

The Effect of Ultrasonic Frequency on Gold Wire Bondability and Reliability

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Abstract

This paper presents a systematic study on the effect of 120KHz ultrasonic frequency on the bondability and reliability of fine pitch gold wire bonding. The study was carried out on a thermosonic ball bonder that is allowed to easily switch between ultrasonic frequency of 60KHz and 120 KHz by changing the ultrasonic transducer and the ultrasonic generator. Bonding parameters were optimized through design of experiment methodology for four different cases: 25.4 μm wire at 60 kHz, 25.4 μm wire at 120 kHz, 17.8 μm wire at 60 kHz, and 17.8 μm wire at 120 kHz. The integrity of wire bonds was evaluated by six response variables. The optimized bonding process was selected according to the multi-attribute utility theory. With the optimized bonding parameters developed on one metallization for each of the four cases, 8100 bonds were made on five different metallizations. The samples were then divided into three groups. The first group was subject to humidity at 85°C/85% RH for up to 1000 hours. The second group was subject to thermal aging at 125°C for up to 1000 hours. The third group was subjected to temperature cycling from -55°C to +125°C with one hour per cycle for up to 1000 cycles. The bond integrity was evaluated through the wire pull and the ball shear tests immediately after bonding, and after each 150, 300, 500, and 1000 hours time interval in the reliability tests. Results show that 120 kHz frequency requires less ultrasonic power than 60 kHz when all other parameters are equal. Results also indicate that bonding at 120 kHz frequency is less sensitive to different metallizations than bonding at 60 kHz. All three reliability tests do not negatively affect the bond integrity of Au wire bonds on a variety of Au metallizations for both frequencies. Furthermore, as the reliability test time increases, both pull and shear strengths of Au wire bonds on Au pads increase.

Keywords: Wire bonding, ultrasonic frequency, reliability, bondability, organic substrate

1. Introduction

Wire bonding has been and is still the dominant electronic interconnection technique between the semiconductor chip and the substrate in electronic packaging. Wire bonding typically uses 60 kHz ultrasonic frequency. The original reason for choosing 60 kHz in 1960s was that this frequency resulted in transducers and tools that were appropriate to dimensions for microelectronic assemblies and stability during the bonding load [1, 2].

Beginning in the early 1990s, researchers started to investigate higher frequencies to improve wire bondability. Ramsey and Alfaro [3] studied the effect of ultrasonic frequency in range of 90 to 120 kHz on intermetallic reactivity of Au ball-bonding on Al pads and reported positive results using such frequencies. Further advantages of 120 kHz ultrasonic frequency in Au wedge bonding were presented by Shiral, et al. [4].

Several studies have shown that increasing ultrasonic frequency from 60 kHz to over 90 kHz can

reduce bonding time [2, 3, and 5], lower bonding temperature [3, 4], lower bond deformation [4, 6], increase bond strength [6], improve process over soft polymers such as Teflon or unreinforced polyimide [7]. However, no significant improvement in wire bondability by using 100 kHz over 60 kHz on the Al + 1% silicon metallization was reported by Charles, et al. [2]. Charles, et al. [2] also concluded that the 60 kHz system produced more consistent bonds than the 100 kHz system in the transition from rigid to soft substrates with gold metallization. In the authors' opinion, existing knowledge on the effect of ultrasonic frequency in wire bondability and reliability is still very limited and more studies are needed.

The objectives of this study are: 1) to evaluate the bondability of fine pitch gold wire bonding on organic substrates at 120 kHz ultrasonic frequency, 2) to compare the reliability of the diffusive bonds (fine pitch Au bonds on organic substrates with Au metallization) made at 120 kHz and those made at 60 kHz.

