Sensing performance of plasma-enhanced chemical vapor deposition SiC-SiO$_2$-SiC horizontal slot waveguides

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Abstract. We have studied, for the first time, the sensing capabilities of plasma-enhanced chemical vapor deposition (PECVD) SiC-SiO$_2$-SiC horizontal slot waveguides. Optical propagation losses were measured to be 23.9 dB/cm for the quasi-transverse magnetic mode. To assess the potential of this device as a sensor, we simulated the confinement factor in the slot. This simulation revealed that SiC-based slot waveguides can be used, advantangeously, for sensing as the confinement strongly varies with the refractive index of the slot material. A confinement factor change of 0.15/refractive index units was measured for different slot materials. © *2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.JNP.6.063530]

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1 Introduction

Optical waveguide-based sensors are considered to be very powerful tools in the field of biochemical sensing, because they offer the possibility to achieve high sensitivity and a high degree of on-chip integration. For this reason, over the past decade, many attempts have been made to find new configurations of optical waveguides that optimize light-analyte interaction. For applications in biochemical and environmental monitoring, this implies confining the light in a low index media. A possible approach, to improve the light-analyte interaction, is the use of liquid core waveguides. Previous approaches were often based on antiresonant-reflecting or Bragg confinement effect.[1,2] Another important example of a waveguide structure that is able to confine light in a liquid channel is given by the slot waveguide.[3]

In a slot waveguide, the high index contrast at the waveguide interfaces enhance the light in a nanometer-wide region filled with a low refractive index medium. This strong optical confinement increases the interaction of the field with the low-index media, which promotes very high sensitivity detection of substances in water-based solutions. For this reason, slot waveguides are widely applied as highly sensitive tools, especially in biochemical and environmental applications, and have demonstrated very high flexibility for integration in more complex lab-on-a-chip systems.[4–6]

Silicon is commonly used as material for the high refractive index regions, while oxide or liquids/biological materials are used as the low refractive index region.[7]

The fabrication of a vertical slot involves local etching. This can cause large roughness in the vertical interfaces and, thus, large propagation losses.[8] Furthermore, when these devices are used for handling very small objects such as trapping and transporting of nanometer-sized particles, the high optical absorption poses a restriction on the amount of optical power that can be applied (the high heat generation damaging the biological targets).[9,10] These problems can be overcome by working in the visible range, where the absorption coefficient of water is about 2000 times

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lower than in the near infrared range. Moreover, in label-based sensing methods, the possibility to operate in the visible range of the electromagnetic spectrum permits the use of commercially available fluorescence markers for molecular labeling. Due to the enhanced E-field intensity in the slot region, it has been demonstrated that the use of a slot-waveguide can improve both the excitation and the collection efficiencies with respect to a single slab waveguide.[11]

To overcome losses, horizontal slot-waveguides are preferred as they do not involve etching but a control of the deposited layers. Experimental demonstration of horizontal slot-waveguides in a $\mathrm{Si/SiO_2}$ material system with good propagation losses have been recently reported.[12] In this case, smoothing the bottom silicon interface eliminates scattering loss. However, achieving low losses requires a very tight control of the waveguide dimensions, especially for amplification purposes where the size of the slot is on the order of 10 nm.

When replacing silicon with a material of lower refractive index such as silicon carbide (SiC), the slot height can be designed to be larger (to achieve the same power in the slot) due to a weaker optical confinement making their filling with liquid or biological samples for sensing easier. SiC has, in this case, an important advantage compared to silicon nitride (SiN) as it is chemically a much stronger material.[13] This makes SiC extremely interesting for applications in harsh environments.[14]

In this work, we propose horizontal slot waveguides that make use of SiC as the high refractive index material. We show that the fabricated slot waveguides have a high tolerance to dimension deviations during fabrication and do not require etching of the high refractive index regions. Propagation losses have been measured and (by replacing the slot filling material) the sensitivity of such wave guiding system is estimated both theoretically and experimentally.

