Propagation of surface plasmon polaritons at the interface of metal-free metamaterial with anisotropic semiconductor inclusions

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Herein, we deal with the propagation of surface plasmon polaritons at the interface of metal-free metamaterial with anisotropic inclusions. The anisotropy effect of conventional and well-known nanostructured metamaterial combined of alternating layers is enhanced by employing anisotropic semiconductor sheets into the structure. The former provides a fertile ground for a wide range of tunability features with no needs of changing the geometry of the structure. Moreover, the current approach stands for as a perfect tool aiming to control propagation length of surface plasmon polaritons.

Introduction

Metamaterials are regarded as the artificial electromagnetic multi- functional materials constructed aiming to comply with the specified conditions going beyond the characteristics of natural media [1]. Surface plasmon polaritons (SPPs) [2] are the optical resonant modes comprised of a decaying evanescent wave that couples to the oscillating wave of free electrons at the surface of a conductor. Usage of metamaterials can lead to a strong localization and enhancement of fields. In this relation, one may use them to enhance the sensor selectivity of detecting nonlinear substances and to allow for a detection of extremely small amounts of analytes [3]. Doing so, a wide range of novel or advanced applications of metamaterials has been suggested. For instance, replacement of metal inclusions by metamaterials in surface plasmon resonance sensors was suggested to improve the sensing operation [4], and employing metamaterials as high frequency sensors was also studied [5].

While the dielectric-based optics does not provide the background for the realization of nanoscaled optical devices [6], metal-based surface plasmon polariton seemingly does. SPP optical waves on a metal-dielectric interface can be confined much below the optical wavelength,[7] and even offer a way to overcome the diffraction limit [8]. Propagation of SPPs at the boundary of anisotropic materials has been extensively covered so far [9]. It has been concluded, that tunability properties are possible due to the geometrical changes of the inclusions comprising metamaterials under study [10, 11]. An ad-hoc neural network topology assisting the study of the said propagation when several parameters, such as wavelengths, propagation length and metal thickness are considered [12]. Another way to achieve tunability is to include graphene layers [13, 14] into nanostructure under investigation. It is impossible to generate SPPs at frequencies in the mid-infrared to terahertz range employing conventional plasmonic materials such as noble metals. However, application of the graphene material allows to overcome the challenge. It should be mentioned, that lifetime and confinement volume of such SPPs are much longer and smaller, respectively, than those in metals. In the light of the above stated, graphene plasmonics has potential applications in novel plasmonic sensors. Doing so, various concepts have been proposed. However, the former results in a list of challenges including graphene cost.

In this paper we propose and explore the concepts of metal-free metamaterial for SPP guiding and manipulation in the optical regime based on low dimensionality anisotropic semiconductor layered systems. The realization of plasmonics employing semiconductor may revolutionize this field by allowing high level integration and mainly the realization of dynamic plasmonic elements and possible plasmonic amplification by carrier injection. In this paper, we have presented a theoretical study on enhancing the multilayer metamaterial structure by embedding anisotropic semiconductor inclusions. Aiming to achieve the optical responses, we have developed a novel dispersion relation that was obtained based on the Maxwell-Garnett effective medium theory for anisotropic composites. The effects of applied magnetic field strength and ambient temperature have been studied.

Theoretical background

For a magnetic field applied along the *z*-axis which is normal to the sample surface, the components of the dielectric tensor element characterized by the Drude model as below [15]:

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_b \left(1 - \frac{\omega_p^2 \left(\omega^2 + i\gamma\omega \right)}{\left(\omega^2 + i\gamma\omega \right)^2 - \omega^2 \omega_c^2} \right) \tag{1}$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = \frac{i\varepsilon_b \omega_p^2 \omega\omega_c}{\left(\omega^2 + i\gamma\omega \right)^2 - \omega^2 \omega_c^2}, \tag{2}$$

ε_b is the background high-frequency dielectric constant, $\omega_p = \sqrt{Ne^2 / \varepsilon_b \varepsilon_0 m^*}$ is the plasma frequency, *N* and *m** are the carrier density and effective mass, respectively. $\omega_c = eB / m^*$ is the cyclotron frequency, and γ is the damping constant.

