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BEHAVIOUR OF SURFACE PLASMONS ON THE SURFACE OF C, SiC, AgCl, NaCl, KCl, InSb, GaAs IN NON-DISPERSIVE MEDIUM

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Abstract: The possibility of interaction of surface optical phono at different material surfaces has been discussed with the help of its dielectric functions in a non-dispersive dielectric medium. This study has been discussed for the study of the frequency of surface optical phonon coupled oscillations at the surface of different nanomaterials and this theory is applied to obtain the dispersion relation for semi-infinite single plane boundary [1]. A surface optical phonon mode can exist at the interface between the nanostructure and the surrounding medium, which is of primary interest in this work. The optical mode is dominated by oscillations from atoms at the surface of semiconducting materials. We use theoretical methods for calculating the surface optical phonon frequency curves concerning mediums. The existence of waves of different materials at the nanoscale range has been observed in non-dispersive mediums (Air) using the Hydrodynamical model.

Keywords: Optical phonon, Plasma frequency, Hydrodynamical model, and non-dispersive medium.

Introduction:

In recent years theoretical studies of surface vibrations, phonons, and plasmons in solids have attracted the attention of several researchers in this field of surface excitations depending essentially on the geometry of the surface. Their dispersion relations have been studied in different geometrical shapes in plane bounded surfaces, thin films, spheres, cylinders, etc. by using various methods, such as the hydrodynamical method [2]. When semiconducting materials are made in the nano range, they enhanced optical properties against their bulk medium due to their quantized size and increased surface-to-volume ratio. Surface Phonon is a collective excitation in atomic arrangements in condensed matter physics in solids and liquids as a quasiparticle [3]. The concept of phonons was introduced in 1932 by Soviet physicist Igor Tamm. Phonon is quantum elementary vibrational motion in atomic arrangements which uniformly oscillates at a single frequency [4]. Here we have been discussing optical phonons at the surface of various semiconducting nanomaterials. In surface optical phonons the movements of atoms in periodic arrangements are out-of-phase. Some ionic crystals are known as optical because fluctuations create an electrical polarization in the electromagnetic field [4]. The recent work demonstrated that when an optical phonon contains nanoscale semiconducting materials the excitation of these leads to the formation of dispersion of lattice [5]. Nanophotonic concepts are of particular interest in the mid-to-far infrared (3–100μmm), where technologies are less mature, operate below theoretical efficiency limits [6], and the mismatch between photon wavelength and electronic degrees of freedom results in naturally weaker light-matter interaction.[7] The appearance of surface optical Phono modes of nanostructure was predicted theoretically and detected experimentally in a few papers [8]. We choose the nano range because these particle ranges have a large surface-to-volume ratio, with the help of this we can determine the properties of materials, when we reduce the dimensions to extremely small the surface modes can exist [9]. In most cases, optical modes in most of the nano range materials are due to the discontinuity in the transition symmetry on the surface. In long-wavelength optical phonon modes are not observed experimentally [10].

Theoretical Explanation

We know that surface plasmon and surface optical phonons interact with each other in polar semiconductors if their frequencies are of the same order. To study the coupling of surface optical phonons at the surface of semiconducting nanomaterials we must know the dispersion relation which can be obtained by various methods. Here we are using the plane bounded surface method.

First, we calculate the wave frequency for a plane semi-infinite ionic compound bounded by a dielectric medium of constant ε_2 with the help of its dispersion relations. Let the surface be defined by Z=0 to plane ionic compound occupies the space Z>0 whereas the space Z<0 is occupied by the dielectric because in absence of any external field the electric field arises only due to polarization charges and by symmetry it has the same magnitude but opposite direction at the two sides at the interface. When we apply the condition of electric displacement at the interface is given as

$$D_{Z1} = D_{Z2} \quad \text{at} \quad Z=0$$

Or

$$\varepsilon_L(\omega)E_{Z1}|_{Z=o} = \varepsilon_2 E_{Z2}|_{Z=0} \quad (1)$$

We obtain

$$\varepsilon_L(\omega) = -\varepsilon_2 \quad (2)$$

$$\varepsilon_L(\omega) = \varepsilon\infty \ \omega^2 - \varepsilon_0 \omega_t^2 / \omega^2 - \omega_t^2 \quad (3)$$

Where

$$\omega_t^2 = (\varepsilon\infty + 2/\varepsilon_0 + 2)\,\omega^{-2} \quad (4)$$

'ω_t 'is transverse optical phonon frequency

Equation (2) is the dispersion relation for surface optical phonons. It shows that the dielectric function of one medium must be negative at the frequency (ω) of the surface wave. The negative value of the dielectric constant shows the medium is active and the other value of the dielectric constant is positive which means the medium is inactive and does not interact with the surface of semiconducting materials.

