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RESPONSE SURFACE METHODOLOGY IN THE CHARACTERIZATION OF WIRE BOND PROCESS

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RINGKASAN: *Dalam industri pembuatan semikonduktor, kebolehharapan wayar dalam proses ikatan wayar dipastikan menerusi ujian dengan musnah yang dikenali sebagai ujian penarikan wayar. Parameter-parameter yang mempengaruhi penarikan wayar ialah kuasa ikatan, masa ikatan dan daya ikatan. Untuk mengenalpasti kesan parameter-parameter di atas ke atas penarikan dawai, suatu rekabentuk tertib pertama yang berdasarkan metodology sambutan permukaan telah dijalankan. Rekabentuk tersebut terdiri daripada 12 siri eksperimen yang telah dijalankan dengan berbagai-bagai kombinasi parameter-parameter di atas. Berdasarkan data-data yang telah diperolehi, rekabentuk tertib pertama telah dibangunkan. Keputusan menunjukkan bahawa kuasa ikatan adalahlah faktor terpenting dalam mempengaruhi penarikan dawai. Dengan ini, ia telah dipilih sebagai masukan untuk parameter-parameter proses kawalan.*

Penarikan dawai juga berhubung kait dengan lebar/ketebalan ikatan. Sebarang variasi/ perubahan dalam ketebalan ikatan akan memberi kesan kepada daya penarikan. Seterusnya, dengan mengawal kuasa ikatan, ketebalan dawai boleh dikawal dan had ketebalan yang tertentu akan memastikan kebolehharapan pengikatan wayar. Dengan mengaplikasikan carta kawalan "Purata berpemberat berubah secara eksponen", ketebalan pengikatan wayar diperiksa secara berterusan. Sebarang perubahan pada ketebalan ikatan akan dikawal dengan melaraskan kuasa ikatan pada mesin. Ini tentunya dapat menidakkan ataupun menolak keperluan untuk melakukan ujian dengan musnah untuk wayar.

ABSTRACT: In the semiconductor industries, the reliability of the wire in a wire-bond process is ensured through a destructive test known as the wire pull test. The parameters influencing the wire pull are the bond power, bond time and bond force.

In order to find out the effect of these parameters on the wire pull, a first-order design based on the response surface methodology has been done. The design consisted of twelve experimental runs with various combinations of these parameters. Based on the experimental data, a first-order model has been developed which indicates that the bond power is the most significant parameter influencing the wire pull. With this finding, the bond power has been selected as an input to a process control parameters.

The wire pull is again correlated to the bond width. Any variation in the bond width influences the wire pull force. Hence by controlling the bond power, bond width could be controlled and a certain range of bond width value will ensure the reliability of the wire bonding. By applying the 'exponentially weighted moving averages' (EWMA) control chart, bond width of the wire is checked continuously. Any variation of the bond width is controlled by adjusting the bond power on the machine and this will ultimately help eliminate the need for destructive wire pull test.

KEYWORDS: Response surface methodology, mathematical model, wire pull, wire bond process

INTRODUCTION

Semiconductor industries have evolved through fast and rapid growth in the past twenty years. The major challenge currently encountered by the industries is the shrinkage of transistors. The shrinkage directly affects the die size which consequently poses a challenge to the Wire bond process. With the reduction of pad size and pad pitch, an improvement of the Wire bond machine capability on the bond placement needs in-depth research.

Wire bonding techniques were first introduced in 1950's to provide interconnection for the electronic integrated chips. Harmon gave a very detailed description of the wire bonding reliability and yield problems. As for the wire bond adhesion reliability test, the techniques in practice so far are the wire pull and shear tests which are both destructive methods. Wire bonding techniques provide interconnections between the semiconductor chips and the exterior contacts of the electronic packages. The wire bond machine set-up parameters are the most important parameters which control the bond quality. These parameters are the bond power, bond time, and bond force.

In this paper, the knowledge of response surface methodology has been applied to find out the most important parameter affecting the wire pull. The response surface methodology was initially developed and described by Box and others (1955, 1957, 1951) in the study of optimisation problems in chemical engineering. This has been used in tool life modelling, surface roughness modelling, and in other machining processes [Taraman; Baradie (1991); Choudhury & Baradie (1995a & 1995b); Padmanabhan (1992); and Padmanabhan & Murty (1991)].

By controlling the most significant parameter during the wire bond placement, wire pull test could be avoided to find out the reliability of the wire. A mathematical model utilising the response surface methodology has been developed for predicting the wire pull. In this model, a 2^3 factorial design (Montgomery, 1984) has been used to investigate the effect of bond power, bond time, and bond force.

