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NDE Applications in Microelectronic Industries

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ABSTRACT

New concepts in assembly technology boost our daily life in an unknown way. High end semiconductor industry today deals with functional structures down to a few nanometers. ITRS roadmap predicts an ongoing decrease of the “DRAM half pitch” over the next decade. Packaging of course is not intended to realize pitches at the nanometer scale, but has to face the challenges of integrating such semiconductor devices with smallest pitch and high pin counts into systems. Advanced techniques of nondestructive evaluation (NDE) with resolutions in volume better than 1 micrometer vixen size are urgently needed for the safety and reliability of electronic systems, especially those that are used in long living applications. The development speed of integrated circuits is still very high and is not expected to decrease in the next future. The integration density of microelectronic devices is increasing, the dimensions become smaller and the number of I/O's is getting higher. The development of new types of packages must be done with respect to reliability issues. Potential damage sources must be identified and finally avoided in the new packages.

In power electronics production the condition monitoring receives a lot of interest to avoid electrical shortcuts, dead solder joints and interface cracking. It is also desired to detect and characterize very small defects like transportation phenomenon or Kirkendall voids. For this purpose, imaging technologies with resolutions in the sub-micron range are required.

Keywords: Power Electronics, Micro NDE, Packaging, ITRS Road Map, 3D x-ray Laminography, Acoustic Microscopy, AFAM, Thermography

NDE HISTORY

New NDT techniques were created in response to new technologies being developed. The most important applications during the early days of NDT have been focused to customs and railroad applications. Important progress has been made in the 50th and 60th of the last century in response to demands from pressure vessel and nuclear industry. In recent 20 to 30 years, save mobility by automobiles and aircraft required a lot of new developments of conventional NDT but also advance NDE techniques. Today microelectronic components are more and more integrated in complex smart structures where they have to operate under harsh environments reliable for many years and have safety relevant functions. This requires a new class of NDE applications for technology development and product inspection with resolution down to few nanometers. For instance power electronics and monitoring system for wind turbines and electro mobility requires life prediction technologies that are unthinkable without nondestructive inspection [1].

FIGURE 1. NDE History in Context of Industry Demand and Important Invocations

CHALLENGES FOR NDE OF MICROELECTRONIC AND MEMS COMPONENTS

Challenge Electronics Packaging

Electronics and microsystems technology are characterized by an ongoing miniaturization and a growing up of complexity of semiconductor components. These trends are described by Moore's Law and the terms "More Moore" and "More than Moore" as follows: "The combined need for digital and non-digital functionalities in an integrated system is translated as a dual trend in the International Technology Roadmap for Semiconductors: miniaturization of the digital functions ("More Moore") and functional diversification ("More-than-Moore")." (cited from [2] page 8, see Fig. 2). The most important driver of this development is the respective market of the final products – driven by the costs. In this context the development of electronic and micro technical systems is inseparably connected with the corresponding electronics packaging and the required non-destructive testing methods.

FIGURE 2. Development of electronics and the challenges of packaging [2]

The speed of development of integrated circuits is still very high and is not expected to decrease in the next future. ITRS roadmap [2] predicts an ongoing increase of the complexity of integrated circuits, which has a deep impact on all packaging relevant parameters on the first and second interconnection level. In this context often the term “nano packaging” is in use. Figure 3 shows some usual interface constructions and the ZVEI commitment to the beginning of nano-scaled interfaces (ZVEI - German abbreviation of the electronics industry association). So nano packaging is defined beginning with ball diameters of 150 µm and smaller (see [3] and [4]).

FIGURE 3. Interface constructions and changes in the ratio between ball size and pad size [4]

Currently are three technological main trends in nano packaging visible (see Fig. 4):

- Miniaturization of electrical connections (e.g. solder joints, buried vias in PCBs (PCB – printed circuit board) & wire bonding connections)
- Use of sequential build-up techniques
- 3D integration with hidden structures.

FIGURE 4. Main trend examples: buried vias in a PCB (a), overmolded devices (b) & stacked memory dies (c)

New kinds of damage processes and defect modes are going hand in hand with this miniaturization because some of the material behavior is changing when object size is shrinking as well as nano scaled materials with new properties are necessary to realize these small interconnects. Some of the expected defects are shown in Fig. 5.

