High Performance of the Graphene-Coated Bloch Surface Waves Biosensor

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Abstract

We propose a finely tuned performance Bloch Surface Waves (BSWs) based biosensor combining the graphene coating and a defective layer X: (X = TiO_2, AlAs, GaP) on the top a photonic structure prism/[TiO_2/MgF_2]2. The simulation of the performance of the biosensor is carried out considering the effects of refractive index and thickness of a terminate layer X as well as the number of graphene layers. Moreover the figures of merit of the biosensors are compared.

Keywords: Bloch Surface Waves biosensor, Kretschmann configuration, biosensor performances, graphene coating.

INTRODUCTION

Photonic crystals are periodic structures characterized by the existence of frequency band gap where light propagation is prohibited [1, 2]. Particular attention is paid to the one dimensional photonic crystals (1D-PC) which are periodic stack of dielectric thin films with high and low refractive index. Breaking the periodicity of the structure induces permitted states inside the photonic band gap. These states are evanescent waves localized at the interface of the PC and the surrounding medium and are commonly called Bloch surface waves (BSWs) [3- 5]. Owing to their sensitive aspect to the refractive index of the surrounding medium BSWs are widely exploited in the last decade in real time refractive index bio-sensing [6- 9].

BSWs have the advantage of being tuned by the appropriate choice of the dielectric photonic structure surpassing in bio-sensing the surface plasmon waves relying on the use of metallic structures [10]. Moreover BSWs exist for either (s/p) states polarized incident light [11].

We know that a full destructive interferences phenomenon exist using a quarter wave stacks of dielectric layers which prohibits transmission of light. Adding a dielectric layer on the top of the PC breaks its space symmetry and allows transmitted waves appearing as a sharp dip in the angular reflectance.

The angular sensitivity of the biosensor is defined as a ratio of a refractive angle change $\Delta\theta$ and the sensing medium refractive index change Δn [12]:

$$S = \frac{\Delta\theta}{\Delta n} \quad (1)$$

Performance of the bio-sensor is connected mainly to its sensitivity, the full wide at half maximum FWHM and the extremes of the reflectance (R_{max}. and R_{min}). The Figure of merit (FoM) of a biosensor play a pivotal role in comparing performances of the biosensors, it is defined as [13]:

$$FoM = S \times \frac{R_{max} - R_{min}}{FWHM} \quad (2)$$

In other side, due to its high ability of surface fixation and recognition of bio-molecules, graphene has emerged as a promising 2D non invasive material for biosensing [14] and human health monitoring [15]. Many works proposed graphene based biosensors sustaining BSWs [16-18].

In the present work, we investigate the effect a terminate layer X (X=TiO_2, AlAs, GaP) coated with graphene layers on the performance of the proposed biosensors.

MATERIALS AND METHODS

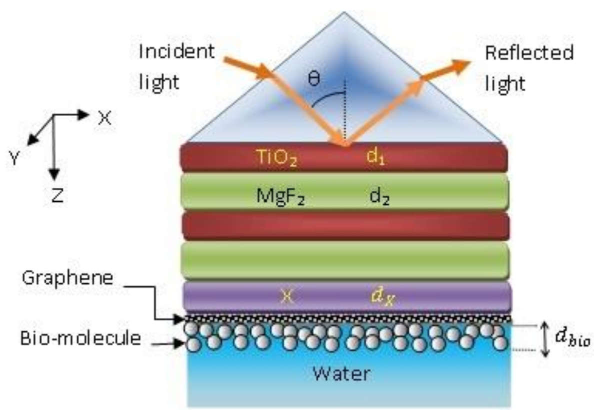
The considered biosensor is represented in Fig. 1. The prism coupling technique is used to excite BSWs using p state polarized incident light at $\lambda = 633\ nm$.

The refractive indices in RIU of prism (K-LaSFn1), TiO_2, MgF_2, AlAs, GaP and graphene at 633 nm are respectively 1.8 [19], 2.583[20], 1.3769 [21] 3.1009 [22], 3.3183[23]and $3 + 1.149\,i$ [24].

The TiO_2 and MgF_2 thicknesses are respectively $d_1 = 61.25\ nm$, and $d_2 = 114.92\ nm$. The optical properties of the photonic structure without terminate layer provide total reflection of incident light. A sharp dip appears in the angular reflectance when a terminate layer X with appropriate thickness on the top of the structure is added which reveals the transmittance of the light in the photonic band gap.

