in the production processes. Also how the product materials react and interact under the applied stresses at the application conditions and their effect on the reliability. The product is designed with built-in reliability, which is quantified by the physics of failure models for each failure mechanism. Although this method is at infancy stage, it is gaining grounds very rapidly.

MISSION PROFILE

Mission profile refers to a set of operational and environmental conditions that are experienced during the operating life of a device. Any of these conditions or combination of these conditions has influence on the failure rate and the wear out of the device.

A typical example for a mission profile of a high-speed rail traction application is shown in Table 1.

The operating life of a product is determined for the given operational and environmental conditions. Experiment and simulation methods are used to determine this. This method gives a better estimation of the device under the real application conditions.

SUMMARY:

To summarise, due to the complexity in construction, the overall reliability of the IGBT module depends on the individual components, their material properties, and their interactions with external and internal stresses imposed by the operating conditions. There are several methods available to predict the failure rate of the module, each has its advantages and disadvantages. The physics of failure method is the emerging method and will require some time before it is fully accepted. The most meaningful method of predicting the reliability is the use of "Mission-profile".

Table 1: Typical Mission Profile for rail traction application

Stress condition	**Temperature range**	**Cycles over 30yr life**
Overnight shed stop	-40°C to operating temp.	Worst case 10,000
Station stop	Heat-sink to operating temp.	~3.5E5
Traction/braking	Experimentally measured at 30°C	~3.4E7
Power cycling	< 1°C	~7E11

CONCLUSION

A brief introduction to the concept of reliability related to the IGBT module is given.

The methods used to quantify the reliability are explained. Also it has been emphasised that the Mission Profile method gives the best reliability prediction. Dynex can provide service to calculate FIT and lifetime for a given customer “mission profile” upon request.

Table 2: IGBT Module Qualification Tests (Traction application)

	Qualification Test	Test Method	Test Conditions	Qualification Standard
Environmental Assessment	Passive Cycling	IEC60068-2-14	ΔT = 80K T_{min} = 25°C (+/- 5) External or internal heating and external cooling 2 m< t cycle<6 m	20,000 Cycles for MMC base plate 5000 cycles for copper base plate
	Temperature Cycling	IEC60068-2-14	$T_{stg\ min}$ to $T_{stg\ max}$ $T_{dwell} \geq$ 1hour Transfer time = 30s	100 Cycles
	Vibration	IEC60068-2-6	F = 55 to 500Hz Acceleration = 10g	6 hours total 2 hrs in each of 3 mutually axes
	Mechanical Shock	IEC60068-2-27	Acceleration = 20g Pulse width =20ms half sine	5 shocks in both positive and negative direction of 3 axes
	Salt mist	IEC60068-2-11	Ka Test	168 hours
	Low Temperature Storage	IEC60068-2-1	$T_{amb} = T_{storage\ min}$	1000 hours
	High Temperature Storage	IEC60068-2-1	$T_{amb} = T_{storage\ max}$	1000 hours
	High Humidity High temperature (H3TRB)	IEC60749-5	T_{amb} = 85°C Relative Humidity = 85%,V_{ce} =+ 80V V_{ge} = 0V	1000 hours
Electrical Assessment	High temperature gate bias (HTGS)	Dynex	$T_j=T_{jmax}$ V_{ge} = +20V, V_{ce} =short	1000 hours
	High temperature reverse bias (HTRB)	Dynex	$T_j = T_{jmax}$ $V_{ce}=0.8*V_{ce(max)}$ V_{ge}=short	1000 hours
	Power Cycling	Dynex	ΔT = 60/50K $T_{max}=T_{jmax}$ 2s<cycle time <6 s	1M cycles for ΔT=50K 400,000 cycles for ΔT=60K

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