Ultrasonic Anisotropic Conductive Films (ACFs) Bonding of Flexible Substrates on Organic Rigid Boards at Room Temperature

Kiwon Lee, Hyoung Joon Kim, Il Kim, and Kyung Wook Paik
Nano Packaging and Interconnect Lab. (NPIL)
Department of Materials Science and Engineering
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Kusong-dong, Yusong-gu, Daejeon, 305-701, Republic of Korea
phone: +82-42-869-3386, fax:+82-42-869-3310
email: kiwonlee@kaist.ac.kr

Abstract

In this study, a novel Anisotropic Conductive Film (ACF) bonding method for flexible substrate-organic rigid board bonding was investigated using an ultrasonic vibration. And the ultrasonic (U/S) ACF bonding was characterized in terms of adhesion strength, electrical continuity in comparison with those of thermo-compression (T/C) bonding.

An ultrasonic bonder was used to produce ultrasonic vibration in ACF joints between flexible substrates and organic rigid boards. Test boards were 25 um-thick polyimide based flexible substrates and 1 mm-thick FR-4 organic rigid boards. The effect of process conditions, such as U/S powers, bonding pressures, and bonding times on the ACF temperature were investigated. The in-situ temperature at the ACF layer was measured during U/S bonding to determine the relation between the ACF temperature and the bonding characteristics of ACF joints.

The optimized U/S bonding time was obtained within 5 sec at room temperature. The significant meaning of this result is that the ACF bonding process times can be remarkably reduced by U/S bonding compared with conventional 15 sec T/C bonding at 190 °C. The ACF joints with the optimized U/S bonding conditions showed similar bonding characteristics as those with T/C bonding in terms of the adhesion strength and the daisy-chain contact resistance. The Fourier Transformation Infra-Red (FTIR) spectroscopy showed that the ACF degree of cure was achieved 90 % at 3 sec and 95 % at 4 sec. Reliability test results showed that the U/S bonded test boards had stable daisy-chain contact resistances in 85 °C/85 % RH test and 125 °C high temperature storage test for 1000 hours and -55 °C~125 °C thermal cycling test for 1000 cycles.

1. Introduction

Anisotropic Conductive Films (ACFs) are well known adhesive interconnect materials which consists of conducting particles and adhesive polymer resins in a film format. And they have been widely used as interconnect materials in flat panel display applications such as Out Lead Bonding (OLB), chip-on-glass (COG), and chip-on-film (COF), flex to PCB bonding, and also in flip chip semiconductor packaging applications. ACF interconnects are simple and lead-free processing as well as cost effective packaging method compared with solder interconnects.

For ACF interconnection, thermo-compression (T/C) bonding is the most common method, however it is necessary to reduce the bonding temperature, time and pressure, because T/C bonding is often limited by high bonding temperature, slow thermal cure, uneven cure degree of adhesive, large thermal deformation of the assembly, and high bonding pressure for large number of I/O interconnections. Therefore, there are constant needs of lower bonding temperature and faster cure ACF bonding to replace the conventional T/C bonding at 190°C and 15 seconds.

Ultrasonic (U/S) bonding for solder and metal-to-metal interconnections has been widely investigated and applied in flip chip, TAB, or surface mount technologies due to its low cost, simplicity, and fast assembly time at low temperature with reduced bonding pressure. However, most of these approaches are using lateral direction ultrasonic vibration only. Although there have some attempt to use U/S bonding as an alternative ACF bonding method, there were no previous reports of successive ACF bonding using U/S bonding except one presentation about the demonstration of U/S ACF flip chip bonding [1].

In ACFs U/S bonding, ACFs can be rapidly heated by certain ultrasonic vibration, and it can be described by materials’ complex young’s modulus which consists of storage modulus and loss modulus under cyclic stress conditions. Storage modulus is related to elastically stored energy, and loss modulus is related to energy loss which converts to heat. In general, it is well known that visco-elastic materials such as polymers have large loss modulus. Therefore, it is expected that highly visco-elastic B-stage ACFs may generate a large amount of heat by an ultrasonic vibration. By U/S heating in ACFs, rapid ACF curing and bonding can be obtained without additional chip/substrate heating.

