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An enhanced bridging model for evaluating the failure probability of anisotropic conductive film packages

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This paper develops a computational model for predicting the failure probability of flip chip packages fabricated using anisotropic conductive film (ACF). In the proposed approach, the opening failure probability is evaluated using a conventional Poisson function and the bridging failure probability is estimated using an enhanced box model which takes account of bridging along all the conductive, linear paths between adjacent pads. The opening and bridging probabilities are computed as a function of the volume fraction of the conductive particles within the ACF compound and are plotted in the form of a V-shaped curve, in which the tip value indicates the optimal volume fraction, i.e. the volume fraction which minimizes the overall package failure probability. The computational results indicate that the enhanced bridging model developed in this study provides more logical estimates of the minimum failure probability and optimal volume fraction than the existing bridging models presented in the literature.

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1. Introduction

Anisotropic Conductive Film (ACF), consisting of an insulating adhesive matrix with dispersed conductive particles, is used in a variety of ACF-based packaging techniques, including Flat Panel Displays (FPDs), Liquid Crystal Displays (LCDs), Tape Automated Bonding (TAB), Outer Lead Bonding (OLB), flex to PCB bonding (PCB), Chip-On-Glass (COG) and Chip-On-Film (COF). ACF can be a replacement for traditional soldering or wire bonding technology, and has the advantages of low-temperature assembly, high-density interconnections, flux-less bonding, and low fabrication cost [1-4]. The ACF film not only provides full electrical connectivity in the vertical direction (i.e. between the substrate and the IC), but also enhances the strength of the interconnection and protects the IC/Substrate assembly from accidental damage during handling and from environmental effects.

Fig. 1 presents a schematic illustration of a typical ACF flip chip joint. Significant research has been performed to improve the performance and physical yield of flip chip packages by optimizing the ACF composition and the processing conditions (i.e. the temperature, pressure and bonding time). However, the literature contains relatively few proposals for predicting the electrical failure probability of such assemblies. In practice, the electrical performance of flip chip packages is directly related to the volume fraction of the conductive particles within the ACF compound. As shown in Fig. 1, the probability of a bridging failure (i.e. an undesirable conductivity in the horizontal direction) increases as the volume fraction increases. Conversely, the probability of an opening failure (i.e. a loss of electrical conductivity in the vertical direction) increases as the volume fraction decreases. Hence, in specifying an appropriate volume fraction, a compromise must be obtained which minimizes the risk of bridging failure, while simultaneously ensuring full electrical conductivity between the IC and the substrate.

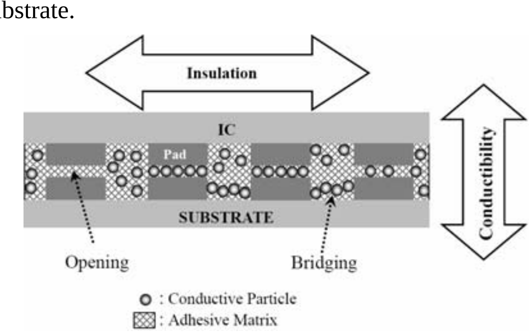

Fig. 1. Illustration of flip chip joint, showing insulation and conductibility properties.

In investigating the problem of opening failures, Williams and Whalley [5] assumed that the conductive particles were distributed on the pads in accordance with a Poisson distribution. Subsequently, Mannan *et al*. [6] proposed a box model for estimating the probability of shorting between neighboring pads. In this model, the probability of bridging is estimated as

$$P_{bridging} = 1 - \left(1 - \left(\frac{6v_f}{\pi}\right)^{\frac{d}{2r}}\right)^{\frac{hl}{4r^2}}, \tag{1}$$

where v_f is the volume fraction of the conductive particles, d is the distance between the pads, h is the pad height, l is the side length of the square pad, and r is the radius of the conductive particles. Significantly, the model assun of the IC, i.e. Eq. (1). In other words, Eq. (1) essentially provides the lower bound of the bridging failure probability.

Lin *et al*. [7-10] modeled the electrical yield of ACF packages using a Poisson function to estimate the opening failure probability and a modified box model to predict the bridging probability. Differing from the former publications, the new bridging model developed in this paper can be used to calculate the bridging probability with a more logical mathematical model. As shown in Fig. 2, the opening and bridging probabilities were plotted as a function of the volume fraction of the conductive particles within the ACF compound. The resulting V-shaped curve not only enables the failure probability to be rapidly determined for any given value of the volume fraction, but also indicates the optimal volume fraction, i.e. the volume fraction which minimizes the overall package failure probability.

