International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Research Article)

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The impact of magnetic field on the surface of carbon-insulator-GaAs Semiconductors which is tunable with a frequency range in the presence of surface magneto Plasmon

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International Journal of Science and Research Archive, 2022, 07(02), 306–311

Publication history: Received on 16 October 2022; revised on 28 November 2022; accepted on 01 December 2022

Article DOI: https://doi.org/10.30574/ijsra.2022.7.2.0279

Abstract

In this paper, group velocity and frequency wave can be tuned with an applied external magnetic field when we increase the magnetic field from 0-4 tesla the frequency range can be reduced for given semiconductor materials. The excitation of the two layers of semiconducting material propagating band structures can be explained by the oscillations of electrons in semiconductors on applying the magnetic field, we study the effects of an external magnetic field in the band structure of C-insulator-GaAs materials in presence of surface magneto plasmons concerning plasma frequency below and above the surface band structures. The surface magneto plasmon bands get excited and show the dispersion relation with frequency range. The higher dispersion band moves in faster than the lower dispersion band structure of semiconducting material. The most energy is stored in a lower surface of magneto plasmon. When we increase the magnetic field, the surface of the semiconductor moves opposite to the lower surface of the semiconductor material. Here, we use semiconducting materials instead of metals because metal cannot support a wide frequency range on the magneto-plasmonic surface providing a good tunning property and more flexibility in this mechanism, which is widely useful in telecommunications, magneto-plasmonic devices, and data processing unit. This study is widely more promising due to its wavelength confinements of electromagnetic fields on semiconducting and insulating layers. Due to nonreciprocal effects, the dispersion of frequency waves varies with different band structures and group velocity also varies with two propagating directions among semiconductor-insulator-semiconductor layers.

Keywords: Surface magneto Plasmon; Group velocity; Semiconducting materials; Plasmonic devices

1. Introduction

1.1. Light-matter interaction

The interaction of lights with matter i.e., light-matter interaction derives from many devices such as Quantum devices, solar cells, and LEDs. The emission and absorption of light on the surface of matter take a timescale of attoseconds to picoseconds, using a tunneling microscope (STM) can be studied light-matter interaction. When Electromagnetic radiation interacts with matter surface leads to excitations such as magneto plasmons, collective oscillations, excitons, and electronic transitions [1]. When light interacts with the surface of the matter it causes oscillations matter emits light that interferes with the incident light. We know that different materials respond to light in different manners because of the different shapes, sizes, and chemical compositions of materials. Here we will study C-insulator-GaAs materials in presence of surface magneto plasmons. Light exerts a force on electrons and these moving electrons produce a field on the surface of the materials that must be included in modifies wave equation. In an insulator, each electron is bound to its atoms while in a semiconductor the mobility of electrons is higher because of their different band structures and scattering properties [2].

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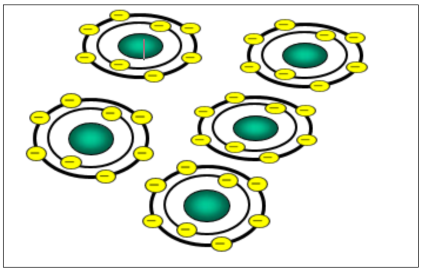

