Comparing Finite Element Analysis and Analytical Approaches for Determining the Equivalent Thickness of a Taiko Wafer using ANSYS Software

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Abstract The warpage of large semiconductor wafers is a major challenge in the semiconductor manufacturing process. The Taiko method is a commonly used technique to mitigate warpage by creating a thicker ring region along the wafer's rim. This study focuses on front side metalized Taiko wafers and introduces the concept of the equivalent thickness. The equivalent thickness is a measure of the effective thickness of a Taiko wafer that accounts for the influence of the ring region. A slope that can be plotted as a function of these quantities was identified. The equivalent thickness of a Taiko wafer was investigated using an analytical approach and a finite element analysis (FEA) namely ANSYSY® Mechanical Enterprise 2023/R2 software. The curvature of the wafer was investigated as a function of the stress of the metal layer, considering main design factors such as the thickness of the substrate in the central region, the thickness of the thin metal film, the height of the step, and the width of the annular ring region. The results show that the equivalent thickness of a Taiko wafer is expected to be set between the thickness of the central region of the substrate and that of the annular region due to the influence of the ring region. This study provides insight into the warpage of Taiko wafers and can be a useful tool for their production. The results of this study can be used to optimize the design of Taiko wafers to minimize warpage by comparing the analytical approach and the finite element analysis using ANSYSY® Mechanical Enterprise 2023/R2 software to model the equivalent thickness of a Taiko wafer. By systematically varying the thickness of the central region of the taiko wafer while fixing the remaining three, the curvature as a function of stress induced by a thermal load set at a given nominal temperature was investigated in the linear regime.

Introduction: the fundamental Stoney equation, $\sigma = \frac{1}{6}\kappa\frac{E_s}{1-\upsilon_s}\frac{h_s^2}{h_f}$, which allows to reckon the stress from the curvature of a substrate, is valid for a plain wafer. In the case of a complex design, such that of a taiko wafer, the equation is not valid. The idea which is behind this work is to develop an equivalent layer, $h_{s,eq}$,which will allow to extend to the case of a taiko wafer the Stoney formula.

