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Research Article

Sensing Performance Study of SiC, a Wide Bandgap Semiconductor Material Platform for Surface Plasmon Resonance Sensor

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The sensing properties of a surface plasmon resonance (SPR) based waveguide sensor on a wide bandgap semiconductor, silicon carbide (SiC), were studied. Compared to other waveguide sensors, the large bandgap energy of SiC material allows the sensor to operate in the visible and near infrared wavelength range, while the SPR effect by a thin gold film is expected to improve the sensitivity. The confinement factor of the sensor at various wavelengths of the incident light and refractive index of the analyte were investigated using an effective index method. Since the change of analyte type and concentration is reflected by the change of refractive index, the sensing performance can be evaluated by the shift of resonant wavelength from the confinement factor spectrum at different refractive index. The results show that the shift of resonant wavelength demonstrates linear characteristics. A sensitivity of 1928 nm/RIU (refractive index unit) shift could be obtained from the refractive index of 1.338~1.348 which attracts research interests because most biological analytes are in this range.

1. Introduction

In the fields of clinical diagnosis, drug detection, food safety and environmental health [1–4], and so forth, identification and quantification of biological and chemical analytes in water, blood, or other carriers, as well as detection of interactions at interfaces, are very important. Various sensing methods have been developed with focus on sensing performance of accuracy, sensitivity, and real-time detection [5–7]. Among these sensing technologies, surface plasmon resonance (SPR) technique has been proven to be extremely powerful in label-free detection of biological analytes such as virus, bacteria, antibody, and antigen [8–10]. SPR sensor is highly sensitive to the change of refractive index at the interface between sensor and analytes [11], which enables quantifying the concentration of the analyte and its changes. Table 1 lists the refractive index of some typical biological analytes which attract wide research interests. In this refractive index range of 1.338~1.348, SPR sensors such as prism coupler [12] and grating coupler [13] have been reported. They measure the shifts of resonant angle or phase to characterize the changes of the refractive index by concentration in these analytes.

In this paper, we studied a waveguide SPR sensor based on a wide bandgap material platform, silicon carbide (SiC), which is widely studied for electronic device applications [14]. The sensing performance was characterized by investigating the confinement factors of the sensors in fundamental transverse magnetic mode (TM_0) at different wavelengths and refractive index, from which the shift of resonant wavelength with refractive index was compared. When used for chemical and biological sensing with water or water based medium, SiC is more desirable over conventional materials such as silicon (Si) because the large bandgap energy (2.2 eV in 3C-SiC polytype versus 1.12 eV in Si) allows SiC waveguide sensor to operate in visible and near-infrared light range. This advantage efficiently overcomes the large absorption coefficient of water in the near infrared range, which is the challenge faced by Si with strong absorption below the wavelength of 1.1 μm. Other advantages of SiC include the first order electrooptic (EO) effect (Pockels effect) and large EO coefficient

Table 1: Refractive index of some typical biological analytes.

Analytes	Blood plasma [24]	Stroma of cornea [25]	HBV (20 ng/mL) [26]	Glucose (10 mg/mL) [27]
Refractive index	1.3479	1.345	1.3492	1.344

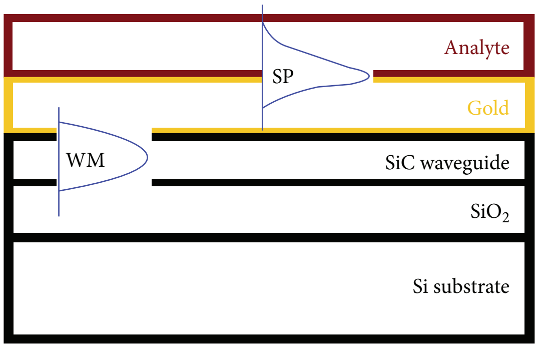

Figure 1: Cross-sectional view of SiC SPR sensor structure. WM: waveguide mode; SP: surface plasmon wave.

