Determination Of Wafer And Process Induced Resonant Frequency Variation In Silicon Microdisk-Resonators

William A. Zortman, Michael R. Watts, and Douglas C. Trotter
Sandia National Labs, P.O. Box 5800, Albuquerque, New Mexico 87185
wzortm@sandia.gov

Abstract: By comparing the frequency deviations of the TE and TM modes of identically designed silicon microdisk-resonators across a wafer, we demonstrate that layer thickness non-uniformity is the dominant cause of fabrication-induced microdisk-resonator frequency deviation.

OCIS codes: (130.3120) Integrated Optical Devices ; (130.4110) Modulators; (230.7370) Resonators

1. Introduction

A broad range of silicon microphotonic devices is being developed for both telecom and datacom applications, including filters [1], modulators [2-4], and high-speed bandpass switches [5]. Many such devices have been based on microring and microdisk resonators because of their ability to modulate and actively multiplex and demultiplex with high-fidelity and minimal power while consuming little chip real-estate [1]. The performance of microring and microdisk resonators are particularly sensitive to variations in frequency due to minute changes in geometry (i.e. guide width/height and diameter) resulting from deviations in the fabrication process. In CMOS circuit manufacturing, variations in silicon manufacturing are common and have been overcome with statistical process control followed by testing and binning post-fabrication. As with electrical devices understanding the impact of process variation on device performance is critical to establishing a manufacturable process.

In this paper, the transverse electric (TE) and transverse magnetic (TM) resonant frequencies are measured for sixteen identically designed microdisk resonators fabricated in different locations on the same SOI wafer. Using the differences in the TE and TM mode susceptibilities to thickness and diameter changes in the microdisk computed with a finite difference cylindrical modesolver [6], we estimate the changes in the silicon layer thickness and microdisk diameter at +/- 4nm and +/- 2.5nm, respectively. Despite, the relatively similar degrees of variation, the resonant frequency susceptibility to layer thickness is considerably larger, leading to ~2 THz swings resulting from layer thickness non-uniformity and only ~0.15 THz from microdisk diameter variations.

2. Device Testing

The tested device is a 6um diameter microdisk resonator with a 245nm thick silicon layer coupled to a ~370nm wide silicon waveguide with a separation distance of ~330nm between waveguide and the microdisk. Fabrication was done on 150mm SOITEC Silicon on Insulator (SOI) consisting of a 260nm thick silicon layer and one micron buried oxide. The thickness variation of the silicon layer was +/- 8nm (+/- 3σ) with a 1σ value of 2.5nm as measured by the vendor. The waveguide and disk were defined using optical lithography from a 248nm ASML laser scanner-stepper. Etching was performed using a reactive ion etcher. The patterned silicon was subsequently oxidized (~15nm silicon loss) and dopants were implanted to create a vertical PN junction and ohmic contacts for active structures. The chosen wafer had minimal doping (i.e. $\sim 5\times 10^{17}/\text{cm}^3$), so as to minimize any doping induced variation. The structures were then buried in 2um of oxide, and contacts were made with tungsten vias and subsequently connected with aluminum lines as described in [5].

The devices were tested using an Agilent 81600B series swept laser source and 81635A sensor module with a frequency resolution of 0.5pm and +/-0.8pm repeatability. The measurement pattern followed was a simple cross from the left to right of the wafer (notch down) and then from the top of the wafer down to the notch. Figure 1A is the measurement done from the top of the wafer down to the notch where the mean is over all 16 data points. The TE mode shows almost 1THz of variation across the wafer. The frequencies of the two modes move together indicating the two polarizations are being driven by similar factors. However the TM swings are more dramatic which is consistent with its greater sensitivity to thickness variations (see Table 1). Previous tests on similar devices show that 3.5V reverse bias is needed to shift though 25GHz [4]. Simulations have shown that these devices will break down at about 7V meaning there is a maximum electrical tuning bandwidth of 50GHz. The source of the frequency variation is assumed to be due to changes in the thickness and diameter of the ring which would modify the TE and TM resonances based on changes in the transverse fields imposed by the dimension shifts.

