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Design and Evaluation for Mechanical Strength of an Anodically Bonded Pressurized Cavity Array for Wafer-Level MEMS Packaging

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We present a strength evaluation method and design guidelines for a pressurized cavity array fabricated by the anodic bonding of silicon substrates to glass cavity plates. The mechanical strength of the bonding of a pressurized cavity array has been evaluated in terms of the interfacial fracture toughness measured for a silicon-glass specimen with pre-inserted blades. From a set of the glass-silicon bonding specimens, we have obtained an average value of the critical interfacial fracture toughness of 6.12 J/m^2. Using a theoretical analysis, a simple fracture mechanics model of the pressurized cavity array has been developed. The interfacial fracture toughness for a bonded cavity of infinitely wide plates has been derived analytically in terms of cavity dimensions, material properties and cavity pressure. For a bonded cavity of plates of finite width, we performed a finite element analysis and evaluated interfacial fracture toughness by varying intercavity bonding length. In the case of a cavity array with an intercavity bonding length longer than half the cavity length, the bonding strength approaches that of an infinite plate. For a cavity array having shorter intercavity bonding length, however, the bonding strength of the cavity array decreases as the ratio of the bonding length to the cavity size decreases. The measured interfacial fracture toughness and the derived equations result in a cavity design chart, which enables us to determine the ratio of bonding length to cavity size required for the failure-free wafer-level MEMS packaging of a pressurized cavity array.

1. Introduction

Wafer-level packaging of pressurized cavity arrays (Fig. 1) is required for the mass production of MEMS devices, where the microstructures need a fixed, reduced or increased pressure, such as pressure sensors,(1) vibrating gyroscopes,(2) biochips, and fluidic devices.(3) For the low-cost fabrication of the pressurized cavity arrays, the intercavity

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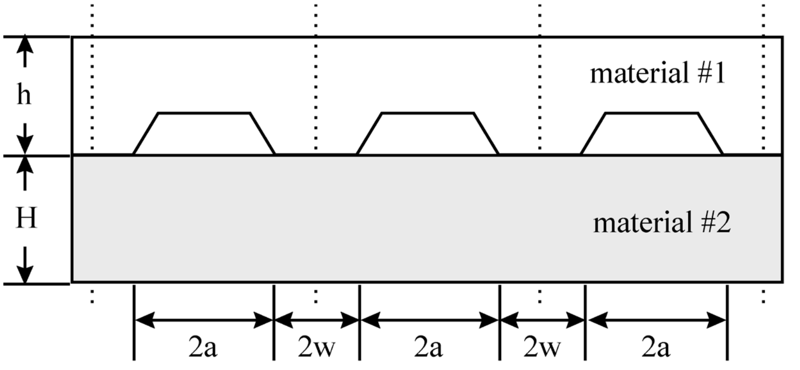


Fig. 1. Cross-sectional view of pressurized cavity array, fabricated by wafer-level anodic bonding of two dissimilar materials.

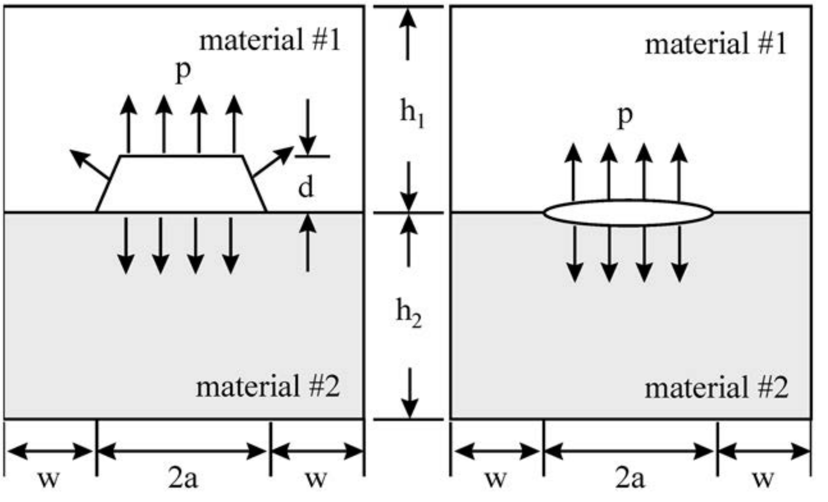
bonding areas should be reduced while maintaining the minimum mechanical bonding strength required for a given cavity pressure.

