STRENGTH AND FRACTURE ANALYSIS OF SILICON CHIPS TO BE EMBEDDED INTO PRINTED CIRCUIT BOARDS

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ABSTRACT

The ongoing trend to further miniaturise electronic devices in Printed Circuit Board (PCB) technologies has pointed out the embedding of components as a principal design strategy. The reliability of the PCB relies on the functionality of the embedded components as well as on their structural integrity in order to survive the embedding process. Therefore, the strength of such components should be determined at the relevant length scale. In this work, silicon chips (ca. 2 x 2 x 0.12 mm^3) to be employed as embedded components into PCBs are investigated in order to determine their strength and fracture behaviour. The Ball-on-three-Balls (B3B) test has been employed for the mechanical characterisation under biaxial flexure. Experimental results have been analysed by means of Weibull statistics and fractographic investigations. This study shows that the geometry of the embedding components and their location within the PCB could involve significant differences in terms of strength reliability, with effects on the PCB functionality.

KEYWORDS

PCB, Silicon, Failure analysis, Weibull statistics, Brittle fracture, Biaxial strength, Functional applications

INTRODUCTION

In the recent years, embedding of electronic components directly into Printed Circuit Boards (PCB) has emerged as innovative high-added value technology. Using this concept, it is possible to produce more circuits per fabrication panel, which allows obtaining a smaller board with the same functions. Other advantages involve the option to add other functionalities to the circuit, and the achievement of higher speeds and lower noise [1]. However, since PCBs with embedded components are produced by thermal pressing, a high mechanical reliability of components is generally required to survive the mechanical stresses during the process. The embedded devices (*e.g.* ceramic capacitors or silicon chips) are very brittle and their fracture force can be in the order of few Newtons. Thermo-mechanical stresses may occur during operation of the board; hence the functionality of the entire package also relies on the mechanical strength of the components. Semiconductor silicon chips are among the most commonly employed embedding components. The mechanical properties of such materials could be different depending on the crystallographic direction of the surface subjected to tensile stress [2]. The degree of surface finishing or the presence of

deposited metal contacts also plays a determinant role [3, 4]. Hence, a different mechanical reliability of the board may be attained, depending on the side of the device that is exposed to tensile stresses.
The evaluation of mechanical properties is of primary importance in order to estimate the performance limits of the entire package. Mechanical testing is generally carried out with biaxial fixtures, and the brittle nature of many components (*e.g.* silicon) employed for embedding makes the use of Weibull statistics necessary for strength determination [5, 6]. The purpose of the present investigation is to determine the strength and fracture features of silicon components to be embedded into PCBs. Strength measurements are performed using the biaxial Ball-on-three-balls (B3B) test on thin 2 x 2 mm^2 plate-like single-crystalline silicon specimens. The experimental results are interpreted using Weibull statistics and fractography.

MATERIALS AND METHODS

Silicon chips derived from single crystalline wafers were supplied by the company AT&S (Leoben, Austria). The Si chips (dimensions: 2 x 2 x 0.125 mm^3) presented two different sides: one constituted by mirror-polished pure silicon and the other side with deposited Cu-metal contacts and Al-interconnects, as shown in Fig. 1. The two surfaces will be henceforth referred to as “Si-side” and “Metal-side”, respectively. Specimens grown on the (111), (101) and (001) planes were considered for this analysis. The crystallographic directions of the Si chips were identified with the aid of Electron Back-Scattered Diffraction (EBSD - EDAX, Mahwah, NJ, USA).

