Failure Strength Weibull Analysis of 4H-SiC Die through a 3-PB test

Authors

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Abstract

The paper reports the mechanical properties of 4H-SiC die with different thicknesses, that have been determined through a 3-point bending (3-PB) test. In particular, it reports 1) the measurement of the failure strength of thin 4H-SiC rectangular die; 2) the Weibull analysis of the failure strength of 4H-SiC die, exploited to determine the maximal load that can be applied to the die, without any breakage; 3) the measure of 244±15 GPa for the flexural Young modulus *E* of SiC die, gained from the 3-PB test elaborations.

Keywords: Silicon Carbide, 3-Point Bending test, Weibull Analysis, Young Modulus

Introduction

The presence of imperfections, damages and defects [1] [2] [3] in substrates, such as in silicon carbide can elicit cracks, in packaged die, compromising the reliability required to set a mission profile in SiC based power devices and modules [4] [5]. Indeed, during their operation lifetime packaged die, intended e.g. for automotive and industrial applications, undergo remarkable thermal cycles, which unleash mechanical stresses. The accidental presence or generation of cracks [6] [7] can compromise the operating life of a device missing the strict qualification standards for the packages that must be complied within the automotive industry (e.g. AEC-Q 101). In this respect an upstream investigation of the mechanical properties which can determine the mechanical failure in 4H-SiC die can be of use within the power devices and modules semiconductor industry.

In this work, a three-point bending (3-PB) test has been exploited to investigate the failure strength of 4H-SiC die. Indeed, due to its large diameter and low thickness, the determination of the fracture strength of SiC at wafer level would be impracticable. Thus, it is more appropriate to determine the SiC strength at die level, thereby providing a better understanding of the stress accumulated in the die before failure.

The failure strength or flexural stress (FS) of a material is the maximum stress occurring at breakage [8] [9] [10]. The stress σ varies linearly with respect to the distance z from the neutral axis of the beam according to the equation $\sigma = \frac{M}{I} z$, where M is the bending moment and I is the second moment of area. This determines a tensile stress or a compressive stress accordingly to the sign of z . By indicating with t the thickness of the sample, the maximum stress in a 3PB test fixture occurs at $|z| = t/2$ and at the center of the beam, where the moment M reaches a maximum, which equals $FL/4$, being F the maximum load, and L the distance between the two supports (Fig.1). By considering that the second moment of area I (usually referred as the moment of inertia) of a beam having a rectangular cross section with thickness t and width W is $I = \frac{Wt^3}{12}$, the resulting flexural stress is:

$$\sigma_{FS} = \frac{M}{I} z = \frac{FL/4}{\frac{Wt^3}{12}} \frac{t}{2} = \frac{3}{2} \frac{FL}{Wt^2}. \quad (1)$$

It is of worth to compare the flexural stress with the stress on the substrate induced by a thin metal film. A first difference is that the deflection of the beam has a cubic dependence, which implies that the curvature, in the small deflection approximation, increases linearly by moving towards the center of the beam. Instead the curvature, in the Stoney approximation [11], [12] [13] is constant and the deflection has a quadratic dependence. In the case of a 3PB beam the deflection is maximal at the center of the beam and a maximum extension or deflection δ at the maximum load F is measured by the equipment. It is easy to prove that for the deflection δ the following equation holds $\delta = \frac{1}{4} \frac{FL^3}{EWt^3}$, where E is the Young Modulus of the bulk substrate. From the measurement of the maximum load and extension δ, the Young modulus can be easily recovered as $E = \frac{1}{4} \frac{FL^3}{\delta W t^3}$, and with easy passages the dependence of the Young Modulus E can be gained from the ratio between the flexural stress σ_{FS} and the deflection δ:

$$E = \frac{\sigma_{FS} L^2}{6t\delta}. \quad (2)$$

Finally, it is worth to observe that the stresses as determined by the flexural strength and thin metal films can be related to the ratio of the respective curvatures of the substrate,

$$\frac{\sigma_{3PB}}{\sigma_{Sub,Stoney}} = \frac{E \frac{t}{2} \frac{1}{\rho_{3PB}}}{\frac{Et}{6(1-\nu)} \frac{1}{\varrho_{Stoney}}} = \frac{3}{1-\upsilon} \frac{\frac{1}{\rho_{3PB}}}{\frac{1}{\varrho_{Stoney}}}. \quad (3)$$