In this paper, we present a method of evaluating strength and design guidelines for a pressurized cavity array (Fig. 1), fabricated by the wafer-level anodic bonding of two dissimilar materials. Previously, bonding quality has been described in terms of bonded area,[(4)] gas tightness[(5)] and tensile strength.[(6,7)] The bonded area and the gas tightness, however, cannot be a direct indication of the mechanical strength of bonding. The tensile strength cannot be used as a consistent measure of the bonding strength, since tensile test results are largely dependent on loading conditions and specimen geometry. In addition, the tensile strength test is difficult in terms of preparing the specimen and making the measurements, especially for the evaluation of high strength bonding between thin and brittle layers. We consider interfacial fracture toughness[(8)] appropriate for the consistent measurement of bonding strength of anodically bonded pressurized cavity arrays, since it is a material property and is insensitive to the specimen geometry and loading conditions. On this basis, we have developed guidelines for the determination of intercavity spaces or bonding areas required for the failure-free bonding of a pressurized cavity array.

2. Theoretical Analysis

The strength of a pressurized cavity is evaluated in terms of interfacial fracture toughness.[(8)] When the interfacial fracture toughness of a bonded cavity under internal or external pressure exceeds the critical value, the mechanical failure of the bonded area occurs.

In order to obtain the interfacial fracture toughness, we apply interfacial fracture mechanics[(9)] to the pressurized cavity as shown in Fig. 2(a). We consider a unit cavity cell



(a) (b)

Fig. 2. Fracture mechanics models of pressurized cavity cell: (a) physical model; (b) simplified theoretical model.

of the pressurized cavity array formed by the bonding of two dissimilar and linearly elastic materials. We assume that the cavity depth, *d*, is small compared with the thickness of materials, *h*, and the cavity length of the unit cavity cell, 2*a*. Thus, we simplify the pressurized cavity cell in Fig. 2(a) into the simple crack model in Fig. 2(b).

Figure 3 illustrates the principle of superposition, which enables us to obtain an equivalent crack model from the simplified model in Fig. 2(b). The model in Fig. 3(a) can be expressed by the superposition of Fig. 3(b) and Fig. 3(c). In Fig. 3(c), the crack face closes due to a uniform compressive pressure so that the plate behaves as if the crack does not exist. Since the interfacial fracture toughness due to the pressure in Fig. 3(c) is zero, the interfacial fracture toughness of the pressurized cavity in Fig. 3(a) is equivalent that in Fig. 3(b). Thus, the physical model of Fig. 2(a) is reduced to the fracture mechanics model of Fig. 3(b), as summarized in Fig. 4.

For an infinitely wide plate (infinite *w* in Fig. 4(b)) showing no shear effect, the total strain energy stored in the two material plates is

$$U_T = U_1 + U_2, \tag{1}$$

where U_i is the stored strain energy in material i. Interfacial fracture toughness in terms of crack propagation in the infinite plate, G_i, can be estimated as follows:

$$G_i = \left(\frac{\partial U_T}{\partial a}\right)_P = \frac{c_1 p^2 a^4}{6h_1^3}\left(1 + \gamma\eta^3\right), \tag{2}$$

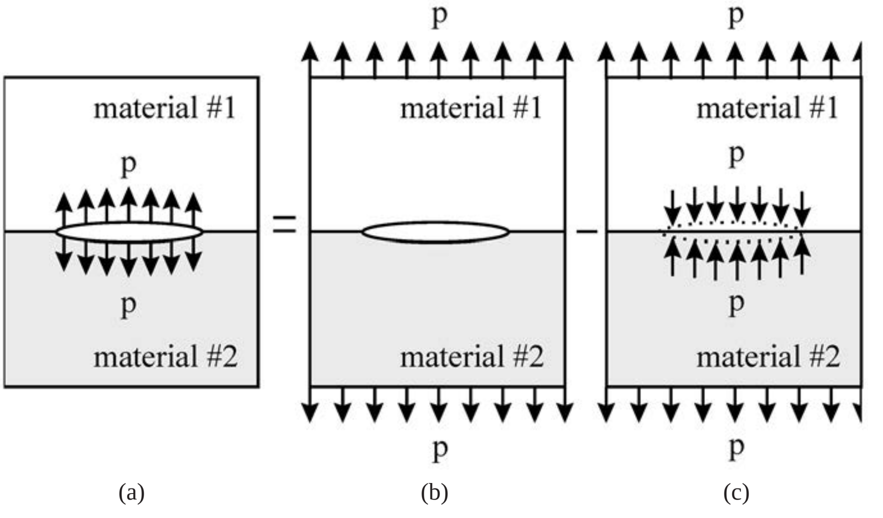


Fig. 3. Superposition method of equivalent crack model with pressurized cavity.