The frequency of surface modes is determined by the substituting value of $\varepsilon_L(\omega)$ from equation (3) which is shown below

$$\omega^2_{SOP} = (\varepsilon_0 + \varepsilon_2/\varepsilon_\infty + \varepsilon_2)\,\omega_t^2 \quad (5)$$

It clears the frequencies depending on the properties of the surrounding medium i.e., they vary with the dielectric medium.

i.e.,

$$n_0(r^-) = 0$$

and

$$n_1(r^-, t) = 0 \quad (6)$$

for Z < 0 means non dispersive medium

since the subscripts '1' and '2' is used for semiconducting and for dielectric respectively. The medium '2' has been taken as non - dispersive, no free electrons are present in it for electrical conduction.

$$[(\varepsilon_L + \varepsilon_2)\,\omega^2 - \bar{\varepsilon}\,\omega_p^2]\,[\,(\omega_p^2 - \omega^2\,) + K^2\beta^2\,]^{½} = \varepsilon_2\;K\,\beta\,\omega_p^2 \qquad (7)$$

The above equation shows the dispersion relation for the surface mode. For semiconductors we know ε_L is background dielectric functions is frequency-dependent, therefore this equation gives two roots of ω on neglecting very small 'K β' this equation reduces to

$$(\varepsilon_L + \varepsilon_2)\,\omega^2 = \bar{\varepsilon}\,\omega_p^2$$

$$\omega^2 = \bar{\varepsilon}\,\omega_p^2/\,\varepsilon_L + \varepsilon_2 = \omega_P^2/\,\varepsilon_L + \varepsilon_2 \qquad (8)$$

This equation is derived by Chiu and Quinn [10] by solving Maxwell's equation. Now substituting the value of $\varepsilon_L(\omega)$ from equation (3) in equation (8).

$$[\,\varepsilon_\infty\;\omega^2 - \;\varepsilon_0\,\omega_t^2/\,\omega^2 - \omega_t^2\; + \varepsilon_2\,]\;\;\omega^2 = \omega_p^2$$

$$\varepsilon_\infty\,(\omega/\omega_t)^2 - \varepsilon_0 \;+\; \varepsilon_2\,(\omega/\omega_t)^2 - \varepsilon_2\,]\;\;(\omega/\omega_t)^2 = (\,\omega_p/\,\omega_t)^2[\,(\,\omega/\omega_t)^2 - 1]$$

$$(\varepsilon_\infty \;+\; \varepsilon_2)\,(\omega_p/\,\omega_t)^4 - [\,(\varepsilon_0 \;+\; \varepsilon_2\,) + (\,\omega_p/\,\omega_t)^2]\,(\omega/\omega_t)^2 \;+ (\,\omega_p/\,\omega_t)^2 = 0 \qquad (9)$$

This is a biquadratic equation in 'ω/ω_t' and it contains both optical phonon frequency (ω_t) and plasmon frequency (ω_p), hence there is the possibility of two modes between coupled surface modes for semiconductors and dielectric medium. We can also calculate the frequencies of uncoupled surface plasmons and surface optical phonons from equations (8) and (9) taking as an independent.

If we replace $\varepsilon_L(\omega)$ by $\bar{\varepsilon}$ we can get equation (8) as Plasma frequency

$$\omega_{SP} = \omega_p/\,(\,\bar{\varepsilon} + \varepsilon_2) \qquad (10)$$

If we assume ω_p to zero, the equation (9) will give surface optical phonon frequency as

$$\omega^2_{SOP} = (\varepsilon_0 \;+ \varepsilon_2/\,\varepsilon_\infty \;+ \varepsilon_2)\,\omega_t^2$$

$$\omega_{SOP} = [\,\varepsilon_0 \;+ \varepsilon_2/\,\varepsilon_\infty \;+ \varepsilon_2)\,\omega_t^2]^{1/2} \qquad (11)$$

