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STUDY OF SURFACE PLASMONS OF DIFFERENT MATERIALS AT INTERFACE OF DISPERSIVE MEDIUM AT NANOSCALE

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Abstract

The Hydrodynamic model has been discussed for the study of frequency of surface optical phonon coupled oscillations at the surface of different nano materials and this theory is applied to obtained the dispersion relation for semi-infinite single plane boundary [1]. The possibility of interaction of surface optical phono at different material's surface has been discussed with the help of its dielectric functions at different mediums. 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 the calculation of surface optical phonon frequency curve with respect to different mediums. The appearance of SOP waves of different materials has been observed in dispersive medium (Glass).

Keywords: *Hydrodynamical model, optical phonon, plasma frequency and dispersive medium.*

Introduction:

Semiconducting nanomaterials have great attention of researchers, due to their wide applications in the field of solid-state physics, nanotechnology as well as in fundamental science. When these semiconducting materials made in nano range, an enhanced optical property against their bulk medium due to their quantized size it increased surface to volume ratio. Surface Phonon is a collective excitation in atomic arrangements in condensed matter physics in solids and liquids. Basically, a quasiparticle [2]. 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 [3]. 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 of fluctuations creates an electrical polarization in electromagnetic field [4]. Frequency of Surface optical Phonons were observed in the range of 496-572 cm^{-1} on semiconducting and conducting material's sample [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 predicted theoretically and detected experimentally in few papers [8]. We choose nano range because these particle range have a large surface - to- volume ratio, with the help of this we can determine the properties of materials, when we reduce the dimensions extremely small the surface modes can exist [9]. In most of the cases optical modes in most of the nano range materials are due to the discontinuity in the transition symmetry on surface. In long wavelength optical phonon modes are not observed experimentally [10].

Materials and Methods

We know that surface plasmon and surface optical phonons interact with each other in polar semiconductors if their frequencies are of same order. In order to study 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 plane bounded surface method.

First, we calculate the wave frequency for a plane semi-infinite ionic compound bounded by a dielectric medium of constant $\mathcal{E}_2$ 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

$$\mathcal{E}_L(\omega)E_{Z1}\,|_{Z=o} = \mathcal{E}_2\, E_{Z2}\,|_{Z=0} \tag{1}$$

We obtain

$$\mathcal{E}_L(\omega) = -\,\mathcal{E}_2 \tag{2}$$

$$\mathcal{E}_L(\omega) = \mathcal{E}\infty \;\; \omega^2 - \mathcal{E}_0\,\omega_t^2/\,\omega^2 - \omega_t^2 \tag{3}$$

Where

$$\omega_t^2 = (\mathcal{E}\infty + 2/\,\mathcal{E}_0 + 2)\,\omega^{-2} \tag{4}$$

'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 of medium must be negative at the frequency (ω) of the surface wave. The negative value of dielectric constant shows the medium is active and the other the value of dielectric constant is positive which means the medium is inactive which does not interact with the surface of semiconducting materials.

The frequency of surface modes determined by the substituting value of $\mathcal{E}_L$ (ω) from equation (3) which shown below

$$\omega^2_{SOP} = (\mathcal{E}_0 + \mathcal{E}_2/\,\mathcal{E}_\infty + \mathcal{E}_2)\,\omega_t^2 \tag{5}$$

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

i.e.,

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

and

$$n_1(r^-, t) = 0 \tag{6}$$

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 is present in it for electrical conduction.

$$[(\mathcal{E}_L + \mathcal{E}_2)\,\omega^2 - \bar{\varepsilon}\,\omega_p^2]\,[\,(\omega_p^2 - \omega^2\,) + K^2\,\beta^2\,]^{1/2} = \mathcal{E}_2\; K\,\beta\,\omega_p^2 \tag{7}$$

The above equation shows dispersion relation for the surface mode. For semiconductors we know $\mathcal{E}_L$ 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

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

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

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).

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

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

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

This is biquadratic equation in ‘ω/ω_t’ and it contains both optical phonon frequency (ω_t) and plasmon frequency (ω_p), hence there is 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 equation (8) and (9) taking as an independent.

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

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

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

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

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

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,

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

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 ($\varepsilon_2 = 4.8$), we get

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

It gives two solutions for angular frequency

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

table-1. shows the values of surface optical phonon frequency and surface plasmon frequency of these materials on dispersive dielectric medium(glass) at different values of static dielectric constant and optical dielectric constant

Materials	Ɛ2	ωsop	ωp	ωSP
MgO	4.8	30.21217	14.67646	6.101681
C	4.8	83.89833	39.70364	9.612562
SiC	4.8	57.93096	22.85321	6.564727
Ge	4.8	26.06078	6.85443	5.089216
Si	4.8	40.71086	12.60769	5.518387
GaAs	4.8	21.85894	6.858187	5.169117
InSb	4.8	16.78092	4.380205	4.970569
NaCl	4.8	11.10533	6.428562	5.715098
AgCl	4.8	8.127915	3.537591	5.047384
KCl	4.8	12.09184	7.506525	6.072292

fig-1. shows the modes of optical phonon frequency waves on plasma frequency of these materials in dispersive medium.

