Relation between Vibration of Wedge-Tool and Adhesion of Wire to Substrate during Ultrasonic Bonding*

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The present study relates the vibration behavior at the tip of wedge-tool during ultrasonic wire bonding with the state of adhesion at the interface of aluminum wire and silicon substrate. Cyclic change in amplitude by applying time of ultrasonic vibration is successfully detected by monitoring the vibration at the tip of wedge-tool. The spectral analysis indicates that local adhesion is not formed during increasing and high-amplitude stage of the cycle, while that is formed during decreasing and low-amplitude stage. By repeating such adhesion and separation, wire is deformed to a sufficient level to form a macroscopic bond. The ultrasonic vibration enhanced deformation of wire possibly occurs when the local adhesion is achieved. The amplitude of vibration affects the deformation rate.

Key Words: Ultrasonic wedge bonding, Thick wiring, Vibration spectrum, Wire deformation, Slip-and-fold mechanism

1. Introduction

Ultrasonic bonding is one of solid-state bonding techniques, in which the bodies to be welded are pressed to each other applying ultrasonic vibration parallel to the bonding interface. Owing to its ability to form bonds under a considerable low temperatures¹⁾, it is suitable for bonding materials whose functions are spoiled by heating²⁻⁴⁾. Typically, the technique has been applied to form electrical interconnections between integrated-circuit chips and outer circuits^{1,5-8)}. In addition, the interconnections formed by ultrasonic bonding are free of low melting-point phases like solders. This feature is preferred in electronic devices used in high temperatures and/or high thermal cycle conditions, *e.g.*, heavy-duty power electronics.

Power electronics is now recognized not only as an accurate machine controller but also as a key technology for energy saving. Their application fields are broadening rapidly and the demands on them are getting severer⁹⁾. Power electronic devices are connected to outer circuits using ultrasonic bonding of thick wires. Each connection must guarantee quite high reliability, since only one failure in the interconnections will halt the entire system. To achieve such a high reliability in manufacturing, *in-situ* monitoring of the bonding processes and rapid feeding back of the judgments to the processes are required^{10,11)}. Therefore, correct understanding on the phenomena occurring at the bond interface during ultrasonic bonding in relation with the monitored data is required for precise judging of the monitored process. However, the relation between the vibration behavior of the wire

and the state of adhesion at the wire / substrate interface during ultrasonic bonding is not clearly understood. The difficulty arises due to the very short process time of ultrasonic bonding which is generally shorter than one second.

The present study challenges to correlate the state of adhesion with the spectral aspects of the ultrasonic vibration behavior at the tip of a wedge-tool, *i.e.*, the position nearest to the wire. The behavior was monitored with a laser-Doppler vibrometer.

2. Frictional Sliding and Adhesion at the Interface

The vibration behavior will change by the presence of adhered areas in the wire / substrate interface. In the case that no adhesion at the interface has been formed, which corresponds to the initial state of ultrasonic bonding, there exists no local constraint in the contact interface. The wire slides smoothly on the substrate suffering a slight friction between the wire and substrate. As far as the bonding force is kept constant, the friction force is considered to be kept almost constant. This condition will result in a steady-state vibration which consists of the fundamental wave and its higher harmonics of the ultrasonic frequency. On the other hand, the vibration of the wire under existence of adhered areas in the contact interface will be complicated. The adhered areas work as local constraint for the motion of the wire. The wire needs to be deformed in the vicinity of the adhered areas. Under a sufficient amplitude of vibration, the wire yields. Local plastic deformation of the wire induces work-hardening, heating, softening by recovery or recrystallization, *etc.* These changes in the properties of the wire material affect the motion of the wire. In addition to the deformation of the wire, the dimensions and distribution of the adhered areas will change. Thus, the vibration becomes non-smooth. The monitored waveform will consist of a number of anharmonic frequency

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components.

Standing on this consideration, the state of adhesion at the wire / substrate interface will be reflected in the spectrum of the waveform of vibration.

3. Experimental procedure

High purity (99.99 %) as-drawn Al wires of which diameter were 300 μm and 1.0-mm-thick (001) Si single crystal wafers cut to 5.0 mm square chips were used as wire and substrate specimens, respectively, in the present study. The specimens were cleaned with an ultrasonic acetone bath and then dried with air jet just before the bonding experiment. The substrates were fixed on the work bench of the ultrasonic bonding apparatus, whereas the wires were gripped by U-grooved wedge-tool made from tungsten carbide.

Ultrasonic bonding were operated under the frequency of 60 kHz, ultrasonic power of 0.51 W (corresponding to the amplitude of 2.52 μm for load-free vibration), vibration time of 35 ms, and bonding force of 1.0 N. One might notice that the ultrasonic power is higher and the bonding force is lower than those commonly employed in practical bonding. They were selected to make the interfacial slip and adhesion overt. The vibration time of 35 ms was selected as the minimum time required for the formation of a macroscopic adhesion. The wires are barely deformed to adhere under this bonding condition. The prolonged vibration time was not employed in the present study, since only the non-smooth vibration will proceed after achieving the macroscopic adhesion.

The vibration of the wedge-tool was monitored by laser-Doppler vibrometer with the sampling rate of $2.56 \times 10^6 \text{ s}^{-1}$ at a point close to the wire-gripping groove where the wire deformed during bonding does not interfere the measurement. The vibration was then analyzed with the Fast Fourier Transform (FFT) technique.

