Journal of Engineering Research and Reports

20(10): 57-64, 2021; Article no.JERR.70870
ISSN: 2582-2926

Investigation on the Flexural Modulus of Silicon Dies to Improve Die Mechanical Modeling Accuracy

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/JERR/2021/v20i1017389
Editor(s):
(1) Dr. Djordje Cica, University of Banja Luka, Bosnia and Herzegovina.
Reviewers:
(1) Merad Faiza, Abou Bekr Belkaid University, Algeria.
(2) Khalid Fazaa Mahmmod, Ninevah University, Iraq.
Complete Peer review History: https://www.sdiarticle4.com/review-history/70870

Short Research Article

Received 10 May 2021
Accepted 17 July 2021
Published 21 July 2021

ABSTRACT

Mechanical modeling of integrated circuit (IC) dies is commonly performed using the mechanical properties of the bulk silicon material. However, modeling results such as die deflection and the actual results were observed to have significant difference. This paper discusses the investigation done on the flexural modulus of actual IC dies used in package assembly manufacturing. Results were then compared with the modulus of the bulk silicon die or mirror die. The measurement of flexural modulus was done using the standard 3-point bend test. It was found out that the flexural modulus of the actual IC die is significantly lower than the flexural modulus of the bulk silicon or dummy die. Even with the actual IC die, the flexural modulus of the active side is also lower than the back side. From this study, it can be concluded that mechanical modeling involving IC dies could be improved by characterizing the properties of the actual die used. The common practice of using the properties of the bulk silicon die in mechanical modeling would not provide accurate results.

Keywords: Silicon die; flexural modulus; 3-point bend test; active die; dummy die.

1. INTRODUCTION

Material mechanical parameters, such as Young's modulus or flexural modulus, residual stress, and so on, not only have great effect on the functions of devices such as Micro-Electro-Mechanical System (MEMS), but also have great influence on yield, service life, and the work

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reliability of the devices [1]. The Young's modulus (E) of a material is a key parameter for design and analysis. Silicon, commonly used in fabricating integrated circuits, is an anisotropic crystalline material whose material properties depend on orientation relative to the crystal lattice. Since the silicon's elastic behavior depends on the orientation of the structure, choosing the appropriate value of E can appear to be a challenging task. However, the possible values of E for silicon range from 130 to 188 GPa and the choice of E value can have a significant influence on the result of a design analysis [2,3]. The dependence of modulus on the silicon crystal structure's orientation on the wafer surface gives rise to anisotropic elasticity [4,5].

The choice of the appropriate flexural modulus has influence on the accuracy of mechanical modeling results using finite element analysis (FEA), which is usually done during semiconductor package design and development. In a semiconductor package, the integrated circuit (IC) silicon die has a set of functional electronic circuits. Actual IC die used in package assembly and manufacturing has active circuits formed on a silicon substrate. However, the common practice in mechanical modeling is to assume the mechanical properties of the die to be the same as pure silicon. This results in the discrepancy between the mechanical modeling results and the actual results.

This paper discusses the investigation done on the flexural modulus of actual IC silicon dies used in semiconductor packages. The purpose of the work conducted was to improve the die mechanical modeling accuracy by using the modulus measured from the actual dies. Characterization of the die's flexural modulus is also using the 3-point bend test, which is the method used in die strength measurement [6,7]. In this study, the predicted die deflection from mechanical modeling using the actual flexural modulus was compared with actual die deflection.

2. MEASUREMENT OF FLEXURAL MODULUS

The modulus of a material could be determined by measuring the deflection of the beam loaded in bending [8]. In this study, the flexural modulus of the die was measured using an Instron MicroTester with a 3-point bend fixture compliant to the international standard SEMI G86-0303 for measurement of die strength [9]. The 3-point bend setup and testing procedure were based on that SEMI standard.

