Low propagation loss photonic wire and ring resonator devices in silicon-on insulator using hydrogen silsesquioxane electron-beam resist

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Abstract. *We demonstrate propagation loss as low as 1 dB/cm in photonic wire waveguides based on Silicon-on-Insulator. A high repeatability process based on hydrogen silsesquioxane electron-beam resist (HSQ) is demonstrated with small dispersion of the resonance frequency of coupled micro-ring resonators and optical delay lines.*

Introduction

Silicon-on-insulator (SOI) technology is a promising platform for constructing functional micro-scale optical devices for a high density photonic integration. Sub-micron cross-section waveguides and micrometer-size bend radii are allowed by the high refractive-index contrast between silicon and typical cladding materials such as silica.

The small dimensions also imply the need for stringent manufacturing tolerances and for reduction of the sidewall roughness that is the main source of the propagation losses due to scattering. With optimized etching processes, lithographic pattering becomes the only significant source of imperfection –through sidewall roughness.

In most work to date, electron-beam resists such as PMMA and ZEP together with a transfer mask layer of silica or silicon nitride, have been used to transfer the require device pattern into the substrate. But in the recent years Hydrogen silsesquioxane (HSQ) has proven to be a promising electron-beam resist because it combines high resolution at a moderate sensitivity, with minimal line edge roughness, together with a substantial level of etch resistance. Despite of all these positive characteristics, several papers have shown that HSQ suffers from significant process delay effects that result in a fluctuation of the optimum e-beam dose and pattern size.

In this work we show that very low propagation loss silicon wires and low resonance-frequency dispersion coupled micro-ring resonators can be fabricated by using HSQ e-beam resist. The patterning process was optimized both in terms of its repeatability, accuracy and edge roughness.

Fabrication

A 220-nm silicon core layer on 1-µm buried oxide sample of SOI wafer from SOITEC was spin-coated with a FOX16-HSQ, diluted with MIBK at a ratio of 1:1. All the structures were patterned using a VISTEC VB6 electron-beam lithography (EBL) machine and a SF_6 plus C_4F_8 gas combination in an STS-ICP machine. The cross-section of the resulting fabricated waveguides is 500 x 220 nm^2 which provides single-mode operation in the third telecommunications wavelength window.

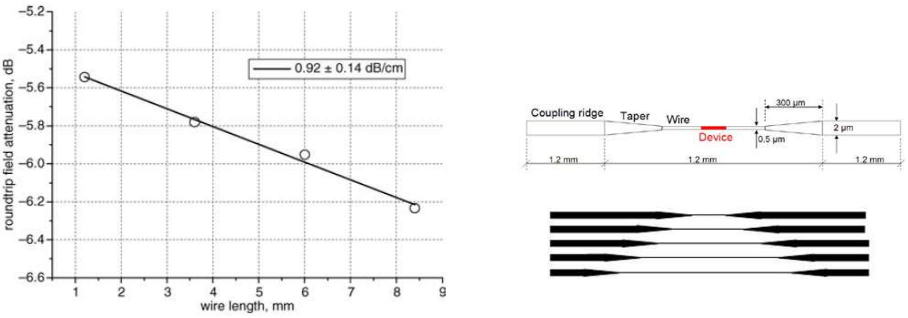
Loss Measurements

Propagation loss reduction is critical for the development of photonic wire based devices in SOI. Given the high quality of the SOI wafers available, the major source of propagation losses is the scattering due to sidewall roughness [1].

Optimizing the HSQ process parameters (baking time and temperature, thickness of the mask layer) and etching conditions (temperature, gas flow rate and pressure), we have achieved substantial improvements in comparison with previous values (~ 2-3 dB/cm) and have measured propagation losses just below 1 dB/cm, with a standard deviation of 0.14 dB/cm [2], for a photonic wire waveguides without silica upper-cladding, as is shown in Fig. 1. To our knowledge this is the lowest value reported for a non-embedded photonic wire.

We extracted the propagation loss value using a combination of Fabry-Perot fringe and cut-back techniques for a set of waveguides with different lengths varying between 1 mm to 9 mm, adiabatically tapered to 2 µm wide coupling ridge waveguides.

The FP fringes generated by the cleaved facets allow the extraction of the round-trip attenuation independently of the input optical power coupled into the system.



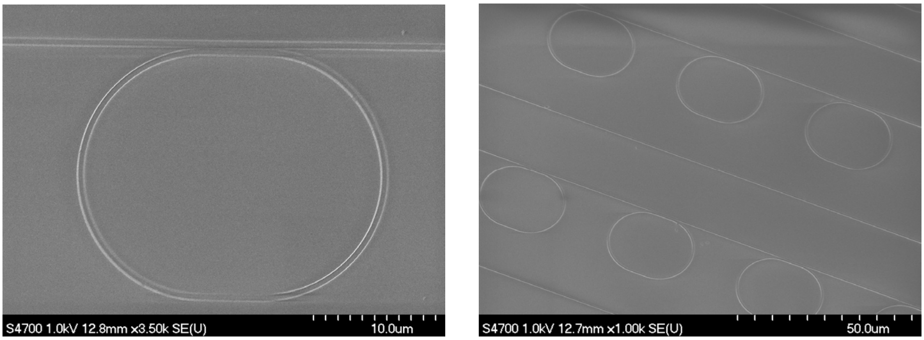
a) **b)**

Fig. 1: **a)** Loss measurements obtained using the combined FP and cut-back technique. **b)** Schematic of the standard waveguide design with the input/output tapered waveguides (top) and device layout for the cut-back loss measurement technique (bottom) [2].

