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Analysis of dielectric function and dynamic structure factor of a multi-component plasma in a wurtzite GaN

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ABSTRACT

We investigated dielectric responses of a multi-component plasma at finite temperature and applied the results to spectral analysis of dynamic structure factor of a photo-generated high density plasma in a wurtzite GaN. The behavior of effective dielectric function and dynamic structure factor in energy loss measurement are examined focusing to the effects of dynamic screening of carriers in the plasma. Features of their spectral behavior are illustrated including the roles of various elementary excitations in the three-component solid state plasma.

1. Introduction

Dielectric functions and dynamic structure factor provide useful information about the elementary excitations of a many-body system, and the number of plasma components has an influence on the response functions of the system [1,2]. Many of existing studies on the dielectric response were on the single component plasmas (scps) formed such as in doped semiconductors [3]. We consider a multi-component solid state plasma generated optically by exposing an undoped material to a high power laser exciting electrons into the conduction band leaving various holes in the valence bands [4,5] (See Fig. 1.) In a photo-generated multi-component plasma (mcp), carrier temperatures for different types of carriers are not identical, the carrier effective 'kinetic' temperature T_{eff} is meaningful in experiments [5,6], where T_{eff} is a measure of the average kinetic energy per carrier in the sample. In the present case, the number of electrons in the conduction band is equal to the sum of the heavy and light hole numbers in the valence bands. Electrons and holes have different effective masses and, hence, they act differently to an external disturbance. It is known that, for example, their respective effective masses are $m_e = 0.22m_0$, $m_{hh} = 1.3m_0$, and $m_{lh} = 0.3m_0$ for electrons (e's) in the conduction band and heavy (hh) and light (lh) holes in the respective valence bands in a wurtzite GaN. Through mutual Coulombic interaction, they form an interacting mcp, i.e., two-component (e-hh) plasma at lower electron densities and three-component (e-hh-lh) plasma at higher electron densities [7]. Since the dynamic structure factor is defined as the space-time Fourier transform of the density–density correlation function, it can be measured in the energy loss or light scattering experiments [8]. In this work, we evaluated plasma component-resolved polarization functions and dielectric function of a photo-generated high density mcp as a function of momentum ($\hbar q$) and energy transfer ($\hbar\omega$) at finite temperature and applied the results to the case of a three-component (consisting of conduction electrons, heavy holes, and light holes) solid state plasma in a wurtzite GaN. We employed formulation of Ref. [7], in which dielectric functions are formulated at finite temperature for multi-component hot carrier plasmas and illustrated the results for a photo-generated two-component plasma comparing with that of single component plasma. In the present work, we extended the formulation in detail and applied to spectral analysis of dynamic structure factor of a high density three-component plasma focusing to the role of optic and acoustic plasmon excitations in the energy loss responses of the plasma.

2. Formulation

Dielectric responses of multi-component plasma are examined by writing the response of a many-particle system to an external

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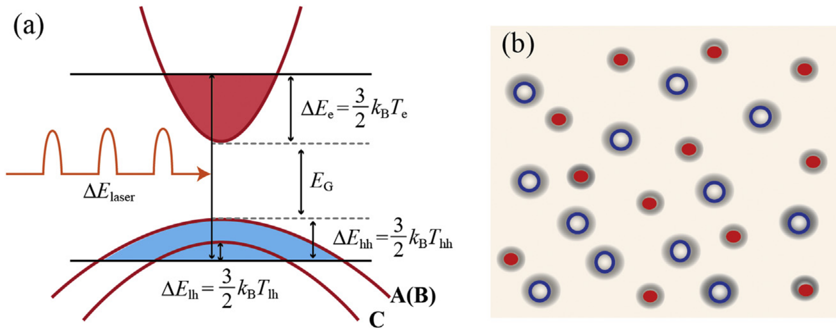

Fig. 1. Schematics of a photo-generated multi-component plasma. (a) photo-generation of electron–hole plasma formed in an ideal wurtzite GaN. (b) an interacting multi-component electron–hole plasma.

disturbance [7]. If we apply an external disturbance ϕ_{ext} to the system, density fluctuations $\delta\rho_\ell$ for the ℓ^{th} plasma component (ℓ = e, hh, or lh for electron, heavy hole, and light hole) are induced in the plasma. The density fluctuation can be written, in terms of the external disturbance ϕ_{ext} and the polarization function Π, as $\delta\rho_\ell = v_q \sum_{\ell'} \prod_{\ell\ell'} \phi_{ext}$. Here v_q is the three-dimensional Fourier transform of the bare Coulomb interaction $v(q) = 4\pi e^2/q^2$, and the response function $\Pi_{\ell\ell'}$ is the full polarization function defined, as the Fourier transform in the time coordinate of the density–density correlation function, by $\prod_{\ell\ell'}(\vec{q},w) = -i\int_0^\infty dt\, \exp^{i(\omega+i\eta)t}\langle[\rho_\ell(\vec{q},t),\rho_{\ell'}(-\vec{q},0)]\rangle$ [9], where $\rho(\vec{q},t)$ is the particle density operator in the Heisenberg picture. In the absence of Coulomb interaction between carriers, $\phi_{eff} = \phi_{ext}$ and $\Pi(q,\omega)$ is well known as $\Pi^{(0)}(q,\omega)$. The retarded response function $\prod_{\ell\ell'}^{(0)}(q,\omega)$ is given by the generalized Lindhard polarization function [9]

$$\prod_{\ell\ell'}^{(0)}(\vec{q},\omega) = 2\sum_{\vec{k}} \frac{f^{(0)}_{k+q,\ell} - f^{(0)}_{k,\ell'}}{\varepsilon^{(0)}_{k+q,\ell} - \varepsilon^{(0)}_{k,\ell'} - \hbar\omega - i\eta}. \tag{1}$$

