

Accelerated Characterization of Bonding Wire Materials

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Abstract

Trends in the microelectronics industry are driving the development of novel materials for microelectronic wire bonding. The wire bonding industry is looking towards extending the use of Cu as a new wire material to replace Au. The development of Cu wires that overcome oxidation issues can be too time consuming. One reason for this is that the effects of shielding gas on the electrical flame off (EFO) process and the free air ball (FAB) formation are not fully understood. In this study an online method for characterizing FABs using in-situ thermosonic wire bonding is used to study the effects of shielding gas flow rate. The FAB heights before deformation (H_{FAB}) and after deformation (H_{def}) are measured using online z-position measurements for various wires. Effects such as large variation in H_{FAB} at a single flow rate, abrupt changes in H_{FAB} with increasing flow rate, or discrepancies between the trends in H_{FAB} and H_{def} indicate undesirable EFO processes. Using this online method the EFO process and the performance of novel wires can be determined quickly and efficiently. Ninety FABs can be characterized in 2 minutes for a specific set of EFO parameters. A complete characterization of a novel Cu wire with respect to FAB consistency can be done in less than 4 hours which includes determining process windows for different shielding gas flow rates. Traditional sample preparation, optical microscopy and manual measurement methods can take many days to obtain the same results.

Keywords: copper wire bonding, wire characterization, electrical flame off, free air ball, online, forming gas.

1 Introduction

There are three main trends in the microelectronics industry. These trends include: miniaturization, higher performance, and lower costs [1]. Thermosonic wire bonding with Au wire is the most common first level interconnect technology used for integrated circuit (IC) packaging [1, 2]. However, the trends in the microelectronics industry are driving the research and development of alternative bonding wire materials. Two examples of these being Cu wires offered by MK Electron Co. Ltd., Yongin, S. Korea, and insulated wires such as X-wireTM offered by Microbonds Inc., Markham, Ontario, Canada

Finer pitches between bond pads and longer wire loops are required for miniaturization. This leads to issues with shorting of the wires due to wires sagging or sweeping during molding of the package. Stiffer wire materials such as Cu or insulated wires such as Au X-wireTM have been developed to address electrical shorting.

For high performance and more economical solutions Cu wire has become an attractive alternative to Au wire due to superior electrical and thermal conductivity, increased bond reliability, and lower costs [1-3]. Despite all of the advantages of Cu wire, Cu is harder than Au wire and oxidizes in air. The higher hardness of Cu wire increases the likelihood of chip damage during bonding [1, 3, 4]. Research on softening the Cu wire and the free air ball (FAB) during bonding can be found in [5-7]. This study focuses on the oxidation and the complications associated with adding forming gas to the electrical flame off (EFO) process used to form the FAB. The FAB shape and surface quality are essential for reliable ball bonds [2, 8, 9].

Currently the oxidation of the Cu wire during bonding is reduced by providing a protective atmosphere to the EFO site during FAB formation. The protective “forming gasses” are composed of a mixture of H_2 and an inert gas such as Ar or N_2 [10]. A mixture of 5 % H_2 and 95 % N_2 is the most com-

mon forming gas mixture used today. The H_2 is added to the gas mixture to reduce the oxide on the wire surface during EFO [9]. Hydrogen is an additional expense to the wire bonding industry and is a safety concern because mixtures with a H_2 composition above 5 % are considered flammable [10].

The melting and solidification of the wire during EFO has been studied extensively for Au wire [11]. The formation of the Cu FABs is more complex due to oxidation taking place on the surface and the effects of the shielding gas. Factors such as extensive oxidation and convective cooling can lead to miss-shaped FAB defects as well as bonding and reliability issues [2, 9, 12]. The amount of oxidation, convective cooling and therefore, FAB quality are affected by forming gas type and flow rate [12]. A novel wire material that can eliminate the shielding gas all together would be a breakthrough in the Cu wire bonding industry. The development and characterization of these new bonding wire materials is time consuming and the effects of insulation layers, oxidation, and shielding gas on the formation of the FAB are not fully understood.