(70% higher than GaAs) [15] which are preferred by waveguide. Furthermore, excellent material properties such as the chemical inertness [16], radiation hardness [17], and compatibility between SiC device fabrication and standard Si device fabrication are suitable for manufacturing and on chip integration.

2. Device Design and Structure

The structure of SiC waveguide based SPR sensor is shown in Figure 1. The thickness of the SiC waveguide layer is 100 nm. Because of the smaller refractive index of SiC ($n = 2.62$) compared to Si ($n = 3.5$), a 3 μm thick SiO_2 isolation layer with the refractive index of 1.45 was added between SiC waveguide and Si substrate. This SiO_2 layer is thick enough for optical isolation and to reduce the loss due to Si substrate leakage. On top of the SiC layer, a thin metal film which is 50 nm thick gold (Au) in this study was added for the SPR effect. For device fabrication, the SiC layer can be grown on SiO_2 by chemical vapor deposition (CVD) [18] and the Au film by thermal or ebeam evaporation.

3. Results and Discussion

When the incident light (633 nm in this study) is applied on a waveguide sensor, the light of a guided mode is confined in the SiC waveguide layer. The evanescent wave, which is a small portion of the incident light, propagates in the surrounding medium with a low refractive index, that is, analyte. This results in attenuation of the output power. For the waveguide structure, the evanescent wave absorption follows Lambert-Beer's law, in which absorbance A is [19] as follows:

$$A = \log\left(\frac{I_0}{I_a}\right) = f\alpha lc, \qquad (1)$$

where I_0 is the light intensity transmitted in the waveguide when there is no absorption of evanescent wave in analyte, I_a is the light intensity transmitted with absorption, α is the absorption coefficient, l is the waveguide length, and c is the analyte concentration. The change of c results in the change of refractive index. f is the confinement factor, which represents the ratio of the optical power confined in analyte to the total incident optical power. Since the sensitivity S of the waveguide sensor is characterized by the change of absorbance A to the change of concentration in analyte as $S \propto \Delta A/\Delta c = f\alpha l$ when combining with (1), it is clear that a higher confinement factor indicates a better sensitivity of the waveguide sensor.

With the thin Au film on top of the SiC waveguide, surface plasmon enhancement effect [20] dominates in the optical power distribution. A surface plasmon wave at the interface between metal and analyte is excited by the evanescent wave if the coupling (resonant) condition between the guided mode and surface plasmon wave is satisfied, that is, when their propagation constants are equal. As a result of such resonance, a portion of energy from the incident light is transferred to surface plasmon wave, resulting in a decrease of the output light intensity (power). When the refractive index of analyte is changed, the coupling condition is also changed due to the field redistribution of the surface plasmon wave. This leads to the shift of resonant wavelength (or frequency). This phenomenon can be employed to assess the sensitivity of a SPR waveguide sensor by comparing the shift of resonant wavelength per refractive index unit (RIU). In this study, an effective index method (EIM) [21] was applied using COMSOL Multiphysics software to model the SiC SPR sensor structure and obtain the resonant wavelength for different refractive index. A perfectly matched layer (PML) was used as outer boundary condition to truncate the computation region, and the continuous inner boundary condition was also applied. Since surface plasmons are transverse magnetic (TM) polarized, only TM light was used to excite the surface plasmons. We investigated the fundamental TM mode (TM_0) in this study considering the lowest loss of TM_0 mode in waveguide. Also we focus on the refractive index of 1.338~1.348 since most bioanalytes attracting research interests are in this range as shown in Table 1. Another important factor considered in the model is that the refractive index of amorphous SiC varies with the wavelength of incident light.

