WHITE PAPER

Failure Mechanisms in IGBTs Related to Voiding

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Abstract

An insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch that, as it was developed, came to combine high efficiency and fast switching. It switches electrical power in many modern appliances: variable frequency drives (VFDs), electric cars, trains, variable speed refrigerators, lamp ballasts, air conditioners, and even stereo systems with switching amplifiers. Because they are designed to turn on and off rapidly, amplifiers that use IGBTs often synthesize complex waveforms with pulse-width modulation and low-pass filters. In switching applications, modern devices feature pulse repetition rates well into the ultrasonic range—frequencies that are at least ten times the highest audio frequency handled by the device when used as an analog audio amplifier.

The IGBT combines the simple gate-drive characteristics of MOSFETs with the high current and low saturation voltage capability of bipolar transistors. The IGBT combines an isolated-gate FET for the control input and a bipolar power transistor as a switch in a single device. The IGBT is used in medium- to high-power applications like switched-mode power supplies, traction motor control, and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities on the order of hundreds of amperes with blocking voltages of 6000 V. These IGBTs can control loads of hundreds of kilowatts.

These devices are highly complex and expensive and place huge demands on their component parts. The majority of the failure mechanisms in IGBT units in the field are traceable back to excessive internal temperatures and/or thermal stress. It is well proven and accepted that voiding at critical interfaces is the major contributing factor to these failures.

This paper investigates these voiding issues and explores x-ray technology as a non-destructive and non-damaging method of inspection during and immediately after production. The aim is to improve the process by reducing voiding and therefore increase long term reliability of these often expensive to replace parts. This affects not only the unit cost, but the location and also the costs incurred until the unit can be replaced. These units are often in remote or critical situations and failure causes huge cost and warranty issues.

Keywords: IGBT, x-ray, voiding, reliability, quality

Background

Currently, the main uses for IGBT technology are in electric vehicles/hybrid electric vehicles (EV/HEVs) renewable energies, motor drives, uninterruptable power supplies (UPSs), and transportation: these key applications will drive IGBT growth to $6B by 2018. After a few hiccups in 2011 and 2012, we expect a return to steady growth for the IGBT market; specifically, from $3.6B today to $6B by 2018. Motor drives are fueling the growth of IGBTs the most; renewable energies (photovoltaics and wind) are also trending well. Because they rely on government investments, they can be unpredictable, but Japan and several developing countries will make up for Europe's slowdown. Mass transportation and UPSs are based on infrastructure needs, so the need for greater efficiency is pushing these markets. For hybrid and electric cars, questions still remain. Market growth will occur, but nobody can predict its extent. This forecast is based on the latest Q1/2013 results and from an understanding of technology adoption.

IGBT modules are now common in everyday life; consumer electronics and home appliances are now part of the equation. In addition to the key applications, secondary applications are worth mentioning, including important trends not to be missed: the so-called "inverterization" trend is one of them. Home appliances increasingly require inverter-based motor drives, which provide better performance, comfort and efficiency—all "musts" for high-end products. Consumers are also using more advanced home solutions, like induction-based plates for rice cookers. These new applications will contribute to IGBTs' growth in consumer applications. In 2012, there was a crisis in the power devices markets, for IGBTs in particular. Multiple factors explain this: the slowdown of PVs (photovoltaics) installations due to the reduction of feed-in-tariffs in Europe, the slowdown of wind turbine installations in China, the train accident in China that halted the high-speed train production line, and the fact that global economic recovery has been much slower than expected (thus affecting the consumer markets). Also, the 2011 earthquake in Japan caused system makers to secure their orders. All these factors combine to explain 2011's overproduction, which was paid for in 2012 and early 2013.

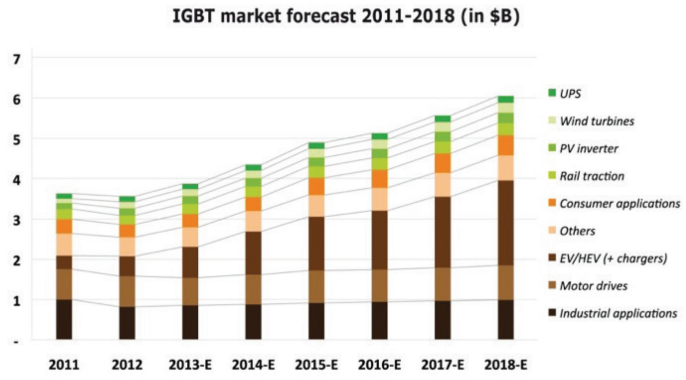


Figure 1. IGBT market forecast.

