Considerations for bond strength metrology and standards

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Abstract
Chevron based bond strength structures provide significant advantages over the double cantilever beam method commonly in use. We introduce new bond strength test structure designs with the goal of simplifying the implementation of the chevron test and improving the availability of bond strength metrology. We describe designs based on chip-to-chip bonding which could be expanded to chip to wafer. There are both asymmetric bond structures based on separate designs for the top and bottom chips and symmetric designs in which the same chip design serves as both top and bottom. We describe a fabrication process which is compatible with both blanket dielectric and metal bonding surfaces as well as patterned surfaces including hybrid bonding type materials. We also describe a testing apparatus and the potential to adapt commercial die shear testers for this measurement. Finally, we describe a plan to realize research grade test materials based on these test structures.

Key words
bond strength, chevron, fabrication, and standards

I. Introduction
The utilization of advanced bonding and integration techniques has dramatically increased in the last decade. Dielectric to dielectric direct bonding forms the basis for hybrid dielectric/copper bonding employed for the finest pitch chip to chip, chip to wafer, and wafer to wafer interconnects [1]. Additionally, dielectric bonding is employed for a wider variety of materials than ever before for emerging technologies [2]. Development of bond strength measurements and standards have not tracked with technological advances. Dielectric bonding processes can have exceptionally high bond strengths. While this trait is clearly desirable, it increases the difficulty of assessing the actual bond strength and dependence of bond strength on process conditions. Here, we survey existing bond strength measurements and standards and propose tracks of investigation to improve measurements and standards with an eye to improving range of bond strength, ease of use, and extension to more formats of test structures.

II. Bond strength measurements and Standards
The most common dielectric bond strength measurement is the double cantilever beam (DCB) method also known as the Maszara test [3] in the wafer bonding field. The simplicity of the method is largely responsible for the wide adoption. In the most common implementation, a razor blade is driven into the bonded surface at the edge of two bonded wafers. The beveled edge of the wafers facilitates directing the razor blade. Imaging, typically in infrared, is used to measure the distance between the crack front and the razor blade. This distance is used along with dimensions of the razor blade and dimensions and properties of the substrate to infer the bond strength that is preventing further propagation of the crack front. Drawbacks of the method include the inability to initiate a crack for high bond strengths, a requirement for beveled edges typically only found with wafer-to-wafer bonding, and sampling only of the edge of the bonded wafers. Additionally, time dependent behavior of the crack front has been observed due to interaction with atmospheric

water vapor [5]. DCB tests can also be performed on small test samples diced from bonded wafer pairs. However, since these chips do not generally have beveled edges, the DCB test is difficult to realize. Despite the issues with the DCB method, the simplicity of the approach and minimal sample preparation, have facilitated adoption over other more preparation intensive methods such as four-point bending or nano-indentation testing.

In the 2000s, a bond strength method and associated standard (SEMI MS5) based on chevron notch testing was developed to address some of the shortcomings of the DCB method [6] while attempting to limit sample preparation burden. Chevron notch testing is widely employed to measure material toughness to crack formation and uses a V-shaped notch to initiate stable crack growth [7]. To realize this for wafer bonding, micro-chevron mesas are patterned into one wafer and bonded to another un-patterned wafer. Individual bonded test structures are diced out, each structure has pull studs attached with glue, and a destructive pull test is conducted. Each micro-chevron structure design requires mechanical finite element modeling (FEM). The required FEM modelling produces characteristic force vs. distance curves for both successful (fracture at the bonded surface) and unsuccessful (for instance fracture of the substrate). Further advantages of this method are the ability to map bond strength across a wafer and the ability to do chip to chip bonding and testing.

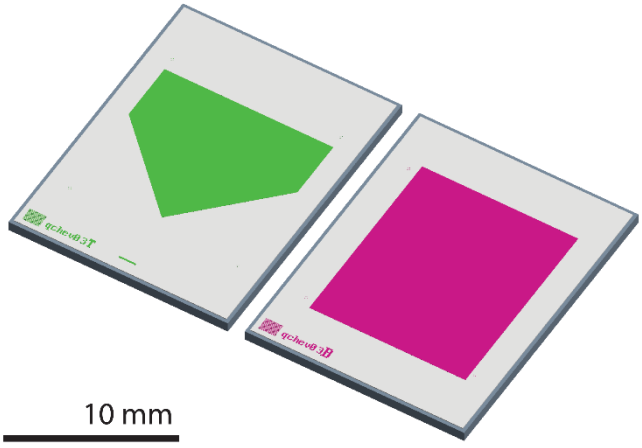


Figure 1. Rendering showing the design of a bond test die pair. Both the top die and the bottom die are 13 mm by 17 mm. Each die has a bonding surface mesa. The top die mesa (green) has a chevron structure consistent with SEM MS5 to initiate the crack. The bottom die (violet) has a "blanket mesa" etched into it. The different colors are for clarity. The bonding materials could be the same or different.

