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X-ray absorption-based technique to measure the thickness of multi-layered structures

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ABSTRACT

The gray level information gathered from using the X-ray absorption-based technique was used to determine the thickness of multi-layered structures in semiconductor components. Various thickness combinations of silicon, copper, tin and silver material were used to construct a range of triple-layered structures. The minimum thickness resolution achievable in copper and tin, for both silicon–copper–tin (Si–Cu–Sn) and silver–tin–copper (Ag–Sn–Cu) combinations were in the order of 0.001 mm. This value was comparable to a single layer of copper and tin, respectively. The gray level information was also applied to detect the presence of a void or an imperfect solder bump, which is increased of approximately 7% and 30–40%, respectively, in the gray values was observed compared to a defect-free and complete solder.

1. Introduction

Lead–tin solders are frequently used as an interconnect but due to an international legislative to ban lead, as the material is considered a health hazard, alternative lead-free solders were developed. Lead-free solders are normally tin-rich alloys containing elements such as silver, copper, zinc of a certain composition, and are of different shapes, thickness and diameter, as shown in Fig. 1. Voiding at reflow soldering however, remains a problem as it compromises the mechanical properties of joints and adversely impact the strength, ductility, creep and fatigue life of the component. Premature solder joint failures can also occur as a result of high stress regions formed due to missing and/or inconsistent heights of the bumps. Optical inspection has been actively used to identify these variations and defects; however the measurement accuracy may be affected by the irregular optical reflection rate because of the difference in brightness of the bump surface. Development of new metrology techniques is therefore required to not only provide fast and reliable inspection but also be effective to a widespread of in-situ industry applications. The X-ray imaging technique may provide this alternative solution.

X-ray imaging technique provides information on the hidden features in an object based on the differences in the material absorption characteristics. The amount of X-rays passing through a material is largely governed by a number of interrelated factors [1–3]. The characteristics of the incident X-rays and the nature of the material are two significant attributes. The incident X-ray characteristics are influenced by three main factors; the energy distribution, the applied current and the target material. Varying the tube voltage changes the X-ray energy distribution and, therefore, the penetrating power. The increment of the accelerating voltage would shift the energy distribution to a higher level, and thus increasing the extent of X-ray transmission through a material. As the energy range for the interaction between a material and X-ray photons is wide, the knowledge of the X-ray spectral distribution for a specific material type and sample geometry is required in order to optimize the quantitative absorption-based measurements. The current emitted to the target primarily measures the number of electrons that are incident onto the target. The increase in applied current will generate a higher number of X-ray photons leading to greater X-ray intensity. The target material affects the efficiency of the X-ray tube in generating X-rays and it is proportional to its atomic number [3,4]. Materials with high atomic number are preferred so that transitions of high enough energy to emit X-ray radiation are possible for the same electron beam. The accelerating voltage and applied tube current were the easiest of the three variables to adjust and were used to optimize the system resolution [5–8].

The principal material factors that affect the amount of X-rays transmitting through a material include the specific absorption characteristics of the constituent elements, sample thickness and density. X-rays are more penetrative to low atomic number materials. Heavier, thicker and denser materials offer a greater

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resistance to radiation penetration as a result of the higher energy absorption caused by the increase in the subatomic particles interaction.

Knowledge on the attenuation of single energy X-ray photons as they pass through an absorbing material was used to characterize a material. This non-contact method can be used to define the material thickness if both the composition and the mass density of the material are known or likewise, the average mass density along the radiation path can be determined if the composition and thickness of the material are known. Earlier works have revealed the capability of using the gray values obtained from the X-ray-based absorption measurements in providing quantitative material thickness analysis in single- [7] and dual-layered [8] systems. These preliminary works have also demonstrated that the gray level information gathered from the direct digital detector (DDD) was used for quantitative measurement with a thickness resolution varied from 0.001 to 0.025 mm depending on the material type. Characterizing larger number of combinations and applying this technique to real components would be challenging, which this study tends to demonstrate.

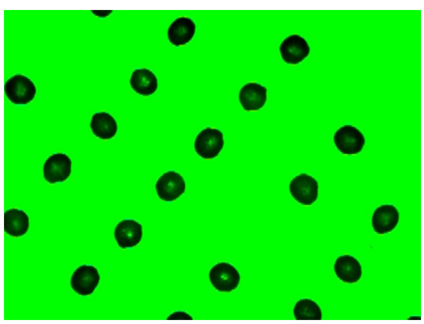

Fig. 1. Example of solder balls of different shapes and conditions.

Fig. 2. A Nanofocus Focus FOX 160.25 X-ray imaging system.

2. Materials used and methodology of X-ray absorption-based technique

2.1. Thickness measurement of multi-layered structure

A Nanofocus Fein Focus 160.25 X-ray imaging system equipped with a 16 bit Varian DDD, as shown in Fig. 2, was used in this work. Thin and pinhole free 99.99% pure foils of tin, silver and copper of different thickness were used to construct the multi-layered configuration. Table 1 provides a summary of the experimental configuration. Silicon wafer of 0.5 mm thickness was used as a substrate in the construction of the multi-layered structure.

The substrate was first positioned followed by the second and third layer placed on top of one another, at the centre of a light cone, at an equidistant position between the tube and detector, as shown in Fig. 3. The latter positioning would limit the effect of the geometric unsharpness and difference in path length associated with the cone beam. The accelerating voltage and applied tube current of the X-ray was set at 60 kV 54 μA for the Si–Cu–Sn combination, and 66 kV 64 μA for the Ag–Sn–Cu combination so as to optimize the instrumental system. 16-bit clear images were captured after integrating 3 frames per second and the gray level statistics were extracted from a 2 by 2 cm area of the image using the Image Analysis Software. The second and third layer was also analyzed as a single material at similar accelerating voltage and applied tube current settings for comparison. The Ag–Sn–Cu combination was repeated another three times to study the repeatability of the results.

In measuring the thickness of a layer in a multiple layer configuration, it was assumed that the X-ray beam is of uniform intensity and monochromatic. The reduction of the X-rays of the silicon wafer or silver with a fixed thickness representing the substrate was initially measured using an exponential relationship known as Beer's Law. This law can be expressed by Eq. (1) [1,3]

$$\ln\left(\frac{I_1}{I_o}\right) = -\mu_1 x \qquad (1)$$

where I_1 is the intensity of transmitted beam I_o after passing through a thickness, x, as shown in Fig. 4(a) and μ_1 is the linear absorption coefficient which is dependent on the material considered, its density and the wavelength.

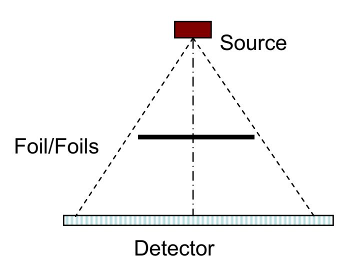

Fig. 3. Positioning of the foils at the centre of a light cone at an equidistance position between the tube and the detector.

Table 1
Summary of the multi-layered combination at different thicknesses and materials

Triple-layered configuration	Substrate		2nd layer		3rd layer		Settings	
	Material	Thickness (mm)	Material	Thickness (mm)	Material	Thickness (mm)	kV	μA
Si–Cu–Sn	Si	0.5	Cu	0.001–0.01	Sn	0.001–0.005	60	54
Ag–Sn–Cu	Ag	0.025	Sn	0.001–0.004	Cu	0.001–0.025 (exclude 7–9, 17–19 and 21–24 μm)	66	64