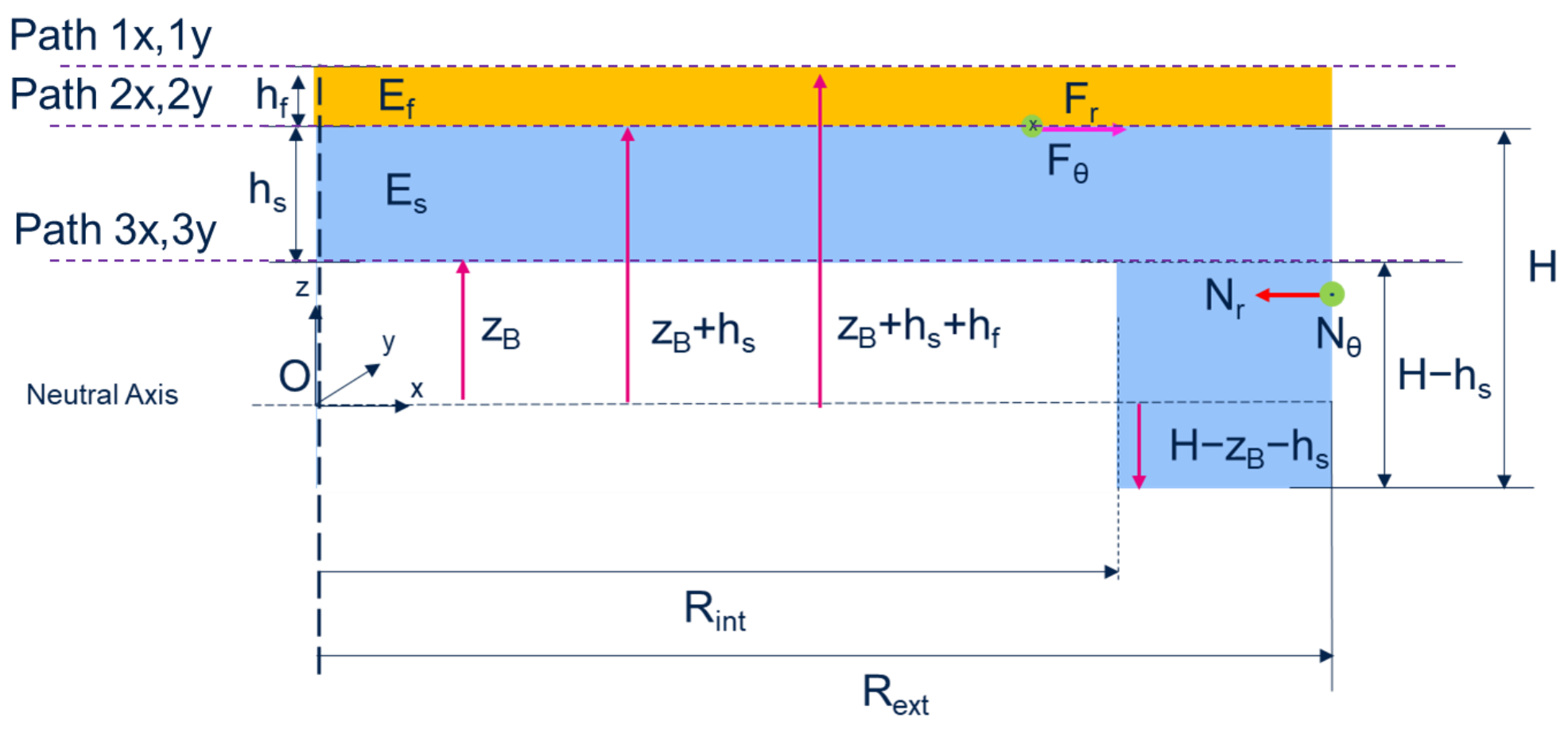

Fig. 1. Cross section of a front side metal (FSM) taiko wafer illustrating the quantities determining the warpage of the FSM taiko wafer. R_{int} is the internal radius, R_{ext} external radius, h_s thickness of the substrate and H the height of the ring. The FSM taiko wafer is subject to a radial force at the internal step edge of the ring, whose value per unit length is F_r. The wafer is supported at the external ring R_{ext} and N_r is the reaction force evaluated 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 equal to $H - h_s$.

Symbol	Quantity	Typical Value
h_s	*Substrate Thickness (μm)*	*100*
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*
R_{ext}	*Wafer Radius (mm)*	*200*

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

Methods: Develop independently, an analytical and a numerical FEA description of a FSM-taiko wafer and compare them.

Part I: analytical description

Stoney Equation
$$\sigma_f = \frac{E_s h_s^2}{6h_f(1-\upsilon_s)}\kappa$$

Modified Stoney Equation
$$\kappa_{Stoney,taiko} = \frac{M_{taiko}}{E_s I_{taiko}}$$

M_{taiko} is the bending moment determined by the FSM

$E_s I_{taiko}$ is the flexural rigidity of the FSM-taiko wafer

$$Following\ ref\ [1]$$

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

Determination of the moment of inertia

$$\frac{E_s I_{sub}}{1-\upsilon_s} = \frac{E_f}{3(1-\upsilon_f)}\left[(h_s + z_B + h_f)^3 - (h_s + z_B)^3\right] + \frac{E_s}{3(1-\upsilon_s)}[(h_s + z_B)^3 - {z_B}^3]$$

Evaluation of $z_{B,1}$ and $z_{B,2}$

$$z_{B,1} = -\frac{1}{2}\frac{h_s^2 + \frac{2E_s}{1+\upsilon_s}\frac{1}{R_{int}^2}[-H^2 + 2Hh_s]I_1}{h_s + \frac{2E_s}{1+\upsilon_s}\frac{1}{R_{int}^2}HI_1}$$

$$I_1 = \frac{1}{1+\upsilon_s}\frac{2}{R_{int}^2}\int_{R_{int}}^{R_{ext}}\left(\frac{\partial^2\zeta_{ext,Norm}}{\partial r^2} + \frac{\upsilon_s}{r}\frac{\partial\zeta_{ext,Norm}}{\partial r}\right)rdr$$