Online methods have been developed to characterize wire deformation / hardness and the resulting in-situ underpad stresses during bonding [4, 13]. Online methods are quicker and more efficient than the conventional manual characterization methods. They are especially useful for characterizing new prototype wires, determining process windows, and optimizing process parameters [4, 7, 13-15]. A prototype wire that does not meet certain standards can be discarded early preventing wasted time performing tedious manual characterization techniques. In this study an online method is presented that can be used to quickly characterize the FAB shape and quality. The online method is used to investigate the effects of varying flow rates of a 5 % H_2 + 95 % N_2 forming gas on the FAB formation of Cu and Au wires. The common types of miss-shaped FABs and the conditions at which they occur are identified.

2 Experimental

All of the bonding in this study is performed using the ESEC 3100 thermosonic wire bonder manufactured by Besi ESEC, Cham, Switzerland. The wire bonder has been retrofit with a Cu kit consisting of a means of supplying a shielding gas to the EFO site during FAB formation. In this study two Cu wire types (Cu1 and Cu2) and one Au wire type are used. The wires are bonded using a SBNE-35BD-AZM-1/

16-XL capillary tool manufactured by Small Precision Tools Ltd., Lyss Switzerland.

The parameters for the EFO process used in this study are shown in Table 1 for FABs formed in the 5 % H_2 + 95 % N_2 forming gas mixture. The EFO parameters are optimized to produce a FAB with a diameter of approximately 50 μm in a similar manner to those in [7].

In online methods signals from sensors are used to characterize wire materials and / or to optimize a process. For the purpose of characterizing FABs, the z-position of the capillary during bonding is of interest. The z-positions of the capillary tip are derived from signals provided by an encoder. These signals are recorded during bonding. The z-position encoder is located at one end of the bondhead rocker arm as illustrated in Fig. 1. The bondhead displacement is measured with sub-micron precision [13]. Other signals such as the bond force and US level are also given for clarity. Fig. 2 shows an example of the online force, US level, and z-position signals recorded during the bonding cycle used in this study.

The bonding cycle used in this study is similar to that described in [13]. However, the rows of ball-stitch bonds as shown in Fig. 3 have alternating ball-wedge directions. The z-position of the capillary is used to derive a reference height (H_{ref}) of the bonding surface, the Z_1 height of the undeformed FAB, and the Z_2 height of the deformed FAB. The Z_1 height is taken when the FAB is touched down with 20 mN force as illustrated in Fig. 3. The 20 mN force is too low to cause significant deformation of the FAB [15]. The Z_2 height is taken after the FAB has been deformed with a force of 600 mN as illustrated in Fig. 3. Once the Z_2 height has been measured the deformed ball is bonded by applying the bonding force and ultrasound (US) in order to complete the process. The locations where the H_{ref} , Z_1 , and Z_2

Table 1: Required EFO parameters for 50 μm diameter FAB using forming gas with a flow rate of 0.5 l/min and a tail length of 500 μm .

	Wire Type		
	Cu1	Cu2	Au
Electrode to Wire Distance [μm]	300	300	500
EFO Current [mA]	80	80	52
EFO Time [ms]	0.43	0.43	0.5

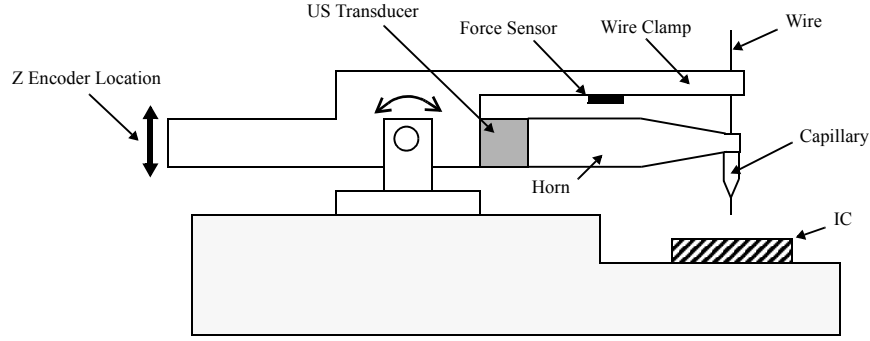


Figure 1 : Schematic drawing of bondhead rocker arm assembly. Dimensions not to scale.

