SURFACE PLASMON POLARITON OBSERVATION AT NARROW-GAP SEMICONDUCTOR Bi_2Se_3 AND Sb_2Te_3

ELVIN HUSENAGA ALIZADE
Institute of Physics, of Azerbaiyan NAS
131, H. Javid ave., Baku, AZ 1143,
E-mail: alizadeelv@gmail.com

The application of the surface plasmon resonance (SPR) in the mid IR spectrum is able to recognize a wide range of compounds based on selective binding and vibration modes. This paper presents the results of investigation of the bulk or volume plasmon polariton (VPP) and surface plasmon polaritons (SPP) in the IR spectrum on the well-known layered compounds Bi_2Se_3 and Sb_2Te_3. The plasmon in the mid-IR spectrum was studied at IR spectroscopic ellipsometry. The dispersion of the plasmon polariton was calculated in case of ambient air medium. Also, the dispersion of the plasmon polariton was calculated in 3 different mediums – KRS-5, ZnSe and Si. Furthermore, the spectral dependence of the plasmon propagation length were calculated.

Keywords: plasmon, surface plasmon resonance, spectroscopic ellipsometry, plasmon dispersion.
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1. INTRODUCTION

For several years, the SPR effect in the noble metals has been actively applied for sensing compound [1] [2] [3] [4]. SPR is the result of collective oscillations of free carriers at the metal-dielectric interface. SPR is a promising tool to perform rapid tests for a wide range of applications to monitor environmental changes and chemical composition. Increasing the sensitivity and expanding the possible application has become a necessity, thus, the task of finding new materials in addition to noble metals has become extremely important. Narrow-gap degenerate semiconductors with a high concentration of free carriers are very interesting for plasmonic applications in the IR spectrum.

Most of the work on the observation and application of the plasmon phenomenon was done in the visible region. The several methods were used for plasmon coupling. The most common method of coupling is with a prism, so called Kretschmann configuration. The projection onto the surface of the wavenumber in a cylindrical prism takes the form $k_x = \frac{\omega}{c}\sqrt{\varepsilon_a}\sin(\theta)$ [4]. The necessary condition to excite the plasmon is when $k_x = k_{spp}$, where k_{spp}–the real part of SPP wavenumber. The choice of material in the visible region of the spectrum is limited, for example quartz should have $\varepsilon_a = 3.4$. There are wide range of materials for the IR spectrum, while ε_m for these materials is greater than ε_m for quartz. This makes it possible to operate plasmon in a wide range of the spectrum. In this work, we used the KRS-5 ($\varepsilon_m = 5{,}66$), ZnSe ($\varepsilon_m = 5{,}91$) and Si ($\varepsilon_m = 11$) prism to calculate beehavior of SPP. It is essential to evaluate the shifts of the plasmon resonance energy in different ambient for further application.

In this paper, for the first time, it is proposed to consider the application of the SPR in the IR spectrum, investigating in Bi_2Se_3 and Sb_2Te_3. Plasmons in these compounds were previously reported [5] [6], but their use in SPR devices was not proposed.

2. THEORETICAL DETAILS

The model of the interface between the ambient air and plasmonic material is selected for calculation of the dispersion (Fig. 1.).

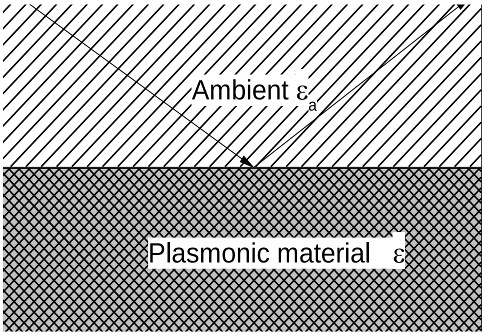

Fig. 1. Schematic representation of the model for calculation.