2. Experiments

2.1 Equipment and Materials

Thermosonic wire bonding in this study was performed on a F&K Delvotec ball bonder (model No. 5410). The bonder is allowed to easily switch between ultrasonic frequencies of 60 kHz and 120 kHz by changing the ultrasonic generator and transducer. Two 99.99% Au wire sizes, 1.0 mil (25.4 μm) and 0.7 mil (17.8 μm) in diameter, were used. The 0.7 mil Au wire supplied by SPM had a minimum tensile strength of 0.039 N (4 gram-f) and an elongation of 3-6%. The 1.0 mil Au wire from K&S had a tensile strength of 0.069 N (7 gram-f) minimum and an elongation of 5-8%. All wire bonds were made on organic substrates with Au metallizations. The integrity of the wire bonds was evaluated by the wire pull test and the ball shear tests conducted on a Dage 4000 tester.

2.2 Research Methodology

Figure 1 shows the research methodology of this study. Wire bonding process parameters were optimized through design of experiment methodology for four different cases: 1.0 mil wire at 60 kHz, 1.0 mil wire at 120 kHz, 0.7 mil wire at 60 kHz, and 0.7 mil wire at 120 kHz. With the optimized bonding parameters developed on one metallization for each of four cases, 8,100 bonds were made on five different metallizations. The samples were then divided into three groups and each group was subjected to one of three reliability tests: humidity 85°C/85%, thermal aging, and temperature cycling. The bond integrity was evaluated through the wire pull and the ball shear tests immediately after bonding, and after each 150, 300, 500, and 1000 hours time interval in the reliability tests.

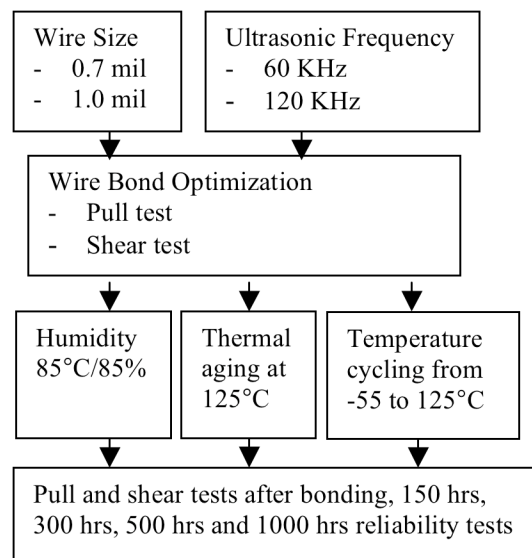


Figure 1: Research Methodology

2.3 Bonding Process Optimization

Experiments were conducted to optimize the wire bonding process parameters: ultrasonic power, bonding force, bonding time, and bonding temperature. To make the experiment size manageable, we decided to fix the settings of some process variables and their levels. Experience indicates that a high bonding temperature makes Au wire bonding easier, but the organic substrate limits the maximum bonding temperature to 140°C. In this study, we set a bonding temperature of 135°C (at the bonding pad) for both frequencies and both wire sizes. Too low bonding force and too high bonding force have detrimental effect in transferring the ultrasonic power efficiently to the interface between the bonding pad and the wire. Based on our results of a trial experiment, we set the 1st bond force of 0.245 N (25 gram force) and the 2nd bond force of 0.461 N (47 gram force) for the 0.7 mil wire, the 1st bond force of 0.304 N (31 gram force) and the 2nd bond force of 0.519 N (53 gram force) for the 1.0 mil wire. Thus, only the ultrasonic power and the bonding time are left for optimization. The range of ultrasonic power and bonding time to be able to make a successful bond was also found from the trial experiment. Optimization experiments were designed and conducted to optimize ultrasonic power and bonding time for four different cases: 1.0 mil wire at 60 kHz, 1.0 mil wire at 120 kHz, 0.7 mil wire at 60 kHz, and 0.7 mil wire at 120 kHz.

The bonding pattern of the optimization experiment is shown in Figure 2. To minimize the effect of the position of pads in a substrate on bond quality, we divided each substrate into 16 bonding areas (4 rows and 4 columns) with five bonding pads each and randomly assigned a bonding area to a treatment in the experimental design. Both the 1st and 2nd bonds were made on one rectangular pad.

