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COUPLING OF THE TRANSVERSE PLASMON AND TRANSVERSE OPTICAL PHONON IN n-GaAs

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The effect on temporal and spatial dispersion curves of the coupled transverse plasmon and TO phonon in n-GaAs for different electron concentrations and damping parameters has been evaluated.

This note calculates temporal and spatial damped dispersion curves, ω versus q, of the coupling between the transverse plasmon and the transverse optical (TO) phonons in n-GaAs for various electron concentration (N) and optical phonons lifetimes ($1/\gamma$), and electron collision-times ($1/\nu$). Laser Raman spectroscopy has permitted the measurements of effects of the coupling among various elementary excitations, in particular the coupled LO phonon-plasmon, and TO phonon-photon. We show damping has an important effect on dispersion curves.

The transverse plasmon or dressed photon is a quasiparticle consisting of a photon dressed by an electron cloud. The electromagnetic field is strongly coupled to the collective electron response, as witnessed by the modification of the photon's dispersion relation given by $\omega^2 = c^2q^2/\epsilon_\infty + \omega_p^2/\epsilon_\infty$, where c is the velocity of light, q is the propagation constant of the light, ϵ_∞ is the high frequency dielectric constant of the medium, and ω_p is the plasma frequency for the electrons.

The total dielectric function [1] of a system consisting of optical phonons and conduction band electrons in GaAs in the long wavelength and SCF approximation is

$$\epsilon_{T,L}(\omega) = \epsilon_\infty - \frac{4\pi}{i\omega}\sigma_{T,L} - \frac{(\epsilon_0 - \epsilon_\infty)\,\omega_{TO}^2}{\omega^2 - \omega_{TO}^2 + i\gamma_{T,L}\,\omega} \quad (1)$$

where the subscripts T, L correspond to transverse and longitudinal modes respectively. The first contribution to the dielectric function is due to bound electrons, the second to conduction band electrons, and the last to the polar nature of the GaAs lattice. In eq. (1) $\epsilon_0 = 13.3$ is the static dielectric constant, $\epsilon_\infty = 11.3$ is the high frequency dielectric constant, $\omega_{TO} = 5.04 \times \times 10^{13}\ \mathrm{sec}^{-1}$ is the TO phonon frequency in GaAs, and $\gamma_{T,L}$ is the lifetime of the TO and LO phonons respectively due to multiphonon processes, and $\sigma_{T,L}$ is the transverse and longitudinal conductivity respectively.

The condition on the dielectric function for the longitudinal modes and transverse modes obtained from Maxwell equations are $\epsilon_L(\omega) = 0$ and $\epsilon_T(\omega) = c^2 q^2/\omega^2$ respectively. The longitudinal and transverse conductivity [2] are $4\pi\sigma_L/i\omega = = \omega_p^2(\omega - i\nu)/\omega^3$ and $4\pi\sigma_T/i\omega = \omega_p^2(\omega - i\nu)/\omega(\omega^2 + \nu^2)$. In these equations $1/\nu$ is the electron collision time with thermal phonons and impurities, and $\omega_p^2 = 4\pi Ne^2/m^*$ where $N, m^* = 0.07\ m_e$, and e are respectively the density of conduction electrons, their effective mass, and the electronic charge.

Fig. 1(a) shows dispersion relations $\mathrm{Re}\,\omega$ versus $\mathrm{Re}\,q$ calculated from eqs. (1) for different N taking γ_T and ν as zero. Curve 1 shows the well-known coupling of the photon and TO phonon in GaAs, commonly called the Polariton mode. The dashed curves are the uncoupled photon and TO phonon dispersion curves. However, the transverse field of the photon couples strongly with the TO phonon. The transverse mode splits into a high-frequency mode (ω_+) and a low-frequency mode (ω_-). Stationary states of ω_- are photon-like at low q and phonon-like at large q. Stationary states of ω_+ are phonon-like at small q and photon-like at large q. However, in the vicinity of the intersection point, stationary states are neither photon- nor phonon-like.

