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Fabricating Strained Silicon Substrates Using Mechanical Deformation during Wafer Bonding

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Mechanical straining during wafer bonding combined with thinning has recently been used to fabricate substrates with tensile and compressive uniaxial strained silicon layers. Mechanics analyses are presented here that allow for a better understanding of this fabrication process as well quantitative prediction of the strain in the final substrates. The analysis, results, and a comparison to reported experimental data are presented.

Introduction

Mechanical strain in silicon is well known to enhance carrier mobility. There has been significant work over the past decade aimed at developing substrates with strained silicon layers to provide enhanced device performance. Much of this work has used layers of silicon germanium to introduce strain into a silicon layer through a lattice mismatch. However, there has been recent work that has pursued an alternate approach based on the use of mechanical straining combined with bonding to create strained silicon substrates and devices (1-4). The use of mechanical straining techniques is motivated, in part, by the fact that strained layers with a uniaxial strain state can be achieved. Uniaxial strain allows higher mobilities to be achieved at lower strain levels compared to biaxial strain. Recently, there have been demonstrations of the fabrication of substrates with strained silicon layers in uniaxial tension (3) and uniaxial compression (4) by bonding wafers while elastically deformed and subsequently thinning. In the present work, a mechanics analysis is presented that allows for the prediction of strain in substrates fabricated by wafer bonding in a deformed state followed by thinning.

This paper provides a route to calculate the strain in the thinned layer for the two cases shown in Figs. 1 and 2. In the first case examined, a uniform elastic strain is applied to both wafers [Fig. 1(a)], the wafers are bonded while strained and the loads required to initially strain the wafers are removed [Fig. 1(b)], finally the top layer is thinned [Fig. 1(c)]. In the second case examined, the two wafers are deformed against a curved chuck [Fig. 2(a)] to introduce a strain gradient in each layer, the wafers are bonded and released from the chuck [Fig. 2(b)], and then the top layer is thinned [Fig. 2(c)]. In both cases, either tensile or compressive stress can be induced in the thinned layer. The first case has elements that are similar to concepts proposed in ref. (1), while the second case is exactly like the method used in refs. (3,4).

In this paper, the mechanics analyses of both cases are presented followed by a summary of the results. The general behavior of these systems is reported along with a comparison of the model to recently reported experimental data (4).

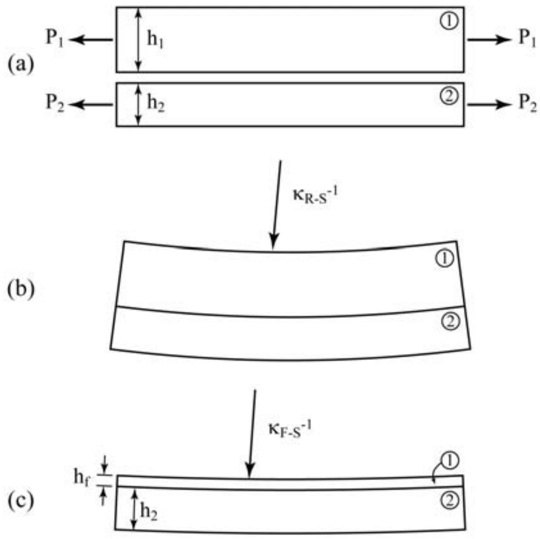


Figure 1 – Schematic of method for creating a strained substrate through wafer bonding and thinning using initial stretching of the wafers.

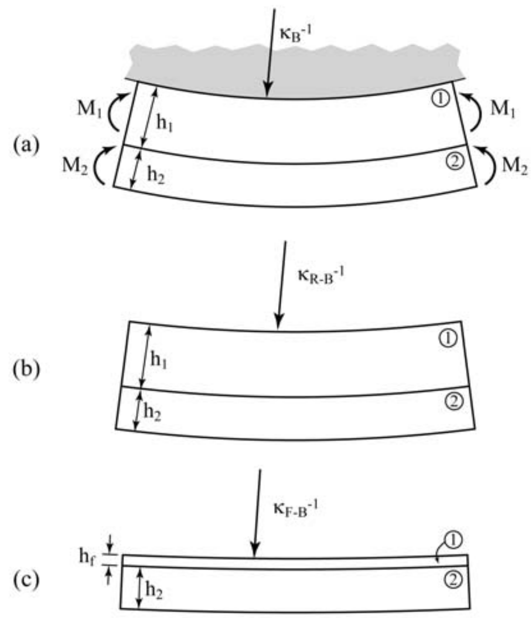


Figure 2 – Schematic of method for creating a strained substrate through wafer bonding and thinning using initial bending of the wafers.

