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Optical properties of polar semiconductors due to interaction of surface plasmon, phonon and polaritons

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Abstract : The effect of interaction of surface plasmon, phonon and polaritons on optical properties of polar semiconductors have been studied. This has shown, how a polar semiconductor behaves as low band, and high pass filter.

Keywords : Plasmon, phonon and polariton interaction

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Recently, Srivastava *et al* [1] have studied the coupled surface plasmon-polariton, surface phonon-polariton and surface plasmon-phonon-polariton modes in polar semiconductors. In the present work, an attempt has been made to show how due to above interactions a polar semiconductor can behave as low, band and high pass filter by studying the variation of refractive index with frequency.

Effect of coupled surface plasmon-polariton modes on refractive index

Consider the space $z < 0$, to be occupied by the bounding, non-dispersive dielectric medium characterized by frequency independent dielectric constant ε_B and the region $z > 0$ is occupied by the polar semiconductor characterized by frequency dependent dielectric function $\varepsilon(\omega)$ given by [2]

$$\varepsilon(\omega) = \varepsilon_L(\omega) - \bar{\varepsilon}(\omega_p/\omega)^2. \tag{1}$$

$\varepsilon_L(\omega)$ being the lattice dielectric function given by

$$\varepsilon_L(\omega) = \frac{\varepsilon_\infty \omega^2 - \varepsilon_0 \omega_t^2}{\omega^2 - \omega_t^2}. \tag{2}$$

where ε_0 and ε_∞ are low and high frequency dielectric constants, ω_t is the transverse optical phonon frequency. ω_p in eq. (1) is the bulk plasma frequency and $\bar{\varepsilon}$ [= $(\varepsilon_0 + \varepsilon_\infty)/2$] is the frequency independent approximation of ε_L [3].

The dispersion relation for coupled surface plasmon-polariton modes for a polar semiconductor-dielectric plane interface has been derived by Srivastava *et al* [1] as

$$\varepsilon_B \varepsilon_L \Omega^4 - \left[\bar{\varepsilon}\, \varepsilon_B + (\varepsilon_L + \varepsilon_B) K^2\right]\Omega^2 + \bar{\varepsilon} K^2 = 0, \tag{3}$$

where $\bar{K} = c\bar{k}/\omega_p$ and $\Omega = \omega/\omega_p$ are dimensionless reduced wave vector and frequency.

The refractive index of a medium may be defined in terms of the magnitude of the wave vector of the propagating surface wave [4] as

$$n = \frac{ck}{\omega}. \tag{4}$$

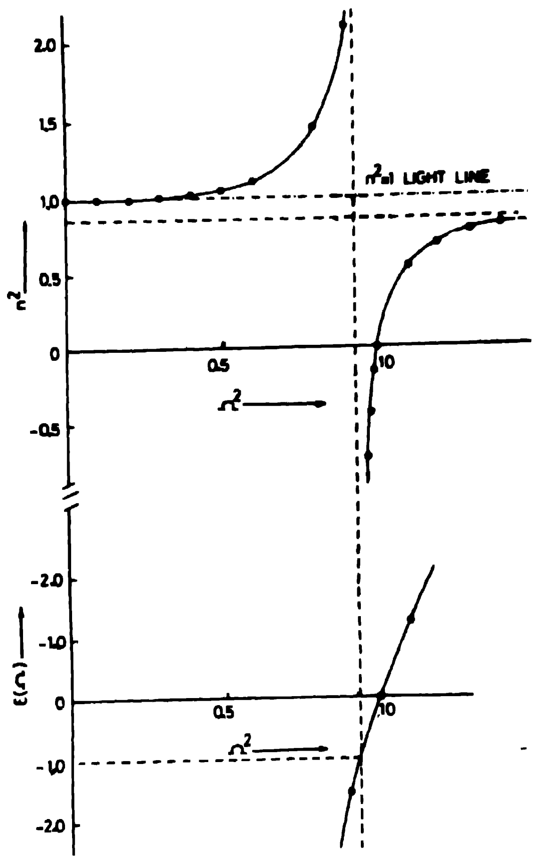

Figure 1. Plot of n^2 *vs* Ω^2 and $\varepsilon(\Omega)$ *vs* Ω^2 due to coupled surface plasmon-polariton modes for InAs-vacuum plane interface.

Using eqs. (3) and (4), we get

$$n^2 = \frac{\varepsilon_L - \bar{\varepsilon}/\Omega^2}{1+\varepsilon_L - \bar{\varepsilon}/\Omega^2} = \frac{\bar{\varepsilon}(1-1/\Omega^2)}{1+\bar{\varepsilon}(1-1/\Omega^2)}, \tag{5}$$

where the bounding medium is taken to be vacuum *i.e.* $\varepsilon_B = 1$.

