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Extension of the Equivalent Thickness Concept to the Bifurcation of Large Semiconductor Front Side Metal Taiko Wafers investigated by ANSYS Finite Element Analysis Methods

Vincenzo Vinciguerra *, Giuseppe Luigi Malgioglio and Marco Renna

STMicroelectronics, Automotive & Discrete Group (ADG) R&D, Stradale Primosole 50, 95121 Catania, Italy
* Correspondence: author: vincenzo.vinciguerra@st.com

Abstract: Scaling up the production of power devices involves, in the semiconductor industry, the use of large semiconductor 8" and 12" wafers of Si or SiC. Their use implicates a successful an effective monitoring and control of wafer warpage, as the geometrical size of the substrate increases, as well as a command control on the degeneration of non-linear warpage into critical phenomena known as bifurcation or buckling. To mitigate the warpage, the use of taiko wafers, which consists of wafers having a thicker region on the rim region of the wafer, has been generally adopted in the production lines. In a previous work [1] we investigated the warpage of taiko wafers by introducing the concept of *equivalent thickness*, in the linear approximation, for the case of a front side metalized taiko wafer. However, as the thickness of the central semiconductor substrate region decreases the possibility that also the taiko wafer bifurcates emerges. For this reason, in this work we have investigated the occurrence of bifurcation or buckling in a taiko wafer. In particular, we implemented a finite element analysis method by using ANSYS Mechanical Enterprise 2023/R2 to investigate the phenomenon of bifurcation in a taiko wafer. The investigated system consisted of a 200 mm Si (001) front side metalized (FSM) taiko wafer, having a substrate thickness ranging from 100 µm to 400 µm, with a step height fixed to 450 µm. The FSM layer consisted of an Al layer of 4.5 µm thin. The system was subjected to a thermal load such that, getting cooled from a nominal temperature T to 25°C, the metal layer can develop a residual stress. To investigate the bifurcation, an asymmetry was induced in the system by applying a slight force on a point of the circumferential region perpendicularly to the substrate. The temperature investigated ranged from 30 °C to 170 °C. From this investigation, it results that also the bifurcation is mitigated by the taiko structure. Indeed, the bifurcation emerges at higher values of the stresses with respect to the case of flat wafers having the same size and thickness of the substrate. Moreover, the concept of equivalent thickness needs to be reformulated by taking into account of the bifurcation phenomenon. Indeed, from the warpage at the bifurcation point $\boldsymbol{Warpage_{bif}}$ of the taiko wafer, we can determine an overall equivalent thickness of the taiko wafer, such that the taiko wafer act as with a thickness of $\boldsymbol{h_{tot,eq} = h_{s,eq} + h_{m,eq} = 2Warpage_{bif}/\sqrt{1+\nu_s}}$ of an equivalent flat wafer.

Keywords: bifurcation; Taiko wafers; finite element analysis (FEA); ANSYS; thermomechanical simulations; warpage; modelling; equivalent thickness

Introduction

A scale-up of the semiconductor integration process of power devices, involving the use of large (e.g. 8" and 12") Si or SiC wafers, requires an accurate control of the wafer warpage since early stages of the large-scale integration process, to prevent undesirable asymmetric degeneration of the warpage, known as wafer bifurcation or buckling. A commonly adopted solution is the taiko method [1], which involves creating a thicker ring region around the wafer's rim to mitigate this issue. In previous research [2,3] we delved into the factors influencing the warpage of a front side metalized (FSM) taiko wafer in the linear case and introduced the concept of equivalent thickness of

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a taiko wafer. In this work, we investigated the behaviour of a taiko wafer with respect to the bifurcation. The main question regards the extension of the concept of equivalent thickness in the non-linear range where bifurcation phenomena can onset.

Background

The Stoney equation [4,5] is fundamental to determine the stress of a metal layer from the curvature of plain substrates and wafers. However, it is not applicable for complex designs such as taiko wafers [1–3]. A modification of the Stoney formula for a taiko wafer has been proposed for the general cases of a back side metal (BSM) taiko wafer [1] and recently extended to the front side metal (FSM) taiko wafers case [2,3].