Since the two curvatures differ at least by two orders of magnitude, it results that the flexural stress is way higher than the stress on the substrate determined by a thin film metal ($\sigma_{FS} \gg \sigma_{Sub,Stoney}$) [14].

Materials and Methods

A three-point bending (3-PB) technique has been exploited to determine the flexural strength of a set of silicon carbide (SiC) die. The 3-PB test consists in increasing at a constant rate a load applied at half a distance (*L/2*), with the respect to two supports. A wedge leans against the sample, fixed in a test fixture, to measure the flexural extension at the center line of the sample. This quantity is reported as a function of the load up to the brakeage of the sample. Hence the maximum load at maximum extension is recorded and the flexural or failure strength is determined according to geometric factors gained from the beam-line theory. In figure 1, a schematic of the test fixture, with the main characteristic quantities involved, has been reported. In this work, an Instron 5566 equipment, with a machine accuracy of 0.5%, was used. The operating range for the load spans from 2N to 10kN, the speed goes from 0.005 to 500 mm/min, the temperature can be regulated from -70 to 350°C. In the present report a speed of 0.5 mm/min has been used.

Going into details, plain die samples, 11mm x 4mm in size, distinguished in two types according to their thickness, which was 350 µm and 362 µm, respectively and in a number of 25 per type, along with 24 samples of SiC die, 5.38mm x 4.46mm in size and 180 µm thick, underwent the 3-PB test.

Collected data have been analyzed to gain conventional statistical indicators (e.g. average, standard deviation, quartiles), with the aim to determine the dispersion of the data and allow a comparison among the SiC die types. These preliminary investigations have been complemented with a Weibull analysis of the flexural strength, which has been carried out to determine the characteristics of SiC die in terms of fracture reliability. The achieved statistical assessments have been discussed to determine the maximum load which the SiC die can withstand, an accurate and consistent evaluation of the Young modulus of SiC, an evaluation of the flexural strength.

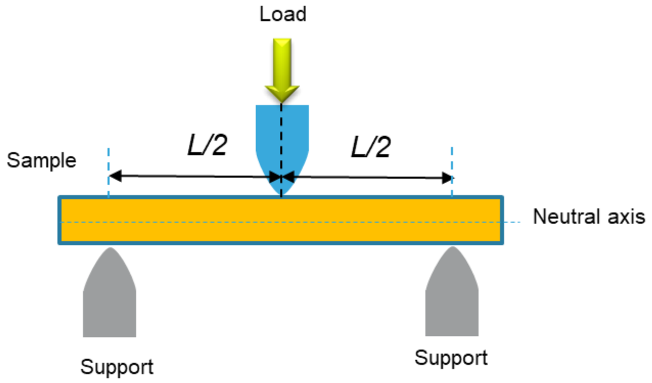

Fig.1. Schematic of a 3PB test fixture. The support span length L amounts to 5 mm ± 0.03mm, for the die of 350 µm and 362 µm, and 3 mm ± 0.03 mm for the case of 180 µm.

Results and *Discussion*

The data on the flexural stress measured obtained from the set of samples have been sorted from the lowest to the highest and reported in table 1. Each value has been labeled with an integer rank i ranging from 1 to the maximum number of analyzed samples N =24/25 per type. Median ranks have been evaluated according to the Benard's approximation $P_i = \frac{i-0.3}{N+0.4}$ and associated to their respective flexural stress σ_{i} . For a given measured flexural stress σ_{i}, data have been best fitted according to a 2-parameters Weibull distribution

$$P(\sigma_i) = 1 - e^{-\left(\frac{\sigma_i}{\sigma_0}\right)^m} \; (4),$$

where m is the Weibull modulus and σ_0 is the scale parameter.