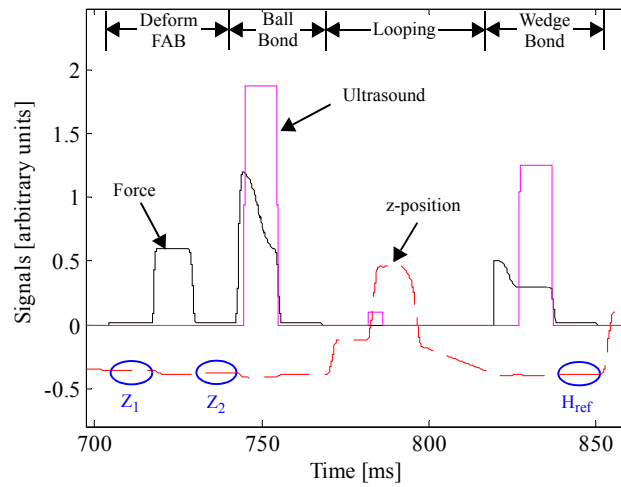


Figure 2 : Representative signals for z-position, force, and ultrasound produced by wire bonder. The measurement periods for Z_1 , Z_2 , and H_{ref} are indicated by circles.

measurements are taken during the bonding cycle are illustrated in Fig. 2. The FAB height (H_{FAB}) is calculated using

$$H_{FAB} = Z_1 - H_{ref} \quad (1)$$

and the deformed ball height (H_{def}) is calculated using

$$H_{def} = Z_2 - H_{ref}. \quad (2)$$

The H_{FAB} and H_{def} measurements are taken for each of the three wire types using forming gas. The wire bonder is not capable of reading flow rates below 0.2 l/min and flow rates above 1.0 l/min promotes miss-shaped FABs. Therefore, a total of 90 ball-stitch bonds are made at each of the flow rates from 0.2 l/min to 1.0 l/min at 0.05 l/min increments. Up to 1530 data points for one wire material are collected and analyzed in less than 4 hours.

Scanning electron microscopy (SEM) images are used to characterize the FABs size, shape and surface condition at various flow rates. SEM images of the FABs produced in these unstable EFO processes help identify the possible mechanism for the defect. FAB defects such as variation in diameter, pointed shape, or golf-clubbed shape as shown in Fig. 4 a), b), and c), respectively, are identified using the online method in parallel with SEM images.

3 Results

3.1 Cu wire Cu1

The results for the online FAB characterization of the Cu1 wire are shown in Fig. 5. From the online measurements no monotonous trend in H_{FAB} is observed with increasing the flow rate of the forming gas. For flow rates above 0.7 l/min the H_{FAB} does not

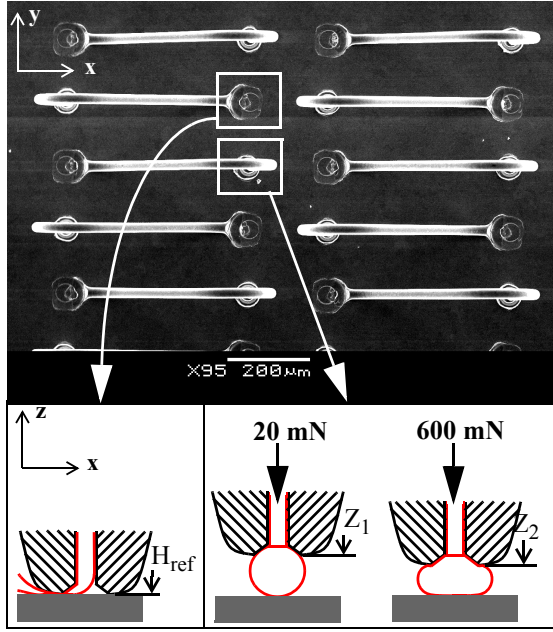


Figure 3 : Rows of ball-stitch bonds for reference height (H_{ref}), Z_1 , and Z_2 measurements.

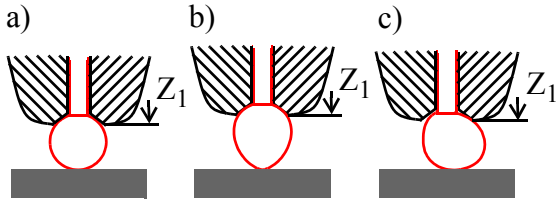


Figure 4 : Common FAB shapes. a) Spherical FAB, b) Pointed FAB defect, c) Golf Clubbed FAB defect.

change and the standard deviation increases drastically. The H_{def} measurements have a lower standard deviation than the H_{FAB} measurements and do not follow the same trend as the H_{FAB} measurements.