Indeed, by following ref [1–3], the curvature κ of a taiko wafer, resulting at the center of the substrate, can be expressed in a modified Stoney equation as

$$\kappa_{Stoney,taiko} = \frac{M_{taiko}}{E_s I_{taiko}} \quad (1)$$

where M_{taiko} is the bending moment determined by the FSM layer and $E_s I_{taiko}$ is the flexural rigidity of the FSM-taiko wafer. By opportunely developing the theory, it is possible to write down Equation (2) expressing the curvature of the taiko wafer:

$$\frac{E_s I_{sub}(z_B)}{(1-\upsilon_s)} \frac{\partial^2 \zeta_{int}}{\partial r^2} = \sigma_f h_f (h_s + z_B) \quad (2).$$

This equation can be considered as the extension of the Stoney formula for the case of an FSM taiko wafer. In Equation (2), $E_s I_{sub}$ and $\frac{\partial^2 \zeta_{int}}{\partial r^2}$ are the flexural rigidity and the curvature of the central substrate region, respectively, E_s is the Young modulus and υ_s the Poisson coefficient of the substrate. Whereas σ_f is the stress generated by the FSM layer, h_f the thickness of the FSM layer, h_s the thickness in the central region of the taiko wafer, and z_B is the position of the neutral plane. In general, Equation (2) can be solved once $I_{sub}(z_B)$ and z_B are known. In Figure 1 a schematic of a FSM taiko wafer, reporting the whole set of quantities involved, is reported. In Table 1, we report the typical value of the quantities defined in Figure 1 involved in the description of the 8″ taiko wafers.

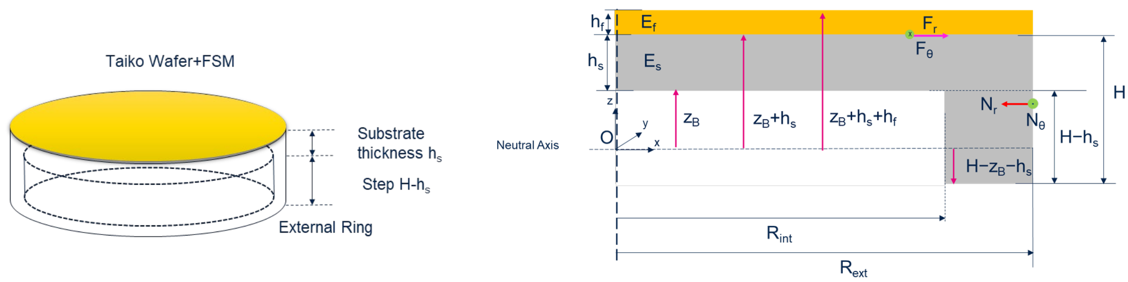

Figure 1. On the left, schematic of a front side metalized taiko wafer. On the right cross section of a front side metal (FSM) taiko wafer illustrating the quantities determining the warpage of the FSM taiko wafer. R_{int} is the internal radius, R_{ext} external radius, h_s thickness of the substrate and H the height of the ring. The FSM taiko wafer is subject to radial and circumferential forces at the FSM/substrate interface, whose value per unit length are F_r and F_θ, respectively. The wafer is supported at the external ring R_{ext} and N_r and N_θ are the radial and circumferential reaction forces per unit length. The front of the wafer is at $z = z_B$ with respect to the neutral plane. The step height is fixed and put equal to $H - h_s$.

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Table 1. Table reporting the typical value of the geometrical properties of the investigated FSM-taiko wafer.

Symbol	Quantity	Typical Value
h_s	Substrate Thickness (μm)	200
$H - h_s$	Step Height (μm)	450
h_f	Front Side Metal Thickness (μm)	4.5
$R_{ext} - R_{int}$	Ring Width (mm)	3.7

In paper [2] we defined the equivalent thickness in terms of the slopes which increase as the thickness in the central region decreases.

Though the behaviour with respect to warpage of the FSM taiko wafer is described well for low values the stresses [2], as the stress increases non-linear phenomena emerge [6,7] and by increasing further the stress a degeneration of non-liner phenomena will emerge. This degeneration of warpage is known as bifurcation or buckling [8–11]. It has been investigated to some extend for the case of plain wafers by recurring to simulation tools [12–20], however as far as we know it has never been investigated for the case of taiko wafers.

Methodology

In this work we further extended the concept of equivalent thickness of front -side metalized taiko wafers by including the case of bifurcation. The investigation has been carried out by recurring to finite element analysis methods. Indeed, modelling can be beneficial due to the limited number of types of taiko wafers that can be produced in a production line. In particular, we developed a finite element analysis (FEA) approach using ANSYS® Mechanical Enterprise 2023/R2 simulation tool to model the equivalent thickness of a bifurcated taiko wafer. In details, the curvature as a function of the stress of the metal layer was investigated, considering key design factors such as the thickness of the central region of the substrate, the thickness of the thin metal film, the step height, and the width of the ring region.