DEVELOPMENT OF A MATHEMATICAL MODEL

Mathematical Model

The three key machine parameters for wire bond process are the bond power, bond time and bond force. The relationship between the wire pull known as the response and the independent variables (the bond power, bond time, and bond force) can be represented by the following equation

$$Y = C T^{l} P^{m} F^{n} \varepsilon' \tag{1}$$

where Y is the wire pull in gram, T, P, and F are the bond time (millisec), bond power (machine units), and bond force (gm) respectively, and C, l, m, n are constant and exponents and ε' is a random error. Equation (1) can be written in the following form

$$\ln Y = \ln C + \ln T + \ln P + \ln F + \ln\varepsilon' \tag{2}$$

The linear model of equation (2) is

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \tag{3}$$

where y is the measured wire pull in a logarithmic scale, $x_0 = 1$ (dummy variable), $x_1 = \ln T$, $x_2 = \ln P$, $x_3 = \ln F$, and $\varepsilon = \ln\varepsilon'$. ε is assumed to be a normally distributed uncorrelated random error with zero mean and constant variance. $\beta_0 = \ln C$, β_1, β_2, β_3 are the model parameters to be estimated. The estimated response can be written as

$$y_{\text{estimated}} = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{4}$$

where b_0, b_1, b_2, and b_3 are estimates of β_0, β_1, β_2, and β_3 respectively.
The parameters of equation (4) have been calculated by the method of least squares using a Matlab computer package and the significance of these variables are judged by statistical analysis. The matrix form of equation (4) is

$$b = (X^T X)^{-1} X^T \hat{Y} \tag{5}$$

where $X = [X_0\ X_1\ X_2\ X_3]$, an array of independent variables x_0, x_1, x_2, and x_3. X^T is the transpose of X, and $\hat{Y}$ is the matrix of measured response (wire pull).

Experimental Design and Conditions

To develop the first order model, a design consisting of twelve experiments was selected. Eight experiments constitute 2^3 factorial design with an added centre point repeated four times. The added centre point is used to estimate the pure error. The design provides three levels for each of the independent variables. The resulting twelve experiments form the central composite design. A 2^3 central composite design is shown in Figure 1. Such a design have been used by different researchers (Wu, 1964; Bandopadhyay & Teo, 1990) in metal cutting. Table 1 shows the levels of independent variables and coding identifications while the experimental cutting conditions together with the wire pull values are presented in Table 2 (Periasamy, 1997).

The wire pull tests were performed after the bonding process for various combinations of the bond time, bond power, and bond force. The test values represent failure criteria of the wire bond. A schematic of the wire pull testing method is shown in Figure 2.

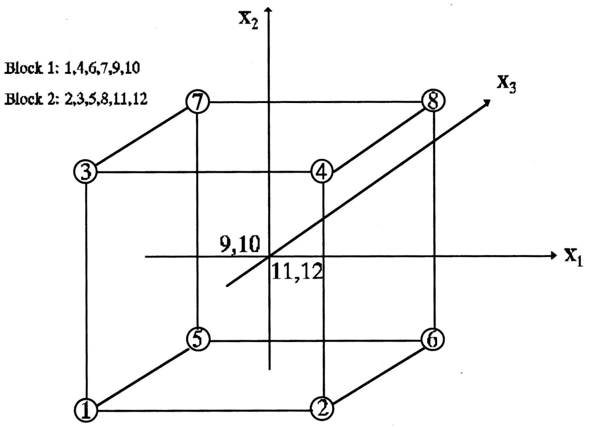

Figure 1. *2^3 factorial first-order central composite design.*

Table 1. Levels of independent variable

Levels	**Low**	**Centre**	**High**
Coding	-1	0	1
Bond time (millisec)	15	20	25
Bond power (machine units)	100	110	120
Bond force (gm)	35	40	45

Table 2. Design of experiments and the experimental data

No. of runs	**Natural variable**			**Coded variable**			**Wire pull y (gm)**
	Bond time	**Bond power**	**Bond force**	x_1	x_2	x_3	
1	15	100	35	-1	-1	-1	4.8
2	25	100	35	1	-1	-1	6.2
3	15	120	35	-1	1	-1	7.8
4	25	120	35	1	1	-1	6.4
5	15	100	45	-1	-1	1	5.2
6	25	100	45	1	-1	1	6.3
7	15	120	45	-1	1	1	6.0
8	25	120	45	1	1	1	6.8
9	20	110	40	0	0	0	8.2
10	20	110	40	0	0	0	8.4
11	20	110	40	0	0	0	8.1
12	20	110	40	0	0	0	8.3

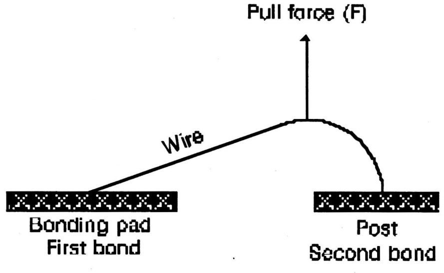

Figure 2. *A schematic of the wire pull test method*

RESULTS AND DISCUSSION

First Order Model

The wire pull model based on the twelve set of experiments is

$$y = 1.912 + 0.047x_1 + 0.092x_2 - 0.013x_3 \tag{6}$$

The transforming equation for each of the independent variables are as follows:

$$x_1 = \frac{\ln T - \ln 20}{\ln 25 - \ln 20},\ x_2 = \frac{\ln P - \ln 110}{\ln 120 - \ln 110}\ x_3 = \frac{\ln F - \ln 40}{\ln 45 - \ln 40} \tag{7}$$

