Acoustic Imaging for IGBT Reliability

Uneven solder thickness can allow localized overheating

Insulated Gate Bipolar Transistors, or IGBTs, are widely used in, trains, elevators, windmills and many other applications where robust high-power switching is required. Not surprisingly, IGBTs generate considerable heat in operation, and the heat must be efficiently dissipated to prevent the IGBT from overheating and failing electrically. Preventing electrical failure is especially important in critical IGBT applications such as high-power switching on military aircraft.

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IGBTs have many designs, but typically the power ICs are attached to a highly thermally conductive ceramic which bears the copper traces. The bottom side of the substrate is bonded by solder or another adhesive to a metal or composite heat sink. After assembly of the IGBT, a critical performance detail is the integrity of the solder bond between the substrate and the heat sink. Voids in the solder, delaminations along either solder interface, or uneven solder thickness can significantly reduce or modify heat flow across the interface and cause the unit to overheat and fail.

A similar heat dissipation requirement exists in flip chips used as high-performance microprocessors that are bonded to a more modest heat sink by an adhesive or an electronic grease whose thickness must be within specified values and which must be free from voids. IGBTs have far more heat to be dissipated, but the requirements for adhesive thickness and integrity are roughly similar. Sonoscan's applications laboratories have seen increasing numbers of IGBTs used in diverse applications in recent years.

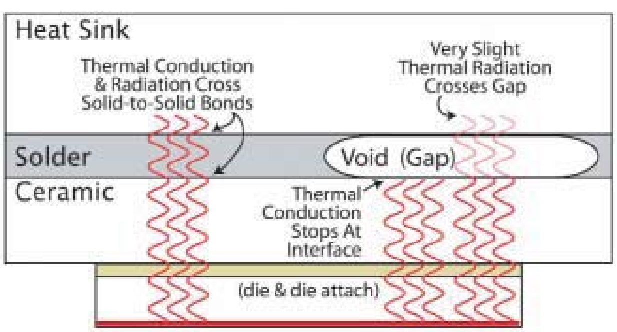

Figure 1: The effect of a gap on heat transfer through solid materials

The inverted cross-section in Figure 1 shows the normal arrangement for acoustic imaging of the solder adhesive, where the ultrasonic transducer raster-scans the heat sink surface. This figure shows what may happen to thermal energy that flows from the ICs of an IGBT and encounters the solder between the ceramic and the metal heat sink. Thermal energy travels by two modes, conduction and radiation. If the ceramic and the heat sink are well bonded by the solder layer (at left in Figure 1), heat will flow efficiently across the interface and the IGBT will not overheat. But there may be a gap at the interface - "gap" meaning a void within the solder or the separation of the solder from either surface. When thermal energy reaches the interface between the ceramic (a solid material) and the gap (a gas such as air, or a vacuum), heat transfer by conduction ceases (Figure 2). Heat transfer by radiation continues but is reduced by orders of magnitude by the gap. The gap is a good thermal insulator.

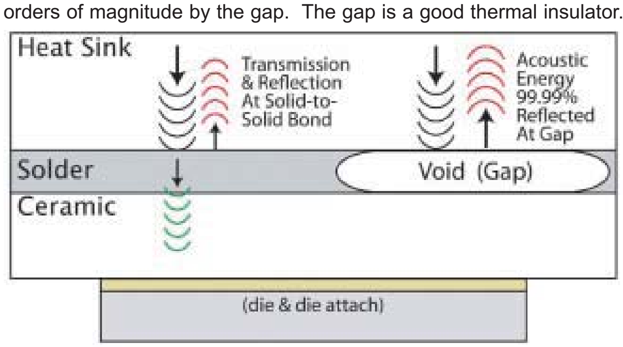

Figure 2: The solid-to-gap interface reflects virtually all of the ultrasound

Thermal energy that does not cross the gap is reflected back toward the ICs. If the combined area of gaps is large enough, the IGBT will overheat and fail. It may also overheat and fail in the absence of gaps if there is sufficient variation in the thickness of the solder adhesive In this case, removal of heat takes place unevenly across the area of the ceramic. As a result, hot spots may develop on the die.

Examining the interface between the heat sink and the ceramic nondestructively with an acoustic microscope is preferable to destructive methods, which would leave the IGBT in pieces and which would probably reveal the condition of the interface only at a few spots. The value of acoustic microscopy is that ultrasound is reflected only from interfaces between materials, whether the interfaces are two solids or a solid and a gap.

In practice, the transducer of the acoustic microscope raster-scans the metal heat sink at the bottom side of the IGBT. Several thousand times a second, ultrasound at a selected frequency (typically 30

MHz or 50 MHz) is pulsed into the IGBT and the return echo signals are collected by the transducer. Ordinarily in acoustic imaging only the return echo signals from a depth of interest are used to make the acoustic image; signals from other depths are discarded. The return echo signals are said to be gated on the desired depth, with both a start point and a stop point, each expressed in nanoseconds. In the case of an IGBT being scanned along the heat sink surface, the depth of interest includes the solder and its interfaces with the ceramic and the heat sink.