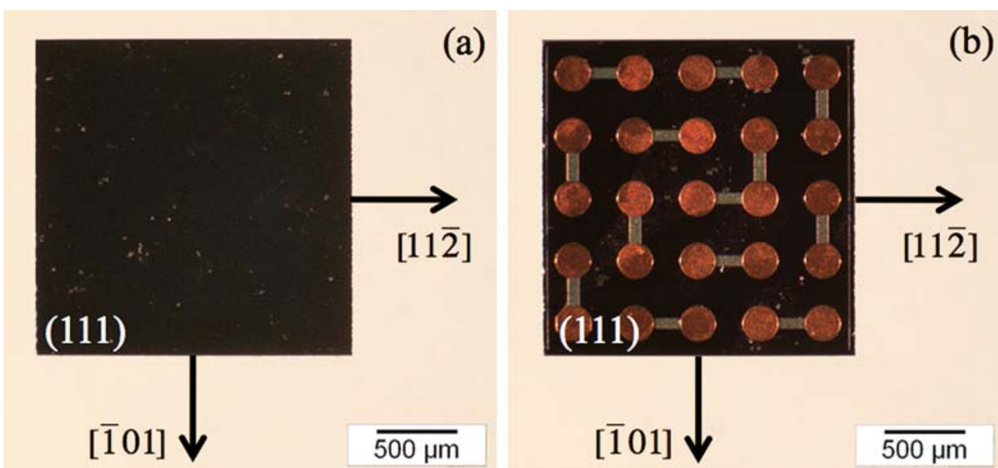

Fig. 1: (a) Si-side and (b) metal-side with Cu-contacts (red) and Al-interconnects (white) of (111) single-crystalline Si chips. Crystallographic directions (as determined by EBSD) are explicitly indicated.

The strength of the Si-chips was determined using the B3B test (see Fig. 2a). In this testing method, a rectangular plate (or a disc) is symmetrically supported by three balls on one side and loaded by a fourth ball in the centre of the opposite side, which produces a very well defined biaxial stress field [7-9]. The load is increased until fracture occurs, and the fracture load can be used to calculate the maximum tensile biaxial stress in the specimen at the moment of fracture, given by:

$$\sigma_{\max} = f \cdot \frac{F}{t^2}, \qquad (1)$$

where F is the maximum load at fracture, and t the specimen thickness. f *is* a dimensionless factor, which depends on the geometry of the specimen, the Poisson's ratio of the tested material and on details of the load transfer from the jig into the specimen. A numerical analysis of the system based on a FE simulation (ANSYS 11, ANSYS, Canonsburg, PA, USA) has been carried out in order to calibrate the factor f for this configuration, resulting in a value of $f = 2.21$ (Fig. 2b). In order to reproduce the possible stress states occurring during the embedding process, two testing configurations were adopted for specimens of all orientations: (i) pure silicon surface under tension (referred to as *Si-side*) and (ii) surface with metal contacts and interconnects under tension (named *Metal-side*). All B3B tests were carried out in a universal testing machine (Zwick Z010, Zwick/Roell, Ulm, Germany) with the aid of a jig especially designed in-house for very small specimens. Optical examination of fracture surfaces was carried out with an Olympus BX50 light microscope and an Olympus SZH10 stereo microscope (Olympus, Tokyo, Japan).

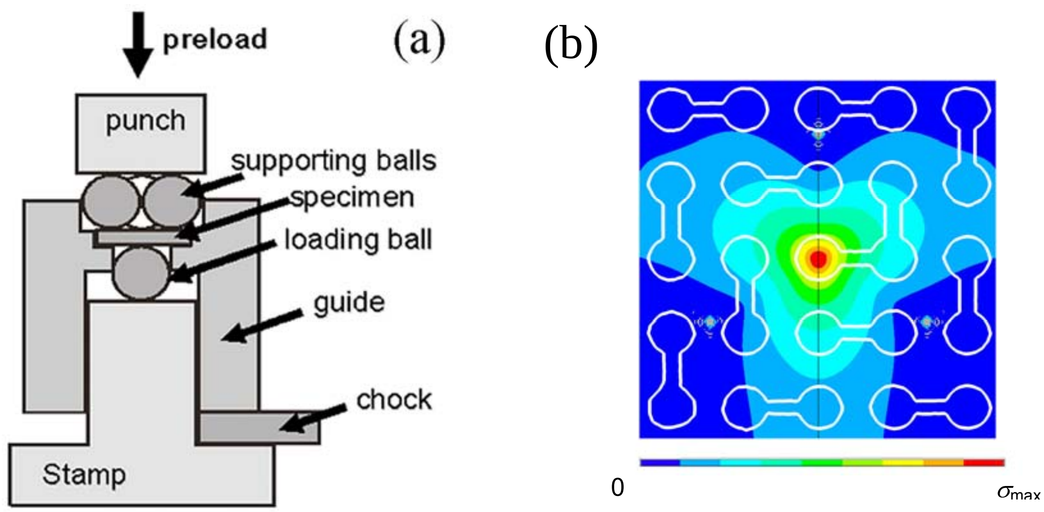

Fig. 2: (a) Schematic drawing of the B3B fixture. (b) Stress field developed in the specimen during B3B testing, calculated with FEM. The position of metal contacts with respect to the applied stress is also indicated. The maximum stress corresponds to the central contact.