Equation (6) describing the wire pull can be transformed by using equation (7) as a function bond time, bond power, and bond force as

$$y = -3.3 T^{0.211}\ P^{1.067}\ F^{-0.11} \tag{8}$$

The equation indicates that the most significant parameter which influence the wire pull is the bond power. Equation (6) is plotted in Figure 3 as contours for each of the response surfaces at three bond forces (35, 40, 45 gm). For a bond force of 35 gm and a bond time of 20 milliseconds, wire pull may vary from 6.5 gm to 7.5 gm depending on the bond power. Similar conclusions could be drawn from other contours. From these contours it is possible to select a combination of bond time and bond power that maximises the wire pull.

Adequacy of the Model

In the analysis of variance, the total sum of squares Σy^2 is divided into contributions due to 'zero-order-term', first-order-terms', 'lack of fit', and 'pure error' (Draper & Smith, 1981). The formulae for analysis of variance is presented in Table 3. N is the total number of experimental points, K is the dimension of the design, n_0 is the number of central points, n_c is the number of corner points, y_i is the logarithmic values of the observed responses, and y_{ni} are those of the central points with mean equal to y_0. b_i are the estimated parameters and $y_i\ x_i$ are the cross products.

Table 4 gives the analysis of variance results with 95% confidence interval. The sum of the squares of the individual items divided by their respective degrees of freedom gives the mean squares. The ratio of mean square due to lack of fit to the mean square due to pure error indicates the adequacy of the model. If the ratio is less than the *F-ratio* obtained from the table at 95% confidence interval, then the model is adequate and the lack of fit is insignificant. It is clear from Table 4 that the *F-ratio* calculated is less than the *F-ratio* from the table. The ratio of lack of fit to pure error at 95% confidence is found to be 0.574 while its tabulated value is 9.01. Hence the model is found to be adequate.

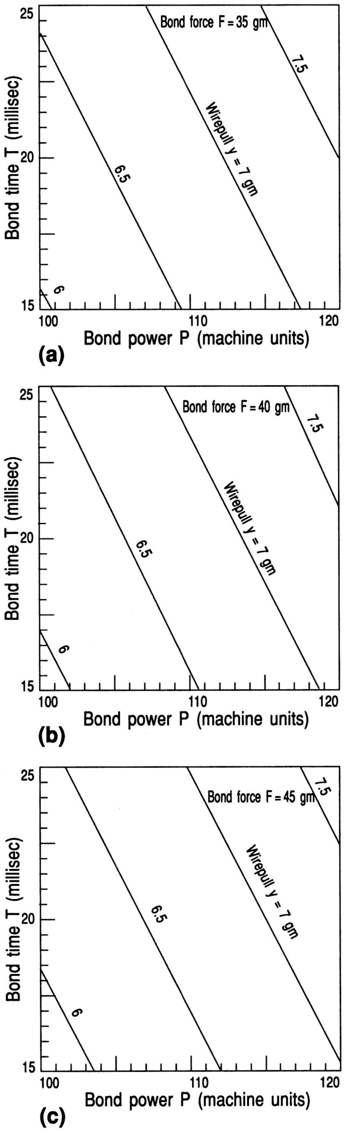

Figure 3. *Wire pull contours in bond power-bond time plane for three different bond forces; (a) F = 35 gm, (b) F = 40 gm, (c) F = 45 gm.*

Table 3. Formulae for analysis of variance

Source	Sum of squares	Degrees of freedom
Zero order term	$\frac{1}{N}\left[\sum_{i=1}^{N} y_i \right]^2$	1
First order terms	$\sum_{i=1}^{k} b_i (y_i x_i)$	k
Lack of fit	By subtraction	$n_c - k$
Pure error	$\sum_{i=1}^{n_0} (y_{ni} - y_0)^2$	$n_0 - k$
Total	$\sum_{i=1}^{N} y^2_i$	N

Table 4. Analysis of variance

Source	Sum of squares	Degrees of freedom	Mean square	$F_{calculated}$	F_{table}
Zero order term	43.860898	1	43.860898		
First order term	0.0868407	3	0.0289469		
Lack of fit	0.150946	5	0.0301892	0.574	9.01
Pure error	0.157746	3	0.052582		
Total	44.25643085				

CONCLUSION

The methodology adopted illustrates a useful technique that could be applied to other industrial processes. By proper experimental design, three independent variables were investigated simultaneously to study their effects on the wire pull. First order wire pull model has been developed from the factorial design of experiments. Analysis of the variance has confirmed that the first order model is adequate. The model equation has revealed that the effect of bond power is much more pronounced on the wire pull than the remaining two parameters. Response surface methodology is a useful technique for determining the most critical parameter influencing the wire pull. The model equation has been utilised to obtain contours of the wire pull in planes containing two of the independent variables. With the variation of the bond force, a shift of the wire pull is clearly depicted on the contours.

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