IGBT technology faces competition from thyristors, SiC and GaN devices, and MOSFETs. The IGBT market also faces competition from external, market-impacting trends. The drivers behind IGBT have never been so active: a bunch of start-up companies are proposing solutions offering more design flexibility and/or higher performance. Other companies are structuring offers at the power stack level; the IGBT is no longer the only high-end device solution. SiC devices are ready, and GaN devices are at the sample stage. Adoption roadmaps are clearer now. We've seen the first full SiC PV inverters based on MOSFETs or IFETs. The IGBT is slowly moving to medium- and low-end solutions, allowing SiC devices to handle higher voltages and GaN devices to capitalize on lower voltages. The need for efficient energy solutions is stronger than ever, and IGBT devices are still undergoing developments and improvements: thinner wafers, more efficient production, integration of functionalities, etc. All of these external pressures lead to a need for cost reduction; ultimately, better yields and higher reliability will be key factors determining how long IGBT devices will be successful.

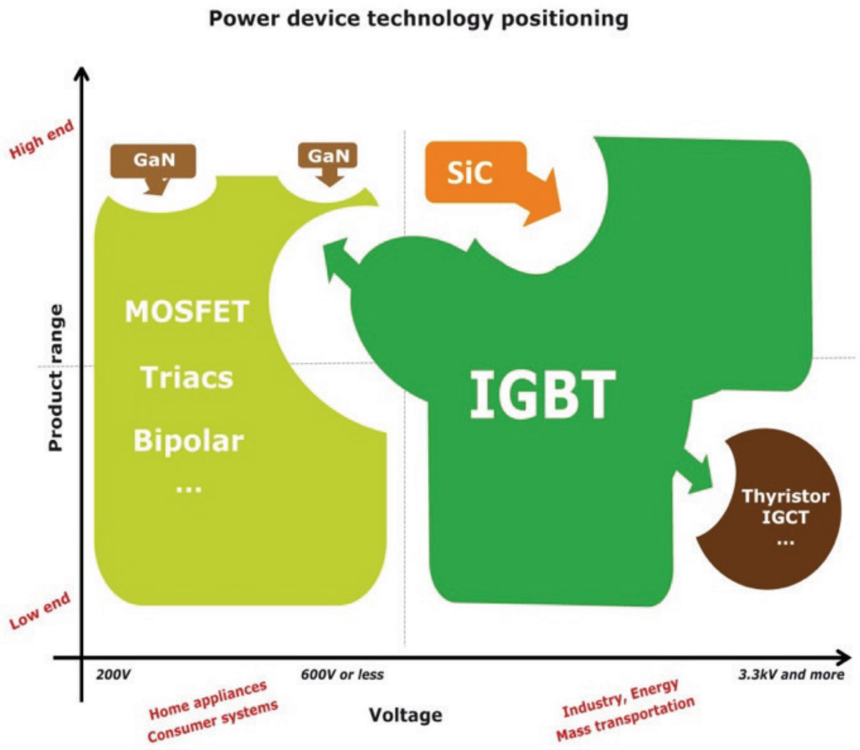


Figure 2. Technology positioning.

Voiding Background

Because they are high-voltage and high-power switches, IGBT modules generate a great deal of heat that must be dissipated at a rate sufficient to avoid over-heating. Some heat escapes upward from the top of the die and through the plastic encapsulant, but much more heat travels downward through a pathway designed to provide an adequate rate of dissipation for that particular module. Multiple die are typically attached to a ceramic substrate by the die attach material, which also serves as a type of Thermal Interface Material (TIM). The bottom surface of the ceramic is in turn bonded to a metal heat sink by a second TIM, usually solder. Note that each TIM has interfaces above and below, making a total of four internal interfaces that are important in interface-sensitive acoustic imaging.

The purpose of the IGBT module's layered design is to create an efficient, low thermal resistance pathway from the circuitry atop the die to the bottom side of the heat sink, where the heat is carried away. Including the die, heat in this typical design will travel through five layers of material. The ceramic substrate and the heat sink are chosen in part for their low resistance to the propagation of thermal energy, as are the TIMs.