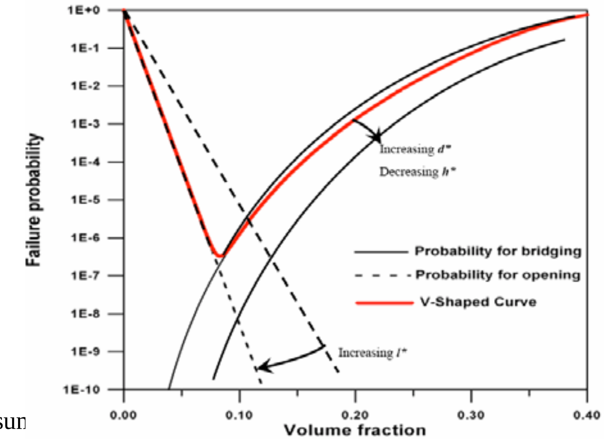

Fig. 2. Illustrative V-shaped curve for ACF probability failure estimation.

In the modified bridging model [7], the original model presented by Mannan *et al*. [6] was amended to reflect the possibility of shorting occurring along any of the linear paths through the ACF compound between adjacent substrates. In the proposed approach, the bridging probability was computed using a summation technique in which all of the possible intersections of events from $B_1, B_2, \cdots, B_n$ (shown in the Eq. 2) were obtained and their respective probabilities were computed, i.e.

$$P_{bridging} \equiv P\left(\bigcup_{i=1}^{n} B_i\right) = \sum_{i=1}^{n} P(B_i) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} P(B_iB_j) + \sum_{i=1}^{n-2}\sum_{j=i+1}^{n-1}\sum_{k=j+1}^{n} P(B_iB_jB_k) - \cdots + (-1)^{n-1}P(B_1B_2\cdots B_n), \tag{2}$$

where B_i is the events about the bridging failure.

However, in actually computing Eq. (2), only the first term, i.e. $\sum_{i=1}^{n} P(B_i)$, was considered. Consequently, the modified box model was formulated as

$$P_{bridging}\left(l^*, h^*, d^*, v_f\right) = \sum_{i_1=1}^{l^*}\sum_{i_2=1}^{l^*}\sum_{j_1=1}^{h^*}\sum_{j_2=1}^{h^*}\left(\frac{\left(\frac{6v_f}{\pi}\right)^{\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}} - \left(\frac{6v_f}{\pi}\right)^{d^*h^*l^*+1}}{1-\left(\frac{6v_f}{\pi}\right)}\right), \tag{3}$$

where $P_{bridging}$ is the bridging probability, v_f is the volume fraction, h^* is the dimensionless pad height and is equal to $\left[h/2r\right]$, d^* is the dimensionless distance between neighboring pads in the pitch direction and is equal to $\left[d/2r\right]$, l^* is the dimensionless pad height and is equal to $\left[l/2r\right]$, (i_1, i_2, j_1, and j_2) are calculation indices.

However, in developing this model, it is assumed that the bridging conditions over two or more conductive paths in the meanwhile are neglected. As a result, Eq. (2) tends to over-estimate the bridging failure probability. In other words, Eq. (2) essentially provides the upper bound of the bridging failure probability.

Accordingly, this paper attempts to improve the accuracy of the estimated bridging probability by modifying the bridging model proposed by Mannan *et al.* [6] and Lin et al.[7], and to take into account the occurrence of the bridging paths under a more logical model.

2. Application of probability theory to opening and bridging failure analysis

2.1 Opening failure analysis using poisson function

In ACF assemblies, the absence of particles on a pad results in an open circuit between the substrate and the IC. Therefore, when evaluating the electrical performance of such assemblies, it is essential to have some idea of the number of particles located on each pad. According to Williams and Whalley [5], the probability of there being *n* particles on a pad is given by

$$P(n) = \frac{{\mu_1}^n e^{-\mu_1}}{n!}, \tag{4}$$

$$\mu_1 = \frac{3l^2 v_f}{2\pi r^2} = \frac{6l^{*2} v_f}{\pi}, \tag{5}$$

where μ_1 is the average number of particles on the pads in the vertical direction.