Mechanics Analysis

Stretching Analysis

To illustrate the basic mechanics of pre-strained layered stacks, the simplified case shown in Fig. 1 is considered first. The layers have thicknesses h_1, h_2, Young's moduli, E_1, E_2, and Poisson's ratio, ν_1, ν_2. A 2-D plane strain analysis is assumed throughout. The sign convention used denotes a positive strain as a tensile strain, a negative strain as a compressive strain, and a positive curvature as concave up [e.g., Fig. 1(b)].

Prior to bonding, strains ε_{S1} and ε_{S2} are applied to layers 1 and 2, respectively. The loads per unit width required to induce these strains in both layers are:

$$P_1 = \overline{E}_1 h_1 \varepsilon_{S1} ,$$
$$P_2 = \overline{E}_2 h_2 \varepsilon_{S2} , \qquad [1]$$

where the plane strain moduli are $\overline{E}_1 = E_1/(1-\nu_1^2)$, $\overline{E}_2 = E_2/(1-\nu_2^2)$. After bonding, the loads that provided the pre-strain are removed and, as a result, the bonded stack will deform to a new equilibrium configuration. The equilibrium shape of the stack can be calculated by treating the bonded stack as a composite layered structure. The deformation of a two-layer structure is described by the position of the neutral axis, and the force-strain and moment curvature relationships:

$$z_0 = \frac{\Sigma\eta^2 - 1}{2\eta(\Sigma\eta + 1)} h_1 \qquad [2]$$

$$M = \frac{\Sigma^2\eta^4 + 4\Sigma\eta^3 + 6\Sigma\eta^2 + 4\Sigma\eta + 1}{12(\Sigma\eta + 1)} \overline{E}_2 h_2^3 \kappa \qquad [3]$$

$$P = (\Sigma\eta + 1)\overline{E}_2 h_2 \varepsilon_{NA} \qquad [4]$$

where z_0 is the distance of the neutral axis from the interface, M is the moment applied about the neutral axis, P is the axial load applied on the neutral axis, κ is the curvature, ε_{NA} is the strain at the neutral axis, η is the thickness ratio ($\eta = h_1/h_2$) and Σ is the modulus ratio ($\Sigma = E_1/E_2$). Upon removal of the loads that provided the initial pre-strain after bonding, a moment, M_R, and load, P_R, are applied to the bonded stack:

$$M_R = P_1(h_1/2 - z_0) - P_2(h_2/2 + z_0)\,, \qquad [5]$$

$$P_R = -(P_1 + P_2)\,, \qquad [6]$$

where P_1 and P_2 are defined by equation [1]. Setting $M = M_R$ (Eqs. [3] and [5]) and $P = P_R$ (Eqs. [4] and [6]), the curvature, $\kappa_{R\text{-}S}$, and the strain at the interface, $\varepsilon_{0R\text{-}S}$, after the pre-strain loads are removed are solved for,

$$\kappa_{R-S} = \frac{\varepsilon_{S1} - \varepsilon_{S2}}{h_2}\left(\frac{6\Sigma\eta(\eta + 1)}{\Sigma^2\eta^4 + 4\Sigma\eta^3 + 6\Sigma\eta^2 + 4\Sigma\eta + 1}\right), \qquad [7]$$

$$\varepsilon_{0R-S} = -\frac{\varepsilon_{S1}(\Sigma^2\eta^4 + 3\Sigma\eta^2 + 4\Sigma\eta) + \varepsilon_{S2}(4\Sigma\eta^3 + 3\Sigma\eta^2 + 1)}{(\Sigma^2\eta^4 + 4\Sigma\eta^3 + 6\Sigma\eta^2 + 4\Sigma\eta + 1)}\,. \qquad [8]$$

This result is consistent with the equations given in ref. (5) for a thick biaxially residually stressed film on a substrate. If layer 1 is subsequently thinned to a thickness of h_f, the stack will relax and deform to a new curvature, $\kappa_{F\text{-}S}$. In the stretching case under consideration here, the final curvature, and interface strain, $\varepsilon_{0F\text{-}S}$, are simply modified versions of Eqs. [7] and [8] where η is replaced by ζ, which is the final thickness ratio, $\zeta = h_f/h_2$.