Figure 1(a) an Insulator

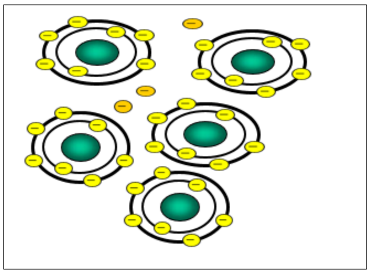

Figure 1(b) Semiconductor

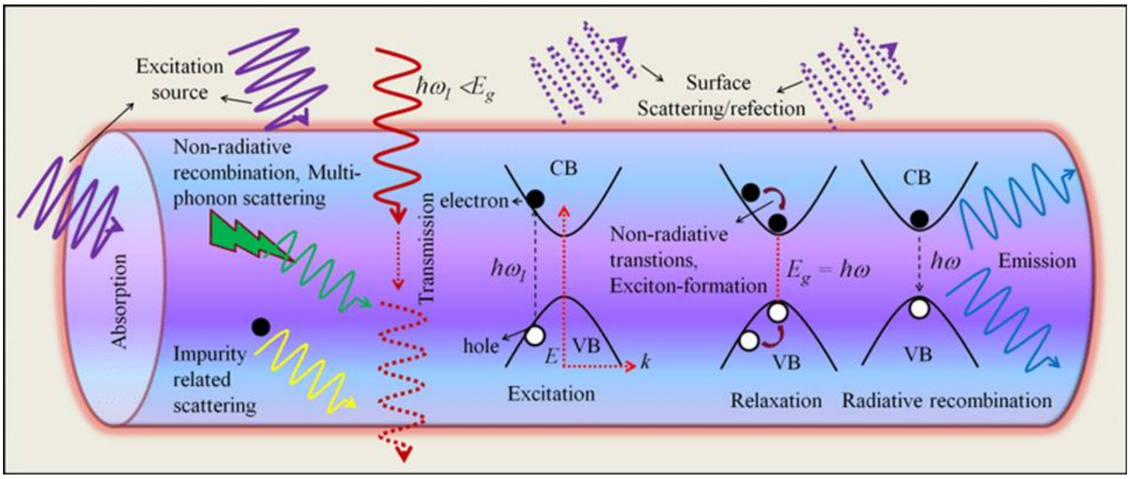

Figure 2 The light-matter interaction for the semiconductor material [2]

Light-matter interaction technique is widely useful in the enhancement of a strong magnetic field, compact photonic circuitry, sensing, and spatial localization.

1.2. Surface Magneto Plasmon's

Surface Magneto Plasmon is a process when in which electromagnetic waves are confined on and propagate along the surfaces of conductors, semiconductors, or metals in the presence of a magnetic field. Magneto plasmons are caused due to free electron oscillations in semiconductors, conductors, or metals with incident electromagnetic waves. During this process, two kinds of frequencies occur at these surfaces, Plasma frequency, and cyclotron frequency [3]. Plasma frequency depends on the free electron motions due to the presence of an external magnetic field. We can change the motion of charge carriers due to Lorentz force in this condition cyclotron frequency occur which is a function of the effective mass of the charge carriers and the applied magnetic field.

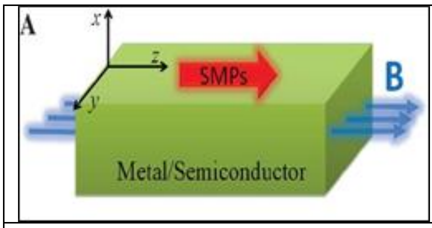

Figure 3(a)

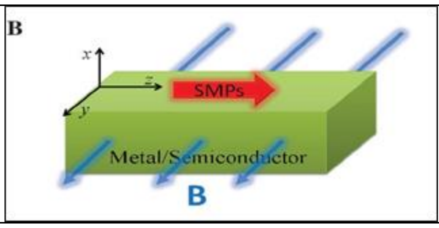

Figure 3(b)

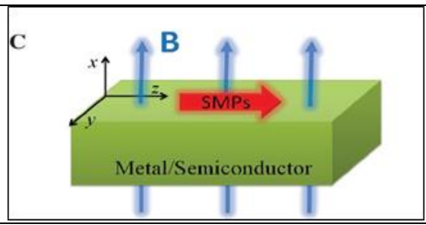

Figure 3(c)

Figure 3 (a) The magnetic field is parallel to the surface of the semiconductor and the surface wave. 3(b)The magnetic field is to the surface and perpendicular to the surface wave and 3(c) Surface magneto plasmon propagates perpendicular to the semiconductor surface in which the magnetic field is perpendicular to both surface and surface wave [11]

The above figures define surface magneto plasmons propagating in different structures.

