Ultrasonic friction power during Al wire wedge-wedge bonding

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Al wire bonding, also called ultrasonic wedge-wedge bonding, is a microwelding process used extensively in the microelectronics industry for interconnections to integrated circuits. The bonding wire used is a 25 μm diameter AlSi1 wire. A friction power model is used to derive the ultrasonic friction power during Al wire bonding. Auxiliary measurements include the current delivered to the ultrasonic transducer, the vibration amplitude of the bonding tool tip in free air, and the ultrasonic force acting on the bonding pad during the bond process. The ultrasonic force measurement is like a signature of the bond as it allows for a detailed insight into mechanisms during various phases of the process. It is measured using piezoresistive force microsensors integrated close to the Al bonding pad (Al–Al process) on a custom made test chip. A clear break-off in the force signal is observed, which is followed by a relatively constant force for a short duration. A large second harmonic content is observed, describing a nonsymmetric deviation of the signal wave form from the sinusoidal shape. This deviation might be due to the reduced geometrical symmetry of the wedge tool. For bonds made with typical process parameters, several characteristic values used in the friction power model are determined. The ultrasonic compliance of the bonding system is 2.66 μm/N. A typical maximum value of the relative interfacial amplitude of ultrasonic friction is at least 222 nm. The maximum interfacial friction power is at least 11.5 mW, which is only about 4.8% of the total electrical power delivered to the ultrasonic generator. © 2009 American Institute of Physics. [DOI: 10.1063/1.3158065]

I. INTRODUCTION

Ultrasonic wire bonding is widely used in microelectronics packaging to make interconnections between the integrated circuit chip and the package metallization.¹ It is a solid state welding process in which a thin wire is welded to a metallized surface using a combination of normal force and ultrasonic energy. However, despite being a widely accepted process in industry, there is a general lack of understanding of the bonding mechanisms in ultrasonic wire bonding. A complete quantitative model of the wire bonding process does not exist.¹

Several investigations have been performed to understand the physics of the wire bonding process.²–¹⁰ In addition to the conventional offline process monitoring methods such as visual inspection, wire pull testing, and bond shear testing, novel real-time monitoring techniques such as the measurements of ultrasound amplitudes using laser interferometry,¹¹ piezoelectric sensor attached to the horn,¹² piezoelectric sensor mounted to the heater block,¹³ and integrated piezoresistive microsensors¹⁴–²⁵ have been applied to gain a better understanding of the process mechanisms.

The Au wire ball bonding on Al pads was studied in detail using integrated piezoresistive microsensors to measure the in situ forces caused by the ultrasound induced to the pad.¹⁴–¹⁷ Based on the first and third harmonics of the recorded ultrasonic signal, five bond phases are distinguished during the process. The third harmonic of the ultrasonic force signal was used to explain two friction processes: ultrasonic stick-slip friction between the Au ball and Al pad before and during bond formation and friction between ball and capillary after bond formation.¹⁶,¹⁷ It was concluded that the relative stick-slip motion between the ball and the pad produces wear, which is a prerequisite for high quality Au ball bonding on Al pads.

The concept of stick-slip friction was further developed in Refs. 18 and 19. A friction power model was formulated based on Amontons laws of friction to calculate the friction power delivered to the bond. In Ref. 20, a bond quality factor was introduced based on friction power. This model was extended in Ref. 11 to include wire deformation during the process.

In Ref. 21, the microsensor method was applied to study the Cu–Al ball bonding process. It was concluded that although reduced in relative magnitude compared to the Au–Al process, the amount of stick-slip friction in Cu–Al process is still an important mechanism for a successful Cu ball bonding on Al pads.

