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Surface plasmon resonance based silicon carbide optical waveguide sensor

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A B S T R A C T

In this paper, we investigated a new surface plasmon resonance (SPR) based optical waveguide sensor formed on a wide bandgap semiconductor material – silicon carbide (SiC). The wide bandgap energy of SiC (Eg=2.2 eV of 3C-SiC polytype) enables the waveguide to operate in the visible and near-infrared wavelength range. Assessment of the potential sensing properties was performed by investigating the confinement factor in fundamental transverse magnetic mode (TM_0) using the effective index method (EIM). The results show that at the incident light of 633 nm, a confinement factor of 0.95 can be achieved at the refractive index of $n=1.45$. Comparing to reported non-SPR structure, the confinement factor of SiC SPR sensor was clearly improved over the refractive index range of $n=1.3$–1.5, and by more than 3.3 times at $n=1.35$. The improved sensing property by SPR structure combined with the superior chemical/biological inertness of SiC material and compatibility between SiC and Si device manufacturing makes the proposed SiC SPR sensor very promising for chemical sensing and bio-sensing.

1. Introduction

Among many sensor technologies, optical waveguide structures are considered to be very useful because they offer the advantages [1–3] of good control of light path, easy measurement of input and output light intensity, high sensitivity, high degree of on-chip integration, etc. Particularly in photonic integrated circuits, optical waveguide based device is desirable for on-chip integration over other configurations such as the Turbadar–Kretschmann configuration. Structures such as vertical slot waveguide [4], horizontal slot waveguide [5], and evanescent optical waveguide [6,7] for sensor platforms have been reported. When used in chemical sensing and bio-sensing with water based sensing medium [8–11], the optical waveguide sensors are desirable to operate in the visible light wavelength range to overcome the large absorption coefficient of water in the near-infrared range. Due to this requirement, conventional silicon (Si) based optical devices are not desirable in such sensors owing to the narrow bandgap of Si (Eg=1.12 eV) and therefore the strong absorption below the wavelength of 1.1 μm. Significant efforts have been made for new sensor materials and configurations, among which silicon carbide (SiC) attracts the attention of researchers.

SiC is a wide bandgap semiconductor with Eg=2.2 eV (in 3C-SiC polytype), therefore its transparent wavelength over visible and near-infrared range satisfies the aforementioned requirement. The first order electro-optic (EO) effect (Pockels effect) and large EO coefficient (70% higher than GaAs) [12] of SiC make it suitable for optoelectronics devices, such as modulators and high speed switches [13,14]. SiC also has excellent material properties especially the chemical inertness [15] and biocompatibility [16], which makes SiC an ideal candidate for chemical and bio-sensing. One more important advantage of SiC is that its device fabrication is compatible with standard Si device fabrication, and desirable for manufacturing and on-chip integration. SiC as a material for optical waveguide has been studied [17,18] and recently SiC–SiO_2–SiC horizontal slot waveguide [19] and SiC evanescent wave optical sensor [20] have been published. In this paper, we investigated a new SiC optical waveguide sensor with sensing properties significantly improved by a surface plasmon resonance (SPR) effect [21].

2. Design and modeling

Our proposed SPR based SiC waveguide sensor structure on a Si substrate is shown in Fig. 1. The 3C-SiC is doped by nitrogen with a concentration of $10^{17}\,cm^{-3}$. Because of the smaller refractive index of SiC ($n=2.64$) compared with Si ($n=3.5$) at 633 nm, an isolation layer of SiO_2 ($n=1.45$) is required between the SiC layer and Si substrate. Technology such as chemical vapor deposition (CVD) [22,23] can be used to grow SiC on SiO_2. To efficiently confine the optical power in the sensing medium for a high

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confinement factor, the SiO_2 layer must be thick enough for optical isolation between SiC film and Si substrate and to reduce the loss due to Si substrate leakage. Therefore, a 3 μm-thick SiO_2 layer was chosen in the study in order to deliver the best optical confinement results and in the meantime not to complicate SiO_2 deposition process. The SPR effect is employed in the sensor by adding a thin metal film, which is gold (Au) in this study, between the SiC layer and sensing medium as shown in Fig. 1. The width of the sensor was 10 μm. The sensing medium was kept at 3 μm thick. The optimized thickness of SiC and Au layer was investigated in this study.