But IGBTs can still overheat and fail in service. There are two commonly seen failure mechanisms:

1. Voids, delaminations or other gaps within or adjacent to a TIM. Even if they are very thin, gaps are efficient insulators. Thermal energy is transmitted downward from the die by conduction. Little thermal energy crosses a gap (void); instead, it is redirected back toward the die. In gap-free regions, conduction and radiation continues across the material interfaces until, at the bottom of the heat sink, the heat is carried away from the module. The greater the collective x-y area of the gaps, the more thermal energy is aimed back at the die, and the greater the risk of IGBT failure.
2. Occasionally, a ceramic element is warped or tilted; the die above may be tilted as well. The warping or tilting may cause the solder TIM between the ceramic and the heat sink to create a hot spot that can cause the die to overheat or crack. This is really void-related as the gap between the component parts creates a void below.

Challenges

IGBT modules have always had issues related to temperature; they generate a lot of heat and controlling and managing that heat has always been a challenge. Some units have operating temperatures >350°C; a look at the design and the materials used (Figures 3 and 4) makes it easy to see the potential pitfalls.

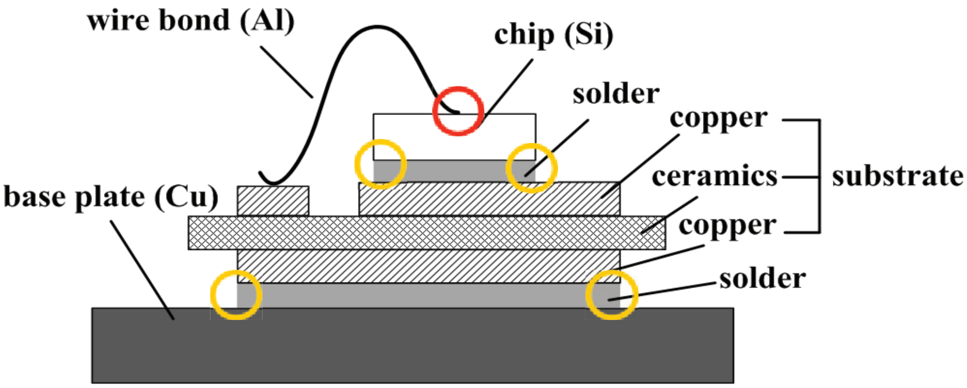


Figure 3. Module layout showing materials and junctions.

Material	CTE (10^{-6} K^{-1})	Conductivity
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	137
Si	2.6	148
AlSiC	7.5	200

Figure 4. Material properties.

Note the huge range of different coefficients of thermal expansion (CTEs)—from silicon at 2.6 to aluminum almost 10 times higher at 23.5, with copper coming in at 17.5 and molybdenum at 5.1. Add to this the fact that some of these materials are in amalgams like solder or adhesives, which affects the understanding of the overall picture. In addition, their conductivities vary from 24 (Wm-1K-1) to 394—more than 16 times greater. So when a unit is designed, fully tested and meets all the relevant approvals, it will then overcome these challenges. However, as we all know, manufacturing is not an exact science and although samples for testing can be built in a near-perfect environment, production almost by definition has some variability, which is the crux of this paper. A void within this mix dramatically affects the thermal performance of the unit and may also create a hot spot, which can cause stress-related damage, leading to an "in service failure" of the unit. This is expensive and damaging in many ways, from the actual cost of replacing a module in a wind turbine in a remote location to angry commuters on a broken-down train.