Figure 2 shows the confinement factors of SiC SPR waveguide sensor structure in comparison with the values of non-SPR structure at different incident light wavelength and the refractive index of analyte in the range of $n = 1.338$~1.348. The confinement factor peaks at the resonance wavelength as explained in the previous section. For SPR structure, the increase of refractive index by a unit of 0.002 results in an average shift of resonant wavelength by about 3.8 nm towards

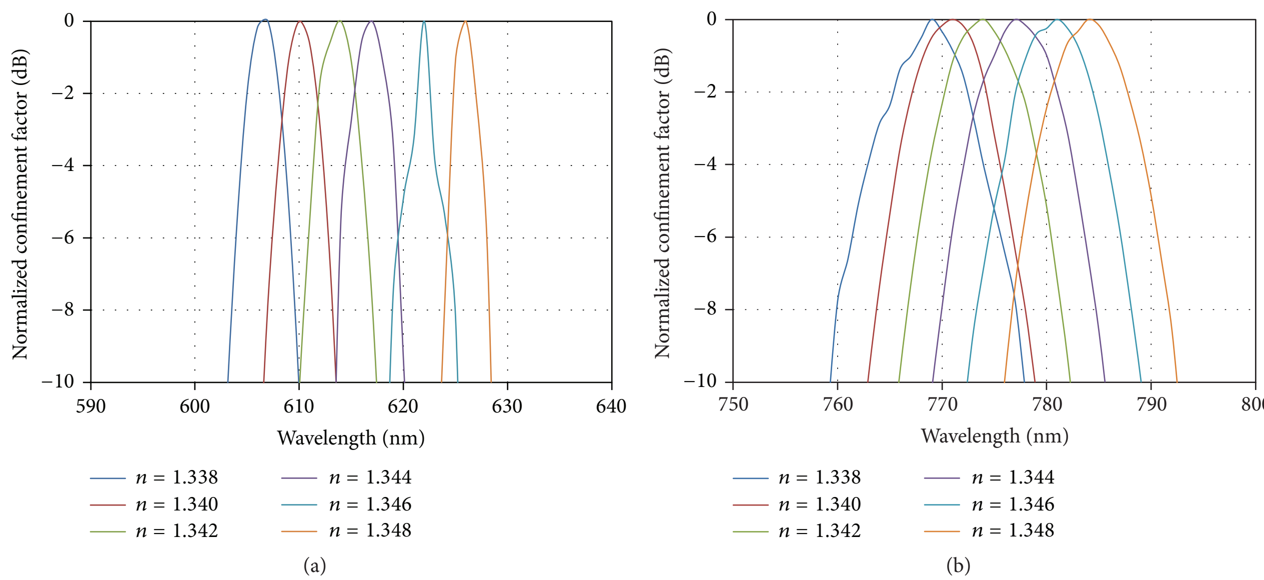

Figure 2: Spectrum of confinement factors in (a) SPR and (b) non-SPR SiC waveguide sensors with different analyte refractive index.

longer wavelength. This equals 1900 nm/RIU (refractive index unit). Non-SPR sensor shows sensing behavior similar to the SPR sensor but with smaller shifts. Note that, at each refractive index value, the resonant wavelength is different in SPR and non-SPR structure. This is due to the different resonant conditions which are determined by the sensor's configuration. It is also clearly shown in Figure 2 that the band width of the confinement factor spectrum from SPR sensor is much narrower than that of non-SPR sensor, which leads to a higher resolution preferred by sensors. This is because, in SPR sensor, the resonance coupling effect between waveguide mode and surface plasmon mode dominates the sensing performance. The coupling effect is weakened at wavelength off from the resonant wavelength, resulting in quick decrease of the confinement factor and therefore the narrow spectrum and higher resolution. In the non-SPR sensor, although the evanescent field component changes in response to the change of refractive index, this component is only a small portion of the total light propagating in the waveguide. Therefore, reduction of the confinement factor due to the refractive index change in non-SPR sensor is relatively small, resulting in a larger spectral width. It also needs to be pointed out that the thickness and its change of analyte also affect the resonant wavelength, leading to a shift of the cutoff wavelength of the second surface plasmon mode in a specific wavelength range [22]. In this study, we focused on only the change of refractive index, with the thickness of sensing medium fixed to be 5 μm.