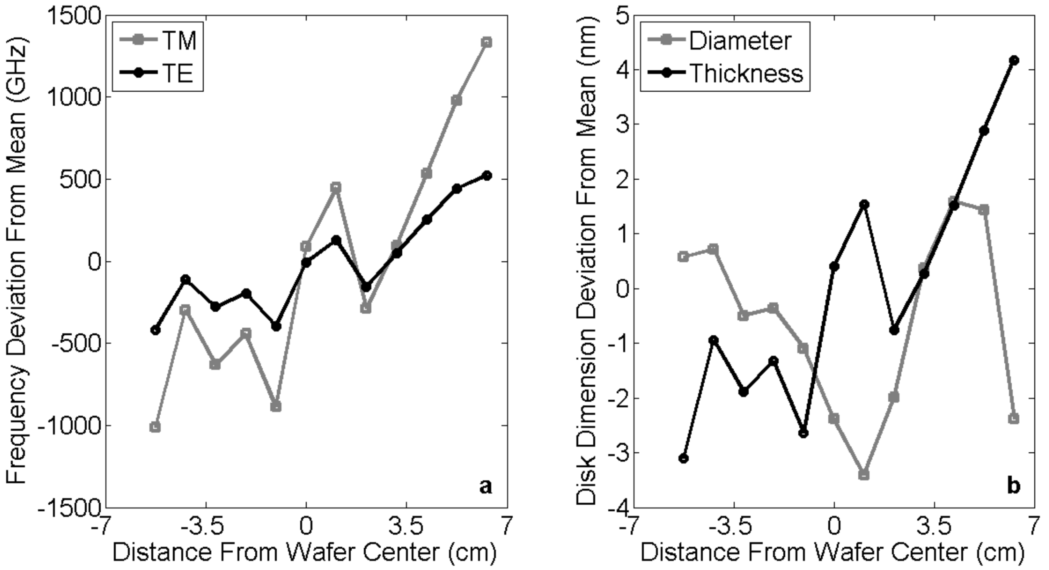

Figure 1: (a) The variation in resonant frequency for the TE and TM modes across the center of the wafer. (b) The calculated dimensional deviation (i.e. diameter and thickness) from the finite element modesolver required to produce the frequency variations in (a).

3. Analysis

To determine the source of the variation (silicon thickness or diameter variation) we employed a cylindrical finite element modesolver [6] to derive expected frequency variation Δf for the TE and TM modes versus changes in thickness and diameter. These modesolver predictions are listed below in Table 1.

Table 1: The polarization dependent frequency variation with thickness and diameter in a microdisk resonator as predicted by a finite element modesolver.

	TE	TM
Δf(GHz)/Thickness(nm)	140	330
Δf(GHz)/Diameter(nm)	26	18

The TM mode exhibits twice the susceptibility to variations in thickness as the TE mode, but less susceptibility to changes in diameter. In both the TE and TM cases, the impact of diameter variations on the resonant frequency are much less significant than thickness variations. With this information a system of equations (1) can be formulated and then solved simultaneously using linear least squares fitting to obtain predicted thickness ΔT and diameter ΔD skews.

$$\begin{bmatrix} \left.\dfrac{df}{dT}\right|_{TE} & \left.\dfrac{df}{dD}\right|_{TE} \\ \left.\dfrac{df}{dT}\right|_{TM} & \left.\dfrac{df}{dD}\right|_{TM} \end{bmatrix} \times \begin{bmatrix} \Delta T \\ \Delta D \end{bmatrix} = \begin{bmatrix} \Delta f_{TE} \\ \Delta f_{TE} \end{bmatrix} \qquad (1)$$

This formulation takes into account the simulated variation in frequency with disk thickness and diameter shown in the first matrix, the thickness and diameter variation in the unknown vector and finally the measured results on the right side.

The solved thickness and diameter variations are plotted in Figure 1b. The measured swings in resonant frequency are largely the result of thickness variation. The calculated variation in thickness (+/-4nm) is consistent with the measured variation across the wafer provided by the vendor.