The probability of an open circuit between the pads can be expressed as

$$P_{opening}(0) = e^{-\mu_1} = e^{-\frac{6l^{*2} v_f}{\pi}}. \tag{6}$$

It has been reported that in IC / substrate assemblies with an inter-pad spacing of 50 µm, the use of an ACF compound with six particles per pad ensures a stable contact resistance during testing at high temperatures (85°C) and high relative humidity (85%) [11,12]. In other words, a density of more than five particles per pad is required to prevent opening. Under these conditions, the Poisson function for the opening failure probability can be expressed as

$$P_{opening}(n \le 5, \mu_1(v_f)) = \sum_{n=0}^{5} \frac{{\mu_1}^n e^{-\mu_1}}{n!} = \sum_{n=0}^{5} \frac{\left(\frac{6l^{*2} v_f}{\pi}\right)^n e^{-\frac{6l^{*2} v_f}{\pi}}}{n!}. \tag{7}$$

2.2 Bridging analysis

Fig. 3 presents a schematic illustration of an adhesive compound brick between two neighboring pads. An assumption is made that the conductive particles are randomly distributed within the ACF resin. If the adhesive compound brick is assumed to comprise a total of *N* cubic boxes and to contain a total of *k* particles, then the volume fraction of the particles within the resin is given by

$$v_f = \frac{k\left(\frac{4\pi r^3}{3}\right)}{N(2r)^3}. \tag{8}$$

The probability that any box is occupied, i.e. contains a particle, is given by

$$P_{box} = \frac{k}{N} = \frac{6v_f}{\pi} = \mu_2, \tag{9}$$

where *N* is the number of cubic elements (i.e. boxes) in the region between the adjacent pads, *k* is the number of cubic elements containing particles in the region between the adjacent pads, μ_2 is the probability of an element containing a particle between the adjacent pads. Clearly in Eq. (9), the ratio of *k* to *N* should be less than 1 and the volume fraction should be smaller than π /6.

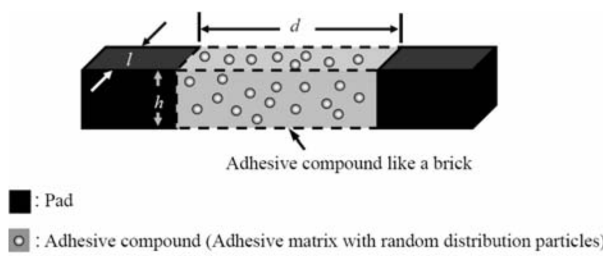

Fig. 3. Adhesive matrix with randomly distributed particles between adjacent pads.

Fig. 4 presents a detailed schematic of the ACF compound brick between two neighboring pads. As shown, the brick is meshed by cubic elements (boxes), some of which contain a conductive particle. In the enhanced bridging model developed in this study, it is assumed that bridging takes place along all feasible linear paths between neighboring pads provided that the path comprises a continuous chain of conductive particles (as shown in Fig. 4). In this sense, the current model differs markedly from those presented in [6] and [7], respectively. For example, in the original model [6], bridging is assumed to take place only along the shortest path between the two pads, i.e. from (i_1, j_1) on the side wall of the left-hand pad to (i_1, j_1) on the side wall of the right-hand pad.

Meanwhile, in the modified model [7], bridging is assumed to take place along all of the feasible linear paths between neighboring pads, irrespective of the fact that some of these paths do not actually comprise a continuous chain of conductive particles. In constructing the current bridging model, each bridging path is indexed by its start point (i.e. its left-hand end) and its end point (i.e. its right-hand end), i.e. (i_1, j_1) and (i_2, j_2), respectively.

