Risk assessment for bonding wires instantaneous touch in high density packaging

Cheng Ma¹, Sujuan Zhang, Guicui Fu, Bo Wan, Maogong Jiang and Changcheng Wang

School of Reliability and System Engineering, Beihang University, Beijing, China
¹ E-mail: machengrms@buaa.edu.cn

Abstract. This paper studies the risk assessment method of bonding wires instantaneous touch during mechanical shock tests. Under-damping vibration motion is used to describe bonding wire’s motion state with mechanical shock loads. The influence of loop span, wire diameter and loop height on the amplitude and frequency of wire’s vibration are analysed based on the results of finite element analysis and design of experiments. The detection experiments of bonding wire’s instantaneous touch are conducted to get the vibration amplitude and vibration damping coefficient. Then, the risk assessment method is built by the analysis of simulation data and experiments data to evaluate the probability of adjacent wire’s transient touch under mechanical shock load.

1. Introduce
At present, packaging density of integrated circuits continuously improves due to the demand for miniaturization and high performance of equipment. For high density packaging, wire bonding is still the main method for electrical interconnection. Ultra fine pitch wire bonding technology is usually used for high density packaging. The gap of adjacent bonding wires is constantly decreasing [1]. At the same time, for some kinds of high density packaging such as three-dimensional stacked packaging, there are some bonding wires with long span and fine diameter. Generally, loop span, wire diameter and loop height influence stability of the wire structure, and the challenge is to develop more robust bonding wire to resist sweep and sway with ultra fine pitch technology [2-3].

Wire sweeping is one of the major causes of shorts in devices and the relationship between wire configuration and wire sweep stiffness is studied during the transfer molding process [4-6]. However, wire sweeping under mechanical stress has not been studied. Adjacent bonding wires transient touch is the potential failure mode under mechanical shock load which will cause logic confusion and even short burnout.

The objective of this paper is to design experiments to detect the transient wire touch during mechanical shock tests and build the risk assessment method to evaluate the probability of wire touch under mechanical shock load considering wire structure parameters.

2. Mechanical shock test

2.1. Design of test sample
When integrated circuits are subjected to mechanical impact stress, the bonding wire’s motion will be under-damping vibration. The main parameters of under-damping vibration are initial amplitude $X$,
vibration frequency $f$ and damping coefficient $\zeta$. This paper design experiments to acquire the initial amplitude and damping coefficient with the detection method of bonding wire touching electrical signal. The structure chart of test sample is shown as figure 1 and figure 2.

Figure 1. Structure of test sample.

Figure 2. A single bonding wire and adjacent metal block; parallel bonding wires.

Pin-1 and pin 9 are power suppliers and they will be connected to the high voltage test point. Pin-2, pin 3, pin-10 and pin-11 are ten parallel wires whose spans of adjacent bonding wires differ by 0.1mm, and the gap between parallel bonding wires are shown in table 1.

| No. | Pin-2 | Pin-3 | Pin-10 | Pin-11 |
|-----|-------|-------|--------|--------|
| Gap/μm | 146.8 | 208.7 | 348.2  | 240.6  |

Table 1. The gap of parallel bonding wires of each pins.

Pin-4 to pin-8 and pin-12 to pin-16 all consist of a bonding wire and an adjacent conductive metal block and the gaps between them are shown in table 2.

| No. | Pin-4 | Pin-5 | Pin-6 | Pin-7 | Pin-8 | Pin-12 | Pin-13 | Pin-14 | Pin-15 | Pin-16 |
|-----|-------|-------|-------|-------|-------|--------|--------|--------|--------|--------|
| Gap/μm | 358   | 237   | 206   | 183   | 143   | 72.5   | 59.5   | 81     | 129.9  | 79.5   |

Table 2. The gap between the single bonding wire and its adjacent metal block.

During mechanical shock test, Pin-1 and Pin-9 should be connected to high voltage test point. The other pins should be connected to low voltage test point one by one, and the schematic diagram of test circuit is shown as figure 5.

2.2. Construction of experiment platform

Bonding wires touching can be converted into a electrical signal by the testing circuit. This paper build an experiment platform to detect the voltage signal by high precision oscilloscope. The test platform is shown as figure 3 and figure 4.

Figure 3. Experiment platform.

Figure 4. Test sample and its jig.