In this paper, a study of in situ ultrasonic force signals of an Al wedge bonding process on Al pads is reported. Al wedge bonds are investigated for the same or similar mechanisms observed previously during Au–Al ball bonding processes. In combination with measurements of the current supplied to the ultrasonic transducer and free-air vibration amplitude of the tool tip, the measured ultrasonic force is used to derive the ultrasonic friction power during the Al–Al wedge bonding process.
II. EXPERIMENTAL

Ultrasonic wire bonding is performed using a 25 μm diameter AlSi1 wire on Delvotek 6319 wedge-wedge bonder (Delvotek, Ottobrunn, Germany), having an ultrasonic frequency $f=95$ kHz. The tool used for bonding is a tungsten carbide wedge tool ET-25-50-45, manufactured by Erosionstechnik Neudegger, Puchheim, Germany. A test chip with integrated piezoresistive microsensors,17 shown in Fig. 1, is mounted on the vacuum chuck of the bonding table. The test chip is die bonded to a 20-pin SOIC package using a commercial silver filled epoxy, which is cured at 150 °C for 90 min. The connection pads to the package terminals are connected to the microsensor by Au wire ball bonds. The package terminals are then soldered to a printed circuit board (PCB) as shown in Fig. 2. The PCB is mounted on a glass slide using a double sided tape and then fixed on the vacuum chuck of the bonding table.

A. Microsensor

The microsensor test chip used in this study is manufactured using a standard 0.8 μm double polysilicon complementary metal oxide semiconductor process and is provided by Oerlikon Esec, Cham, Switzerland. The test chip consists of 48 bonding pads with integrated microsensors shown in Fig. 1, which are addressed using a multiplexer circuitry co-integrated on the chip. The design and operation of the microsensor and the various electrical components integrated in the test chip are explained in detail in Refs. 16 and 17 and briefly described below. The microsensor is shown in Fig. 3(a). It consists of four slanting line $n^+$ diffused Si piezoresistors integrated next to the bonding test pad as shown by the illustration in Fig. 3(b). This design is selectively sensitive to the force component in the direction of ultrasonic vibrations, denoted y-force.16,17 The piezoresistors are connected in a Wheatstone bridge configuration, which is powered by a constant supply voltage, $V_s=3.75$ V. The voltage across the bridge is calculated using $V_H=V_H-V_L$, where $V_H$ is the voltage taken between $R_1$ and $R_3$, and $V_L$ is the voltage taken between $R_2$ and $R_4$.

The microsensor is calibrated for tangential force using a standard sensor provided by Oerlikon Esec, Cham, Switzerland. This standard sensor has a sensitivity of $10.2 \pm 0.5$ mV/V N.16,17 To calibrate the microsensor, ball bonding tests are performed with a 50 μm diameter Au free air ball (FAB) on an ESEC 3100 automatic ball-wedge bonder. This bonder offers a software feature that allows to split the bonding operation into multiple segments. The duration, bonding force, and ultrasound level for each segment can be adjusted separately, resulting in parameter profiles of varying complexities. The ultrasound parameter (USP) profile for the calibration test is defined in Table 1. The tests are performed at room temperature. The unit “%” is used for the ultrasonic parameter. It is proportional to the ultrasonic vibration amplitude where 1% is equivalent to a peak to peak amplitude of 26.6 nm measured at the center of the transducer tip.

A high normal bond force of 1000 mN for all segments ensures that there is no friction between the ball and pad during the calibration. Since the ultrasound levels selected are lower than those required for bonding, the deformed FAB does not stick to the pad and is removed from the pad and subsequently bonded at the second bond position defined on the package. For the next test, a fresh FAB is fired. The tests are repeated on ten samples of each type of microsensor.

The microsensor response $S$ is defined by the ratio $V_H/V_L$, where $V_s=3.75$ V. The response $S$ has a high frequency ($U/S$ frequency) and a low frequency content. For simplicity, only the amplitude of $U/S$ frequency, $E$ is used. An example $E$ from a calibration test is shown in Fig. 4(a). Values of $E$ are evaluated as the average of the microsensor response for each level of ultrasound in Fig. 4(a). Figure 4(b) shows a linear relationship between the evaluated values from the microsensor and from the standard sensor. The cali-
ibration factor of the microsensor is evaluated as the slope of the linear fit in Fig. 4(b) and is determined to be \( f_{\text{calib}} = 5.9 \pm 0.33 \text{ mV/V N} \). The error value includes the fit error and the sensitivity error of the standard sensor. Thus, the ultrasonic force measured using the microsensor is

\[
F_T(t) = \frac{S(t)}{f_{\text{calib}}}
\]