By systematically varying the thickness of the central region of the taiko wafer, the curvature as a function of stress induced by thermal load in the linear and non-linear regime was explored, and the evolution of the bifurcation diagrams have been determined. In particular, by applying a slight perturbation as indicated in the paper [17] we have been able to induce a bifurcation also in the taiko wafer.

Results

In Figure 3 we report the trend of the simulated curvature as a function of the stress, for a set of taiko wafers whose central substrate region thickness ranges from 100 μm to 400 μm. An asymmetry has been induced in the wafer by applying a slight force at the rim of the wafer, such that to ignite the bifurcation. We observe that, differently from Figure 2, as the stress reaches a critical value the taiko wafer bifurcates. Moreover, as we decrease the thickness of the central region the bifurcation point occurs at lower values of the FSM stress. The resulting graph is a bifurcation diagram, which can be of help in the comprehension of how to extend the concept of equivalent thickness to the bifurcated case.

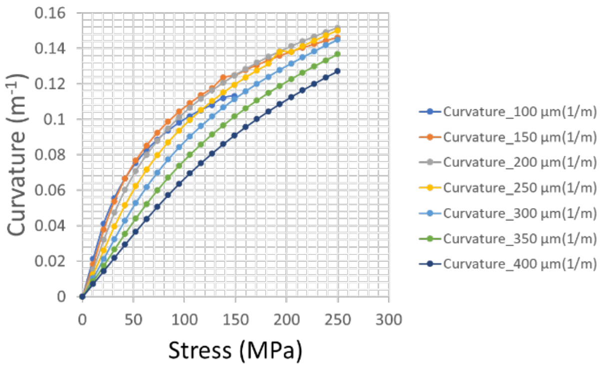

Figure 2. Curvature as a function of the stress for a taiko wafer, reported from ref. [2] with hs ranging in the interval 100 - 400 μm and the other quantities fixed to the typical value reported in table.

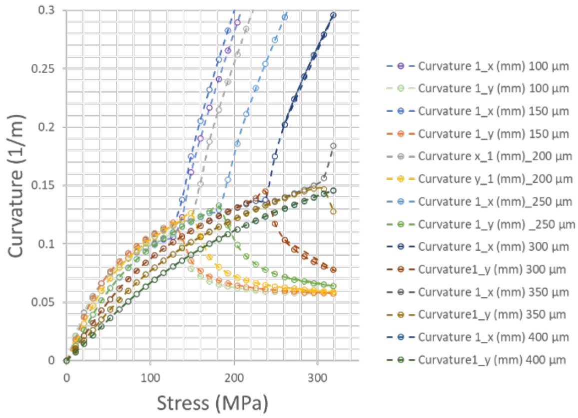

Figure 3. Bifurcation diagrams reporting the curvature as a function of the stress of the metal layer for a set of taiko wafers whose central substrate region thickness ranges from 100 μm to 400 μm. The bifurcation ignites for all the thickness in the range of the thickness investigated, except for the 400 μm case. The curvature at the bifurcation point, as well as its bifurcation stress increase with the thickness h_s of the substrate.

Indeed, to further investigate the degeneration of this non-linear phenomenon, in Figure 4 we focused on the bifurcation diagram reporting the warpage of a FSM 200 μm taiko wafer as a function of the stress σ of the metal layer . The behavior of the taiko wafer is compared with a flat 200 μm Si/Al wafer. As we can see, the bifurcation in the case of a 200 μm thin flat wafer occurs at lower values of the stress, occurring above around 30 MPa. To fit the bifurcation diagram of the taiko wafer, we need to increase the thickness of the wafer up to 350 μm and set the thickness of the Al metal layer to 4.97 μm. Also in this case, with respect to the case of a plain wafer, the bifurcation is mitigated by the ring region.