2-channel oscilloscope are used to get electrical signals from the high voltage test point and the low voltage test point. The schematic diagram of test circuit is as shown in figure 5. During mechanical
shock tests, bonding wires can be equivalent to a switch. If adjacent bonding wires touch, the switch is closed and the test circuit is turned on. Theoretically, the value of the high voltage test point will decrease from 10V to 5V and the value of the low voltage test point will rise from 0V to 5V. The voltage signals displayed by the oscilloscope is shown in figure 6.

![Figure 5. The schematic diagram of test circuit.](image1)

![Figure 6. The voltage signal captured by the oscilloscope.](image2)

2.3. Data of experiments
The result of mechanical shock tests consist of two parts. First, initial amplitude measurement data and corresponding mechanical shock load. This part is shown in table 3 and will be used to calculate the initial speed of bonding wire during transient dynamics simulation. Second, the gap between parallel adjacent wires and corresponding mechanical shock load, which are also listed in the table 3 and will be used to calculate the damping coefficient.

| No. | Pin-4 | Pin-5 | Pin-6 | Pin-7 | Pin-8 |
|-----|-------|-------|-------|-------|-------|
| Gap/μm | 358   | 237   | 206   | 183   | 143   |
| Critical Impact Load | —     | 2317g | 2044g | 1817g | 1506g |

| No. | Pin-12 | Pin-13 | Pin-14 | Pin-15 | Pin-16 |
|-----|--------|--------|--------|--------|--------|
| Gap/μm | 72.5   | 59.5   | 81     | 129.9  | 79.5   |
| Critical Impact Load | 795g   | 649g   | 867g   | 1458g  | 854g   |

| No. | Pin-2  | Pin-3  | Pin-10 | Pin-11 |
|-----|--------|--------|--------|--------|
| Gap/μm | 146.8  | 208.7  | 348.2  | 240.6  |
| Critical Impact Load | 1556g  | 1705g  | 2195g  | 1805g  |

3. Simulation analysis of bonding wire under mechanical shock test

3.1. Extraction of characteristic parameters of bonding wire
This paper use loop span, loop diameter and loop height to describe a Q-loop bonding wire. Q-loop is a simple loop profile which is defined in the wire bonder and its structure is shown in figure 7. Different finite element models are established by changing the three structure parameters and the structure is shown in figure 8.

This paper selects multiple parameters nodes in order to get the relationship between structure parameters and vibration parameters. The range of loop span, wire diameter and loop height is shown in table 4 and the sample points are also shown in it.

![Figure 7. Structure parameters of a Q-loop bonding wire.](image3)
Figure 8. Finite element model of a Q-loop bonding wire.

Table 4. Structure parameter nodes of finite element modes of bonding wires.

| Structure Parameter | Range   | Sample points    |
|---------------------|---------|------------------|
| Loop span/mm        | 3.1~4.6 | [3, 3.5, 4, 4.5, 5] |
| Wire diameter/μm    | 25&30   | [20, 25, 30, 35]  |
| Loop height/μm      | 300~475 | [300, 350, 400, 450, 500] |

The material parameters of bonding wire is shown in table 5. Golden bonding wire is selected because of its widespread use.

Table 5. Material parameters of bonding wire.

| Material Parameter | Value   |
|--------------------|---------|
| Density/(kg/m³)    | 19300   |
| Young’s modulus/Pa | 60G     |
| Poisson’s ratio    | 0.44    |

3.2. Vibration analysis of bonding wire

3.2.1. Initial velocity calculation. The initial velocity of bonding wire should be calculated by the experimental data before transient dynamic analysis. The mapping relationship between initial amplitude and mechanical shock load can be built from the data, which is shown in figure 9. Meanwhile, the finite element model which has the same structure parameters to test sample’s bonding wires. Then, the mapping relationship between initial amplitude and initial velocity can also be established, which is shown in figure 10. Use these two prediction models to calculate the initial velocity of simulation bonding wires at the mechanical shock load points like 500g, 1000g, etc.
The prediction function of initial amplitude from simulation data is shown in equation (1), and \( x \) is initial velocity, \( f(x) \) is initial amplitude.

\[
 f(x) = -9.614 \cdot x^2 + 101.9 \cdot x - 2.385 \\
(1)
\]

The prediction function of initial amplitude from experiments’ data is shown in equation (2), and \( x \) is mechanical shock load, \( f(x) \) is initial amplitude.

\[
 f(x) = 0.1061 \cdot x - 12.71 \\
(2)
\]

This paper selects 6 mechanical shock load points to perform transient dynamics analysis and the corresponding initial velocity of finite element models of bonding wires are shown in table 6.