Indeed, two methods have been considered.

By exploiting the linearization

$$ln\left(ln\left(\frac{1}{1-P_i}\right)\right) = m(ln\sigma_i - ln\sigma_0) \; (5)$$

the parameters of the Weibull distribution have been determined from a linear best-fit and reported in table 2.

Moreover, a Maximum Likelihood Estimate, which also allows an evaluation of the confidence interval of the parameters according to the Fisher information matrix method [15], has been considered. The 90% confidence bounds have been hence determined by following [16].

Rank i	Flexural stress (MPa) 350 µm	Flexural stress (MPa) 362 µm	Flexural stress (MPa) 180 µm
1	607.733	520.819	525.643
2	647.088	670.153	618.614
3	675.114	682.474	655.758
4	726.1	692.681	713.306
5	745.688	697.303	716.426
6	767.981	701.441	722.579
7	798.562	717	793.982
8	954.099	775.136	828.342
9	965.335	804.631	840.424
10	969.612	852.593	861.456
11	1002.41	857.38	869.505
12	1038.823	867.684	871.723
13	1070.85	881.995	883.793
14	1133.106	917.081	912.623
15	1137.707	950.873	925.702
16	1249.15	961.166	931.2
17	1255.179	1027.17	1003.359
18	1275.529	1050.487	1006.81
19	1301.926	1056.539	1085.667
20	1450.267	1128.627	1135.592
21	1529.44	1160.323	1145.566
22	1531.624	1231.921	1295.084
23	1540.317	1232.865	1330.063
24	1666.078	1321.055	1365.901
25	1786.832	1603.834	

Table 1. Data on the flexural stress measured, from left to right on the samples 350 µm, 362 µm, 180 µm.

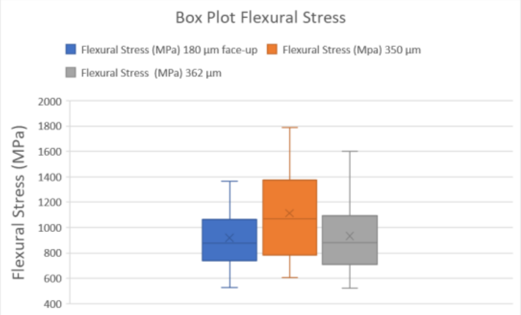

Fig.2. Box Plot of the flexural stress of the three cases examined.

In figure 2 the box plot with the minimum and maximum values, the first and third quartiles, the medians, and the averages of the flexural stress for the three examined cases have been reported. All the three set of samples show very similar distribution of the flexural stress, confirming that the data on the flexural stress are consistent. In table 2, the main statistical indicators have been reported, along with the parameters of the Weibull analysis within an interval confidence of 90%.

Sample type	σ_0 (MPa)	m	$\langle\sigma\rangle$ (MPa)	Standard deviation (MPa)	Min (MPa)	Max (MPa)
350 µm	1234±76	3.7±0.7	1113	332	608	1787
362 µm	1025±56	4.4±0.7	934.5	243.7	521	1604
180 µm	994±57	3.9±0.7	918.3	216	526	1366

Table 2. Values of the σ_0 and m parameters and of their respective errors (C.I. 90%), average of the flexural stress, standard deviation, minimum and maximum values.

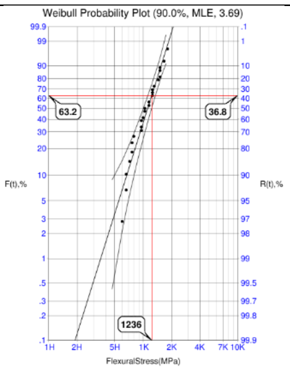

Fig. 3a) Weibull plot of the flexural strength for the 350 µm thin plain samples.

