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Investigation of Interfaces With Analytical Tools

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Invited Paper

***Abstract*—This paper focuses on advancements in three areas of analyzing interfaces, namely, acoustic microscopy for detecting damage to closely spaced interfaces, thermal imaging to detect damage and degradation of thermal interface materials and laser spallation, a relatively new concept to understand the strength of interfaces.**

Acoustic microscopy has been used widely in the semiconductor assembly and package area to detect delamination, cracks and voids in the package, but the resolution in the axial direction has always been a limitation of the technique. Recent advancements in acoustic waveform analysis has now allowed for detection and resolution of closely spaced interfaces such as layers within the die.

Thermal imaging using infrared (IR) thermography has long been used for detection of hot spots in the die or package. With recent advancements in very high-speed IR cameras, improved pixel resolution, and sophisticated software programming, the kinetics of heat flow can now be imaged and analyzed to reveal damage or degradation of interfaces that are critical to heat transfer. The technique has been demonstrated to be useful to understand defects and degradation of thermal interface materials used to conduct heat away from the device.

Laser spallation is a method that uses a short duration laser pulse to cause fracture at the weakest interface and has the ability to measure the adhesion strength of the interface. The advantage of this technique is that it can be used for fully processed die or wafers and even on packaged devices. The technique has been used to understand interfaces in devices with copper metallization and low-k dielectrics.

I. INTRODUCTION

AN INCREASE in performance of semiconductor products is usually associated with an increase in the number of transistors and layers in the device and package. With use of copper metallization and low-k dielectrics on the device and increasingly more complex packaging requirements, maintaining integrity of interfaces plays a major role in assuring reliability of the product in field applications.

The perpetual drive to compaction usually results in an increase in the number of layers in the die and packages. As power consumption increases with performance, the need for effective heat dissipation becomes critical for optimum performance and product reliability. Understanding the integrity of thermal interfaces during reliability tests is critical in development of low thermal resistance materials. These technology drivers result in a steep increase in the number of interfacial layers and the use of adhesion and barrier materials between the layers. In the portable products area such as cell phones and PDAs, increase in functional capability such as convergance of voice, video, and data has resulted in the use of multiple thin die stacked packages with closely spaced interfaces.

Maintaining the integrity of multiple complex interfaces is of paramount importance for assuring the reliability of these new technologies. The ability to characterize and quantify the adhesion strength of these multiple interfaces plays a key role in accelerating product development and certification. While there is a number of adhesion metrologies traditionally used to understand interfaces, most of them have limitations in their use. For example, interfacial crack propagation tests and three-point bend tests require that a test coupon have only a single or double layer applied to the substrate. This prevents evaluation of the influence of topography and multiple processing effects on the adhesion strength of the interfaces.

There are a number of methods and techniques used to analyze interfaces, such as mechanical stress tests that measure interface fracture strengths, surface analysis techniques that identify the chemistry of interfaces and imaging techniques to detect degradation of interfaces. This paper evaluates three promising analytical methods used to understand integrity of interfaces within the die and package. Advances in acoustic inspection techniques are shown to help detect and quantify interface irregularities and defects. High-speed IR thermography can be used to understand degradation of interfacial thermal resistance. Laser spallation is a new technique that can be used to quickly quantify adhesion strength of interfaces in a fully processed device or package. Details of these techniques are described below.

II. ADVANCEMENTS IN ACOUSTIC MICROSCOPY

Scanning acoustic microscopy (SAM) is widely used in the electronic industry to inspect for cracks, delamination, and voids in packages. The nondestructive nature of the technique, the short time for image acquisition, and its ability to identify the location of the defect makes SAM a critical tool for evaluating package integrity during reliability stressing and failure analysis. The technique is very sensitive in detecting interface delamination, cracking, and degradation. While submicron air gaps can easily be detected, Z resolution of closely spaced interfaces is an issue because of the relatively large depth of focus of the transducers. The use of high-frequency transducers in the 175–230 MHz improves resolution, but the depth of penetration into the package is reduced due to greater attenuation of the signal at higher frequencies. This attenuation