4. Results

Figure 1 shows the vibration behavior of the wedge-tool tip during ultrasonic bonding of an Al wire to Si substrate. The amplitude of vibration changes periodically showing almost constant high- and low-amplitude stages of approximately 2.5 μm and 2.1 μm , respectively. The vibration starts with a high-amplitude stage. After the high-amplitude stage is maintained for 2.5 ms, the amplitude decreases gradually to the level of the low-amplitude stage. The low-amplitude stage lasts for 4.0 ms. Then, the amplitude starts to increase again to the level of the high-amplitude stage. In the second cycle of the amplitude

change, the high- and low-amplitude stages are kept for 4.4 and 4.7 ms, respectively. These stages in the second cycle are slightly longer than those in the first cycle. On the other hand, the time taken by the amplitude-decreasing and -increasing stages in the first and the second cycle appear almost unchanged.

The vibration behavior shown in Fig. 1 was then analyzed by FFT. 4096 consecutive data corresponding to the vibration time of 1.60 ms were taken from the middle of each stage for the analysis. Consequently, the frequency resolution is 625 Hz. Figure 2 shows the spectra of each stage in the first cycle. In the spectrum of the high-amplitude stage shown in Fig. 2(a), only the fundamental wave of the ultrasonic vibration appears strong. This result implies that the vibration is smooth, *i.e.* no interfacial adhesion is formed at this stage. On the other hand, a number of anharmonic frequencies appear strong in the spectrum of the low-amplitude stage, as shown in Fig. 2(c). This result indicates that the vibration is not smooth at this stage. Therefore, adhered areas will exist in the interface. The spectra of amplitude-decreasing and -increasing stages shown in Figs 2(b) and 2(d), respectively, are similar to each other having an intermediate pattern between those of the high- and low-amplitude stages. Since anharmonic frequency components are already excited in the spectra, adhered areas will exist in the interface during the amplitude-decreasing and -increasing stages.

The vibration in the second cycle was also analyzed in the same way. The spectra of the high- and low-amplitude stages in the second cycle shown in Fig. 3 indicate that this cycle proceeds in the same manner as the first cycle: the vibration of the high- and low-amplitude stages are smooth and non-smooth, respectively.

Fig. 1 Vibration behavior monitored at the tip of the wedge-tool during bonding of Al wire to Si substrate under the ultrasonic bonding condition of 60 kHz, 0.51 W, 35 ms, 1.0 N.

5. Discussion

By the spectrum analysis of the vibration at the tip of the

Fig. 2 Spectra of vibration transformed from each stage of the first cycle of amplitude change appearing in Fig. 1. (a) The high-amplitude stage, (b) the amplitude-decreasing stage, (c) the low-amplitude stage, and (d) the amplitude-increasing stage.

wedge-tool, the interfacial sliding behavior and the state of adhesion in the early stage of ultrasonic bonding has been successfully correlated. The high-amplitude stage corresponds to frictional sliding without interfacial adhesion. Formation of local adhered areas shifts the vibration to the amplitude-decreasing stage. In the following low-amplitude stage, the maximum area of adhesion in the cycle of the amplitude change is achieved. In the amplitude-increase stage, however, the adhered areas start to shrink.

Al wires and Si substrates are known that they are not adhered by applying only the bonding force of 1.0 N at room temperature. It is due to the existence of stable oxide films on both Al and Si. In order to adhere Al wires to Si substrate, these oxide films have to be scraped away from the interface by applying ultrasonic vibration of the wire. This process is called “slipping.” Therefore, to start the vibration with a high-amplitude smooth slide agrees with the state of the interface.

The vibration proceeds to the amplitude-decreasing stage by forming local adhesion at the interface. The gradual decrease of the amplitude may correspond to the gradual increase of the adhered areas. The adhered areas will increase until its rate balances with the separation rate. An attention should be paid to that the ultrasonic vibration of the wire enhances both adhesion and separation. The balance is maintained during the low-amplitude stage. In this stage, the adhered areas constrain the

Fig. 3 Spectra of vibration transformed from two stages of the second cycle of amplitude change appearing in Fig. 1. (a) The high-amplitude stage, (b) the low-amplitude stage.

sliding motion of the wire. The wires will suffer a cyclic deformation in the vicinity of the adhered areas. The plastic deformation of the wire expands the area of the contacting interface. This process is called “folding.” The amplitude of the vibration then turns to increase. The adhered areas are considered to be shrinking in this stage. By completing the separation, the vibration proceeds to the high-amplitude stage of the second cycle. In this way, adhesion and separation are repeated in the ultrasonic bonding. The repetition of the cycles increases the area of contacting interface. Therefore, the adhered area formed in the later cycles should be larger than that in the earlier cycles. A macroscopic adhesion is achieved after sufficient repetition of the cycles.

6. Conclusions

The early stage of adhesion process in ultrasonic bonding was investigated focusing on the vibration behavior at the interface of wire and substrate. The amplitude of vibration at the tip of wedge-tool changes periodically showing four stages, *i.e.* high-amplitude, amplitude-decreasing, low-amplitude, and amplitude-increasing. The spectrum of each stage shows characteristic patterns which are correlated to the state of adhesion at the wire / substrate interface. In the early stage of ultrasonic bonding, the interface repeats local adhesion and separation until a sufficient area of adhesion to avoid separation is achieved.

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