Figure 3 summaries the shift of resonant wavelength as a function of refractive index in both SPR and non-SPR SiC sensors. In the refractive index range of $n = 1.338{\sim}1.348$, the shift clearly shows a linear characteristic, with a sensitivity of 1928 nm/RIU from SPR sensor versus 1542 nm/RIU from non-SPR sensor structure, that is, nearly 20% improvement.

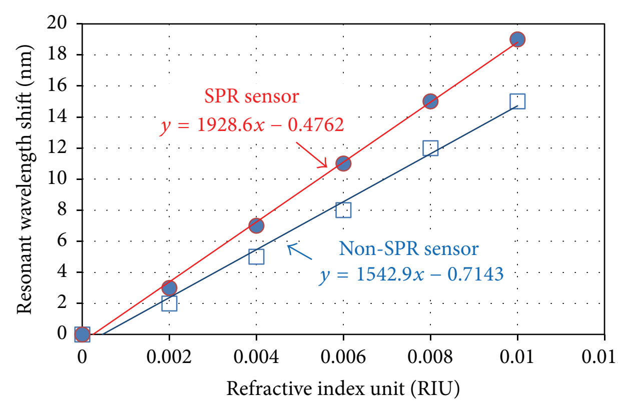

Figure 3: Shift of resonant wavelength as a function of refractive index from $n = 1.338$ to 1.348.

It is necessary to point out that the incident light coupling with surface plasmon wave is dependent on not only the refractive index, but also the sensor structure especially the thickness of the waveguide layer and metal film. Figure 4 shows the spectrum of confinement factor from SiC SPR sensor with various SiC waveguide layer thicknesses. The refractive index of analyte is 1.344. It clearly shows that the resonant wavelength shifts to longer regime when SiC waveguide layer thickness increases. The absolute value of confinement factor at each wavelength is also a function of the SiC thickness, which has been studied elsewhere [23]. In this paper, we chose the thickness of 100 nm for SiC waveguide to ensure larger confinement factor and lower material growth cost. The study also indicates that the resonant wavelength shift or sensor performance can be further improved by

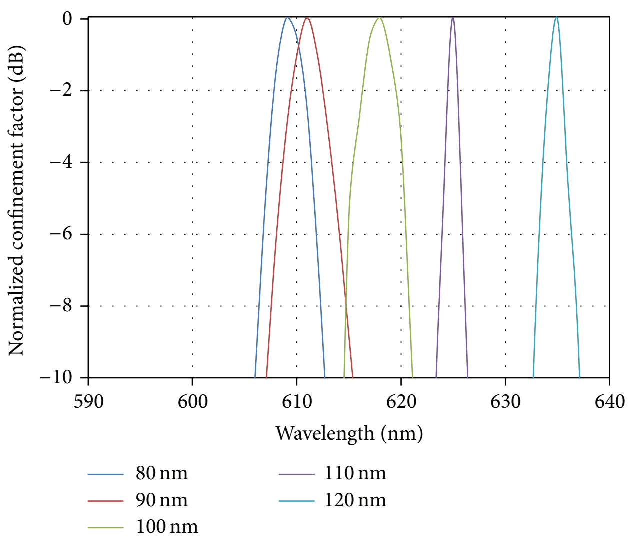

FIGURE 4: Confinement factor from SiC SPR structure with different thickness of the SiC waveguide layer. Refractive index of analyte $n = 1.344$.

optimizing the sensor design. Considering the excellent integration capability of waveguide structure, simple device fabrication process, high sensitivity, and advantages of SiC material, the SiC SPR waveguide sensor is promising for next-generation chemical and biological sensing.