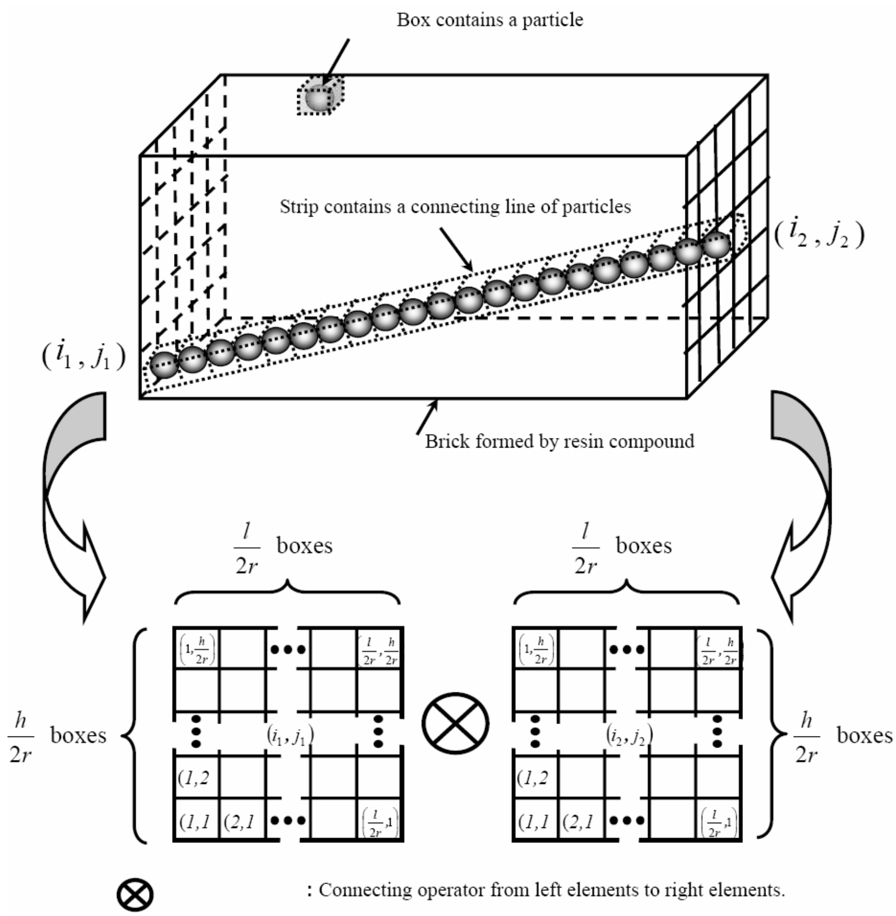

Fig. 4. (a) Finite connective model considering bridging in all directions; and (b) calculation of bridging probability using product operation.

Clearly, the shortest dimensionless distance between (i_1, j_1) and (i_2, j_2) is given by $\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}$. As a result, the minimum number of particles (i.e. boxes) required to bridge the gap between neighboring pads is $\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}$. These boxes form a continuous strip with a bridging probability of

$$P_{strip} = (P_{box})^{\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}} \tag{10}$$

where P_{box} is the bridging probability of the box; P_{strip} is the bridging probability of the strip between (i_1, j_1) and (i_2, j_2). However, not all of the linear lines between the side walls of the two adjacent pads comprise a continuous chain of particles. In other words, some of these lines have an insulating property. The insulation probability of a bridging strip is given by

$$P_{strip}{}^{C} = 1-(P_{box})^{\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}} \tag{11}$$

Therefore, the insulation probability of the bridging brick is expressed as

$$P_{brick}{}^{C} = \prod_{\substack{i_1,i_2:1\to l^* \\ j_1,j_2:1\to h^*}} (1-(P_{box})^{\sqrt{(d^*)^2+(i_1-i_2)^2+(j_1-j_2)^2}}) \tag{12}$$

where $\prod$ denotes a chain of product operations.

As a result, the bridging probability of a brick (containing $\left(h^* \times l^*\right)^2$ strips) is given by.

$$P_{brick} = 1 - \prod_{\substack{i_1, i_2 : 1 \to l^* \\ j_1, j_2 : 1 \to h^*}} (1 - (P_{box})^{\sqrt{\left(d^*\right)^2 + (i_1 - i_2)^2 + (j_1 - j_2)^2}}) \quad (13)$$

In Eqs. (10) and (11), P_{strip} and $P_{strip}{}^C$ are complementary events, and therefore $P_{strip} + P_{strip}{}^C = 1$. Similarly, P_{brick} and $P_{brick}{}^C$ can be expressed as $P_{brick} + P_{brick}{}^C = 1$.