$$z_{B,2} = -\frac{1}{2}\frac{h_s^2 + \frac{2E_s}{1+\upsilon_s}\frac{1}{R_{int}^2}[-H^2 + 2Hh_s]I_2}{h_s + \frac{2E_s}{1+\upsilon_s}\frac{1}{R_{int}^2}HI_2}$$

$$I_2 = \frac{2}{R_{int}^2}\int_{R_{int}}^{R_{ext}}\left(\upsilon_s\frac{\partial^2\zeta_{ext,Norm}}{\partial r^2} + \frac{1}{r}\frac{\partial\zeta_{ext,Norm}}{\partial r}\right)rdr$$

R_{ext} (mm)	Width (mm)	R_{int} (mm)	$Step = H - h_s$ (μm)	Poisson's coefficient υ_s	E_s Young Modulus (GPa)	I_1	I_2
100	3.7	96.3	450	0.27	130	-1.5894	5.5181

Table 2. Values of the Integrals I_1 and I_2

$$\begin{cases} \frac{\kappa_{z_{B,rr}}}{\sigma_f} = \frac{(1-\upsilon_s)h_f(h_s + z_{B,r})}{E_s I_{sub}(z_{B,r})} = \frac{3(1-\upsilon_s)h_f(h_s + z_{B,r})}{E_s\left[(h_s + z_{B,r})^3 - {z_{B,r}}^3\right]} \\ \frac{\kappa_{z_{B,\theta\theta}}}{\sigma_f} = \frac{(1-\upsilon_s)h_f(h_s + z_{B,\theta})}{E_s I_{sub}(z_{B,\theta})} = \frac{3(1-\upsilon_s)h_f(h_s + z_{B,\theta})}{E_s\left[(h_s + z_{B,\theta})^3 - {z_{B,\theta}}^3\right]} \end{cases}$$

$$\frac{6(1-\upsilon_s)h_f}{E_s h_{s,eq}^2} = \frac{3(1-\upsilon_s)h_f(h_s + z_B)}{E_s[(h_s + z_B)^3 - {z_B}^3]}$$

$$h_{s,eq} = \left[\frac{6(1-\upsilon_s)h_f}{E_s\left(\frac{\kappa}{\sigma_f}\right)_{Slope}}\right]^{1/2}$$

Part II: Ansys numerical description

Layer	E (GPa)	ν	Thickness (μm)	CTE (°C^{-1})
Al	68	0.33	4.5	2.4·10^{-5}
Si (001)	130	0.27	200	2.8·10^{-6}

- ANSYS® Mechanical Enterprise 2023/R2
- Mesh preferences *non-linear mechanical*
- Foundation stiffness = *1 N/mm³*
- Large deflection *on*
- Thermal load: stress free condition @ T °C nominal temperature, cooled down to T = 25 °C.

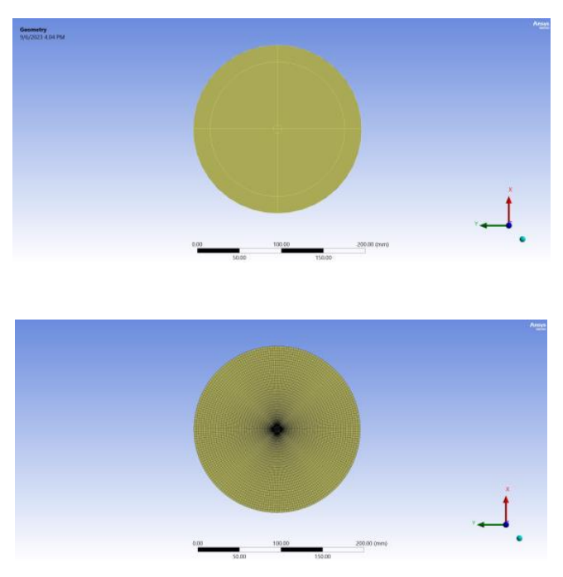

Fig. 2a. Top plan-view of the simulated taiko wafer and of the used mesh for the simulation.