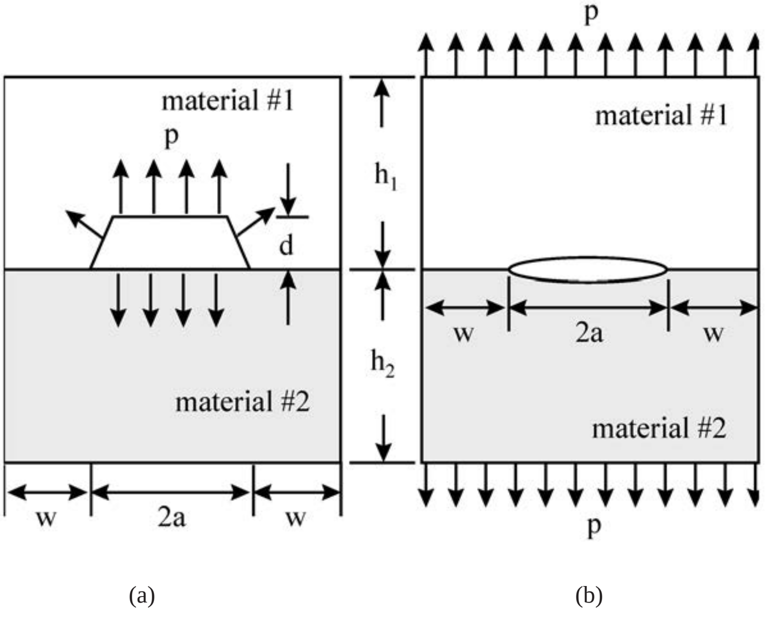


Fig. 4. Equivalent crack models for pressurized cavity cell: (a) physical model of Fig. 2(a); (b) fracture mechanics model derived from superposition principle.

where *a* denotes the crack length; *p*, the applied pressure; and h_i, the thickness of material i. The other constants, γ and η, are defined as follows:

$$\gamma = \frac{c_2}{c_1} \tag{3a}$$

$$\eta = \frac{h_2}{h_1} , \tag{3b}$$

where c_i denotes the material compliance component of the material i as follows:

$$c_\mathrm{i} = \frac{8(1-\nu_\mathrm{i})}{E_\mathrm{i}} . \tag{4}$$

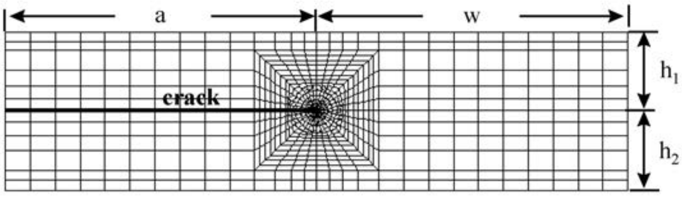
For a plate of finite width (finite *w* in Fig. 4(a)) having an identical crack, the interfacial fracture toughness is different from that of the infinitely wide plate. As the plate width decreases, the stress distribution near the outer boundary becomes different from that of the infinitely wide plate. We perform finite element analysis(10) with a crack size of a=2 mm and a substrate thickness, h_2=500 μm. Figure 5 depicts a meshed crack model with a crack. ABAQUS, a finite element analysis program, is used to obtain the value of the *J* contour integral,(9) which is the same as the interfacial fracture toughness for a linear elastic material. From the meshed crack model in Fig. 5(a), we obtain the normalized interfacial fracture toughness (Fig. 6) in terms of intercavity bonding length, cavity length ratio (w/a) and plate thicknesses (h_1, h_2). Figure 6 compares finite-element analysis results, G_f, for the plates of finite width and the theoretical interfacial fracture toughness, G_i, of the infinitely wide plates.

