UNDERSTANDING SILICON DIE FRACTURE STRENGTH USING WEIBULL ANALYSIS

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ABSTRACT

Investigation on the fracture strength of silicon die has gained more attention as more issues related to die crack are encountered in the assembly of IC flash memory products. Silicon die is a brittle material component of our flash memory packages that cracks or breaks when the principal stress experienced by the die reaches its fracture strength.

It is known that brittle solids have "unpredictable behaviour" under stress. Many components will fail at stresses much below and much above the average strength. The typical bend test samples for brittle materials have non-uniform stress distribution that affects test results. Knowledge of the standard deviation or the average strength is helpful, but does not explain the mechanism of the scatter nor gives it an estimate of failure probability at any given stress.

This study uses another approach called Weibull analysis to understand the fracture strength behaviour of silicon die and predict its failure probability when subjected to a given stress. Actual die fracture strength data were collected and analyzed by implementing the 3-parameter Weibull distribution. Mathcad numerical software was used to determine the threshold stress, below which no failure or die breaking will occur. This is one of the 3 parameters calculated from Weibull analysis which is very important in addition to failure probability prediction.

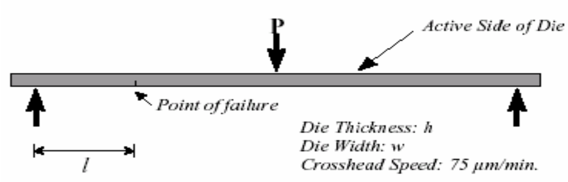
1. 0 INTRODUCTION

Knowledge of the average strength of brittle materials is of little value, since many components will fail at stresses much below and much above the average strength [3]. Brittle materials also break easily and their strength varies unpredictably from component to component even if a set of nominally identical specimens are tested under the same conditions. Therefore, the strength of a brittle material is not a well-defined quantity and has to be described with respect to fracture statistics. Furthermore, the assessment of reliability of brittle materials also requires a probability approach [2].

Since silicon die is a brittle material, its strength has to be described using fracture statistics. A well-known method on fracture statistics is Weibull analysis [2, 3]. So this study applies the Weibull analysis method on the die fracture strength for Assembly Test Vehicle (ATV) silicon daisy chain (SiDC) die and the bare silicon die (mirror die).

1.1 Die Fracture Strength

One important component of an electronic package is the die. While the elastic and thermal expansion behavior of the silicon is well known, the fracture behavior of the die is less so. The fracture strength is decreased by the presence of flaws or surface damage introduced during wafer fabrication and die production. In theory, if the distribution and nature of these flaws could be fully characterized, linear elastic fracture mechanics could be used to determine the stress at which a die would develop a catastrophic crack [4].
The fracture of silicon die will occur when the stress generated in the die exceeds the fracture strength of the silicon. The fracture strength is a function of the backside treatments to which the dice are exposed, and the inherent damage incurred during these treatments, such as back grinding [5].



$$\sigma_f = \frac{3Pl}{wh^2}$$

Figure 1. Illustration of a 3-Point Bend Test Method

One method used to measure die fracture strength is the 3-point bend test method as shown in Figure 1 [4]. But usually the point of failure will be in the middle so ***l*** will just be the half of the distance between the two supports.
Another method is the 4-point bend test method similar to the sample illustration in Figure 2 below.

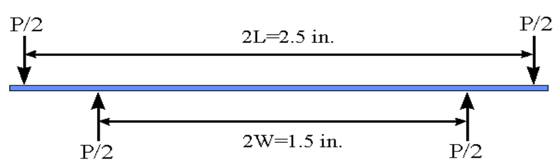


Figure 2. Four-point Bending Schematic

The maximum load P_F is the load at failure and is used to determine the fracture strength as

$$\sigma_F = \frac{3P_F(L-W)}{bh^2}$$

where b is the width of the specimen, h is the thickness, and L and W are defined in Figure 2 [5].

But in this study, the 3-point bend test method was used in obtaining the die fracture strength data that were analyzed using Weibull analysis since this has easy experimental set-up for small specimens like silicon die.

