PHOTOINJECTED CARRIER'S ACOUSTIC PLASMA OSCILLATIONS

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ABSTRACT

Resorting to the Nonequilibrium Statistical Operator Method (NSOM) we calculate the Raman spectrum of the double (electrons and holes) photoinjected plasma in direct-gap polar semiconductors. It allows us to identify four types of elementary excitations in the photoexcited carrier system. Besides the expected Raman bands corresponding to single quasi-particle excitations and a higher frequency plasma wave (labelled optical), there appear two low-frequency bands. They show a linear energy dispersion relation and are labelled acoustic plasma oscillations. While the optical plasma branch is ascribed to the out of phase collective movement of both types of carriers interacting through the bare Coulomb interaction, the acoustic branches are ascribed to the in-phase oscillation of each type of carriers interacting through the screened part of Coulomb interaction.

KEYWORDS

Photoexcited carrier elementary excitations; collective plasma oscillations; photoinjected carriers' Raman scattering.

ACOUSTIC PLASMONS IN PHOTOEXCITED SEMICONDUCTORS

We consider a semiconductor with inverted parabolic bands illuminated with continuous laser light intense enough to produce electron-hole pairs (carriers) on the metallic side of Mott transition. To evidence the elementary excitations of this system we calculate the electronic Raman spectrum. We recall that the Raman-scattering cross section is proportional to the imaginary part of the dynamic (frequency and wave-vector dependent) dielectric function $\epsilon(\vec{q}, \omega)$. The latter, according to Maxwell equations, is related to the Fourier amplitude of the polarization charge $n(\vec{q}, \omega)$ induced by a probe charge of amplitude r_0 , namely $\epsilon^{-1}(\vec{q}, \omega) - 1 = n(\vec{q}, \omega)/r_0$. The quantity $n(\vec{q}, \omega)$ is given by

$$n(\vec{q}, \omega) = \sum_{\vec{k}} (n_{\vec{k}+\vec{q}}^e + n_{\vec{k}}^h) \quad , \quad (1)$$

where

$$n_{\vec{k}+\vec{q}}^e = \text{Tr} \{ c_{\vec{k}+\vec{q}}^\dagger c_{\vec{k}} \rho \} \quad ; \quad n_{\vec{k}}^h = \text{Tr} \{ h_{\vec{k}}^\dagger h_{-\vec{k}-\vec{q}} \rho \} \quad , \quad (2)$$

are the non-diagonal elements of the single-particle density matrices of electrons and of holes respectively, and ρ is the nonequilibrium statistical operator in Zubarev's (1974) approach, in a form appropriate for the description of the system (Tomé, Vasconcellos, and Luzzi, 1987). The NSOM-equations of motion for the quantities of Eq. (2) are

$$i\hbar \frac{\partial}{\partial t} n_{\vec{k}+\vec{q}}^e(t) = V(\vec{q}) (f_{\vec{k}+\vec{q}}^e - f_{\vec{k}}^e) [r_0 + n(\vec{q}, t)] + \\ + (\epsilon_{\vec{k}+\vec{q}}^e - \epsilon_{\vec{k}}^e) - iB_{\vec{k}+\vec{q}}^e n_{\vec{k}}^e(t) + iB_{\vec{k}}^e n_{\vec{k}+\vec{q}}^e(t) \quad , \quad (3)$$

where $\epsilon_{\vec{k}}^{e(h)} = \hbar^2 k^2 / 2m_e(h)$; $f_{\vec{k}}^{e(h)}$ are Fermi-Dirac distribution functions; $V(q) = 4\pi e^2 / V \epsilon_0 q^2$, with V the volume of the system and ϵ_0 the background dielectric constant; and coefficients $B_{\vec{k}\vec{q}}^{e(h)}$ couple electrons and holes through, mainly, recombination effects (the influence on these terms of laser and phonon effects is negligible). Coulomb interaction has been dealt with in the Random Phase Approximation.

Transforming Fourier Eqs. (3) and using Eq. (1) we obtain for the dielectric function

$$\epsilon(\vec{q}, \omega) / \epsilon_0 = 1 - V(q) \sum_{\vec{k}} M(\vec{k}, \vec{q}; \omega) D^{-1}(\vec{k}, \vec{q}; \omega) \quad (4)$$

where

$$M(\vec{k}, \vec{q}; \omega) = [(f_{\vec{k}+\vec{q}}^e - f_{\vec{k}}^e) - (f_{\vec{k}+\vec{q}}^h - f_{\vec{k}}^h)] [\hbar\omega - i(B_{\vec{k}\vec{q}}^e + B_{\vec{k}\vec{q}}^h)] - [(f_{\vec{k}+\vec{q}}^e - f_{\vec{k}}^e)(\epsilon_{\vec{k}+\vec{q}}^e - \epsilon_{\vec{k}}^e) + (f_{\vec{k}+\vec{q}}^h - f_{\vec{k}}^h)(\epsilon_{\vec{k}+\vec{q}}^h - \epsilon_{\vec{k}}^h)] \quad (5a)$$