We find that, for the case of $w > 0.5a$, the bonding strength of the plates of finite width approaches that of the infinite plates. For $w < 0.5a$, however, the bonding strength of the plates of finite width decreases as w/a decreases.

3. Experimental Analysis

For a quantitative evaluation of the bonding strength of the anodically bonded pressurized cavity array, we experimentally measured the critical interfacial fracture toughness from the blade test specimen,(8) as shown in Fig. 7. A set of test specimens has been fabricated by the anodic bonding of 500-μm-thick Pyrex 7740 glass (material 1) and 500-μm-thick silicon substrate (material 2) with an 80-μm-thick pre-inserted aluminium blade at the bonded interface. Figure 8 shows the anodic bonding apparatus, for which we control bonding load, temperature, voltage and time. Using this apparatus, we have fabricated a set of anodically-bonded test specimens (Fig. 7) at 460°C by supplying an anodic potential of 800 V for 25 min with a bonding load of 45 gf/cm^2. From three test

(a)



(b)

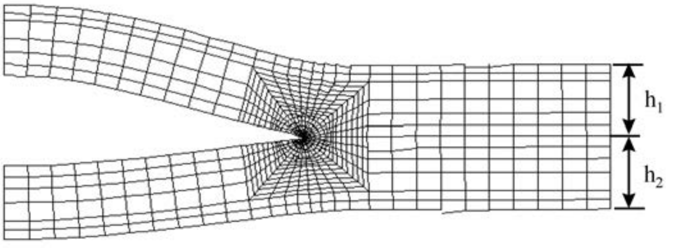
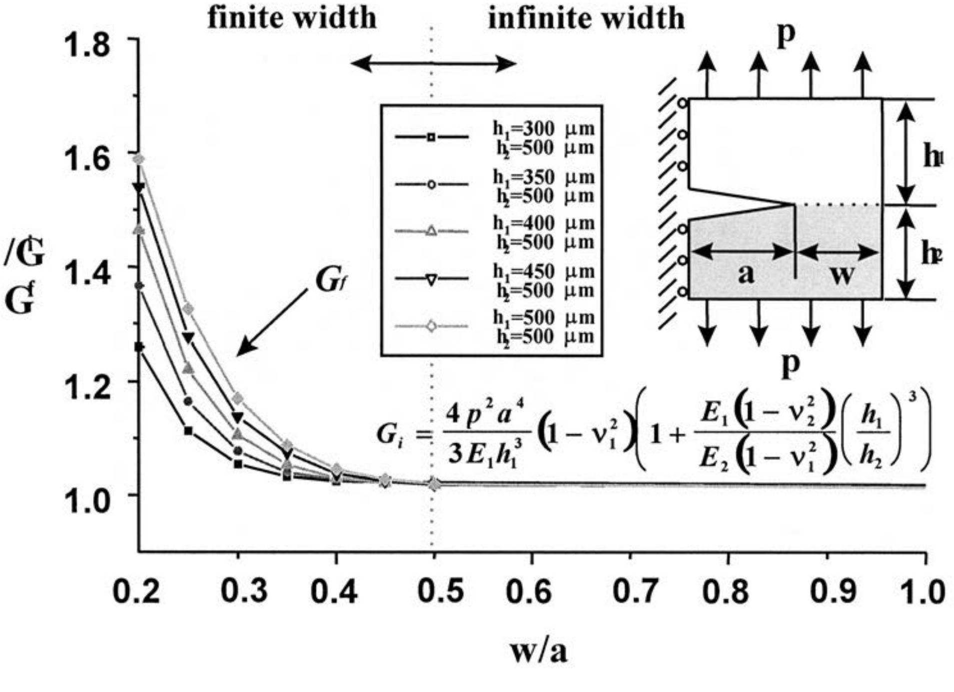


Fig. 5. Finite-element analysis of plate of finite width with crack: (a) finite-element model; (b) results of finite-element analysis deformed shape.



$$G_i = \frac{4p^2a^4}{3E_1h_1^3}\left(1-\nu_1^2\right)\left(1+\frac{E_1\left(1-\nu_2^2\right)}{E_2\left(1-\nu_1^2\right)}\left(\frac{h_1}{h_2}\right)^3\right)$$

Fig. 6. Interfacial fracture toughness of plate of finite width, G_f, and that of infinite plate, G_i, with identical crack.