Parameters of InAs are ε_b=16.3, $m^* = 0.026 m_e$, γ=4.7 THz, $N = 5.76 \times 10^{14} T^{1.5} e^{\left(-0.26/2 \times 8.625 \times 10^{-5} T \right)}$ cm^{-3}.

Tunable metamaterial made of semiconductor-dielectric multilayers

Herein we will consider a semiconductor based metamaterial heterostructure consisting of stacked anisotropic semiconductor sheets separated by dielectric layers, as demonstrated schematically in Fig. 1.

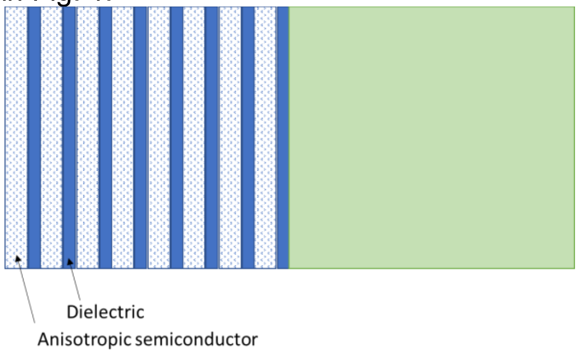


Fig. 1. Schematic view of an interface separating an infinite layered nanostructured metamaterial formed by alternating semiconductor (InAs) and dielectric layers and air. The SiC is a dielectric and non-absorbing layer with ε_{SiC}=4.4.

To describe the optical response of such a system, we apply the effective-medium approach [16] which is justified if the wavelength of the radiation considered is much larger than the thickness of any layer. It is based on averaging the structure parameters. Hence, further in this paper we consider the effective homogeneous media for the semi-infinite periodic structure. The effective permittivities of the nanostructured metamaterial comprised of alternating semiconductor and dielectric layers are as follows [17]:

$$\varepsilon_{\parallel} = \frac{\varepsilon_{xx} d_{InAs} + \varepsilon_{SiC} d_{SiC}}{d_{InAs} + d_{SiC}} \tag{3}$$

$$\varepsilon_{\perp} = \frac{\varepsilon_{xy} \varepsilon_{SiC} \left(d_{InAs} + d_{SiC} \right)}{\varepsilon_{xy} d_{SiC} + \varepsilon_{SiC} d_{InAs}}, \tag{4}$$

Matching the tangential components of the electrical and magnetic fields at the interface implies the dispersion relation for the surface modes localized at the boundary separating two anisotropic media.

We assume the permittivities $\varepsilon_{xx,xy}(\omega)$ to be frequency dependent as the corresponding layers are represented by semiconductor.

It should be mentioned, that the frequency range of the surface wave existence could be dramatically controlled by modifying the permittivities and thicknesses of the layers [18] employed in the metamaterial. One needs to evaluate the tangential components of the electric and magnetic fields at the interface and obtain a single surface mode with the propagation constant seeking to get the unique dispersion relation for the surface modes confined at the interface between metamaterial and air [19].

$$\beta = k\sqrt{\frac{\left(1-\varepsilon_{\|}\right)\varepsilon_{\perp}}{1-\varepsilon_{\perp}\varepsilon_{\|}}}, \tag{5}$$

where k is the absolute value of wavevector in vacuum and β is the component of the wavevector parallel to the interface. By substituting (3), (4) in (5) we arrive at the dispersion relation aiming to characterize propagation of surface plasmons at the boundary of the semiconductor based metamaterial:

$$\beta = k\sqrt{\frac{\varepsilon_{SiC}\varepsilon_{xy}\left(d_{InAs}+d_{SiC}-d_{SiC}\varepsilon_{SiC}-d_{InAs}\varepsilon_{xx}\right)}{d_{InAs}\varepsilon_{SiC}+d_{SiC}\varepsilon_{xy}-d_{SiC}\varepsilon_{SiC}^{2}\varepsilon_{xy}-d_{InAs}\varepsilon_{SiC}\varepsilon_{xx}\varepsilon_{xy}}} \tag{6}$$

