High-performance sensor based on surface plasmon resonance with chalcogenide prism and aluminum for detection in infrared

Rajan Jha	extsuperscript{1,*/} and Anuj K. Sharma	extsuperscript{2,++}

	extsuperscript{1}ICFO–Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

	extsuperscript{2}Jacob Ruisdaellaan 3, 5581 JK, Waalre, The Netherlands (anujsharma@gmail.com)

Corresponding author: rajaniiitd@gmail.com

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A high-accuracy aluminum-based surface plasmon resonance (SPR) chalcogenide sensor is proposed for IR. The structure is based on widely used 2S2G chalcogenide glass with aluminum as the SPR active metal. The angular interrogation method has been used to study the performance of the sensor in terms of intrinsic sensitivity (IS) that includes the width and shifts of the SPR curve for a given refractive index of sensing layer. The IS of Al-based chalcogenide glass sensor is almost 400% more as compared with an Au-based one, which is the most widely used SPR active metal. The oxidation problem of an Al-based SPR sensor has been addressed. © 2009 Optical Society of America

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Since its first application in gas sensing [1], surface plasmon resonance (SPR) has been widely used for sensing applications owing to its ability of determining small changes in refractive index at a metal–dielectric interface. The conventional SPR sensor structures are based on Kretschmann and Reather’s attenuated total reflection (ATR) configuration. If structures are based on Kretschmann and Reather’s dielectric interface. The conventional SPR sensor sensing applications owing to its ability of determining plasmon resonance (SPR) has been widely used for Since its first application in gas sensing [1], surface refractive index of sensing medium, then the resonance wavelength for a given refractive index of sensing layer is determined with utmost accuracy. The parameter that affects the width and hence the performance of an SPR-based sensor is the attenuation properties of the metal that depend on the dielectric constants of the metal. Usually, the metallic layer used in SPR measurements consists of either silver (Ag) or gold (Au). Au demonstrates a higher shift and is chemically stable. Ag, on the other hand, displays a narrower resonance curve but is prone to oxidation. The performance can be enhanced by using aluminum (Al), which is not only an SPR active metal but is relatively economical as compared to Au or Ag as being the third most abundant element therein, after oxygen and silicon. In the past, Al has been used as an SPR active metal for sensing studies [3]. It has been shown that Al may provide a sharper SPR curve than Ag, Au, and Cu [4]. Practically, Al also has poor chemical stability, which makes it difficult to get a reliable sensor for practical applications. However, a new structure of bimetallic layers (few nanometers of Au as the outer layer) may not only protect the thicker Al layer from oxidation but also enhance the overall sensor performance as compared to a single layer of Au [4].

Generally, SPR measurements with a silica-based prism do not allow for the detection in the IR wavelength region, which requires attention owing to its many environmental, medical, and security applications. Moreover, the SPR-based structures in IR have substantially different parameters of excitation and support certain advantages for sensing applications in terms of high probe depth [5] and a more accurate determination of the SPR dip [6]. SPR sensing in the near IR with a silicon prism has showed interesting results for further studies in the IR regime [7]. In this view, chalcogenide glasses based on the group VI chalcogen elements (sulfur, selenium, and tellurium) can be the potential candidate for designing SPR sensors to operate in IR owing to their transparent behavior in the near to mid-IR region [8]. Chalcogenide glasses are formed by adding materials, such as arsenic, gallium, germanium, and antimony, to the above-mentioned chalcogenide elements and have been widely used for different applications, [9,10] including sensing [11,12].

In this Letter we have proposed and theoretically analyzed the design of an Al-based SPR sensor with a chalcogenide prism in the IR region. The performance has been analyzed in terms of intrinsic sensitivity (IS) that takes into account the shift in resonance angle, width of the SPR curve, and refractive index difference of the sensing layer. The oxidation problem of an Al-based SPR sensor has been addressed by coating it with an ultrathin gold layer. The physical explanation related to the results has been provided.

For the present structure, the base of the chalcogenide glass prism is coated with a metal (Au or Al) layer followed by a biomolecular layer as shown in Fig. 1. This biolayer is finally covered by the sensing...
medium under detection. The light from the source at a particular wavelength is launched at one of the prism faces and is collected at the other face. Prisms based on chalcogenide glass are better compared to other glasses, as they have higher thermal stability, better chemical reactivity, and a higher refractive index [12]. Further, for the dispersion in metal layer, we use the Drude equation as

\[ \varepsilon_m(\lambda) = \varepsilon_{m0} + i \varepsilon_{m1} = 1 - \frac{\lambda^2 \lambda_c}{\lambda_p^2(\lambda_c + i\lambda)}, \]  

(2)

where \( \lambda_p \) and \( \lambda_c \) denote the plasma wavelength and the collision wavelength, respectively. The following values of the plasma wavelength and the collision wavelength for Au and Al are used: \( \lambda_p = 1.6826 \times 10^{-7} \text{ m} \) and \( \lambda_c = 8.9342 \times 10^{-6} \text{ m} \) (for Au) and \( \lambda_p = 1.0657 \times 10^{-7} \text{ m} \) and \( \lambda_c = 2.4511 \times 10^{-5} \text{ m} \) (for Al). For calculations, the biolayer is assumed to be a homogeneous layer of refractive index 1.45 whose thickness increases with the attachment of biomolecules to the probe. To obtain the expression for the reflected signal for a \( p \)-polarized incident beam, we consider the \( N \)-layer transfer matrix method [13]. In general, the performance of the SPR sensor is determined in terms of two aspects. First, the shift in resonance angle (\( \delta \theta_{\text{SPR}} \)) for a given change (\( \delta n_s \)) in the sensing layer refractive index (\( n_s \)) should be as large as possible. Second, the FWHM corresponding to the SPR curves (\( \delta \theta_{\text{FWHM}} \)) should be as small as possible so that the error in determining the resonance angle is minimum. To take both above aspects into account, a performance parameter called IS of the sensor is defined as directly proportional to \( \delta \theta_{\text{SPR}} \) and inversely proportional to the average FWHM of two SPR curves for a given change (\( \delta n_s \)) in the sensing layer refractive index [6]. Mathematically, IS of the sensor is

