Weibull Statistics of Silicon Die Fracture

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Abstract
In order to guarantee reliability of semiconductor devices for automotive applications an optimized package design is required. Clearly the design must be based on the best choice of geometry, materials and manufacturing processes. It is well known that the various process steps involved during package manufacturing occur at relatively high temperatures. Consequently, due to the mismatch of thermal expansion coefficients of the package materials, high thermal stresses arise at operating temperatures and may lead to failure of the device. Typical device failure modes include delamination of material interfaces or bulk material fracture. In this paper we focus on the prediction of silicon fracture in the microchips of electronic devices. Due to their brittle nature the strength data of silicon dies will scatter and a probabilistic approach to failure is required. For this purpose Weibull theory will be used and combined with analytical as well as numerical tools in order to describe the state of stress in the package and in particular within the silicon die. As a result of the analysis the probability of fracture in a microchip can now be assessed and used for further quality assurance purposes.

The paper will start with a brief introduction to Weibull theory and present the 3-Point-Bending (3PB) experiments that were used to obtain the Weibull parameters for characterization of a combination of surface and edge flaw induced silicon die fracture. Moreover, the ball-on-edge and ball-on-ring tests will be described and used to separately characterize edge or surface flaws, respectively. Particular emphasis will also be given to the transferability of Weibull probability results from one specimen configuration to another resulting in a change of surface size and stress. In this context it will be described how a stress distribution and, in particular, a multiaxial state of stress influences the variability in strength. Moreover it will be shown how the corresponding Weibull integrals can be implemented numerically and used for postprocessing of finite element results. The paper concludes by demonstrating how these procedures can be used for optimizing the design of a real silicon die package.

1. Flaw Population Selective Fracture Tests
Depending on the preparation and processing of the silicon die different flaw populations will be induced which essentially lead to different failure modes during use, in particular when the die is embedded in a molded package and, therefore, subjected to a multiaxial state of stress acting on the edges as well as on the surfaces. We may say that surface defects are essentially induced during wafer processing, such as etching and grinding. On the other hand, edge defects will originate from cutting processes. Figure 1 shows the chipping of a silicon wafer caused by the singulation procedure. During a bending test the different flaw distributions on the chip result in cracks that statistically emanate from either the surface or the edge (cf., Figure 2).

Consequently, the question arises as to whether and how the different flaw populations can be distinguished and quantitatively assessed. Due to the statistical nature of brittle fracture, which is also pertinent to silicon, Weibull statistics will preferably be used, which, however, must first be put in context with experimental setups characteristic of the various flaw populations in question. In particular we shall use the so-called Ball-On-Edge (BOE) test to quantify edge flaws populations, whereas the Ball-On-Ring (BOR) (cf., [1]) test will serve as a tool for surface flaw analysis. It should be noted that the traditionally used 3 and 4 Point-Bending (3PB/4PB) tests always lead to a combination of surface and edge induced failure. This becomes evident if one realizes that both tests show a maximum tensile stress of equal magnitude along the edges as well as on the surface of the tested specimen. In what follows we shall briefly summarize some essentials on Weibull statistics, comment on results from 3PB tests, and will then discuss in detail the experimental setup and strength data stemming from BOE-tests.

2. Elements of Weibull Theory
During fracture of a batch of specimens made of brittle materials some will fail at very low loads, others are capable of withstanding very high loads, but most of them show some intermediate strength. Clearly, the strength of a high quality material should not show high variability in strength.
Consequently, such products are characterized by a narrow strength distribution, whereas a broad distribution indicates a less advanced material, or even a processing fault. By cumulative summation of the probability data, $P_i$, the cumulative distribution of strength in Figure 3 can be constructed. If the ordinate is normalized with respect to the total number of specimens in the batch, $N$, the resulting plot presents a measure for the probability of failure, $P_i$, where $i$ refers to the specimen of strength $\sigma_i$:

$$P_i = \frac{i - 0.3}{N + 0.4}, y_i = \ln \ln \frac{1}{1 - P_i}, x_i = \ln \sigma_i.$$  

(1)

Experience shows that for brittle materials $P_i(\sigma_i)$ can be fitted reasonably well using a two-parameter Weibull distribution:

$$P(\sigma) = 1 - \exp \left( - \left( \frac{\sigma}{\sigma_0} \right)^m \right)$$  

(2)

High variability of strength within a particular batch of specimens is characterized by a small Weibull modulus or $m$-value. $\sigma_0$ is known as the scale parameter.

Based on three principles, viz., (i) statistical homogeneity and isotropy of the material, (ii) statistical independence of subvolumina and subsurfaces, and (iii) the weakest link concept the probability of failure for a body subjected to a spatially varying, but uniaxial, state of stress can, according to Weibull [3], be written for surface dominated flaws:

$$P = 1 - \exp \left( - \frac{1}{A_{ef}} \int \int \left[ \frac{\sigma(x,y)}{\sigma_{max}} \right]^m dx dy \right),$$  

(3)

$$A_{ef} = \int \int \left[ \frac{\sigma(x,y)}{\sigma_{max}} \right]^m dx dy.$$  

(4)

$A_{ef}$ and $A$ denote the effective and total surface of the specimen. $\sigma(x,y)$ and $\sigma_{max}$ are the arbitrary, uniaxial tensile (positive) stress distribution and the maximum stress at the specimen surface, respectively. It is assumed that only tensile stresses influence the probability of failure. Some information on how the surface integration is performed can be found in [2].

3. Selected Results on 3-PB-Tests

3PB tests were performed at the Technische Universität in Berlin using a Tytron 250 provided by MTS. The 3PB-test setup is shown in Figure 4. The specimens were loaded until fracture occurred and the loads at fracture were recorded. A typical fracture pattern is shown in Figure 5.