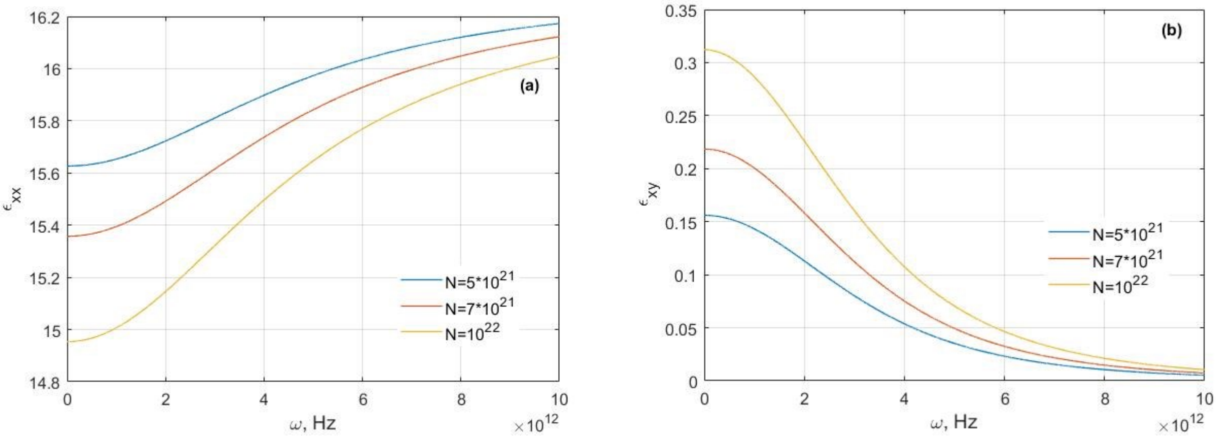
By taking d_1 out of the brackets, we arrive at the equation as follows:

$$\beta = k\sqrt{\frac{\varepsilon_{SiC}\varepsilon_{xy}\left(1+d_{SiC}/d_{InAs}-\left(d_{SiC}/d_{InAs}\right)\cdot\varepsilon_{SiC}-\varepsilon_{xx}\right)}{\varepsilon_{SiC}+\left(d_{SiC}/d_{InAs}\right)\cdot\varepsilon_{xy}-\left(d_{SiC}/d_{InAs}\right)\cdot\varepsilon_{SiC}^{2}\varepsilon_{xy}-\varepsilon_{SiC}\varepsilon_{xx}\varepsilon_{xy}}} \tag{7}$$

It can be concluded from Eq. (7), that dispersion maps of SPPs are not affected by the geometry of the structure. Ratio $d_{\mathrm{SiC}}/d_{\mathrm{InAs}}$ is making an impact only.

Results and discussion

Dependencies of the anisotropic semiconductor dielectric tensor real components upon frequency are presented in Fig. 2. Imaginary dielectric tensor components are shown in Fig. 3. It should be mentioned, that Im(ε_{xx}) is positive at the investigated frequency range, Im(ε_{xy}) is hegative. The tunability of the components by means of engineering concentration is depicted in Figs. 2(a), (b). The way of modifying properties by means of magnetic field is considered in Figs. 2(c), (d). As Figs. 2(a)-(d) demonstrate, the real $\varepsilon_{xx,xy}(\omega)$ parts are positive over the whole frequency range. ε_{xx} smoothly increases with the increase of frequency, ε_{xy} decreases. As the Fig. 2(a) illustrates, there is clear difference between ε_{xx} values at low frequencies, however, at high frequencies impact of the concentration becomes less observable. Dramatic impact of magnetic field is clearly shown in Fig.2(d) at low frequency range, with the increase of frequencies the impact becomes less significant.



