Longitudinal optical phonon-plasmon interaction in Ga-group V compounds for IR and THz applications

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In this paper we present the numerical results of the optical response of doped Ga-group V (N, As, Sb) compounds in the medium IR and THz wave spectrum. Specific features of the optical response depends on the strength of the LO phonon-plasmon coupling, which can be controlled by the free carrier concentration and the compound composition. The impact of this coupling will be evaluated at different free carrier concentrations. Potential applications will be discussed for CO_2 laser wavelengths and for a new generation of THz lasers.

Introduction

The development of terahertz (THz) technology involves many scientific fields like semiconductor devices manufacturing, biomedical imaging, security imaging and ultrafast spectroscopy of semiconductors and nanostructures. Recent developments in photonics and nanotechnologies make THz operating devices one of the important issues of modern electronics [1]. The THz band has a large number of spectral features related to physical processes such as lattice vibration in solids and intra-band transitions in semiconductors.

Properties of Ga-Group V Compounds

The III-V semiconductor family represents a wide group of materials which are used to design electronic and photonic devices. The development of these devices requires understanding of all relevant material properties such as optical and free carrier absorption spectra, phonon frequencies and refractive index calculation.
Gallium antimonide (GaSb) is typically used in binary superlattices for detectors and emitters in the far and mid-IR due to the formation of a narrow effective energy gap [2]. Gallium arsenide (GaAs) was considered as the replacement of silicon (Si) for some applications due to its superiority in electrical and optical properties. It has a higher mobility resulting in a higher effective saturation velocity which increases the semiconductor device performance [3]. GaN is optically transparent for the visual spectrum, such that it allows electronic and microscopic detection of processes in biophysical and biochemical applications. It has exceptional chemical and physical stability, and so it is ideal for immobilization of bio-molecules. It is used in biosensor fabrication because its surface has no toxic content like As which can affect the living cell [4].

Dielectric Function and Optical Parameters

The optical properties of materials can be described and analyzed by means of the complex dielectric function for a given photon frequency. The dielectric function of solids is given by the sum of phonon and plasmon contributions using the simple harmonic oscillator model:

$$\varepsilon(\omega)=\varepsilon_{\infty}\left(1-\frac{\omega_p^2}{\omega(\omega+i\Gamma)}+\frac{\omega_{LO}^2-\omega_{TO}^2}{\omega_{TO}^2-\omega^2-i\omega\gamma}\right) \tag{1}$$

where ε_∞ is the high frequency dielectric constant, ω_{LO} and ω_{TO} are the longitudinal (LO) and transversal (TO) optical phonon frequencies, respectively, Γ and γ are the plasmon and phonon damping constants, respectively, and ω_p is the plasmon frequency given by

$$\omega_p^2=\frac{e^2N}{\varepsilon_o\varepsilon_\infty m^*}\quad\text{(rad./s)} \tag{2}$$

with N the free carrier concentration, m^* the electron effective mass, e the electron charge and ε_o the vacuum permittivity [5].

For frequencies of plasmons and LO phonons close to each other, they interact such that coupled plasmon-LO phonon modes are produced with frequencies given by [6]:

$$\omega_{\mp}=\frac{\omega_{LO}^2+\omega_P^2}{2}\mp\sqrt{\left(\frac{\omega_{LO}^2+\omega_P^2}{2}\right)^2-\omega_p^2\omega_{TO}^2} \tag{3}$$

Note that the damping effect is neglected here. The dielectric constant is related to the complex refractive index n^* as [7]:

$$n^*=n+ik=\sqrt{\varepsilon}=\sqrt{\varepsilon_1+i\varepsilon_2} \tag{4}$$

where n is the ordinary refractive index, and k is extinction coefficient (attenuation index). The absorption coefficient of the propagating light in a medium is then given by:

$$\alpha=\frac{4\pi k}{\lambda} \tag{5}$$

where λ is the light wavelength in vacuum. The normal incident reflectivity of light is:

$$R=\frac{(n-1)^2+k^2}{(n+1)^2+k^2} \tag{6}$$

Results and Discussion

The absorption coefficient and reflectivity for normal incident light on GaN, GaAs and GaSb have been calculated for different doping concentrations / plasmon frequencies (ω_p) in the CO_2 laser and THz region. Figures 1, 3 and 4 show the impact of the phonon-plasmon coupling on the optical properties of the selected materials. The phonon effect on the absorption coefficient and reflectivity is represented by the peak, while the plasmon effect lies near the plasmon frequency. Note that the impact of the plasmon frequency on the absorption coefficient and reflectivity is relatively small at low optical frequencies (20 meV) as compared to larger optical frequencies (120 meV).