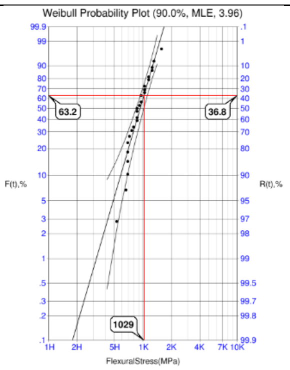

Fig.3b) Weibull plot of the flexural strength for the 362 µm thin plain samples.

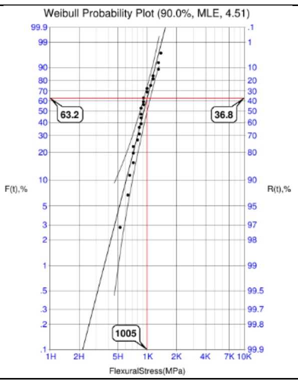

Fig. 3c) Weibull plot of the flexural strength for the 180 µm thin samples.

Weibull Plots of the three examined three cases have been realized by exploiting the online resources for the plotting [17] and reported in figure 3 going from a to c. By inspecting the Weibull charts, it results that all the three SiC samples show a reliability range which is comparable and consistent among them. A flexural stress below 500 MPa determines a reliability which is above the 97% for all three die. This value corresponds to a maximum load, which is $F_{Max} = \sigma_{FS}\frac{2}{3}\frac{Wt^2}{L}$, that if applied at the center of the sample will not determine any breakage and corresponds to $F_{Max} = 14.8\ N$ for the case of the 350 µm, to $F_{Max} = 15.9\ N$ for the case of 362 µm and $F_{Max} = 8.9\ N$ for the 180 µm sample, respectively. This means that, to avoid any damage to the chips, the forces applied to the resulting packaged die cannot be higher than these values.

The flexural extension or deflection δ has also been measured along with the corresponding flexural stress. To investigate the relationship between the two quantities, plots of the flexural stress as a function of the deflection δ have been reported in Fig.4a, 4b and 4c for the samples at 350 µm, 362 µm and 180µm, respectively. By performing a regression analysis, the two quantities show an optimal linear correlation, inferred from their respective R^2 values.
According to the elastic beam approximation there is a relationship between the flexural stress σ_{FS} and the deflection δ. Indeed, being the Young modulus E determined by

$$E = \frac{\sigma_{FS}L^2}{6t(\delta-\delta_0)} \quad (6),$$

it holds that there must be a linear relationship between the flexural stress σ_{FS} and the deflection δ

$$\sigma_{FS} = E\frac{6t}{L^2}\delta - E\frac{6t}{L^2}\delta_0 \quad (7)$$

From the best fit performed for the three cases, it is possible to determine a slope and an intercept. Since, the thickness of the samples and the span length of the test fixture are known it possible to determine the values of the Young Modulus E for the SiC substrates as well as the average reference value δ_0 for the deflection. The values of these quantities have been reported within an interval confidence of 95% and amounts to 251±20 GPa for the 350 µm, 212±34 GPa for the 362 µm and 251±32 GPa for the 180 µm, respectively. The set of three measures are consistent. In fact, the data for the 180 µm and 350 µm cases overlap perfectly, whereas for the 362 µm case, the interval determined by the upper limit overlaps with the lower limits of the intervals determined by the measures for the 180 and 350 µm cases. A weighted mean of the Young modulus for the SiC provides the value of 244±15 GPa.