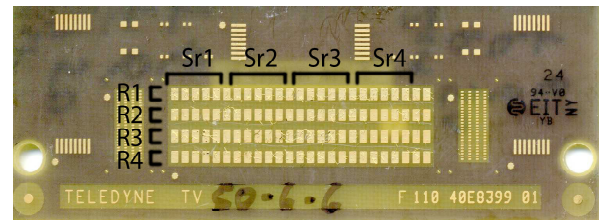


Figure 2. Bonding pattern of optimization experiment

One important question to ask is how to assess wire bond quality. The fundamental criterion of optimized bonding integrity is problematic. The goal of wire bonding is to make the wire stick to the bonding pad, but it is a challenge to measure the integrity between the wire and the bonding pad in practice. Common methods for test and evaluating wire bonds include a wire pull test and a ball shear

test [8]. Various other test methods were presented by Schafft [9]. In recent two peer-reviewed journal articles on high frequency wire bonding studies, the wire pull test and the widths of deformed wire were used to evaluate the bondability of wedge bonding [6], the ball shear test was used for ball bonding [2]. In this study, multiple response variables were used to determine if a bond was optimized. These response variables include mean and standard deviation of pull strength in a wire pull test, failure modes of the wire pull test, mean and standard deviation of shear strength of a ball shear test, and failure modes of the ball shear test. Since pull strength is known to be loop dependent [10, 11], the loop parameters were programmed to be the same for both frequencies and both wire sizes. Cares were taken in both pull and shear tests to ensure results were meaningful. The position of the hook was placed consistently in the loop during the pull test and the shear height was kept consistently in the ball shear test.

2.4 Reliability Tests

Figure 3 shows the bonding pattern of a substrate in reliability tests. The bonding pads in a substrate were divided into four blocks: B1, B2, B3, and B4 as shown in Figure 3. Pads of block B1 were assigned for bonding of 1.0 mil wire at 60 kHz; pads of block B2 were assigned for bonding of 1.0 mil wire at 120 kHz; pads of block B3 were assigned for bonding of 0.7 mil wire at 60 kHz; and pads of block B4 were assigned for bonding of 0.7 mil wire at 120 kHz. This block design was aimed to make the bonding conditions similar for these four cases through reducing the variability of the pad in different locations of a substrate.

With the optimized bonding parameters, 2025 bonds (5 bonds per area x 9 areas per substrate x 9 substrates per metallization x 5 metallizations = 2025 bonds) were made for each frequency and wire size combination. Thus, total 8100 wire bonds were made for the reliability evaluation. There were five different Au metallization schemes in the experiment. The nine substrates were then divided into three groups. The first group consisting of three randomly selected substrates was subjected to 85°C/85% relative humidity (Test type 1) for up to 1000 hours. The second group consisting of three randomly selected substrates was subjected to thermal aging at 125°C (Test type 2) for up to 1000 hours. The third group consisting of three remaining substrates was subjected to temperature cycling from -55°C to +125°C (Test type 3) with one hour per cycle for up to 1000 cycles. The bond integrity was evaluated through the wire pull and the ball shear tests immediately after bonding (Test time 1), and after each 150 hours (Test time 2), 300 hours (Test time

3), 500 hours (Test time 4), and 1000 hours (Test time 5) time interval in the reliability tests. The pull and shear data were then analyzed to compare the performance of wire bonds made at 120 kHz and at 60 kHz ultrasonic frequencies. Failure modes of pull and shear tests were summarized as well.