The probability of each box containing a particle is given by μ_2. Therefore, the maximum probability of bridging along the path between (i_1, j_1) and (i_2, j_2) is $\mu_2{}^{\sqrt{\left(d^*\right)^2 + (i_1 - i_2)^2 + (j_1 - j_2)^2}}$. Consequently, the corresponding insulating probability is $1 - \mu_2{}^{\sqrt{\left(d^*\right)^2 + (i_1 - i_2)^2 + (j_1 - j_2)^2}}$. If the brick is considered to be 100% insulating, then clearly it must be insulating along all of the feasible linear paths between the side walls of the two pads. The insulating probability between neighboring pads can therefore be derived as

$$P_{insulating} = \prod_{\substack{i_1, i_2 : 1 \to l^* \\ j_1, j_2 : 1 \to h^*}} \left(1 - \mu_2{}^{\sqrt{(i_1 - i_2)^2 + (j_1 - j_2)^2 + d^{*2}}}\right) \quad (14)$$

The bridging probability in all directions in the brick is given by $1 - P_{insulating}$, i.e.

$$P_{bridging} = 1 - \prod_{\substack{i_1, i_2 : 1 \to l^* \\ j_1, j_2 : 1 \to h^*}} \left(1 - \mu_2{}^{\sqrt{(i_1 - i_2)^2 + (j_1 - j_2)^2 + d^{*2}}}\right), \quad (15)$$

where i_1, j_1, i_2 and j_2 are coordinate indices referencing the individual cells on the side walls of the pads (see Fig. 4).

Substituting $6v_f / \pi$ into μ_2, Eq. (15) can be expressed as

$$P_{bridging} = 1 - \prod_{\substack{i_1, i_2 : 1 \to l^* \\ j_1, j_2 : 1 \to h^*}} \left(1 - \left(\frac{6v_f}{\pi}\right)^{\sqrt{(i_1 - i_2)^2 + (j_1 - j_2)^2 + d^{*2}}}\right). \quad (16)$$

This equation can then be processed using a numerical method to calculate the bridging probability for any given values of d^*, h^*, l^* and v_f. Significantly, compared to the modified box model given in Eq. (2), Eq. (16) is more computationally straightforward and thus there is no need to exclude any of its terms in order to improve the computational efficiency.

3. Failure analysis and V-shaped curve method

3.1 Combining opening and bridging effects in analyzing ACF package failure

ACF flip chip packages may fail as a result of either opening or bridging. As a result, the overall failure probability is defined as

$$P_{opening \cup bridging} = P_{opening} + P_{bridging} - P_{opening \cap bridging}, \quad (17)$$

where $P_{opening \cup bridging}$ is the probability of opening or bridging; $P_{opening}$ is the probability of opening; $P_{bridging}$ is the probability of bridging; and $P_{opening \cap bridging}$ is the probability of both opening and bridging.

If opening and bridging are regarded as independent events, the overall failure probability, $P_{opening \cap bridging}$, can be expressed as follows:

$$P_{opening \cap bridging} = P_{opening} \cdot P_{bridging} \quad (18)$$

Substituting Eq. (18) into Eq. (17), the failure probability of the IC / substrate assembly can be formulated as

$$P_{failure} = P_{opening \cup bridging} = P_{opening} + P_{bridging} - P_{opening} \cdot P_{bridging} . \quad (19)$$

3.2 Failure probability under assumption that volume fraction remains constant following compression stage of packaging process ($v_o = v_b = v_f$)

Substituting Eq. (7) (i.e. the Poisson function for the opening probability) and Eq. (16) (i.e. the enhanced bridging model) into Eq. (19) yields the following:

$$P_{failure} = \sum_{n=0}^{5} \frac{\left(\frac{6l^{*2}v_f}{\pi}\right)^n e^{-\frac{6l^{*2}v_f}{\pi}}}{n!} + \left(1 - \prod_{\substack{i_1,i_2:1\to l^* \\ j_1,j_2:1\to h^*}} \left(1 - \left(\frac{6v_f}{\pi}\right)^{\sqrt{(i_1-i_2)^2+(j_1-j_2)^2+d^{*2}}}\right)\right) - \sum_{n=0}^{5} \frac{\left(\frac{6l^{*2}v_f}{\pi}\right)^n e^{-\frac{6l^{*2}v_f}{\pi}}}{n!} \cdot \left(1 - \prod_{\substack{i_1,i_2:1\to l^* \\ j_1,j_2:1\to h^*}} \left(1 - \left(\frac{6v_f}{\pi}\right)^{\sqrt{(i_1-i_2)^2+(j_1-j_2)^2+d^{*2}}}\right)\right). \quad (20)$$

When plotted as a function of the volume fraction (v_f), Eq. (20) has the form of a V-shaped curve (see Fig. 2). The tip of this curve indicates both the lowest failure probability of the IC / substrate assembly and the corresponding volume fraction. The minimum failure probability can be found by differentiating Eq. (20) with respect to the volume fraction, i.e.

$$\frac{\mathrm{d}\left[\mathrm{P}_{failure}(v_f)\right]}{dv_f} = 0 \qquad (21)$$

Equation (21) can be solved using numerical methods. The corresponding value of v_f gives the optimal volume fraction, i.e. the volume fraction which minimizes the overall failure probability.