**Table 6. Initial velocity of finite element model at points of mechanical shock loads.**

| Mechanical shock load | 500g | 1000g | 1500g | 2000g | 2500g | 3000g |
|-----------------------|------|-------|-------|-------|-------|-------|
| Initial velocity/(m/s)| 0.43 | 1.04  | 1.75  | 2.64  | 4.04  | 5.31  |

3.2.2. Initial amplitude analysis. There are 100 bonding wires with different structure parameters which will be applied 6 different mechanical shock load on and carry on transient dynamic analysis. The shape variable maximum position is extracted to get initial amplitude. The relation between loop span, wire diameter, loop height, mechanical shock load and initial amplitude are shown in figure 11.

**Figure 11.** The analysis on the influence of initial amplitude.

Wire diameter, loop span, and loop height have linear relation with initial amplitude and mechanical shock load has a nonlinear relation with initial amplitude. Fit the relationship with multivariate regression algorithm and the prediction model is shown in table 7.

**Table 7. The prediction model of initial amplitude.**

| Independent variable | [L,H,D,F,F²] |
|----------------------|--------------|
| Prediction model     | \( Y = -99.8 + 42.9 \cdot X_1 + 17 \cdot X_2 - 37.5 \cdot X_3 + 71.8 \cdot X_4 - 6.8 \cdot X_4^2 \) |
| \( R^2 \)            | 0.956        |
| RMSE                 | 12.3         |
3.2.3. **Vibration frequency analysis.** 100 bonding wire’s vibration frequency are obtained by modal analysis, and the relation between loop span, wire diameter, loop height and vibration frequency is shown in figure 12.

![Vibration frequency analysis](image)

**Figure 12.** The analysis on the influence of vibration frequency.

Wire diameter, loop height have linear relation with vibration frequency and loop span has a nonlinear relation with vibration frequency. Fit the relationship with multivariate regression algorithm and the prediction model is shown in table 8.

| Multi Variate regression |  |
|-------------------------|----------------|
| Prediction model        | $Y = 11399 - 4278 \cdot L + 385 \cdot L^2 - 147.4 \cdot H + 934.1 \cdot D$ |
| $R^2$                   | 0.963          |
| RMSE                    | 198.8          |

3.2.4. **Damping coefficient calculation.** The damping coefficient is calculated by the data from mechanical shock tests of adjacent bonding wires. The damped vibration waveform function of a single bonding wire is shown in equation (3).

$$x = X e^{-\frac{t}{\zeta \omega_n}} \sin(\omega_n t)$$  \hspace{1cm} (3)

And $\omega_n = \omega_0 \sqrt{1 - \xi^2}$ When the damping coefficient is small enough, it can be approximated as equation (4).

$$x = X e^{-\frac{t}{\zeta \omega_n}} \sin(\omega_n t)$$  \hspace{1cm} (4)

Therefore, formula (5) can be used to determine whether adjacent bonding wires touch or not.

$$X_1 e^{-\frac{t}{\zeta \omega_n}} \sin(\omega_1 t) + [-X_2 e^{-\frac{t}{\zeta \omega_n}} \sin(\omega_2 t)] \geq d$$  \hspace{1cm} (5)
$d$ is the gap of the test sample between adjacent bonding wires, $X_1$ and $X_2$ are initial amplitudes, $w_1$ and $w_2$ are vibration frequency. $\xi$ is damping coefficient. The critical mechanical shock load indicates that the equal sign is established at this point, Then

$$\max \left\{ X_1 e^{-\xi \omega_1 t} \sin(\omega_1 t) + [-X_2 e^{-\xi \omega_2 t} \sin(\omega_2 t)] \right\} = d$$

(6)

| span | Height | diameter | Critical shock load | gap | Damping coefficient |
|------|--------|----------|---------------------|-----|---------------------|
| 4mm  | 0.4mm  | 0.025mm  | 1556g               | 146.8um | 0.018              |
| 4.1mm| 0.4mm  | 0.025mm  | 1705g               | 208.7um | 0.011              |
| 4mm  | 0.4mm  | 0.025mm  | 1805g               | 240.6um | 0.008              |
| 4.1mm| 0.4mm  | 0.025mm  | 2195g               | 348.2um | 0.0045             |

The damping coefficient is obtained in table 9 and the mean value of the calculated results is used as the estimation of damping coefficient, the mean value of $\xi$ is 0.0104.