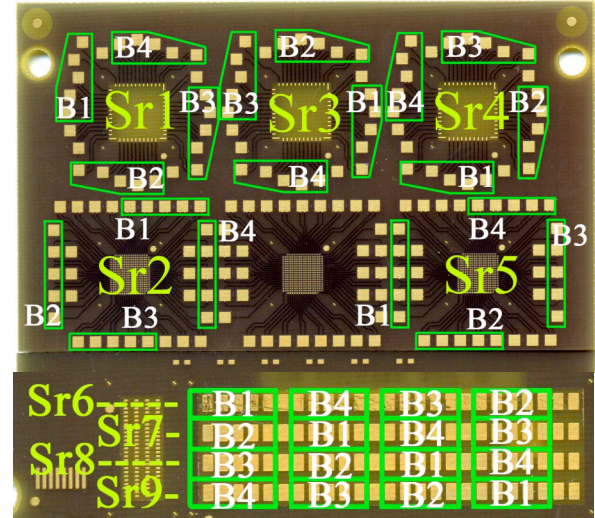


Figure 3. Bonding pattern of reliability tests

3. Results and Discussion

3.1 Process optimization results

Tables 1 to 4 summarize pull strength, shear strength, and failure modes of 0.7 mil Au wire at 120 kHz, 1 mil Au wire at 120 kHz, 0.7 mil Au wire at 60 kHz, and 1 mil Au wire at 60 kHz, respectively. The mean and standard deviation of the pull or shear strength are statistics of 20 bonds.

In this study, an optimized bonding process is defined as bonds made at the process settings having a) maximum mean of pull strength, b) minimum standard deviation of pull strength, c) maximum failure mode of loop break in the pull test, d) maximum mean of shear strength, e) minimum standard deviation of shear strength, f) minimum failure mode of ball lift or maximum failure mode of ball shear in the shear test. Using the multi-attribute utility theory [12], we selected the optimized bonding parameters as listed in Table 5. Note that the optimized processes were developed on substrates with Au metallization #1. The substrate temperature was set at 135°C. We acknowledge that it was not easy to select the optimal process settings since several settings lead to bonds having very close total scores in the multi-attribute evaluation.

The optimized settings in Table 5 show that bonding at 120 kHz uses less ultrasonic power than bonding at 60 kHz. If the same power level were chosen, bonding at 120 kHz would require shorter bonding time than bonding at 60 kHz. This means

that the high ultrasonic frequency transfers ultrasonic power efficiently to the interface between the Au wire and the bonding pad on the organic substrate.

Table 6 lists the mean pull strength and shear strength for the corresponding optimized bonding parameters. The data show that the mean pull strength at the hook made at 120 kHz is lower than that of bonds made at 60 kHz. The difference was mainly resulted from different loop heights between

120 kHz bonds and 60 kHz bonds. The measured loop height and the distance between the 1st and the 2nd bonds are shown in Table 7. After adjusting the loop profile difference, the mean pull strength at the bond made at 120 kHz is approximately same as that of bonds made at 60 kHz. The slightly smaller of mean shear strength of 120 kHz bonds than 60 kHz bond is because the deformed ball size at 120 kHz is slightly smaller than that at 60 kHz.

Table 1. Pull strength, shear strength, and failure modes of 0.7 mil Au wire bonds at 120 kHz

1 st Bond Power (setting)	1 st Bond Time (ms)	Wire Pull Test					Ball Shear Test			
		Pull Strength (gram-f)		Failure Modes (%)			Shear Strength (gram-f)		Failure Modes (%)	
		Mean	St Dev.	Ball neck break	Wedge heel break	Loop break	Mean	St Dev.	Ball lift	Ball shear
160	30	4.30	0.77	90	5	5	55.81	3.92	0	100
180	30	4.64	0.69	85	5	10	57.11	2.78	0	100
200	30	4.70	0.74	70	10	20	54.86	8.16	0	100
160	40	4.69	0.67	90	0	10	55.76	3.88	0	100
180	40	4.71	0.48	93	0	7	57.12	2.07	0	100
200	40	4.51	0.68	87	0	13	56.99	2.62	0	100
100	20	4.29	0.75	100	0	0	47.14	7.45	33	67
120	20	4.46	0.67	93	0	7	53.33	3.12	0	100
140	20	4.42	0.67	80	0	20	53.20	5.77	0	100
100	30	4.13	0.71	93	7	0	54.03	4.16	0	100
120	30	4.46	0.84	80	0	20	53.82	4.74	0	100
140	30	4.00	0.64	93	0	7	54.86	3.21	0	100
100	40	4.57	0.54	87	0	13	53.18	6.77	13	87
120	40	4.41	0.64	100	0	0	54.63	3.71	0	100
140	40	4.38	0.81	87	0	13	55.45	2.98	0	100

Table 2. Pull strength, shear strength, and failure modes of 1.0 mil Au wire bonds at 120 kHz

