High-quality-factor micro-ring resonator in amorphous-silicon on insulator structure

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Abstract. *Micro-ring resonators have been fabricated in hydrogenated amorphous silicon on silica structure. The intrinsic quality factor is estimated as 56,000 and the notch depth is ~ 30dB. The intrinsic loss per unit length is 15.3dB/cm, comparable to 9.16dB/cm in the single-crystalline silicon ring of the same geometry.*

Introduction

Micro-ring resonators have found wide applications in optical filtering, add-drop multiplexing, dispersion compensation and bio-sensing [1-4]. Q values larger than 10^5 have been demonstrated in single-crystalline silicon-on-insulator (SOI) structure [5-6]. There have been some reports on amorphous silicon rings [7], but the results are not well-comparable to single-crystalline silicon rings. From fabrication aspects, amorphous silicon (α-Si:H) can be readily deposited using low temperature plasma enhanced chemical vapour deposition (PECVD) with good uniformity. The thickness can be varied flexibly. Commercial SOI wafers, on the other hand, are fabricated using expensive wafer-bonding technology and usually the silicon thickness cannot be chosen freely. The common belief is that α-Si:H exhibits much higher material loss. In this work, we fabricate micro-rings in both α-Si:H and single-crystalline SOI of the same lateral and vertical geometry during the same process. By comparison we show that the performance of the α-Si:H ring resonator is at least comparable to that of the single-crystalline ring and α-Si:H is a promising platform for high quality photonic devices.

Theory

Time-domain coupled mode theory is applied to analyze the filter consisting of a single waveguide side-coupled to a ring [8-9]. The schematic is shown in Fig. 1. We assume that wave coming from the waveguide excites only one of the travelling modes in the ring, which in turn generates the other counter-travelling mode. We allow the mutual coupling between the two ring modes because we have introduced some nanometre-scaled periodic roughness on the ring sidewalls. This periodic roughness works as gratings. The period and amplitude can be tuned during the fabrication process. In the optimal case, it only improves the mutual mode coupling and does not significantly deteriorate the intrinsic Q. The presence of mutual mode coupling makes it easier to reach deep transmission notches for detection [10].

We study the steady-state solution and assume $e^{j\omega t}$ time dependence for the resonator and waveguide modes. The transfer function can be derived as

$$T(\omega) = \frac{\left|S_{-2}\right|^2}{\left|S_{+1}\right|^2} = \left|\frac{D}{C}\right|^2 \qquad (1)$$

where $C = AB + u^2$, $D = C - \left|\kappa_a^2\right|B$, $A = j(\omega - \omega_a) + \dfrac{1}{\tau_a}$ and $B = j(\omega - \omega_b) + \dfrac{1}{\tau_b}$.

For power conservation, the mutual coupling coefficient u is a real number. $\omega_{a,b}$ are the resonant frequencies for the ring resonator modes, τ is the photon life time, and κ is the coupling coefficient between the ring and the waveguide. The reciprocal of photon life time is the decay rate $1/\tau$, which is related by power coupling to the waveguide ($1/\tau_e$) and power dissipating due to intrinsic losses ($1/\tau_i$). Thus, $1/\tau = 1/\tau_e + 1/\tau_i$. The quality factor (Q) is decided by the photon life time, i.e., $Q = \omega_0\tau/2$. The waveguide/ring coupling coefficient and the power decay rate are related by $|\kappa|^2 = 2/\tau_e$.

From Eq. (1), the transfer function in general is not of Lorentzian shape. The Q value of the system cannot be estimated from the division of resonance frequency by 3dB bandwidth. The transmission spectrum has to be fitted to obtain the Q factors numerically.
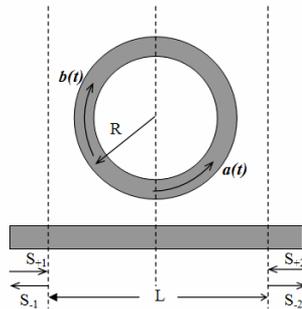

Fig. 1 Schematic of a ring resonator side coupled to a waveguide.

It is convenient to define a mutual coupling Q factor Q_u. Assume $\omega_a = \omega_b = \omega_0$,

$Q_u = \dfrac{\omega_0}{2|u|}$. Q_u is not related to any power loss in the system. It is merely a figure that

manifests the mutual coupling rate for the two travelling modes in the ring.

In practice it is difficult to guarantee the conventional critical coupling, when $Q_{ai} = Q_{ae}$, for complete channel drop. However, with the help of mutual coupling, the notch depth improves and it is possible to reach new critical coupling. When u further increases, the resonance notch will split [10].

Fabrication

α-Si:H is deposited by PECVD (STS). The refractive index variation is less than 1.0×10^{-3}. From atomic force microscope, the root mean square of the surface roughness is measured as 7.5 Å for the chamber deposition temperature 250 °C. The device sample has a top α-Si:H layer of 250 nm and silica buffer layer 3 μm.