The contribution to the frequency shift for the two polarizations from thickness and diameter non-uniformity across the wafer is plotted in Figure 2 along with their sum. Comparing to Figure 1b it is clear that comparable swings in diameter have much less impact compared to the thickness non-uniformity. The total frequency variation almost exactly overlays the thickness contribution for the TM case, indicating little impact from diameter deviations. If thickness variations were zero, note that the frequency deviation due to diameter would still be beyond the scope of electrical tuning for a significant portion of the wafer.

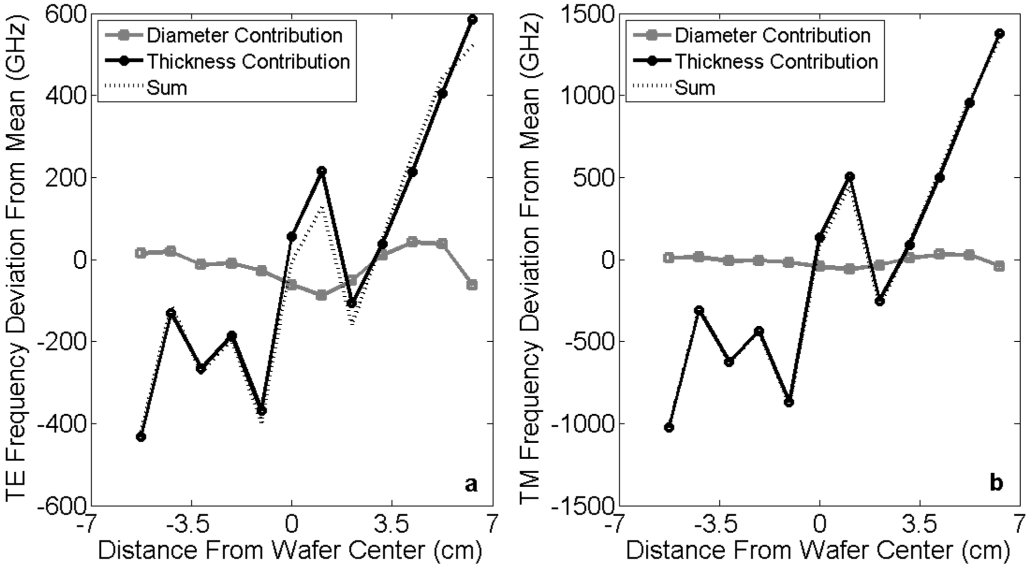

Figure 2: The calculated contributions of thickness and diameter variation to the (a) TE and (b) TM resonances.

3. Conclusions

A finite element modesolver was used to model the impact of dimensional variation on the TE and TM resonant frequencies of a microdisk resonator and the differences in their susceptibilities to thickness and diameter changes was used to isolate the contributions of each to the total fabrication induced frequency variations in a series of samples collected across a single 150mm wafer. Thickness non-uniformity on the SOI silicon wafer was determined to be the driving factor for deviation in the devices tested. A segmented approach such as this will likely be necessary to isolate non-uniformities in bringing silicon photonics to high volume manufacturing. The thickness non-uniformity is consistent with the non-uniformity in the SOI starting material. The cause of the diameter non-uniformity is believed to be a result of variations in optical lithography. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

4. References

[1] T. Barwicz, M. R. Watts, M. A. Popovic, P. T. Rakich, L. Socci, F. X. Kärtner, E. P. Ippen and H. I. Smith, "Polarization-transparent microphotonic devices in the strong confinement limit," *Nature Photonics* **1**, 57 – 60 (2006)

[2] A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," Nature **427**, 615-618 (2004)

[3] Q. Xu, B. Schmidt, S. Pradhan and M. Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature* 435, 325-327 (2005)

[4] M. R. Watts, D. C. Trotter, R. W. Young, and A. L. Lentine, "Ultralow Power Silicon Microdisk Modulators and Switches", IEEE Group IV Photonics, Sorento, Italy (2008)

[5] M.R. Watts, D.C. Trotter, R.W. Young, "Maximally Confined High-Speed Second-Order Silicon Microdisk Switches", Optical Fiber Communications Conference (OFC) 2008 PDP14, San Diego, Ca (2008)

[6] M.A. Popovic, "Complex-frequency leaky mode computations using PML boundary layers for dielectric resonant structures," Integrated Photonics Research Conference (IPR) 2003 Washington, DC (2003)