The dielectric function for pure plasmons in polar semiconductor in terms of Ω is given [5] as

$$\varepsilon(\Omega) = \bar{\varepsilon}(1-1/\Omega^2) \tag{6}$$

Figure 1 shows the variation of n^2 with Ω^2 along with $\varepsilon(\Omega)$ *vs* Ω^2 curve for InAs [6] polar semiconductor. It is observed that for $\Omega^2 < 0.931$, the surface modes are bound, non-radiative and the incident wave is not transmitted. As $\Omega^2 \to 0.931$ (pure SP frequency for InAs) $n^2 \to \infty$. This is a resonance condition and strong coupling between incident photon and surface plasmon takes place, whole of the incident energy remain localized at the surface and the wave do not propagate. As frequency increases beyond this frequency, n^2 takes on negative values and increases from $-\infty$ to zero and acquires positive values gradually. For $0.931 < \Omega^2 < 1$, refractive index is imaginary and this is the condition of total reflection and in this frequency range, no surface mode exists and a forbidden gap is formed. As $\Omega^2 \to 1$, $n^2 \to 0$ which is the condition of total transmission, the surface mode becomes radiative and incident wave is totally transmitted through the polar semiconductor. For all $\Omega^2 > 1$, the surface mode becomes radiative. The incident wave is transmitted and the polar semiconductor behaves as a high pass filter.

Effect of surface phonon-polariton modes on refractive index

The dispersion relation for surface phonon-polariton modes in polar semiconductor-vacuum plane interface taking $\varepsilon_B = 1$ is given by [1]

$$\varepsilon_\infty W^4 - \left[\varepsilon_0 + (1+\varepsilon_\infty)K_1^2\right]W^2 + (1+\varepsilon_0)K_1^2 = 0, \tag{7}$$

where $K_1 = \dfrac{c\bar{k}}{\omega_t}$ and $W = \dfrac{\omega}{\omega_t}$ are the dimensionless reduced wave vector and frequency.

Using eqs. (2), (4) and (7), refractive index due to coupled surface phonon-polariton modes is obtained as

$$n^2 = \frac{\varepsilon_\infty W^2 - \varepsilon_0}{(1+\varepsilon_\infty)W^2 - (1+\varepsilon_0)}. \tag{8}$$

A plot of n^2 *vs* W^2 is shown in Figure 2 for InAs alongwith $\varepsilon_L(W)$ *vs* W^2 curve. From this figure, it is clear that for $W^2 < 1$, the surface modes are radiative. The incident wave is transmitted and the polar semiconductor behaves as a low pass filter. As $W^2 \to 1.19$ (pure SOP frequency for InAs), $n^2 \to \infty$; this is a resonance condition and strong coupling between incident photon and SOP takes place and discontinuity in the n^2 *vs* W^2 curve occurs. At this frequency, surface modes are non-radiative and no transmission of the incident radiation takes place and the wave do not propagate, instead the whole of incident energy is localized at the surface. For $1.19 < W^2 < 1.21$, refractive index becomes imaginary, which is the condition of total reflection of incident wave. As $W^2 \to 1.21$, both n^2 and $\varepsilon_L(W)$ become zero which shows the perfect transmission of the incident EM wave.

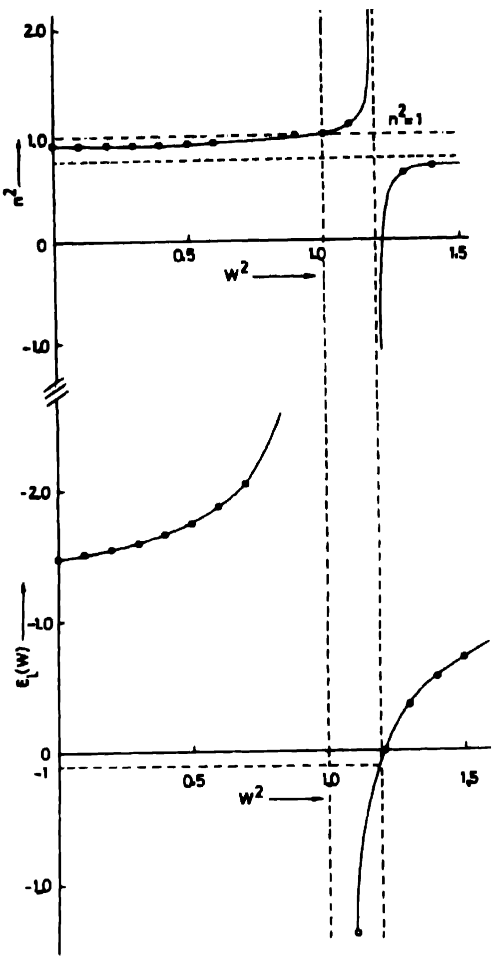

Figure 2. Plot of n^2 *vs* W^2 and $\varepsilon_L(W)$ *vs* W^2 due to coupled surface phonon-polariton modes for InAs-vacuum plane interface.