The calculation was carried out using the data of the dielectric function obtained by spectroscopic ellipsometry according to the equation [3]:

$$k = k_1 + ik_2 = \left[\frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_m}{\varepsilon_1+\varepsilon_m}\right)^{1/2}\right] + i\left[\frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_m}{\varepsilon_1+\varepsilon_m}\right)^{3/2}\frac{\varepsilon_2}{2(\varepsilon_1)^2}\right]$$

where k_1 and k_2–real and imaginary parts of the wave vector, respectively, ω–photon frequency, c–speed of light, ε_1 and ε_2–real and imaginary parts of the dielectric function, respectively, and ε_m–dielectric function of the medium. The SPP loses energy as it propagates along the surface. This important property of the plasmon characterizes the imaginary part of the wave vector. The distance along the propagation of the SPP at which it decays by 1/e is called the propagation length. The propagation length is calculated by the following equation:

$$L_{SPP} = \frac{1}{2k_2}$$

The parameter of the skin-layer thickness is used to assess the penetration depth of the SPP into the depth of the metal. This thickness characterizes the attenuation of the SPP 1/e when the SPP penetrates deeply into the metal. Skin thickness is obtained from the equation:

$$\Delta = \sqrt{\frac{2}{\sigma\mu\omega}}.$$

Propagation length and skin layer thickness are important parameters in the future study of localized SPP and for plasmon coupling.

3. EXPERİMENTAL DETAILS

This work is a continuation of the study of plasmons in Bi_2Se_3 and Sb_2Te_3 by using spectroscopic ellipsometry, which were reported earlier [5] [6].The dependence of the dielectric function of the photon energy is extracted by the spectroelipsometric method with the help of the J.A. Woollam IR-Vase ellipsometer. Data on the sample preparation, structure of the samples, some transport properties and spectroscopic ellipsometry experimental results are given in [5]. These data were used in our current calculations.

4. RESULTS AND DISCUSSION

Figures 2a and 2b show the calculation of the plasmon dispersion in air and various prism materials.

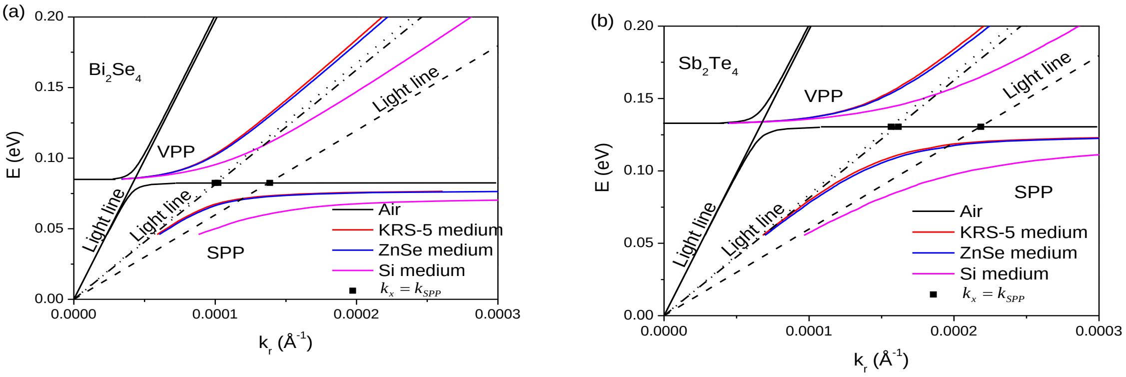

Fig. 2. Plasmon dispersion for Bi_2Se_3 (a) and Sb_2Te_3 (b). Solid line is light line in air case, dotted line in KRS-5 prism case, dash-dot line in ZnSe prism case and dashed line in Si prism case

In the air, the SPR is excited at the photon energy of 0.083 eV for Bi_2Se_3; by selecting a prism, it is possible to tune the SPR excitation energy. Thus, in a KRS-5 and ZnSe medium, it will be possible to excite an SPR at a photon energy of 0.075 eV, and in a Si medium at the photon energy of 0.067 eV. Similarly, for Sb2Te3 due to the external environment, it is possible to tune the SPR. In the air an SPR is excited at the photon energy of 0.130eV, in a KRS-5 and ZnSe medium, 0.123eV, and in the Si medium, the SPR is excited at the photon energy of 0.110eV. There is a sensitive shift in SPR energies for different prism materials A device based on the SPR will have the best qualities if the shift of its resonant wavelength $\delta\lambda_{SPR}$ is significant relative to the change in the refractive index of the external medium δn_m. This property is called sensitivity and is defined as [8]

