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https://doi.org/10.15017/2552950

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 5, pp.100-102, 2019-10-24. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

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Abstract: *Breath sensing system based on cavity ring-down spectroscopy (CRDS) technique is attractive due to its real time sensing in addition to the capability of high sensitivity. Utilizing waveguide for CRDS may realize ppm-order components into a compact area. This work have exploited thermal oxidation technique to silicon high-mesa waveguides for sensing-application. Significant propagation loss reduction from 1.45 to 0.84 dB/cm at a waveguide width of 500 nm has been achieved by the technique successfully.*

Keywords: Loss reduction, High-mesa waveguide, Thermal oxidation, CRDS.

1. INTRODUCTION

Breath sensor is a noninvasive and convenient fashion for health-monitoring [1]. In order to detect ppm-order breath content in addition to the real time sensing, breath sensing system based on cavity ring-down spectroscopy (CRDS) technique has been researched as a candidate [2]. Compared to the conventional bulk CRDS system [3], utilizing waveguide as the gas sensing cell may realize several meters sensing path which is needed for measuring ppm-order components in human breath within a compact area [4]. This brings the possibility of integrating CRDS system into a cell phone or other mobile equipment for powerful in-situ and real-time health-monitoring. One issue is the propagation loss of the waveguide as it may prevent ppm-order gas detection.

In a CRDS system, the length of a regular sensing cell is about 1 meter needed for measuring ppm-order breath content [3, 5]. If the propagation loss of the waveguide exceeds 0.2 dB/cm, the total loss of the waveguides is higher than 20 dB. This high loss causes the waveguide impossible to be used even if an optical amplifier is introduced in the CRDS system [5]. A 1 m-long waveguide with the propagation loss $\leq$ 0.2 dB/cm is required to be applied as the sensing cell. Recently, a novel high-mesa waveguide structure has been proposed by our group for the compact and high-sensitive CRDS system [4, 6, 7]. Compared to the slot waveguide [8] and the conventional channel waveguide, it not only provides the evanescent field sufficient touching the breath gas, but also avoids the surface to be contaminated by particles in air. A high-mesa silicon-on-insulator (SOI) waveguide with 260-nm thick silicon (Si) as the core has been fabricated [6, 7], but its propagation loss (α) was still too high to be as the sensing cell [9].

In order to decrease α, this work designed and fabricated a 100 nm thick Si high-mesa waveguides in this work. After fabrication, This work applied dry thermal Si oxidation technique for further reduction. After thermal oxidation, the propagation loss was effectively reduced from 1.45 to 0.84 dB/cm for width=0.5 μm and from 0.29 to 0.2 dB/cm for width= 3μm. The reduction of α was attributed to the decrease of the sidewall scattering loss and the absorption loss from the damaged Si.

2. EXPERIMENTS and RESULTS

The designed 100 nm thick Si high-mesa waveguide is shown in Fig. 1 (a). The device layer of the SOI is 100 nm and the top SiO2 cladding is 2 μm. The bottom SiO2 cladding is etched with a thickness of 1 μm. The width of the waveguide is variable to optimize α.

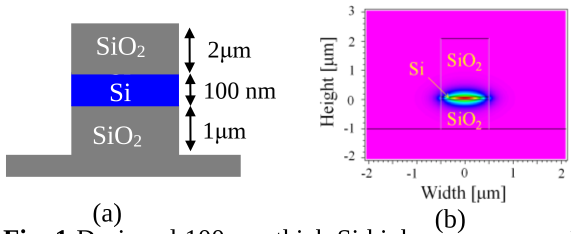
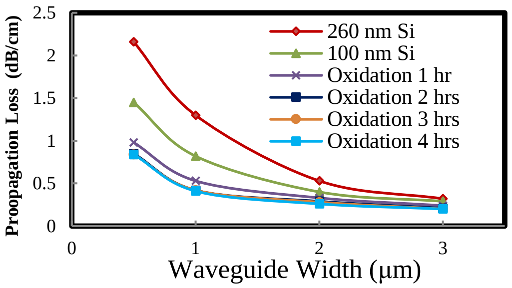


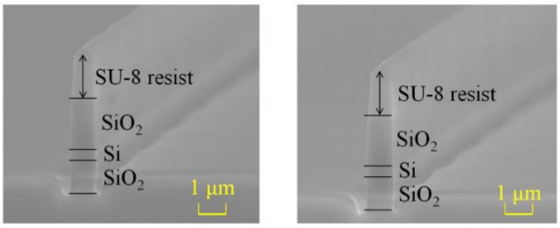
Fig. 1 Designed 100 nm-thick Si high-mesa waveguide. (a) Cross-section and (b) TE mode light profile when width=1 μm

The propagation loss α of a waveguide is generally attributed to three different mechanisms: radiation loss, absorption loss and scattering loss. The simulated TE mode in Fig. 1(b) indicates that the optical field is well-confined in the waveguide. In addition, the materials, Si and SiO_2, are highly transparent around 1550 nm. As a result, the main reasons of α in our case are the scattering loss $\alpha_{scattering}$ origining from the rough sidewall and the absorption loss $\alpha_{absorption}$ from damaged Si caused by the ICP etching. Oxidation of Si has been shown to be effective at reducing the sidewall scattering and recovering the damaged Si [4]. After oxidation, a thin Si layer near the sidewall is oxidized into SiO_2, so that the effective refractive index (n_{eff}) of waveguide is reduced and the damaged Si is recovered. According to the Payne-Lacey model [5], a lower n_{eff} indicates a lower $\alpha_{scattering}$. In addition, the $\alpha_{absorption}$ from damaged Si is also reduced due to the transformation to SiO_2.Based on the design and analysis above, high-mesa waveguides were fabricated on a SOI wafer. A 2 μm-thick SiO2 top cladding was deposited on the SOI wafer via chemical vapor deposition. The wafer was coated with electron beam (EB) resist SU-8 and patterned by EB lithography. The exposed wafer was etched in an inductively coupled plasma (ICP) etching machine by using CHF3 gas.