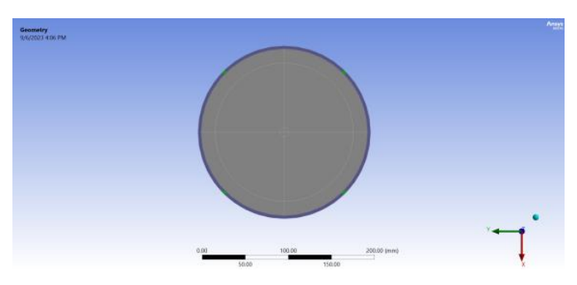

Fig. 2b. Rear plan-view of the simulated taiko wafer. The ring region and the four pins are highlighted.

ANSYS Results

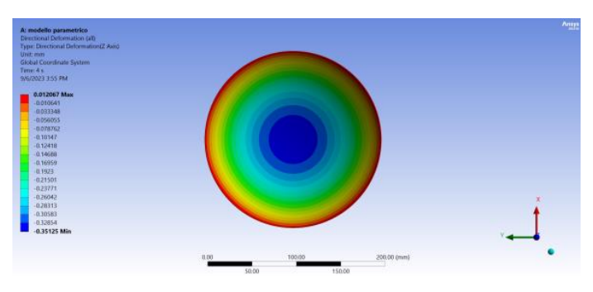

Fig. 3a. Distribution of the directional deformation along the z direction for a taiko wafer 200 μm thin, simulated at a nominal temperature of T = 50 ºC.

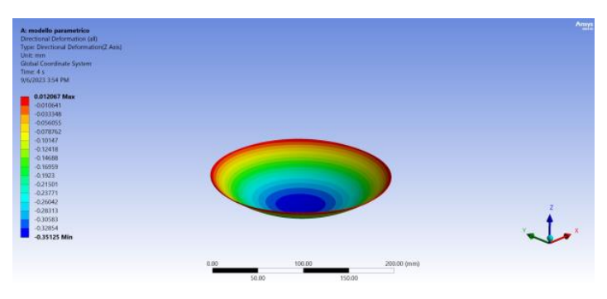

Fig. 3b. Projection of the distribution of the directional deformation along the z direction for a taiko wafer 200 μm thin, simulated at a nominal temperature of T = 50 ºC, the magnification is 100 x.

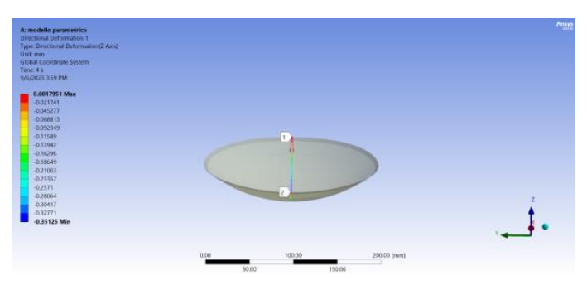

Fig. 4a. Snapshot of the first path used to probe the z_deformation along x direction.

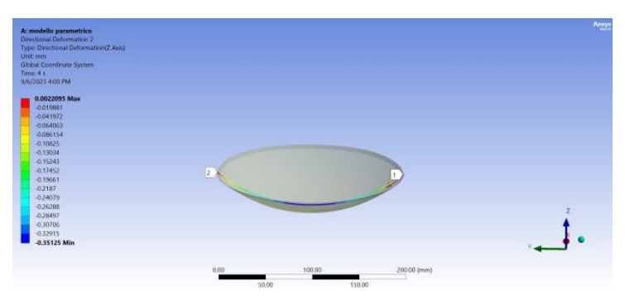

Fig. 4b. Snapshot of the first path used to probe the z_deformation along y direction.