1.2 Weibull Analysis

Weibull analysis is the process of discovering the trends in product and system failure and using them to predict failures in similar situations [6]. It is commonly used for understanding the variations in strength of brittle materials [7].

The 3-parameter Weibull distribution [1] has the given cumulative probability distribution function:

$$F(x) = 1 - e^{-\left[\frac{(x-\gamma)}{\eta}\right]^{\beta}}$$

The density function is just the derivative of the cumulative distribution function as is given as follows:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{x-\gamma}{\eta}\right)^{\beta}} ;\beta>0,\eta>0,x>=\gamma>=0$$

The following are the meaning of the 3 parameters as applied to material strength:

β = shape parameter or Weibull modulus

η = scale parameter (normalized material strength)

γ = location parameter (threshold stress, below which no failure will occur)

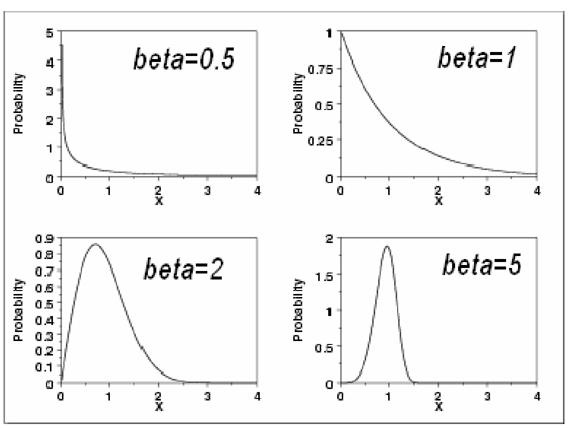


Figure 4. Shapes of Weibull Probability Density Function at Different Values of β [9]

2.0 EXPERIMENTAL SECTION

2.1 Die Fracture Strength Measurement

The method used in obtaining the silicon die fracture strength was the 3-point bend test method using the INSTRON 4342 tester as shown in Figure 5 below and 3-point bend test jig was also part of the set-up. Data gathering was conducted by Intel.

Figure 5. Instron 4342 Tester

Basically, the silicon die was placed on a 3-point bend test jig and then a load was applied until the die broke. The load at the time when the die broke or what we usually call as the die breaking load was recorded. Then the fracture strength was calculated using the 3-point bend test stress formula:

$$\sigma f = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2}$$

where,

σf = die fracture strength

P = die breaking load

L = distance between support

b = die width (parallel to the support axes)

h = die thickness

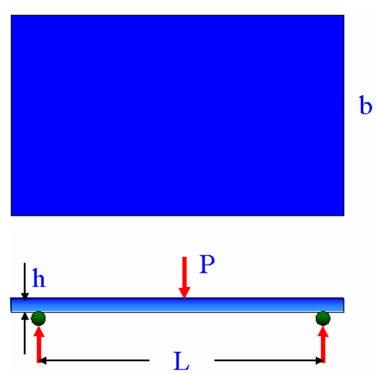


Figure 6. Schematic of the 3-point Bend Test

Fracture strength data were calculated for the 32 samples on SiDC die and 32 samples also for the Mirror die.

2.2 Analysis Methodology

Mathcad numerical software was used for the 3-parameter Weibull analysis. Initially, JMP statistical software was used but then there were some convergence problems during the parameter calculation. The JMP software was just fine for 2-parameter Weibull distribution.

Before using Mathcad, the calculated fracture strength data were placed in an excel format and ranked in ascending order. The cumulative probability $F(x_i)$ is estimated using the Mean Rank Method. For this method, $F(x_i) = \frac{i}{n+1}$ where i = the rank, n = the number of data points.

On Mathcad, die fracture strength data in excel format were imported to form a Mathcad array of the fracture strength data and the corresponding cumulative probability. These data points were then plotted into a graph and fit the data to the best-fit 3-parameter Weibull curve. The fracture strength (in MPa) was in the x-axis and the cumulative probability in the y-axis. The best-fit curve was determined by minimizing the mean squared error (MSE). The algorithm for the curve-fitting was formulated in Mathcad using some predefined or built-in functions.
The following Mathcad mathematical expressions illustrate how the 3 parameters in the Weibull distribution were obtained using Mathcad in this study:

$$F(FrS,\gamma,\eta,\beta) := 1 - \exp\left[-\left[\frac{(FrS-\gamma)}{\eta}\right]^{\beta}\right]$$

$$SSE(\gamma,\eta,\beta) := \sum_{i}\left(Pr_i - F\left(FrS_i,\gamma,\eta,\beta\right)\right)^2$$

The first expression defines the Weibull cumulative probability distribution function in Mathcad format. Then the second expression is for the mean squared error to be minimized for obtaining the values of the 3 parameters that will give the best-fit curve to the actual data.

