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AN INTENSITY TESTING MODEL AND EXAMINATION OF GOLD–SILICON WAFER BONDING

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A bonding intensity testing method, called Press-arm model, has been successfully designed and verified by Ansys finite element analysis. The gold–silicon bonding strength $[\sigma_2]$ = 238 MPa has been measured by the Press-arm model. We can probably determine the $[\sigma_2]$ value and compare the bonding strengths by the Press-arm length *l*. The model can also be used in other type of bonding. The bond region is sufficiently stronger than the silicon substrate. A substrate-Si/Cr/Au/poly-Si/Au and a silicon substrate is bonded at 380–450°C. It occurs as soon as the dissolving of the SiO_2 layer by silicidation of the Cr barrier layer. To avoid gold contamination to the silicon die, an excess annealing temperature (about 20°C higher than Au–Si eutectic horizontal) is used. The bonding surface with brick pattern is in favor of Au–Si bonding.

Keywords: Eutectic bonding; gold–silicon; strength test.

1. Introduction

Silicon wafer-to-wafer bonding offers important technical and economic opportunities for manufacturing in MEMS such as Au–Si bonding, which has attractive features like low processing temperature, liquid-phase and insensitivity to minor geometrical irregularity.[1] The mechanism and intensity are extensively investigated.[2] The bonding is to merge wafers containing circuits with micromechanically-processed wafers, and without degradation of either performance. Obviously, oxide on the circuit wafer is for passivation and thus is functional, which implies that it cannot be removed for wafer-bonding convenience. Usually a titanium or chromium layer is deposited between the oxidized silicon substrate and the gold layer to ensure adhesion.[2] However, silicide grains are formed at the bonding interface.[3] The oxides, which inhibits the bonding, can also be avoided in vacuum or in nitrogen ambient to some extent.[4] If we know the intensity value of the bonding interface through a model, we can rearrange the bonding model for the sake of getting the optimum procession of the wafer capsulation.

This paper shows that a Press-arm style model has been designed, and verified by Ansys finite element analysis method. The bonding strength is determined. The optimum processing and the additional layers and the mechanism have been discussed.

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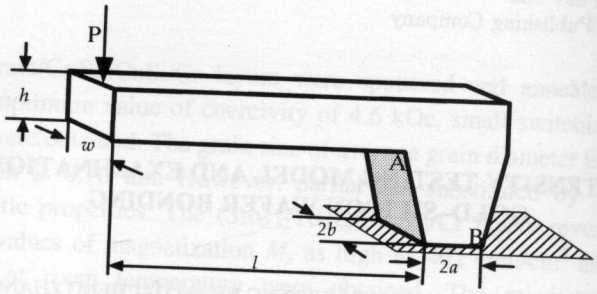


Fig. 1. Scheme and size of Press-arm style model.

2. Design and Analysis for Test Model

A test structure of Au–Si Bonding intensity is designed in Fig. 1. We call it Press-arm model. To ensure that it does not crack at the point A, the formula of σ_1 must come into existence as

$$\sigma_1 = \frac{Pl \cdot (h/2)}{wh^3/12} = \frac{6Pl}{wh^2} \leq [\sigma_1] . \tag{1}$$

If the crack occurs at the point B, formula (2) can be driven

$$\sigma_2 = \frac{P(l+a) \cdot a}{2b \cdot (2a)^3/12} - \frac{P}{2a \cdot 2b} \geq [\sigma_2] . \tag{2}$$

We may suppose

$$w = 2b . \tag{3}$$

$$a = b . \tag{4}$$

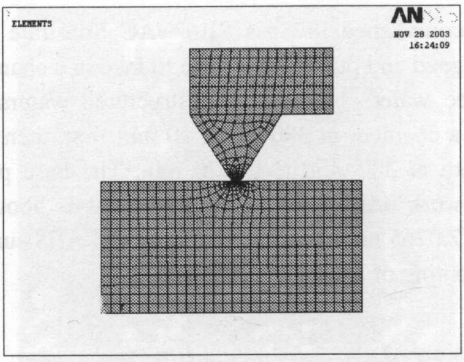
From formula (1)–(4), we can get

$$\frac{4a^3[\sigma_2] - 2Pa}{3P} \leq l \leq \frac{ah^2[\sigma_1]}{3P} . \tag{5}$$