As a first step we optimize the thickness d_X of the terminate layer X to obtain higher sensitivity considering the monolayer graphene coating. We study in the second step the effect of adding more graphene layers on the performance of the biosensors. The simulation is carried out using the transfer matrix method [25]. We consider the sensing medium refractive index 1.34 RIU

Figure 1: The proposed biosensor: Prism /$[TiO_2/MgF_2]^2$/X (X= TiO_2, AlAs, GaP) / graphene/sensing medium

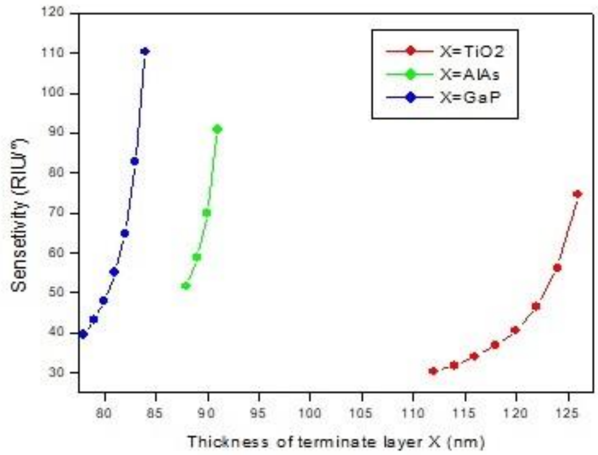


RESULTS AND DISCUSSION

A. Graphene monolayer coating

The calculated angular sensitivity is shown in Fig. 2 for biosensors corresponding to the three terminate layers. The sensing medium refractive index is water with 1.33 RIU which changes to 1.34 RIU by adding bio-molecules. The angular sensitivities are increasing with increasing the thickness of the terminate layers. The maximal sensitivity is 110°/RIU reached for the GaP terminate layer with thickness d_{GaP} =84 nm which decreases to 90.5 and 63.5 °/RIU for the terminate layers AlAs (91 nm) and TiO_2 (125 nm) respectively. The higher is the terminate layer refractive index the higher is the maximal sensitivity of the corresponding biosensor.

Figure 2: Sensitivity as function of thickness of the layer X (X=TiO_2, AlAs, GaP) for a biosensor with a graphene monolayer. Thickness of bio-molecules is 160 nm



The angular reflectance of the biosensor is illustrated in Fig.3. Fig.3(a) illustrates the effect of increasing the thickness of the terminate layer TiO_2. We notice that as the thickness increases the resonance angles are shifted to higher angles.

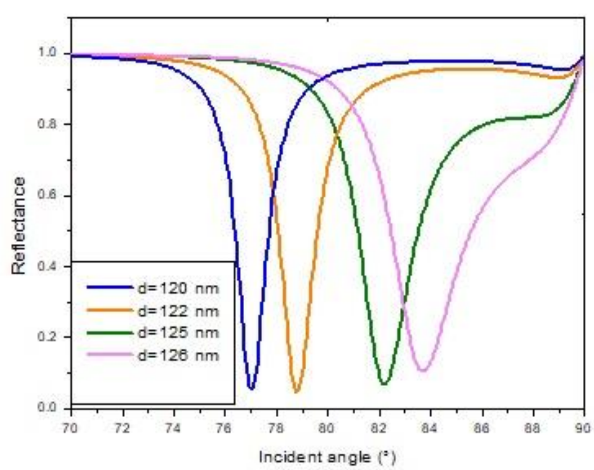
Fig.3(b) shows angular reflectance of the biosensors with different terminate layers (X= TiO_2 (120 nm), AlAs (90 nm) and GaP(84 nm)) . The curves reveal that the BSW resonant angles are as higher as the refractive index of the terminate layer is higher.

For both insets of Fig.3 we notice that angular reflectance curves are as broadened as the thickness and/or the refractive index increases. The broadening effect is attributed to absorption of light in a multilayer photonic structure.

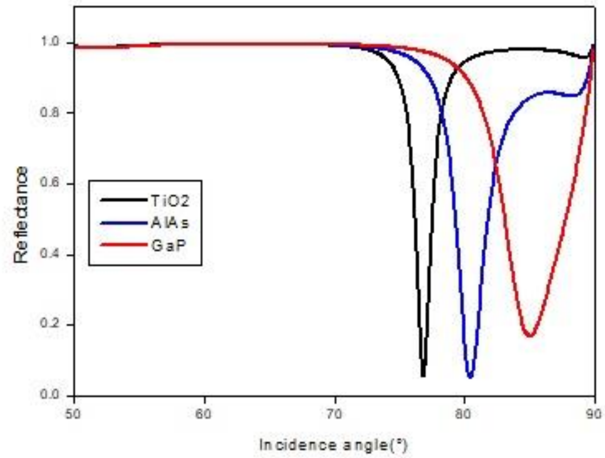
This effect is confirmed by the calculated values of the FWHM presented in Table 1 for the proposed biosensors which show increasing FWHM with increasing terminate layer refractive index reaching a maximal value of 4.26° for a monolayer coating.

