Influence of Thermo-mechanical Effects induced by 3D Assembly on Silicon Microring Resonator

Audrey Michard, Nicolas Michit, Jean-Baptiste Quelene, Jean-François Carpentier, Pietro Maris Ferreira

Influence of Thermo-mechanical Effects induced by 3D Assembly on Silicon Microring Resonator

A. MICHARD[1,2*], N. MICHIT[1], JB. QUELENE[1], JF. CARPENTIER[1], P. MARIS FERREIRA[2]

[1]STMicroelectronics, 850 rue Jean Monnet, Crolles, 38926, France

[2]GeePs, UMR CNRS 8507, CentraleSupélec, 3 rue Joliot Curie, Gif-sur-Yvette, 91192, France

*audrey.michard@st.com

Silicon photonics is considered as a prime technology for communication and high-speed computing applications. Ring resonator modulators are one of the key components, especially for next-generation high data-rate and high density interconnects. Indeed ring-based transceivers have been proposed to implement energy-efficient optical links in order to meet power and bandwidth datacoms standard [1]. The design of such a transceiver requires a careful integration between photonic and CMOS chips. The hybrid solution employed in [1] consists of a flip-chip integration and is often preferred thanks to separated design and process technology optimisation for the best performance of each circuit. However the introduction of micro copper-pillars to connect both chips can induce thermo-mechanical stresses on silicon waveguides. This issue is not without consequence for the optical properties which will be discussed in the following, after the quantification of 3D assembly-induced stress.

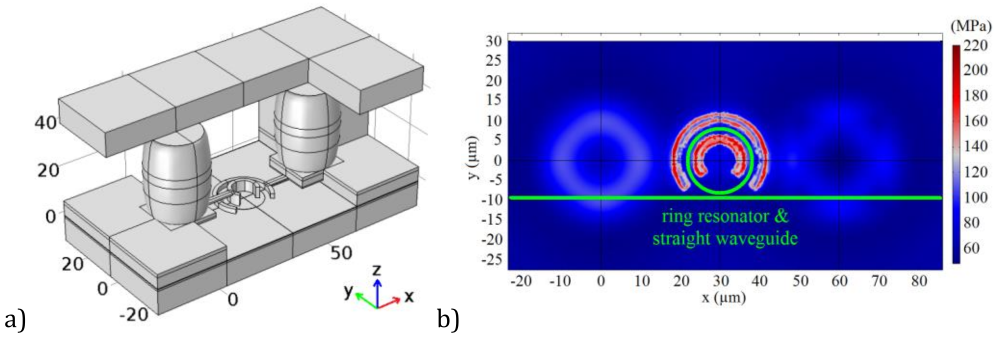

Fig. 1. a) 3D model of a photonic IC with a ring resonator connected to two Cu-pillars; b) Von Mises stress tensor map (MPa) on silicon plane.

During chips fabrication and micro-pillars contacting, high temperature processes are applied. The cooling leads to strained silicon waveguide since silicon and copper used for connections have distinct coefficients of thermal expansions. To evaluate the resulting stress, a finite element modelling was set similarly to the study performed in [2]. Figure 1.a) shows the geometries used to model the flip-chip assembly. The ring resonator has an 8-µm radius and is surrounded by two bumps spaced of 60 µm. The top, middle and bottom diameters of the Cu-pillars are respectively 25, 30, and 25 µm while their heights are 40 µm. The photonic die model includes also the aluminium pads and the ring copper contacts to simulate the BEoL stack. Flip-chip processes are simulated thanks to a uniform thermo-mechanical cooling with temperature differences of 220°C, 170°C, and 80°C for respectively the top die, the underfill material (a non-conductive paste was used), and the bottom die. Figure 1.b) represents the stress distribution in the silicon layer with ring and straight waveguides in green. More precisely, x, y, and z components of stress tensor (σ_x, σ_y, and σ_z) along the straight waveguide are reported on figure 2.a). It shows that the stress can reach the order of 60 MPa either in "tension" near the ring or in "compression" under the Cu-pillars. Waveguide optical properties are modified by stress due to the photo-elastic effect. This effect was measured in a Si ring resonator in [3] and was demonstrated to be consistent with that of bulk Si. As a consequence, the change in refractive index tensor (Δn_x, Δn_y, and Δn_z) is modelled by the stress-optic constants of Si (C_1 and C_2) and is expressed as Eq. (1) [4]. The shear stresses are very small and, hence, their impact on refractive index is negligible in this paper. Wave propagation in photonic devices is dictated by the effective index. The stress-induced variations of effective index (Δn_{eff}) can be derived as Eq. (2), where coefficients a_1 and a_2 are given in [4] for a TE mode. For a TM mode, Eq. (2) is assumed to be also valid with $a_{1,TM} = a_{2,TE} = 0.219$ and $a_{2,TM} = a_{1,TE} = 0.844$. Figure 2.b) shows the estimated effective index profile along the straight waveguide for both TE and TM modes.