Using SEM images the actual shape and quality of the FAB is determined at each of the different flow rates. SEM images of Cu1 FABs produced at different flow rates are shown in Fig. 6. From the SEM images in Fig. 6 a) and c) it can be seen that the FAB is spherical and of good quality at flow rates of 0.2 l/min and 0.5 l/min. It is also important to note that from the online method the standard deviation of the H_{FAB} measurements are the lowest at 0.2 l/min and 0.5 l/min with values of 0.44 μm and 0.51 μm , respectively. The FABs are pointed at flow rates of 0.4 l/min and 0.75 l/min. The standard deviation of

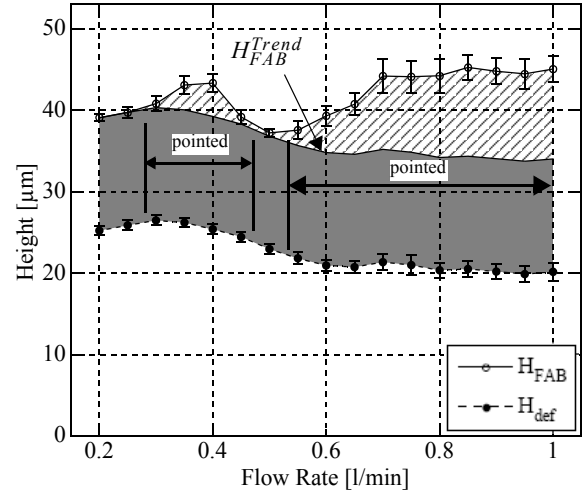


Figure 5 : Cu1 wire H_{FAB} and H_{def} measurements from online FAB characterization. The miss-shaped FAB area is identified by the hatched region.

the H_{FAB} measurements at these flow rates increases to 1.08 μm and 1.95 μm , respectively.

From the SEM images it can be concluded that the changes in H_{FAB} measured using the online method are due to changes in the FAB shape. The H_{def} measurements are more dependent on the volume of the FAB rather than its shape. Therefore, in a process where a spherical FAB is produced at all flow rates, the H_{FAB} measurements only vary due to changes of FAB diameter and follow the same trend as the H_{def} measurements. Such H_{FAB} measurements are named H_{FAB}^{Trend} and are calculated by

$$H_{FAB}^{Trend} = H_{def} + \Delta H_{min} \quad (3)$$

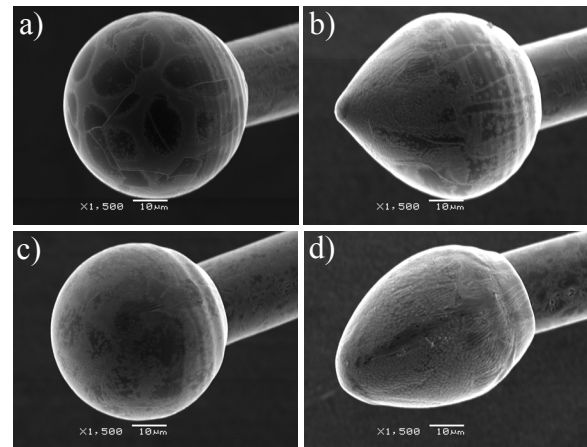


Figure 6 : SEM images of Cu1 FABs produced in forming gas at flow rates of a) 0.2 l/min, b) 0.4 l/min, c) 0.5 l/min, and d) 0.75 l/min.

where, $\Delta H_{\min}$ is the minimum difference between H_{FAB} and H_{def} for all flow rates. When H_{FAB} is approximately equal to H_{FAB}^{Trend} as illustrated in Fig. 5 for the Cu1 wire at flow rates of 0.2 l/min, 0.25 l/min and 0.5 l/min, the FAB is spherical and of good quality. All other flow rates where pointed FABs are produced, are identified by the hatched area above H_{FAB}^{Trend} termed the miss-shaped FAB area. The size of the miss-shaped FAB area is a good indication of the robustness of a wire material during EFO.

