Application of acoustic time-frequency domain imaging for the evaluation of advanced microelectronic packages

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Abstract

Acoustic micro imaging (AMI) is used as an important non-destructive inspection tool in semiconductor reliability evaluation and failure analysis. As advanced microelectronic packages are being produced smaller and thinner, detection of the internal features and defects in the packages are approaching the resolution limits for conventional AMI. Recently acoustic time-frequency domain imaging has been proposed by the authors to generate interface images with higher resolution. In this paper, acoustic time-frequency domain imaging is applied to real 3D RF data acquired from modern microelectronic packages. Experimental results in applications such as flip-chips and stacked dies are presented. The super resolution of acoustic time-frequency domain imaging is demonstrated by revealing more image details and enhancing image contrast in comparison with conventional time domain imaging.

1. Introduction

As packages are being produced smaller and thinner, detection of the internal features and defects in the packages is approaching the resolution limits for conventional acoustic micro imaging (AMI). The resolution of an AMI system is determined largely by the frequency and design of the installed transducer. Although higher frequency transducers are capable of higher resolution, their acoustic signal does not penetrate very deeply. Today a ~200 MHz transducer can resolve 10 – 15 µm in spatial X and Y but is limited to samples that are no thicker than a millimetre. For 3D microelectronic packages, there is the additional complication of multiple interfaces, where each interface has its associated attenuation and acoustic reflection. The attenuation drops the signal level and the multiple reflections complicate the interpretation of data. The key acoustic challenges for inspection of modern microelectronic packages are axial resolution for delamination and cracks at closely-spaced interfaces and penetration through multiple interfaces with high delta Z (acoustic impedance changes)\(^{(1)}\). When the layer thickness is less than or comparable to the wavelength of the ultrasound, the reflected echoes from the front and the back surface of
the layer overlap. The interference between the two echoes results in pulse distortion, degrading ultrasonic C-scan images. In addition, the different propagation modes, diffraction, and dispersive attenuation make the interpretation of ultrasonic signals/images even more complex.

2. Acoustic time-frequency domain imaging

2.1 Conventional acoustic micro imaging

Acoustic microscopes operate in the pulse-echo mode, typically over a range from 5 to 300 MHz, to produce images of samples at specific depth levels. With conventional time domain AMI, a focused ultrasonic transducer alternatively sends pulses into and receives reflected echoes from discontinuities within the sample. By inspecting the reflected echoes, the ultrasonic pulse-echo method is used to characterise the propagation path and/or to determine the physical properties of reflectors in terms of their location, size, orientation, and microstructure. Acoustic micro imaging can be optimized for analytical studies where layer-by-layer analysis is needed. Since the echoes are separated in time, based on the depths of the reflecting features in the sample, a gate corresponding to a time gate can be used to select a specific depth or interface to view. A mechanical scanner moves the transducer over the sample, producing C-scan (interface scan) images. At each x-y position only the peak intensity value and the polarity of the echo within the gate are displayed in the C-scan image. In AMI, the higher resolution capabilities require higher acoustic frequencies. Lower frequencies, however, provide more penetration through materials. A frequency that provides the best compromise of resolution and penetration can be found to suit most applications. AMI can help solve problems with adhesion, delamination, disbond, cracking, wetting, and voiding in the evaluation of microelectronic packages.

2.2 Acoustic frequency domain imaging

Acoustic frequency domain imaging is one method that can extract information at or slightly beyond the limits of conventional AMI by using the frequency content of the signal[2]. In most commercial AMI systems, each reflected echo has a broad range of frequencies whose distribution is similar to a Gaussian function. The gated signals from A-scans can be decomposed into the frequency domain by the Fast Fourier Transform (FFT), resulting in a dozens of individual FFT images.

When inspecting modern microelectronic packages, high acoustic frequencies are often chosen in order to gain resolution. As the ultrasonic pulse propagates from the transducer through water coupling into the IC package and back, the higher frequencies in the incident pulse suffer more attenuation than the lower frequencies, resulting in frequency downshifting. Suppose that a gated signal is comprised of two echoes which are overlapped in the time domain, and the spectra of the two echoes are separated partly in the frequency domain. Due to phase change, some frequencies of an echo undergo constructive interference while others undergo destructive interference. At a fixed frequency, the
frequency strength might come mainly from the expected echo with the interfering echo giving minor contribution. In this case, frequency imaging still gives a high contrast FFT image at this frequency, though the time domain image is poor due to the echo superposition. However, at some frequencies the FFT images would have poor performance in terms of resolution and contrast. A limitation of frequency imaging is that if a gated signal includes more than two echoes, the spectrum is more complicated, and the FFT images are difficult to interpret because they have no time resolution. Generally speaking, frequency imaging is not an interface scan method. Additionally, it is hard by quantitative analysis to give the values of the frequencies where high contrast can be achieved in practical applications.