RESULTS AND DISCUSSION

B3B strength results

Figure 3a shows the results of B3B tests conducted both on the Si-side and on the Metal-side of single-crystalline Si chips. The crystal orientation of the tested specimens´ plane was (111), (101) or (001). Data are represented in terms of fracture load (and strength, *cf.* Eq. (1)) vs. the probability of failure. The scale chosen in the graph allows representing Weibull–distributed data as a straight line. Each distribution was collected on a sample of ~30 specimens, which ensures statistical significance for the Weibull analysis [5]. Figure 3b reports the nominal characteristic strength σ_0 (*i.e.* the stress with a probability of failure of $F = 63.21\%$) and the corresponding Weibull moduli, m, for both Si-side and Metal-side testing configurations for each crystal orientation. Values of σ_0 and m for all tested specimens of dimensions 2 x 2 x 0.125 mm^3 are reported in Table 1.

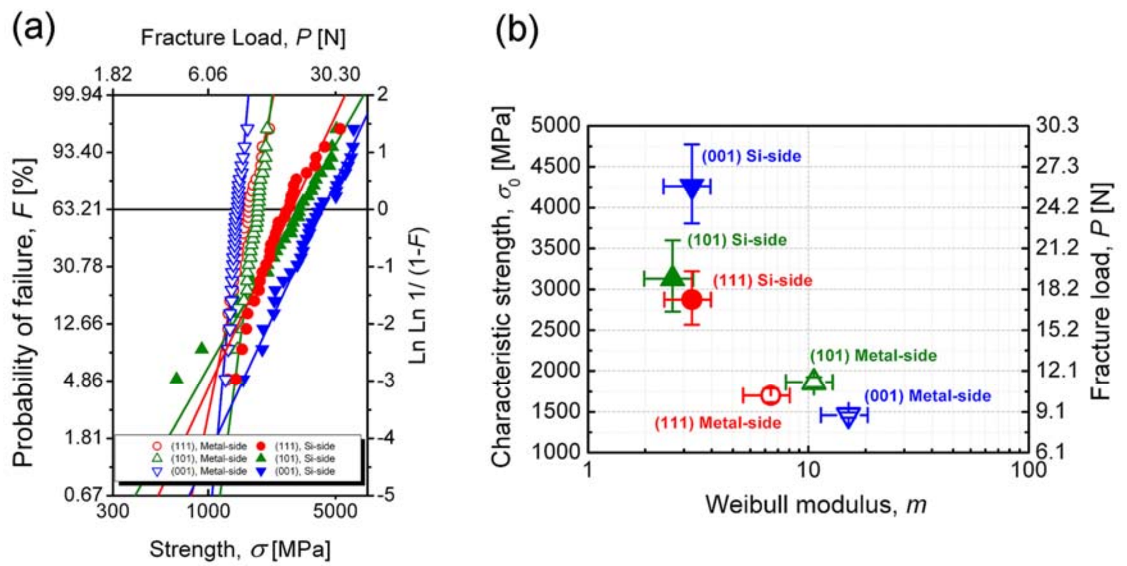

Fig. 3: (a) Results of B3B tests on Si-side and Metal-side Si chips of different orientations. (b) Characteristic strength vs. Weibull modulus diagram for the tested specimens.