(1)

B. Experimental plan

Al wire wedge bonding is performed on the Al test pad of the microsensor and the in situ ultrasonic force variations during the bonding process is measured simultaneously. The first bond is performed on the microsensor test pad and the second bond is made on the package rim as shown in Fig. 5(a). An example wedge bond on the microsensor test pad is shown in Fig. 5(b). The parameters used for bonding are shown in Table II. Note the different USP used compared to that previously described for the ball bonder. The technical USP of the wedge bonder is dimensionless and ranges from 0 to 200 units. To relate it to a physical quantity, the transient free-air vibration amplitude of the tool tip, \( A_0(t) \), is measured using a Laser Interferometer OFV 501 and a Vibrometer Controller OFV 3000 of Polytec GmbH, Waldbronn, Germany. A laser spot of 6 \( \mu \)m in diameter is focused at the center of the tool tip while vibrating freely in air \( (F_N=0, \text{no wire}) \) for USP=100 units. A typical plot of \( A_0(t) \) is shown in Fig. 6, resulting in a maximum vibration amplitude, \( A_0^{\text{max}} = 0.75 \mu \text{m} \). The result shows that there is \( \approx 6.5 \) ms time lag to reach 95\% of \( A_0^{\text{max}} \).

C. Results and discussion

1. Ultrasonic force signal

An example ultrasonic force signal is shown in Fig. 7(a). The signal consists of approximately 3500 cycles of ultrasonic vibrations. As soon as the ultrasonic period starts, \( F_T \) rises sharply for approximately 2.5 ms when a break-off in the signal is observed. About 1.5 ms after the break-off, the signal starts to rise gradually until the end of the ultrasonic period. The waveforms of the signal at various times are shown in Fig. 7(b). It is found that immediately after the break-off, the signal waveform deviates from the sinusoidal shape it had initially at 1 ms. This deviation is observed in only one direction of the ultrasonic cycle, i.e., when the \( F_T \) rises from the negative half cycle to the positive half cycle. The waveform returns to sinusoidal shape about 10 ms after the break-off. In contrast, the break-off reported previously in Au wire ball bonding on Al pads is characterized by a cropped sinusoidal waveform.

The ultrasonic force signal is filtered at its fundamental and second and third harmonic frequencies and the resulting amplitudes are plotted in Fig. 8. Amplitudes of harmonics higher than the third are negligible and hence not shown. Four phases (1–4) can be distinguished for the Al–Al process. During phase 1, the wire sticks to the pad. This is because \( A_0(t) \) is not high enough to overcome the static frictional force \( (F_b) \) required to cause any sliding at the interface. Phase 2 starts at time \( t_b \) when the fundamental (first harmonic) of \( F_T \) shows the characteristic break-off. At the same time, the second and third harmonics start to increase sharply from zero. This is caused by the onset of friction at the wire-pad interface. The friction facilitates the relative sliding of the wire on the pad causing bond area cleaning by

![Fig. 4.](image-url)
wear of the native oxide layers at the interface. Moreover, the first harmonic does not rise any further until the end of this phase at $t_{b2}$, indicating the need of “minimum cleaning” or minimum amount of friction work (wear) to accumulate before the native oxide layers are sufficiently removed from the interface to allow the formation of bonded areas.

The cleaning continues and is accompanied by bonding during phase 3 when the first harmonic of the ultrasonic force signal starts to rise again. Bonding is expressed by the formation of welded areas at the interface that grow larger where the metals at opposite sides have been sufficiently cleaned. The sum of all bonded areas is the effective bonded area, which is growing due to the friction power that continues to clean the interface. During phase 4, the fundamental and harmonics of the ultrasonic force signal remain relatively constant. It is believed that bonding action has ended at the onset of this phase and ultrasonic friction power might not aid in any further bonding.

### 2. Second harmonic

In contrast to any ball bonding process, the second harmonic amplitude of the ultrasonic force signal is found to be predominant during the Al–Al wedge bonding process. This is consistent to the previously reported studies involving measurement of ultrasonic amplitude during Al–Al wedge bonding.