Despite these advantages, the micro-chevron method and standard have not seen widespread adoption. Here, we propose modified versions of the method which should have multiple advantages. We suggest a chip-to-chip micro-chevron test structure that does not require glued studs, which should decrease test cycle times and more efficiently test the impact of process conditions. This variant can also utilize symmetric test structures in which identical chips are bonded together

III. Test Structure Design

A primary goal is to increase adoption of the chevron style bond test structure. To that end, we seek to produce a structure which does not require glueing of metals studs to accomplish the bond strength test. Through bonding of two similarly sized rectangular die, the resulting structure will be a central bonded region with the overhanging edges of one chip used to mount the structure in a fixture, while an overhanging edge of another chip can be used to apply a force for the bond strength measurement.

Initially, we chose to develop a test structure compatible with Si to Si bonding, but expandable to other materials and material combinations. Fig. 1 shows an asymmetric test die set based on the chevron structure described in SEM MS5 and FEM from that standard is applicable. Fig. 2 shows a different chevron design which requires different FEM modeling, but with this symmetric version the same design serves as both the top and bottom die. We also note that we have designed test structures compatible with the pull-stud type test for comparison with these newer test structures. Fig. 2 also shows some common features of the asymmetric and symmetric test structures. The die size is 13 mm by 17 mm, but other sizes are possible. The dies have a raised mesa for the bonding surface and alignment marks that allow micron level alignment and measurement of post-bond alignment. An optional feature is an additional etch at the edges of the die. The intent of this etch is to limit the impact of particles that accumulate from handling during the bonding processes. The hope is that most particles from tweezers are situated well below the bonding surface.

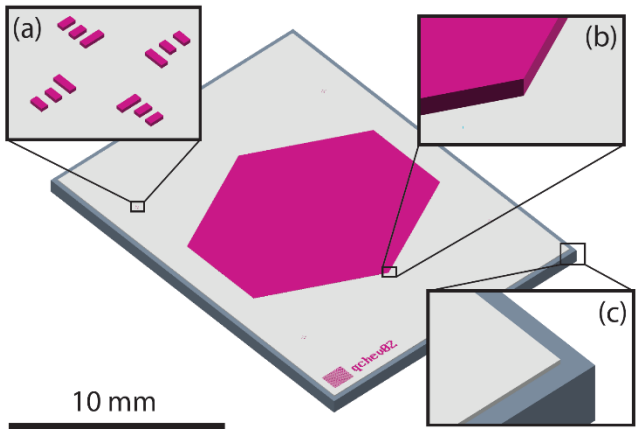


Figure 2. Rendering showing the design of details of the test structure die configured for a symmetric test in which the same design serves as the top and bottom die. (a) detail of the vernier alignment. (b) detail of the mesa etch showing the chevron point to initiate the crack. (c) detail of the die edge showing the trench etch included to prevent particles resulting from handling from interfering with bonding

IV. Fabrication and Bonding

The fabrication begins with bare silicon wafers of 150 mm diameter and 0.675 mm thick. The wafers are double side polished and of <100> orientation. The wafers are intrinsic wafers grown with a float zone process. The total thickness variation of the wafer batch is less than few µm.

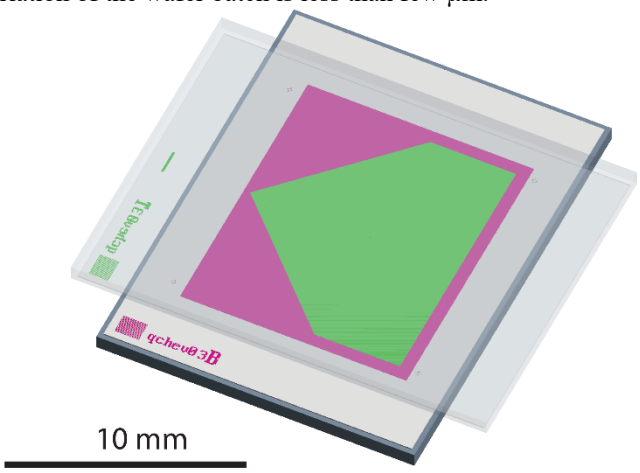


Figure 3. Rendering of asymmetric bonded structure using die shown in Fig. 1. The top die with green mesa is flipped onto the bottom die with violet bonding mesa. The top die substrate is rendered partially transparent for clarity. The exposed edge on the bottom die allows for mounting in fixturing while the exposed edge on the top die provides a region to apply force

All lithography is accomplished with an i-line step and repeat exposure system. In the first step, and i-line photo-resist nominally 1 µm thick is coated and baked on the wafer. Alignment marks are patterned on the wafer and etched approximately 120 nm deep. After solvent stripping, the mesa and bonding alignment marks are patterned into 4 um thick resist and etched using a Deep Reactive Ion Etching (DRIE) process. The DRIE etch yields mesas that are 5 µm to 7 µm raised features. The mesa top is the bonding surface and in this case is silicon, but other blanket or patterned dielectrics or metals could be built into the mesa. The last fabrication step is a trench etch either 50 µm or 100 µm deep and 200 µm wide around the perimeter of the die. The 10 µm thick photo-resist used for this step is left on the wafer to serve as protective dicing resist. The wafer is then diced with streets aligned to the center of the trenches.

