Exploiting Atomic Nature of the Interface for Controlling Mode Coupling in Microresonators

Xingchen Ji[1,2,*], Andres Gil-Molina[1], Michal Lipson[1,*]
[1]*Department of Electrical Engineering, Columbia University, New York, NY 10027, USA.*
[2]*Currently at John Hopcroft Center for Computer Science, Shanghai Jiao Tong University, Shanghai 200240, China.*
[*]*xj2168@columbia.edu and ml3745@columbia.edu*

Abstract: We show the ability to control the degree of mode coupling in high quality factor silicon nitride (Si_3N_4) microresonators by controlling the atomic nature of the resonators interface. © 2022 The Author(s)

Mode-coupling induced resonance splitting is a phenomenon commonly observed in optical microresonators. Owing to the small resonator mode volume and high quality factor, extremely small defects such as nanoscale surface imperfection or deposited particles can cause coupling between clockwise and counterclockwise modes, as evidenced in spectral splitting. This mode splitting can be exploited for sensing applications [1], and to create highly efficient narrowband reflectors which is greatly beneficial to laser applications [2]. Previously, this splitting has been widely reported in microspheres or microtoroids due to their high quality factors. And the mode splitting is artificially controlled by introducing a subwavelength near-field tip into the cavity's near-field [3] or by embedding small silicon nanocrystals in the cavity [4]. Most recently, due to the significant improvement of nanofabrication processes, mode splitting has become more commonly observed in integrated microresonators, such as silicon nitride (Si_3N_4) [5-8]. However, mode splitting in these integrated devices is heavily dependent on the nanofabrication process, which normally results in a very limited amount of splitting and is not easily controllable since the device performance is sensitive to even sub-nanometer roughness [9].

Here we leverage the fact that the presence of chlorine as a precursor to control the atomic nature of the interface between the Si_3N_4 and SiO_2 interface, thus controlling the mode splitting. Precursors such as dichlorosilane (SiH_2Cl_2) and ammonia (NH_3) are widely used for Si_3N_4 film deposition in the furnace. In order to utilize chlorine in the precursor to control the interface, we have modified our fabrication process flow. In a conventional process, we directly anneal the device after Si_3N_4 film deposition or after device layer patterning, which is annealed without any oxide cladding as shown in Figure 1(a). In our new process, we don't perform any annealing after Si_3N_4 film deposition or after device layer patterning. We perform the annealing only after oxide cladding as shown in Figure 1(b). The slight change of the annealing process sequence prevents the chlorine to diffuse out, and with the existence of oxide cladding, the atomic nature of the interface between the Si_3N_4 and SiO_2 were changed by forming a nanometer-thick intermedium layer.

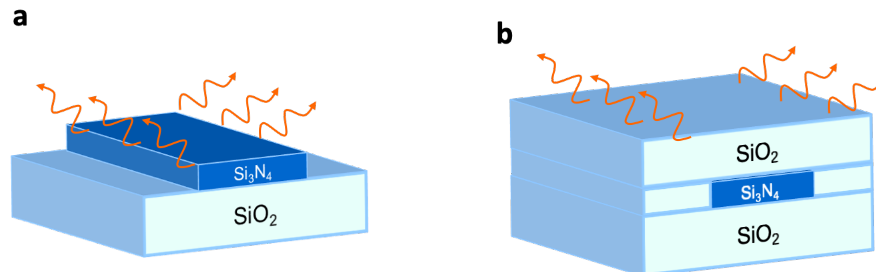

Fig. 1. (a) Conventional process. The device is annealed directly after Si_3N_4 film deposition or after device layer patterning, and it is annealed without any oxide cladding. (b) New process. The device is annealed only after oxide cladding deposition.

We demonstrate that we can control the thickness of a sub-nanometer layer at the resonators interface by using different annealing temperatures allowing us to achieve a significant change in the amount of mode splitting. We measured the normalized transmission spectrum of three identical microresonators with conventional annealing, 1050 ºC with new annealing, and 1200 ºC with new annealing. Our measurement results are shown in Figure 2. We observed no splitting with conventional annealing, whereas we observed clearly splitting in both 1050 ºC and 1200 ºC with new annealing. For 1050 ºC new annealing, the ratio between splitting and full width half maximum (FWHM) of the resonance is around 1.3. For 1200 ºC new annealing, this ratio is around 3.1. We also used high-resolution Transmission Electron Microscopy (TEM) and Energy Dispersive Spectroscopy (EDS) to determine the thickness of the intermedium layer and the distribution of chlorine element. As shown in Figure 2, for conventional

annealing, we observed no chlorine signals and no intermedium layer. For 1050 ºC new annealing, we measured an intermedium layer with a thickness of around 1.8-1.9 nm and strong chlorine signals at the Si_3N_4-SiO_2 interface. For 1200 ºC new annealing, we measured an intermedium layer thickness of around 2.2-2.3 nm, strong and concentrated chlorine signals at the Si_3N_4-SiO_2 interface. We show that by using different annealing temperatures with the new process, we can tailor the thickness of the intermedium layer, which further controls the mode splitting.

