Strain energy due to splitting forces as a basis for bonding criterion in wafer bonding

Y. Zimin*, T. Ueda

Graduate School of Information, Production and Systems, Waseda University, 2-7 Hibikino, Wakamatsu-ku, Kitakyushu-shi, Fukuoka 808-0135, Japan

A B S T R A C T

Direct wafer bonding is an important technology in sensor manufacturing, but bonding strength between different materials is still in need of improvement due to thermally induced internal stresses. To estimate the negative influence of the internal stresses, a bonding criterion has been established that compares the surface energy, which dissipates as the bond is formed, to the specific strain energy, which is stored in bilayers structure due to internal stresses. In the literature, general practice assumes that the specific strain energy is the strain energy of pure bending. However, from the physical standpoint, the strain energy due to pure bending represents neither the total strain energy nor the strain energy due to the splitting forces.

We have calculated the exact total strain energy of a curved bilayer and its two components: the strain energy due to the forces parallel and perpendicular to the interface. The strain energy of the forces perpendicular to the interface (splitting forces) has been proposed as the specific strain energy for the bonding criterion. The new specific strain energy strongly depends on the thickness ratio of the layers and can even equal zero at a certain thickness ratio called the point of equivalence. In turn, the point of equivalence does not depend on the total thickness of the bilayer structure. The point of equivalence, where internals stresses do not affect the bonding strength, was calculated for five structures: Si/Al_2O_3, $Si/GaAs$, $Si/LiNbO_3$, Si/SiC, and Si/InP.

The derived result has considerable importance for applications because it demonstrates how to avoid completely the negative influence of even strong internal stresses on the bonding strength.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Direct bonding of dissimilar materials requires a specialized approach due to the internal stresses created from differences in thermal expansion coefficients. Even bonding at room temperature does not eliminate the problem of residual stresses because the working temperatures of the devices can exceed 150 °C. Deviations from the ideal flatness of the wafers also create internal stresses after bonding that reduces the bonding strength and functionality of electronic devices. Therefore, bonded wafers with their complex structure of internal stresses require a proper theoretical study. A foundation for the analysis of internal stresses in bilayer structures was laid by Timoshenko; he analyzed the stresses in the central part of a bimetallic strip inside a bimetal thermostat [1]. In addition, he predicted inhomogeneity of shearing stress distribution at the edges of the structure and drew attention to its importance.

Much later [2] the residual stresses directed normally to the interface were shown to be created by the gradient of the shear stresses, one of the reasons for bilayer structure debonding. However, this phenomenon was of the "local" type [1] and concentrated near the edge of the structure [2,3]. Considerable effort has been devoted to analyzing residual stresses at the edge of bonded structures [4–8]. Authors [9–12] have proposed a bonding criterion for assessing the quality of bonding based on a comparison of surface energy and strain energy. Surface energy is dissipated as the bond is formed and can be measured experimentally using the crack-opening method [13], the chevron method [14], or their modern equivalents. Strain energy is due to the internal forces that directly affect the bonding strength so-called specific strain energy (SSE) must be calculated theoretically.

Influence of deviation from ideal flatness at the bonding strength was analyzed on an example of undulations of sine shape comparable with the thicknesses of the wafers by size [15,16]. Randomly distributed micro roughness as the reason of attenuating adhesion was considered in [17–19]. It is shown that negative influence of micro roughness on bonding strength occurs because of two rea-

* Corresponding author. Tel.:+81 070 5400 7578.
  E-mail address: ziminyury78@gmail.com (Y. Zimin).

sons: by means of reducing the bonding energy and increasing the SSE. Authors of [20,21] attempted to formulate the bonding criterion through comparison the internal stresses oriented parallel to interface with the strength of the bond oriented perpendicular to the interface. The proposed criterion does not appear to be physically enough substantiated because the stress and the bond are mutually orthogonal. General bonding criterion which is appropriate for bonding of blank and patterned wafers has been developed in [22–25]. The criterion is quite similar to the well-known Griffith criterion for the fracture and is based on the same concept.

In spite of the diversity of theoretical models, all models are based implicitly or explicitly on the general assumption that the only reason the strain energy affects the bonding plate is the energy stored in pure bending. This assumption can be accepted for some special cases but is definitely inappropriate for establishing the general bonding criterion. Pure bending or, more precisely, bending moment is just one of two elements of a statically equivalent force system for a bilayer structure; the second element is the axial force. In the full system, bending moment and axial force replace the joint action of all forces in the bilayer structure, but these are not the real forces acting in it; a fortiori, a bending moment without axial force cannot replace the real forces in bilayer structures. The strain energy due to axial force is an integral part of both the total strain energy of the bonded structure and the SSE. The combination of the bending moment and axial force provides a static equilibrium.