**TABLE II. Optimized wedge bond parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic parameter USP</td>
<td>100 units</td>
</tr>
<tr>
<td>Bond force $F_N$</td>
<td>250 mN</td>
</tr>
<tr>
<td>Touchdown force</td>
<td>50 mN</td>
</tr>
<tr>
<td>Time</td>
<td>35 ms</td>
</tr>
</tbody>
</table>

**FIG. 5.** (Color online) (a) Overview photograph showing Al wire wedge bonds on microsensor chip; (b) closeup of example wedge (first) bond on microsensor test pad.

**FIG. 6.** Free-air vibration amplitude of tool tip $A_0(t)$ for USP=100 units.

**FIG. 7.** (a) In situ ultrasonic force signal of Al–Al wedge bonding process; (b) Signal waveforms at different times after ultrasound on.

**FIG. 8.** (Color online) Amplitudes of harmonics of ultrasonic force signal of Al–Al wedge bonding process shown in Fig. 7(a).
bonding process using piezoelectric sensors attached to the horn and to the heater block. This may be attributed to the reduced geometrical symmetry of the wire and the wedge tool [Fig. 9(b)], possibly causing the different vibration shapes for positive compared to negative half cycles as observed in the 3, 6, and 9 ms signal waveforms in Fig. 7(b). In particular, the geometry of the tool tip shown in Fig. 10 is not symmetrical since the tip radii at the left and right sides are 25 and 15 μm, respectively. In contrast, the rotational symmetries of the ball and the capillary geometry illustrated in Fig. 9(a) result in identical ultrasonic vibrations for both positive and negative half cycles during ball bonding.

III. ULTRASONIC FRICTION POWER

The ultrasonic friction power delivered at the interface during the bonding process can be derived from the measured $F_T(t)$ using

\[ P(t) = 4 \cdot f \cdot A_{rel}(t) \cdot F_T(t), \]

where $f=95$ kHz is the ultrasonic frequency and $A_{rel}(t)$ is the amplitude (zero-to-peak) of relative motion between the wire and the pad. To derive experimental values for $P(t)$, a number of evaluation steps are necessary, which are outlined in Fig. 11. The amplitude of relative motion, $A_{rel}(t)$, is derived using a simplified model describing the interfacial friction during the wire bonding process. The current supplied to the ultrasonic transducer during the bonding process [measured simultaneously with $F_T(t)$] is used to derive a free-air equivalent of ultrasonic vibration amplitude during the bonding process, $A_g(t)$. The value of $A_g(t)$ is then used to derive $A_{rel}(t)$. All the formulas associated with this derivation are described in the subsections that follow.

A. Free-air equivalent of ultrasonic vibration amplitude

The ultrasonic vibrations are generated by a piezoelectric transducer. During the free-air vibration, the transducer current $I(t)$ is proportional to $A_0(t)$,

\[ k_1 = \frac{I(t)}{A_0(t)} = \frac{A_{max}}{A_{0max}} = 0.19 \pm 0.01 \text{ A}/\mu\text{m}, \]

where $k_1$ is the constant of proportionality and $I_{max}$ is the maximum value of current supplied to the generator in the free-air vibration case (FVC).

However, during the actual bonding process, the normal force $F_N$ presses the wire to the pad. Friction (dynamic or static) damps the vibration amplitude as seen by less current going to the transducer during the bonding process case (BPC) as compared to the FVC shown in Fig. 12(a). The transducer current measured during BPC is $I_b(t)$ and is used to define the free-air equivalent of the ultrasonic vibration amplitude during the bonding process,

\[ A_b(t) = \frac{I_b(t)}{k_1}. \]

An example plot of $A_b(t)$ is shown in Fig. 12(b).
B. Amplitude of relative motion

Interfacial welding in BPC is generated by the ultrasonic friction. During ultrasonic friction, \( F_T(t) \) is acting at the wire-pad interface. The ultrasound causes both the wire and the pad to vibrate at the interface. The vibration amplitudes of the wire bottom and pad top are denoted as \( a_w(t) \) and \( a_p(t) \), respectively, as illustrated in Fig. 13. The relative motion between the wire and the pad is

\[
A_{rel}(t) = a_w(t) - a_p(t) \tag{5}
\]