Coupled Ring Resonators

Optical delay lines can be formed by using a cascade of resonant cavities [3] e.g. ring resonators (Fig. 2a) coupled together that slow the propagation of through the combined effects of resonance and increased optical path length.

All-Pass Filters (APF) can be constructed from a series of distinct photonic wire ring-resonators separately coupled to a single photonic wire bus (see Fig. 2b).



a) **b)**

Fig. 2: SEM micrographs of **a)** Singe ring resonator. **b)** All pass filter multiple ring resonators configuration.

Mismatch between the resonance frequencies related to each ring has the additional effect of broadening the spectrum – and such mismatch can compromise the correct operation of the fabricated device structures. The HSQ-based fabrication technology suffers from significant aging effects. In particular, the dose changes significantly with the elapsed time from dilution of the base material, even when the resist is stored in a refrigerator. The resulting expansion or contraction of the written pattern modifies the characteristic properties of the devices produced.

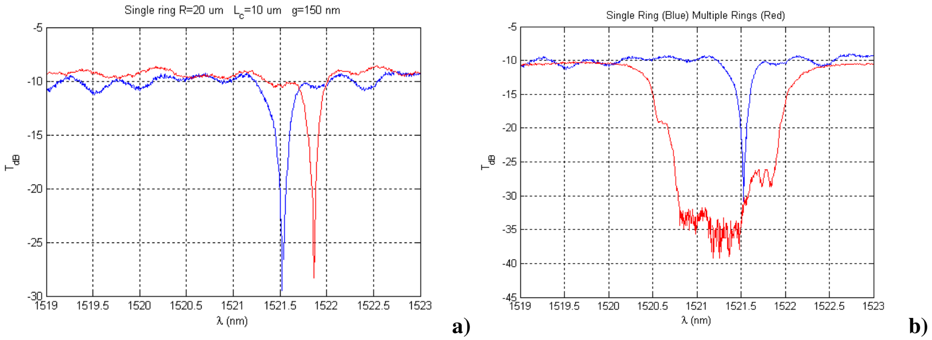
An assessment of the optical resonance of single and cascaded racetrack resonators provides information on both the long-term stability and uniformity of the HSQ e-beam resist [4].

We have fabricated 500 nm wide and 20 µm bend radius ring-resonators, transversely coupled to a bus waveguide in APF configuration. To increase the coupling strength, straight waveguide coupling regions with a length, L, of 10 µm have been introduced into the design. The gap between the bus waveguide and the coupling region of the ring was 150 nm.

A 1 µm thick upper-cladding layer of silica is deposited by PECVD, to reduce the dependence of the device characteristics on the etching depth, all the samples were slightly over-etched and subsequently covered with silica. Antireflection coatings were deposited after the cleaving of the sample section, in order to reduce the Fabry-Perot resonance effects.

We have produced device structures using newly diluted HSQ at different times over a period of several weeks and have obtained more consistent results than those obtained by preparing a single dilution of HSQ to be used over the same period; Fig. 3(a) shows the resonances obtained from two devices fabricated at times separated by five days, from the same batch of diluted HSQ.

A shift in the resonance wavelength of 0.33 nm was observed, corresponding to a change in waveguide width of 0.43 nm.



a) b)

Fig. 3: Measurements of the resonance for (**a**) two different single ring devices fabricated on different days on two different substrates, (**b**) a single ring and 64 rings fabricated on the same substrate.

The results of a second experiment using 64 separate ring resonators along a bus waveguide are shown in Fig 3 (b). From the broadening of the resonance peak, it can be deduced that the average variation of the resonance wavelengths over the cascade of 64 rings is approximately 0.7 nm.

This result also provides a test of the fidelity of the proximity effect correction used in the electron-beam writing process, since the rings at either end of the cascade require different doses to those in the centre.

Conclusions

In conclusion, propagation losses and aging effects of the HSQ were accurately measured in single-mode silicon wire waveguides. Propagation losses as small as 0.92 ± 0.14 dB/cm were measured by a combined Fabry-Perot fringes and cut-back techniques.

Samples made with newly diluted HSQ resist have shown more consistent results than those obtained by preparing a single dilution of HSQ to be used over the same period. This suggests the use of a fresh dilution all the times that the dimensions are critical for the performance of a device e.g. photonic crystals, photonic micro-cavity, waveguide gratings, etc.

These loss figures and the development of HSQ lithographic processes are useful for further development of silicon photonics circuits on SOI technology.

References

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