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MECHANICAL CHARACTERIZATION OF GLASS FRIT BONDED WAFERS

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Abstract: *Wafer bonding is a key technology in the manufacturing of microelectronic and micromechanical systems on industrial scale. Especially glass frit bonding is often used for the encapsulation of MEMS devices on wafer level. To ensure the reliability of these bonds and to prevent critical failure of the systems, characteristic mechanical properties of the bonded interface are required. The fracture toughness and the shear strength are suitable values to characterize the bonding strength and can be determined by micro chevron and shear testing. They depend on the bonding parameters as well as the test speed. Due to the correlation between measured bonding strength and test speed a maximum test speed has to be identified to obtain reliable failure criteria regarding the fracture toughness and the shear strength.*

Key words: *glass frit bonding, stress intensity coefficient, fracture toughness, shear strength, influence of test speed.*

1. Introduction

Wafer bonding is a key technology in the manufacturing of micro electro mechanical systems (MEMS) on industrial scale. It describes various techniques of joining two wafers with or without thin intermediate layers. Thereby, glass frit bonding is used in a wide range of industrial applications, especially for the encapsulation of surface mechanical sensors like gyroscopes and acceleration sensors. The reliability of glass frit bonded MEMS devices is directly affected by the strength of the bonded interface.

The fracture toughness and the shear strength are suitable values to characterize the bonding strength. They enable an estimation of lifetime for the whole MEMS device as well as the comparison of different bonding technologies and process parameters during bonding.

2. Technology and Methods

2.1. Glass frit bonding

During glass frit bonding, two or more wafers are joined using a low melting point glass as intermediate layer. It is commonly used for the encapsulation of surface mechanical sensors as well as bonding fully processed wafers [1]. To prevent any temperature related deterioration of the

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fully processed wafers and their metal components, the process temperatures have to be smaller than 450 °C to form a mechanically strong and hermetically sealed bond. Due to the deposition of the intermediate layer and the bonding process itself, glass frit bonding enables the hermetic sealing of structured wafers with metal conductor paths by compensating variations in roughness and thickness of the bonded surfaces.

Glass frit bonding is carried out in three major steps [2]. The glass deposition is followed by its thermal conditioning and the bonding process itself.

The deposition of the low temperature melting point glass by means of commonly used techniques such as sputtering or chemical vapour deposition (CVD) is very difficult or almost impossible. Therefore, screen printing is used for a structured deposition of glass compound. Screen printing also offers the additional benefits of compensating variations in surface roughness and wafer bow. The glass compound consists of a glass, an organic components to control the viscosity of the glass. Filler particles can be included as well to adjust the coefficient of thermal expansion (CTE) of the glass to the wafer material.

During the thermal conditioning, the deposited glass compound is transformed into glass. After screen printing, the glass compound has to be dried at 120 °C to remove all solvents and form a stable layer. Afterwards, the organic binders are burned out at 330 °C. Melting the compound at the so called wetting temperature of 430 °C and cooling down to room temperature in the last step, a homogenous solid glass layer is formed.

During bonding, the wafers are again heated to the wetting temperature of 439 °C to decrease the viscosity of the glass. By applying a mechanical pressure, the glass wets the surfaces and compensates the wafer bow, the roughness of the surfaces as well as small surface steps due to metal layers and variations in the thickness of the glass layer due to screen printing. While reducing the temperature, the glass forms a strong, hermetically sealed bond.

2.2. Mechanical Characterization

A reliability assessment and the determination of the lifetime for the bonded interface and the whole MEMS device require the determination of the bonding strength itself. Therefore different qualitative methods like dicing test and tape test as well as quantitative approaches such as shear test and micro chevron test are available. Because dicing is a commonly used technique to separate the chips during MEMS manufacturing, the dicing test is often used to monitor the bonding strength. Quantitative approaches provide adequate failure criteria for finite element analysis during the design of new MEMS devices and enable the comparison of different bonding technologies and process parameters.