Figure 3: Angular reflectance of the biosensor with graphene monolayer coating a) for layer X = TiO_2 with layer thickness d_{TiO2} =120,122,125 and 126 nm. The bio-molecules bending layer thickness is 160 nm. b) For a terminate layers X=TiO_2 (n=2.5836, d_{TiO2} =120 nm), X=AlAs (n=3.1009, d_{AlAs} = 90nm) and X=GaP (n=3.3183, d_{GaP} = 84 nm). The bio-molecules bending layer thickness d_{bio} = 160 nm.

(a)



(b)



B. Graphene multi-layer coating

To further enhance the sensitivity we propose the addition of more graphene layers on the top of the photonic structure. The considered biosensors are then:

1)prism/[TiO_2/MgF_2]^2/TiO_2(125nm)/graphene(L), 2)prism/[TiO_2/MgF_2]^2/AlAs(91nm)/graphene(L) and

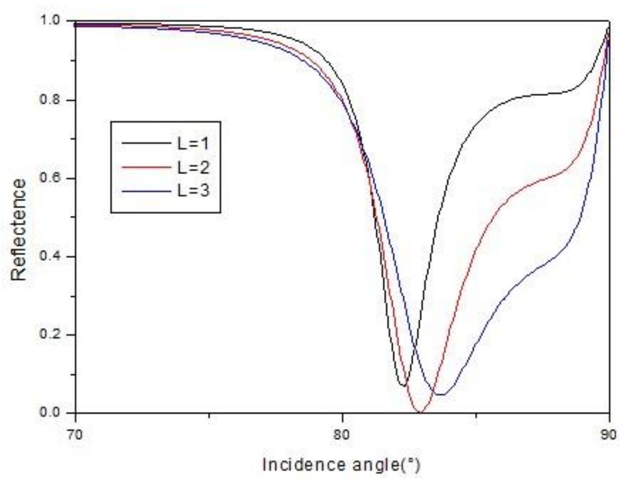
3)prism/[TiO_2/MgF_2]^2/GaP(84nm)/graphene(L).

The angular reflectance for the proposed biosensors with additional graphene layers (L=1-3) are shown in Fig.4: (a) X= TiO_2, d_{TiO_2} =125 nm; (b) X=AlAs, d_{AlAs} =91 nm; (c) X= GaP, d_{GaP} = 84 nm.

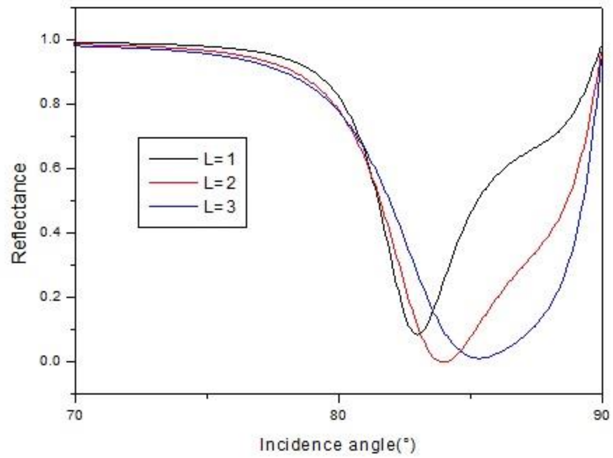
A prominent broadening of the angular reflectance curves is explained by large absorptions engendered in the photonic structure as the graphene layer number increases. This is justified by calculated FWHM values shown in Table 1

Figure 4: Angular reflectance for photonic structure with additional graphene layers (L=1-3) and terminate layer (a) X= TiO_2, d_X=125 nm, (b) X=AlAs, d_X=91 nm, (c) X= GaP, d_X = 84nm.The bio-molecular layer thickness =160 nm.