now we will calculate the frequencies of surface optical phonons of various semiconducting materials with the help of equation (11)]

$$\omega_p/(\,\bar{\varepsilon} + \;\varepsilon_2)^{1/2} = [\,\varepsilon_0 \;+ \varepsilon_2/\,\varepsilon_\infty \;+ \varepsilon_2]^{1/2}\,\omega_t$$

$$\omega_p = [\,(\varepsilon_0 \;+ \varepsilon_2)/\,\varepsilon_\infty \;+ \varepsilon_2)\,((\,\bar{\varepsilon} \;+ \varepsilon_2)]^{1/2}\,\omega_t$$

Or,

$$\omega_p = [(\varepsilon_0 \;+ \varepsilon_2)/\,(\varepsilon_\infty + \varepsilon_2) * (\,\bar{\varepsilon} \;+ \varepsilon_2)/\;\bar{\varepsilon}\;]^{1/2}\,\omega_t \qquad (12)$$

From equation (7), we have

$$[(\varepsilon_2 + 1)\,\omega^2 - \omega_p^2]\,[\,(\omega_p^2 - \omega^2) + K^2\beta^2]^{½} = \varepsilon_2\ K\,\beta\,\omega_p^2$$

For ($\varepsilon_2 = 1$), we get

$$(2\,\omega^2 - \omega_p^2)\,[\,(\omega_p^2 - \omega^2) + K^2\beta^2]^{1/2} = K\,\beta\,\omega_p^2 \qquad (13)$$

It gives two solutions for angular frequency

This is the dispersion relation for semiconducting at a non-dispersive medium interface.

Table 1. Shows the values of surface optical phonon frequency and surface plasmon frequency of these materials on non-dispersive dielectric medium(Air) at different values of static dielectric constant and optical dielectric constant

Materials	Ɛ2	ωsop	ωp	ωSP
MgO	1	25.03134	13.50142	2.197465
C	1	64.88152	28.14242	4.411203
SiC	1	48.85122	18.83208	2.454215
Ge	1	23.40701	5.940506	1.250654
Si	1	35.39921	10.4641	1.596245
GaAs	1	19.23298	5.856454	1.315202
InSb	1	15.23369	3.877982	1.151012
NaCl	1	8.401197	5.159924	1.734509
AgCl	1	6.993962	3.315506	1.231854
KCl	1	8.803172	5.622924	1.953038

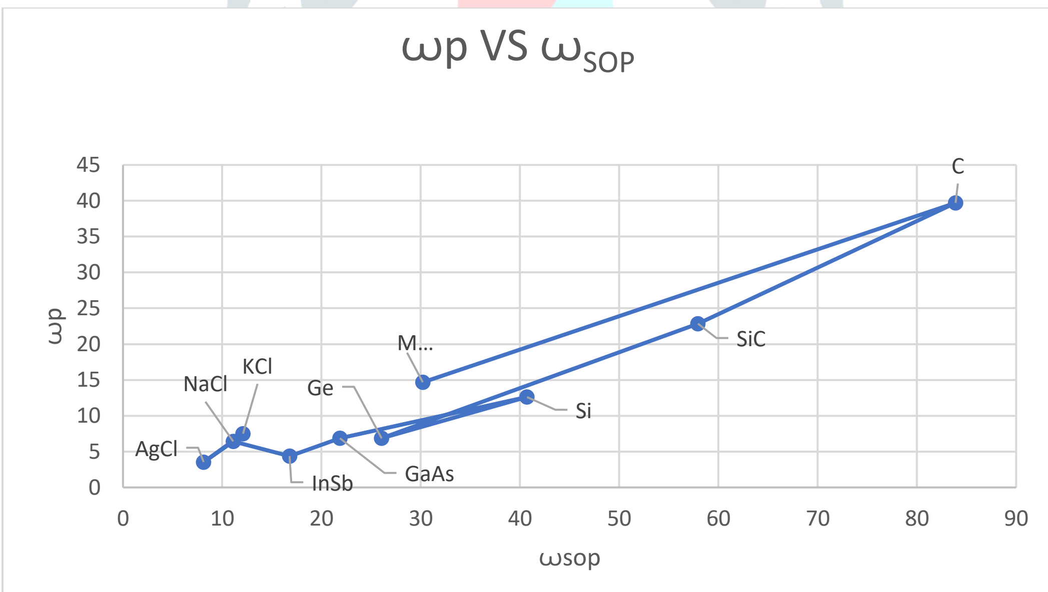

Fig.1 Shows the modes of optical phonon frequency waves on plasma frequency of these materials in the non-dispersive medium.