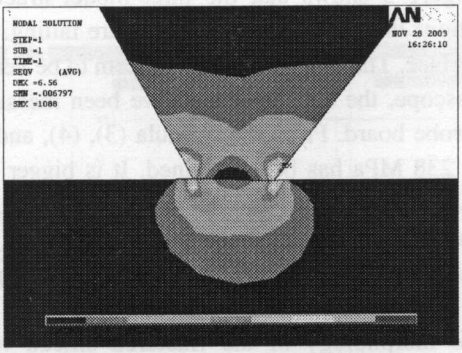
According to the ICP processing, thickness h should be $\leq 150\ \mu$m.[1,5] When we select values of $[\sigma_1] = 200$ MPa, $[\sigma_2] = 260$ MPa, and $P = (1/2)\{[\sigma_1] + [\sigma_2]\}$, formula of σ_1 must come into existence, and the formula of σ_2 can be determined

$$\frac{8a}{3} \leq l \leq \frac{50000}{a} . \tag{6}$$

From formula (6), we can get the probable size of the model structure, and obtain the value of P. It is equal to 0.5–3 kg, which can be measured on the probe board.



(a)



(b)

Fig. 2. Stress simulation of Press-arm style model by Ansys software: (a) grid segmenting and (b) stress distributing.

Bonding strength $[\sigma_2]$ can be driven when l and a value are measured.

If select a series of l values in different models, we can probably determine the $[\sigma_2]$ value by a definite l when the bonding interface is cracked. So we can compare the bonding strengths of different models from the different sizes of l.

From Fig. 2, we can simulate the test structure by Ansys finite element analysis. The simulating result is consistent with what we calculate by Press-arm model measuring above. These two methods should be verified in experiment in the below section.

3. Experiments

The two- or three-model-structured wafers are bonded. One side of the frame has been sputtered with multilayer structures as substrate-Si/SiO_2 (nature oxide)/Cr (200 Å)/Au (1000 Å)/Si (500 Å)/Au (1000 Å). The matching surface is pure Si substrate. The other bonding surface is designed with brick pattern to compare with the pure Si substrate.

The bonding is accomplished in Suss SB6 VAC Substrate Bonder system. Two structured wafers are aligned and put together face to face in a chamber at 380–450°C for 10–15 min, and in three wafers bonding, two structured wafers are aligned and put together face to face in a chamber at 380°C for 10 min first, then put the third piece of wafer together with them at 380–450°C for 20 min. The base pressure is lower than 1×10^{-4} mbar and the work pressure of the nitrogen gas is about 1.01325 mbar. The vertical bonding load is 2.0265 mbar, and a PHI-610/SAM AES survey system is used to check the element distributing of Au–Si eutectic section.

4. Results and Discussion

The two-model-structured wafers are bonded. They are successfully cut into small units about 6.5 × 6.5 mm. Figure 3 shows that the three-model-structured wafers are also bonded. The razor insertions in the bonding specimens are failing. There are no obvious voids in the bonding interface. The assembled wafers seem to be very tight.

Under optical microscope, the l and a value have been measured, and P value has been examined on the probe board. From the formula (3), (4), and (2), the gold–silicon bonding strength $[\sigma_2]$ = 238 MPa has been obtained. It is bigger than silicon substrate strength $[\sigma_1]$ = 180–200 MPa. We have selected a series of l values in different models. So we have probably determined the $[\sigma_2]$ value by a definite l, when the bonding interface is cracked. In a word, we can compare the bonding strengths from the sizes of l.

Figure 4 shows the morphology of the fractured silicon lump adhered on the solidified eutectic, and the bonding interface is still unchanged. This indicates that the bonded region is sufficiently stronger than the silicon substrate. The bonding surface is designed with brick pattern. Only part area of the matching interface is required to touch. The wedge-shaped groove accommodates the swelling and shrinking of the gold–silicon eutectic, when heating up and cooling down. So the brick pattern is useful for bonding.

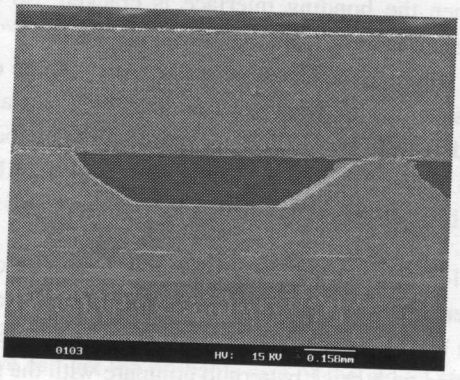


Fig. 3. Cross-sectional SEM image of the tri-wafer bonded structure.