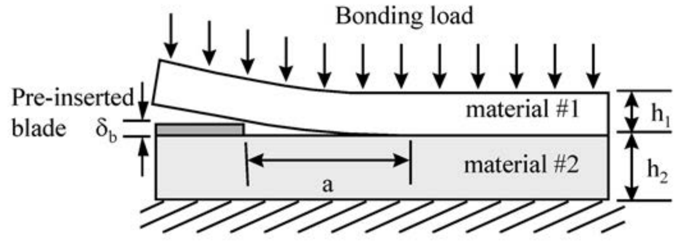


Fig. 7. Test specimen with preinserted blade.[(4)]

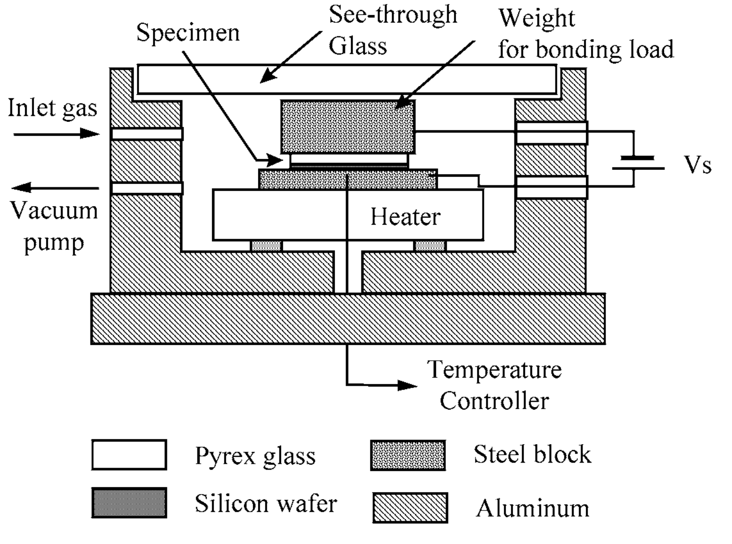


Fig. 8. Apparatus for anodic bonding with controlled bonding load, temperature, voltage and time.

specimens, we have measured the crack propagation length (Fig. 9) and obtained the average values of the critical interfacial fracture toughness, G_c, of 6.12 J/m^2, as listed in Table 1. More details on the blade test method and specimen fabrication process can be found in previous work.[(8)]

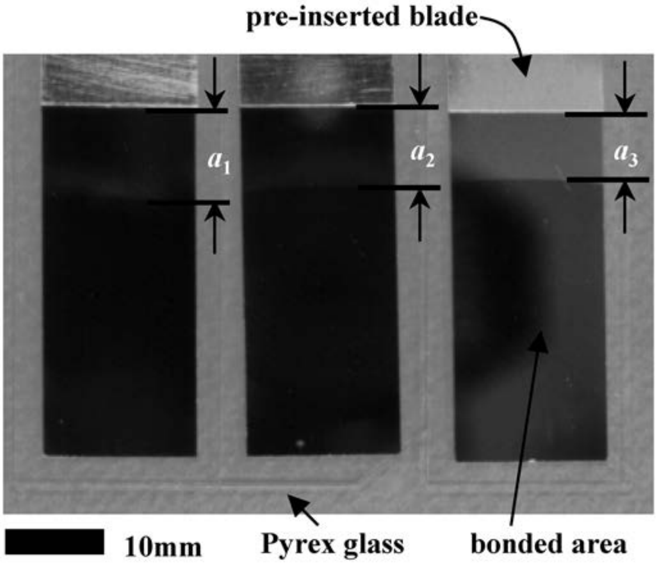


Fig. 9. Interfacial crack propagation length, a_i, under same bonding conditions.

Table 1
Crack propagation length and energy release rate measured from blade test specimen in Fig. 7.