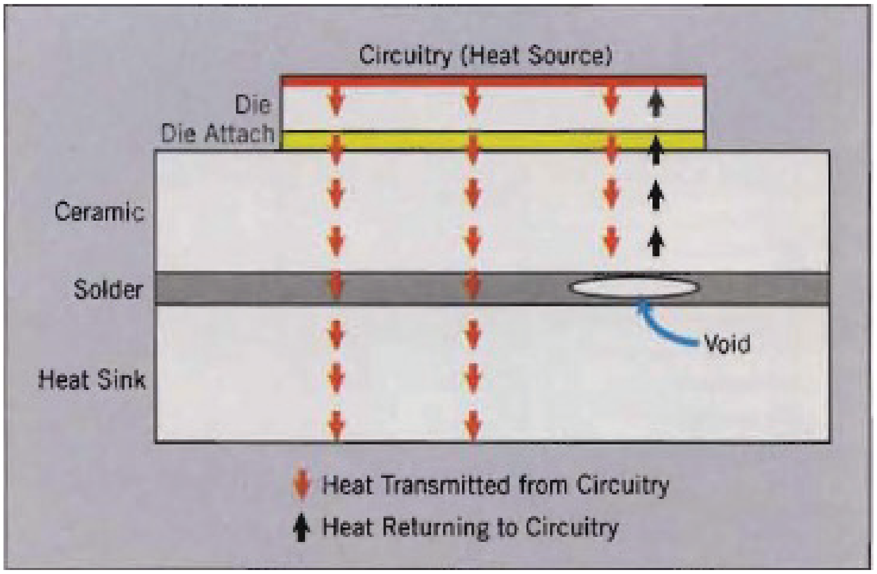


Figure 5. The effect of voids on heat transfer.

Standard IGBT Test Methodology

Although mapping or predicting Mean Time to Failure (MTTF) has been used as a standard test methodology, it has some issues.

MIL-HDBK-217 Handbook: Reliability Prediction of Electronic Equipment

The MIL-217 Handbook provides formulas to estimate failure rates for military electronic equipment. A constant failure rate is assumed. However, no formula is provided for IGBT; therefore, a MOSFET and bipolar junction transistor (BJT) were modeled in series to represent an IGBT.

The MIL-HDBK-217 method does not account for temperature cycling loading and other relevant loading conditions.

The 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. Using MTTF to predict IGBT lifetime is not sufficient to avoid unexpected failures in the field due to the variability in prediction. The 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. Obviously, this method of predicting lifetime is not really working for IGBT modules.

Another method is to subject samples to HAST or other accelerated aging or stress testing to try to obtain data that can be used to predict lifetime; without going into any depth, the issues in the previous example are also relevant here. These methods are also time-consuming and very expensive because they require very specialized equipment and highly skilled operators.

End-of-line stress testing or using elevated temperature testing for all units in environmental test cabinets is also expensive, time-consuming and not particularly effective.

Clearly, another solution is needed as cost and efficiency become bigger issues in the manufacturing cycle.

This is where voiding comes to the fore; as stated earlier, most failures in service are traceable to a failure mechanism related to voiding caused during manufacture. There might be several secondary mechanisms, but the root cause is thermal or mechanical strength issues related to voiding at the various interfaces within the IGBT device. What is really needed is a way of measuring these voids during production and setting acceptable limits; this would allow for process control instead of predictive failure analysis or expensive end-of-line testing.

Two accepted methods of measuring voiding within electronics devices are loosely non-destructive: acoustic microscopy and x-ray imaging. They are only loosely non-destructive because the first involves immersion of the sample in water, which may be detrimental to the product unless dried out perfectly.

Acoustic Microscopy

Acoustic microscopes image IGBTs and other samples by using a transducer that pulses high-frequency ultrasound into the sample while scanning the sample's surface. The job of the moving transducer is to send a pulse of ultrasound into the sample and to receive the return echoes from various depths a few millionths of a second later. In one second, the transducer can collect echoes from thousands of x-y coordinates, picking up data that will create thousands of pixels. Ultrasound is "interface sensitive" because it is reflected only from the interfaces between both solid materials and gaps but not from the bulk of homogeneous materials. The ultrasonic frequencies used for imaging IGBTs are typically from 30 MHz to 50 MHz. Because ultrasound will not travel through air, it must be coupled to the sample surface by water or another fluid.

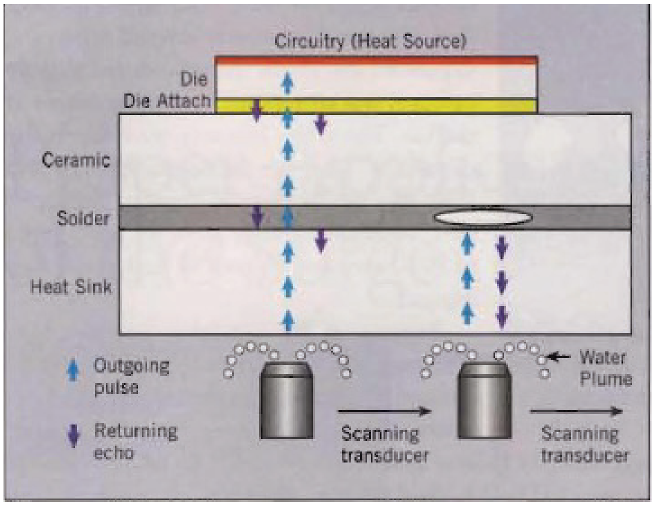


Figure 6. The basics of acoustic microscopy.