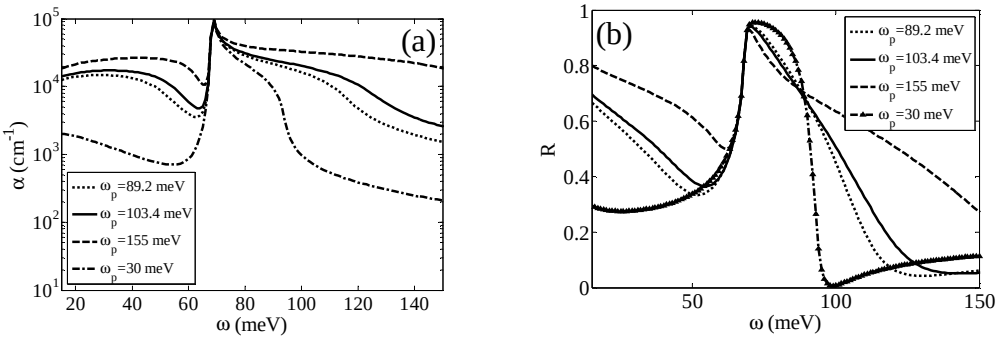

Fig. 1: (a) Absorption coefficient and (b) reflectivity for GaN versus the incident photon energy for different doping concentrations.

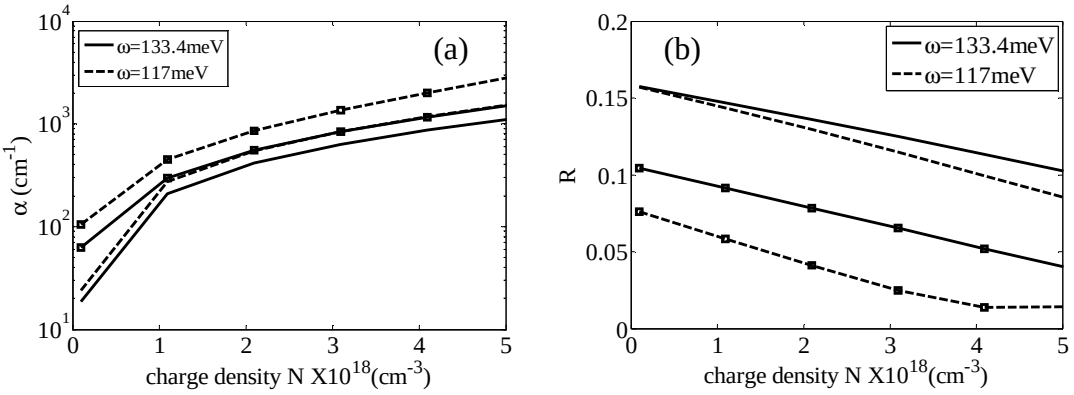

Fig. 2 (a) Absorption coefficient and (b) reflectivity for GaN versus doping concentrations for different models (with markers : plasmon and phonon effects, and without markers: only phonon effect).

Figures 1, 3 and 4 show that the absorption coefficient increases for increasing plasmon frequency from 30 to 155.0 meV. This is related to the free electron absorption process. In general, low reflectivity prevails for $\omega > \omega_p$ and high reflectivity prevails for $\omega_{TO} < \omega < \omega_{LO}$. In the strong coupling case, however, ω_{LO} (ω_p) substantially shifts to lower (higher) optical frequencies ω_- (ω_+) and the dependence between the reflectivity and carrier concentration inverts in the ω_- - ω_+ region as shown in figure 1.
Figure 2 shows the dependency of the absorption coefficient and reflectivity on the charge density for GaN for two CO_2 laser wavelengths. The results strongly depend on the fact whether only the plasmon effect is taken into account, or the combined plasmon-phonon effect.