2.1 Testing Equipment and Setup

The Instron MicroTester equipment used in the study and the corresponding test setup are shown in Fig. 1. The MicroTester has a load cell that measures the amount of force applied to the specimen in a 3-point bend setup. The silicon die is supported at the bottom by 2 stationary support anvils and force is applied from the top with the movable upper anvil.

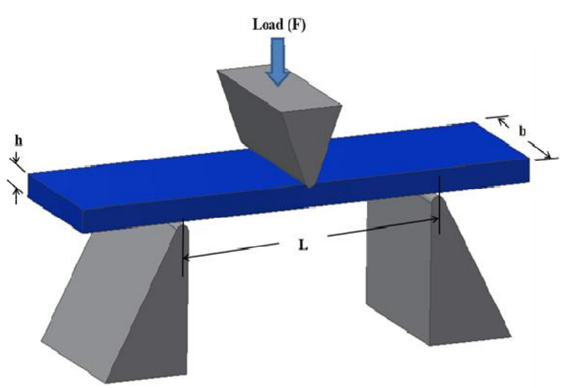
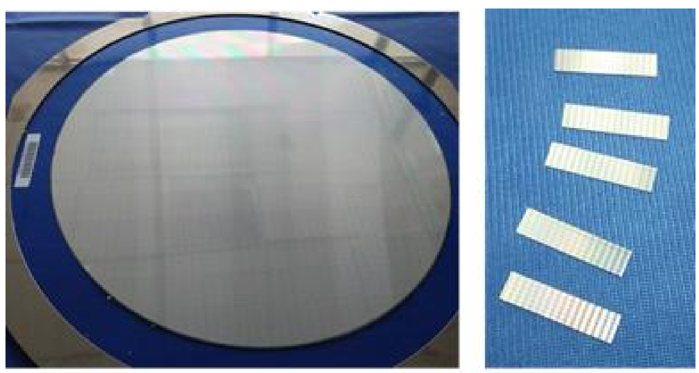


Fig. 1. Instron MicroTester and the corresponding 3-point bend test setup

The Instron MicroTester applies an increasing load to the die until the die rectangular beam sample breaks. The flexural modulus is calculated automatically from the load-displacement curve using Instron Bluehill software, the computer application that controls the Instron MicroTester equipment. In this study, the E-modulus calculation option in Bluehill software was chosen. This calculation is performed in accordance with the EN10002 and ASTM E8 standards. It determines the elastic modulus of the material by using a standard linear regression technique. The portion of the curve to be used for the calculation is chosen automatically and excludes the initial and final portions of the elastic deformation where the stress-strain curve is non-linear [10].

2.2 Silicon Die Samples

There were 2 types of die samples tested in this investigation. The first type was an actual IC die, where there is an active integrated circuit on the silicon die substrate as shown in Fig. 2. The size of the actual IC rectangular die tested was 6.08 x 20.95 x 0.14 mm. For the actual IC dies, 25 samples (A_Back) were subjected to 3-point bend test to get the load-displacement curve and the flexural modulus of the die back side. In this case, the die back side was oriented such that the back side was facing downward and subjected to tensile stress. The other 25 die samples (A_Front) were subjected to the same 3-point bend test but the orientation was different. The sample was placed on the 2 support anvils in such a way that the front side or active side was facing downward. The second type was a mirror or dummy die as shown in Fig. 3. The mirror die is just a wafer silicon material with no active circuit. There were 15 samples (M) tested to get the flexural modulus of the rectangular beam dummy silicon die. The size of the mirror die tested was 6.0 x 22.0 x 0.07 mm.



a) b)

Fig. 2. Actual IC die samples: a) wafer, b) rectangular beam samples from the wafer