3. Micro Chevron Test

The micro chevron test is a hybrid method combining experiment with finite element analysis to determine the fracture toughness of bonded packages. Based on a mode I crack opening, it represents the most critical failure mechanisms of MEMS devices. Therefore, the micro chevron test is commonly used for silicon direct and anodic bonded structures and becomes more important for the analysis of metallic and glass frit bonded wafers [3, 4, 5].

3.1 Micro Chevron Test Samples

The analyzed micro chevron specimens consist of two silicon chips with the length

L and width W. To minimize the mixed mode loading and ensure a mode I crack opening, the thickness of the bonded wafers h_W is equal, while the thickness of the glass layer h_S is significantly smaller than the wafer thickness. The chevron structure itself is defined by the initial crack length A_0 and the maximum mouth length A_1, depending on the chevron notch angle φ and the width of the sample, Fig. 1.

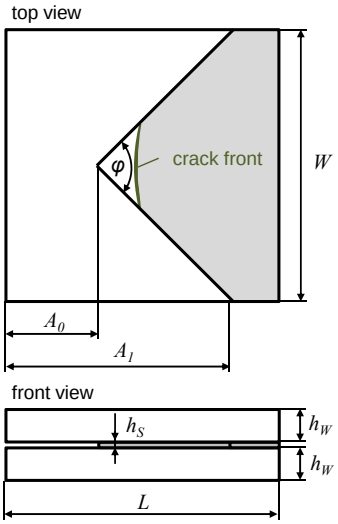

Fig. 1. *Micro chevron test sample*

While the geometries with fully bonded chevron structures are sufficient for direct bonded specimens, alternative designs are required for glass frit bonded samples. During the deposition of the glass by screen printing, the formation of "beads" can be observed, Fig. 2.

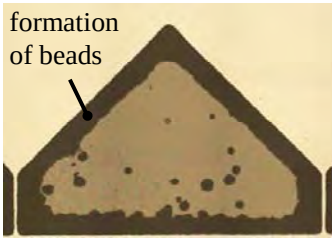

Fig. 2. *Formation of beads after screen printing*

These beads cannot be avoided by changing the printing parameters and form at the edges of the chevron geometry. In the regions of the beads, the thickness of the glass layer increases from 15 µm to about 19 µm. The large variations in the glass thickness directly affect the quality of the bond, because no area wide contact between glass and wafer can be achieved.

Instead of the fully bonded samples, a partial bonded chevron structure is required for glass frit bonded specimens, Fig. 3. Therefore, the intermediate glass layer consists of a pattern of stripes with the width W_S and a gap G_S between two stripes.

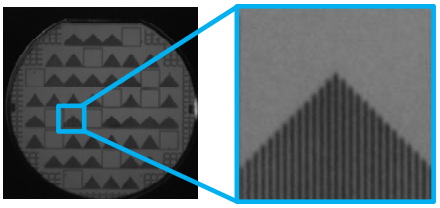

Fig. 3. *Patterned micro chevron test sample*

3.2. Micro Chevron Test Procedure

During micro chevron testing, the Specimen is loaded perpendicular to the chip plane (xy-plane), Fig. 4. After the self initiation of the crack at the tip of the chevron notch, a mode I crack opening can be observed.

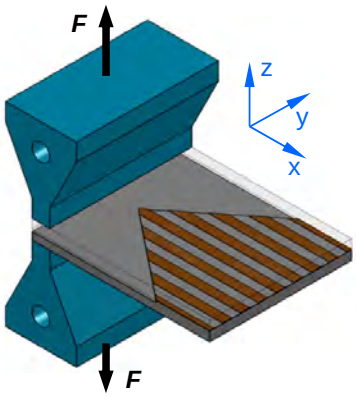

Fig. 4. *Principle of micro chevron test*

The propagation of the crack is affected by two counteractive effects [6]. While the stress intensity factor increases with further crack propagation, the length of the crack front increases as well. The elongation of the crack front causes a reduction of the stress intensity factor. As a result of these counteractive effects, a stable crack growth can be observed in the region of the chevron structure before reaching the critical crack length, when stable crack growth becomes instable. The maximum force and the stress intensity coefficient K_{IC} are directly related to the critical crack length. Therefore, no measurement of the crack length itself is required during experiment, Fig. 5.