In this study, a novel Anisotropic Conductive Film (ACF) bonding method for flexible substrate-organic rigid board bonding was investigated using an ultrasonic vibration. And the ultrasonic (U/S) ACF bonding was characterized in terms of adhesion strength, electrical continuity in comparison with those of thermo-compression (T/C) bonding, and its reliability was evaluated.

2. Experiments

2.1 Materials preparation

Test boards were 25 um-thick polyimide based flexible substrates and 1 mm-thick FR-4 organic rigid boards. Figure 1 shows the design of test boards which have 300 um pitch Cu patterns. The ACF was epoxy based adhesive film with 40 um thickness, and they contained Au coated Ni particles with 8
um diameter as conductive particles. Table 1 summarizes the specifications of test boards and the ACF.

![Table 1. The specifications of test boards and the ACF](image)

**Table 1. The specifications of test boards and the ACF**

<table>
<thead>
<tr>
<th>Flexible substrate</th>
<th>Materials</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>FR-4</td>
<td>Polyimide film</td>
<td>25um</td>
</tr>
<tr>
<td>Base film</td>
<td>Epoxy based adhesive</td>
<td>40um</td>
</tr>
<tr>
<td>ACF</td>
<td>Conductive particle</td>
<td>8um diameter</td>
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</table>

2.2 Equipment

Figure 2 shows the ultrasonic horn and test boards in this experiment. The ultrasonic energy of 160 W ~ 240 W was applied perpendicularly on the test boards.

![Figure 2. An ultrasonic bonder set-up showing an U/S horn and a test sample](image)

2.3 Decomposition temperature of materials

During U/S bonding, test boards or the ACF can be decomposed due to rapid increase of ACF temperature. Therefore, decomposition temperatures of flexible substrates, organic rigid boards and the ACF were measured to prevent decomposition of materials during U/S bonding. Decomposition temperatures were measured by TGA (Thermo-Gravimetric Analysis) with 10°C/min heating rate.

2.4 ACF temperature vs. U/S bonding conditions

In-situ ACF temperature during U/S bonding was measured to investigate the effect of U/S bonding conditions such as U/S power and bonding force on ACF temperatures. Figure 3 shows the in-situ ACF temperature measurement set-up with 40um-thick k-type thermocouples and a thermometer with 150ms sampling period.

![Figure 3. A schematic diagram of in-situ ACF temperature measurement](image)

2.5 Adhesion strength vs. U/S bonding conditions

To determine the relation between the ACF temperature and adhesion strengths, adhesion strengths of ACF joints after U/S bonding were measured using a 90° peel tester as shown in figure 4. Peel test was performed with a peel rate of 10 mm/min, and adhesion strengths of ACF joints were monitored during peel test using a load cell.

![Figure 4. A schematic diagram of 90° peel test](image)

2.6 Daisy-chain contact resistance vs. U/S bonding time

Daisy-chain contact resistances of test boards were measured after various U/S bonding conditions to examine the electrical continuity of ACF joints. Figure 5 shows the daisy-chain structure of test boards.

![Figure 5. The daisy-chain structure of test boards showing a flexible substrate bonded on a organic rigid board using ACFs](image)
2.7 Reliability evaluation of U/S bonding
Reliability tests were performed with the optimized U/S bonding conditions in terms of the adhesion strength and the daisy-chain contact resistance. Reliability requirements were 85 \(^\circ\)C/85 % RH test and 125 \(^\circ\)C high temperature storage test for 1000 hours, and -55 \(^\circ\)C to -125 \(^\circ\)C thermal cycling test for 1000 cycles. Using 10 test boards for each test, total daisy-chain contact resistances were measured for every 100 hours and 100 cycles.