2 Theoretical Filling Factor and Sensitivity of SiC-Based Slot Waveguides

At 1.3 μm, the wavelength used to simulate the device performances, plasma-enhanced chemical vapor deposition (PECVD) SiC has a refractive index of 2.34 and no absorption.[15] Previous work on PECVD SiC waveguides has shown reasonably low losses in the visible (5 dB/cm) and a very low loss behavior at 1.3 μm.[15,16] It is, therefore, possible to have sensors based on slot waveguides working in a very large wavelength range with high confinement in the slot region. This is not possible with Si-based slot waveguides due to the absorption of Si in the visible.

In order to evaluate the feasibility and the performance of SiC-based slot waveguides, we have investigated the dependence of the filling factor, such as the power coupled, in the gap region. We estimated the maximum confinement, such as the power in the slot divided by the power launched, using MIT photonic bands when oxide ($n = 1.45$) fills the slot as illustrated in Fig. 1.[17] In the following, W_{slab} represents the thickness of the SiC films and W_{slot} represents

Fig. 1 Schematic of the simulated slot waveguide, W_{slab} represents the width of the region of high refractive index (here SiC), W_{slot} the width of the guiding region (here water). The refractive cover of the cover is 1 and the substrate is chosen infinite and has a refractive index of 1.45.

the thickness of the filling material in the slot region. In our current simulations, no specific width of the waveguide is defined, but the surrounding medium is set to be air ($n = 1$).

Figure 2 shows the dependence of the filling factor, such as the power flux in the region of width W_{slot}, at a wavelength of 1.3 μm when W_{slab} equals 78, 117, and 156 nm. We see that when W_{slab} gets thicker, the confinement factor tends to reach a limit (0.3) and this occurs for every W_{slot}. This is an important result for the fabrication as it relaxes the tolerance on the layer thicknesses that are often difficult to control, especially when using PECVD depositions.

In Fig. 3, we plotted the variation of the confinement factor depending on the refractive index of the filling material in the slot. The sensitivity, also referred to as the slope, of 0.15/ refractive index unit (RIU) is found. The changes of refractive effective index of the slot waveguide (n_{eff}), compared to the refractive index changes of the filling material (or bulk sensitivity), are often used to evaluate the maximum performance of a propagating waved sensor.[18] The sensitivity, in that case, is found to be 0.75. However, in the following, we concentrated on experimentally estimating the confinement factor of SiC-based slot waveguides with different filling materials, so we keep the first evaluated sensitivity; refer to Fig. 3 as reference.

3 Optical Losses of SiC-Based Slot Waveguides

After estimating the sensitivity of SiC based slot waveguides, we fabricated some devices to measure their propagation losses. We first deposited a 2 μm thick PECVD SiO_2 layer on a standard ⟨100⟩ Si wafer. The oxide serves to optically isolate the circuit from the substrate, thus reducing the loss due to substrate leakage. Then, a 118 nm thick PECVD SiC layer is deposited using silane and methane. A 268 nm SiO_2 forms, then, the slot and 118 nm SiC seals the slot waveguide. The layers are chosen thicker here than in the previous section to

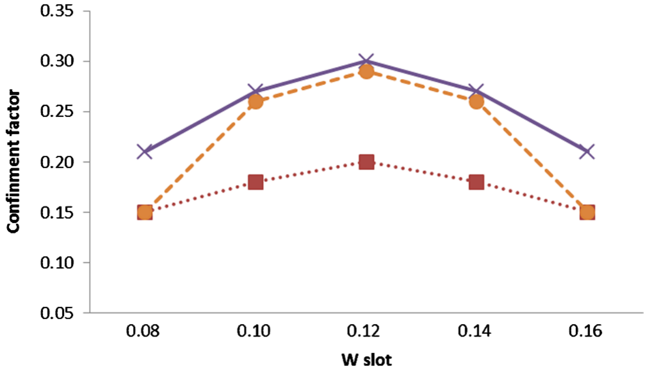

Fig. 2 Dependence on W_{slot} of the filling factor for a quasi-TM mode in the gap region of an SiC-based slot in the case of an oxide filling. W_{slab} being 78 nm (....), 117 nm (——) and 156 nm (plain).