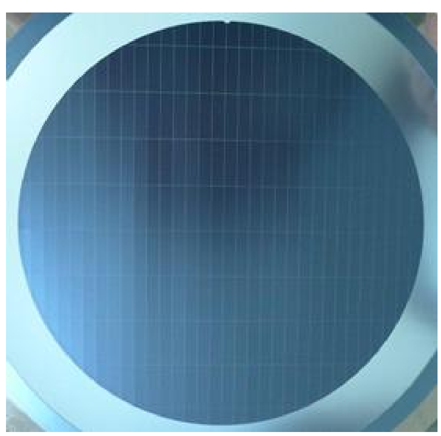


Fig. 3. Mirror die samples (no active circuit or IC)

2.3 Die Mechanical Modeling

With the flexural modulus measurements obtained from 3-point bend test, mechanical modeling using finite element analysis (FEA) technique was performed to predict the deflection of the actual IC die under a given applied force. The force was arbitrarily chosen as 10 N and applied in the FEA model shown in Fig. 4. The FEA predicted deflection was then compared with the actual deflection to validate the improvement when using flexural modulus of the actual die instead of just assuming the modulus to be the same as that of the mirror or bulk silicon die as usually done in most die mechanical modeling.

3. RESULTS AND DISCUSSION

From the 3-point bend test conducted, the flexural modulus results are plotted in Fig. 5. The flexural modulus of the mirror or dummy silicon die (M) is having an average value of 161000 MPa. This agrees very closely with the elastic modulus of the silicon material reported by Ritchie [11], which is 160000 MPa. However, it can be observed that flexural modulus of the actual IC die is much lower. The actual IC die back side orientation (A_Back) shows an average flexural modulus of 129000 MPa and the active side orientation (A_Front) has 124000 MPa flexural modulus. This shows that with the presence of circuit metal traces, the effective flexural modulus of the silicon die is reduced.

The flexural modulus results were also analyzed statistically with one-way ANOVA (Analysis of Variance) as shown in Fig. 6. Analysis shows that the means are significantly different. However, the flexural modulus values of the actual IC die A_Back and A_Front are close to each other. It follows from the fact that these measurements came from the same die with circuit traces and the only difference is the die orientation during 3-point bend testing. The data collected from 3-point bend test clearly reveal that the flexural modulus of the dummy or mirror silicon material is way higher and using its properties such as the flexural modulus in FEA die mechanical modeling would not be accurate.

The representative load-displacement curves for the actual IC die back side (A_Back) and die front side (A_Front) are shown in Fig. 7. The die deflection is the net displacement of the Instron MicroTester loading anvil from the time it touches the die rectangular beam center up to the point where the force applied is at 10 N as indicated. For the die back side (A_Back), an average die deflection of 35 microns was calculated from the 25 samples. On the other hand, an average deflection of 37 microns was obtained from the other 25 samples (A_Front).

