Ultrathin SOI strip-loaded resonators: Permanent mitigation of losses using UV light

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ABSTRACT

The performance of integrated micro-photonic devices relays majorly on the mitigation of optical losses. Here, we report on the design, fabrication and characterization of Silicon Nitride strip-loaded guiding optical components realized on a sub-30 nm ultra-thin SOI platform [1]. Omitting physically etched boundaries within the guiding core is known to suppress significantly the scattering loss, as shown by us previously for Si3N4 devices. Here, contrary to expectations, the freshly fabricated SOI devices suffer large losses of 5 dB/cm. We first relate this to the absorption by free carriers, which accumulated under the positively charged Si3N4 loading layer, and successively, demonstrate that exposures to UV light neutralize progressively and permanently Si3N4's bulk charge, associated with diamagnetic K^+ defects. As a result, a net decrease of electron concentration in the SOI layer reduces the propagation losses down to 0.9 dB/cm. We performed accurate cavity linewidth measurements showing how the intrinsic cavity Q's boost from 70,0000 up to 500,000 after UV illumination. Our results may open routes towards engineering of new functionalities in photonic devices, unveil the origin of induced optical nonlinearities in Si3N4/Si micro-photonic systems, as well as envisage possible integration of these with standard as well as ultrathin SOI electronics.

Keywords: Silicon-on-insulator, silicon nitride, waveguides, optical loss, ultraviolet light.

1. INTRODUCTION

Circular microresonators, in which the electromagnetic radiation is confined via resonant circulation, are essential building blocks for planar integrated photonics [2]. The spectral width of resonances in these devices is inversely proportional to the amount of optical power which is lost per round trip. Generally, the power is lost due to material absorption, α_m, scattering on boundary imperfections, α_{sc}, and out-radiation, α_{rad}, due to the curved geometry. A reducing the intrinsic loss enables a number of applications from passive filtering in optical communication networks to quantum optics, space and sensing. Thus, in order to push the device characteristics to an ultimate limit, the challenge is to limit the intrinsic losses to only that of the material [3]. Towards this goal, approaches, such as strong modal confinement and realization of smooth device boundaries are necessary to achieve minute contributions from radiative and scattering loss.

Here we report on the design, fabrication and characterization of high-Q micro-optical components on a sub-30nm thick SOI platform [1]. In these devices, the light is guided in the Si slab layer underneath a patterned layer of loading stoichiometric Si3N4. The absence of physically etched device boundaries in the SOI layer is expected to provide with ultimately low losses, limiting them to that of the intrinsic absorption of the lightly doped p-type Si layer. We have used successfully this approach in past to achieve resonance quality factors $Q \sim 4 \times 10^6$ on an 80 nm thick Si3N4 platform with SiO2 loading strips [4]. Here, surprisingly, we measured up to 5 dB/cm propagation losses in the freshly fabricated silicon devices. We related these losses to the absorption of free (mirror) carriers within the Si layer, which are accumulated due to the presence of a large fixed positive charge in the Si3N4 material. Successively, we neutralized permanently the charge in Si3N4 by exposing our devices to 254nm wavelength UV light. As a result, the propagation losses improved permanently summing to 0.9 dB/cm. The corresponding Q's of ring resonators thus boosted from an initial 70,000 up to 500,000.

2. RESULTS AND DISCUSSION

We realized the samples starting from 6" SOI wafers with a 3 μm-thick buried oxide (BOX) and a 250 nm (100)-Si device layer of a nominal resistivity of 15 Ω.cm (Soitec). The Si layer thickness was reduced down to 27nm via thermal oxidation and removal of the grown oxide in a buffered HF solution. A 145 nm thick LPCVD Si3N4 film was deposited at 780°C. The wafer was patterned lithographically using a Nikon stepper and transferred to Si3N4 using a combination of ICP dry etch, finalized with e wet etch for the last 10 nm with a wet

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etching step to guarantee a smooth top surface of the Si device layer (Fig. 1). The fabricated chips were diced and characterized in optical transmission experiments.

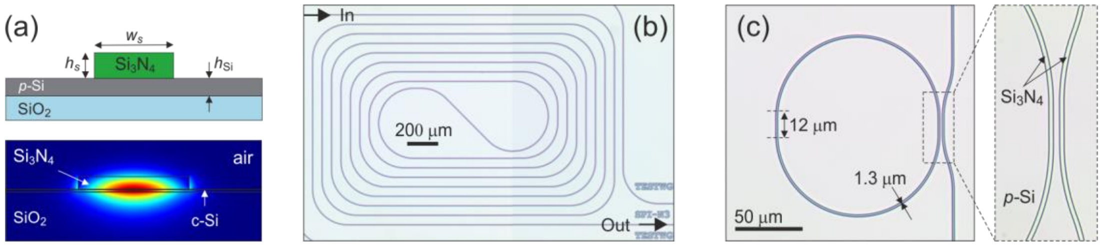

Figure 1. (a) The cross-sectional view of the waveguide and the distribution of the simulated electric field intensity of a transverse electric (TE)-polarized mode. Optical micrographs of a typical (b) spiral waveguide and (c) a ring resonator.

We report in Fig. 2(a) the results of waveguide transmission experiments. The freshly fabricated waveguides. show a propagation loss of about 3.83(0.26) dB ⁄cm according to the Beer–Lambert law (red squares), which, if attributed to sidewall scattering, are unexpectedly high for the adopted processing technology [4].