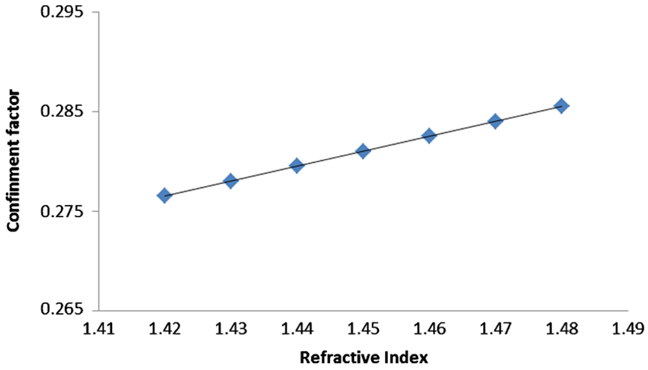

Fig. 3 Variation of the confinement factor for different refractive indices in the case of an SiC-based slot waveguide with $W_{\mathrm{slot}} = 117$ nm and $W_{\mathrm{slab}} = 156$ nm.

ease the coupling in and out of the waveguides. Finally, a 2 μm thick PECVD SiO_2 layer covers the stack to make a perfectly symmetrical structure. There is a 10 nm difference between the deposited SiC layers and the layers with best confinement (30 nm for SiO_2). Due to the layers being thin, some discrepancy in the expected and obtained thicknesses can occur as the deposition times are short. However, as we used a lower refractive index layer than Si as confining material, the SiC/SiO_2 system has much higher tolerance as shown in Fig. 2. The temperature of deposition of all the layers is 400°C which ensures compatibility with CMOS processes.

The horizontal confinement is ensured by patterning the whole stack with a mask containing 2.8 μm wide waveguides. Inductively coupled plasma process is used to etch down to the first oxide layer. Figure 4 shows a scanning electron microscope (SEM) view of the fabricated slot waveguide.

The slot waveguides were characterized in terms of losses using the cutback method. The technique consists of measuring the total insertion loss caused by the waveguide for different waveguide length. By doing so, it is possible to isolate the contributions from propagation and total coupling losses. The characterization was done at 1.3 μm using a fiber coupled superluminescent diode. Light was sent into the waveguide and collected at the output using butt-coupled standard single-mode fibers (SMF28). The optical bench used here is depicted elsewhere.[19] The results for both the quasi-TE and the quasi-transverse magnetic (TM) modes are presented in Table 1. As expected, the quasi-TM mode gives the lowest losses (23.9 dB/cm), while the quasi-TE mode has higher losses (38.8 dB/cm).[20]

The strong polarization dependency makes it experimentally easier to be sure that the light is coupled into the waveguides and not in the oxide slab. The loss figure is in agreement with previously reported losses obtained with vertical slot waveguides made on an SiN/SiO_2 material system.[13] By making the lateral dimension of the waveguide smaller, the quasi-TE mode will disappear, which leads to a fully single polarization device. In the present paper, we concentrated on the suitability of SiC for sensor purposes, therefore, we did not attempt to make the waveguides narrower. Having a single polarization structure will be required when considering the slot waveguides in sensor platforms to limit, for example, cross sensitivity. In the current study, the quasi-TM mode is anyway insensitive to lateral dimensions fluctuations.

We measured, by atomic force microscope (AFM), the roughness at the surface of the SiC layer after deposition on a PECVD oxide layer. The roughness was found to be 15 nm RMS which is much higher than the 0.5 nm reported roughness of an amorphous SiN/SiO_2 interface.[21]

In order to decrease the roughness of the PECVD layers, which is source of losses in the present structure, several techniques can be used such as polishing. Unfortunately, such

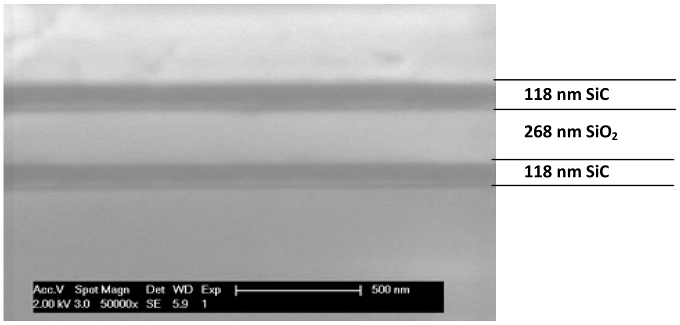

Fig. 4 Fabricated optimized SiC-SiO_2-SiC slot waveguide. The thickness of the SiC layers was found to be 118 nm with SEM.