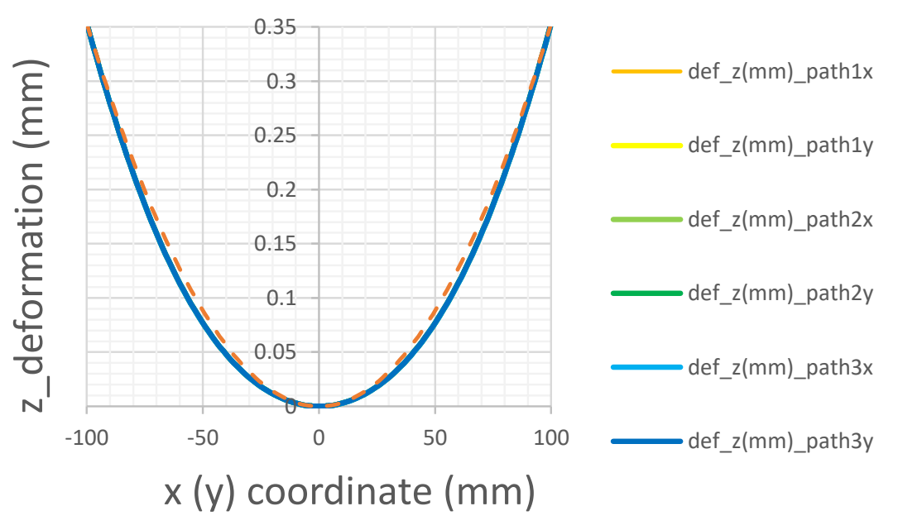

Fig. 5. Directional deformation along the z direction for each pair of paths 1x, 1y, 2x, 2y, 3x and 3y, reported as a function of the coordinate x (y) along the path, for the case of FSM-taiko wafer 200μm thin. All the paths provide the same deformation. The curvature has been determined from a parabolic approximation and the trend according to the theory reported for comparison.

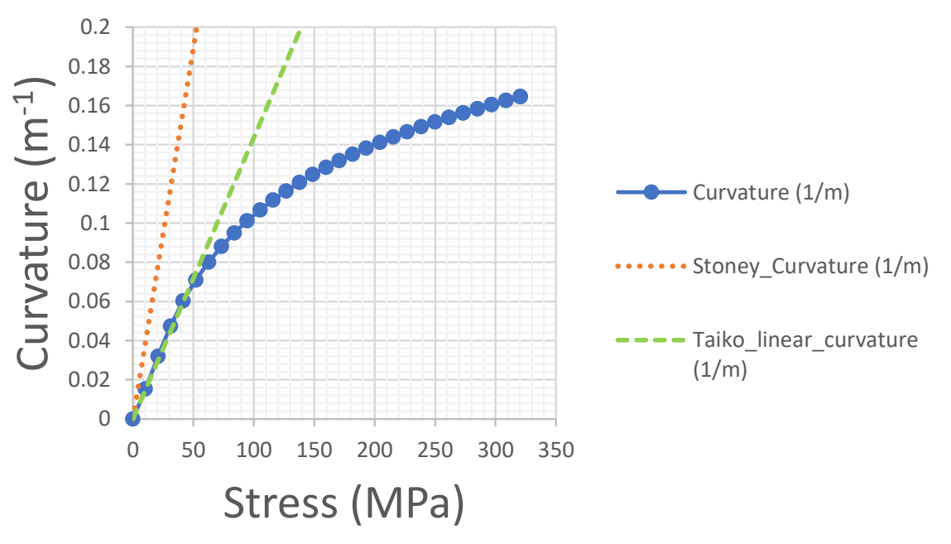

Fig. 6. Curvature as a function of the stress for a taiko wafer having hs =200 μm and the other quantities fixed to the typical value reported in table 1. In the graph, it is reported the line determined by the slope of the Stoney equation and the tangent line to the Curvature vs Stress curve. The slope and hence the curvature for the taiko wafer is lower with respect to the Stoney case.

