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Non-destructive degradation study of copper wire bond for its temperature cycling reliability evaluation☆

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ABSTRACT

Wire bonding is essential for the electrical connection of integrated circuit (IC) devices, therefore its quality and reliability is of utmost importance. During the wire bonding process, several parameters need to be well controlled in order to achieve a well bonded wire. Furthermore, the migration to copper (Cu) wire from gold (Au) due to its high cost has resulted in an even more stringent and narrow process window. Current industrial practices to evaluate wire bond quality after the assembly and packaging process are either done destructively which may result in loss of critical information, or non-destructively which are limited by resolution, cost and time. In this work, the quality of copper wire bond is being evaluated by electrical means that is non-destructive, fast and accurate. This makes it suitable for use in the production line for wire bond quality evaluation. Experimental results showed that there is a good correlation with conventional wire assessment methods. Furthermore the electrical method is sensitive enough to pick out degraded wires that conventional methods are unable to identify.

1. Introduction

Wire bonding is still the most widely used interconnect method by the integrated circuits (IC) assembly and packaging industry. The main role of wire bonds is to provide electrical signal paths between the outside world and the IC chip, where its failure can be detrimental to the overall functionality of the device. Since wire bonding is done towards the end of the semiconductor chip manufacturing process, its failure will have a great impact on the time and manufacturing cost invested. As a result, industry is constantly trying to improve its yield by improving wire bonding process to ensure better quality wire bonds. IC manufacturers also see the need to accommodate the ever increasing pin count and decreasing chip size which renders an even more challenging wire bonding process [1–3]. At the same time, to stay competitive, there is a need to drive towards cost reduction.

The need to achieve high yield, fine pitch and low cost wire bonding leads manufacturers to consider other wire material options other than Au. In recent years, Cu wire bonding technology has been extensively studied to replace Au wire due to its high cost. However, there are several challenges faced by manufacturers in the Cu wire bonding process which may result in potential reliability concerns [4–6]. Cu wires are easily oxidized and require either an inert or reducing gas environment during bonding to ensure a symmetrical and spherical free air ball (FAB) formation. The deviation in the size or shape of the FAB due to oxidation may cause poor adhesion with the pad interface resulting in reliability issues [7,8]. The higher hardness and Young's modulus of Cu requires a higher bonding force during the bonding process, but this creates higher risk for pad splash, cracking and cratering issues which may damage the underlying circuitry [9–12]. Cu is also very susceptible to corrosion, which has prompted much research interest and attention to be paid to coated Cu wires, different pad finishes as well as the choice of mold compound used where its halogen content and pH level are taken into consideration to minimize corrosion [13–16]. These challenges require the need for stringent process control and any process deviation may affect wire bond quality and reliability. Therefore the evaluation and inspection of the bonded wires after the assembly and packaging process becomes important to pick out abnormal wires and to ensure good quality and reliable wire bonds.

Several methods are used by the industry to evaluate wire bonds and they can be categorized as a destructive or non-destructive test. One of the most conventional methods to test for the mechanical strength of the wires after bonding are the wire pull and shear tests [17,18]. They are often destructive and are used in the qualification of wire bonds to test for process consistency. Evaluation of the wire bonds can also be done by visual inspection using Scanning Electron Microscopy (SEM). However, there is a destructive de-capsulation process prior to the inspection when the device has already been molded. In addition the

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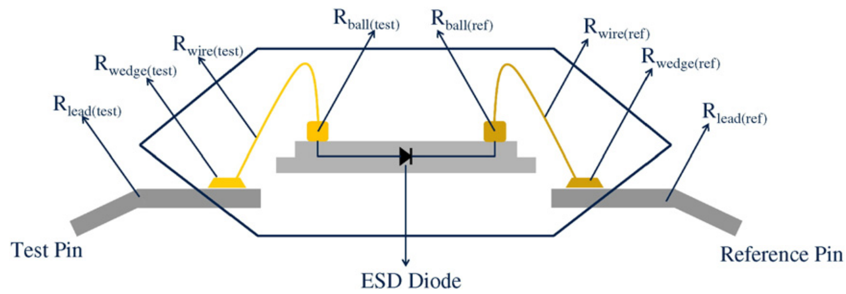

Fig. 1. Resistor components in current path during electrical measurement.

de-capsulation process may subject the wires to damage by chemical attacks during de-capsulation, causing important information to be lost in the process, resulting in inaccuracies in subsequent analysis. Cross-section analysis can also be done to evaluate wire bonds especially at the bond–pad interface, but it is impractical and costly for the production line especially for dies that involve complex fabrication processes.