The final strain in the two layers after bonding and subsequent thinning is of paramount concern in the present application. As the bonded stack deforms via bending, there is a strain gradient in each layer. The final strains in layer 1 ($z \geq 0$) and layer 2 ($z \leq 0$) are:

$$\varepsilon_{1F} = \varepsilon_{S1} + \varepsilon_{0F-S} - \kappa_{F-S} z\,,$$

$$\varepsilon_{2F} = \varepsilon_{S2} + \varepsilon_{0F-S} - \kappa_{F-S} z\,. \qquad [9]$$

These equations describe the full strain distribution in each layer, however the average strain is of interest for mobility enhancement. The average final strain in layer 1 after thinning is:

$$\varepsilon_{1-avg} = (\varepsilon_{S1} - \varepsilon_{S2})\left(\frac{1 + \Sigma\zeta^3}{\Sigma^2\zeta^4 + 4\Sigma\zeta^3 + 6\Sigma\zeta^2 + 4\Sigma\zeta + 1}\right) \qquad [10]$$

Note that when the layer is thinned considerably, $\zeta \rightarrow 0$, the average strain in layer 1 is simply equal to the initial misfit strain, which is:

$$\varepsilon_M = \varepsilon_{S1} - \varepsilon_{S2} \qquad [11]$$

Bending Analysis

The strain in a wafer pair that is bonded while held at a curvature κ_B, as shown in Fig. 2, is considered below. Elements of this analysis are similar to that presented for an analysis of the bonding of wafers with initial curvature (6,7). In this case, the mismatch strain at the interface is due to the fact that the bottom of layer 1 is in tension and the top of layer 2 is in compression when bent to a positive curvature as shown in Fig. 2(a). The strains in each layer when deformed to the bonding curvature, κ_B, are

$$\begin{aligned} \varepsilon_{B1} &= \kappa_B h_1\left(\frac{1}{2} - \frac{z}{h_1}\right), \\ \varepsilon_{B2} &= -\kappa_B h_2\left(\frac{1}{2} + \frac{z}{h_1}\right). \end{aligned} \qquad [12]$$

If the wafers are bonded and then released from the chuck, they will relax to a new curvature, $\kappa_{R\text{-}B}$, as shown in Fig. 2(b). The change in curvature from κ_B to $\kappa_{R\text{-}B}$ that occurs when the bonded pair is released from the chuck can be determined from the moment removed when the pair is released from the chuck, M_R, and Eq. [3]. The moment per unit width removed when the wafer pair is released from the chuck is:

$$M = -(M_1 + M_2) \qquad [13]$$

where

$$\begin{aligned} M_1 &= \frac{1}{12}E_1 h_1^3 \kappa_B \\ M_2 &= \frac{1}{12}E_2 h_2^3 \kappa_B . \end{aligned} \qquad [14]$$

The curvature after release is subsequently determined from the change in curvature,

$$\kappa_{R-B} = \kappa_B\left(\frac{3\Sigma\eta(\eta+1)^2}{(\Sigma^2\eta^4 + 4\Sigma\eta^3 + 6\Sigma\eta^2 + 4\Sigma\eta + 1)}\right). \qquad [15]$$

Next, the curvature and strain after release and subsequent thinning is again determined by considering the bonded stack as a composite structure with properties given by Eqs. [2]-[4]. When layer 1 is thinned, there are moments as well as a force that act on the bonded pair and determine the final equilibrium state:

$$P_1 = \frac{1}{2}E_1 h_f^2 \kappa_B\left(\frac{h_1}{h_f} - 1\right), \qquad [16]$$

$$M_1 = \frac{1}{12}E_1 h_f^3 \kappa_B , \qquad [17]$$

$$M_2 = \frac{1}{12}E_2 h_2^3 \kappa_B . \qquad [18]$$

The total force and moment that are set equal to Eqs. [3] and [4] to determine the final strain and curvature of the bonded pair are:

$$P = -P_1 , \qquad [19]$$

$$M = P_1(h_f/2 - z_0) - M_1 - M_2 . \qquad [20]$$

The strain at the interface that occurs during relaxation is

$$\varepsilon_{0F-B} = \frac{h_2\kappa_B}{2}\left(\frac{-\Sigma^2\zeta^4\eta + 4\Sigma\zeta^3 - 3\Sigma\zeta^2\eta 3\Sigma\zeta^2 - 4\Sigma\zeta\eta + 1}{\Sigma^2\zeta^4 + 4\Sigma\zeta^3 + 6\Sigma\zeta^2 + 4\Sigma\zeta + 1}\right), \quad [21]$$

and the final curvature of the bonded and thinned stack is

$$\kappa_{F-B} = \frac{\kappa_B(1+\eta)}{2}\left(\frac{6\Sigma\zeta(1+\zeta)}{\Sigma^2\zeta^4 + 4\Sigma\zeta^3 + 6\Sigma\zeta^2 + 4\Sigma\zeta + 1}\right). \quad [22]$$