The real and imaginary parts of $\Pi^{(0)}_{\ell\ell}$ are written, respectively, as

$$\mathrm{Re}\prod_{\ell\ell}^{(0)}(\vec{q},\omega) = 2\sum_{\vec{k}} f_{k,\ell}(T_\ell)\left(\frac{1}{\varepsilon_{k+q,\ell} - \varepsilon_{k,\ell} + \hbar\omega} - \frac{1}{\varepsilon_{k+q,\ell} - \varepsilon_{k,\ell} - \hbar\omega}\right) \tag{2}$$

with singularities at $\hbar\omega = \pm(\varepsilon_{\vec{k}+\vec{q},\ell} - \varepsilon_{\vec{k},\ell})$, and

$$\mathrm{Im}\prod_{\ell\ell}^{(0)}(\vec{q},\omega) = 2\pi\sum_{\vec{k}}\left[f_{k,\ell}(T_\ell) - f_{k+q,\ell}(T_\ell)\right]\delta\left(\varepsilon_{k+q,\ell} - \varepsilon_{k,\ell} - \hbar\omega\right). \tag{3}$$

For the case of parabolic energy dispersion, the summation over $\vec{k}$ can easily be carried out [10].

In the independent particle regime, there is no interference between waves scattered from different particles located at different places. In the presence of carrier–carrier interaction, the polarization function of the plasma would be modified drastically. Each carrier responds to the effective potential field ϕ_{eff}, which is the sum of the external disturbance ϕ_{ext} and the induced potential field ϕ_{ind}, the solution of Poisson's equation $\nabla^2\phi_{ind} = -\rho_{ind}$, where $\rho_{ind} = \sum_\ell \delta\rho_\ell$. Therefore, it would be more physical to write $\delta\rho_\ell$ as $\delta\rho_\ell = v_q \sum_{\ell'} \tilde{\Pi}_{\ell\ell'}\phi_{eff}$. Here $\tilde{\Pi}$ is the proper polarization function [11], which is connected self-consistently to the full polarization function Π by

$$\Pi_{\ell\ell'} = \tilde{\Pi}_{\ell\ell'} + \sum_{mn} \tilde{\Pi}_{\ell m} V_{mn} \Pi_{n\ell'} \equiv \tilde{\Pi}_{\ell\ell'} \Big/ \varepsilon, \tag{4}$$

where $V_{ij} = v_q\ (-v_q)$ for carriers of equal (unequal) charges. Equation (4) also defines the effective dielectric function ε of the mcp. The screened interaction $\tilde{V}_{ij}$ between particles i and j is now given, in terms of $\tilde{\Pi}_{mn}$ and ε, by $\tilde{V}_{ij} \equiv V_{ij}/\varepsilon$, where [11]

$$\tilde{V}_{ij} = V_{ij} + \sum_{mn} V_{im}\tilde{\Pi}_{mn}\tilde{V}_{nj}. \tag{5}$$

The second term on the right hand side of Eq. (5) includes such effect as that a particle m (=e, hh, or lh) in the polarization cloud going along with the particle j scatters particle i via Coulomb field V_{im} and then interacts with j via screened interaction $\tilde{V}_{nj}$. (See Fig. 2.) For the interacting plasma, the full polarization function $\Pi(q,\omega)$ need be determined self-consistently by truncating the repeatedly connected relation of Eq. (4) at an appropriate stage. In the random phase approximation (RPA), the instantaneous fluctuation beyond the pairwise averaged mean field is ignored approximating $\tilde{\Pi}$ by $\prod^{(0)}$ to have [6,7]

$$\Pi_{\ell\ell} = \prod_{\ell\ell}^{(0)}\left[1 + \frac{v_q \prod_{\ell\ell}^{(0)}}{1 - v_q \sum_{\nu=e,A,B,C} \prod_{\nu\nu}^{0}}\right]. \tag{6}$$

Then the RPA dielectric function of the mcp is given by

$$\varepsilon_{RPA}(\vec{q},\omega) = 1 - v_q \sum_{\nu=e,A,B,C} \prod_{\nu\nu}^{(0)}(\vec{q},\omega). \tag{7}$$

Within the RPA, the density–density correlation function is given, including the Coulomb interactions, by $\Pi(q,\omega) = \prod^{(0}/\varepsilon$. For the case of a scp, the full polarization function Π and dielectric function ε are reduced, respectively, to $\prod_{\ell\ell}^{(scp)} = \prod_{\ell\ell}^{(0)}/(1 - v_q\prod_{\nu\nu}^{(0)})$ and