Finally, This work applied dry thermal oxidation at 1000 ℃ from 1 to 4 hours (hrs) under the gas condition as O_2:N_2=1:4 (mole ratio). The propagation loss α was evaluated by using Fabry–Perot interferometric method [14]. Light from a distributed feedback laser source was coupled into the waveguide in TE mode through a polarization-maintaining lensed fiber. A polarizer was used to align the input light polarization between the laser and the fiber. Output optical power of the waveguide is collected using a photo-detector and the detected data were recorded automatically by a computer.



(a)



(b) (c)

Fig. 2 Optical properties of the high-mesa waveuides (a) Measured propagation loss before and after oxidation (260 nm data for comparison) and Captured SEM images (b) before oxidation and (c) after 4 hrs oxidation.

The estimated α as a function of the waveguide width is shown in Fig. 2 (a). The loss of 100 nm Si waveguides at the wavelength of 1550 nm even without oxidation are lower than those of 260 nm-Si waveguides. This is because that the effective refractive index (neff) is lower when the Si core is thinner and thus the αscattering is lower according to the Payne-Lacey model. After sufficient oxidation (⩾3 hrs), α is effectively reduced from 1.45 to 0.84 dB/cm for width=0.5 μm and from 0.29 to 0.2 dB/cm for width= 3μm, which follows our above analysis of the oxidation of Si. Longer time oxidation (4 hrs) does not induce obvious further reduction of α, which is attributed to the formation of SiO_2 preventing oxygen from diffusing through the grown oxide film into the Si [15]. Figure 2(b) and (c) show the SEM images of the 1 um wide waveguide before oxidation and after 4 hrs oxidation, respectively. The waveguide structure seems to be secure even after long oxidation process as shown in Fig. 2(b) and (c).

3. DISCUSSIONS

From Fig. 2(a), the curve slope of the measured α becomes lower and lower with the increasing waveguide width. When the width reaches around 3 μm, the curve seems to be almost flat, which indicates that α goes constant when the width > 3 μm. Therefore, α at the width of 3 um is considered to be totally caused by the damaged Si absorption αabsorption. By using thermal oxidation, αabsorption has been reduced down from 0.29 to 0.2 dB/cm. Subsequently, αscattering at each waveguide width is readily obtained just by using αscattering = α - αabsorption. According to the Payne-Lacey model [13], αscattering is given as follows

$$\alpha_{scattering} \propto (n_{eff} - n_0)^2 \sigma^2 \Gamma_{air} \quad (1)$$

where n0 is the refractive index of the cladding, σ the sidewall roughness and Γair the portion of the guided light out of the waveguide. This work fitted the αscattering according to Eq. 1 by continuously changing σ until the fitted curve overlaps with the measured result. When the σ is 11.5 nm, for the un-oxidated waveguides, This work find that the fitted and measured curves overlap each other well. After sufficient oxidation (⩾3 hrs), the fitted and measured curves overlap each other well when the σ is 9.4 nm, which means that the oxidation improves the σ as high as 2.1 nm. This 2.1 nm can not be observed in Fig. 2(b) and (c) obviously because of the limilted resolution of the SEM.

Based on the 3 μm wide waveguide, This work design a photonic integrated circuit for the CRDS system as schematically shown Fig. 3. On the chip, it integrates a tunable laser (TL), a semiconductor optical amplifier (SOA), an optical coupler (CP) with a splitting ratio 9:1, a 1 m long waveguide gas sensing (WGS) cell and a photo-detector (PD) [4]. In this work, This work take CH_4 for the targeted gas as an example and use the 3 μm wide waveguide with the measured α=0.2 dB/cm and the calculated Γair =2.6%. In the CRDS system, the ring-down times are 200, which means the effective sensing path is 200 m [4]. Consequently, the sensitivity of the integrated CRDS circuit is determined by the α and Γair of the WGS and the CH_4 absorption cross section. The detailed calculation method has been demonstrated in our previous work [4]. Based on this method, the calculated sensitivity of the CRDS is ranging from 104 to 10 ppm depending on the gain of the SOA [5]. Since the CH_4 concentration in exhaled breath of 2-10 ppm indicates a buerger disease [4], our waveguide has a promising potential to be applied in an integrated CRDS system.

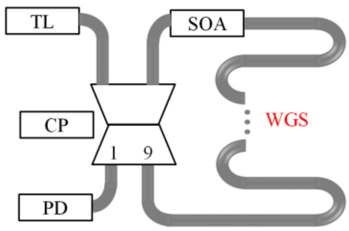


Fig. 3 Schematic of designed photonic integrated circuit for the CRDS systerm

4. CONCLUSIONS

Authors have designed and fabricated 100 nm-thick Si core high-mesa waveguides for breath sensors. By using dry thermal oxidation, $\alpha_{scattering}$ and $\alpha_{absorption}$ are reduced effectively and the final achieved α satisfies the requests of the low loss of a compact CRDS system.

5. ACKNOWLEDGMENT

This work is supported in finance by SECOM Science and Technology Foundation.

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