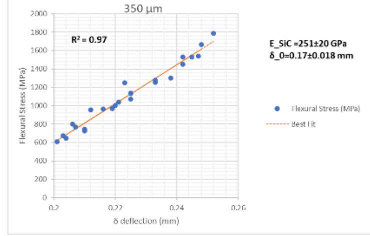	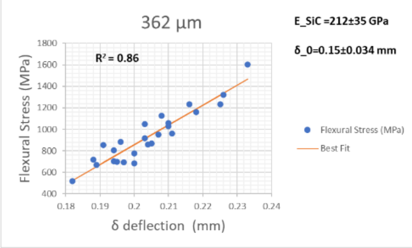	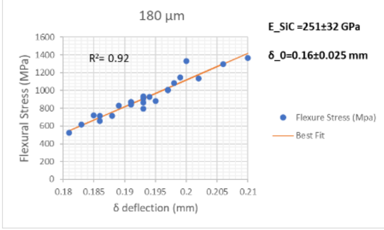
Fig.4a. Flexural Stress as a function of the δ deflection for the 350 µm case. The line is the best fit of the data. The value for the Young Elastic Module obtained from the linear regression equals 251± 20 GPa.	Fig.4b. Flexural Stress as a function of the δ deflection for the 362 µm case. The line is the best fit of the data. The value for the Young Elastic Module obtained from the linear regression equals 212± 35 GPa.	Fig.4b. Flexural Stress as a function of the δ deflection for the 180 µm case. The line is the best fit of the data. The value for the Young Elastic Module obtained from the linear regression equals 251± 32 GPa.

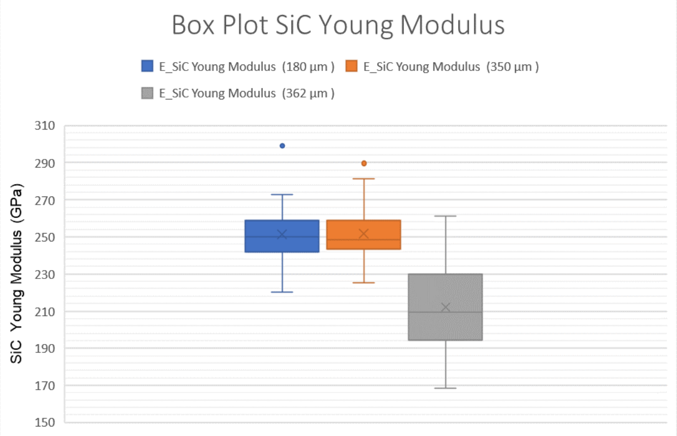

Fig.5. Box Plot of the Young Modulus for the three cases examined. The 180 µm and 350 µm cases coincide, the 362 µm case overlaps with the previous cases. These distributions are consistent with the value of the weighted mean of the Young modulus for the SiC die of 244±15 GPa.

Finally, with the value of δ_0 for the deflection available for each case, the whole set of data have been analyzed point by point according to eq.6 and a box plot which compares the three cases have been reported in Fig. 5. Also in this case, the 180 and 350 µm cases overlap perfectly, whereas the 362 µm interval overlaps with the two previous cases. All the three distributions are consistent with the value of 244±15 GPa for the Young Modulus of the SiC die. However, the determined value differs from the ideal values reported in the literature [18] of 410 GPa or over 500 GPa [19] [20]. It should be considered that the determined Young module is an effective quantity. Indeed, it has been reported in the literature that the presence of defects can lower the value of the Young Modulus of SiC [21] [22]. Moreover, it is likely that the dicing of the SiC die can introduce further defects that can elicit the break earlier with respect to an ideal case. As a result, the measured Young modulus is lower with respect to the ideal case [23].

Conclusions

By nature, being SiC a brittle material, even moderate stresses could result in detrimental failures such as cracking and fractures in the die. In addition, wafer processing steps such as thinning and sawing could further induce defects in the die. Moreover, several factors influence the die strength such as the surface conditions of the die which include grinding-mark direction and surface roughness, the edge crack of the die, called chipping created during the wafer-sawing process, the intrinsic defects of the crystals, such as plane dislocations of the crystal lattice of SiC, and occasionally, the test methods with different loading types. In this paper some of these aspects have been investigated by means of the 3-PB test. In particular, the flexural stress of SiC die has been measured and a Weibull analysis has been reported to gain a maximum load that can ensure a reliability of 97% for each of the three SiC die examined. Moreover, a measure of the effective Young modulus for 4H-SiC has been obtained and amounts to 244±15 GPa, which is lower with respect to the reported ideal values.

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