Table 1 Optical losses of the proposed slot waveguide measured by cut back technique for both quasi-TE and quasi TM-modes.

	Losses in dB/cm	Error in dB/cm
Quasi-TM	23.9	±1.3
Quasi-TE	38.8	±1.2

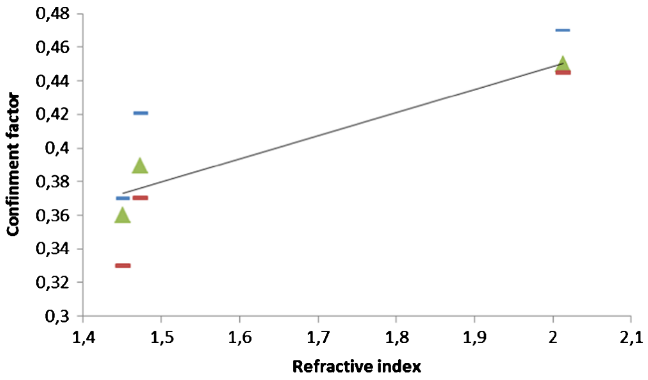

Fig. 5 Experimental confinement factor in function of the refractive index with the errors bars associated.

processing is not cost effective for sensor systems. However, in optical sensing, very compact but highly sensitive devices can be designed to make the loss figure less of a problem.[22]

4 SiC Slot-Based Sensitivity

To estimate the sensitivity of the device to refractive index changes and confirm what was shown in the simulation section, we made slot waveguides with TEOS oxide and SiN as slot material. The fabrication process of these new slot waveguides follows the one described in Sec. 2 with the deposition of PECVD TEOS (at 350°C in this case) and PECVD SiN, respectively, instead of SiO_2. The fabricated slots are also patterned and etched to ensure a horizontal confinement.

By measuring the propagation losses for each material, like in Sec. 2, we also know the coupling losses such as the confinement. Figure 5 shows the measured confinement factor versus the refractive index (n). It can be demonstrated that the sensitivity (S) and the power confinement in a slot waveguide (Γ_s) are related to each other by Ref. 23,

$$S \cong \frac{n_s^0}{n_{\mathrm{eff}}}(\Gamma_s + \delta_z), \tag{1}$$

z being the propagation direction, $n_s{}^0$ the refractive index in the slot when not filled, n_{eff} the effective mode index, and δ_z the intensity confinement factor. In the present paper, we study the sensing capabilities of the fabricated slot waveguides and, therefore, we limited ourselves to the study of the confinement factor. To fabricate a sensor, structures like interferometers or ring resonators are required.[24] However, the study of the confinement factor for Si slot waveguides have shown that for three different slot materials, namely air, water, and silicon oxide, the confinement varies by 0.14 per refractive index unit (RIU).[23]

The sensitivity of the proposed slot structure is measured by estimating for every filling materials (SiN, TEOS, SiO_2) the coupling losses. The coupling losses are obtained from cut back measurements by intersecting the linear fit with the vertical axis. The coupling losses are then plotted against the refractive index which is shown in Fig. 5, and the slope of the linear fit defines the sensitivity. Here, a 0.15/RIU sensitivity is obtained. The measured performance compares with the confinement of Si-based devices.

5 Conclusions

A PECVD $SiC/SiO_2/SiC$ horizontal slot waveguide sensor has been demonstrated. Propagation losses of 23.9 ± 1.2 dB/cm for the quasi-TM mode have been measured using the cut back method. This promising first demonstration of horizontal silicon carbide/silicon oxide slot-waveguide devices makes this material system an appropriate trade-off between high integration and ease of access to the slot region (larger dimension) for sensing photonic devices based on integrated slot-waveguides. Further, the sharp changes in confinement factor when the slot dimensions vary can find application not only in refractive index measurement setups, but also in pressure sensors. As the light is so confined in the slot region, they are also ideal as transducers read out.

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