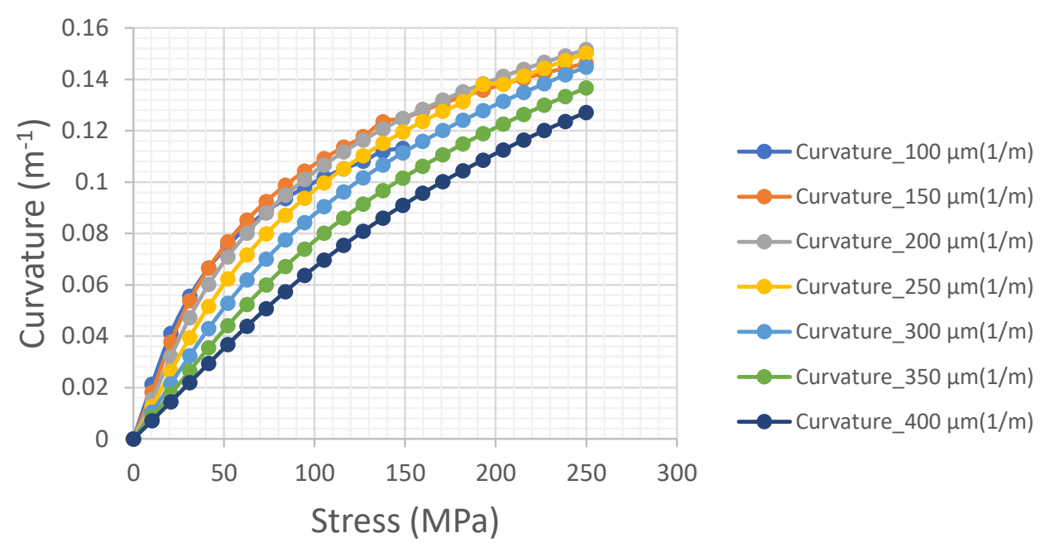

Fig. 7. Curvature as a function of the stress for a taiko wafer with h_s ranging in the interval 100 - 400 μm and the other quantities fixed to the typical value reported in table 1.