1 st Bond Power (setting)	1 st Bond Time (ms)	Wire Pull Test					Ball Shear Test			
		Pull Strength (gram-f)		Failure Modes (%)			Shear Strength (gram-f)		Failure Modes (%)	
		Mean	St Dev.	Ball neck break	Wedge heel break	Loop break	Mean	St Dev.	Ball lift	Ball shear
160	40	9.85	0.66	40	0	60	62.00	3.04	0	100
180	40	9.91	0.51	30	0	70	65.20	2.90	0	100
200	40	9.77	0.42	33	0	67	60.52	7.35	0	100
160	50	9.68	0.53	40	0	60	62.75	3.46	0	100
180	50	9.66	0.50	15	5	80	63.41	5.46	5	95
200	50	9.88	0.32	47	0	53	64.64	6.07	5	95
150	20	9.42	0.70	53	0	47	37.99	7.15	87	13
170	20	9.69	0.55	40	0	60	40.16	10.47	87	13
190	20	9.53	0.92	33	0	67	44.02	9.82	73	27
150	30	9.90	0.56	20	0	80	48.77	4.65	47	53
170	30	9.24	1.29	60	0	33	45.35	16.03	47	53
190	30	9.61	0.86	40	0	53	45.13	6.75	57	43
150	40	9.11	1.22	27	0	53	42.15	10.47	67	33
170	40	9.34	0.74	53	0	47	46.80	11.56	73	27
190	40	9.78	0.49	33	0	60	48.57	9.07	53	47

Table 3. Pull strength, shear strength, and failure modes of 0.7 mil Au wire bonds at 60 kHz

1 st Bond Power (setting)	1 st Bond Time (ms)	Wire Pull Test					Ball Shear Test			
		Pull Strength (gram-f)		Failure Modes (%)			Shear Strength (gram-f)		Failure Modes (%)	
		Mean	St Dev.	Ball neck break	Wedge heel break	Loop break	Mean	St Dev.	Ball lift	Ball shear
80	30	4.63	0.86	95	0	5	52.35	7.55	5	95
100	30	4.97	0.82	85	0	15	53.88	7.11	5	95
120	30	5.97	0.49	60	10	30	56.47	5.15	0	100
80	40	4.86	0.99	87	0	13	54.04	5.78	0	100
100	40	5.13	0.73	80	0	20	55.66	5.95	0	100
120	40	5.36	0.53	75	0	25	55.33	6.16	0	100

Table 4. Pull strength, shear strength, and failure modes of 1.0 mil Au wire bonds at 60 kHz

1 st Bond Power (setting)	1 st Bond Time (ms)	Wire Pull Test					Ball Shear Test			
		Pull Strength (gram-f)		Failure Modes (%)			Shear Strength (gram-f)		Failure Modes (%)	
		Mean	St Dev.	Ball neck break	Wedge heel break	Loop break	Mean	St Dev.	Ball lift	Ball shear
120	40	9.72	0.52	20	0	80	58.42	10.33	10	90
150	40	9.71	0.80	20	0	80	62.13	5.57	0	100
180	40	10.22	0.50	10	0	90	67.16	6.47	0	100
120	60	9.82	0.63	25	0	75	61.43	6.36	0	100
150	60	10.09	0.46	15	0	85	64.97	7.26	0	100
180	60	9.71	0.48	30	0	70	65.69	6.49	0	100

Table 5. Optimized bonding parameters

Wire Size (mil)	Ultrasonic Frequency (KHz)	1st bond (Ball)			2nd bond (Wedge)			Substrate Temperature (°C)
		Power in Watts (Setting)	Force (gram-f)	Time (ms)	Power in Watts (Setting)	Force (gram-f)	Time (ms)	
0.7	60	2.35 (120)	25	30	0.98 (50)	47	50	135
	120	1.55 (120)	25	30	0.91 (70)	47	30	135
1	60	3.53 (180)	31	40	2.35 (120)	53	60	135
	120	2.33 (180)	31	40	1.81 (140)	53	60	135