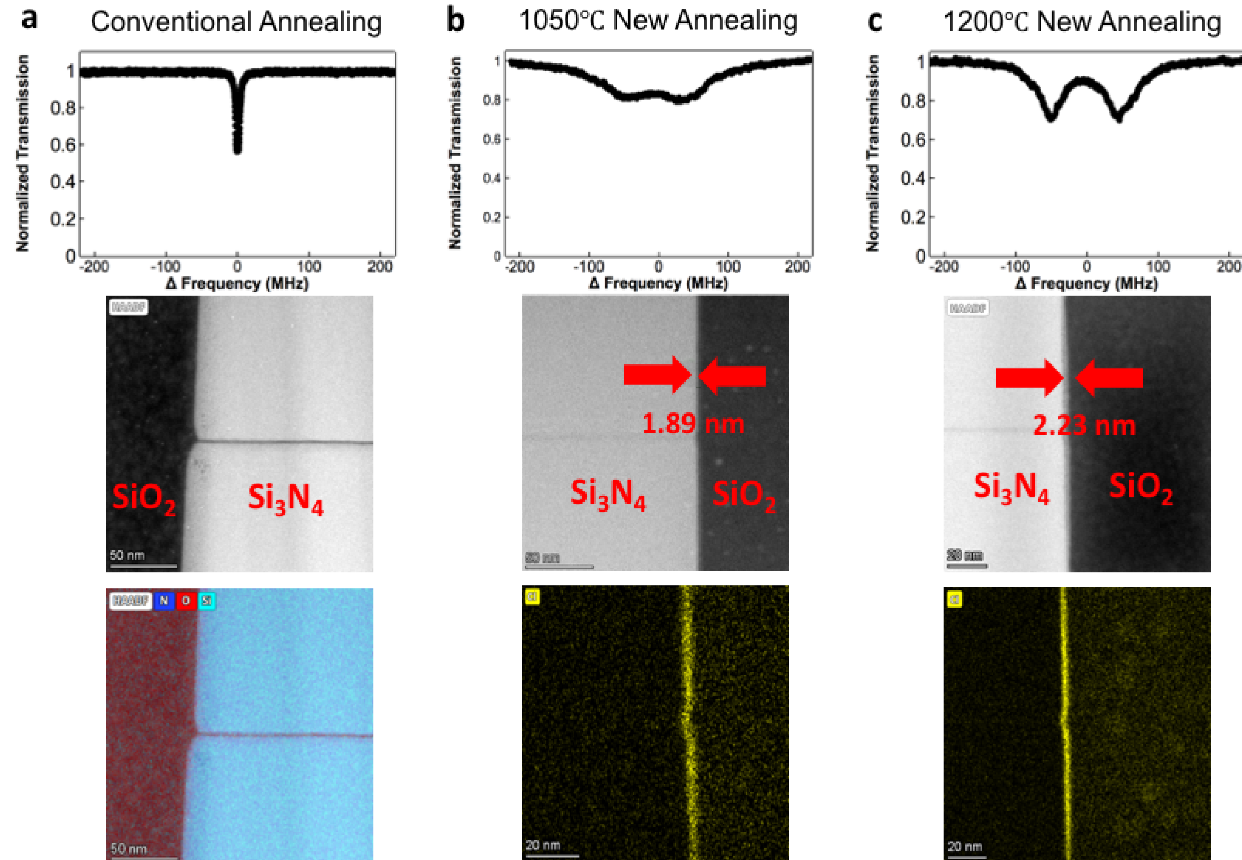

Fig. 2. (a) Normalized transmission spectrum without conventional annealing. No visible splitting or intermedium layer was observed using high-resolution Transmission Electron Microscopy (TEM). No chlorine signals observed using Energy Dispersive Spectroscopy (EDS), only Si, N and O signals are observed. (b) Normalized transmission spectrum with 1050 ºC new annealing. Visible splitting and intermedium layer was observed using high-resolution TEM. The intermedium layer thickness is measured to be around 1.8-1.9 nm. Strong chlorine signals were observed at the Si_3N_4-SiO_2 interface using EDS. The ratio between splitting and full width half maximum (FWHM) of the resonance is 1.3. (c) Normalized transmission spectrum with 1200 ºC new annealing. Visible splitting and intermedium layer was observed using high-resolution TEM. The intermedium layer thickness is measured to be around 2.2-2.3 nm. Strong and concentrated chlorine signals were observed at the Si_3N_4-SiO_2 interface using EDS. The ratio between the splitting and FWHM of the resonance is 3.1.

In conclusion, we leverage the fact that the presence of chlorine as a precursor to control the atomic nature of the resonators interface, and this atomic change allows us to control the mode splitting. We propose a new process with a slight change in the annealing process sequence. We demonstrate that by using different annealing temperatures with the new process, we can tailor the thickness of the intermedium layer, which enables us to realize a large amount of mode splitting in a controllable way. This work provides a method to induce significant mode splitting and can benefit applications such as ultra-narrow linewidth laser, laser stabilization, and sensing.

References

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