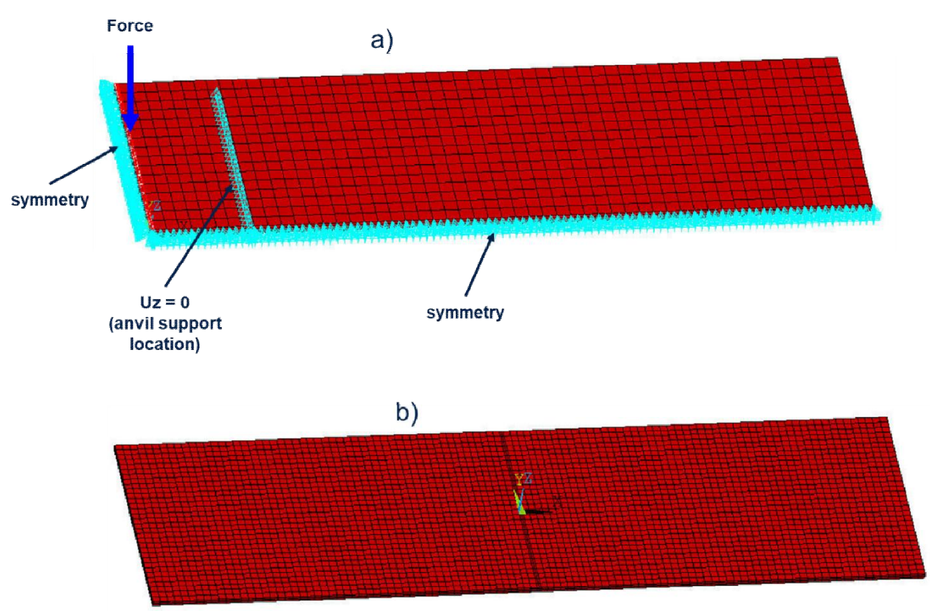


Fig. 4. FEA die model: a) quarter model with boundary conditions and load, b) full model symmetry expansion

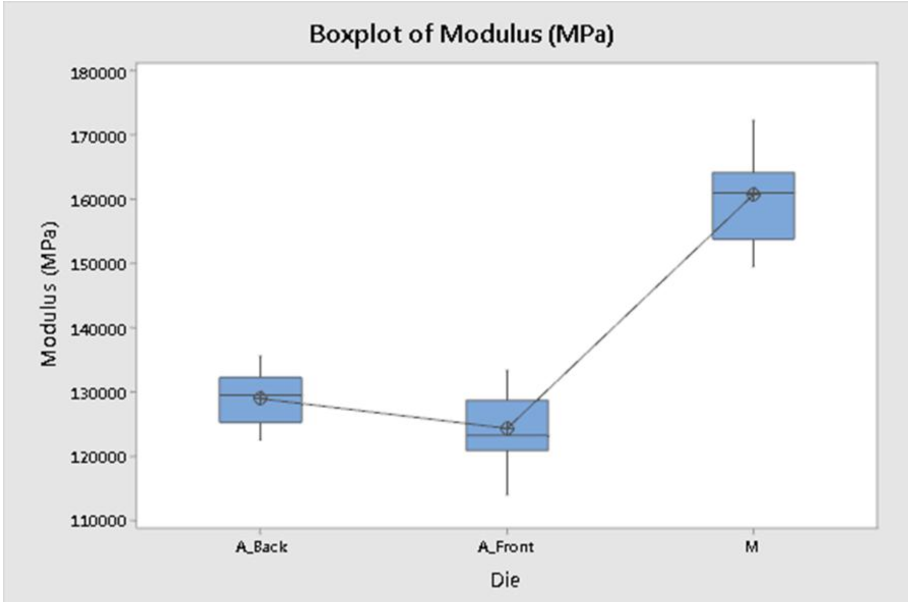


Fig. 5. Boxplot of the flexural modulus for the actual IC die back side (A_Back), front side (A_Front) and the dummy or mirror die (M)

One-way ANOVA: Modulus (MPa) versus Die

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Die	N	Mean	Grouping		
M	15	160707	A		
A_Back	25	128969		B	
A_Front	25	124353			C

Means that do not share a letter are significantly different.