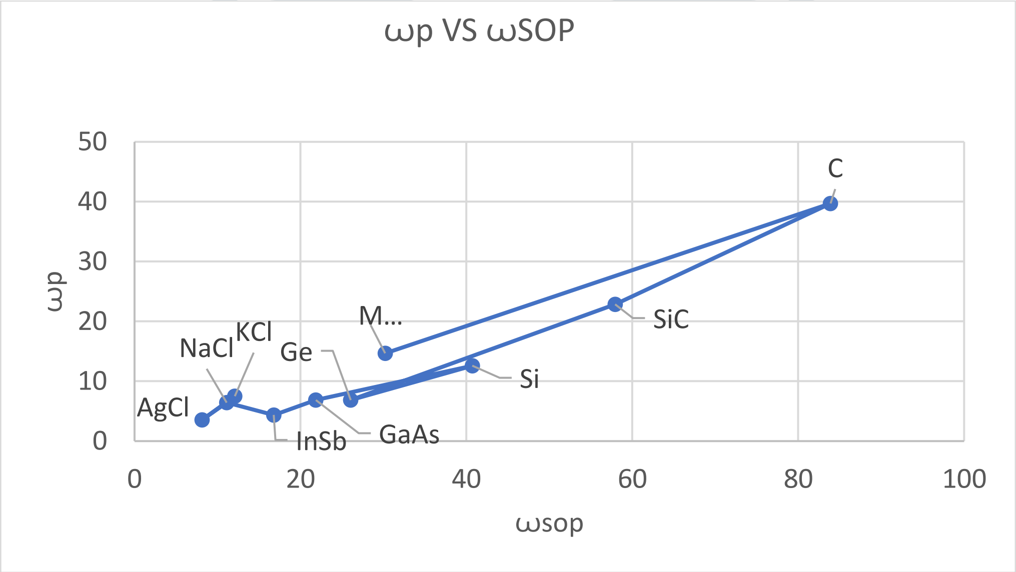

Fig-2. shows the modes of surface optical phonon frequency waves on surface plasma frequency of these materials at dispersive medium.

Results and Discussion

We observe the data and figure we found that Surface Plasma will always have a less frequency than plasma frequency when angular frequency is greater than plasma frequency the material becomes in non-dispersive nature and plasma consider virtually absent. For ratio of plasma frequency and transverse frequency is greater than one shows two modes on surface of materials. The lower mode at surface acts surface plasmon and upper mode acts as surface optical phonons. If 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. At non-dispersive dielectric medium, the Carbon nano material has greater value of surface optical phonon and atomic amplitudes are confined to the near surface region increase exponentially high compare to other materials. The optical phonons are generated at the interface between different materials with dielectric functions and propagate along the interface. When take dielectric medium as dispersive due to transparency in nature we see the variation of frequency range is low but higher than non-dispersive but frequency of surface plasmon is increased its 2-3 times. The value of ωp is less than ω_{SOP} for all materials and ω_{SP} is very much less than ω_{SOP} for all given materials in table 1. At this medium the AgCl shows 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 surface of these material While C, SiC and MgO shows high values which is useful in nanotechnology.

Conclusions:

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

References:

[1]. Ajay Tondon, dispersion relation for plasmon optical phonon surface waves in polar semiconductors, 1988

[2]. Schwabl, Franz (2008) Advanced Quantum Mechanics, Springer. P 253 IBSN 978-3-540-85062-5

[3]. Simon, Steven H (2013). The Oxford Solid state basics P.82. ISBN 978-0-19-968077-1

[4]. Girvin, Steven M; Yang, Kun (2019) Modern Condensed Matter Physics. Cambridge University Pres. 78- 96 ISBN 978-1-107-13739-4

[5]. B. Hadzic, N. Romcevic, surface optical phonons in ZnO nanoparticles (2012), 10.1016

[6]. Christopher R. Gubbin, Simone De Liberato and Thomas G. Folland Surface phono polaritons for infrared optoelectronics, 10.1063/5.0064234 (2022)

[7].A. Rogalski, "History of infrared detectors A," Opto-Electron. Rev. **20**, 279 (2012). https://doi.org/10.2478/s11772, **Google Scholar**

[8]. G.A Stern and R.A Ferrell, Phys.Rev. 120,130(1960)

[9]. K.W Chiu and J.J Quinn, Phys. Letts. 35A, 469(1971)

[10].W.K.H. Panofsky and M. Phillips, Classical electricity and Magnetism, Addision-wealey Pub. Inc. (1962). P. 31-31 and 139-140