$$D(\vec{k}, \vec{q}; \omega) = [i(\epsilon_{\vec{k}+\vec{q}}^e - \epsilon_{\vec{k}}^e + \hbar\omega) + B_{\vec{k}\vec{q}}^h] [i(\epsilon_{\vec{k}+\vec{q}}^h - \epsilon_{\vec{k}}^h - \hbar\omega) - B_{\vec{k}\vec{q}}^e] + B_{\vec{k}\vec{q}}^e B_{\vec{k}\vec{q}}^h \quad (5b)$$

The differential Raman cross section is

$$d^2\sigma/d\omega d\Omega \sim [1 - e^{-\hbar\omega/kT}]^{-1} \text{Im} \epsilon^{-1}(\vec{q}, \omega) \quad (6)$$

which we calculate numerically using parameters characteristic of GaAs, and low temperatures (such as to allow the use of step functions for the Fermi-Dirac distributions), obtaining the results shown in Fig. 1 for the case of a photoconcentration $n = 10^{16} \text{ cm}^{-3}$.

Fig. 1. Raman Cross Section

Fig. 2. Real Dielectric Function

In Fig. 1 full line corresponds to $q = 10^4 \text{ cm}^{-1}$, dashed line to $q = 10^2 \text{ cm}^{-1}$, and dot-dashed line to $q = 50 \text{ cm}^{-1}$. v_{Fe} is the Fermi velocity of electrons and a band centered at nearly $\Omega_{pl} = [8\pi n e^2 / (m_e^{-1} + m_h^{-1})^{-1}]^{1/2}$ (optical plasma) is not included in order to concentrate the figure in the low frequency region. The Raman spectrum is composed of four bands: one around Ω_{pl} , another in the region $0.6 \lesssim \omega/qv_{Fe} \lesssim 1$, and two (one intense and another weak) at low frequencies. The position of the peaks of the latter two is almost in coincidence with the frequencies that make null the real part of the dielectric function, as shown in Fig. 2, for (a) $q = 10^4 \text{ cm}^{-1}$ and (b) $q = 100 \text{ cm}^{-1}$. Inspection of Figs. 1 and 2 tells us that the two low frequency bands merge and disappear in the broad band of quasi-particle excitations, that becomes dominant and with its characteristic form, for decreasing values of q . This is also the case with increasing temperatures (T no longer very much smaller than T_{Fe}). The position of the peaks of the low frequency bands (lower L and upper U) follow a linear relationship

$$\omega_{AL} = s_{AL}q \quad \text{and} \quad \omega_{AU} = s_{AU}q,$$

where we find numerically that $s_{AL} \approx (m_x/3m_h)^{1/2}v_{Fe}$ and $s_{AU} \approx (m_e m_x/3m_h^2)^{1/2}v_{Fe}$, where m_x is the exciton reduced mass. These expressions can be alternatively written $s_{AL} = \Lambda_{FT}^{-1}\omega_{ple}$ and $s_{AU} = \Lambda_{FT}^{-1}\omega_{plh}$, where Λ_{FT} is Fermi-Thomas screening length and $\omega_{ple(h)}$ are the plasma frequencies of the individual systems of electrons and of holes. It should be noted that these values for the group velocities s can be obtained from the expression for the unperturbed plasmon frequency $\omega^2 = (n/m)V(q)q^2$, if in this expression m is taken alternatively as the electron and the hole mass and $V(q)$ is taken as the Coulomb screened potential $V(q) = 4\pi e^2/\epsilon_0(q^2 + \Lambda_{FT}^{-2}) \approx 4\pi e^2\Lambda_{FT}^2/\epsilon_0$ for small q . (The high frequency band at Ω_{pl} follows for $m = m_x$ and $V(q)$ taken as the bare Coulomb interaction). These results lead us to identified these two low frequency bands as due to scattering by acoustic plasmons, to be interpreted as a result of the collective oscillation of electrons (at ω_{AU}) and of holes (at ω_{AL}) while interacting through the screened part of Coulomb interaction.

Hence, the spectrum of elementary excitations of the electrons and holes in the steady state, when photoinjected in a semiconductor by the action of c.w. laser light, is composed of the contribution of single-particle excitations and three branches of collective excitations: optical plasma waves at Ω_{pl} (collective motion of the carriers), and two acoustic plasma waves, one at ω_{AU} (collective motion of electrons), and another at ω_{AL} (collective motion of holes).

REFERENCES

- Tomé, T., A.R. Vasconcellos, and R. Luzzi (1987). *Physica* 144B, 376-390.
 Zubarev, D.N. (1974). *Nonequilibrium Statistical Thermodynamics*. Plenum Press, New York.