Table 6. Mean pull strength and shear strength for the corresponding optimized bonding parameters

Wire Size (mil)	Ultrasonic Frequency (KHz)	Pull Strength (gram-f)		Shear Strength (gram-f)	
		Mean	Std. Dev.	Mean	Std. Dev.
0.7	60	5.97	0.49	56.47	5.15
	120	4.46	0.84	53.82	4.74
1	60	10.22	0.50	67.16	6.47
	120	9.91	0.51	65.20	2.90

Table 7. Loop profile

Wire Size (mil)	Ultrasonic Frequency (KHz)	Distance between the 1 st and the 2 nd bonds (μm)	Loop height (μm)
0.7	60	875	215
	120	880	170
1	60	882	220
	120	884	190

3.2 Analysis of reliability testing data

The reliability test data were analyzed using analysis of variance (ANOVA). Tables 8 and 9 are ANOVA tables for the wire pull strength and for the ball shear strength of 0.7 mil Au wire. ANOVA tables for the pull strength and shear strength of 1 mil wire are similar.

The ANOVA tables show that there is strong interaction between the ultrasonic frequency and the Au metallization of the substrate. The interaction plots are presented in Figures 4 and 5. Since the wire bonding process was optimized on metallization scheme #1, the process may not be suitable for substrates with other metallization schemes. The data clearly show that 120 kHz bonding is less sensitive to different metallization than 60 kHz. Through examining the failure modes, the weak pull strengths of 60 kHz on metallizations #2 and #4 were due to the primary failure mode of wedge bond (2nd bond) lifting. Note that the different pull strength on

metallization #1 between 60 kHz and 120 kHz was due to different loop heights.

The ANOVA tables also show that the test time has significant effect on the reliability of bonds. Figures 6 and 7 show that both the pull and shear strengths increase as the reliability testing time increases. This is because there is no intermetallic layer in Au wire bonds on Au pads and the heat from reliability tests may have helped the diffusion process to make the bond stronger.

The test type does not have statistically significant effect on the reliability of bonds at 95% confidence level as indicated by the P-value. This indicates that effect of the three reliability tests (thermal aging, temperature cycling, and humidity tests) on bond integrity is similar. This conclusion means that one of three reliability tests is sufficient to examine the integrity of wire bonds. Note this conclusion may only be valid for Au wire bonds on Au pads at the described reliability test conditions.

Table 8. ANOVA for pull strength of 0.7 mil Au wire

Source	Sum of Squares	Degree of freedom	Mean Square	F-Ratio	P-value
Main effect					
A: Ultrasonic frequency	8.61	1	8.61	12.9	0.000
B: Metallization	2088.47	4	522.12	783.7	0.000
C: Test time	106.61	4	26.65	40.0	0.000
D: Test type	3.80	2	1.90	2.85	0.06
Interactions					
AB	2356.47	4	589.12	884.2	0.000
AC	4.70	4	1.17	1.76	0.13
AD	3.62	2	1.81	2.7	0.07
BC	19.25	16	1.20	1.8	0.03
BD	22.86	8	2.86	4.3	0.00
CD	9.16	8	1.14	1.7	0.09
Residual	2602.39	3906	0.666		
Total (Corrected)	7383.57	3959			

Table 9. ANOVA for shear strength of 0.7 mil Au wire

Source	Sum of Squares	Degree of freedom	Mean Square	F-Ratio	P-value
Main effect					
A: Ultrasonic frequency	48342.9	1	48342.9	801.6	0.000
B: Metallization	164819.0	4	41204.7	683.2	0.000
C: Test time	2053.3	4	513.3	8.51	0.000
D: Test type	55.2	2	27.6	0.46	0.63
Interactions					
AB	91194.1	4	22798.5	378.0	0.000
AC	363.5	4	90.87	1.51	0.20
AD	173.9	2	86.95	1.44	0.24
BC	2308.1	16	144.26	2.39	0.001
BD	4133.0	8	516.6	8.57	0.000
CD	1326.9	8	165.87	2.75	0.005
Residual	235567.0	3906	60.3		
Total (Corrected)	566920	3959			