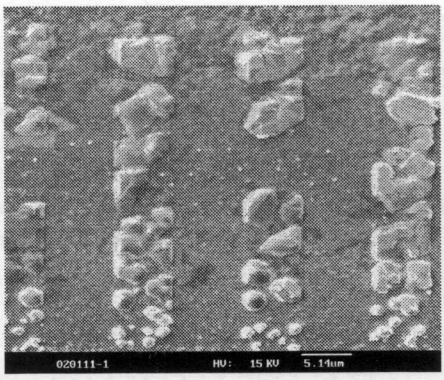


Fig. 4. SEM images of a ruptured bonding surfaces.

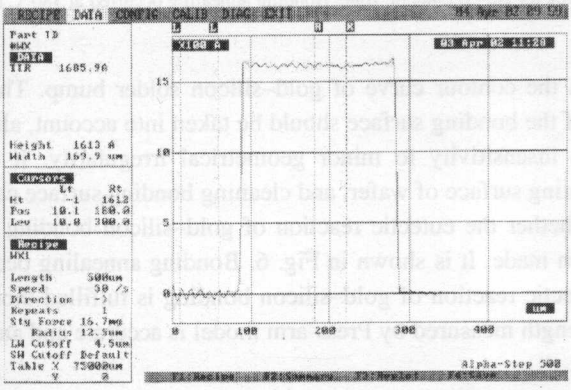


Fig. 5. The contour curve of Au–Si solder bump.

The bonding occurs between substrate-Si/SiO_2/Cr/Au/Si/Au and Si wafer as soon as the dissolving of the SiO_2 (nature oxide) by silicidation of the $CrSi_2$. Since gold is difficult to adhere on a nature oxidized surface of silicon wafer, deposition of a thin intermediate Cr film that adheres well to the oxide, and subsequently the deposition of an Au layer on the top have been applied. The very limited solubility of silicon in chromium would prevent the Au–Si eutectic composition from being reached by difficult diffusion of silicon through the chromium into the gold. Silicidation takes place at about 380°C.[5,6] The bonding temperature of 380–450°C is contributed to overcome the interfacial tension and to the dynamics of silicon diffusion to gold layer.

It is interesting to note that below the eutectic temperature gold diffuses into the silicon rather than the silicon into the gold, and gives rise to silicide ($SiAu_3$) formation.[6] Thus, an excess annealing temperature (about 20°C) over the eutectic temperature (363°C) should be used to avoid gold contamination of the silicon die with the possible deteriorating effect on integrated microelectronic device properties.

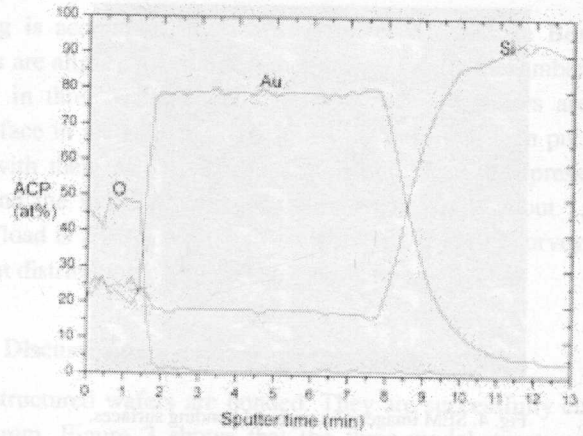


Fig. 6. AES survey for Au–Si eutectic zone. Bonding annealing occurred at 380°C for 15 min.

Figure 5 shows the contour curve of gold–silicon solder bump. The result reveals that the roughness of the bonding surface should be taken into account, although it is said that the bonding is insensitivity to minor geometrical irregularity. It is necessary to choose smoother mating surface of wafer, and cleaning bonding surface carefully.

To check up whether the eutectic reaction of gold–silicon bonding is fulfilled, the AES survey has been made. It is shown in Fig. 6. Bonding annealing occurred at 380°C for 15 min. The eutectic reaction of gold–silicon bonding is fulfilled thoroughly. So the eutectic bonding strength measured by Press-arm model is accurate and authentic.

5. Conclusions

The bonding strength $[\sigma_2]$ = 238 MPa has been measured by the Press-arm model. It is bigger than silicon substrate strength $[\sigma_1]$ = 180–200 MPa. When a series of l values is determined, the $[\sigma_2]$ value will be determined and the strengths can be compared. This model can also be used in other type bonding. The bonding between a substrate-Si/Cr/Au/poly-Si/Au and a silicon substrate has been completed at 380–450°C. It occurs as soon as the dissolving of the SiO_2 layer by silicidation of the Cr barrier layer. To avoid gold contamination to the silicon die, an excess annealing temperature (about 20°C higher than Au–Si eutectic horizontal) should be used. The bonding surface with brick pattern is in favor of gold–silicon bonding.

Acknowledgment

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