Non-destructive tests such as X-ray imaging, Scanning Acoustic Microscopy (SAM) and Computerized Tomography (CT) scan are also some possible tools to evaluate wire bonds. However they are currently limited in terms of resolution, time consuming and are often too costly. Non-destructive electrical testing is practiced in the industry to perform simple evaluation such as open and short wire test where no information on the degradation of wire is provided. However there is potential in using electrical means for wire reliability assessment as several studies have been performed. McCracken et al. [19] attempted to study the degradation of wire using specially built piezoresistive stress sensors placed around the bond pads to detect changes in the stress originating from the bond–pad interface. In their study, specially built chips with sensors are required which make their application to production chips limited. Maiocco et al. [20] attempted to study the degradation of wire bonds by direct probing on the wire ball bonds for resistance measurement while Mayer et al. [21] performed the direct measurement on the wire bond pad for its pad resistance. Their methods however will only be applicable for chips before encapsulation. In addition, all of the above studies concentrated only on the degradation of the bond–pad interface leaving out any form of degradation on the entire wire span. Nevertheless, these methods showed the potential use of electrical measurements for reliability assessment.

This work makes use of a non-destructive, quick and accurate electrical method to extract series resistance from the package electrostatic discharge (ESD) protection diode. The extracted series resistance can be used to study the degradation of the entire bonded wire, including both the wire span and bond–pad interface. Details of the series resistance extraction method can be found in the work of Tan et al. [22]. Experimental results will be verified and compared with conventional destructive wire assessment methods.

2. Direct wire resistance *vs* diode series resistance

Resistance of the wire can either be measured directly from the bonded wire [23,24] or extracted from an ESD protection diode. There are however several advantages of the series resistance extraction method compared to direct wire resistance measurement. One advantage is that the ESD protection diodes are readily available as it is only practical that the internal circuitries are protected from ESD shocks. Utilizing the existing ESD diodes, electrical measurements can easily be made without any modification to existing design and can be applied to any wire bonded product that is protected by an ESD protection diode. In addition, the measurement can be made through the diodes without powering the entire circuitry. The other advantage is that the series resistance extraction method can measure lower resistance as compared to direct resistance measurement. Based on specifications from source meter and device, it is calculated that the minimum resistance detectable is smaller for the diode series resistance extraction method as compared to direct wire resistance measurement which is illustrated below:

$$R_{min} = \frac{V_{min}}{I_{max}} \tag{1}$$

$$I_d = I_s \exp^{(V_s - I_d R_s / nV_T)}$$
$$R_s = \frac{V_s - nV_T \ln(I_d) + nV_T \ln(I_s)}{I_d}. \tag{2}$$

Minimum resistance detectable using direct wire measurement can be easily calculated using Ohm's law shown in Eq. (1). V_{min} is based on source meter specification and I_{max} depended on device maximum current limit. The minimum detectable resistance can be calculated to be 6.25 mΩ based on the Keithley 2606A source meter used in this work. On the other hand, minimum resistance detectable using the diode method can be calculated based on Eq. (2), derived from the diode equation where R_s is the series resistance, V_s is the source voltage, V_T is the thermal voltage, n is the ideality factor, I_s is the saturation current and I_d is the diode current. I_s, n and V_T are assumed to be 10^{-12} A, 1 and 0.026 V respectively while I_d is capped by the device current limit. From Eq. (2), minimum resistance detectable using the diode method can achieve much lower than 6.25 mΩ, down to 0 Ω with *Vs* being 0.635 V.

3. Experimental method

A packaged device with Cu wires thermosonically bonded on aluminum pads are used in our study. The wires are bonded using optimized bonding parameters and are subjected to temperature cycling stress with the condition −65/175 °C. Electrical readouts are taken after

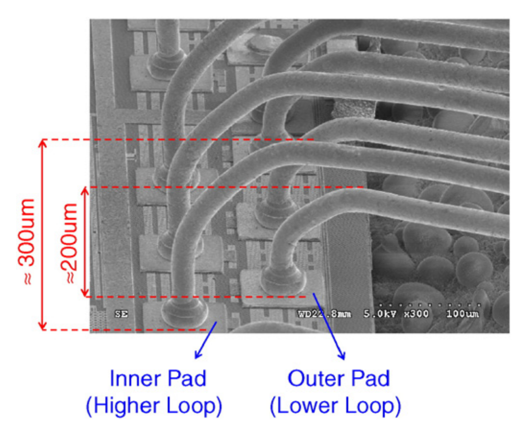

Fig. 2. Dual pad structure with different loop height.