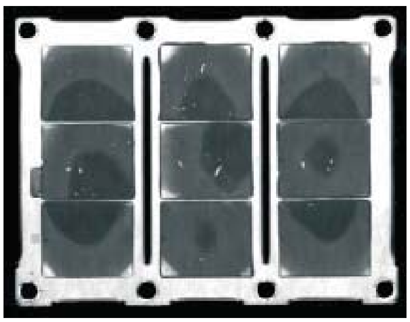

Figure 3: Acoustic image of the solder bond between the ceramic layer and the heat sink in a 9-die IGBT

If the two solid materials are well bonded, the portion of ultrasonic energy reflected at the interface can be calculated by knowing the density and acoustic velocity of each material. But if there is a gap,, the ultrasound will encounter the interface between a solid and a space, and virtually all of the ultrasound will be reflected back to the transducer [Figure 2]. The very high amplitude return echo signal from the solid-gap interface will appear as bright white pixels in the acoustic image, while solid-to-solid interfaces will be some shade of gray. (Where two identical materials are truly bonded, as in direct-bonded silicon wafers, no ultrasound is reflected and the pixels are black.)

Figure 3 is the acoustic image of a 9-die IGBT, made from the return echo signals reflected from the depth between the metal heat sink and the substrate. The heat sink covers all nine ceramic substrates, which are in turned bonded to the nine die that are deeper than the depth of interest displayed in this image. Ideally, all of the ceramic substrates would have the same medium-gray color, but this acoustic image immediately makes it clear that conditions at the interface are not ideal.

A closer look at the acoustic image of the IGBT at top center is shown in Figure 4.. The scattered small white areas are voids in the solder between the ceramic and the heat sink. As shown in Figures 1 and 2, the voids block both heat and ultrasound. Such voids are not unusual, but these voids are too small to have much impact on overall heat transfer.

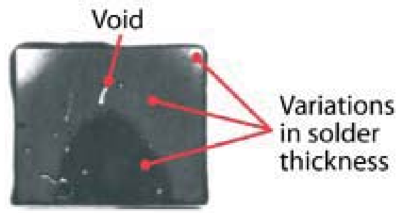

Figure 4: Thickness variation in the solder bond in one IGBT

The bond region itself grades from dark grey to lighter grey to white. This is an unusual acoustic image - a subtle gradation from dark grey to light grey would be more usual. What could cause such an unusual acoustic image?

One anomaly that is fairly frequent in IGBTs is warping and tilting of the ceramic substrates. The larger, thicker metal heat sink remains flat, so the warping of the ceramic causes local changes in the thickness of the solder. The thickness changes are very slight but become visible in acoustic images. The upper left and right corners of Figure 4 appear white because the solder here is so thin that the ultrasonic echoes returning from the top and bottom sides of the solder are so close together in time that the two echoes merge in what is called constructive interference. Here, constructive interference appears white.

As the solder gradually becomes thicker, interference ceases fairly abruptly and the solder appears medium grey. Eventually the solder reaches a thickness that again causes interference, visible where medium grey shifts abruptly to dark gray.

As mentioned earlier, uneven solder thickness can allow localized overheating of the die. Similarly, the electronic grease attaching a heat sink to a flip chip must have a thickness that is between perhaps 30 and 90 microns. An electronic grease thickness outside of this range anywhere in the bond can cause overheating. Deformation and tilting of the ceramic layer that causes the solder thickness to vary is a fairly common problem in IGBTs.

Figure 5 shows an array of six IGBTs. The raster-scanned planar acoustic image is shown at the top of Figure 5. The six IGBTs contain numerous small white voids, large delaminations (#2 and #4) and areas where the solder is too thin (#6). To learn more about the internal condition of the array, a non-destructive acoustic cross section, patented by Sonoscan and called Q-BAM™, was made. The horizontal green line shown in Figure 5 was selected as the vertical slice location, and this line was scanned multiple times at increasing depths to gather the data. The resulting non-destructive Q-BAM cross section is shown in the lower part of Figure 5.

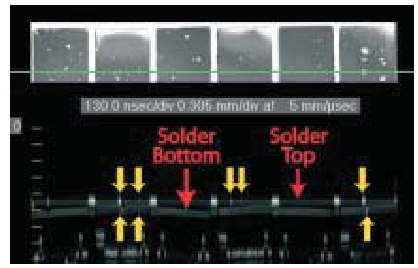

Figure 5: Non-destructive acoustic cross-section of a 6-die IGBT. Note the tilted ceramic members

Two key features in the cross section are the horizontal lines that mark the top and bottom of the solder layer. In this image the heat sink is at the top, and the ceramic layers are below the solder. It is easy to see that some of the ceramic pieces are tilted. Yellow arrows mark some of the voids that lie along the green line and that are in contact with the ceramic or the heat sink. The legend in the Q-BAM image relates ultrasonic travel time to distance, and the ten division markers at the left show that the vertical extent of the array shown here is slightly more than 3 mm. The features near the bottom of Figure 5 are the die and associated bond wires.

Some of the IGBTs imaged by Sonoscan are from development or production environments, but many are field failures where it is desirable to determine the root cause of the failure. Some failed IGBTs look acoustically similar to the images shown here. But some of the IGBTs arriving at a Sonoscan lab have clearly exploded - much of the mold compound has been blown off, and the die is often in fragments. Still, if the ceramic and heat sink are intact, it may be possible to image the wreckage from the back side to determine whether voids or other defects are present. Some anomalies might, of course, have been caused by the explosion.