3.2 Cu wire Cu2

The results for the online FAB characterization of Cu2 are shown in Fig. 7. For the Cu2 wire there is an obvious trend in the H_{FAB} with increasing flow rate. The FAB height increases from 0.2 l/min to 0.3 l/min before decreasing until a flow rate of 0.7 l/min. The increase in H_{FAB} at flow rates from 0.2 l/min to 0.3 l/min is due to the increase in H_2 present during EFO [12]. At flow rates from 0.3 l/min to 0.7 l/min the convective cooling effect dominates and causes the H_{FAB} to decrease [12]. Above 0.7 l/min the H_{FAB} again, remains approximately constant.

Images of the FABs produced with flow rates of 0.2 l/min, 0.5 l/min, 0.65 l/min and 0.8 l/min are shown in Fig. 8. The FABs produced with flow rates below 0.65 l/min are of good quality which correlates well with the low standard deviation values calculated from the online measurements. However, as seen in Fig. 8 c) and d), golf clubbed defects start to occur at flow rates above 0.65 l/min. Also, above flow rates of

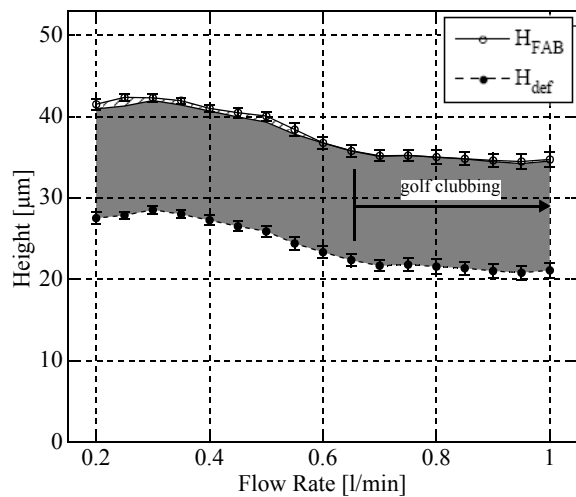


Figure 7 : Cu2 wire H_{FAB} and H_{def} measurements from online FAB characterization. The miss-shaped FAB area is identified by the hatched region.

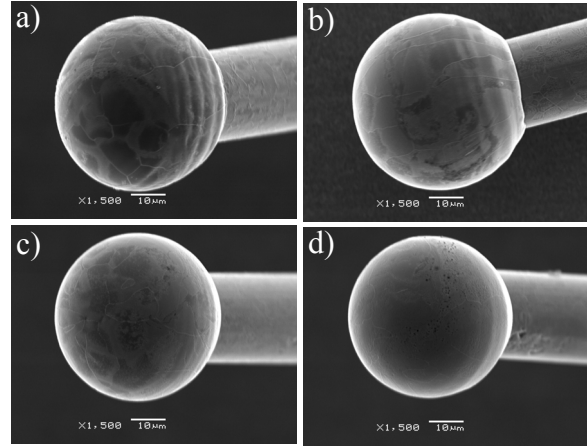


Figure 8 : SEM images of Cu2 FABs produced in forming gas at flow rates of a) 0.2 l/min, b) 0.5 l/min, c) 0.65 l/min, and d) 0.8 l/min.

0.7 l/min the H_{FAB} remains about constant and a thicker oxide is observed on the FAB surface.

The measured H_{FAB} values follow the calculated H_{FAB}^{Trend} values closely for all flow rates and the miss-shaped FAB area is small, as shown in Fig. 7. As expected this indicates that spherical FABs are produced. However, even though the H_{FAB} measurements are equal to the H_{FAB}^{Trend} values above flow rates of 0.7 l/min, golf clubbed FABs are observed. The slope in the H_{FAB} and H_{def} curves however decreases at 0.65 l/min identifying a change in the EFO process and the miss-shaped FABs. Therefore, changes in the slope of the H_{FAB} and H_{def} curves also can be used to identify undesirable EFO processes.

3.3 Au wire

The online FAB characterization results for the Au wire are shown in Fig. 9. Since it is possible to bond Au FABs with no forming gas because oxidation is not an issue, the online characterization method is performed at a flow rate of 0 l/min. The H_{FAB} and H_{def} increase from flow rates of 0 l/min to 0.25 l/min and then decrease steadily until about 0.65 l/min. This trend is similar to the results found for the Cu2 wire and results reported previously [12].