Sample	Characteristic strength, σ_0 [MPa]	Weibull modulus, m	$V_{eff\ (PIA)}$ [mm^3]
(111) Si-side	2874 [2568 – 3221]	3.0 [2.2 – 3.6]	0.0027
(101) Si-side	3130 [2727 – 3599]	2.4 [1.8 – 3.0]	0.0066
(001) Si-side	4259 [3805 – 4775]	3.0 [2.2 – 3.6]	0.0027
(111) Metal-side	1700 [1619 – 1788]	6.8 [5.1 – 8.2]	0.00025
(101) Metal-side	1862 [1804 – 1922]	10.6 [7.9 – 12.9]	0.000082
(001) Metal-side	1460 [1428 – 1492]	15.2 [11.4 – 18.6]	0.000035

Table 1: Values of characteristic strength, σ_0 and Weibull modulus, m obtained on the Si chips tested with the B3B method. 90 % confidence intervals are given in square brackets. The corresponding effective volume for every case is also presented.

It can be clearly inferred from Fig. 3 and Table 1 that testing Si chips with either the pure silicon or the metal-patterned side under tension produces clearly different results. In particular, Si-side specimens possess a higher characteristic strength than the Metal-side ones (*i.e.* ~3500 MPa vs. ~1700 MPa). However, the Weibull modulus for the latter is considerably higher (*i.e.* ~11 vs. ~2.8); the specimens break in a very narrow range of applied stresses (higher mechanical reliability). Being the surface that was put into tension the only difference between the two cases, it seems obvious that there is a strong effect of the deposited metal contacts on the overall strength behaviour of the material. The pure silicon surface, if put under tension *(i.e.* Si-side), presents a rather wide strength distribution but associated with a high resistance to failure, which is in accordance with a well-polished, pure silicon surface [3, 10, 11]. On the other hand, for Metal-side specimens, the lower strength and much narrower strength distribution (*i.e.* higher *m*) could be explained by either the presence of a narrow range of large critical defects or of a stress concentration during biaxial loading.

Fractography

Fractured specimens of all orientations were subjected to EBSD analyses in order to identify the apparently preferred fracture directions observed. Figures 4a, b and c report planar views of (111), (101), (001) Si chip specimens fractured during Metal-side testing, respectively. The crystallographic directions along which fracture occurred are explicitly indicated as determined by EBSD. It could clearly be seen that in the case of (111)- and (101)-oriented specimens (Figs. 4a, b) cracks propagated at 60° (or multiples) from one another. In other words, the preferred fracture direction in the (111) and (101) specimens was along <110> and <111> directions, respectively. On the other hand, regarding the (001) specimens (Fig. 4c), fracture occurred at 90°, which is compatible with cracks propagating along <110>. In single-crystalline silicon, being the atoms arranged with different spacing in different directions, the force needed to cut the atomic bond is also direction-dependent; therefore the surface energy (and the fracture energy) varies with the orientation of the crystal plane [12, 13]. This causes the fracture toughness to be dependent on the orientation of the cleavage planes, varying from $K_{Ic} = 0.73$ MPa·m$^{1/2}$ to $K_{Ic} = 0.89$ MPa·m$^{1/2}$ [2]. In (111) silicon, {110} planes possess the lowest toughness. For (101) and (001) silicon the lowest toughness planes correspond to {111} and {110}, respectively. This explains the orientation of the preferred fracture directions observed in the present study.

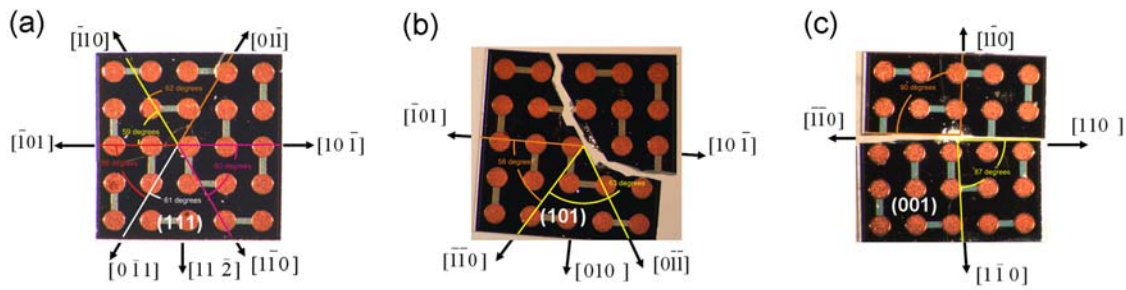

Fig. 4: Preferred fracture directions (as determined by EBSD) in (a) (111), (b) (101) and (c) (001) oriented silicon specimens.