The surface magneto plasmons have great interest in the field of plasmonic nanotechnology due to an externally applied magnetic field the surface magneto plasmon has great properties in non-reciprocal effect and multiband propagation.

2. Material and methods

The Maxwell's Equations in a Medium

$$\nabla \cdot E = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$\nabla \times E = -\,\partial B/\,\partial t \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$\nabla \cdot B = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

$$\nabla \times B = \mu_0 \varepsilon_0 \partial E/\partial t + \mu_0\, \partial P/\partial t \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where P is induced polarization is the response of the atoms to the applied field.

$$P(t) = Nex_e(t)$$

N is the number of electrons oscillating in response to Electric and magnetic fields.

The semiconductor(C)-insulator-semiconductor (GaAs) structure and dispersion relation of the surface magneto plasmon. When an external magnetic field is B is applied on the surface of a semiconductor-insulator-semiconductor along the y-axis in Voigt configuration. In the presence of a magnetic field on surfaces, the dielectric constant of the semiconductor in Voigt configuration is given below [4].

$$\varepsilon_s = \varepsilon_\infty\, [\,\varepsilon xx\ 0\ \varepsilon_{xz}]\ (5)$$

$$0\ \varepsilon_{by}\ 0$$

$$-\varepsilon_{xz}\ 0\ \varepsilon_{xx}$$

In the given expression we have parameters in equation (5)

$$\varepsilon_{xx} = 1 - \omega_P^2 / (\omega^2 - \omega_c^2),$$

$$\varepsilon_{yy} = 1 - \omega_P^2 / \omega^2$$

$$\varepsilon_{xz} = -i\, \omega_P^2\, \omega_c \,/\, [\omega\, (\omega^2 - \omega_c^2)]$$

$$\omega_c = eB/\, m^*$$

$$\omega_p = [ne^2 \,/\, \varepsilon_0\,]^{1/2} \text{ and}$$

$$\omega = ck/\, (\varepsilon_\infty\,)^{1/2}$$

Where;
ω_p is plasma frequency,
ω_c is cyclotron frequency,
ω is the angular frequency,
ε_∞ is the permittivity of high frequency,
B is applied Magnetic field with surface mode and continuity of E_z and H_y at interfaces of semiconductor-insulator-semiconductor,
e charges, and
m^* is the effective mass of electrons.

We can express the lower and higher frequency modes of C and GaAs surface by using equation (5), we have

$$B = \pm m^*/e\,[(\omega_P^2\, \varepsilon_\infty / \omega\, (\varepsilon_d + \varepsilon_\infty)) - \omega] \;\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

From the above equation, we evaluate the surface plasma frequency for C and GaAs semiconductors at different values of an applied magnetic field. i.e., (B= 0T, 1T, 2T, 3T, and 4T)

$$\omega_{sp} = \pm\, \omega \sqrt{(1 + \varepsilon_d / \varepsilon_\infty)} \;\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Here, at + surface plasma frequency is greater than the angular frequency, and at – angular frequency is greater than the surface plasma frequency.

The Dielectric constant of the insulator layer is evaluated with the help of the waveguide dispersion relation given [5].

$$\tanh(wk1)\,[\,1 + (\varepsilon_d/\varepsilon_v)^2 k_2{}^2/k_1{}^2 + (\varepsilon_d/\varepsilon_v)^2\, (\varepsilon_{xz}/\varepsilon_{xx})^2 \beta^2/k_1] + 2\, \varepsilon_d/\varepsilon_v\, k_2/k_1 = 0 \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where;
β is the propagation constant and
ε_d is the dielectric constant of the insulator layer and
ε_v is the Voigt constant of the semiconductor if the polarization of the electromagnetic wave is along the z or x direction then it is considered as permittivity of the semiconductors.