Individual die are cleaned of photo-resist with solvents and treated with a He and H_2 downstream plasma. The plasma head has a linear aperture 25 mm wide and was operated at a power of 100 W. A gas mixture of 6 sccm of pure He and 4 sccm of 3.9% H_2 in He was used to obtain a dilute H_2 in He plasma. The plasma head was positioned 1 mm above the chips, and each chip received four passes of treatment. Studies of bonding strength as a function of treatment are planned.

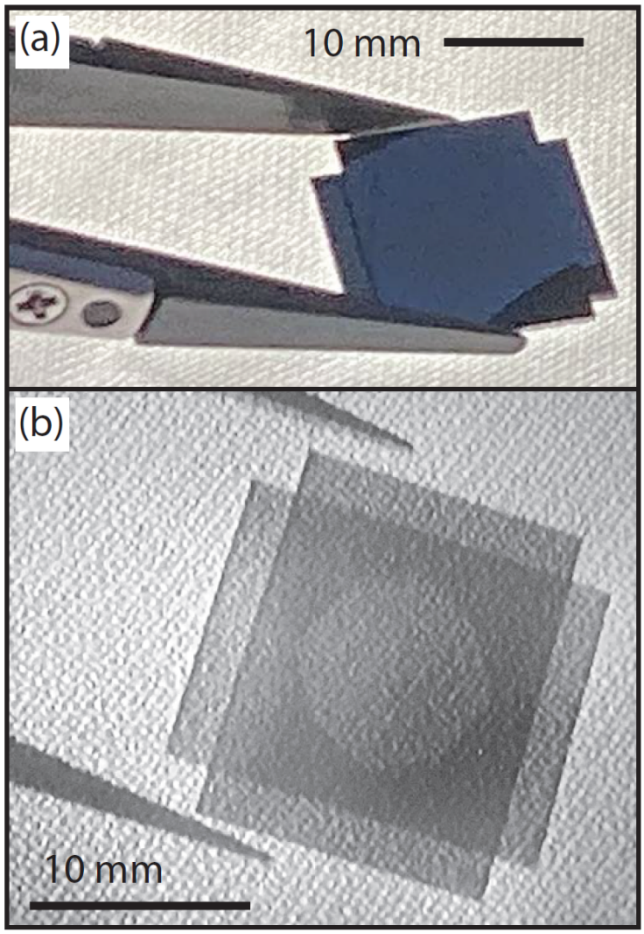


Figure 4. Photographs of a symmetric bonded structure. (a) visible light image of two identical 13mm by 17 mm die bonded together. Tweezers surround the bonded structure. (b) infrared image of bonded structure taken with back illumination. The bonded mesas are visible in the center. The overall texture is due to the part sitting on a cleanroom wipe.

After treatment, a set of chips are bonded in a flip-chip bonder at room temperature. A 12 mm by 12 mm silicon-carbide tool is used to pick up the 13 mm by 17 mm top chip. The top chip is aligned to the bottom chip and adjusted to be coplanar with the bottom chip through either an autocollimator or laser leveling system. Typical applied force is 10 kg-F and pre-bond alignment is generally better

than 1 um. Pre-bond planarity is typically better than 100 µ-radians.
After bonding, infrared microscopy is used to determine post-bond alignment and note if there are any voids present in the bonding region. White-light spectro-photometry is used to measure the chip gap and uniformity of the chip gap. As a last step, the bonded structures are annealed at a temperature of 300 °C for a duration of 4 hours.

V. Bond strength test apparatus

Initial measurements of the symmetric chevron test structure are to be performed using the two-piece test jig shown in Fig. 5. Unlike the pull studs used in the conventional chevron test, this jig requires relatively simple alignment and ensures the pull force is applied to the correct axis. The bonded chip pair is glued to the base and attached to the lower connection to the material test machine. The "grabber" is then aligned below the edge of the upper chip to facilitate a pull test.



Figure 5. Bonded chip pair mounted on materials test machine prior pull test. The chip pair is glued to the lower stud, while the upper "grabber" wraps around the exposed edge of the upper chip to apply force.

The apparatus described above is not necessarily found in micro-fabrication facilities. However, bond testers designed to evaluate die adhesion through shear tests that realize MIL-STD-883 are more common. Through different fixturing the pull test described can be realized with a shear test type configuration and this is an avenue of ongoing study.

VI. Conclusion

Bond strength metrology can benefit from new types of methods and standards. Increasing the availability of chevron type bond tests should allow for more convenient and rapid testing of bond strength with processing conditions. We have demonstrated the fabrication of chevron die test that does not require glueing of studs for pull tests and have manufactured fixtures that are compatible with a metrology grade pull tester. As we gain experience with this type of testing, we will also apply to develop measurement fixtures that are compatible with bond tester equipment that is commonly used for die shear testing. In parallel, we will produce test die for SiO2 to SiO2 and Cu to Cu testing as well have test die with patterned SiO2:Cu material which is representative of what is used in hybrid bonding. We anticipate distributing these structures through the NIST Research Grade Test Material program [8].

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