3.0 RESULTS AND DISCUSSION

3.1 Silicon Die Fracture Strength

Silicon die fracture strength was arranged in ascending order as shown in Table 1 with the corresponding failure probability estimate using the Mean Rank Method for the 32 samples.

Table 1. Estimate of $F(x_i)$ using Mean Rank Method

SiDC		
i	Fracture Strength (MPa)	Failure Probability $F(x_i)$
1	275.2676596	0.03030303
2	292.7688286	0.060606061
3	296.5710211	0.090909091
4	304.1728411	0.121212121
5	328.2037479	0.151515152
6	366.6291067	0.181818182
.	.	.
.	.	.
30	801.0994708	0.909090909
31	821.273597	0.939393939
32	900.9715281	0.96969697

As you can see for the SiDC die, the fracture strength varies greatly from about 275 MPa to about 900 MPa. About the same trend of variation also happens on the Mirror die fracture data used in the study. This just proves that silicon die can fail at stresses much below or much above the average strength and hence, must be described with fracture statistics [3].

3.2 Weibull Analysis Results using Mathcad

Figure 7 shows the Weibull analysis results in Mathcad for SiDC die.

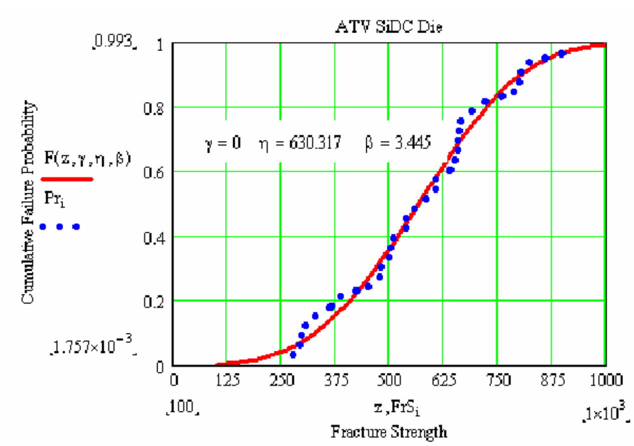


Figure 7. SiDC Fracture Strength vs Cumulative Failure Probability

The Weibull curve (in red color) was fitted to the actual fracture strength data. The parameter values obtained for SiDC are the following:
γ = 0.0 MPa
η = 630.317 MPa
β = 3.445

With this, one can predict the probability of fracture for SiDC die. For instance, if the dice in this case are placed in a situation where the maximum principal stress reaches 200 MPa, then about 1.9% of the dice can be expected to fracture. At 400 MPa, the probability of fracture is about 18.8%. These values are calculated using the fitted Weibull cumulative probability function with the specific values of the 3 parameters and substituting the given stress at which you want to know probability of fracture.

Similarly, for the Mirror die as shown in Figure 8 below,
γ = 362.817 MPa
η = 140.526 MPa
β = 1.088

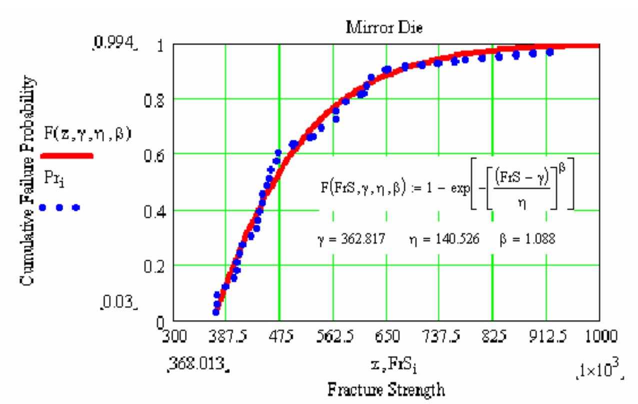


Figure 8. Mirror Die Fracture Strength vs Cumulative Failure Probability

So with the Mirror die, the threshold stress is 362.817 MPa. That means at 200 MPa, the probability of die fracture is 0% or any stress level below 362.817 MPa threshold stress, no fracture will occur. But at a stress level of 400 MPa, the probability of die fracture is 21% which is a little bit higher than that of SiDC at the same stress level.