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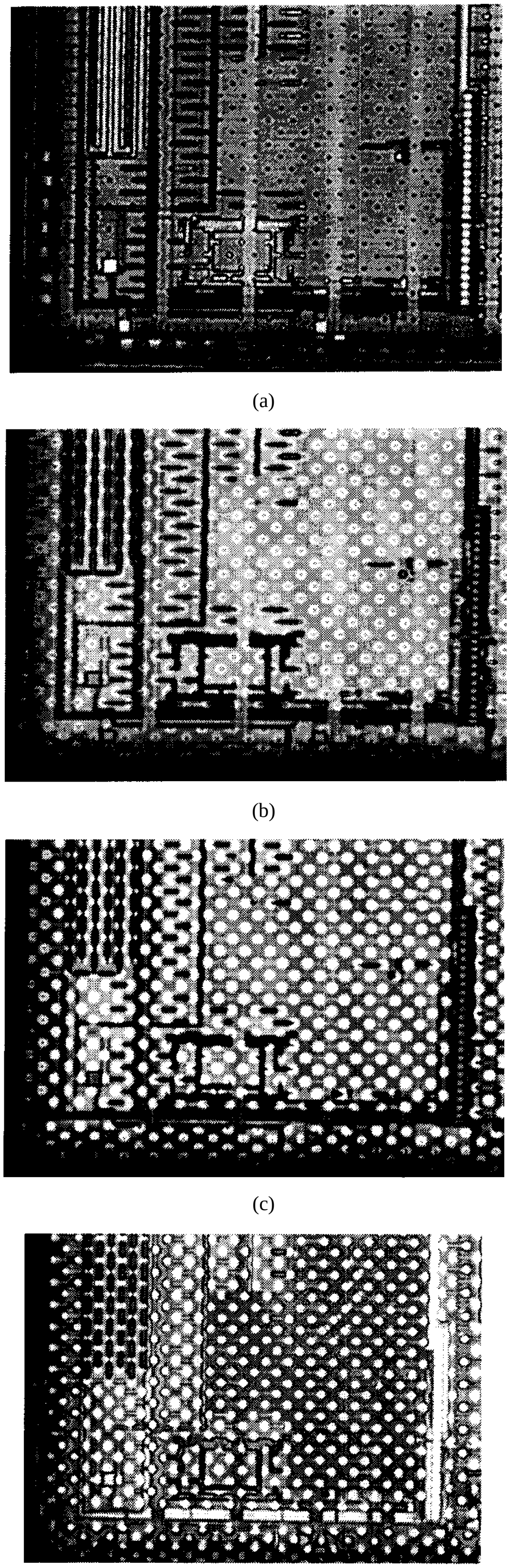
is due, in part, to scattering of filler particles such as silica and antimony oxide. The scattering phenomenon severely limits the highest frequency that can be used on packages with multiple interfaces such as stacked chip scale packages (SCSP). In addition, stacking multiple die of the same thickness results in a ringing effect where multiple reflections of the top die coincide with reflections from the die below and makes distinguishing signals from the two die interfaces difficult.

Acoustic suppliers have continually improved image quality and resolution by improved transducer designs, increase in x–y positioning accuracy, better filtering in receivers etc. Signal quality can also be improved with higher data sampling rates. One promising technique that can be used to improve axial resolution is truncated data collection. In this technique, half cycles or portions of the waveform are used to form the image and images of subsequent sections of the waveform are used to image features and interfaces deeper into the die or package. Fig. 1(a)–(d) is a series of reflected acoustic images usually referred to as C-mode scanning acoustic microscopy (CSAM) of various layers on the die. As can be seen by comparing the images, different structures on the die thin film layers can be imaged by changing the location on the waveform that is gated to form the image. This technique could potentially be used to investigate Z location of thin film delamination on die.

Acoustic CSAM images are traditionally formed by plotting the intensity of the reflected acoustic signal from a certain depth in the sample and it is this intensity image that is used to detect delamination, cracks, and voids in the sample. New data evaluation methods can be used to understand more subtle effects such as material or interface degradation. The frequency imaging technique uses a certain frequency of the reflected signal to form the image and is sensitive to material variations and degradation of materials. Phase imaging is another technique that can also be used and may provide complementary information to intensity and frequency images. Applications of these new imaging methods are just beginning to be evaluated.