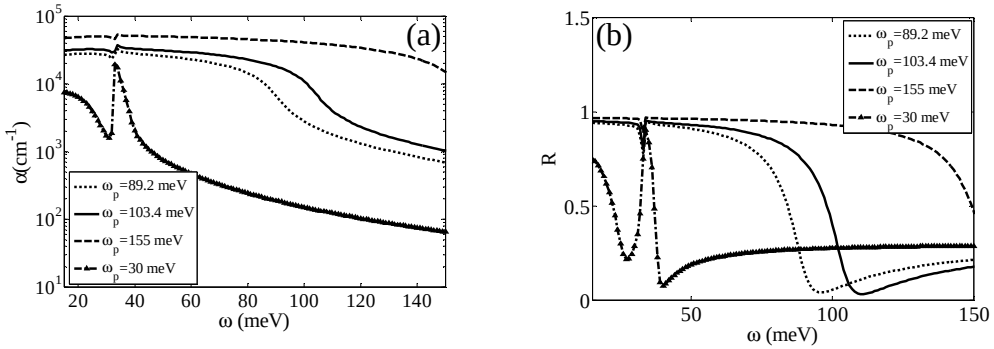

Fig. 3: (a) Absorption coefficient and (b) reflectivity for GaAs versus incident photon energy at different doping concentrations.

The coupled phonon-plasmon frequencies (ω_-, ω_+) are calculated using Eq.3 as a special case where damping effects are neglected (see table 1). Almost no coupling is observed for GaAs and GaSb, whereas for GaN results in a strong perturbation with respect to the uncoupled scenario.

Table 1 : phonon and coupled plasmon phonon frequencies for Ga-group V compounds (in meV)

Compound	ω_{TO}	ω_{LO}	ω_{peak}	ω_p	ω_+	ω_-
GaN	68.3	91.9	69	117	136.8	58.4
GaN	68.3	91.9	69	89.2	117.0	52.1
GaAs	33.1	35.3	34	117	117.7	32.9
GaSb	27.8	28.9	28	117	116.7	29.0

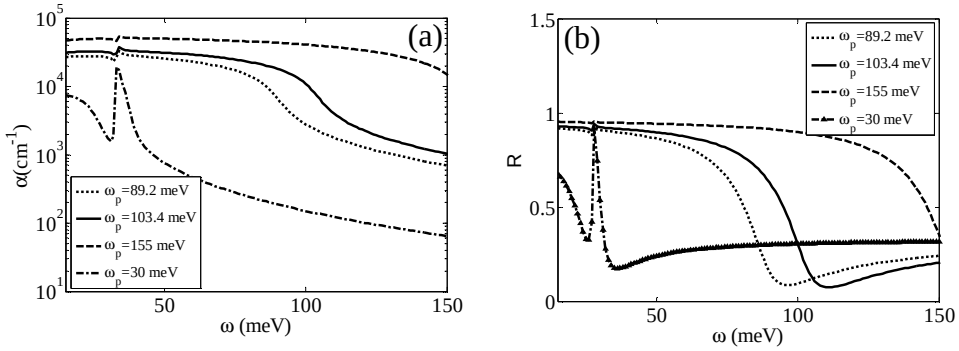

Fig. 4: (a) Absorption coefficient and (b) reflectivity for GaSb versus incident photon energy at different doping concentrations.

Conclusions

GaAs and GaSb have similar optical response as their phonon frequencies are close together and relatively far from the CO_2 laser range plasmon frequency, such that no coupling between both is observed. The contribution of the phonon effect in these materials to the polarization can be neglected. GaN behaves differently as the LO phonon and plasmon frequencies are close together. For GaN, it has been shown that a phonon-plasmon frequency can be realized for the CO_2 laser wavelength range by choosing a doping density with an associated plasmon frequency of about 89.2 meV. This coupling results in an increased absorption coefficient for the CO_2 laser wavelength range. To control the degree of coupling between plasmon and phonon, one can change the material itself to alter the LO phonon frequency or the carrier concentration to alter the plasmon frequency. This coupling can be used to determine the carrier concentration by means of reflectivity and absorption measurements.

Acknowledgement

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