For chemical sensing, the fluid channel which can be formed by controlled local etching of SiC contains the analytes, i.e. sensing medium, and the whole waveguide is excited by the incident light (633 nm in this study). The optical power is distributed in both waveguide and sensing medium, and the part absorbed in the sensing medium results in attenuation of the output power. Based on Lambert–Beer's law, the absorbance A in waveguide structure is given by [20]

$$A = \log(P_0/P_a) = f\alpha lc \quad (1)$$

P_0 and P_a are the light intensity without and with energy absorption in the sensing medium, respectively; f is the confinement factor, which is defined as the ratio of the optical power confined in the sensing medium to the total input optical power; α is the absorption coefficient; l is the length of waveguide and c is the concentration of the sensing medium, with changes reflected by the changes of refractive index. The sensitivity S of the sensor is proportional to the ratio of the change in absorbance A to the concentration change in sensing medium

$$S \propto \frac{\Delta A}{\Delta c} = f\alpha l \quad (2)$$

According to Eq. (2), for a given waveguide length, a higher confinement factor value indicates a better sensitivity of the waveguide sensor. With the added thin metal film, the surface plasmon enhancement effect [21] dominates in the optical power distribution. The evanescent field becomes very strong at the interface between the metal film and the sensing medium due to energy resonant coupling between incident light and surface plasmon wave. This leads to more optical power being confined (absorbed) in the sensing medium by energy transfer from incident light to surface plasmon wave, resulting in improvement of the confinement factor. In this study, we applied the effective index method (EIM) [24,25] using COMSOL Multiphysics software to model the proposed SiC SPR sensor structure and calculate the confinement factor, and compared the results with non-SPR counterpart (similar structure but without the metal layer on top of SiC waveguide). In modeling, a perfectly matched layer (PML) of 3 μm thickness surrounding the whole sensor structure was used as outer boundary condition in COMSOL simulation to truncate the computation region. At the boundary of each layer, the tangential component of electric and magnetic field was defined as the continuous inner boundary condition in COMSOL Multiphysics. 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.

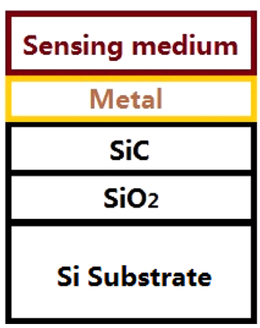

Fig. 1. Cross-sectional view of proposed SPR based SiC optical sensor structure.

3. Results and discussion

Fig. 2 illustrates the distribution of electric field in TM_0 mode in SiC SPR sensor structure in comparison with non-SPR structure reported in reference [20]. Thickness of the SiC layer was chosen to be 20 nm and the Au layer in the SPR sensor was 50 nm thick. The permittivity of Au is $-12.7+1.36i$ [26]. Fig. 2 shows clearly that in the non-SPR structure, the optical power disperses in both sensing

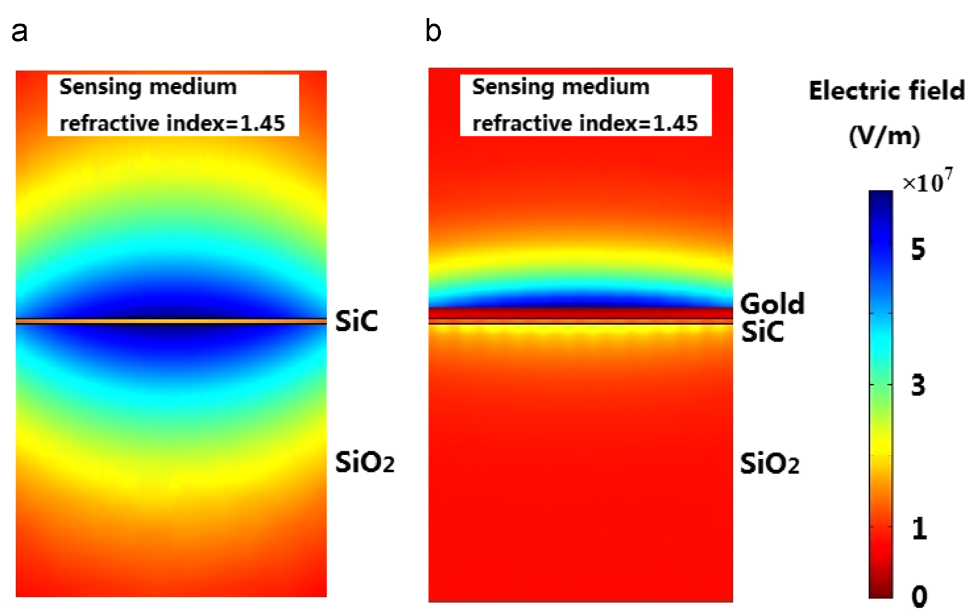

Fig. 2. TM_0 mode electric field distribution in (a) a non-SPR SiC sensor structure reported in [20] and (b) proposed SPR sensor structure. The refractive index of the sensing medium is 1.45.