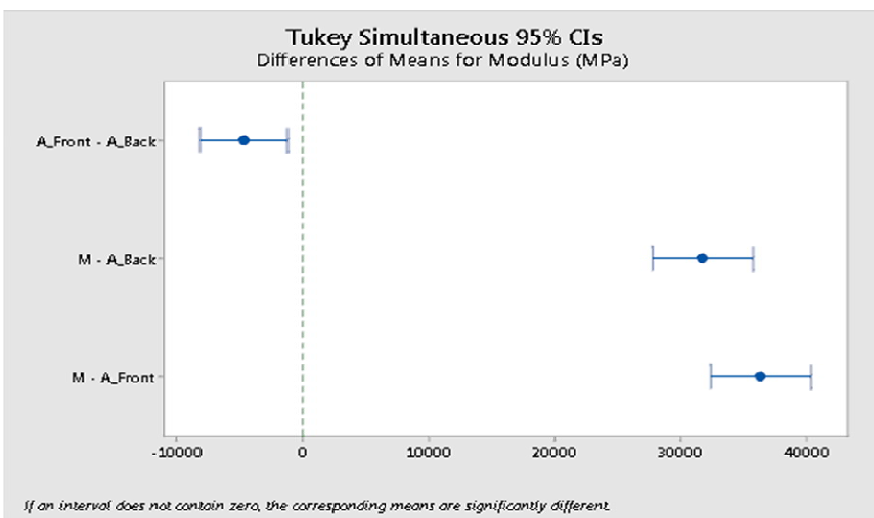


Fig. 6. One-way ANOVA of the modulus for the actual IC die back side (A_Back), front side (A_Front) and the dummy or mirror die (M)

As shown in Fig. 8, the die deflection result predicted when using the flexural modulus of the actual IC die is 34 microns for A_Back and 35 microns for A_Front. However, the die deflection is only 27 microns when the mirror or dummy silicon die flexural modulus is used. Fig. 9 shows the comparison of FEA predicted results with the actual values obtained from 3-point bend test. It is clear that there is a large discrepancy in the die modeling results when the flexural modulus used is that of the dummy or mirror silicon die. This shows that accurate die modeling results could not be achieved when the die flexural modulus is assumed to be the same as the bulk silicon material.

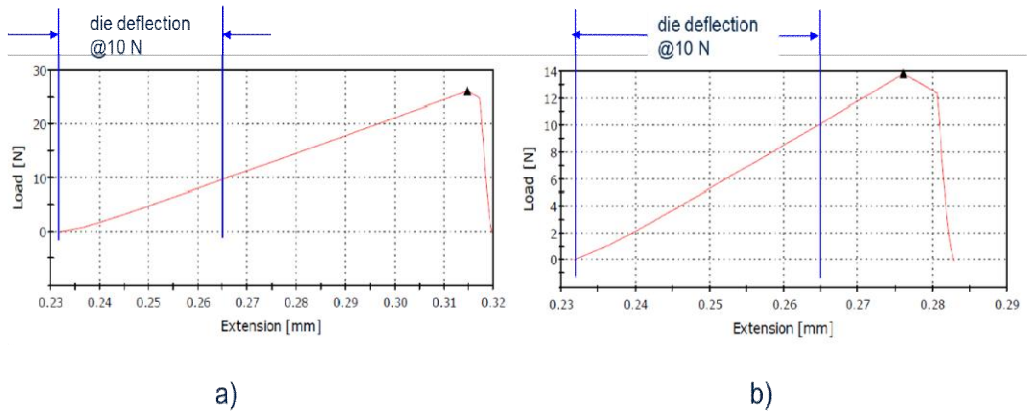


Fig. 7. Representative load-displacement curves of actual IC die: a) back side (A_Back), b) front side (A_Front)