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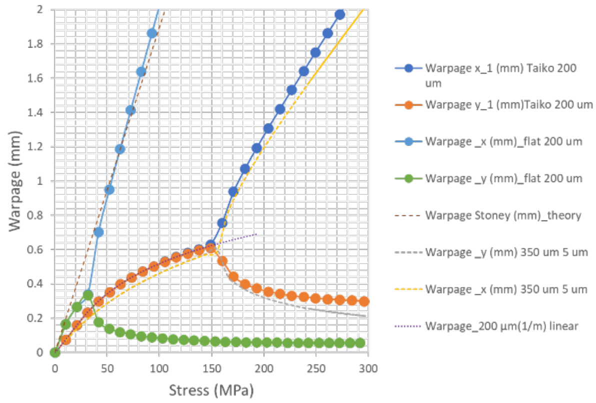
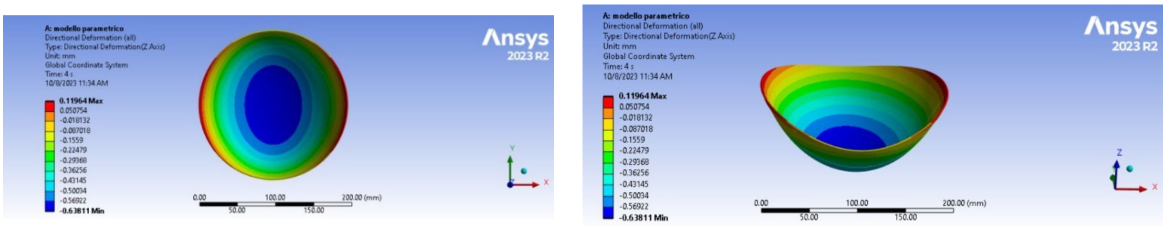


Figure 4. Bifurcation diagram reporting the warpage of an FSM 200 μm taiko wafer as a function of the stress σ of the metal layer. The behaviour of the taiko wafer is compared with a flat 200 μm Si/Al wafer and with the case of flat Si/Al having a thickness of the silicon layer of 350 μm and of the Al metal layer of 4.97 μm.

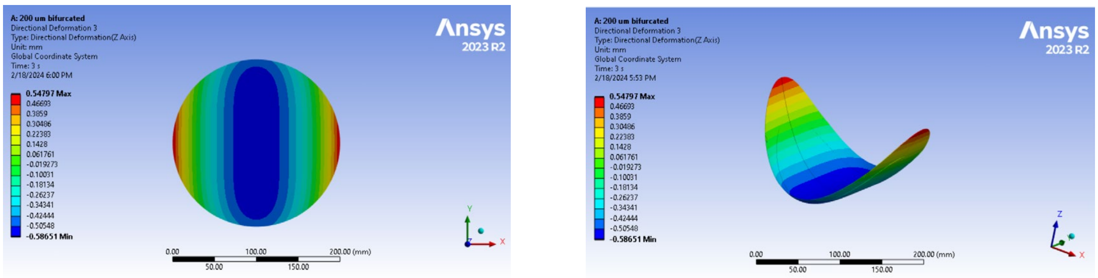
In Figure 5a we report the top view of a snapshot of the directional deformation or warpage along the z direction of the 200 mm FSM taiko, 200 μm thin in the central region. Whereas Figure 5b reports the projected view of the same warped FSM taiko wafer. The wafer is bifurcated.



(**a**) (**b**)

Figure 5. (**a**). Top view of the directional deformation of a bifurcated taiko wafer simulated at a nominal temperature of T = 100 °C. The substrate region has a thickness of 200 μm, the step height is of 450 μm. (**b**). rojection of the directional deformation of the same bifurcated taiko wafer simulated at a nominal temperature of T=100 °C. The substrate region has a thickness of 200 μm, the step height is of 450 μm. Magnification 100 ×.

In Figure 6a,b we report a snapshot of the top and projected view of the bifurcated 200 mm plain taiko wafer for comparison, respectively. It is evident that in the case of the plain wafer the resulting warpage at bifurcation is higher with respect to the taiko wafer case reported in Figure 5a,b.



(**a**) (**b**)

Figure 6. (**a**). Top view of the directional deformation of a flat wafer simulated at a nominal temperature of T = 55 °C. The substrate region has a thickness of 200 μm. (**b**). Projected view of the same flat 200 μm wafer. Magnification 100 ×.

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In Figure 7 we report the equivalent thickness in the linear regime of the investigated FSM taiko wafers as a function of the substrate thickness h_s in the central region. These data, which are also reported in ref [2], are shifted by a thickness Δ of about 35 μm, since the 200 μm works as if the equivalent thickness in the bifurcation is higher of this quantity with respect to the linear regime.