Table 2 shows the summary of the comparison between the die stress level and the probability of failure for the Mirror die and the SiDC die. Figure 9 illustrates the comparison in graphical format.

From the results, it could be observed that the Mirror die (bare silicon die) is not prone to die crack at stresses below its threshold stress of about ~360 MPa. But for the SiDC die (silicon die with daisy chain trace routings), there's a probability that about 4% of the die samples would break or crack even at a lower stress of about 250 MPa. This might be due to additional surface flaws introduced during back-grinding and the processes in creating the daisy chain trace routings on the SiDC die as compared to just the bare die with smooth mirror finish (very minimal surface flaws). This could confirm previous studies that surface flaws have the effect of lowering the fracture strength.

Table 2. Probability of Failure for the SiDC and Mirror Die Based on the Fitted Weibull Cumulative Distribution Function

Principal Stress (MPa) (Die Stress Level)	Probability of Fracture (%)	
	SiDC	Mirror Die
200	1.9	0
250	4	0
300	7.5	0
350	12.3	0
400	18.8	21
450	26.9	44.8
500	36.3	62.2
550	46.5	74.5
600	57	82.9
650	67.1	88.7
700	76.2	92.5
750	83.8	95.1
800	89.7	96.8
850	93.9	97.9
900	96.7	98.6
950	98.4	99.1

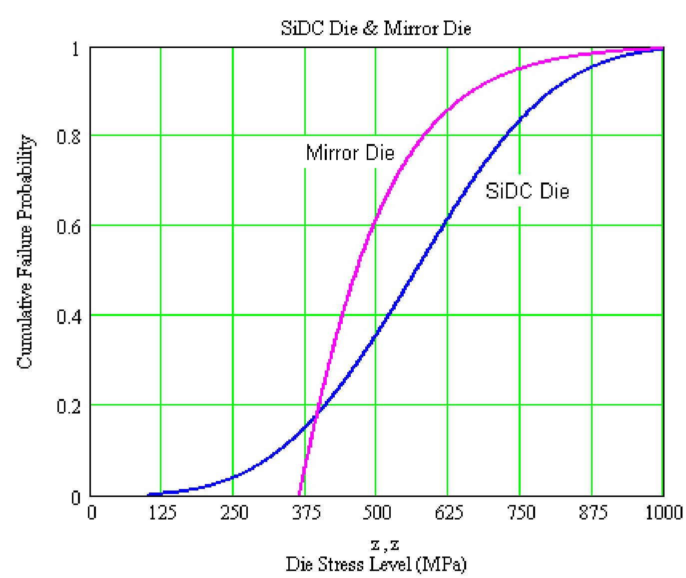


Figure 9. Die Stress Level vs Cumulative Probability of Failure

4.0 CONCLUSION

This study has successfully used Weibull analysis in understanding the silicon die fracture strength. The probability of failure at a given die principal stress can be predicted using the 3-parameter cumulative Weibull probability function. The data gathered also provides baseline on the magnitude of stress that can be sustained by the silicon die in an IC package without resulting to a die crack issue.

The mirror die showed a higher threshold stress than SiDC die. This threshold stress is the stress below which no failure or die crack will occur. But at other stress levels above the threshold stress, the probability of die crack for SiDC die can be lower based on the Weibull analysis results.

5.0 RECOMMENDATIONS

For brittle materials such as silicon die, it is recommended to use Weibull analysis to fully understand the variations in strength which could not be adequately described by just having knowledge of the average strength. And to avoid die crack, the silicon die must not be subjected to stresses higher than its threshold stress.

6.0 ACKNOWLEDGMENT

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