4. Results and discussion

4.1 Comparison between box, modified box and present bridging models

As discussed in the Introduction section, the original box model presented by Mannan *et al*. [6] considers bridging only along the shortest linear path between neighboring pads and thus yields underestimated solutions for the bridging probability. Conversely, the modified box model presented by Lin *et al*. [7] uses a summation technique to calculate the probabilities of bridging along all of possible conductive paths, their results over-estimate the failure probability. The new approach in this paper is the enhanced box model considering all possible linear paths which connecting the grid nodes (i_1, j_1)/ (i_2, j_2) of the left/ right sides. An approximate formulation for closing to the real failure probability can be analytically expressed by an easy formula (see Eq. 16). The enhanced bridging model can especially simply the multifarious considerations and enhance the computational performances under the overall failure analysis. Although the estimation method of the enhanced bridging model is better than the box and modified box models, but the present model isn't still a faithful computational model. An accuracy calculation must consider all possible bridging paths (including curviform, ambagious, and direct paths), and it will be a great deal work impossibly.

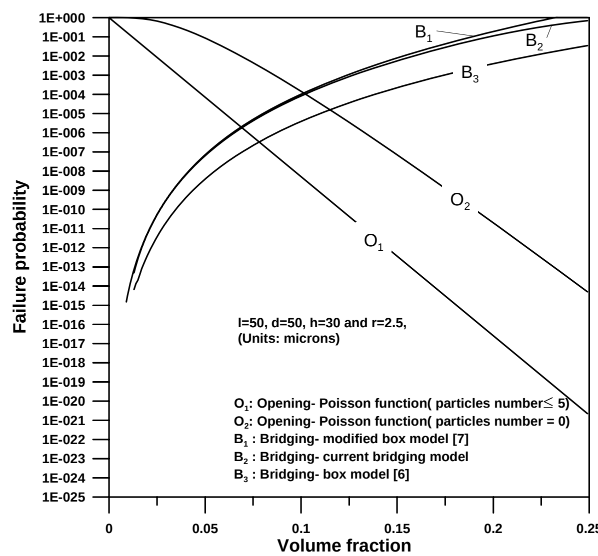

Fig. 5. V-shaped curves obtained using current bridging model, original box model [6] and modified box model [7].

As shown in Fig. 5, the bridging probability calculated using the current model is indeed greater than that predicted by the original box model, but smaller than that estimated by the modified box model. This finding suggests that in practical applications, when defining the V-shaped curve to identify the optimal volume fraction of the ACF compound, the enhanced bridging model presented in this study should be used to avoid over- or under-estimating the bridging failure probability.

4.2 Application of V-shaped curve method

In evaluating the overall failure probability of the ACF package, this study uses the Poisson function to estimate the opening failure probability and the enhanced bridging model to estimate the shorting failure probability. Previous studies have already confirmed the accuracy of the Poisson function in modeling the open circuit. Meanwhile, the enhanced bridging model proposed in this study calculates the bridging failure probability by considering all of the possible linear paths between adjacent pads. Consequently, the bridging estimates are more logical than those generated by the original box model [6] or the modified box model [7].

As discussed in the Introduction section, the V-shaped curve plots the failure probability as a function of the volume fraction of the conductive particles. The tip of the V-shaped curve indicates the lowest failure probability and the optimal volume fraction. Fig. 2 illustrate the effects of the IC / substrate geometry on the opening and bridging failure probabilities. As shown, for a constant volume fraction, the opening failure probability decreases with increasing l^*. Meanwhile, the bridging failure probability reduces with decreasing h^* or increasing d^*. In other words, the major factors governing the yield of the flip chip package are the dimensionless geometry parameters of the IC / substrate assembly, i.e. l^*, h^* and d^*, and the volume fraction, v_f, of the ACF compound.