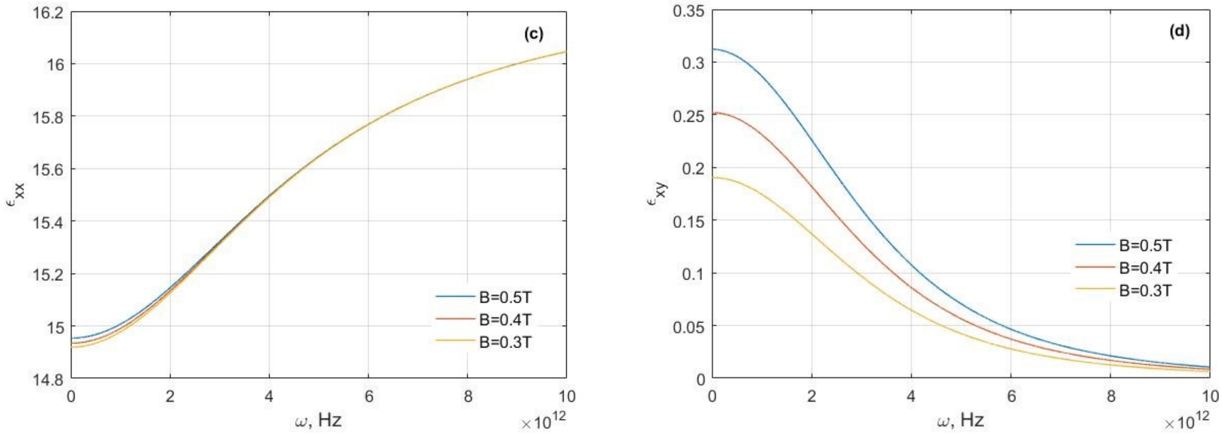


Fig. 2. Dependences of the anisotropic semiconductor dielectric tensor real components upon frequency. B=0.5T in (a), (b); N=10^{22}m^{-3} in (c), (d).