The final strains in layer 1 (z≥0) and layer 2 (z≥0) are

$$\varepsilon_{1F} = \varepsilon_{B1} + \varepsilon_{0F-B} - (\kappa_{F-S} - \kappa_B)z,$$
$$\varepsilon_{2F} = \varepsilon_{B2} + \varepsilon_{0F-B} - (\kappa_{F-S} - \kappa_B)z. \quad [23]$$

The average strain in layer 1 is

$$\varepsilon_{1-avg} = \left(\frac{\kappa_B h_2(1+\eta)}{2}\right)\left(\frac{1+\Sigma\zeta^3}{\Sigma^2\zeta^4 + 4\Sigma\zeta^3 + 6\Sigma\zeta^2 + 4\Sigma\zeta + 1}\right). \quad [24]$$

When the layer is thinned significantly (ζ→0), the second term in the brackets approaches unity and the strain in layer 1 is equal to the original misfit strain at the interface,

$$\varepsilon_M = \left(\frac{\kappa_B h_2(1+\eta)}{2}\right). \quad [25]$$

Results and Discussion

The average strain in the thinned layer (Eqs. [10] and [24]) and the final curvature of the bonded and thinned wafer pair (Eq. [7] with η→ζ and Eq. [22]) are the primary quantities of interest when considering this process. Despite the fact that the two cases considered use very different mechanisms for initial straining, the equations for average strain and final curvature for both cases have similar forms. The final curvature of the substrate in both cases has the same dependence on Σ and ζ, the modulus and the thinning ratio, respectively. The expressions for final curvature reduce to the same equation when they are normalized by the initial mismatch strain for each case (Eqs. [11] and [25]). The same is true for average strain in the thinned layer in both cases. Equations [10] and [24] both have the same dependence on Σ and ζ and reduce to the same expression when normalized by the appropriate initial mismatch strain. It is important to note that the mismatch strain for the bending case depends on the initial thickness ratio, η, while the mismatch strain for stretching case is independent of η.

Figure 3 shows the normalized non-dimensional final curvature for both the stretching and bending cases as a function of Σ and ζ. For the common case where both layers have identical elastic properties (Σ=1), the curvature approaches zero as the layer is thinned. Thus, if two standard thickness silicon substrates (~500 μm thick) were bonded while strained and then one layer was thinned to 0.5 μm thick, corresponding to ζ=0.001, the final substrate would be nearly flat regardless of the magnitude of the strain in the layer. For cases where the substrate is considerably more compliant than the thinned device layer (Σ=10, Σ=100), such as in a flexible electronics applications where

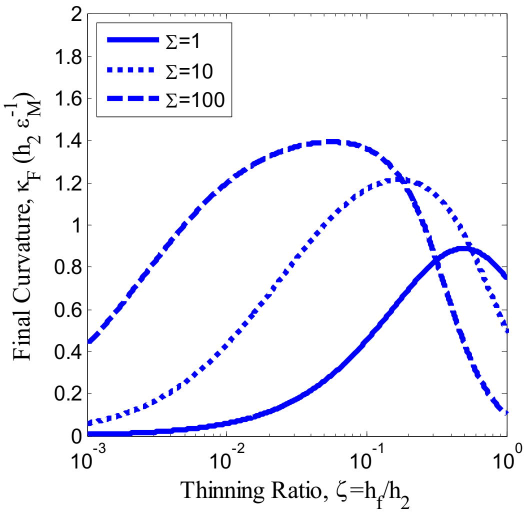


Figure 3 – Normalized final substrate curvature for the bending and stretching cases. The curvature is normalized by the mismatch strains (Eqs. [11] and [25]) and the thickness of layer 2.

the substrate may be a polymer (8), a significant curvature may be present in the final bonded pair even if the layer is thinned considerably.