(a)



(b)



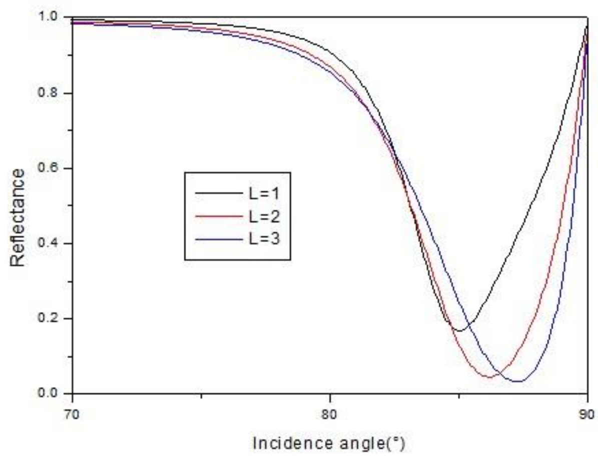


Table 1: Performances of the biosensors for three terminate layers(X= TiO_2 , AlAs , GaP) and multilayer graphene coating (L=1-3)

Terminate layer X	Graphene Layer number L	Sensitivity (°/RIU)	FWHM (°)	Minimum of reflectance	FoM (RIU^{-1})
TiO_2 (125nm)	L=1	63.57457	2.22	0.06	26.91
	L=2	69.57217	5.26	0.002	13.19
	L=3	77.968811	7.2	0.047	10.31
				-	
AlAs (91nm)	L=1	90.56377	3.36	0.085	24.74
	L=2	103.1587	7.02	10^{-4}	14.26
	L=3	127.1491	7.26	0.012	17.30

GaP (84nm)	L=1	110.9556	4.26	0.16	21.87
	L=2	107.9568	5.7	0.045	18.08
	L=3	71.97121	5.46	0.106	11.78

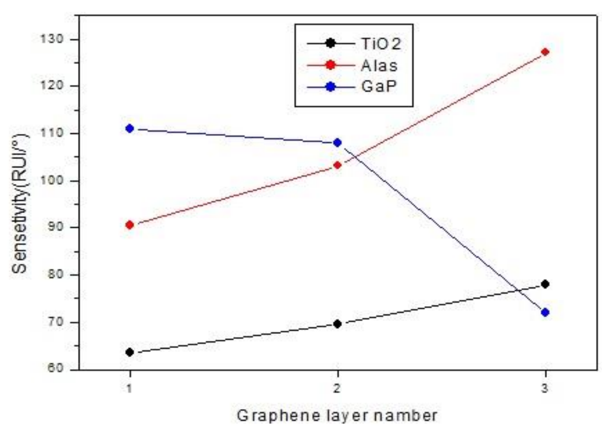
Performances of the proposed biosensors corresponding to the three terminate layers and multilayer graphene coating (L=1-3) are compared in Table 1.

The angular sensitivity as function of the graphene layer number is depicted in Fig.5(a). The sensitivity increases with increasing the graphene layer number L for TiO_2 and AlAs layers, however for the GaP terminate layer it decreases slightly for L=2 and drops out for L=3. The maximum of sensitivity is 127°/RIU reached for a terminate layer AlAS and L=3.

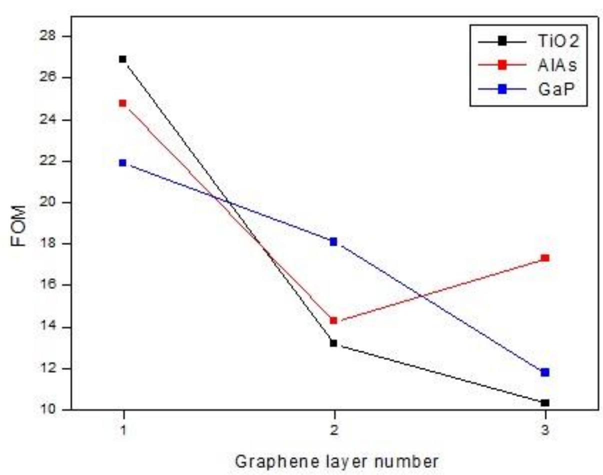
The FoM of the biosensors are presented in Fig.5(b). For the three terminate layers the FoMs are the highest for L=1 with a maximum of 26.91° obtained for TiO_2 layer.

Figure 5: Biosensor performance considering the terminate layers X= TiO_2, AlAs and GaP with d_X=125,91 ,84 nm respectively and bio-molecular layer thickness =160 nm a) Angular sensitivity as function of graphene layer number. b) FoM of the biosensors as function of graphene layer number .

(a)



(b)



CONCLUSION

We show through the study of the multilayer graphene coated biosensors with terminate layer X(TiO_2, AlAs, GaP) that high refractive index terminate layer and a multiple layer graphene coating are two key parameters providing high sensitivity of the biosensor. However the high sensitivity is compromised by a broadening in reflectance curves leading to a decrease of the FoM of the biosensor. The highest FoM is obtained for the lowest refractive index terminates layer (TiO_2) and a monolayer graphene coating.

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