In the case where there is no relative motion between the wire and pad,

\[
A_{rel}(t) = 0 \tag{6}
\]

In the case where the wire is vibrating with the tool in free air (i.e., \( F_N = 0 \)),

\[
a_w(t) = A_{b}(t), \quad a_p(t) = 0, \quad \text{and} \quad F_T(t) = 0 \tag{7}
\]

The amplitudes \( a_w(t) \) and \( a_p(t) \) can be described as functions of \( F_T(t) \) using Eqs. (6) and (7), and the linear model shown in Fig. 14. In this model, it is assumed that the amplitudes \( a_w(t) \) and \( a_p(t) \) vary linearly with \( F_T(t) \). Thus,

\[
a_w(t) = A_{b}(t) - c_w \cdot F_T(t) \tag{8}
\]

and

\[
a_p(t) = c_p \cdot F_T(t), \tag{9}
\]

where \( c_w \) and \( c_p \) are the ultrasonic compliances (inverse stiffnesses) of the wire/tool and pad/chip, respectively.

FIG. 13. (Color online) Illustration of the vibration amplitudes at the wire-pad interface during BPC.

D. Results and discussion

An example plot of \( P(t) \) evaluated using Eq. (2), averaged over ten bonds, is shown in Fig. 15. The friction power \( P(t) \) emerges from zero at \( t_b \) and increases rapidly until it reaches a maximum value \( (P_{max}) \), about 6 ms after ultrasound on. Then it starts to decrease. This decrease is due to bond growth, which reduces the relative motion between the wire and pad. However, the derivation of \( P(t) \) using Eq. (2) is not valid after the end of phase 2, since the linearity as-
The total power supplied to the ultrasonic transducer, \( P_T \), is calculated using

\[
P_T = V_B^{\max} \cdot I_B^{\max} = 238 \pm 6 \text{ mW},
\]

where \( V_B^{\max} \) and \( I_B^{\max} \) are the maximum peak-to-peak values of voltage and current supplied to the ultrasonic generator during BPC, respectively. The maximum friction power is \( P_{\text{max}} = 11.5 \pm 0.7 \text{ mW} \), i.e., only about 4.8\% of the total electrical power delivered to the ultrasonic transducer ends up at the bond interface. The remaining power supplied to the transducer is lost due to either internal friction (damping) in the material or heat dissipation caused by friction between the interfaces of the piezoelectric transducer. With an interfacial bond area estimated at \( 2950 \mu\text{m}^2 \), the maximum friction power density is \( 3.9 \text{ W/mm}^2 \). This value is of the same order of magnitude as those reported for typical macroscopic Al–Al ultrasonic welding processes. The value is about 2–2.6 times and 1.9 times as high as those reported for a typical Au–Al bonding process\(^{25}\) and a Au–SiO\(_2\) friction process,\(^{24}\) respectively.

### IV. CONCLUSIONS

In contrast to previously studied Au ball on Al pad bonding processes, the ultrasonic force transmitted to the Al pad in Al wire wedge-wedge bonding contains a strong asymmetric component. This is expressed by the large amount of second harmonic content found in the force signals. The other signal features are similar to those of a typical Au ball to Al pad bonding process, in particular, the typical time required to have successful bonding.

A method to derive the ultrasonic friction power has been demonstrated for a typical Al–Al wedge bonding process and typical power values have been calculated. The method uses a friction power theory based on Amontons laws of friction and uses the measured ultrasonic force as an input. As a side product, the Al–Al friction coefficient has been measured. Other coefficients are determined as needed by the theory, including an ultrasonic compliance of the bonding system. For the first time, a maximum relative amplitude of the ultrasonic friction at the interface is reported.

In the future, deriving the ultrasonic friction power will help to understand possible interactions between surface physics and the joining mechanisms of this process. The theory might be extended to predict bonding process parameters and bond strength, possibly leading to new control methodologies\(^{25}\) and higher process quality.

### ACKNOWLEDGMENTS

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