Further information that can be drawn from Fig. 4 is the fact that fracture in the Metal-side chips always starts at the border of the central metal contact, and not at the centre of the specimen, where the maximum tensile biaxial stresses are expected. This suggests that the metal-silicon interface could play a determinant role in the fracture of Metal-side tested specimens. Fig. 5 reports a SEM cross-sectional view of the central metal contact. The interface is constituted by an aluminium (Al) layer acting as a buffer for the copper (Cu) metal contact, and by a silica layer which probably formed during galvanic deposition of the Cu-Al layers.

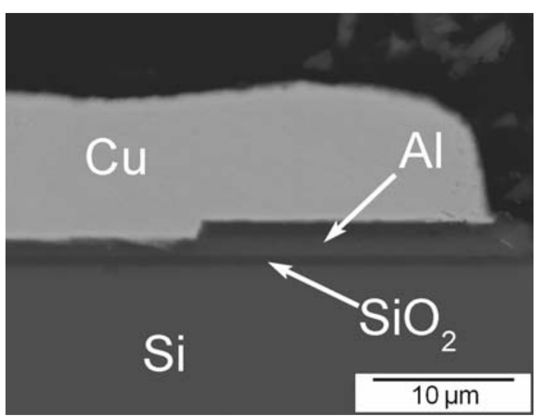

Fig. 5: Cross-sectional view of the central metal contact. Disposition and denomination of layers are indicated.

Fractographic examinations of the central contact area of specimens that failed during Metal-side testing are reported in Figs. 6, 7 and 8 for (111), (101) and (001) oriented specimens, respectively. As it could clearly be seen from the reported pictures, fracture always originated at the border of the central metal contact, and in particular at the interface, in an area comprised between the Al interconnects, the SiO_2 layers and the silicon phase. In each figure red arrows indicate the precise point where fracture initiated.

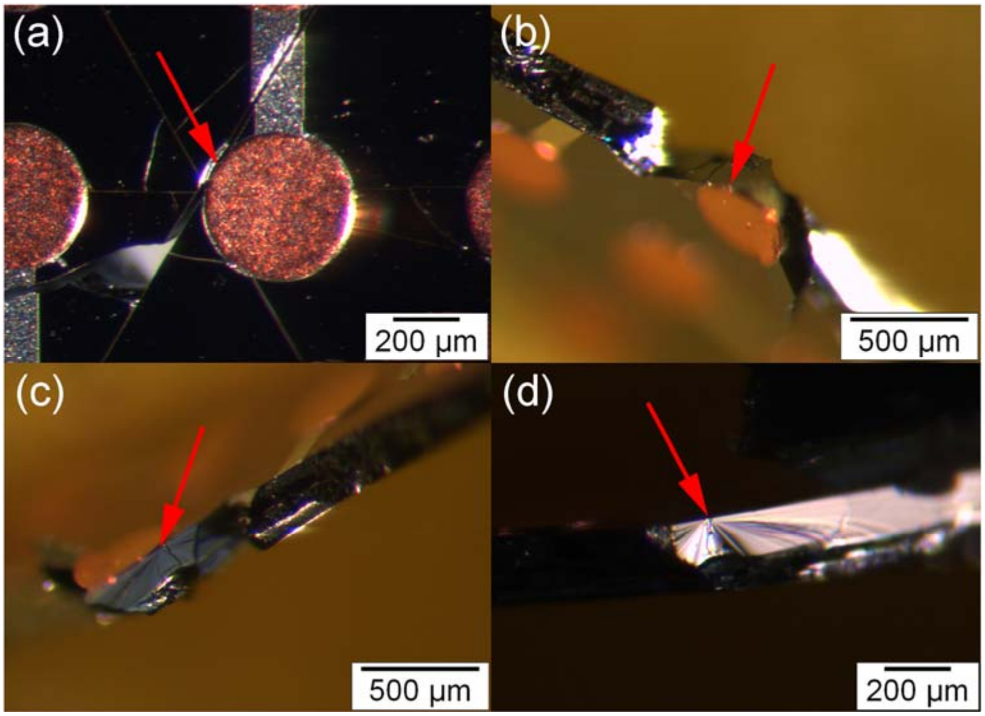

Fig. 6: (a)-(d) Stereo micrographs of the fracture origin in a (111) Metal-side tested specimen (at different magnifications). Fracture initiation is indicated by a red arrow.