In the area of stacked die and the problem associated with ringing from multiple die surfaces, deconvolution techniques will need to be developed to subtract the ringing effects. In addition, a renewed interest in theoretical modeling approaches is beginning to help understand complex interactions that occur at closely spaced interfaces typically involving materials of vastly different acoustic impedances. A broadband pulse propagation model [1] accurately describes the nature of ultrasonic pulses in thin layers in the sample. The model can be used to understand the nature of ultrasonic propagation in the package and relate it to the time traces visible on the oscilloscope (A-Scan).

The challenges in nondestructive imaging of multiple interfaces and in understanding subtle interface degradation effects is being actively pursues by a number of acoustic equipment manufacturers.



(a)

(b)

(c)

(d)

Fig. 1(a)–(d). CSAM images of flip chip die showing different structures on the die thin film layers that were imaged by gating sections of the waveform.

III. THERMAL IMAGING

Effective power dissipation from electronic devices requires integrity of thermal interface materials (TIM) be maintained throughout the life of the product. While acoustic techniques can be used to image defects such as voids and delamination at the interfaces between TIM and the die or lid, it is not very effective in detecting variations in TIM thickness, degradation of the

TIM, and reactions between the TIM and die or lid materials, all of which can affect thermal resistance. Thermal imaging using IR thermography is a technique that can be used to characterize the integrity of thermal interfaces [2].

Traditional IR thermography systems can easily detect flaws in a material that is not highly conductive. The temperature gradient around such a flaw is greater and lasts longer. In contrast, the surface temperature perturbations caused by a flaw in a conductive material such as TIM are not strong because heat is dissipated more rapidly and more evenly on the surface of a highly conductive material such as copper that is used as the heat sink. For these applications, pulsed infrared thermography (PIT) is recommended [3], [4]. A pulse of thermal energy is injected on to sample and this launches a thermal front that propagates into the sample. The sample surface temperature distribution is recorded by an infrared detector. Subsurface defects can alter the thermal resistance of the material and temporarily alter the surface temperature distribution during the early stage of the thermal transient state. As time passes, defect contrast reduces due to lateral heat transfer. This technique has several attractive features: it is nondestructive, easy to set up, and it can provide inspection results quickly. It operates in a pulsed transient regime where a large area can be analyzed due to surface-wide heating. Thus, it is a popular tool for characterizing material defects.

The PIT technique has been effectively used to detect defects in TIM [5]. A schematic of the package cross-section for analysis is shown in Fig. 2 and a schematic of the test layout is shown in Fig. 3.

An external heat pulse was applied to the package surface and the surface thermal response was monitored as a function of time with a high-speed IR camera. The uniqueness of this method lies in the capability of capturing surface temperature distribution in the transient mode at a speed of several hundred frames per second.

The data are integrated to understand the change of the temperature pattern with time which can be correlated to defects such as delamination, degradation and voids in the TIM. Fig. 4 shows the comparison of a package with good TIM adhesion to the lid and die and another unit with poor bonding between the TIM and die/lid. Good TIM adhesion results in effective heat conduction away from the lid surface and hence the lid surface temperature above the die area will be lower that the surrounding lid regions as shown in good unit. TIM delamination or voids in the TIM will result is lid temperatures similar to areas outside the TIM region.

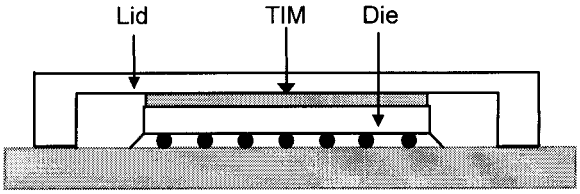


Fig. 2. Schematic of package cross-section showing the TIM sandwiched between the flip chip die and the lid.