3. Results and discussion
3.1 Decomposition temperature of materials

Figure 6. TGA results of flexible substrates, organic rigid boards, and ACF

Figure 6 shows TGA results of flexible substrates, organic rigid boards, and ACF. As shown in the graph, the weight of FR-4 organic rigid boards rapidly decreased at above 300 \(^\circ\)C. However, flexible substrates and the ACF showed negligible amount of decomposition up to 300 \(^\circ\)C. Therefore, ACF heating temperature during U/S bonding was maintained below 300 \(^\circ\)C to prevent FR-4 decomposition.

3.2 ACF temperature vs. U/S bonding conditions

Figure 7. ACF temperatures vs. U/S powers at 5.6 MPa bonding pressure

Figure 7 shows the ACF temperature during U/S bonding with 160 W, 200 W and 240 W powers at constant 5.6 MPa bonding pressure. As shown in the graph, the ACF temperature increased as the U/S power increased. The increase of ACF temperature can be explained with U/S vibration amplitudes. U/S vibration amplitudes increase with larger U/S powers at constant pressures, because the work by U/S vibration increases as the U/S power increases. According to the well-known equation 1,

\[
dQ = \frac{f (\Delta \varepsilon)^2 E''}{2}
\]

Equation 1. Heat generation by cyclic deformation [2]

which explains heat generation under cyclic deformation, heat generation (dQ) is proportional to cyclic strain (\(\Delta \varepsilon\)). [2] And cyclic strain increases as U/S vibration amplitude increases. Therefore, the increase of U/S power causes the increase of U/S vibration amplitude, and cyclic strain of the ACFs resulting in more heat generation.

Figure 8. ACF temperatures vs. bonding pressures at 180W power
Figure 8 shows the ACF temperature during U/S bonding at 4.6 MPa, 6.7 MPa and 8.6 MPa bonding pressures at constant 180 W power. As shown in the graph, the ACF temperatures decrease as bonding pressures increase.

The decrease of ACF temperatures can be explained with U/S vibration amplitudes. U/S vibration amplitudes decrease as bonding pressures increase at constant U/S powers. Because the work by U/S vibration is constant at a certain U/S power, it means that a smaller vibration amplitude can be obtained at larger pressures. Therefore, the increase of U/S powers causes the decreases of U/S vibration amplitude, and cyclic strain of the ACF resulting in a less amount of heat generation.

As explained above, ACF temperatures were dependent on both U/S powers and bonding pressures. Therefore, in order to maintain the ACF temperature below 300 °C, various U/S powers were selected at 4.6 MPa, 6.7 MPa and 8.6 MPa bonding pressures. Figure 9 shows the ACF temperatures during U/S bonding with various bonding conditions.

At 4.6 MPa and 180 W condition, the ACF temperature increased up to 300 °C. However, test boards were decomposed at 6.7 MPa and 200 W condition due to overheating above 400 °C. At other U/S bonding conditions, ACF temperatures were maintained about 200 °C which was relatively lower than that of 4.6 MPa and 180W condition.

3.3 Adhesion strength vs. U/S bonding conditions

Figure 10 shows adhesion strengths of U/S bonded ACF joints at various U/S bonding conditions. As shown in the graph, the maximum adhesion strength was above 600 gf/cm at 3 sec bonding time at 4.6 MPa and 180 W condition. However, at other U/S bonding conditions, adhesion strength showed relatively low 400 gf/cm adhesion strengths. The adhesion strength behavior is well matched with the previous ACF temperature behavior at figure 9. The ACF temperature during U/S bonding at 4.6 MPa and 180 W condition was about 300 °C, and those with other U/S bonding conditions were about 200 °C. Lower adhesion strengths was mainly be due to lower degree of cure of ACF at lower temperatures.
Figure 10. Adhesion strengths of U/S bonded ACF joints at various U/S bonding conditions.