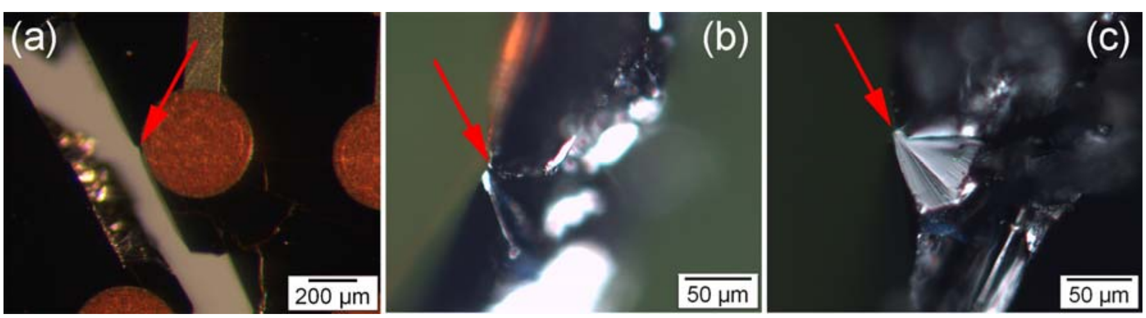

Fig. 7: (a)-(c) Stereo micrographs of the fracture origin in a (101) Metal-side tested specimen (at different magnifications). Fracture initiation is indicated by a red arrow.

There are several mechanisms which could play a role in the displayed fracture cases. The possibility that large defects are present only at the border of the metal contact cannot be ruled out; however, since no defects larger than 500 nm were found in the interfacial area [4], it is unlikely that this is the dominant mechanism. Being the fracture toughness of silica lower than that of silicon (≈0.6 $MPam^{1/2}$ for silica vs. ≈0.8 $MPam^{1/2}$ for silicon) [2, 14], the oxide layer might be responsible for an embrittlement of the Si chips during Metal-side biaxial testing. In addition, the free edges at the end of the Cu and Al layers (perimeter of the metal contact, *cf.* Fig. 5) could act as a notch during biaxial loading, which might produce significant stress concentrations. This stress concentration will be released in proximity of the Al layer, but will become critical at the interface with the brittle silica. It can thus be speculated that cracks will initiate in the silica layer and then, during propagation towards the silicon, could act as an initiation for cracks in the silicon phase.

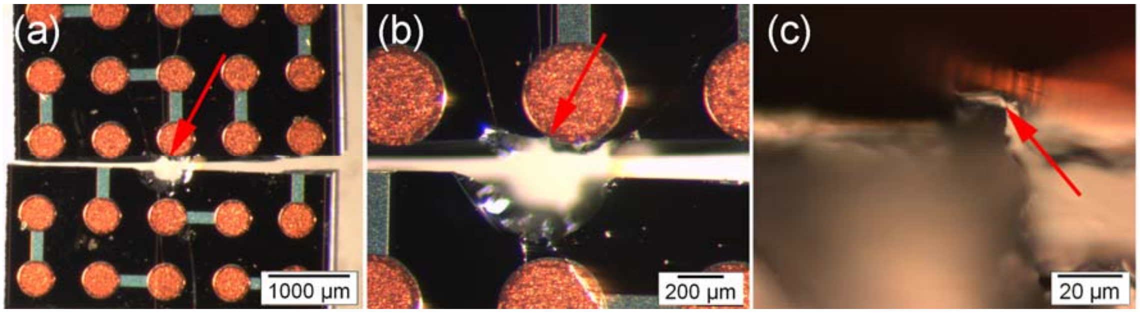

Fig. 8: (a)-(c) Stereo micrographs of fracture origin in a (001) Metal-side tested specimen (at different magnifications). Fracture initiation is indicated by a red arrow.