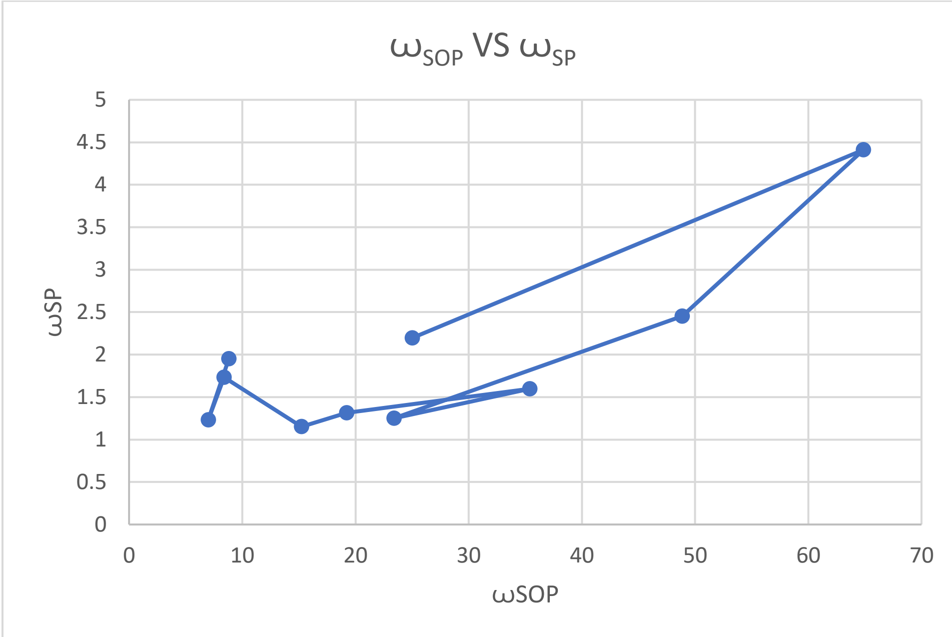

Fig.2 Shows the modes of Surface optical phonon frequency waves on surface plasma frequency of these materials at a non-dispersive medium.

Results and Discussion

We observe the data and figure we found that Surface Plasma will always have a less frequency than plasma frequency when the angular frequency is greater than plasma frequency the material becomes non-dispersive and plasma consider virtually absent. The ratio of plasma frequency and transverse frequency is greater than one showing two modes on the surface of materials. The lower mode at the surface acts as surface plasmon and the upper mode acts as surface optical phonons. If the ratio of plasma frequency and transverse frequency is less than one then it acts as reverse, if it is equivalent to one then it shows both modes superimpose to each other at fixed plasma frequency we can see the strong coupling interaction at the surface [11]. In a non-dispersive dielectric medium, the Carbon nanomaterial has a greater value of surface optical phonon and atomic amplitudes are confined to the near-surface region increase exponentially high compared to other materials. i.e., Carbon nanomaterial is widely used in the nano industry. The optical phonons are generated at the interface between different materials with dielectric functions and propagate along with the interface [12]. At this medium, the AgCl shows a very low frequency of surface optical phonons instead of having good conducting nature. AgCl, NaCl, KCl, InSb, GaAs, and Ge show approximately near about same optical frequency range on the surface of this material While C, SiC, and MgO show high values which are useful in photonic technology.

Conclusions:

We have observed the frequency range of surface optical phonon modes at the surface of different materials, in which we investigate carbon nanomaterial the macroscopic modes of surface optical phonon are high and show high penetration depth. The study of surface optical modes on several materials' surfaces with different mediums is an extremely active and exciting field for the benefits of science and nanotechnology field. This further study in the future on different materials will be useful for the study of characterization of materials and also for the understanding of fundamental processes in the nano range [13]. Surface optical phono modes are widely present in a smaller size of nanomaterials.

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