Low-temperature photoluminescence spectra of highly excited quantum wires

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Abstract

Optical spectra of highly excited quantum wires at low temperatures have been studied within the dynamically screening approximation. We found a strong Fermi-edge singularity (FES) in the photoluminescence spectra. The spectral shape and FES intensity strongly depend on temperature in agreement with recent experimental results.

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1 Introduction

Many-body effects in dense electron-hole (e-h) plasma in semiconductors and their heterostructures have found a growing interest in the recent years. The interaction between the carriers in dense e-h systems causes band-gap renormalization (BGR). The band-gap decrease with increasing e-h pair densities affects the excitation process and leads to optical nonlinearities [1-4].

Optical-nonlinear properties have been studied intensely in bulk and low-dimensional semiconductors [1-12]. At high densities the low-temperature optical spectra of semiconductors show a peak near the Fermi energy. This peak has been known as the excitonic enhancement [1, 3]. In semiconductor quantum wires (QWRs), the screening effect is much weaker so that the excitonic enhancement becomes very strong and one obtains the Fermi-edge singularity (FES) [4]. In their experiments at low temperatures, Calleja et al. [12] have found that the photoluminescence (PL) spectra of modulation-doped GaAs quantum wires are dominated by a Fermi-edge singularity, which shows a strong temperature dependence and a pronounced spectra shape.

In this work, we calculate the low-temperature PL spectra of GaAs QWRs by solving the Bethe-Salpeter equation (BSE) of the e-h pair Green’s function within the dynamically screened approximation. Our calculation includes the following many-body effects: phase-space filling, screening of the Coulomb interaction, band-gap renormalization. Instead of using a phenomenological damping constant we shall take into account the broadening and lifetime effects by determining the imaginary part of the electron and hole self-energy. We shall compare our theoretical results with experimental findings by Calleja et al. in GaAs quantum wires [12] and with theoretical results obtained from the statically screened approximation and the Hartree-Fock approximation as well.

2 Theory

We start from an ideal 2D quantum well in which the electrons and holes are confined laterally by a harmonic oscillator potential with a total intersubband spacing Ω. The 1D Coulomb interaction between the charge carriers is given by averaging the bare 2D Coulomb interaction with the lateral envelope wave functions:

\[ V(q) = \frac{2e^2}{\epsilon_0} \exp \left( \frac{q^2}{4m\Omega} \right) K_0 \left( \frac{q^2}{4m\Omega} \right), \]

where \( m \) is the reduced electron-hole mass and \( K_0(x) \) is the zeroth-order modified Bessel function.

The photoluminescence spectrum \( R(\omega) \) is calculated from the imaginary part of the optical dielectric function \( \epsilon(\omega) \):

\[ R(\omega) \sim \frac{Im\epsilon(\omega)}{e^{\beta(\omega-\mu)} - 1}, \]
where $\beta = 1/k_B T$ is the inverse thermal energy, $\mu = \mu^e + \mu^h$ the combined chemical potential of the e-h pair.

In the linear response theory [2] the optical dielectric function of e-h system is obtained from:

$$
\epsilon(\omega) = \epsilon_\infty - 4\pi e^2 \sum_{k,k'} r_{ve}(k)r^{*}_{ve}(k')G_{eh}(k,k',\omega). 
$$

where $G_{eh}(k,k',\omega)$ is the e-h pair Green’s function [2,5,9-10].