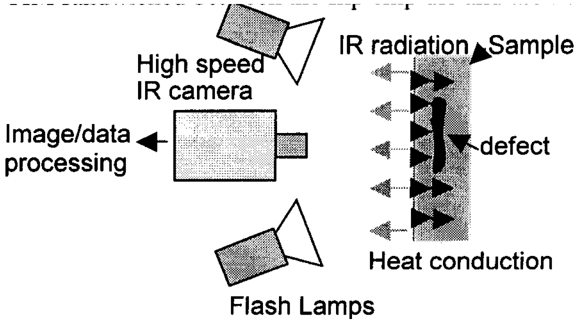


Fig. 3. Schematic of the pulsed IR thermography test layout.

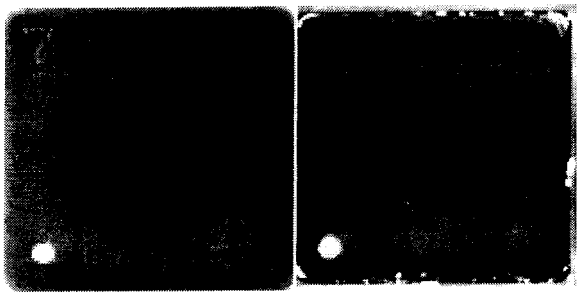


Fig. 4. Thermal images of the package lid surface showing lower temperature (black color) in the die area of good unit and only patchy areas in the bad unit that are lower temperature than the surrounding lid region.

To understand impact of interface defects on lid surface temperature distributions, thermal modeling simulations can be done. For example, thermal modeling can be used to determine if delamination between the lid and TIM can be distinguished from delamination between the TIM and Die. This was done by simulating delamination-like thin defects with dimensions of 8 mm × 8 mm × 0.01 mm at lid/TIM (defect 1) and TIM/die interfaces (defect 2), respectively, as illustrated in Fig. 5(a). The simulated lid temperature distribution at 46 ms is shown in Fig. 5(b). Modeling showed that the maximum temperature contrast (or difference) over the defect was 0.24 °C for defect 1 and 0.21 °C for defect 2. These two defects can be distinguished from each other because the contrast differences (0.03 °C) is greater than the system resolution. This indicates that when delamination area is large, the interface of TIM delamination could be identified nondestructively by the thermal imaging techniques.

One of the main limitations of the thermal imaging technique is the poor special resolution associated with the heat spreading effect if the defect is buried deep from the surface that is images. Methods to combine modeling data with empirical data could help improve understanding of the integrity of thermal interfaces.

IV. LASER SPALLATION

Laser spallation is a new adhesion technique that can be used to determine adhesion strength of interfaces in fully processed samples such as die thin films [6], [7]. In the laser spallation technique, a pulsed Nd:YAG laser energy at 1064 nm is incident on the backside of a die where adhesion of thin films on the frontside is of interest. The die sample is prepared by applying a thin absorbing layer such as aluminum on the backside of the die and coating the absorbing layer with a thin transparent confining layer such as sodium silicate. The laser pulse travels

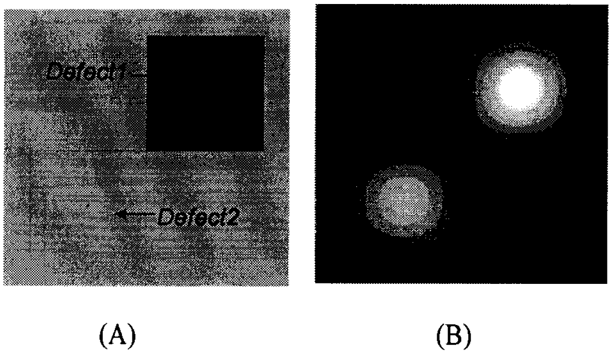


Fig. 5. (a) Top views of two TIM defects located between lid/TIM (defect 1) and TIM/Die (defect 2). (b) Predicted lid temperature distribution at $t = 46$ ms.

through the transparent layer, interacts with the absorbing layer, and rapidly ablates it. The rapid expansion of the ablated layer is constrained by the confining layer and this generates a compressive stress wave that propagates to the frontside of the die. When the compressive wave reaches the active side of the die, it is reflected back as a tensile wave. As the tensile wave travels through the thin films of the die, it can cause ablation of the layers if the tensile stress wave exceeds the adhesion strength of any thin film layer. Fig. 6 schematically represents the interaction between the laser pulse and the die sample.