4. Conclusion

The sensing performance of a SiC waveguide based SPR optical sensor was characterized by the shift of the resonant wavelength of confinement factor under various refractive index of analyte. The different analyte refractive index represents the change of analyte type and concentration. The results showed a linear shift of resonant wavelength with the change of refractive index. The sensitivity of 1928 nm/RIU could be achieved from the SPR waveguide structure, 20% higher than the sensitivity of the non-SPR structure. This sensitivity improvement together with the advantages of SiC material and waveguide configuration makes SiC SPR sensor a very promising candidate for new generation sensing in water or water-based medium.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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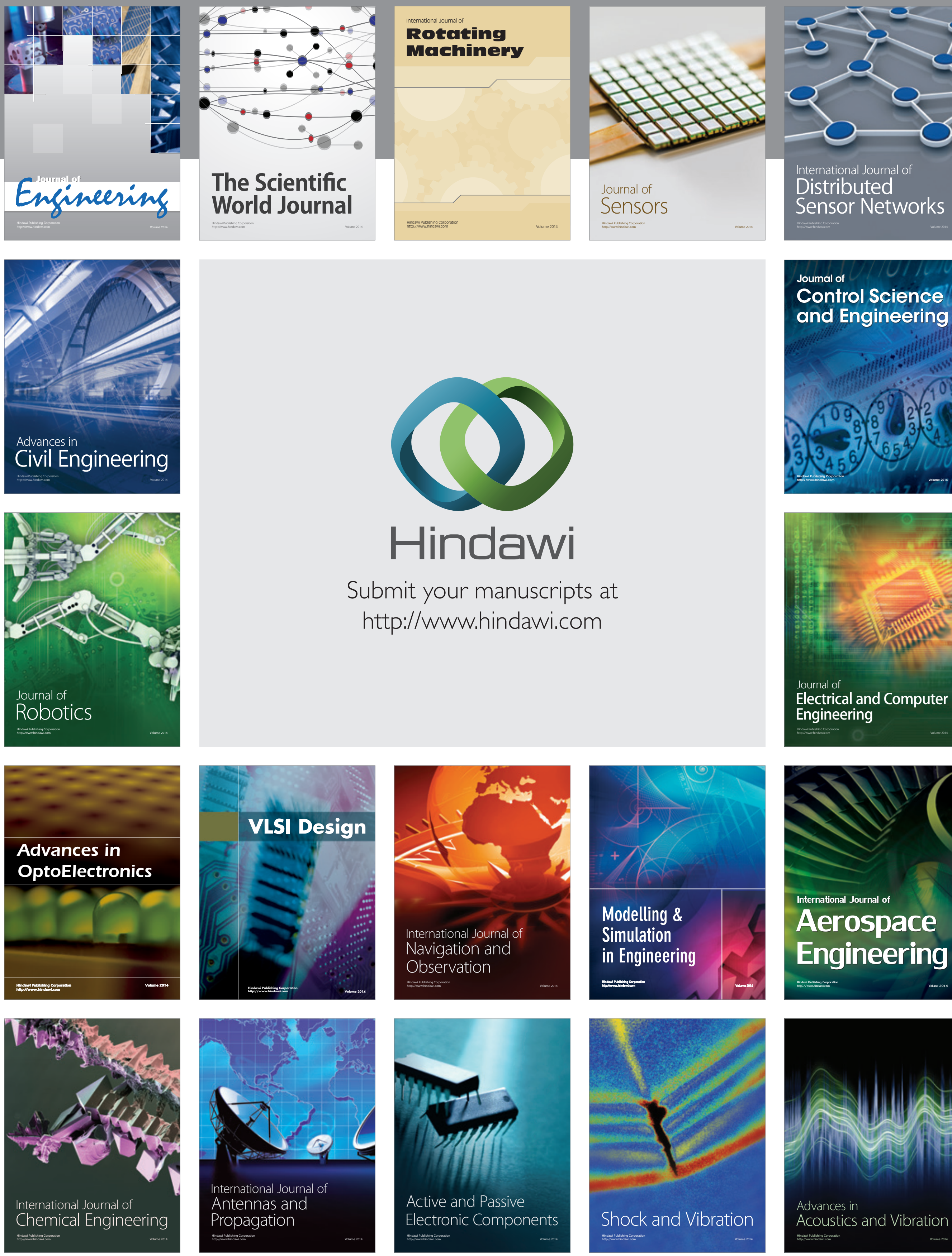

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