The H_{FAB} and H_{FAB}^{Trend} values are similar for flow rates up to 0.5 l/min as shown in Fig. 9. Spherical FABs are produced at flow rates up to 0.5 l/min as shown in Fig. 10 a) and b). Above 0.5 l/min the FAB becomes golf clubbed and at 0.8 l/min the FAB cannot be formed as shown in Fig. 10 c) and d). At flow rates above 0.5 l/min the miss-shaped FAB area

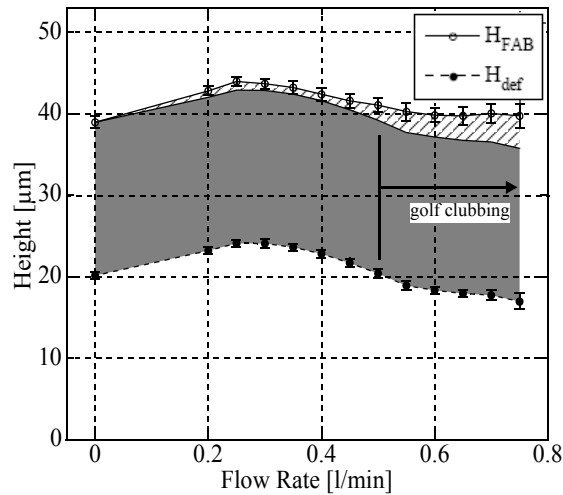


Figure 9 : Au wire H_{FAB} and H_{def} measurements from online FAB characterization. The miss-shaped FAB area is identified by the hatched region.

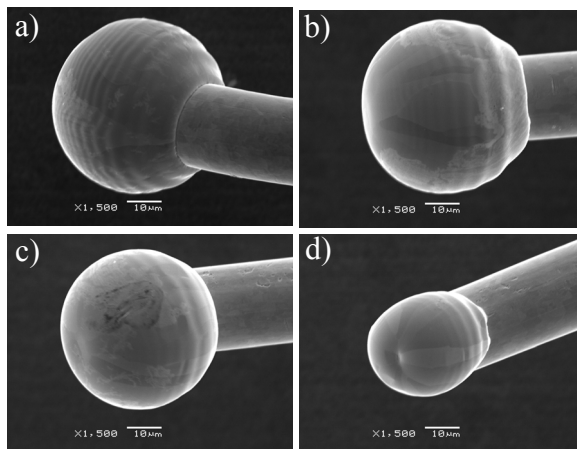


Figure 10 : SEM images of Au FABs produced in forming gas at flow rates of a) 0.25 l/min, b) 0.4 l/min, c) 0.6 l/min, and d) 0.8 l/min.

increases, indicating miss-shaped FABs. Also, the slope in H_{FAB} and H_{def} changes abruptly at flow rates above 0.55 l/min.

4 Discussion

Although the online method can be used to identify where miss-shaped FABs occur it can not be used to distinguish between pointed or golf-clubbed defects. SEM images are still required to identify the type of defect. The standard deviation of the H_{FAB} measurements may be useful in distinguishing

between the type of miss-shaped FAB but further investigation is required to confirm this.

Acceptable Cu FABs cannot be produced above 0.7 l/min. Either pointed FAB defects as produced using the Cu1 wire or golf-clubbed FAB defects as produced using the Cu2 wire are formed at high forming gas flow rates. A change in the slope of both the H_{FAB} and H_{def} trends is observed at high flow rates. This change in slope identifies a change in the EFO process. An increase in oxidation on the FAB surface suggests that a change in the flow type where an increase in mixing of the forming gas and air could be the cause.

5 Conclusions

The effectiveness of the online FAB characterization study was presented. The online method identifies the gas flow rates required to produce acceptable, spherical, Cu FABs in substantially shorter time than with conventional methods. Using the online method discrepancies between the trends in H_{FAB} and H_{FAB}^{Trend} as well as abrupt changes of slope in the H_{FAB} and H_{def} trends are used to identify miss-shaped FABs. The quickness of the online FAB characterization method makes it well suited for evaluating the performance of new wire materials during the EFO process. This method can eliminate the need for tedious sample preparation and optical and SEM image analysis.

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