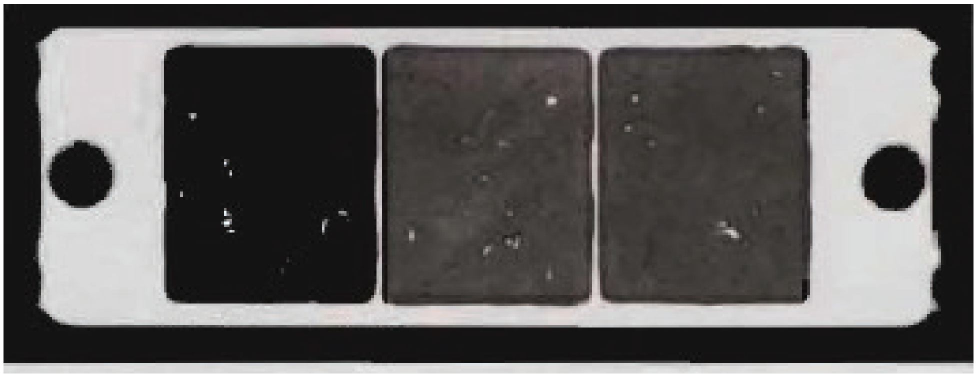


Figure 7A. An acoustic microscopy result. Acoustic image of the solder layer between the heat sink and ceramic single IGBT die. White areas are gaps (voids).

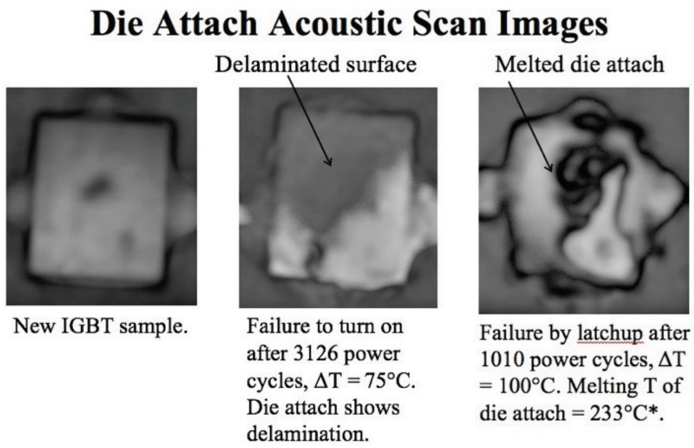


Figure 7B. Scanning Auger Microscopy (SAM) images of die attach failures.

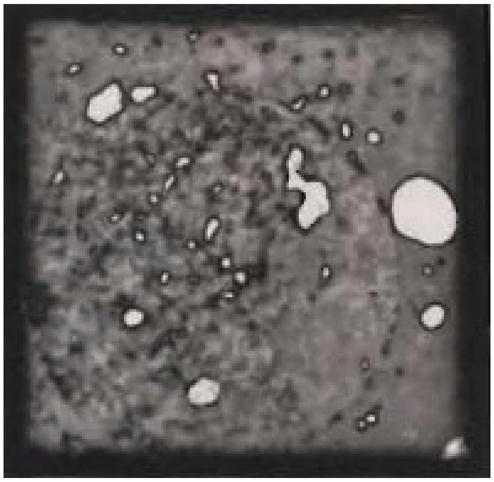


Figure 8. An enlarged SAM view of a single die, showing the voids as white areas.

This technique is quite good as it shows voiding quite well; however, some systems can be limited when it comes to measuring the voiding and working out the percentage area of the voids in relation to the interface. It is much faster than the previous test methods, but several machines would be needed to support a line and do a meaningful Acceptance Quality Level (AQL) check.