4.3 Limitations of proposed bridging model

Although the enhanced bridging model presented in this study yields more logical bridging failure estimates than either the original bridging model or the modified model, it is not without its limitations. For example, the model only considers bridging between two adjacent pads, whereas in practice bridging may occur between any two contiguous pads within the entire IC / substrate assembly. In other words, the current model takes a local rather than global view of the bridging phenomenon [10]. It is worth to be addressed the failure probability of ACF packages is sensitive to the pads array dimension (nxn) and the geometry parameters *l*, *d*, *h*, *r*, etc. The overall global failure probability can be computed by using the Inclusion–Exclusion Principal with the numerical computation. The pads array dimension effects considering the different geometry parameters will be another important issue in the future. Furthermore, in reality, the particles in the ACF compound are dispersed in accordance with a stochastic distribution and the final positions of the particles will change following the compression process. However, the effects of this physical change on the opening and bridging probabilities are not reflected within the current model. Finally, the actual bridging phenomenon is more complex than that modeled in the current study. For example, the proposed model only considers the linear connections between adjacent pads, whereas in practice, bridging may actually occur along curvilinear or winding paths. In addition, many other factors will affect the yield of the ACF packaging like the excessive contact stress results in the rupture of the particles, the environmental effects of the temperature/moisture, the particles redistribution of the bonding processing, the pads number effect, the stochastic errors of the particles distribution [13], the asymmetric pad-height on the IC/ Substrate [14], the deformation effect under thermal cycling condition [15], etc.

5. Conclusions

This study has employed probability theory to develop an enhanced model for estimating the probability of bridging failures in ACF assemblies. Applying the Poisson function to predict the opening failure and the proposed model to estimate the bridging failure, V-shaped curves have been constructed to illustrate the correlation between the failure probability of the IC/ Substrate and the volume fraction of the conductive particles within the ACF compound. The V-shaped curve provides a straightforward means of estimating the package failure probability given a certain volume fraction and for determining the optimal volume fraction, i.e. the volume fraction which minimizes the risk of package failure. The computational results have shown that the proposed bridging model provides more logical estimates of the minimum failure probability and the corresponding optimal volume fraction than those generated using the original box model [6] or the modified box model [7].

The major contributions of the current study can be summarized as follows:

(I). An improvement in the accuracy of the estimated bridging probability as a result of explicitly recognizing the insulating characteristics of the ACF block between neighboring pads.

(II). The application of probability theory to estimate opening and bridging failures in developing a reliable model for predicting the overall failure probability of IC / substrate assemblies.

(III). An improvement in the computational efficiency of the bridging failure model relative to that of the modified box model presented in [7].

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References

[1] J. Lau, Low Cost Flip Chip Technologies, New York: McGraw-Hill, 1 (1996).

[2] J. Liu, Conductive Adhesives for Electrics Packaging, Electrochemical Publications Ltd, June 1999.
[3] H. Date et al., in Proc., Int. Symp. Microelectron., 570, 1994.
[4] A. Torri, M. Takizawa, K. Sasahara, in Proc. 9th Int. Microelectron. Conf., 324, 1996.
[5] D. J. Williams, D. C. Whalley, J. of Electronics Manufacturing **3**, 85 (1993).
[6] S. H. Mannan, D. J. Williams, D. C. Whalley, A. O. Ogunjimi, Chapter 4 in Conductive Adhesives for Electronics Packaging edited by Johan Liu, Electrochemical Publications Ltd, June 1999.
[7] C. M. Lin, M. H. Su, W. J. Chang, IEEE Transactions on Device and Materials Reliability **5**(2), 255 (2005).
[8] C. M. Lin, W. J. Chang, T. H. Fang, IEEE Transactions on Device and Materials Reliability **5**(4), 694 (2005).
[9] C. M. Lin, W. J. Chang, T. H. Fang, Microelectronics J. **37**, 565 (2006).
[10] C. M. Lin, Y. L. Chen, H. M. Chu, Materials Science and Engineering: **432**(1-2), 239 (2006).
[11] H. Ando, Y. Yamada, Y. Suga, Electronic Material, 72, 1995.
[12] Y. Yamada, Proceedings of Fine Process Technology, Japan ’95, Tokyo, Japan, R12, 1995.
[13] C. M. Lin, IEEE Transactions on Device and Materials Reliability **7**(3), 387 (2007).
[14] C. M. Lin, T. C. Lin, T. H. Fang, K. S. Chao, Microelectronics Reliability **48**(7), 1087 (2008).
[15] W. S. Kwon, S. J. Ham, K. W. Paik, Microelectronics Reliability **46**(7), 589 (2006).

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