The strain in the thinned layer, normalized by mismatch strain, is plotted in Fig. 4. As the bonded pairs in both cases deform in bending, there is a linear strain gradient through the thickness of each layer once the substrates are bonded and thinned. Fig. 4 shows the maximum, minimum, and average strain in the thinned layer as a function of thinning ratio. When the thinning ratio is greater than about 0.1, there is a significant strain gradient in the thinned layer, as indicated by differences in the minimum, maximum, and average strains shown in Fig. 4. If the layer is thinned significantly, ζ<0.01, which is often the case in real processes, the strain is nearly uniform throughout the thickness of the layer. From Fig. 4(a), in which Σ=1, the strain increases as the layer is thinned and is nearly equal to the mismatch strain at ζ=0.001. In most applications where this mechanical straining and bonding process would be used, the substrates would

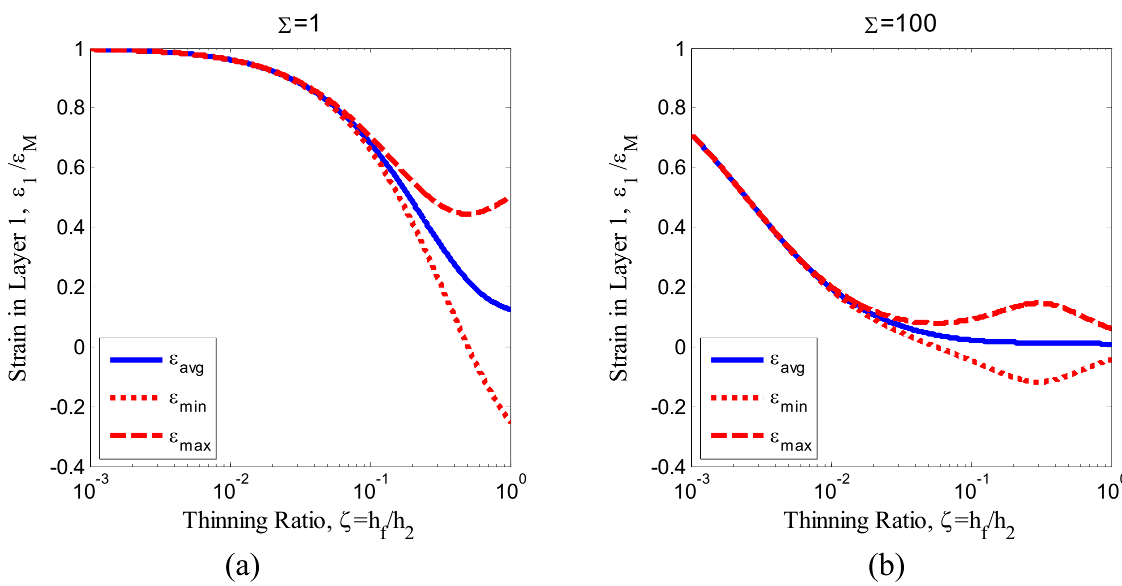
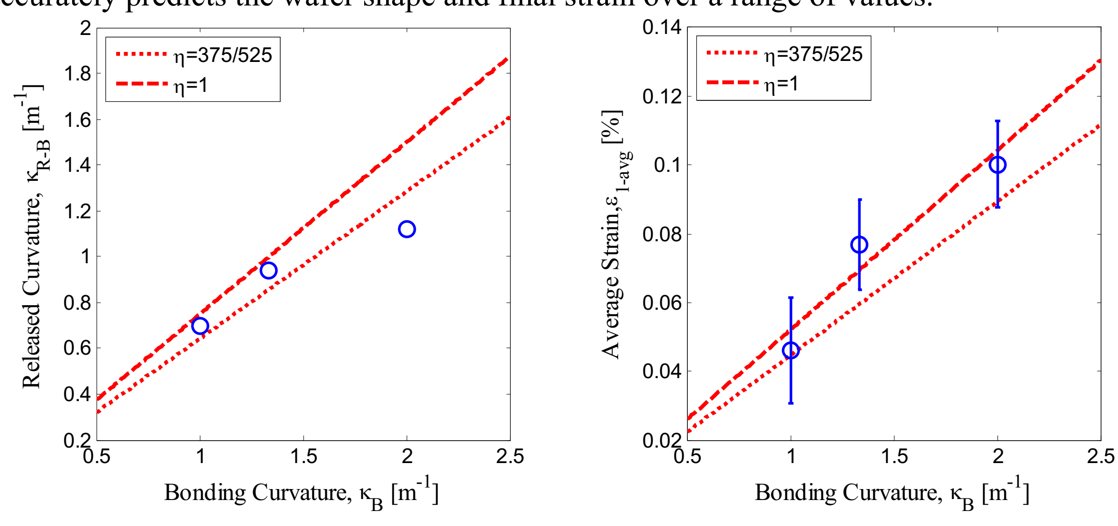