In order to proof the hypothesis of charge-related losses, we performed systematic electrical capacitance measurements using a Hg probe, first, on test samples with the same Si3N4 layer deposited on Si substrates of 15 15 Ω.cm resistivity. Detailed measurements and analysis of C-V curves allowed us to both extract the Nitride's fixed charge as well as permitted to study the effect of UV exposure on its electrical characteristics. In particular, we found that the as-deposited Si3N4 layer contains a large amount of net positive electrical charge related to diamagnetic charge centers K^+ [5]. The C-V curves for these freshly deposited samples has a characteristic flat-band voltage value of $V_{fb} \approx -7.8$ V. The areal density of the corresponding to this situation net positive charge amounts to $\sigma \approx 1.7 \times 10^{12}$ cm^{-2}, in agreement with previous estimations reported for SiNx films deposited using other techniques [6].

Successively, we exposed the film to UV light (254 nm), which is known to neutralize the positively charged K^+ centers into diamagnetic K^0 ones [5]. We carefully characterized the behaviour of the flat band voltage and corresponding charge density attenuation as a function the UV exposure duration. In particular, we succeeded to reduce by more than three orders of magnitude the charge density in Si3N4, bringing it down to 3.1×10^9 cm^{-2}. This value is comparable to the density of charge traps of very-high-quality oxide/Si interfaces, which is also close to the density of dopant ions per centimetre square for a silicon layer of 15 Ω.cm resistivity. Thus, we concluded that the UV exposure could have a large impact on the attenuation of losses in integrated devices.

Therefore, we exposed to UV light the same spiral devices for 21h and measured again the propagation losses. In fact, the waveguides showed significantly improved characteristics (blue diamonds), where the propagation loss has decreased down to 1.55(0.28) dB ⁄cm. Note, that the insertion loss of the waveguides has remained unchanged, since the UV exposure does not affect the quality of facets and the fibre-chip butt coupling. Still, the small number of available spirals provides with few experimental data, which explains the large error bars of experimental points in Fig. 2(a). This limitation was surpassed by measuring many ring resonators and analysing dozens of resonances per ring, therefore, avoiding also errors due to fluctuations of the waveguide facet quality.

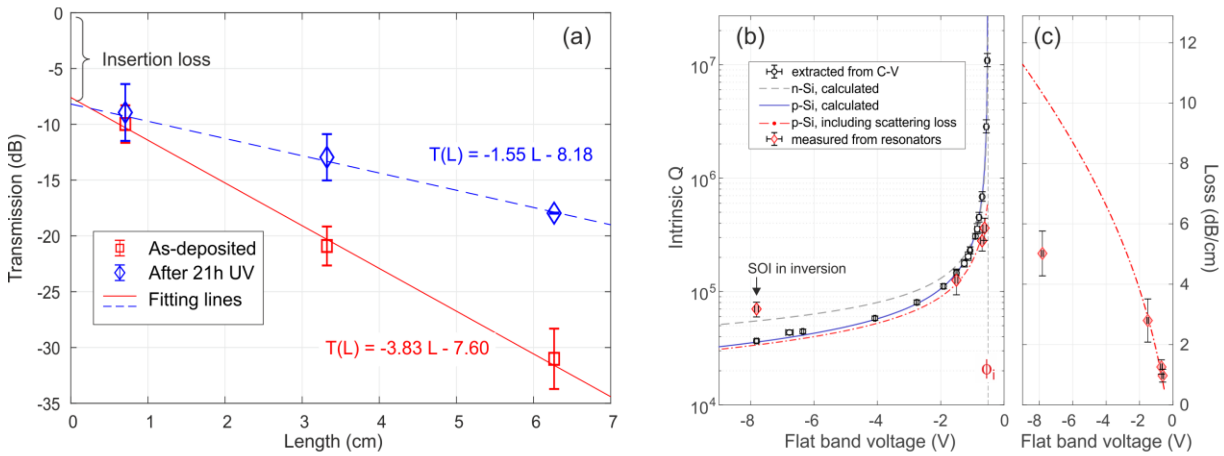

Figure 2. (a) Attenuation of the propagating optical power measured for waveguides of different length before (squares) and after exposure to UV light for 21h (diamonds). (b) Experimental and expected trends of the intrinsic Q of ring resonators as a function of the UV-modified flat-band voltage for p-type Si (blue continuous line). (c) The intrinsic loss α_i, corresponding to that Q's extracted from the ring resonators' spectra (diamonds), plotted against the calculated one (dashed-dotted line).

Figure 2(b) summarizes the measurements of ring resonators – from freshly prepared devices to UV exposures of different duration. The Q-factors estimated from optical measurements on ring resonators are shown as red diamonds, where each point is the result of the analysis of at least ten different resonances per ring. The first point of this dataset, corresponding to the UV-untreated devices, shows an average intrinsic Q of about 70,000, in accordance with the corresponding MOS capacitance experiment. Finally, the rest of the data from the ring resonators, corresponding to long exposures to UV light, can be fit to good approximation by including an additional residual loss with an associated $Q_{ad} \approx 6 \times 10^5$ (red dashed-dotted curve). The corresponding loss values, based on the results from the ring resonators, and the calculated curve for p-type Si in the situation of residual loss are shown in Fig. 2(c). Thus, we revealed a net improvement of losses down to 0.9 dB/cm at the longest exposures, improving the rings' intrinsic Q-factors from 70,000 to 500,000. Finally, we can relate the carrier-induced optical losses to the MOS capacitance measurements of the flat-band voltage (not shown here).

3. CONCLUSIONS

Our results may open the door to the implementation of UV-induced charge modification for the design and study of new photonic devices in which the space-charge-related static electric fields can be engineered to modulate the linear and nonlinear refractive indices of materials. In addition, our findings are general and may be implemented also in other geometries of guiding devices and material systems where silicon nitride is present, such as widely used standard SOI waveguides. We also envisage the possibility of compact integration of micro-photonic components with ultra-thin SOI electronics in the future.

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