New packages, new packaging technologies and new expected defects need corresponding high resolution non-destructive testing methods. But which testing methods are capable imaging nano packaging defects? It is necessary to develop evaluation techniques to find out the possibilities and limitations of different inspection technologies. Some ways like the use of so called reference objects and defect samples are described in [5] and [6].

FIGURE 5. Expected defect modes in small interconnects ([3]; [4])

“Moore's Law of NDE”

Moore's Law predicts the development of the structural size for microelectronic components. The logarithmic plot of transistor counts over the years of introduction shows an almost linear slope since 1971 the introduction of the first Microprocessor by Intel. Also NDE technologies have shown a continuous increase of detectable structural size in response to the requirement of the driving industries (Fig. 6). While acoustic microscopy with 1GHz frequency and hence 1.5 micrometer wavelength in water allows imaging of surface and subsurface features in the micrometer range micro focus x-ray techniques are able to visualize micrometer size structures in the bulk. Both techniques have been available since about a quarter of a century and have been frequently used in microelectronic industry. The x-ray microscopy that by exploring Fresnel lenses enables volume imaging by CT and laminography with a resolution of a few nanometer. That is sufficient for inspection of microchip packages [1].

FIGURE 6. Detectable structural dimensions of NDE techniques

RELIABILITY ASSURANCE AND NDE IN MICROELECTRONIC APPLICATIONS

Future electronic applications must be designed for high reliability under harsh environmental impacts. E.g. satellites in near orbit are forced with temperature changes of $\pm 150^{\circ}\text{C}$ every 45 min or sensors assembled closed to wing tip of aircrafts are highly loaded with vibration overlaying temperature changes. Many physical mechanisms may lead to defects in electronic application and occur as delamination, crack crowing or mechanical weakness of microstructures. State of the art to determine physical failure origins is the metallographic preparation of the object of interest. It has the ability to detect the defect in very high resolution to be able to interpret the failure origin. This preparation comes along as a destructive method and it is very time and financial consuming. Further, there are no chances to monitor the development of failure, e.g. the controlled crack crowing in bearing structures.

There is a strong need from industry of non-destructive evaluation of defects and even more for inline solutions for product quality management.

Additionally, new package technologies forces new kinds of damage processes and defects. These are for example transportation phenomenon and re-crystallization, volume modifications and Kirkendall voids. Fig. 7 shows selection of these expected phenomena. Detecting these defects requires new inspection techniques, new inspection facilities and new knowledge about the physical and chemical effects in nanometer dimensions. For the safety and reliability of electronic systems, especially those that are used in long living applications, advanced techniques of nondestructive evaluation (NDE) are urgently needed. This is valid for both, the development of reliable technologies and a 100% testing of products.

FIGURE 7 Challenges for nano NDE (Source: [3])

A special challenge of nano NDE is the technological gap for NDE techniques in the resolution range between about 100 nm and 10 μm . Fig. 8 presents imaging NDE methods and their resolution. Visible is the above-mentioned gap in the resolution.

Figure 8 Gap of NDE methods

MICRO- AND NANO-NDE METHODS

3D x-ray Laminography

Computed x-ray tomography (CT) is a method to acquire three dimensional data of complex structures by means of recording numerous x-ray radiographs and back-project them to the volume. The Fraunhofer developed geometric setups to overcome large length differences and made so CT to a useful tool for the three dimensional inspection of highly packed printed circuit boards (PCB) in the classical sense and in the meaning of on chip wiring as well. As a further effect these setups allow highest resolution in extended samples without the dynamic limiting artifacts in the reconstruction known in ordinary ROI-CT images. This method allows quality control of micro solder bumps as well as of the classical PCB covering so two decades of voxel size from $>1 \mu\text{m}^3$ up to $>10 \mu\text{m}^3$.

For solder bumps the presence and size distribution of pores is a typical question of QM usually solved by 2D x-ray inspection. 3D methods can help to further qualify voids by the position normal to the plane of the PCB in critical and no critical to increase the yield of the fabrication and make the manufactured devices more reliable. Further the voxel size closed to $1 \mu\text{m}^3$ enables the visualization if macro cracks inside the packages, e.g. solder joints cracks.