X-Ray Inspection

IGBT devices present real challenges for x-ray technology: dense areas of metal that require high power to penetrate them, the need to see very small light areas (voids) through very dark areas of copper, plus the need to separate interfaces within this complex material stack. Many systems struggle to meet these demanding criteria. However, some of the high-end systems, which include inclined CT, do a great job in void location and measurement, as well as checking on die flatness and wire bond quality.

The two biggest areas that x-ray systems have advanced are ease of use and image enhancement. Many systems' can now be controlled with a few clicks of a mouse; indeed, some systems key software features can be activated by a single click. This one-click mentality also has a dramatic effect on throughput and ease of operation. The more sophisticated machines have a Photoshop-type suite of filters that can be used to enhance the image, allowing the operator to see potential faults more clearly. Contrast, stretch and other fine-tuning controls also make it easier to view the more challenging images of today's advanced technology.

Recent advances have gone further with the development of special filters that with one click dramatically enhance the image and make the task of the operator even easier. These sophisticated filter systems have been specifically designed to enhance difficult images. State-of-the-art graphics cards, a technology driven by the games industry, have also led to huge improvements in image quality and processing speed.

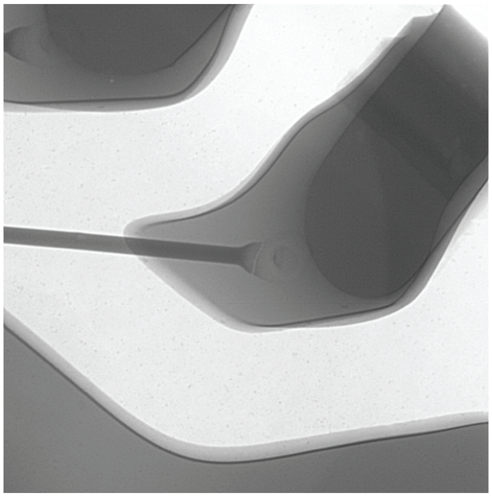


Figure 9. A broken 20-micron bond wire.

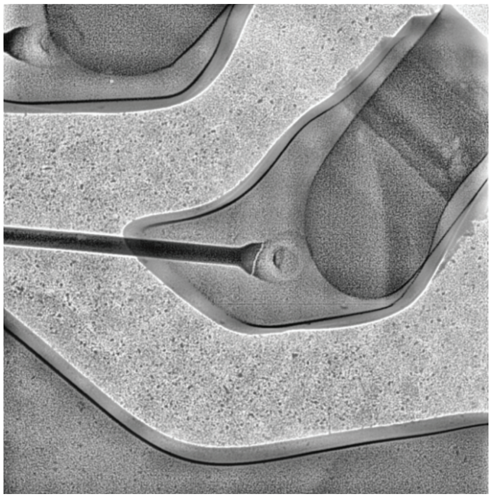


Figure 10. A digitally enhanced version of the image in Figure 9.

A recent advance in the 3D or computed tomography (CT) field goes by several names: inclined CT, oblique CT, partial CT and a few others. This technique has one huge advantage over traditional CT in that it is non-destructive. A region of interest on the board is selected, then a number of images are taken at a fixed angle of view and these images are reconstructed to produce a series of laminography slices, allowing strategic layers within the assembly to be easily viewed and analyzed. In addition to this, these slices can be output to a 3D reconstruction station, where a 3D representation can be built, allowing the operator to rotate, slice, and magnify the sample at will. The use of this technology greatly improves many increasingly important areas of x-ray inspection, including analysis of voids on thermal pads, allowing the efficiency of heat transfer to be calculated.

Voiding at joint interfaces, including those of complex devices, can easily be measured, allowing the operator to calculate the percentage reduction in joint strength attributed to the voiding on that interface. However, the quality and accuracy of these images and results are entirely dependent on the quality of the mechanical system within the machine, the quality of the original images captured, and the algorithms used to reconstruct that data and remove artifacts and noise created by their acquisition.

Inclined CT X-Ray Inspection in Images

Diode bridge Package

Figure 11. The sample.