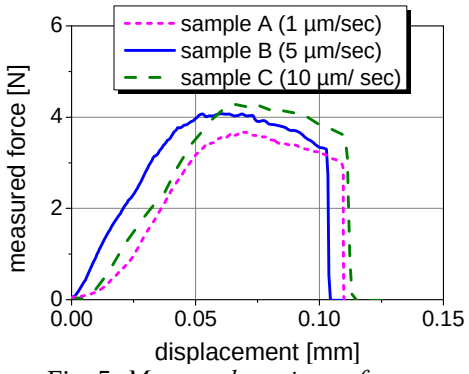

Fig. 5. *Measured maximum forces*

3.3. Stress Intensity Coefficient (FEA)

While the maximum force can be measured during experiments, the stress intensity coefficient has to be determined by numerical simulation. Based on the compliance method, the stress intensity coefficient is calculated for fully bonded chevron structures [6, 7]. The patterning of the chevron structure directly affects the stress intensity coefficient. It is considered by the ratio of the bonded area and the area of the complete chevron structure and causes an increase of the stress intensity coefficient while reducing size of the bonded area, Fig. 6.

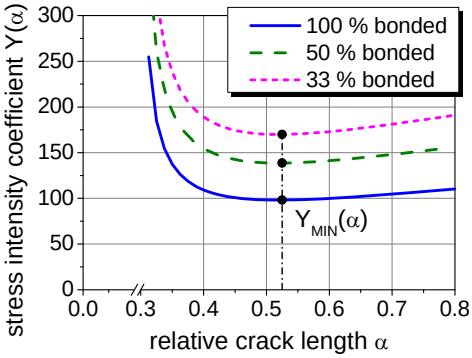

Fig. 6. *Stress intensity coefficients with patterned structure*

Combining these stress intensity coefficients with the measured force, the fracture toughness of the bond can be calculated by

$$K_{IC} = \frac{F_{\max}}{W \cdot \sqrt{L}} \cdot Y_{\min}(\alpha). \qquad (1)$$

4. Shear Test

In the fields of microelectronics and micro systems technology the shear test is often used to evaluate the bonding strength of different packages with and without intermediate layer [5]. Because there are

no limitations regarding the interface geometry, it can be carried out with finished MEMS devices as well as special test structures. The shear strength is a suitable value to characterize thermal loaded packages consisting of materials with different coefficients of thermal expansion.

4.1 Shear Test Samples

Due to the formation of beads during screen printing, the shear test specimens have to e structured as well, Fig. 7. The deposition of bonding frames causes a significant reduction of the bond strength and the required shear force. The size of the bonded area depends on the width of the bonding frame W_B as well as its offset D_B towards the edges of the chip.

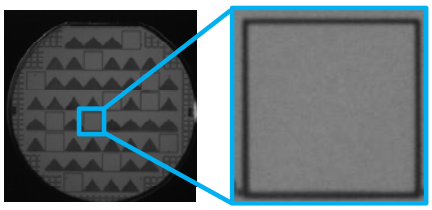

Fig. 7. *Structured shear test specimen with bonding frame*

4.2. Shear Test Procedure

The shear test is carried out as compression shear test. Therefore, the sample is mounted and loaded under 45 °, Fig. 8.