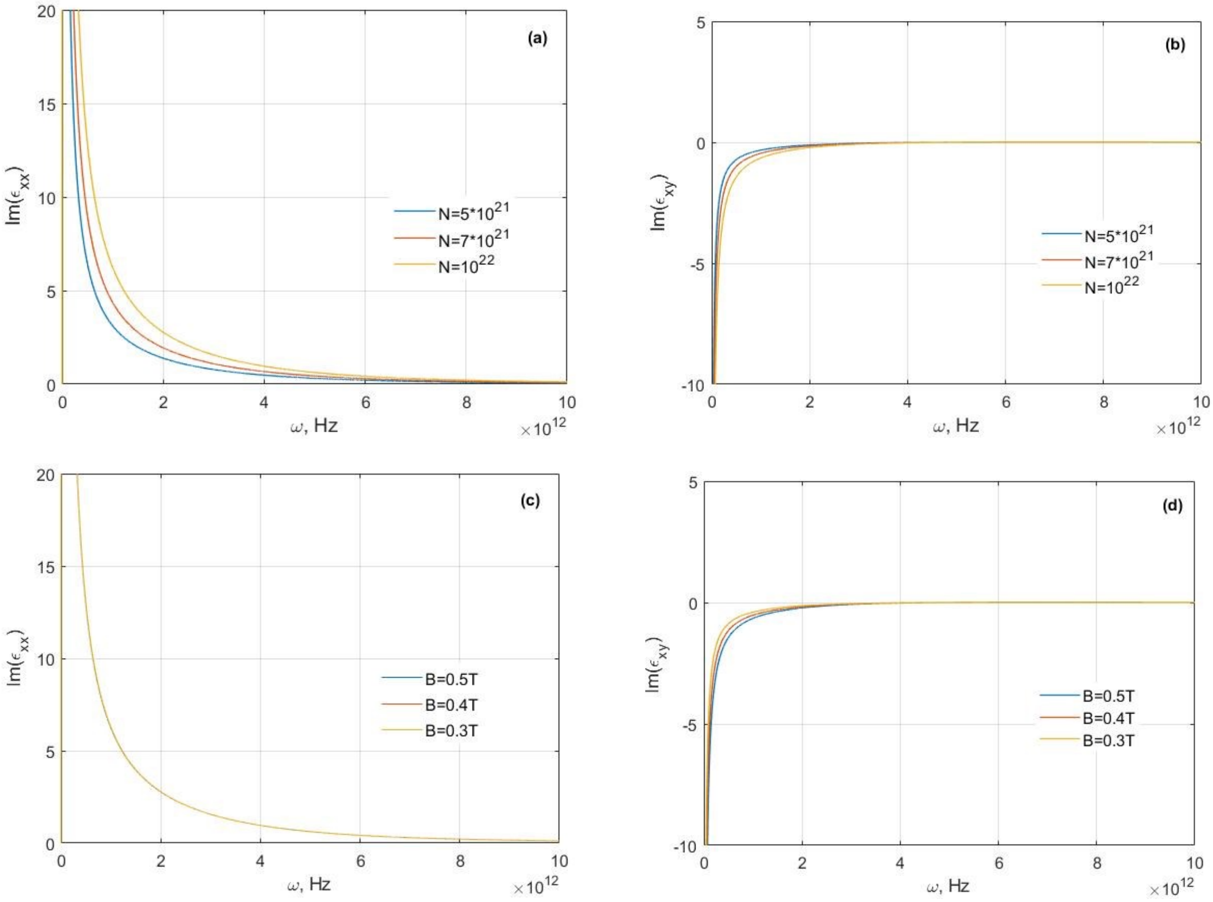


Fig. 3. Dependences of the anisotropic semiconductor dielectric tensor imaginary components upon frequency. B=0.5T in (a), (b); N=10^{22}m^{-3} in (c), (d).