The effective Bethe-Salpeter equation for the e-h pair Green’s function in the dynamically screened approximation is given by [2,5,9-10]:

$$
G(k,k',\omega) = \frac{1 - f^e(e_k^e) - f^h(e_{-k}^h)}{\omega - e_k^e - e_{-k}^h} \left( \delta_{k,k'} - \sum_{k''} V_{\text{eff}}(k,k'',\omega) G(k'',k',\omega) \right), 
$$

where $f^j(\varepsilon) = (e^{\beta(\varepsilon-\mu^j)} + 1)^{-1}$ is the Fermi distribution function,

$$
e_j^j = \frac{E_0^j}{2} + \frac{k^2}{2m^j} + \Sigma^j(k,e^j_k) 
$$

are the renormalized band energies for electrons ($j = e$) and holes ($j = h$),

$$
V_{\text{eff}}(k,k',\omega) = \frac{1}{\beta} \sum_{z,z'} G^e(k,\Omega - z) + G^h(-k, z) \left( \delta_{k,k'} - \sum_{k''} V_{\text{eff}}(k,k'',\omega) G(k'',k',\omega) \right), 
$$

where $f^j(\varepsilon) = (e^{\beta(\varepsilon-\mu^j)} + 1)^{-1}$ is the Fermi distribution function,

$$
\Sigma^j(k,e^j_k) = \frac{E_0^j}{2} + \frac{k^2}{2m^j} + \Sigma^j(k,e^j_k) 
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V_{\text{eff}}(k,k',\omega) = \frac{1}{\beta} \sum_{z,z'} G^e(k,\Omega - z) + G^h(-k, z) \left( \delta_{k,k'} - \sum_{k''} V_{\text{eff}}(k,k'',\omega) G(k'',k',\omega) \right), 
$$

where $f^j(\varepsilon) = (e^{\beta(\varepsilon-\mu^j)} + 1)^{-1}$ is the Fermi distribution function,
where

\[
\zeta(k, k', \omega) = \frac{1}{1 - f^e(e^e_k + e^h_{k'} - \omega)} \frac{1}{1 - f^e(e^e_k + e^h_{k'})} \frac{\omega_p^2(k - k')}{2\omega_{k-k'}}
\times \left[ \begin{array}{l}
\frac{g(\omega_k - \omega)}{e^e_k - e^e_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega - e^e_{k'} - \omega_{k-k'}) - f^e(e^e_k) \\
\frac{g(\omega_k - \omega^2)}{e^h_{k} - e^h_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega^2 - e^h_{k'} - \omega_{k-k'}) - f^h(e^h_{k}) \\
\frac{g(\omega_k - \omega^3)}{e^e_k - e^e_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega^3 - e^e_{k'} - \omega_{k-k'}) - f^e(e^e_k) \\
\frac{g(\omega_k - \omega^4)}{e^h_{k} - e^h_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega^4 - e^h_{k'} - \omega_{k-k'}) - f^h(e^h_{k}) \\
\frac{g(\omega_k - \omega^5)}{e^e_k - e^e_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega^5 - e^e_{k'} - \omega_{k-k'}) - f^e(e^e_k) \\
\frac{g(\omega_k - \omega^6)}{e^h_{k} - e^h_{k'} + \omega_{k-k'}} + 1 + g(\omega_k - \omega^6 - e^h_{k'} - \omega_{k-k'}) - f^h(e^h_{k}) \\
\end{array} \right] \tag{10}
\]

and \(g(\omega) = (e^{\beta\omega} - 1)^{-1}\) is the Bose distribution function.

We calculate the self-energy \(\Sigma^j(k, \omega)\) within the leading-order approximation:

\[
\Sigma^j(k, \omega) = \Sigma^{j}_{HF}(k) + \Sigma^{j}_{corr}(k, \omega), \tag{11}
\]

where

\[
\Sigma^{j}_{HF}(k) = - \sum_{k'} V(k - k') f^j(e^j_{k'}) \tag{12}
\]

is the unscreened Hartree-Fock self-energy and

\[
\Sigma^{j}_{corr}(k, \omega) = \sum_{k'} V(k - k') \frac{\omega_p^2(k - k')}{2\omega_{k-k'}}
\times \left[ \begin{array}{l}
\frac{1 + g(\omega_k - \omega^2)}{\omega - e^j_{k'} - \omega_{k-k'} + i\gamma} + \frac{g(\omega_k - \omega^2) + f^j(e^j_{k'})}{\omega - e^j_{k'} + \omega_{k-k'} + i\gamma} \\
\end{array} \right] \tag{13}
\]