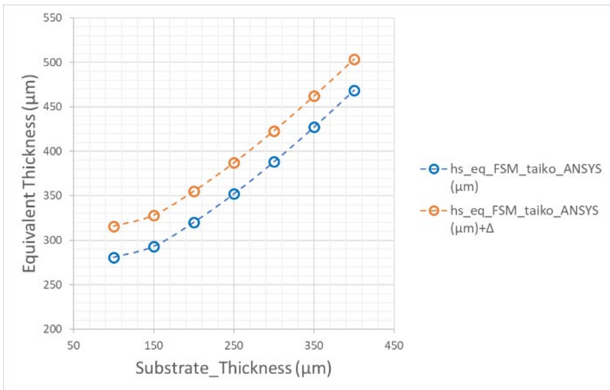

Figure 7. Equivalent thickness of a FSM taiko wafer in the linear regime, as reported in reference [2], as a function of the central substrate thickness of the taiko wafer translated by a thickness Δ of about 35 μm, resulting from the investigation of the 200 μm case reported in Figure 4.

Moreover, from theory [21] it is known that the bifurcation at the curvature is given by:

$$k_{bif} = \frac{4(h_s+h_f)}{R^2\sqrt{1+\upsilon_s}}. \quad (3)$$

Hence, from the data of the equivalent thickness shifted by the thickness Δ we can gain a bifurcation curvature k_{bif} relative to the taiko wafer. In Table 2, we have reported the bifurcation curvatures $k_{bif,ANSYS}$ as obtained from the simulated values reported in Figure 3, and the calculated bifurcation curvatures $k_{bif,Theory}$ according to Equation (3), from the shifted data of the equivalent thickness in the linear regime, as reported in Figure 7.

Table 2. Values of the bifurcation curvatures, obtained from the data reported in Figure 3, as a function of the substrate thickness of the taiko wafer and the theoretical value gained from Equation (3).

Substrate thickness (μm)	**k_bif_ANSYS (m^{-1})**	**k_bif_theory (m^{-1})**
100	0.108	0.112
150	0.118	0.116
200	0.126	0.126
250	0.133	0.137
300	0.139	0.150
350	0.145	0.164

It is worth plotting the resulting data from Table 2. In Figure 8 the $k_{bif,ANSYS}$ and $k_{bif,Theory}$ have been reported as a function of the substrate thickness. It is worth to observe as the bifurcation curvatures report the same trend and order of magnitude and agree better for those substrate thicknesses ranging from 100-250 μm. Instead, above 250 μm there are increasing deviations between the two values.

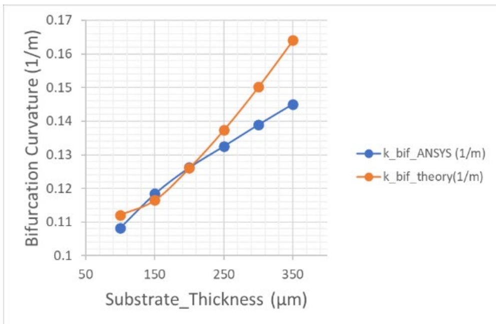

Figure 8. $k_{bif,ANSYS}$ and $k_{bif,Theory}$ gained from Table 2 as a function of the substrate thickness.

Conclusions

In conclusion, by using ANSYS simulation tools, we have investigated the occurrence of bifurcation in 8" taiko wafers. As in the case of the investigation of the warpage in the linear regime, also in this case the presence of the rim of the taiko wafer mitigates the degeneration of non-linear phenomena igniting the bifurcation. To understand better the phenomenon we defined, for a given thickness of the central region of the taiko wafer, an equivalent thickness in the bifurcation regime. In particular, in the case of 200 μm it results that such a thickness is 35 μm higher with respect to the linear regime equivalent thickness case. Hence, by shifting all the equivalent thicknesses of the same quantity of 35 μm, we gained a value of the bifurcation curvatures which can be compared with those obtained from the ANSYS simulations. It results that these values are roughly in agreement in the range of 100-250 μm. Hence Equation (3) can be a useful approximation of the equivalent thickness of a taiko wafer occurring at bifurcation, which in this case can be written as:

$$h_{eq,Bif} = \frac{R^2}{4} k_{bif} \sqrt{1+\upsilon_s} \quad . (4)$$

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