Fig. 9 illustrates the capabilities of a modern method. The object of inspection was a large and very thin ceramic PCB of about 125 mm square with a thickness of about 500 μm carrying altogether 16 identical printed circuits of about 6 mm size. The developed tool was able to inspect an individual circuit three dimensionally with a sufficiently high resolution to inspect the alignment and size of each individual layer without destroying the full board as requested for assembling of the circuits. The separation of the layers is extremely good. Therefore this method is suited to inspect printed circuits of current productions of any size with a high resolution when focusing on special points of increased reliability.

FIGURE. 9. Layers of a ceramic multilayer PCB (total thickness of the PCB is 500 μm ; field of view about 15 mm; PCB was in an array of 16)

Acoustic Microscopy

The acoustic microscope is a well-established tool for studying internal microstructures of non-transparent solids and coatings. It is widely used in detection of cracks and subsurface defects in various materials. Image formation and interpretation strongly depend on frequency and material properties. In scanning acoustic microscopy (SAM) operating in the GHz frequency range, resolutions in the micrometer-range can be reached but the penetration depth is very limited. The NDE problems of packaging require penetration depth in the range of 1 mm, this demands lower frequencies. Depending on the task (flip chip, encapsulated chips, delamination of adhesive layers, leak of underfiller, etc.) transducers in the frequency range between 10 MHz and some 100 MHz are used. The focal lengths of the transducers have to be adapted to the problem. The signals are not always easily to interpret due to various effects as transducer edge waves, mode conversions, multiple reflections in the structure etc. Modelling of the wave phenomena can lead to a better understanding of the situation.

A numerical model of an acoustic microscope based on the elastodynamic finite integration technique (EFIT) has been developed. As example the case of a water filled cavity in a solid material (zinc) is used Fig.10.

FIGURE 10 Numerical CEFIT simulation of acoustic reflection microscopy (25 MHz) at a 100 μm diameter and 70 μm deep water filled spherical cavity. The time snapshots display the absolute value of particle velocity using a linear gray scale. The series of snapshots is arranged from left to right and then from top to bottom.

The first snapshot shows the primary P wave in the moment when it hits the surface. Afterwards the reflected P-wave transmitted P-wave and mode converted waves are visible. In the filled cavity multiple reflections appear which generates secondary echoes traveling through the coupling fluid to the transducer.

Atomic Force Acoustic Microscopy (AFAM)

AFAM uses an Atomic Force Microscope (AFM) where flexural and torsional cantilever vibrations are excited by out-of-plane and in-plane sample surface vibrations. The resolution of conventional acoustic microscopy is limited by the acoustic wavelength. Sub-wavelength resolution can be obtained by near field techniques for example the Atomic Force Acoustic Microscopy (AFAM). The ultrasound is transmitted from the sample into the cantilever while forces act between sensor tip and sample [7]. The sample surface is scanned by the sensor, and an ultrasonic image is acquired simultaneously to the topography image. The contrast comprehended in the ultrasonic image depends on surface topography and on the local elastic properties of the sample. Voids, inclusions, or cracks, which represent regions of different elastic constants in the interior of the material, are sensed by the local elastic response of the tip at the sample surface. As a consequence, information on hidden structures can be derived from the acoustic images.

FIGURE 11 a) SEM image of the silicon sample with a hole milled from the side (hollow arrow) with decreasing diameter up to top of silicon (arrow) creating a thin Si-membrane, b) AFM image of topology scan, c) AFAM image of topology scan with depth information of membrane.

Thermography

Thermal techniques offer a unique contrast due to the microscopic heat flows [8]. There are microscopic thermal wave techniques, where the resolution is determined by a highly focused laser beam that generates local temperature oscillations. The temperature oscillations are detected by infrared detectors, by temperature dependent optical reflection properties or by thermally induced acoustic waves. The contrast is determined by changes of the thermal effusivity, by thermal resistances or by changes of the geometry of the heat flow. A special feature in this kind of thermal imaging is the thermal depth profiling capability (sub- μm to 1 mm), given by a change of sub-surface penetration of the thermal wave by change of the thermal diffusion length. The lateral resolution is limited to about 1 μm when optical excitation is used or to some 10 nm when a modulated electron beam is used for heating. Typical imaging application comprises micro crack detection and determination of thermal resistances of interfaces, including joints.

FIGURE 12. 7 Left: Pulsed thermography image (10 mm x 10 mm) of a microelectronic component after 45 ms triggered by a 5 ms flash (right) revealing internal details only visible after additional thermal excitation.

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