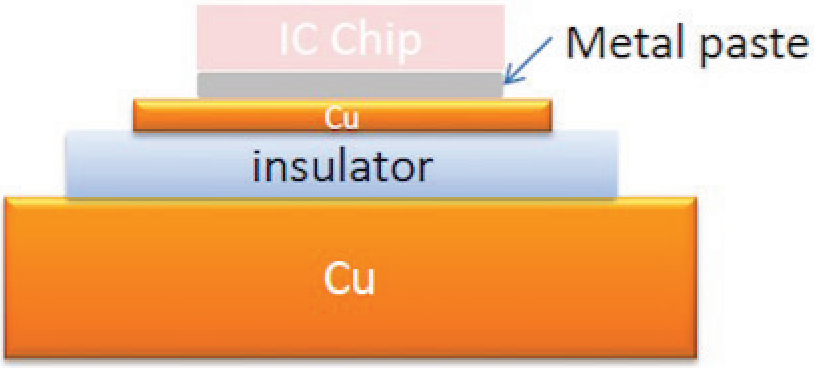


Figure 12. Makeup of the sample.

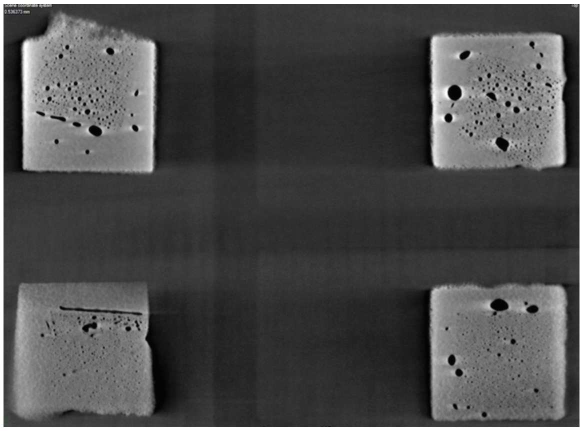
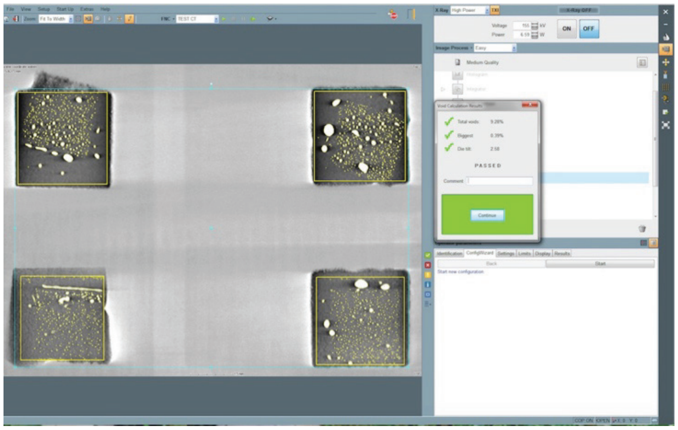


Figure 13. The inclined CT image showing interface voiding (voids are black).



Voltage 155 kV

Power 6.59 W

Void Calculation Results

✓ Total voids: 9.28%

✓ Biggest 0.39%

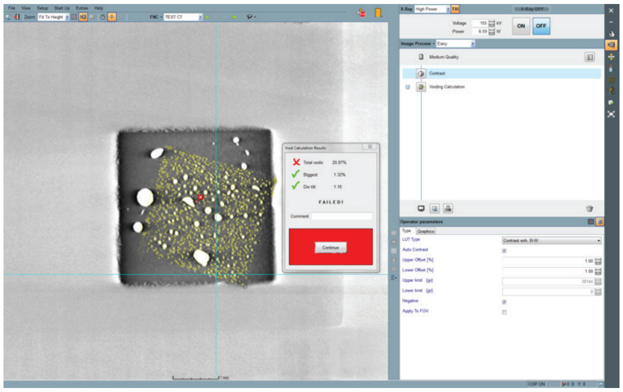
✓ Die tilt: 2.58

PASSED

Comment:

Continue

Figure 14. The voiding is measured and is within acceptable limits.



Void Calculation Results

✗ Total voids: 20.87%

✓ Biggest 1.32%

✓ Die tilt: 1.10

FAILED!

Comment:

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Figure 15. A single interface with excessive voiding.