Figure 4 – The maximum, minimum, and average strains in the thinned layer as a function of thinning ratio for two different modulus ratios: (a) Σ=1 and (b) Σ=100.

have the same elastic properties and the thinning ratio would approach or be less than 0.001. Given the results in Fig. 4, the strain in the thinned layer in these cases can simply be calculated as the mismatch strain given equations [11] and [25]. Fig. 4(b) shows the strains in the thinned layer for a case where the substrate is much less stiff than the thinned device layer (Σ=100). In this case, the strain in the thinned layer only reaches about 70% of the mismatch strain at a thinning ratio of 0.001 as a result of the compliance of the substrate.

The mechanics analysis presented here was compared to the experimental results presented in ref. (4), in which uniaxial compressive strain was imparted in a layer by wafer bonding against a cylindrical chuck and subsequently thinning the bonded pair. Himcinschi et al.(4) reported the wafer bow after release from the chuck (from which the released curvature can be calculated) and the final strain in the thinned layer measured using Raman spectroscopy for bonding against cylinders with three different radii. In the experiments, 3 and 4 in. diameter double side polished wafers were bonded and then the 3 in. diameter wafer was thinned to ~600 nm using the smart-cut process. The initial thickness of the wafers was not reported. Standard thicknesses for single-side polished 3 and 4 in. diameter wafers are 375 and 525 μm, respectively. As the wafers used in ref. (4) are double-side polished, their thickness may be different than these standard values. As such, when calculating the model results for comparison, two different thickness ratios, η=375/525 and η=1, are used. The thinning ratio in the analysis is ζ=0.6/375=0.0016 and it is worthy to note that the final strain is insensitive to small changes in ζ near this value [Fig. 4(a)]. The mechanics analysis and the experimental results [Fig. 5] are in good agreement for most of the released curvature and the average strain values. The only point where there is a significant difference between the model and the experiment is the released curvature value corresponding to a bonding curvature of 2 m^{-1}. This difference may be due to geometric non-linear effects that can arise at large deformations, similar to those described for residually stressed films deposited on substrates (5). With the exception of this point, the linear model presented here accurately predicts the wafer shape and final strain over a range of values.



(a) (b)

Figure 5 – Comparison between the mechanics analysis (red lines) and experimental data in ref. (4) (blue markers). Comparisons are shown for: (a) the curvature after release, Eq. [15], and (b) the magnitude of average strain in the thinned layer. Note, in ref. 4, the induced strains are compressive

Conclusions

A mechanics model for the introduction of uniaxial strain via wafer bonding and layer thinning has been presented. The model provides a route to calculate the final stain and curvature of substrates that are bonded while strained. The results show that the final curvature and strain in the thinned layer scale linearly with the initial mismatch strain for both the stretching and bending cases considered. If the device layer is thinned significantly and the substrate and device layer have similar elastic properties, the average strain in the thinned layer is simply equal to the initial interfacial mismatch strain at the time of bonding. The model has been verified through comparison to previously published experimental results, indicating it captures the relevant mechanics to effectively predict substrate behavior in real processes. The analyses presented here provide a general tool for designing bonding and thinning processes to fabricate strained substrates.

Acknowledgments

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References

1. R. Belford, *US Patent*, 6455397 (2001).
2. R. E. Belford, *Journal of Electronic Materials* ***30***, 807 (2001).
3. C. Himcinschi, I. Radu, F. Muster, et al., *Solid-State Electronics* ***51***, 226 (2007).
4. C. Himcinschi, M. Reiche, R. Scholz, et al., *Applied Physics Letters* ***90*** (2007).
5. L. B. Freund and S. Suresh, *Thin Film Materials: Stress, Defect Formation and Surface Evolution* (Cambridge University Press, Cambridge, UK, 2003).
6. K. T. Turner and S. M. Spearing, *Proceedings of the Royal Society a-Mathematical Physical and Engineering Sciences* ***462***, 171 (2006).
7. K. T. Turner, M. D. Thouless, and S. M. Spearing, *Journal of Applied Physics* ***95***, 349 (2004).
8. D. H. Kim, J. H. Ahn, W. M. Choi, et al., *Science* ***320***, 507 (2008).