The technique can be used qualitatively to compare different device fabrication processes by varying the initial laser pulse energy until ablation occurs for each process condition. Figs. 7 and 8 show how the technique can be used to evaluate different inner layer dielectric (ILD) processed wafers. Quantification of the adhesion strength of the ablated layer is also possible and done by measuring the die surface velocity using a laser interferometry and a high-speed detection system [7]. The tensile wave stress that is responsible for the layer ablation is calculated from the free surface velocity and the die material properties and geometry.

One significant advantage of the laser spallation technique over traditional adhesion metrologies is the ability to determine adhesion strengths in fully processed samples such as production wafers or packages where the influence of multiple processing steps can be evaluated. The technique can be used to accelerate the evaluation of process improvements without the need to assemble the device into packages and conduct the time consuming reliability stresses.

One of the major limitations of this technique is that the high strain rate of the tensile wave does not accommodate any plastic stain effects that the interface normally experiences prior to failure. Hence, adhesion strength values obtained by this technique may not be accurate for compliant materials. Another limitation is that the weakest interface will be the first to spall and this prevents understanding strength of other interfaces. Significant characterization to optimize the technique is needed before it can be used on a routine basis.

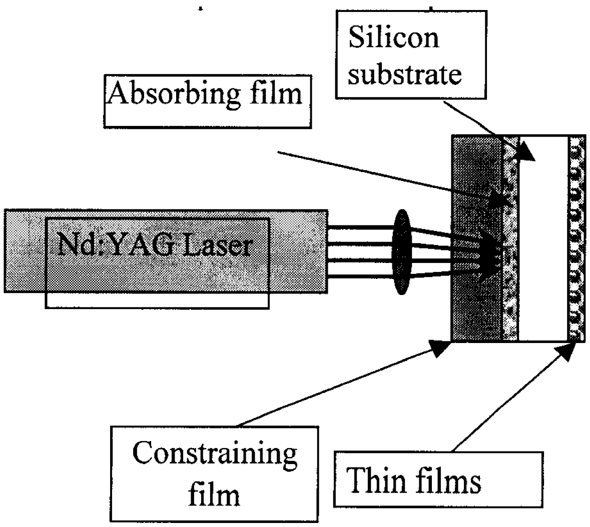


Fig. 6. Schematic representation of the laser sample interaction.

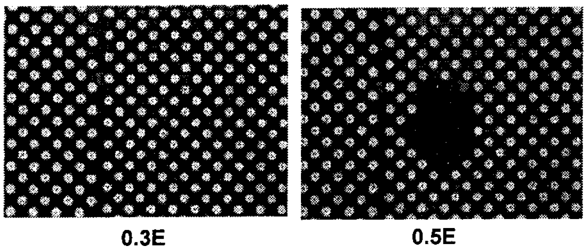


Fig. 7. Optical photos show bumped die surface after $0.3E$ and $0.5E$ laser pulse energy. The $0.5E$ laser energy was able to cause bump spallation. (E is an arbitrary unit.)

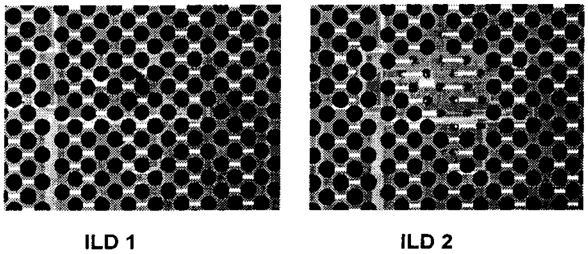


Fig. 8. Optical photos of die surface on two different ILD processed wafers after the laser spallation test with the same laser energy. Only ILD 2 showed bump spallation.

V. CONCLUSIONS

Recent advances in acoustic microscopy can be used to image integrity of closely spaced interfaces to reveal such defects as interface delamination and cracks. High-speed pulsed IR thermography has been shown to be effective in imaging delamination and degradation of interfaces in TIM. Laser spallation is a new technique that can be used to qualitatively and quantitatively determine the integrity of interfaces in die and packages on fully processed samples.

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Rajen Dias, photograph and biography not available at the time of publication.