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Investigation of ultrasonic vibrations of wire-bonding capillaries

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Abstract

Ultrasonic energy is widely used in wire bonding for microelectronics packaging. It is necessary to ensure that the maximum ultrasonic vibration displacement occurs at or near the tip of the bonding tool (capillary) for optimal performance. In this study, amplitude profiles of ultrasonic vibrations along capillaries were measured with load using a laser interferometer. This provided valuable information in understanding and improving capillary performance. The method was applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications. First, the application of a new capillary material with different zirconia compositions was evaluated. The new material with certain amount of zirconia composition showed that it was the capillary material of choice for ultra-fine pitch wire bonding. Next, comparative analysis was conducted to investigate the ultrasonic energy transfer of a new ‘slimline’ bottleneck and the conventional bottleneck. The actual bonding response of the molded slimline bottleneck showed comparable performance with the ground conventional bottleneck using the same bonding parameters. Finally, optimization of a 60-μm-bond-pad-pitch process was performed on a wire bonder. Within the optimized parameter ranges, the ultrasonic displacement of the capillary was monitored. For all possible combinations of bond force and bond power, the ultrasonic displacement of the capillary increased with increasing bond power, without drastic changes caused by bond force changes. This indicated that the selected process window was located in a stable region.

Keywords: Microelectronics packaging; Wire bonding; Ultrasonic vibration; Capillary; Ultra-fine pitch

1. Introduction

The increasing demands for high pin count, high electrical performance and miniaturization have led to significant advances in IC (integrated circuit) fabrication and microelectronics packaging [1–6]. Processing of silicon wafers also plays an enhanced role in manufacturing of microelectronics and micro-electro-mechanical systems [7].

Wire bonding is the most widely used technology in the microelectronics industry as a means of interconnecting IC chips and substrates [8]. Today, more than 90% of IC chips used in the world are with wire bonds because the high-speed automatic wire bonders meet most of the needs of microelectronics devices to the next-level packaging interconnection [9]. Today’s demands for speed, accuracy and reliability are fulfilled with modern cameras, ingenious optics and illumination, modern digital signal processors and intelligent algorithms [10].

A cost analysis [9] has also revealed that wire bonding cost per die decreases with pad pitch increases. Wire-bonding cost per die decreases with chip size decreases. For peripheral array chips, wire bonding is cheaper than flip chip [11,12] if the chip size and the pad pitch are very large.

Microelectronics packaging has sparked intensive interest in ultra-thin packages in which the body thickness is less than 1 mm [13]. This is forced by the demand of assemblies such as Smart Cards and MCMs (multi-chip modules). The emphasis is placed on the interconnect between the chip and its interconnection system. The bond loop height is one of the dominating parameters in reducing the thickness of the ultra thin package [14].

Besides the most commonly used Au wires, Al–Si wires are also used for interconnection in microelectronics devices, including RF power transistors in cellular base stations [15]. To improve the performance of advanced ICs, a transition from Al to Cu metallization is in progress. Despite its many advantages, implementation of Cu poses

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a challenge for integration, even in the case of conventional Au wire bonding technologies [16].

Ultrasonic wire bonding is playing an important role in making interconnections in the microelectronics packaging industry. High quality of the bonds is vital to the performance of an IC chip. Therefore, a proper bonding quality control system is desirable. It is known that the bonding quality can be distinguished by observing the change in vibration amplitude of the fundamental frequency of the transducer [17].

The connections at the bond pad and lead are made by welding the wire to the metal with a combination of ultrasonic energy, pressure, and heat. This task is done with a wire-bonding machine, which has several parameters to set, such as temperature, ultrasonic power, and bond force. The parameter settings for successful wire bonding depend on many factors, including wire size, pad material and geometry, package size, tool type, and the capabilities of the machine. These require expert knowledge to optimize critical process characteristics [18].

Ultrasonic technology can be used for many applications [19,20] by appropriately utilizing its sound wave and high-frequency mechanical energy. In ultrasonic metal welding, the use of ultrasounds allows metals to be cold-welded, i.e. two metals can be welded together remaining at a temperature far below the melting temperatures of the two metals [21]. Ultrasonic energy is used to improve the structure of materials in metallurgy. The acoustic irradiation of molten mass improves degasification and the finer grain structure during the hardening process. To achieve a high level of wire bonding performance and quality, appropriate bonding process parameters must be accurately identified and controlled. Process engineers must identify and control these parameters to obtain desired wire bonding quality for optimizing multiple responses (e.g. maximum ball shear strength, wire pull strength, and appropriate ball size), based on their experience or equipment provider's recommendations [8].

Ultrasonic energy and the normal force to the bonding surface generate the metallurgical interaction causing the atoms of the wire to diffuse into the bonding site. The principal bonding process parameters such as bonding time, normal force, resonant frequency, ultrasonic power, and the amplitude of the tool can affect the bonding quality [22].

In recent years, there are increasing research efforts in the quantitative understanding of the wire bonding process mechanism to relate it to bonding quality. With the application of ultrasonic waves and a static tool tip force, a solid-state weld joint is produced between the wire and the terminal surface. A decisive factor for the electrical and mechanical proprieties of the bond is the vibrational behaviour of the bonding tool, which transmits the ultrasonic energy to the contact zone [23].

Ultra-fine pitch wire bonding [24] and copper bonding require a higher stability and robustness of the ultrasonic vibration generated by the transducer compared with current ultrasonic horns. No theory that can describe and clarify why higher frequencies can modify the results of the wire bonding process has been developed. The reason for the frequency increase of the transducers is that, at higher frequencies, the same bond results can be achieved at a lower bonding temperature reducing the thermal stresses and drifts in wire bonders, and in a shorter bonding time increasing the speed of wire bonders [25].

Ultrasonic welding is a type of deformation weld in which the metal is first softened by the ultrasonic energy. The clamping force deforms the softened wire or ball against the equivalently softened bonding pad, sweeping aside brittle surface oxides and contaminants, leaving clean surfaces in contact. Because little deformation takes place in the center of the weld, the oxides and contaminants remain there, and this area is often observed to remain unwelded. Presumably, the same energy transfer mechanism that softens the metals without significant heat generation also supplies the required activation energy for interdiffusion. This forms the metal-to-metal (atomic) bonds within a few milliseconds [26].

Therefore, in wire bonding, the bonding-tool (capillary) vibration amplitude is one of the most important parameters that influence the energy delivered to the bond zone. It is necessary to ensure that the maximum ultrasonic vibration occurs at or near the tip of the capillary for optimal performance. However, the quantitative understanding of the ultrasonic bonding mechanism still remains insufficient and therefore will continue to pose a huge challenge for future research work.

In this study, ultrasonic amplitude profiles along capillaries were measured using a laser Doppler interferometer. Measurement could be performed with load or in free air without load. To simulate actual bonding conditions, measurements were performed with load in this study. This provided valuable information in understanding and improving capillary performance. The method was applied to real time applications to optimize capillary designs and bonding processes for specific bonding applications. First, the application of a new capillary material with different zirconia compositions was evaluated. Next, comparative analysis was conducted to investigate the ultrasonic energy transfer of a new 'slimline' bottleneck and the conventional bottleneck. Finally, optimization of a 60-μm-bond-pad-pitch process was performed on a wire bonder and within the optimized parameter ranges, the ultrasonic displacement of the capillary was monitored.

2. Experimental setup

A laser Doppler vibrometer is an optical instrument that employs laser interferometric principles to measure velocity and displacement of points on a vibrating structure. The mobile unit of the laser vibrometer, which included a camera, a scanning unit, and an optical sensor head,