Figure 3: Distribution of strength for brittle matter

In practice these two parameters are determined from experiments using a particular specimen and loading type. The resulting strength data are either processed using the method of least squares or the maximum likelihood procedure (see [2] for details): Figure 3.

As mentioned above the mean strength of a specimen made of brittle materials depends on its volume, its surface, its loading conditions and the flaw distribution. Intuitively speaking the more volume or surface exists the higher the chances for a critical flaw to be present will be. For example, a 4PB specimen will break more easily than a 3PB one, because in the case of the latter high tensile stresses are restricted to a much smaller region.

Typically strength measurements are presented in a Weibull plot, where the ordinate and abcissa are divided according to $\ln(\ln(1/(1-P)))$ and $\ln(\sigma)$, respectively. The resulting curve usually matches a straight line that is defined by the Weibull distribution with modulus $m$ and scale parameter $\sigma_0$. Figure 6 shows the Weibull plot for 3PB-tests with the Weibull distribution, where the parameter were determined using the maximum likelihood method.
4. The Ball-on-Edge Test

**Experimental Setup:** The realization of the edge test is shown in Figure 7. The test rig consists of two metal blocks into which spheres have been inserted. The left block (cf., Figure 7) contains three spheres whereas the right block holds only one sphere onto which the force is acting (in horizontal direction). A schematic of the arrangement is shown in Figure 8.

The position of the spheres within the blocks defines the stress distribution in the specimen. The tensile stress concentration on the lower specimen surface directly underneath the single ball triggers brittle failure at this position. The closer the single sphere is moved toward the specimen edge the more the edge will be subjected to tension and the more the edge flaw population will be assessed.

**Experimental Results:** BOE-tests were performed at the Technische Universität in Berlin according to the described experimental setup. The specimens were singulated from wafer by standard sawing procedure at Freescale GmbH. Each specimen consists of an array of 3x3 silicon chips (cf., Figure 9). A batch size of 20 samples was subjected to the testing procedure. The resulting probability of failure vs. the failure load is presented in Figure 10. The graph does significantly deviate from the typical S-shape of a Weibull distribution (cf., Figure 3). It indicates that two active flaw distributions exist. Consequently, fractographic examination is required in order to characterize the fracture origin in each specimen.

![Figure 8: Schematic of BOE rig](image)

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![Figure 9: Silicon specimen – array of 3x3 chips](image)

![Figure 10: Probability of failure vs. the failure load](image)
Indeed, the first three data points below a force of 15 N correlate with a crack initiation at the edge of the specimen, whereas the other data points above 15 N correlate with a crack initiation from the bottom surface underneath the ball (cf., Figure 10). The corresponding fragments are shown in Figure 11 and Figure 12. Thus we detect two distinct flaw distributions for edge and surface failure, respectively.

Figure 11: Specimen fragments indicating edge failure mode

Figure 12: Specimen fragments indicating surface failure mode

**Stress-Analysis and Weibull Parameters:** The resulting stress distribution at the failure load was calculated by means of finite element analysis. Figure 13 shows the meshes of the specimen and the test rig. Note that the deformations shown in the pictures were scaled and in fact remained very small. The balls were represented with elastic half spheres and discretized with tetrahedral elements. The elastic specimen was discretized with hexahedral elements. The failure load was applied to the upper ball, whereas the supporting balls were completely fixed. A contact problem was defined between the balls and specimen. All materials were treated elastically and geometric nonlinear effects were considered. The analysis of the stress state at different load level revealed a linear relationship between load and stress values (cf., Figure 14). Factors of proportionality where extracted from the finite element analysis for easy calculation of maximum stresses on specimen surface and edge at arbitrary loads:

\[
\sigma_{\text{max}} = k F, \quad k = \begin{cases} 12.2 \text{ mm}^{-2} & \text{specimen edge} \\ 17.5 \text{ mm}^{-2} & \text{specimen surface} \end{cases}
\]  

Figure 13: Deformed FE mesh of BOE rig and specimen

Figure 14: Maximum tensile stresses vs. applied force
The resulting tensile stress distribution in the specimen is illustrated in Figure 15. The applied failure load at the upper ball causes a stress concentration on the bottom surface underneath the ball (red color). Due to the proximity of the single sphere to the specimen edge, high stress regions appear at the edge of the specimen as well (yellow color). Maximum tensile stresses were taken from underneath the ball in order to determine the silicon strength for the surface flaw distribution, whereas maximum stresses were taken from the edge in order to determine the silicon strength for the edge flaw distribution.

The statistical evaluation of the strength values were performed separately for each failure mode. The sampled strength data were split into two sets according to the fractographic classification (cf., Figure 11 and Figure 12). Each set were treated as an independent discrete strength distribution. The corresponding Weibull parameters were determined by means of the maximum likelihood method. Figure 16 shows the Weibull plot with the overall specimen failure probability for the BOE-test and the Weibull parameters for both flaw distributions.

Figure 15: Tensile stress distribution in specimen

Figure 16: Weibull plot of the BOE-test

4. Conclusions

A ball-on-edge (BOE) test procedure was developed with the intention of a local strength measurement in regions of the silicon chip surface and the silicon chip edge.

The test rig was designed such, that the fracture origin was triggered at a point close to the die edge in order to capture flaw distributions in this region.

The evaluation of the strength data revealed two independent active flaw distributions, one on the chip surface and another one on the chip edge. Weibull parameters were determined for both distributions.

Further work is required in order to confirm the results and to achieve a sufficient statistical confidence.

Comparative tests with three-point-bending and ball-on-ring setup are planned in order to validate the procedure of failure probability prediction for arbitrary specimen geometries.

The Weibull parameter will be used for the prediction of failure probability for a silicon chip situated in a molded package.

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References