	Crack propagation length, a (mm)	Energy release rate, G_i (J/m^2)
Specimen I	8.10	4.48
Specimen II	6.26	7.45
Specimen III	7.40	6.43
Average value	7.25±0.76	6.12±1.23

4. Design Guidelines for Critical Cavity Pressure

The mechanical failure of the anodically bonded pressurized cavity occurs when the interfacial fracture toughness exceeds the critical interfacial fracture toughness (G_c). For a plate of infinite width (or $w/a > 0.5$), eq. (2) is expressed in terms of the cavity pressure. From considerations of mechanical strength, the critical cavity pressure, p_c, can be obtained as follows:

$$p_c = \left[\frac{6h^3 G_c}{c_1 a^4 \left(1 + \gamma \eta^3\right)} \right]^{1/2}. \tag{5}$$

On the basis of the interfacial fracture toughness in Fig. 6 and the measured critical interfacial fracture toughness (G_c) of 6.12 J/m^2, we have obtained a cavity design chart (Fig. 10) showing the maximum cavity pressure permitted for an anodically bonded silicon-glass cavity array while varying the bonding length and cavity length ratio, *w*/*a,* and the plate thicknesses (h_1, h_2). Figure 10 enables us to determine the failure-free pressure range in the designed cavity array having plate thickness, h_1 and h_2, cavity size, a, with a certain safety factor, s, as follows:

$$p_a = \frac{p_c}{\mathrm{s}}, \tag{6}$$

where p_a denotes the allowable maximum pressure for failure-free packaging.

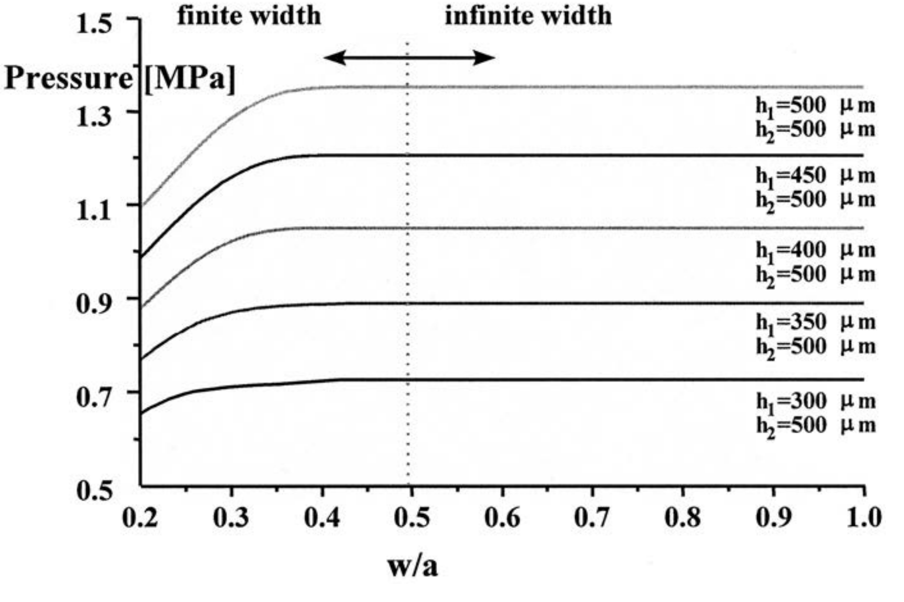


Fig. 10. Critical cavity pressure for anodically-bonded pressurized cavity array in terms of bonding length and cavity length ratio, *w*/*a*, and plate thicknesses (h_1, h_2).

5. Conclusions

In this paper, we presented a strength evaluation method and design guidelines for an anodically bonded pressurized cavity array. The design guideline chart for the failure-free cavity array design shows the maximum cavity pressure permitted for the anodically bonded silicon-glass cavity array. We derived a simple fracture mechanics model of a pressurized cavity cell formed by the anodic bonding of two dissimilar and linearly elastic substrates. In the experimental study, we measured the critical interfacial fracture toughness from a silicon-glass bonding specimen with preinserted blades. The interfacial fracture toughness of the infinite width plates was found as a function of the cavity length, material properties and cavity pressure. For plates of finite width, we performed a finite-element analysis to evaluate the interfacial fracture toughness in terms of the bonding length and cavity length ratio (w/a) and plate thicknesses (h_1, h_2). We found that, for the case of $w > 0.5a$, the bonding strength of a plate of finite width approaches that of the infinitely width plate, while, for $w < 0.5a$, the bonding strength of a plate of finite width decreased as w/a decreased. Using a critical interfacial fracture toughness of 6.12 J/m^2 measured from the anodically bonded silicon-glass plates, we developed a cavity design chart for application to wafer-level MEMS packaging having fracture-free pressurized cavity arrays.

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