$$\begin{cases} \Delta n_x = -C_1\sigma_x - C_2(\sigma_y + \sigma_z) \\ \Delta n_y = -C_1\sigma_y - C_2(\sigma_x + \sigma_z) \\ \Delta n_z = -C_1\sigma_z - C_2(\sigma_x + \sigma_y) \end{cases} \quad (1)$$

$$\Delta n_{eff,TE/TM} = a_{1,TE/TM}\,\Delta n_y + a_{2,TE/TM}\,\Delta n_z \quad (2)$$

In the case of a ring, a change in effective index results in a resonance wavelength shift which can be critical especially for a WDM (wavelength division multiplexing) system. Indeed the previous study indicates a variation of $\Delta n_{eff,TE}$ between 0.0002 and 0.0008 in the ring waveguide, corresponding to a resonance shift of approximately 50 to 250 pm. By comparison, the channel spacing in a WDM transmission is typically 280 pm (50 GHz) or 560 pm (100 GHz) for a communication at 1.3 μm. Therefore the system performance can be greatly deviated from the designed devices. Moreover a cross-coupling between TE and TM modes can appear in the straight waveguide of a WDM system since the Cu-pillars introduce a periodic perturbation as shown in figure 2.b). Consequently a polarization conversion can be achieved resulting in a power loss in TE mode and a possible mode dispersion, degrading thus the global performance.

In conclusion, the impact of 3D assembly on a Si ring resonator has been theoretically investigated for the first time to the authors' knowledge. Next step would be to experimentally quantify the induced stress through the resonance wavelength shift.

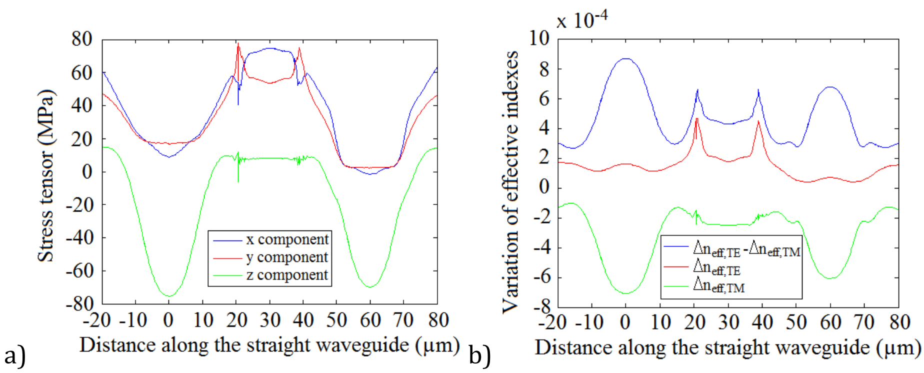

Fig. 2. a) Stress tensor profile and b) Variation of effective index along the straight waveguide.

References

[1] M. Rakowski et al., in IEEE International Solid-State Circuits Conference, pp. 408-410, 2015.
[2] V. Fiori et al., Microelectronics Reliability, vol. 54, no. 4, pp. 764-772, 2014.
[3] Y. Amemiya et al., Japanese Journal of Applied Physics, vol. 47, no. 4, pp. 2910-2914, 2008.
[4] Y. Yang et al., IEEE Photonics Journal, vol. 5, no. 6, 2013.