The waveguide and ring pattern is first defined in electron beam (E-beam) lithography (Raith 150, 25kV) with negative resist ma-N 2405. During the E-beam scan, the ring area is broken down into concentric polygons. By varing the E-beam scan step size, dose factor and resist developing time, the period and amplitude of the grating can be tuned.

Reactive ion plasma etching (ICP DRIE, STS) is then performed to transfer the pattern to the silicon layer. The bending radius of the ring is 40 μm and the cross-section is 400

nm (wide) by 250nm (thick). The width of the air gap between the ring and waveguide is ~ 100 nm to ensure good coupling with the waveguide and thus $Q_{ae} < Q_{ai}$.

Results

The SEM photos and measurement results of α-Si:H ring resonator are shown in Fig. 2. The resonance at 1540.05 nm is split due to mutual mode coupling. Eq. (1) is used to fit the experimental curves. The estimated intrinsic Q value for the notch in Fig. 3(c) is 5.6×10^4.
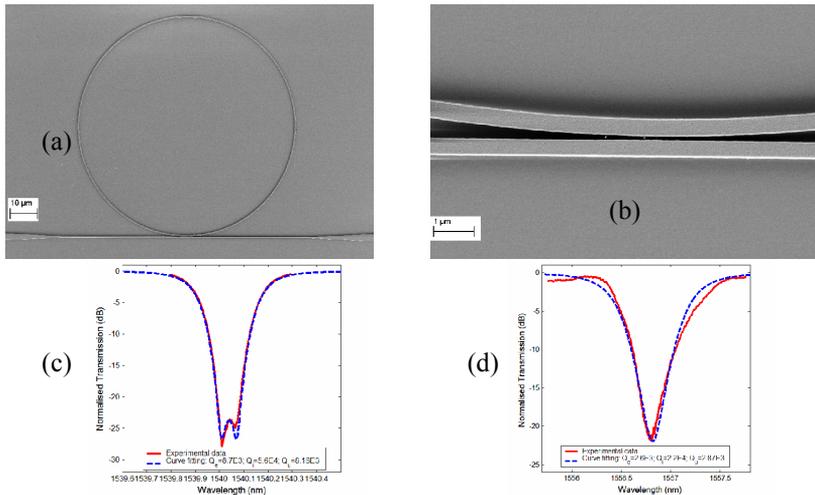

Fig. 2 (a)-(b) SEM photos of the amorphous ring resonator. (c)-(d) Measured transmission spectra (solid) and fitted curves (dashed) using Eq. (1). The resonance at 1540.05 nm is slightly split with intrinsic Q ~ 5.6×10^4 and notch depth ~ 30 dB. The resonance at 1556.57 nm has intrinsic Q ~ 2.2×10^4 and notch depth ~ 22 dB.

To make a comparison, we have fabricated and analyzed the device of the same lateral and vertical geometry in the single-crystalline silicon sample during the same process. The results are shown in Fig. 3. The best notch occurs at 1574.6 nm with intrinsic Q estimated as 9.1×10^4.

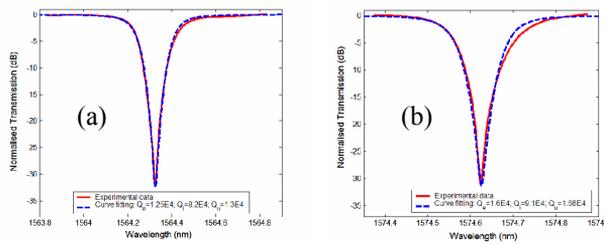Fig. 3 Measured transmission spectra (solid) for the 40-μm-radius single-crystalline micro-ring and fitted curves (dashed) using Eq. (1). (a) The resonance at 1564.32 nm has intrinsic Q ~ 8.2×10^4 and notch depth ~ 33 dB. (b) The resonance at 1574.62 nm has intrinsic Q ~ 9.1×10^4 and notch depth ~ 31 dB.

Note that the intrinsic Q values of α-Si:H and single-crystalline silicon ring resonators are on the same order of magnitude. For α-Si:H, the intrinsic loss per unit length in the ring is calculated as 15.30 dB/cm and for single-crystalline silicon the loss is 9.16 dB/cm.

Summary

To summarize, we have fabricated and analysed micro-ring resonators in the hydrogenated amorphous silicon on silica structure. The intrinsic Q value is estimated as 5.6×10^4. The loss per unit length is calculated to be 15.30 dB/cm. A control device with the same structure but fabricated in single-crystalline silicon on silica structure during the same process gives intrinsic Q of 9.1×10^4 and loss per unit length 9.16 dB/cm. This indicates the fact that ring resonators fabricated using α-Si:H are at least comparable to those fabricated using single-crystalline silicon. With PECVD as a convenient and cheap solution for SOI wafer deposition, α-Si:H is well-suited for high-quality photonic devices.

Acknowledgments

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