4. Risk assessment method

The critical gap can be obtained by formula (7).

$$d_0 = \max \left\{ X_1 e^{-\xi \omega_1 t} \sin(\omega_1 t) + [-X_2 e^{-\xi \omega_2 t} \sin(\omega_2 t)] \right\}$$

(7)

The vibration waveforms of adjacent bonding wires are superposed in figure 13. During the process of vibration, the maximum value of the sum of displacement of the opposite motion can be used as the critical gap between adjacent bonding wires. The value of $d_0$ will reach the maximum point during the whole time of vibration as shown in figure 14.

As shown in figure 13, the vibration phase of two adjacent bonding wires is gradually non-synchronous. The sum of the opposite motion distances of adjacent bonding wires reaches the maximum at the crest of figure 14, and the distance is the critical gap of wires touching.

This paper use the difference between the critical gap $d_0$ and the actual gap $d$ between adjacent bonding wires to make risk assessment. In general, the actual gap can be obtained by measurement and when the actual gap between adjacent bonding wires is significantly greater than the critical gap, the probability of wires touching will be very small. When the actual gap is similar to or less than the critical gap, the judgement of wires touching will occur. It can be described in mathematics as formula (8) and formula (9).
$$P(y=1|d_0,d) = 0, \text{if } d >> d_0$$
$$P(y=1|d_0,d) = 1, \text{if } d \approx d_0 \text{ or } d \leq d_0$$

$P(y=1|d_0,d)$ means the probability of wires touching. This paper uses a sigmoid discriminant function to give the risk value which can be obtained by formula (10).

$$P(y=1|d_0,d) = \frac{1}{1+e^{-z}}, z = \frac{d-d_0}{\sigma}$$

If $d >> d_0$, the value of $P(y=1|d_0,d) \approx 0$, then the risk of wires touching is very low and the failure mode of instant touch between adjacent bonding wires will not happen under the corresponding mechanical shock load. $\sigma$ reflects the dispersion of the predictive value of critical gap and this paper will use RMSE as an estimated value of $\sigma$.

The prediction model of critical gap between adjacent bonding wires is established and loop span, wire diameter, loop height, and mechanical shock load are main independent variables. The prediction model is shown in Table 10.

Table 10. The prediction model of critical gap.

| Multivariate regression          |                      |
|---------------------------------|----------------------|
| Prediction model                | $d_0 = -408.6 + 272.2 \cdot L - 32.4 \cdot L^2 + 19.9 \cdot H - 65.5 \cdot D + 41.7 \cdot F$ |
| $R^2$                           | 0.947                |
| RMSE                            | 13.1                 |

The estimate value of $\sigma$ is 13.1 and $d_0$ can be predicted with the prediction model. Therefore, the risk of wire touching can be calculated by the formula:

$$P(y=1|d_0,d) = \frac{1}{1+e^{-z}}, z = \frac{d - (-408.6 + 272.2 \cdot L - 32.4 \cdot L^2 + 19.9 \cdot H - 65.5 \cdot D + 41.7 \cdot F)}{13.1}$$

5. Conclusions

Under-damping vibration is used to describe the motion state of bonding wire under mechanical shock load. Three vibration parameters, initial amplitude, vibration frequency and damping coefficient, can be measured by mechanical shock test and finite element simulation analysis.

Through multivariate regression algorithm, the mapping relationship of initial amplitude and vibration frequency with loop span, wire diameter, loop height, and mechanical shock load is established. The wire touching failure can be analyzed by waveform superposition and the critical gap between adjacent bonding wires can be calculated.

Use sigmoid discriminant function to assess the probability of adjacent wires transient touch. The calculated critical gap and the real gap are used to quantify the risk and the result can be used to evaluate the risk of adjacent bonding wires transient touch under mechanical shock load for high density packaging integrated circuits.

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