is the correlation self-energy. \(\gamma\) is a small phenomenological damping term describing impurity, defect scattering, inhomogeneities in the system, and other possible broadening processes. \(\gamma\) should be small compared with the excitonic binding energy in quantum wires [10].
If one replaces the effective e-h interaction $V_{\text{eff}}(k, k', \omega)$ in (9) by the statically screened interaction $V_S(k-k')$ or the bare Coulomb potential $V(k-k')$ and the self-energy in (11) by $\Sigma^j(k) = \sum_{k'} \left[ -V_S(k-k')f^j(c_{k'}) + \frac{1}{2}(V_S(k') - V(k')) \right]$ or $\Sigma^j(k) = \Sigma^j_{HF}(k)$, one retrieves the BSE in the statically screened approximation treated by other authors [1-3,11] or in the Hartree-Fock approximation treated by Gréus et al [6]. Note that the self-energy in the statically screened approximation or in the Hartree-Fock approximation is real and one has to introduce a phenomenological damping constant $\Gamma$, which is corresponding to the sum of the imaginary part of the self-energy of electron and hole, to describe the broadening and lifetime effects [1-3,6,11].

3 Numerical results and discussions

We calculate PL spectra by solving the BSE for GaAs QWR using the following parameters: $m_e = 0.067 m_0$, $m_h = 0.46 m_0$, $\epsilon_0 = 13.1$, $\Omega = 5.2$ meV, $E^0_b = 1.53$ eV, $\gamma = 2$ meV $<< E_b$ ($E_b \sim 20$ meV is excitonic binding energy in GaAs QWR).

In Fig. 1 we compare our PL spectra in the dynamically screening approximation (Fig. 1a) with experimental results by Calleja et al. (Fig. 1b) taken for e-h density $n = 5 \times 10^5$ cm$^{-1}$ and at different temperatures [12]. At very low temperature ($T = 1.7$ K) we obtain a strong FES near the chemical potential $\mu$. With increasing temperatures the peak shifts to the red and the FES intensity decreases quickly due to increasing thermal broadening of the Fermi function and increasing thermal collisions. Our theoretical results agree rather well with the PL measured results (Fig. 1b) in modulated-doped GaAs QWRs.

In Figs. 2 we plot PL spectra in the unscreened Hartree-Fock approximation (Fig. 2a) and in the statically screened approximation (Fig. 2b) at $n = 5 \times 10^5$ cm$^{-1}$ using a damping constant $\Gamma = 4$ meV. In this simplest Hartree-Fock approximation the PL intensity increases suddenly when the chemical potential coincides with the excitonic resonance energy (at $T \simeq 10$ K). Besides that, the spectra show a blue shift with increasing temperatures. Contrary to the Hartree-Fock approximation the statically screened approximation shows a red shift with increasing temperatures (Fig. 2b) but the spectral shape is still much less pronounced compared to that of measurements.

In summary, we have studied the temperature dependence of PL spectra of photoexcited QWRs in three different approximations: Hartree-Fock, statically screened-, and dynamically screened approximation. While the dynamically screened approximation agrees rather well with recent experimental findings [12] the statically screened approximation poorly describes the measurements. The unscreened Hartree-Fock approximation, moreover, fails totally to describe the experiments.

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Figure 1a: PL spectra of GaAs QWR for various temperatures in the dynamically screening approximation.

Figure 1b: Experimental PL spectra of GaAs QWRs [12] for various temperatures at evaluated intersubband spacing of 5.2 meV, and plasma density of $5 \times 10^5$ cm$^{-1}$. 
Figure 2a: PL spectra of the GaAs QWR for various temperatures in the Hartree-Fock approximation.

Figure 2b: PL spectra of the GaAs QWR for various temperatures in the statically screened approximation.