\[ \text{IS} = \frac{\delta \theta_{\text{SPR}}}{\delta n_s \times \delta \theta_{\text{FWHM}}}. \]

(3)

Figure 2 depicts the graphical representation of plasmon resonance condition [Eq. (1)] for Au and Al separately. The angular variation of propagation constant of incident light (\( K_{\text{inc}} \)) and of plasmons (\( K_{\text{SP}} \)) for the 2S2G prism is shown. The intersection of the curves corresponding to \( K_{\text{inc}} \) and \( K_{\text{SP}} \) represents the fulfillment of Eq. (1). As is visible for the same \( n_s \), there are two different \( \theta_{\text{SPR}} \) values (one each for Al and Au).

Figure 2 shows that for the same \( n_s \), the resonance takes place at a smaller angle value (\( \theta_{\text{SPR}} \)) for Al as compared to Au. Thus, light coupling as well as plasmon resonance is possible by using 2S2G glass and using Al and Au as the SPR active metals.

Figure 3 shows two SPR curves for \( n_s = 0.002 \) with 2S2G as the coupling medium and Al and Au as the SPR active metal layer of 50 nm. The graph also contains the SPR curve for a bimetallic case with a 47-nm-thick Al layer and a 3-nm-thick Au layer. The operating wavelength is 1 \( \mu\)m. The shift (\( \delta \theta_{\text{SPR}} \)) in the SPR curve for Au as well as Al remains the same (0.07°), i.e., \( \theta_{\text{SPR}} \) shifts from 37.26° to 37.33° in the case of Au, whereas for Al the \( \theta_{\text{SPR}} \) shifts from 36.30° to 36.37°. On the other hand, the FWHM of the SPR curve for Al and Au, respectively, are 0.735° and 0.045°. The much smaller FWHM for Al can be attributed to the smaller value of modulus of \( e_i / e_i \) at a given wavelength as compared to Au. On the other

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Fig. 1. Setup for SPR-based sensing with chalcogenide (2S2G) glass.

Fig. 2. Illustration of matching of plasmon resonance condition in the case of 2S2G glass for Al and Au layers at two different \( n_s \) values.

Fig. 3. SPR spectra based on 2S2G glass for monolayer of Al (50 nm), Au (50 nm), and bimetallic layer (47 nm of Al and 3 nm of Au) at the operating wavelength of 1 \( \mu\)m.
hand if one considers the bimetallic case (47 nm of Al and 3 nm for Au), the angular shift and the angular width of the SPR curve remains almost the same as in the case of 50 nm of Al. Hence, the performance in the bimetallic case remains very close to an Al monolayer case. Moreover, the Au layer protects the Al layer from getting oxidized.

To study the effect of the wavelength on the sensor’s performance, Fig. 4 shows the variation of IS with an operating wavelength for Al (50 nm), Au (50 nm), and an Al–Au bimetal (47 nm–Au (3 nm) bimetal. It can be observed that for the same sensor configuration over a broad wavelength band in the IR region, IS is almost 400% more when the Al layer is used as compared to a sensor based on the Au layer. The high IS can be explained in terms of the imaginary part of K_sp that corresponds to the optical absorption of incident light and has an inverse variation with the wavelength. It implies that light absorption increases with a decrease in wavelength, which causes the reflected light intensity (R_p) to decrease, and the SPR curve shifts downward. Thus, the shorter the wavelength the more the downward shifting (i.e., broadening) of the SPR curve. Further, the angular shift of the SPR dip also gets affected by the wavelength because of the dependences of the real part of the metal–dielectric constant and hence the real part of K_sp. However, the influence of the wavelength is more prominent on the imaginary part rather than the real part of K_sp. Therefore, the variation of IS with the wavelength is largely dictated by the SPR curve’s FWHM in comparison to its shifting. Since the FWHM of the SPR curve is greater at a shorter wavelength, IS gets better at a higher wavelength. It can also be noted that the oxidation problem of an Al-based sensor can be easily handled by using 3 nm of a Au layer that lowers the IS of the sensor by around 3% to 4%, which is negligible considering the fact that a thin layer of Au enhances the longevity of the sensor. Moreover, in Fig. 4, one can also observe that when Au is not used as the outer layer, Al gets oxidized (and gives rise to a thin layer of Al2O3), thereby decreasing the IS. The performance of the sensor degrades because the formation of the oxide layer increases the FWHM of the SPR curve, thereby decreasing the IS of the sensor.

In conclusion, the proposed sensor can be very useful for chemical and biosensing applications in IR owing to a large operating window of chalcogenide materials. A few possible first-hand applications may be environmental analysis, breath analysis, homeland security, and minerals detection. We believe that the proposed model can open a new route in the sensing research for chalcogenide prism-based plasmonic sensors.

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†Both authors contributed equally to this work.

References