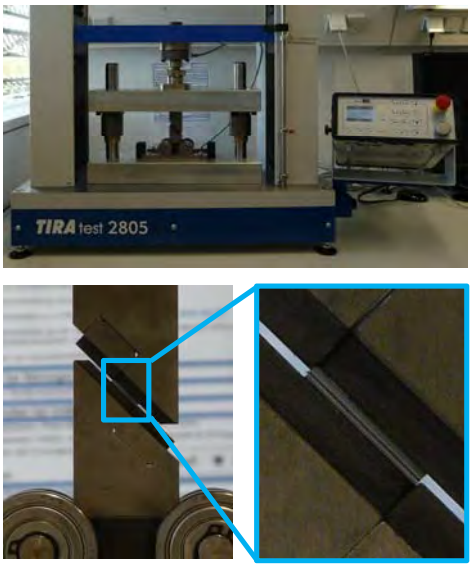

Fig. 8. *Experimental setup for compression shear test of MEMS devices*

Based on the measured maximum force and the geometry of the bonding frame, the shear strength of the bonded interface can be determined by

$$\tau_{schub} = \frac{F_{\max} \cdot \sin(45°)}{A_{bond}}. \qquad (2)$$

5. Results and Discussion

The measured bonding strength not only depends on the bonding process, but the test speed as well. Because of the requirements of quality control during the manufacturing of micro systems, a large number of MEMS devices and test structures have to be characterized. To optimize the yield and provide adequate and reliable material properties, the influence of the testing speed on the micro chevron measurement and the shear test has to be analyzed.

During micro chevron testing, the fracture toughness is directly related to the test speed. Reducing the speed, the

measured fracture toughness converges towards a final value, Fig. 9. Based on the measured maximum forces and the numerically determined stress intensity coefficient, a fracture toughness of 0.57 N $m^{0.5}/mm^2$ can be calculated for the glass frit bonded wafers.

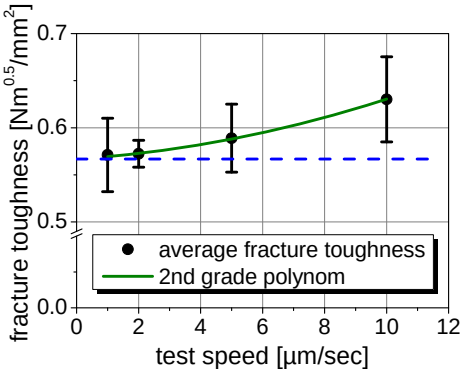

Fig. 9. *Influence of testing speed on the fracture toughness*

Increasing the speed during testing from 1 µm/sec to 2 µm/sec, the change in the average fracture toughness is negligible, while an increased speed of 10 µm/sec causes a 10 % higher fracture toughness. For micro chevron testing the loading speed shall be smaller than 5 µm/sec to minimize the deviation between real fracture toughness and the fracture toughness measured during experiment.

The shear strength also depends on the traverse speed. A correlation between shear strength and test speed can be observed analogues to the micro chevron test, Fig. 10.

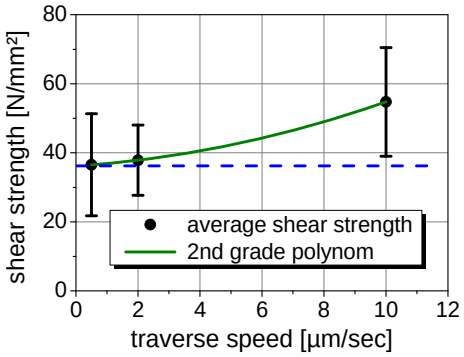

Fig. 10. *Influence of testing speed on the shear strength*

The average shear strength measured during experiment reaches values of 37 N/mm^2. Increasing the traverse speed from 1 µm/sec to 10 µm/sec, the measured shear strength is 50 % higher.

6. Conclusion

Based on the experimental results, a correlation between test speed and the measured bonding strength can be observed. To minimize the influence of the test procedure on the measured fracture toughness, the test speed should not exceed 5 µm/sec. During shear testing, a maximum traverse speed of 4 µm/sec is recommended. Otherwise, a smoothing function is required to determine the fracture toughness or shear strength out of the measured force.

Acknowledgements

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