$$S = \frac{\delta\lambda_{SPR}}{\delta n_m}$$

For the most widely investigated material like gold, the sensitivity is 0.82 μm/RIU (refractive index unit). Table.1 shows the sensitivity values for Bi_2Se_3 and Sb_2Te_3. The sensitivity for Bi_2Se_3 is highest, and for Sb_2Te_3 it is comparable with the sensitivity of the gold. Fig. 3 shows graphs of the plasmon polariton (PP) propagation length. As can be seen, the plasmon propagation length at resonance frequencies is 0. An increase in the dielectric constant of the environment leads to a significant reduction in the PP propagation length for both the VPP and the SPP.

Table 1.

Resonant wavelength SPP and Sensitivity

Compound	λ_1 Mm	λ_2 µm	λ_3 Mm	$\delta\lambda_2$ Mm	$\delta\lambda_2$ µm	S_2 µm/RIU	S_3 µm/RIU
Bi_2Se_3	14.9	16.5	18.5	1.6	3.6	1.17	1.55
Sb_2Te_3	9.5	10.0	11.3	0.5	1.8	0.40	0.75

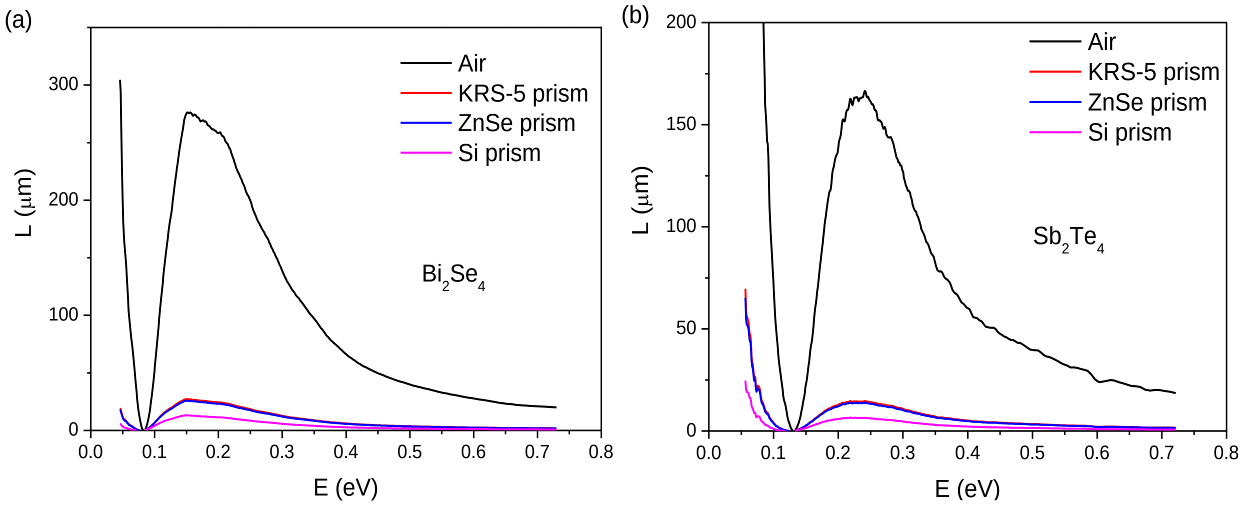

Fig. 3. PP Propagation length (a) Bi_2Se_3 and (b) Sb_2Te_3.

5. CONCLUSION

The possibility of exciting and controlling the plasmon resonance energy in the Bi_2Se_3 and Sb_2Te_3 structures has been shown for the first time. The presented compounds Bi_2Se_3 and Sb_2Te_3 are promising for use as plasmonic materials in the IR spectrum. The PP dispersion calculated in this paper showed the possibility for tuning of plasmon coupling in a wide range of the photon energy spectrum. The sensitivity of the plasmons in Bi_2Se_3 and Sb_2Te_3 is comparable to the sensitivity of the plasmons in gold. For some cases in Bi_2Se_3 the sensitivity is 89% and this is higher than that in gold. The calculated plasmon propagation length significantly exceeds the analogous data for gold.

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