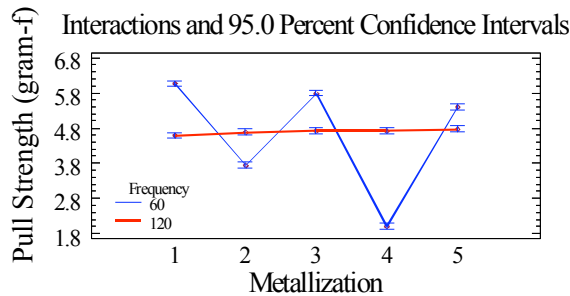


Figure 4. Interaction plot of ultrasonic frequency and the substrate metallization for pull strength of 0.7 mil wire bonds

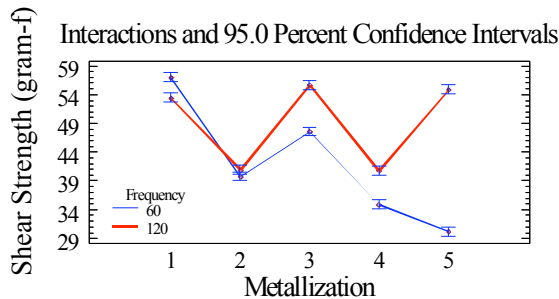


Figure 5. Interaction plot of ultrasonic frequency and the substrate metallization for shear strength of 0.7 mil wire bonds

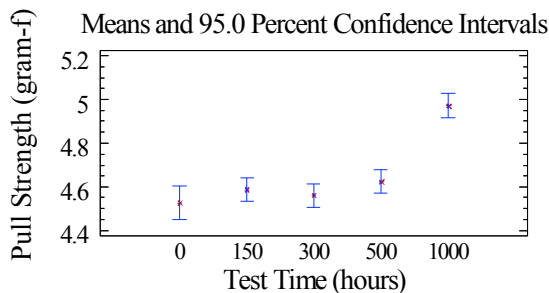


Figure 6. Mean pull strength of 0.7 mil wire bonds vs. reliability test time

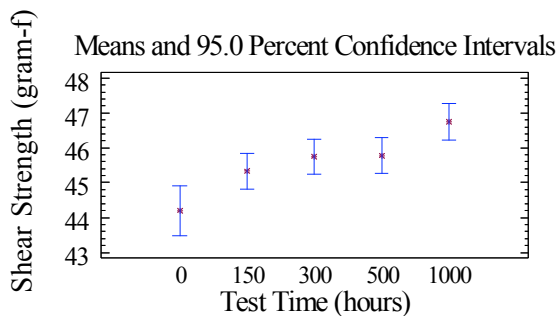


Figure 7. Mean shear strength of 0.7 mil wire bonds vs. reliability test time

4. Summary and Conclusions

A systematic investigation in comparing the bondability and reliability of gold wire bonds made at 60 kHz and at 120 kHz ultrasonic frequencies on organic substrates with gold metallizations was reported. The following conclusions can be drawn from this study:

1. With all other parameters being equal, bonding using 120 kHz ultrasonic frequency requires less ultrasonic power than bonding at 60 kHz. If the same power level were chosen, bonding at 120 kHz would require shorter bonding time than bonding at 60 kHz. This means that the 120 kHz ultrasonic frequency transfers ultrasonic power more efficiently to the interface between the Au wire and the bonding pad on the organic substrate than 60 kHz.
2. Bonding at 120 kHz frequency is less sensitive to different metallizations than bonding at 60 kHz.
3. All three reliability tests (thermal aging, temperature cycling, and humidity tests) do not negatively affect the bond integrity of gold wire bonds for both frequencies on a variety of metallizations. Furthermore, as the reliability test time increases, both pull and shear strengths of Au wire bonds on Au pads increase.
4. There is no statistically significant difference among the three reliability tests (thermal aging, temperature cycling, and humidity tests) on the degradation of wire bonds. This indicates one reliability test is sufficient to examine the integrity of Au wire bonds on Au pads. Significant time and cost saving can be achieved by eliminating two reliability tests.

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