For all $W^2 > 1.21$, the surface mode become radiative and the incident wave propagate through the medium and the polar semiconductor behaves as a high pass filter.

Effect of coupled surface plasmon-phonon-polariton modes on refractive index

The dispersion relation for coupled surface plasmon-phonon-polariton modes at polar semiconductor-vacuum plane interface ($\varepsilon_B = 1$) is given by [1]

$$\varepsilon_\infty\left(\frac{\omega_p}{\omega_t}\right)^2 \Omega^6 - \left[\varepsilon_0 + \left\{\bar{\varepsilon} + (1+\varepsilon_\infty)K^2\right\}\left(\frac{\omega_p}{\omega_t}\right)^2\right]\Omega^4$$

$$+ \left[\left\{(1+\varepsilon_0) + \bar{\varepsilon}(\omega_p/\omega_t)^2\right\}K^2 + \bar{\varepsilon}\right]\Omega^2 - \bar{\varepsilon}K^2 = 0. \qquad (9)$$

Using eqs. (4) and (9), the refractive index is obtained as

$$n^2 = \frac{\Omega^2\left\{\varepsilon_\infty\Omega^2 - \varepsilon_0(\omega_t/\omega_p)^2\right\} - \bar{\varepsilon}\left\{\Omega^2 - (\omega/\omega_p)^2\right\}}{\left\{\Omega^2 - (\omega_t/\omega_p)^2\right\}(\Omega^2 - \bar{\varepsilon}) + \Omega^2\left\{\varepsilon_\infty\Omega^2 - \varepsilon_0(\omega_t/\omega_p)^2\right\}} \qquad (10)$$

and the total dielectric function for polar semiconductor in terms of Ω is written as

$$\varepsilon(\Omega) = \frac{\varepsilon_\infty\Omega^2 - \varepsilon_0(\omega_t/\omega_p)^2}{\Omega^2 - (\omega_t/\omega_p)^2} - \frac{\bar{\varepsilon}}{\Omega^2}. \qquad (11)$$

Eqs. (10) and (11) have been plotted for InAs in Figure 3. It is observed that at $\Omega = 0.76$ and 1.19, $n^2 \rightarrow \pm\infty$; no transmission of incident wave takes place, instead the whole energy

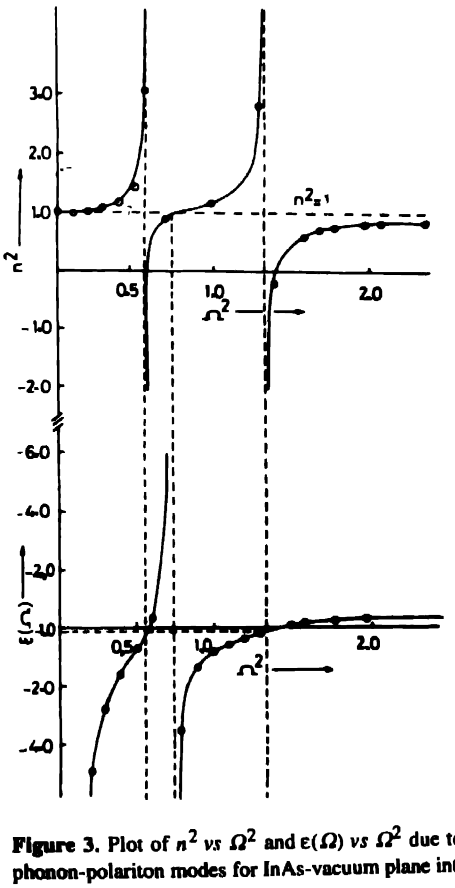

Figure 3. Plot of n^2 *vs* Ω^2 and $\varepsilon(\Omega)$ *vs* Ω^2 due to coupled surface plasmon-phonon-polariton modes for InAs-vacuum plane interface.

remain localized at the surface and discontinuities in the curve occur. For $0.76 < \Omega < 0.848$, both the refractive index and dielectric function are positive, therefore surface mode become radiative. The polar semiconductor becomes transparent to the incident radiation and behaves as a band pass filter. For all $\Omega > 1.19$, both n^2 and $\varepsilon(\Omega)$ are positive, therefore the surface mode is radiative. The polar semiconductor becomes transparent and behaves as a high pass filter.

The present study shows that the presence of surface polariton waves at the interface of a polar semiconductor modifies the reflection and transmission properties of polar semiconductor. At particular frequencies, maximum reflection and transmission take place and the polar semiconductor behaves as a low band and high pass filter for certain range of frequencies due to interaction between surface plasmon, phonon and polaritons. This result is of great importance in the study of wave propagation through surfaces. By variation in doping, a polar semiconductor can be used to work as a low band or high pass filter. It is useful in carrier telephony and communication circuits.

Acknowledgments

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