SUMMARY AND CONCLUSIONS

The strength and fracture features of miniaturised Si chips for embedding into PCBs have been assessed by the B3B testing method for both the pure silicon surface under tension (Si-side) and the metal-patterned side under tension (Metal-side). Specimens with different crystallographic orientations were selected for the study. Strength results showed a clear statistical difference in the characteristic strength for both approaches, being in the Si-side more than 2 times larger (σ_0≈3500 MPa) than in the Metal-side (σ_0≈1700 MPa). The Weibull modulus in the Si-side is in agreement with common values for silicon wafers (*i.e.* m≈2.8), whereas for the Metal-side a very high value is obtained (*i.e.* m≈11). Fractographic analyses of broken specimens suggested that the lower strength of Metal-side specimens could be ascribed to the presence of a brittle silica layer and/or a stress concentration in the region where metal contacts are deposited on the silicon phase. The present findings thus suggest that embedding approaches with Si-side or Metal-side under tension could involve significant differences in the functionality of PCBs.

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REFERENCES

[1] Coombs Jr., C.F.:
Printed Circuits Handbook, 6th ed.
McGraw-Hill, New York, 2008

[2] Tanaka, M.; Higashida, K.; nakashima, H.; Takagi, H.; Fujiwara, M.:
Orientation dependence of fracture toughness measured by indentation methods and its relation to surface energy in single crystal silicon
Int. Journal of Fracture 139 (2006) No. 3, pp. 383-394

[3] Chen, K.-S.; Ayon, A.; Spearing, S.M.:
Controlling and testing the fracture strength of silicon on the mesoscale
J. Am. Ceram. Soc. 83 (2000) No. 6, pp. 1476-1484

[4] Deluca, M.; Bermejo, R.; Pletz, M.; Supancic, P.; Danzer, R.:
Strength and fracture analysis of silicon-based embedding components
Acta Mater., submitted

[5] Danzer, R.; Lube, T.; Supancic, P.; Damani, R.:
Fracture of ceramics
Adv. Eng. Mat. 10 (2008) No. 4, pp. 275-298

[6] Weibull, W.:
A statistical distribution function of wide applicability
J. Appl. Mech. 18 (1951), pp. 293-297

[7] Börger, A.; Supancic, P.; Danzer, R.:
The ball on three balls test for strength testing of brittle discs: stress distribution in the disc
J. Eur. Ceram. Soc. 22 (2002) No. 9-10, pp. 1425-1436

[8] Börger, A.; Supancic, P.; Danzer, R.:
The ball on three balls test for strength testing of brittle discs: Part II: analysis of possible errors in the strength determination
J. Eur. Ceram. Soc. 24 (2004) No. 10-11, pp. 2917-2928

[9] Danzer, R.; Supancic, P.; Harrer, W.:
Biaxial tensile strength test for brittle rectangular plates
J. Ceram. Soc. Jap. 114 (2006), No. 1335, pp. 1054-1060

[10] Funke, C.; Kullig, E.; Kuna, M.; Möller, M.J.:
Biaxial fracture test of silicon wafers
Adv. Eng. Mat. 6 (2004) No. 7, pp. 594-598

[11] Rupnowski, P.; Sopori, B.:
Strength of silicon wafers: fracture mechanics approach
Int. Journal of Fracture 155 (2009), pp. 67-74

[12] Turley, J.; Sines, G.:
The anisotropy of Young´s modulus, shear modulus and Poisson´s ratio in cubic materials
J. Phys. D: Appl. Phys. 4 (1971), pp. 264-271

[13] Cook, R.F.:
Strength and sharp contact fracture of silicon
J. Mater. Sci. 41 (2006), pp. 841-872

[14] Alsem, D.H.; Boyce, B.L.; Stach, E.A.; Ritchie, R.O.:
Effect of post-release sidewall morphology on the fracture and fatigue properties of polycrystalline silicon structural films
Sens. Act. A: Physical 147 (2008) No. 2, pp. 553-560

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