Figure 11 shows adhesion strengths of U/S bonded ACF joints at 4.6 MPa and 180 W condition for 2 sec, 3 sec and 4 sec bonding times. As shown in the graph, the adhesion strength rapidly increased by ACF curing, and reached the maximum value of 630 gf/cm at 3 sec bonding time. And 630 gf/cm maximum adhesion strength obtained by the optimized U/S bonding was similar to the typical 620 gf/cm of T/C bonding with 15 sec bonding time and 190 °C bonding temperature.

Figure 11. Adhesion strengths of U/S bonded ACF joints for 2 sec, 3 sec and 4 sec bonding times at 4.6 MPa and 180 W condition.

As shown in figure 12, the degree of ACF cure measured by FTIR shows more than 90% after 3 sec at 4.6 MPa and 180 W condition.
3.4 Daisy-chain contact resistance vs. U/S bonding time

Daisy-chain contact resistances of ACF joints were measured after U/S bonding at the optimized conditions 4.6 MPa bonding pressure and 180 W U/S power. As shown in figure 13, stable daisy-chain contact resistances were obtained regardless of bonding times after 3 sec. The average daisy-chain contact resistance was 1.13 Ohm at 3 sec U/S bonding time. And it was similar to 1.08 Ohm which was obtained by the typical 15 sec T/C bonding at 190°C. These results show that not only similar adhesion strengths but also similar daisy-chain contact resistances as the typical T/C bonding were obtained using optimized U/S bonding at room temperature and less than 5 seconds bonding time.

3.5 Reliability evaluation of U/S bonding

For reliability evaluations of U/S bonded ACF joints, three kinds of tests were performed with 10 test boards at each conditions. U/S bonding was performed for 3 sec bonding time at room temperature with 4.6 MPa bonding pressure and 180 W U/S power.

As the result, U/S bonded ACF joints showed similar adhesion strengths and daisy-chain contact resistances, and showed stable daisy-chain contact resistance during 125°C high temperature storage test, 85°C/85% RH test and -55°C~125°C thermal cycling test conditions. No significant changes of daisy-chain contact resistance were observed during both tests.
4. Conclusion

In this study, a novel ACF bonding method using ultrasonic vibration was investigated, and its process conditions were optimized for flexible substrate-organic rigid board bonding applications.

The optimized U/S bonding time was 3 sec at room temperature at 4.6 MPa bonding pressure and 180 W U/S power. It was demonstrated that the ACF bonding process can be significantly enhanced by U/S bonding method compared with conventional 15 sec T/C bonding at 190 °C. Using the optimized U/S bonding conditions, the ACF joints showed similar bonding characteristics as T/C bonding in terms of the adhesion strength, the daisy-chain contact resistance, and stable electrical resistances during 125 °C high temperature storage test, 85 °C/85 % RH test, and -55 °C~125 °C thermal cycling test.

Table 2 summarizes results of the optimized U/S ACF bonding in comparison with those of typical T/C bonding.

<table>
<thead>
<tr>
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<th>T/C ACF bonding at 190°C for 15 sec</th>
<th>U/S ACF bonding at room temperature for 3 sec</th>
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<tr>
<td>Peel strength (gf/cm)</td>
<td>622.47 (±28.59)</td>
<td>633.41 (±52.14)</td>
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<tr>
<td>Daisy-chain contact resistance (Ohm)</td>
<td>1.08 (±0.02)</td>
<td>1.13 (±0.04)</td>
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</table>

These results indicate that ACF bonding temperature can be significantly reduced from the typical 190 °C to room temperature, and bonding time can be also significantly reduced from typical 15 seconds to less than 5 seconds by using the U/S bonding.

Therefore, conventional T/C ACF bonding processes can be replaced by the novel U/S ACF bonding process demonstrated in this study.

5. References