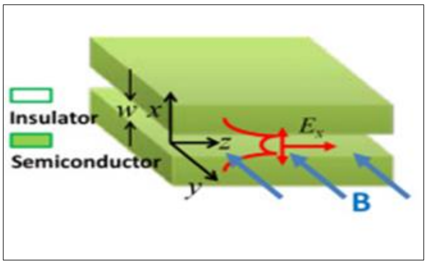

Figure 4 The schematic structure of semiconductor (C)-Insulator-semiconductor (GaAs) materials which show that the magnetic field is applied perpendicular to the direction of THz waves. B is the applied magnetic field, and w is the width of a waveguide [7]

2.1. Group Velocity

Group velocity is the transmission velocity of the wave packet, given as [6].

$$V_g = d\omega/dK \text{ or grad } \omega(K) \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$V_g = \nabla_k\, \omega \;\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Where;
K is the angular wavenumber (radians per meter), and
ω is the angular wave frequency (radians per second).

Here, the gradient $\omega(k)$ function is known as the dispersion relation of propagating waves along the surface of the semiconductor materials which gives ω as a function of K. If the wavenumber is directly proportional to angular wave frequency, then V_g is exactly to phase velocity. The group velocity is not the same in both semiconductor materials, the Carbon material has a greater group velocity than GaAs. When waves propagate through the surface of C and GaAs semiconductor materials then group velocity at various frequency ranges points toward different directions [8].

In this paper, we choose Carbon and GaAs as semiconductor materials. The parameters of these materials are given by

Table 1 Parameters of Carbon and GaAs semiconductors

Name of semiconductor	C	GaAs
m*	0.017	0.067
Ɛ∞	5.5	10.9
Ɛ0	5.5	13.13
ωp	13.56MHz or 0.1356GHz	250GHz
B	0-4T	0-4T
f	3THz	3THz
Ɛxx	-99.9	-57.34
Ɛyy	-99.9	57.34
Ɛxz	0	0

3. Results and discussion

In the high-frequency range, we have the option to replace highly doped semiconductors with metal that possesses lower incident wave frequencies and lower plasma frequency due to which we require a low magnetic field and it is very useful in making tunable devices based on surface magneto plasmon, while in low-frequency range it demands extremely strong magnetic field for fabrication of metallic plasmonic devices [9]. When applied magnetic field is increased from a lower to a higher value i.e., 0Tesla- 4Tesla, then surface magneto plasmon bands get excited, and surface magneto plasmons can propagate at cyclotron plasma frequency which is higher than the surface plasma frequency at higher bands. With an increment of the magnitude of the applied magnetic field, the Carbon semiconducting layer and GaAs semiconducting layer start to move faster but in the opposite direction while the frequency changes from a higher to a lower range. The dispersion curve of C semiconducting material shows a higher band than the GaAs dispersion curve. When an external magnetic field is applied from 0T to 2.5T then we can achieve group velocity up to $10^{-6}c$ for both semiconducting layers above and below the surface magneto plasmon as we increase the magnitude of the magnetic field from 2.5T to 4T then the group velocity starts to decay [10], as it shows value $< 10^{-6}c$ for GaAs semiconducting layer which is below the Carbon, and corresponding frequency range is also decreases from 3THz to 1THz.

4. Conclusion

We can study atomic defects, quantum dots, nanostructures, and single atoms on surfaces using this technique. The light-matter interaction can be used to study the various properties such as light emission of single or double-layer molecules and electron spin resonance, molecular vibrations, and spatial resolution in photonics. It yields results about frequency dependence, resonant behavior, and optical response of matter. This study is widely more promising due to its wavelength confinements of electromagnetic fields on semiconducting and insulating layers. Due to nonreciprocal effects, the dispersion of frequency waves varies with different band structures and group velocity also varies with two propagating directions between semiconductor-insulator-semiconductor layers. This mechanism is useful in magneto plasmonic devices, data processing, biosensing, and telecommunication. Apart from this there are some drawbacks during in-device fabrication losses are high that's why we choose Carbon and Sic as semiconductors because they show great potential in magnetic plasmonic devices.

Compliance with ethical standards

Acknowledgments

The author would like to thank my Supervisor, DayaShanker who support me in this research.

Disclosure of conflict of interest

The authors declare no conflict of interest.

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