2.3 Acoustic time-frequency domain imaging

Recently a number of acoustic time-frequency domain imaging techniques (TFDAMI) were proposed by the authors to achieve super resolution and high robustness\(^{(3,4)}\). For acoustic time-frequency domain imaging, each A-scan is decomposed to the time-frequency domain by a sparse overcomplete signal representation technique such as continuous wavelet transform and matching pursuit. Echo separation is then carried out by exploiting their sparse representability in the time-frequency domain. Finally, an appropriate echo corresponding to an interesting interface is selected by a time-frequency window to produce a C-scan image.

Research shows that sparse overcomplete representation can offer great advantages in many applications. One is that there is greater flexibility in capturing structure in the data. Instead of a small set of general basis vectors, there is a larger set of more specialized basis vectors such that relatively few are required to represent any particular signal. These can form more compact representations, because each basis vector can describe a significant amount of structure in the data. The second is super-resolution. We can obtain a resolution of sparse objects that is much higher than that possible with traditional methods. The third is the shift invariance property. These advantages of sparse overcomplete representations will benefit ultrasonic echo separation in the time-frequency domain. Our previous simulation results have demonstrated that acoustic time-frequency domain imaging can significantly improve the imaging performance\(^{(3,4)}\). But it has not been applied to real 3D acoustic data.

3. Applications

In this section, case studies are presented to demonstrate the performance of acoustic time-frequency domain imaging. The continuous wavelet transform based acoustic time-frequency domain imaging technique proposed in ref. [4] is used in the following application examples. 3D acoustic data are acquired using a commercial AMI system from Sonoscan, Inc. fitted with a Virtual Rescanning Module which allows collection of A-scans in order to produce a virtual acoustic sample. From the stored information images of depths within the device not included in the original gate for the image can be recreated and/or waveforms (echoes) can be viewed for analysis without rescanning the sample. In addition
to this the echoes can be digitally processed to extract further information about the condition of the sample, or extract information at or beyond the limits of conventional AMI.

### 3.1 Flip-chips

In this example, a flip-chip package mounted on a ceramic substrate is investigated. An acquired A-scan example is displayed in upper-left of Fig.1. Under the gate displayed in the A-scan signal, the underfill-substrate interface image obtained using the conventional time domain AMI is shown in the lower-left of Fig.1. The acoustic time-frequency domain image of the same gated area is shown in the lower-right of Fig.1. From Fig.1 it can be seen that the TFDAMI image brings out details not present in the time domain image.

![Acoustic time-frequency domain imaging of a Flip-Chip package mounted on a ceramic substrate.](image)

#### Figure 1. Acoustic time-frequency domain imaging of a Flip-Chip package mounted on a ceramic substrate.

### 3.2 Stacked-dies

Die Stacking is the process of mounting multiple chips on top of each other within a single semiconductor package. Die stacking significantly increases the amount of silicon chip area that can be housed within a single package of a given footprint, conserving precious real estate on the printed circuit board and simplifying the board assembly process. Aside from space savings, die stacking also results in better electrical performance of the device, since the shorter routing of interconnections between circuits results in faster signal propagation and reduction in noise and cross-talk. Die stacking is now synonymous with "vertical
integration', or the integration of circuits in vertical fashion instead of the traditional horizontal or planar approach. However, stacked dies limit the use of high frequency ultrasound even though package features are becoming increasingly smaller and dies increasingly thinner, resulting in significant challenges for reliability testing. Acoustic time-frequency domain imaging can be used to bring out features/defects that were either not clear or not detectable in the time domain images.

![Figure 2. Acoustic time-frequency domain imaging of a stacked die package. (a): A time domain image; (b): A time-frequency domain image; (c): A frequency domain image.](image)

Images of an interested interface in a stacked die packaging obtained using time domain imaging, and time-frequency domain imaging are presented in Figs.2a and 2b respectively. Fig.3 shows an A-scan signal acquired from the package, in which the interface echo used to generate Fig.2a is depicted. Delaminations are much clearly seen in the acoustic time-frequency domain image than in the time domain image. For the purpose of comparison, the frequency domain image obtained using acoustic frequency domain imaging is displayed in Fig. 2c. It can be seen that frequency domain image include the features from
the other interfaces, and the delaminations are blurred as well in this specific frequency used.

![Figure 3. An A-scan signal from the stacked die package.](image)

4. Conclusions

The drive to manufacture smaller and thinner microelectronic packages and features in the packages is pushing the limits of the inspection technologies to resolve/detect these features. The examples presented in this paper demonstrate that higher resolution can be achieved by acoustic time-frequency domain imaging than conventional time domain imaging. Acoustic time-frequency domain imaging can be used to evaluate advanced microelectronic packages.

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References