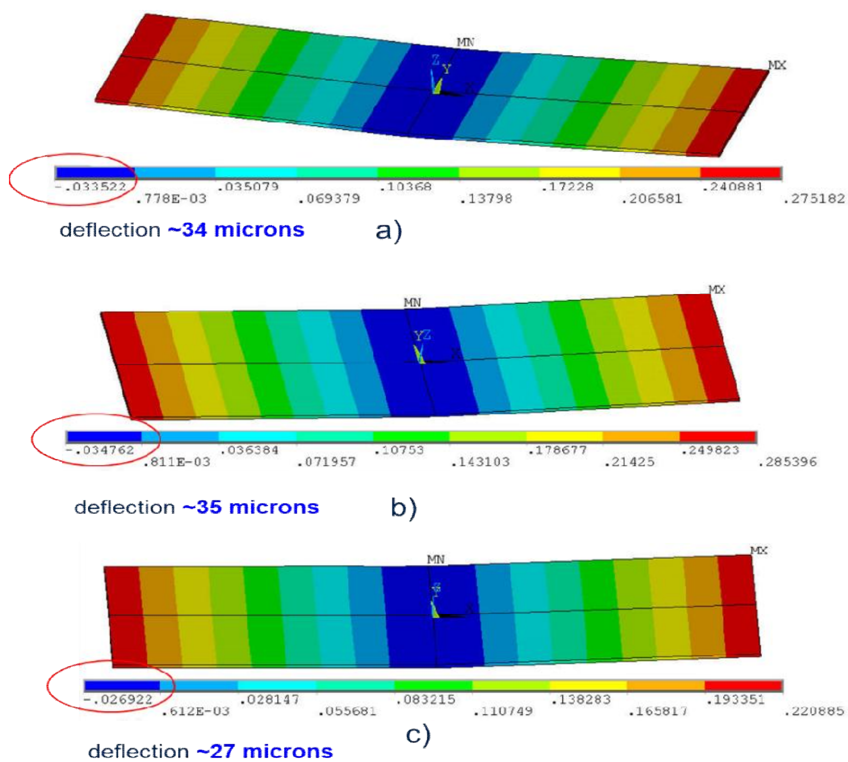


Fig. 8. Die deflection results from FEA modeling: a) using back side modulus (A_back), b) using front side modulus (A_Front), c) using mirror silicon die modulus

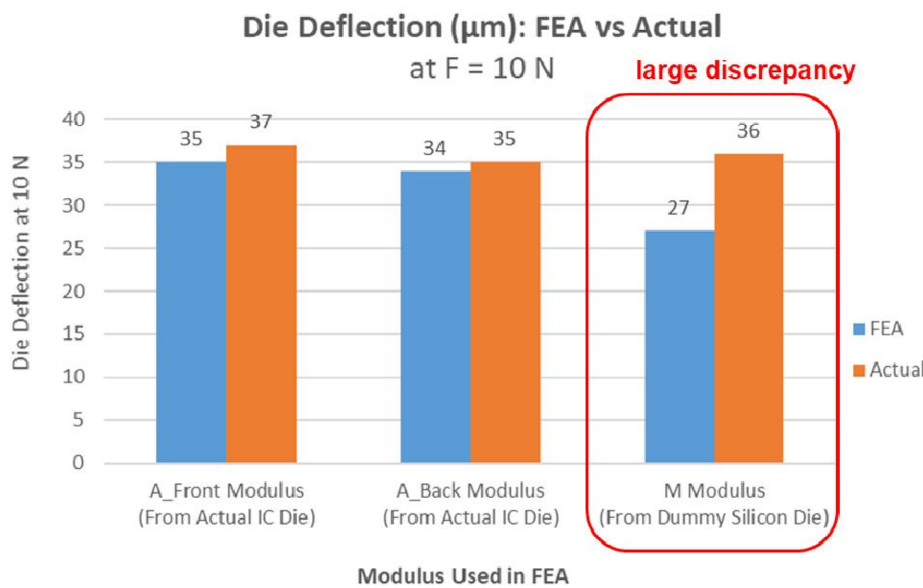


Fig. 9. FEA die modeling results comparison with actual die deflection measurements

4. CONCLUSION

Die mechanical modeling involving active IC dies used in actual semiconductor package manufacturing assembly could be improved by characterizing the properties of the actual die. The characterization of the mechanical properties such as flexural modulus could be done using 3-point bend test. Based on the results of this study, the effective flexural modulus of the actual IC die is significantly lower compared to the modulus of the bulk silicon material or the dummy silicon die. The presence of the integrated circuit metal traces in the actual die already alters its mechanical properties. A large discrepancy in the modeling results could be encountered as shown in this study. Therefore, using the properties of the bulk silicon die in mechanical modeling FEA would not provide accurate results.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

ACKNOWLEDGEMENTS

The author would like to thank STMicroelectronics management especially the New Product Development and Introduction group for the support provided in this study.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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