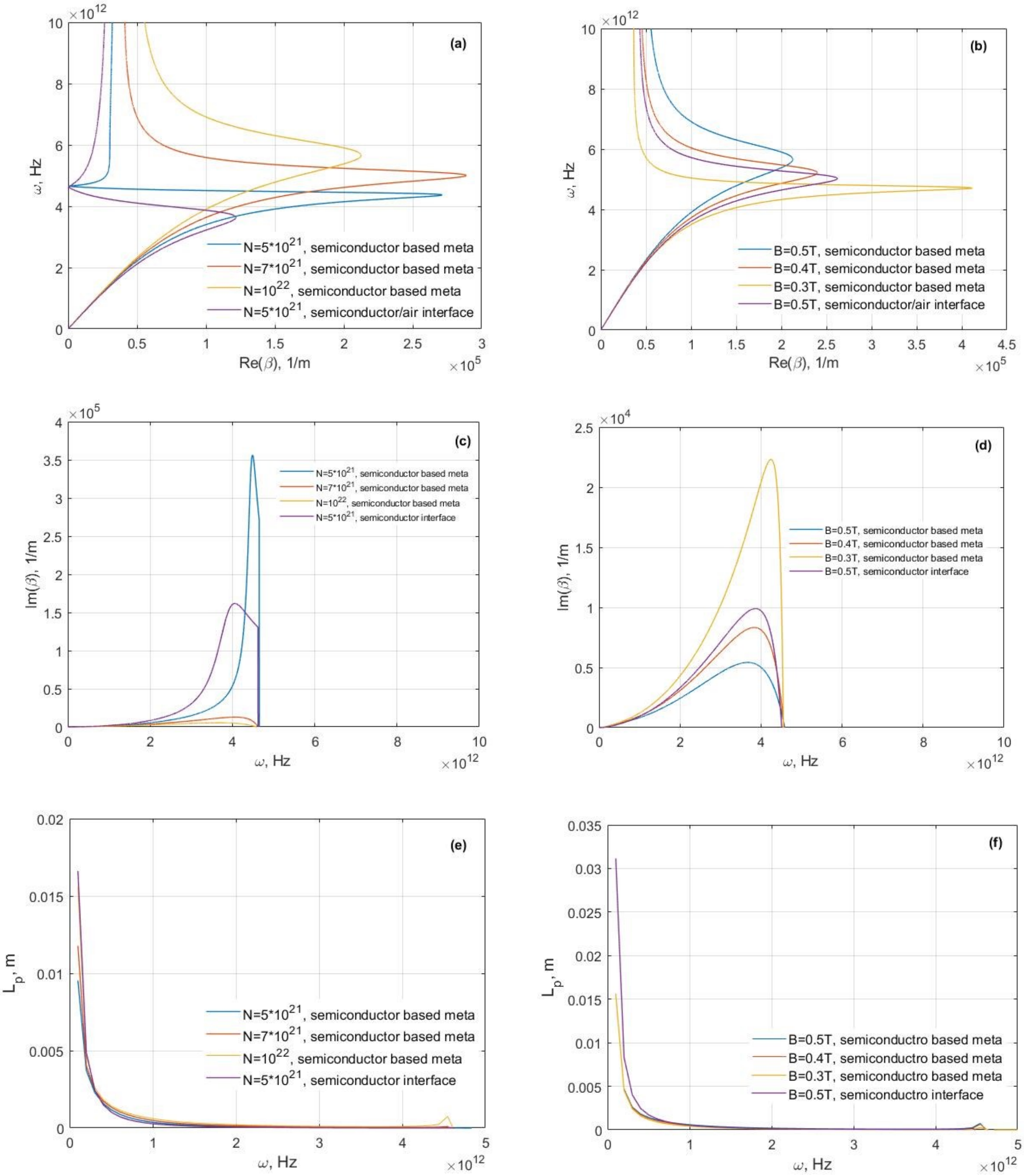


Fig. 4. Real (a, b), imaginary (c, d) dispersion and propagation length (e, f) of the surface plasmon at the interface between anisotropic semiconductor based metamaterial and air: concentration tunable surface plasmon (a), magnetic field tunable surface plasmon (b). B=0.5T in (a), (c), (e); $N=10^{22}m^{-3}$ in (b), (d), (f).

The surface plasmon dispersion calculated according to Eq. (5) presented in “Theoretical background” is shown in Fig. 4. For comparison, the dispersion of a simple surface plasmon at the interface between anisotropic semiconductor and air is also shown. It is worthwhile mentioning that usage of anisotropic semiconductor allows for a wide spectrum of fascinating features. Tunability in this case is achieved by changing the parameters of the semiconductor with no need of the geometrical modifications of the structure. The former provides a fertile ground for a variety of challenging applications, including beam steering with the semiconductor based hyperprism. One may tune propagation length of surface plasmons by modifying either concentration or magnetic field as shown in Fig. 4. It should be mentioned that negative values of electrical length and absorption in Figs. 4(c)-(f) which result from non-physical solutions of the dispersion equation have been omitted in line with [20]. Taking advantage of the absorption resonances (Figs. 4(c), (d)), one can show that the simple multilayer structure without possessing any periodic corrugations have the prospective to act as directive monochromatic thermal sources [21].

It can be observed from Fig. 2(a) that ε_{xx} increases at the higher frequency ranges making an impact at dispersion of SPPs maps (Fig. 4(a)). The highest plasma frequency corresponds to the case of N=10^{22} m^{-3} and to the lowest values of ε_{xx} (Fig. 2(a)). It is shown in Fig. 4(a) that the highest plasma frequency corresponds to the case of B=0.5T. The highest values of ε_{xy} are achieved in this case as well as it is depicted in Fig. 2(d).

Conclusions

Inclusion of the anisotropic semiconductor layer between dielectric sheets aiming to construct hyperbolic metamaterial has been studied. We have developed a method to consider optical response of the geometry under consideration. We have obtained surface plasmon polariton maps. The tunability possibilities including variation of concentration and magnetic field have been considered.

The effects of applied magnetic field strength have been investigated. The results have demonstrated that by increasing the magnetic field the plasma frequency of surface waves moves to the higher frequency range.

Finally, we have studied impact of the semiconductor concentration at the surface plasmon polariton maps. The results have demonstrated increase of the asymptotic frequency if increasing the concentration.

It is worthwhile mentioning that usage of anisotropic semiconductor allows for a wide spectrum of fascinating features. Tunability in this case is achieved by changing the parameters of the semiconductor with no need of the geometrical modifications of the structure. The former provides a fertile ground for a variety of challenging applications, including beam steering with the semiconductor based hyperprism.

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