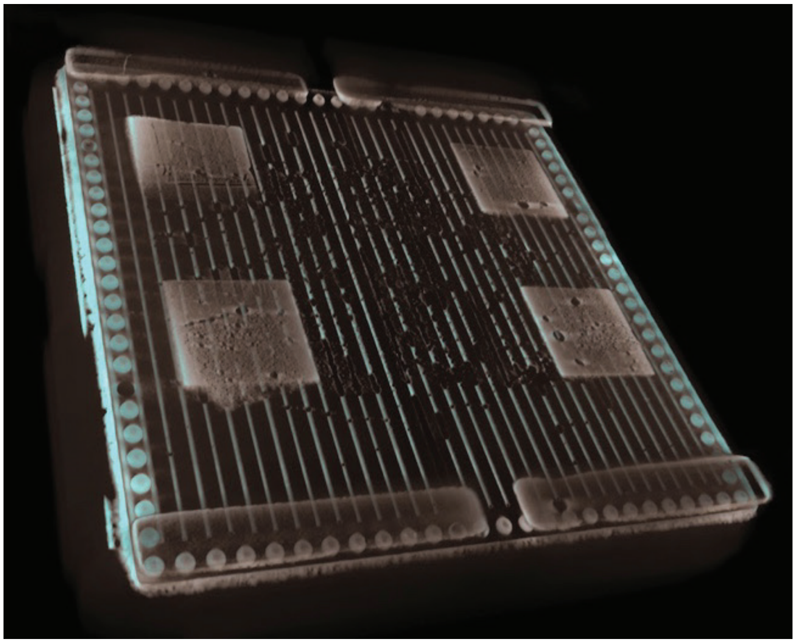

Figure 16. A 3D reconstruction of the device interfaces.

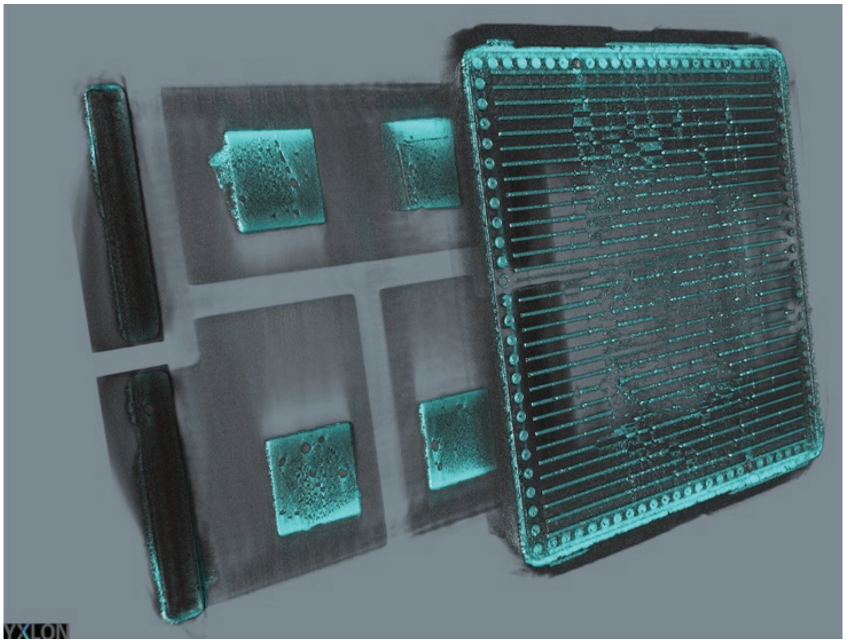

Figure 17. Two reconstructions highlighting the key interfaces.

Conclusion

Due to the economic pressures of IGBT manufacturing and the use of these devices in lower cost and higher volume products, a good method of process control is needed rather than relying on end-of-line testing or MTTF calculations. Weighing the methodologies described would suggest that a high end x-ray system would be the best method of process control and also the best solution to evaluating new processes, reducing voiding and thereby improving the reliability of IGBT modules in the field. The soldering process is seeing many improvements to reduce voiding: In-Line Vapor Phase Reflow, improved materials, Drop Pressure Reflow, Nitrogen Reflow and others. Using x-ray as a tool for evaluating and comparing these processes would offer a very accurate way of checking for any improvement.

However, one critical point remains: How much voiding is acceptable?

Given that we live in the real world and all joint interfaces are prone to some vacating, then operators will need guidelines on acceptable limits. The way forward here is by Continual Service Improvement (CSI); inspect failed units from the field or stress test and measure the voids—this will give unacceptable limits of interface voiding. Then, consider what the numbers should be going forward; it may not be perfect, but it is much better than what most companies are doing today.

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