Curves 2 and 3 of fig. 1(a) show the coupling between the dressed photon and TO phonon. The effect of free electrons on the coupling is readily noticed. The upper mode is phonon-like at low q and photon-like at large q, while the lower mode phonon-like at large q and dressed photon-like at low q. Coupling between the dressed photon and TO phonon decrease as ω_p increases, as shown in curve 2 (strong coupling) and curve 3 (weak coupling). Variation of coupling with concentration could be readily detected by small angle Raman scattering.

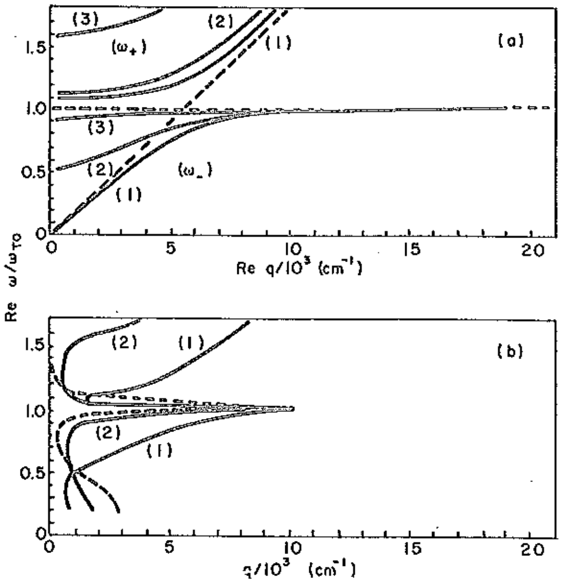

Fig. 1. (a) Dispersion relation for GaAs at various electron concentrations. (1) $\omega_p/\omega_{TO} = 0$; (2) $\omega_p/\omega_{TO} = 2$; (3) $\omega_p/\omega_{TO} = 5$; and $\gamma_T = \nu = 0$.
(b) Spatial dispersion relation for GaAs for (1) $\omega_p/\omega_{TO} = 2$; $\nu/\omega_{TO} = 10^{-1}$; $\gamma_T/\omega_{TO} = 4 \times 10^{-2}$ and (2) $\omega_p/\omega_{TO} = 5$; $\nu/\omega_{TO} = 10^{-1}$; $\gamma_T/\omega_{TO} = 4 \times 10^{-2}$.

Fig. 1(b) shows the spatial dispersion relation of the transverse modes including both electron and TO phonon damping. An electron collision time of 2×10^{-13} sec and a TO phonon lifetime of 5×10^{-13} sec were used for both strong (curve 1) and weak (curve 2) coupling regimes. Finite values of ν and γ_T primarily affect transverse modes at small and large q respectively. The dash curve shown in fig. 1(b) is a plot of $\mathrm{Re}\,\omega/\omega_{TO}$ versus $\mathrm{Im}\,q$ for parameters of the weak coupling regime. $\mathrm{Im}\,q$ governs the spatial absorption of the excitation mode at frequency ω. Phonon and electron lifetimes effect the $\mathrm{Im}\,\omega/\omega_{TO}$ versus $\mathrm{Re}\,q$ but not the $\mathrm{Re}\,\omega/\omega_{TO}$ versus $\mathrm{Re}\,q$ parts of temporal damped dispersion curve. The real part is shown in fig. 1(a). The results of Mooradian et al. [3] agrees with the temporal damped dispersion curves shown in fig. 1 when extended to the experimental momenta of $\sim 2 \times 10^5\ \mathrm{cm}^{-1}$.

1. M. Born and K. Huang, The dynamical theory of crystal lattice (Clarendon Press, Oxford, 1956).
2. R. Tsu, Phys. Rev. 164 (1967) 380.
3. A. Mooradian and G. Wright, Phys. Rev. Letters 16 (1966) 999.