Fabrication of high-Q silicon nitride microdisk resonator coupled with on-chip waveguide

W. Xie and D. Van Thourhout

Photonics Research Group, Department of Information Technology (INTEC), Ghent University-IMEC, Gent B-9000, Belgium.

We designed and fabricated free-standing SiN microdisk resonators vertically coupled with on-chip SiN waveguides. During the full process the temperature is kept below 270°. We experimentally demonstrated an intrinsic quality factor of 1.4×10^5 and a large free spectral range of ~10nm in a microdisk operating near 1310nm. We also showed that the coupling strength between the disk resonator and the bus waveguide can be readily changed by tuning the parameters of the geometric configuration. In the same way, we realized selective coupling to the different radial modes of the disk. These devices are promising for the SiN photonic community.

Introduction

Silicon nitride (SiN) has gained increasing interest recently in various photonic applications including integrated photonic circuits [1], nonlinear optics [2], optomechanics [3], and on-chip biosensing [4], due to its transparency from the visible to the infrared wavelength range and a moderate optical index (~2.0). These unique properties enable making low-loss SiN optical components over a broad wavelength range. Moreover the platform is compatible with fabrication using the same tools as those used for making complementary metal-oxide-semiconductor (CMOS) electronics. However, compared with a high optical index material like silicon, integrated SiN devices have larger footprints to offer sufficient optical confinement and thereby low-loss optical components. In particular, SiN resonators are considered as essential building blocks in SiN photonic community, yet to achieve such a SiN resonator with a high quality factor (Q) but a compact size still remains a challenge. For instance, high-Q SiN ring or disk resonators integrated on chip typically needs a more than 50μm footprint, potentially preventing their large-scale integration on chip.

In this paper, we show the successful fabrication of free-standing SiN microdisk resonators vertically coupled with on-chip SiN waveguides in a lab-built SiN platform developed at a relatively low temperature of 270°. We experimentally demonstrate an intrinsic Q factor of 1.4×10^5 together with a large free spectral range of ~10nm in a disk with only 30μm diameter operating near 1310nm. Furthermore, it is shown that the coupling strength between the disk resonator and the bus waveguide can be readily changed by tuning the parameters of the geometric configuration. We also show that we can control the coupling between the bus waveguide and different radial modes of the disk resonator by taking the advantage of the vertical coupling strategy.

Design and Fabrication

The design of the SiN disk-waveguide vertical coupling configuration is shown in Fig. 1 (a). The design begins with a silicon wafer with a 3μm thermal SiO_2 layer as the optical insulator. The bus SiN waveguide is buried in a SiO_2 cladding with a smooth top surface and the vertical coupling gap between the SiN disk and waveguide is determined by the thickness of an amorphous silicon (a-Si) pillar, as shown in Fig. 1(a). The top SiN disk coupled to the bus waveguide is suspended on the a-Si pillar. The horizontal offset is defined as the relative distance of the center of the bus waveguide with respect to the edge of the disk and varies from -450nm to +450nm as the bus waveguide moves towards the disk as schematically indicated in Fig. 1(a). Following finite-difference time-domain (FDTD) simulations, we choose a thickness of ~400nm for both the waveguide and the disk layers, guaranteeing a fundamental transverse electric (TE) mode with a low loss at ~1310nm. The width of the bus waveguide as well as the diameter of the SiN disk are changed to study the coupling behavior under a fixed vertical coupling gap of ~500nm. The undercut distance *d* as shown in Fig. 1(a) should be sufficiently deep to eliminate leakage of the TE mode to the a-Si pillar. We performed a simulation of the *Q* factor as a function of the undercut distance for the disk with a 30μm diameter, as shown in Fig. 1(b), from which it can be seen that the a-Si pillar has negligible influence on the *Q* of modes in the disk when the undercut distance is above 2.5μm.

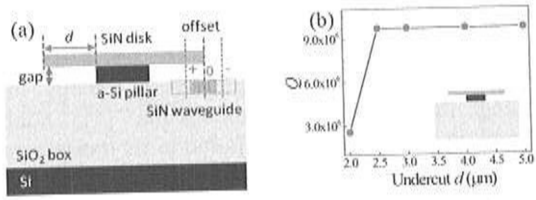

Fig. 1. (a) Cross-sectional view of SiN disk-waveguide vertical coupling configuration. (b) Simulated *Q* factor of the first order TE mode around 1300nm for different undercut etch distance, *d*. The inset shows the structure in simulation with a fixed gap and a diameter of 30μm for the disk.

In Fig. 2(a-f), we schematically show the fabrication flow of the designed SiN disk-waveguide coupling devices. Firstly, a 400nm thick SiN is deposited onto a wafer with a 3μm thermal SiO_2 box layer by using an optimized plasma enhanced chemical vapor deposition (PECVD) process performed at a temperature of 270°, and then the bus waveguide is patterned by using contact lithography and subsequently transferred onto SiN layer by using reactive ion etching (RIE) to form a strip waveguide as shown in Fig. 2(a). Here both the contact lithography and the RIE processes were optimized to be able to define a single mode waveguide with a ~600nm resolution and to have smooth and steep sidewalls of the etched SiN. After waveguide fabrication, a 1.2μm PECVD SiO_2 cladding is deposited (in Fig. 2(b)) and then a chemical mechanical planarization step is applied to flatten the surface with a local roughness below 10nm (in Fig. 2(c)). Next, a gap layer of ~500nm PECVD a-Si and disk layer of 400nm SiN are successively deposited on the planarized substrate, and then the top disk is fabricated, aligned with respect to the buried bus waveguide, as shown in Fig. 2(d) and (e). Finally an alkaline based wet etching is carried out to undercut the a-Si and realize a free-standing SiN disk supported on the a-Si pedestal as drawn in Fig. 2(f). We show one fabricated result in Fig. 3(a) and (b) and obviously the designed configuration of the device is well realized, demonstrating the suitability of our fabrication process to accomplish this on-chip vertical coupling devices.