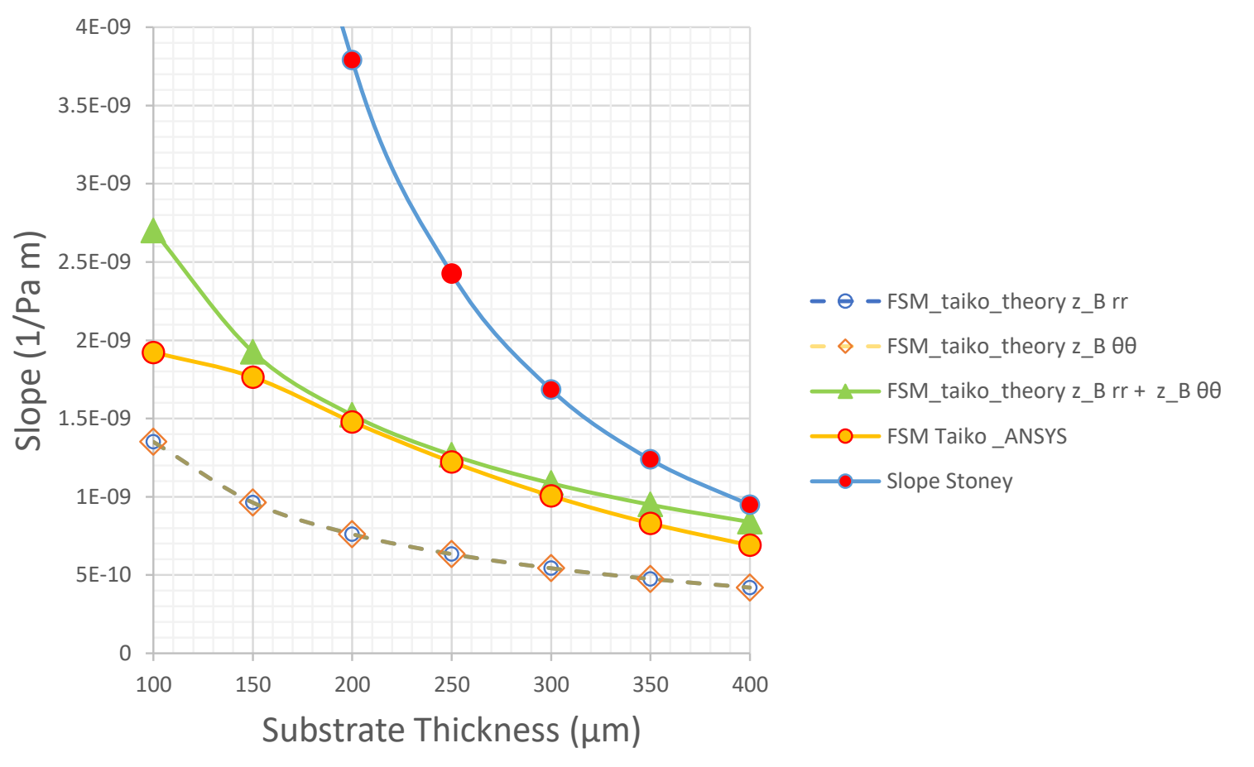

Fig. 8. Slope in the linear case for a taiko wafer reported as a function of the substrate thickness in μm, and its comparison with the slope provided by the Stoney Equation.

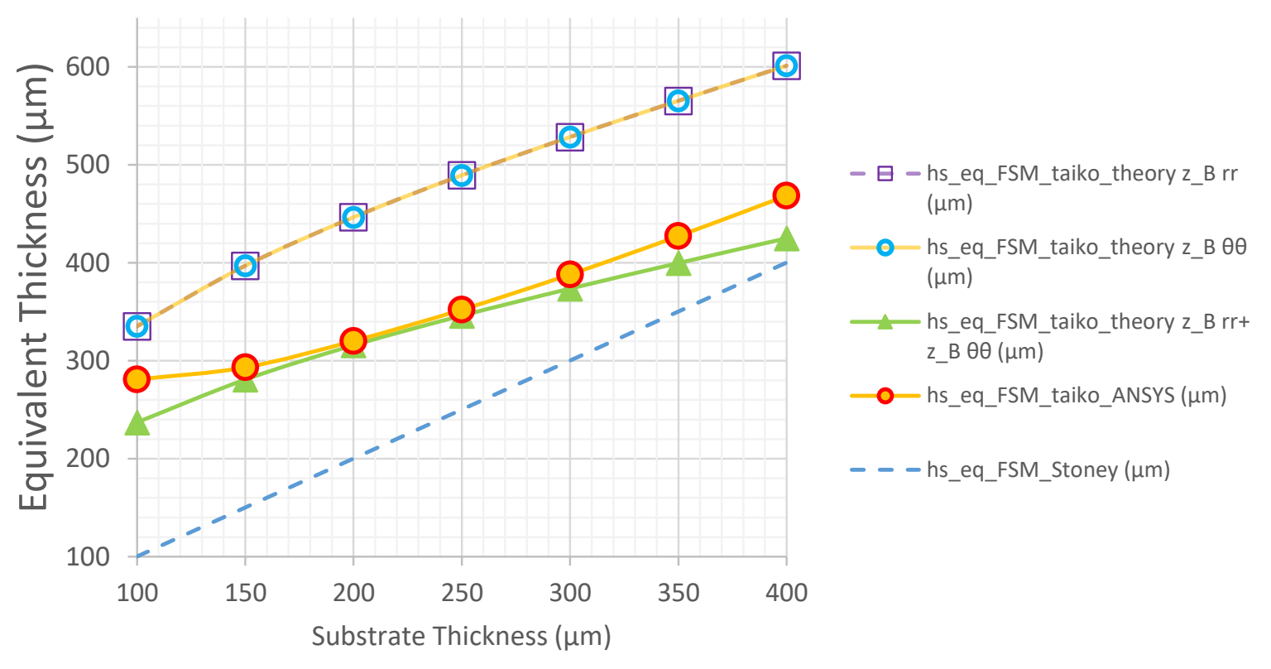

Fig. 9. Equivalent thickness of an FSM-taiko wafer as a function of the substrate thickness.

Conclusions: the equivalent thickness of a front side metallized taiko wafer has been determined theoretically and measured by means of finite element analysis methods. A comparison of the two approach reveals that the analytical solution grasps the order of magnitude and the trend of the mitigation of the curvature due to the structure of the taiko wafer. The FSM-taiko wafer behaves as an equivalent flat wafer whose thickness is higher than the substrate thickness. The obtained results can be extended also to other semiconductors e. g. wide band gap semiconductors such as silicon carbide and gallium nitride.

References

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