The proposed analysis seeks to reveal the SSE and clearly demonstrate its physical basis. The analysis strictly follows strength of materials theory and contains no additional assumptions or approximations. Bending moments and axial forces were considered equally. The calculated SSE seems to be the most appropriate candidate for the general bonding criterion.

2. Theory

The present analysis starts with Timoshenko's theory that was developed for the bimetal thermostat [1]. Similar to Timoshenko's approach, this analysis strictly follows the classical strength of materials theory. The main provisions of the classical theory play a key role in this analysis and are therefore important to note.

2.1. Basic provisions

The law of energy conservation provides additional independent relationships and makes the solution more understandable from a physics viewpoint. For analyzing the strain energy, two provisions must be performed: the material follows Hooke's law; small displacements due to strain do not affect external forces and can be neglected when calculating the stresses [26]. Therefore, the displacements of an elastic system are a linear function of the external loads, independent of the system's complexity. When several forces act on an elastic body, the amount of strain energy does not depend upon the order in which the forces are applied but is wholly determined by their final magnitudes. Whether the forces are applied simultaneously or sequentially, the total work done by all forces will equal the sum of the work done by the individual forces. The strain energy is equal to half of the scalar product of force and displacement; the scalar product means that only the component of the displacement that coincides with the force direction contributes to the strain energy. This feature is important for complicated structures where the action of even one force can cause complicated displacement patterns.

The interface interaction between two layers can be substituted with the statically equivalent system of axial forces and bending moments acting on each layer individually [1]. In this case, the strain energy of the whole structure can be represented as the
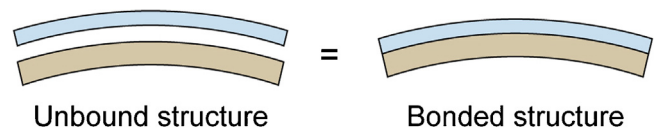

Fig. 1. Equivalency of the bonded and unbound structures of the same shape and size.
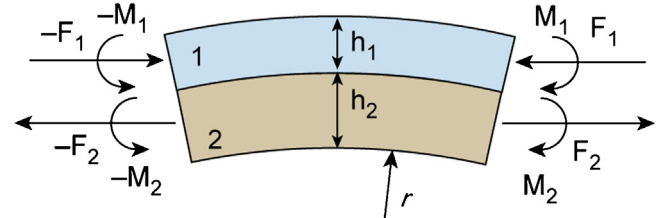

Fig. 2. Statically equivalent force system of element of bilayer structure after bonding at elevated temperatures.

sum of the energies of the individual layers. Thus, the bonded and unbounded layers shown in Fig. 1 are equivalent in terms of the strain energy and the statically equivalent force system assuming that the bonded and unbonded layers have the same shape before and after applying the forces. The only difference is that the bonded structure is deformed by the interface interaction, and the separated layers are deformed by external forces.

External forces applied parallel and perpendicular to the interface can deform the unbound layers to match the bonded structure. Comparing the total strain energy to the strain energy due to the parallel force gives the strain energy due to the perpendicular force, or the SSE. First, we calculate the total strain energy of the bonded structure.

2.2. Strain energy of the bonded structure

The strain energy of a bilayer structure deformed by a difference in thermal expansion coefficients is calculated using the expressions for axial force and bending moment from Timoshenko's model [1]. Let two flat layers of unit width with different thermal expansion coefficients α_1 and α_2 be bonded at elevated temperature. The bonded structure becomes curved during cooling; if $\alpha_1 < \alpha_2$, at room temperature the structure will be convex up (Fig. 2). From the statics analysis, the force interaction at the interface can be represented by a statically equivalent force system of axial force and bending moment. The compressive axial force F_1 and the bending moment M_1 act on layer 1 while the tensile axial force F_2 and the bending moment M_2 act on layer 2 on the concave side of the structure.

Because the bilayer structure is a statically closed system, no external loads are considered and forces acting over any cross section must be in static equilibrium; therefore,

$$F_1 = F_2 = F \tag{1}$$

and

$$M_1 + M_2 = \frac{F_1 h_1}{2} + \frac{F_2 2h_2}{2} = \frac{Fh}{2} \tag{2}$$

where $h = h_1 + h_2$.

Along the interface the longitudinal deformations of layer 1 and 2 must be equal; therefore,

$$\alpha_1 \Delta T - \frac{F_1}{E_1 h_1} - \frac{h_1}{2r} = \alpha_2 \Delta T + \frac{F_2}{E_2 h_2} + \frac{h_2}{2r}, \tag{3}$$

where r is the common radius of curvature of the structure, E_i ($i = 1,2$) is Young's modulus, and ΔT is the difference between the temperature of bonding and the ambient temperature. Eqs. (1–3)