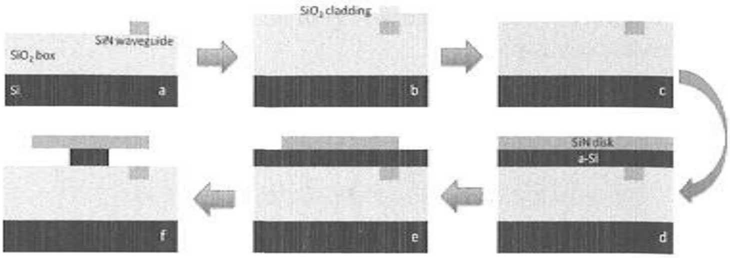

Fig. 2. (a-f) Schematics of the fabrication flow of SiN free-standing microdisk vertically coupled to on-chip waveguide.

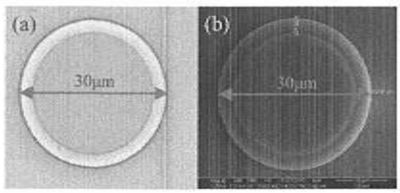

Fig. 3. (a) Optical and (b) scanning electron microscope images of the top view of fabricated device with 30µm diameter disk .

Measurement Results

The fabricated devices were characterized by taking transmission spectra from 1260 to 1360nm by coupling a tunable laser source to the cleaved facets of the bus waveguide. In Fig. 4 we show the transmission of the disk with diameter of 30µm at different offsets of -210nm, +120nm, +450nm, and +620nm, as previously defined. From the FDTD simulation of the TE modes in the disk, we found that the higher order TE mode families have relatively larger free spectral ranges (FSR) and hence we can designate the two sets of resonant modes in the transmission spectra as the first and second TE mode families with some selected modes denoted with red and blue arrows, respectively in Fig. 4. It is obvious that when increasing the offset from -210nm to +120nm the first TE mode family evolves from an undercoupled to the nearly critical coupled regime, with a measured loaded Q decreasing from 47200 to 35300 for the mode around 1310nm. The intrinsic Q_{int} can be calculated by $Q_{int} = 2Q_{load} / (1+\sqrt{T_0})$, where T_0 is the normalized transmission at the resonance [5]. Thus we achieve an intrinsic quality factor of $\sim 0.6\times 10^5$ together with a FSR of ~10nm near the wavelength of 1310nm. When the offset further increases, the coupling moves into the overcoupling regime for the first order modes as shown in Fig. 4 for the offsets of +450nm and +620nm. On the other hand, the transmission depth of the second order modes gradually increases when moving the waveguide closer to the disk, which indicates an increasing coupling strength for this mode family. For the offset of +620nm, the second order modes reach nearly critical coupling with a loaded Q of 17500 around 1310nm. By comparing the transmission spectra with the offsets of +120nm and +620nm in Fig. 4, it is obvious that the critical coupling condition occurs for very different configurations for both mode families. This stems from the separated spatial distribution of the different radial order modes and is a clear advantage of the vertical coupling configuration. Finally, it should be added that we readily achieved an intrinsic Q of $\sim 1.4\times10^5$ around 1310nm by further improving on the fabrication process.

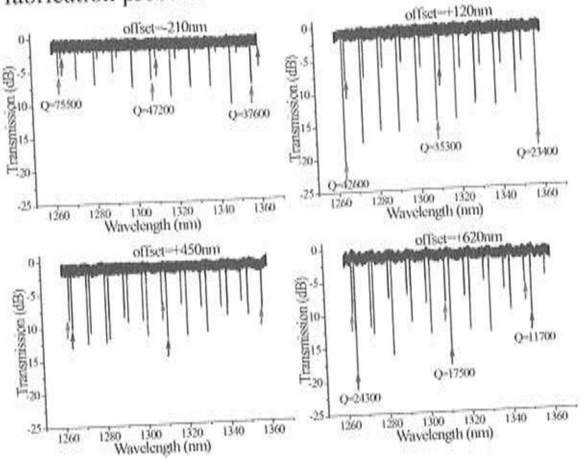

Fig. 4. Normalized transmission spectra of the disk with 30μm diameter at different offsets of -210nm, +120nm, +450nm, and +620nm. Red and blue arrows designate the first and second order TE modes respectively.

Conclusions

We fabricated SiN microdisks coupled with on-chip waveguides with high-Q and compact footprint on a lab-built SiN platform. A controllable coupling for different order modes in the disk was also demonstrated by modifying structural parameters of the device. Since the present design and fabrication of SiN microdisks can also be scaled down to the visible wavelength range, it is believed that these on-chip integrated SiN building blocks provide opportunities for promising applications.

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