EXCITON EFFECT IN THE INTERBAND ELECTRONIC RAMAN SCATTERING IN SEMICONDUCTORS

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The cross section of the interband electronic Raman scattering in the two band gap and with the allowed dipole transition is calculated. The exciton effect was taken into account.

The electronic Raman scattering in a semiconductor was the subject for the theoretical and experimental studies in many works [1–10]. In particular, the authors of Refs. [3, 4] have considered the interband electronic Raman scattering in a semiconductor with a direct band gap. In the final state of this process there is an electron-hole pair. In the papers [1–8, 10] however, the Coulomb interaction of the electron and the hole in the final state was not taken into account. In the article by Enderlein and Peuker [9] the Raman scattering with the creation of excitons in the discrete spectrum was studied. In this paper we study the influence of the Coulomb interaction on the shape of the cross section near the high frequency edge of the spectrum, i.e., study the role of the exciton effect on the scattering cross section in the continuous spectrum. For simplicity we consider a model with a two-band semiconductor with a direct band gap and with the allowed electrical dipole transition.

By means of the standard calculation it can be shown that if we neglect the Coulomb interaction then at the edge of the spectrum where the difference of the incident and scattered photon energies ω_1 and ω_2 is nearly equal to the band gap E_g the cross section of the interband scattering process is determined by the approximate formula [10]

$$\frac{d\sigma_0}{d\Omega\, d\omega_2} = A|M_0|^2 (\tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g)^{3/2} \tag{1}$$

where:

$$A = \frac{\sqrt{2}}{3} \frac{e^4}{\varepsilon_0^2} \frac{\mathscr{P}^2}{m_0^2} \left(\frac{\mu}{R}\right)^{1/2} \frac{\omega_2}{\omega_1}, \tag{2}$$

$$M_0 = \frac{1}{\tilde{\omega}_2}, \tag{3}$$

$$\tilde{\omega}_i = \frac{\omega_i}{R}, \quad \tilde{E}_g = \frac{E_g}{R}, \quad R = \frac{1}{2\mu a_0^2}, \quad \mu = \frac{m_e m_h}{m_e + m_h}, \tag{4}$$

m_0 is the free electron mass, m_e and m_h are the effective masses of the electron and the hole in the semiconductor, ε_0 is the background dielectric constant, e is the electron charge, a_0 is the exciton radius, $\mathscr{P}$ denotes the interband transition matrix element with the photon in the same polarization state e_1, as the incident photon:

$$\mathscr{P} = \langle c | e_1 \nabla | v \rangle . \tag{5}$$

Due to the Coulomb interaction of the electron and the hole the intermediate and final state of the scattering process may contain the electron-hole pair either with the discrete energy or with the energy in the continuous spectrum. For the cross section of the scattering process with the creation of an electron-hole pair in the continuous spectrum, by applying the reasonings as in Ref. [11] we have got the following approximate expression of the cross section:

$$\frac{d\sigma}{d\Omega\, d\omega_2} = A |M(k)|^2 \frac{2\pi(\tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g + 1)}{1 - \exp\left(-\dfrac{2\pi}{\sqrt{(\tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g)}}\right)} \tag{6}$$

where

$$M(k) \approx \left\{ \int dr \left[\sum_m \frac{F^s_m(0)\, F^s_m(r)^*}{\tilde{\omega}_1 - \tilde{E}_g - \tilde{E}_m} + \int d\eta\, \frac{\tilde{F}_\eta(0)\, \tilde{F}_\eta(r)^*}{\tilde{\omega}_1 - \tilde{E}_g - \tilde{E}_\eta} \right] e_2 \nabla\, \tilde{F}_k(r) \right\} \cdot \tag{7}$$

$$\cdot \left\{ \int dr' \left[\sum_{m'} F^s_{m'}(0)\, F^s_{m'}(r')^* + \int d\eta'\, \tilde{F}_{\eta'}(0)\, \tilde{F}_{\eta'}(r')^* \right] e_2 \nabla\, \tilde{F}_k(r') \right\}^{-1} ,$$

$$k^2 = \tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g = \tilde{E}_k , \quad \tilde{E}_n = -\frac{1}{n^2} ,$$

$F^l_n(r)$, $\tilde{F}_k(r)$ are the exciton hydrogenic wave functions of the discrete states and continuum states, respectively.

In the case of the scattering process with the creation of an exciton with the principal quantum number n we have the cross section

$$\frac{d\sigma}{d\Omega\, d\omega_2} = 2\pi A \sum_{n \geqq 2} |M(n)|^2 (\tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g)\, \delta\left(1 - \frac{1}{\sqrt{(\tilde{E}_g + \tilde{\omega}_2 - \tilde{\omega}_1)}}\right) \tag{8}$$

where

$$M(n) \approx \left\{ \int dr \left[\sum_m \frac{F^s_m(0)\, F^s_m(r)^*}{\tilde{\omega}_1 - \tilde{E}_g - \tilde{E}_m} + \int d\eta\, \frac{\tilde{F}_\eta(0)\, \tilde{F}_\eta(r)^*}{\tilde{\omega}_1 - \tilde{E}_g - \tilde{E}_\eta} \right] e_2 \nabla\, F^p_n(r) \right\} \cdot \tag{9}$$

$$\cdot \left\{ \int dr' \left[\sum_{m'} F^s_{m'}(0)\, F^s_{m'}(r')^* + \int d\eta'\, \tilde{F}_{\eta'}(0)\, \tilde{F}_{\eta'}(r')^* \right] e_2 \nabla\, F^p_n(r') \right\}^{-1} .$$

At high values of $\tilde{\omega}_1 - \tilde{E}_g$ the amplitudes M_0 and M are almost equal one to another:

$$M_0 \simeq M , \quad \tilde{\omega}_1 - \tilde{E}_g \gg 1 .$$

Therefore, the exciton effect is significant only near the high frequency edge of the spectrum

$$\omega_2 \simeq \omega_1 - E_g$$

where $d\sigma_0/d\Omega\, d\omega_2$ decreases as $(\tilde{\omega}_1 - \tilde{\omega}_2 - \tilde{E}_g)^{3/2}$ with $\omega_2 \to \omega_1 - E_g$ but $d\sigma/d\Omega\, d\omega_2$ tends to a finite constant

$$\frac{d\sigma}{d\Omega\, d\omega_2} \to 2\pi |M|^2 .$$

For the comparison we represent the values of the cross section $d\sigma_0/d\Omega\, d\omega_2$ and $d\sigma/d\Omega\, d\omega_2$ at $\omega_2 < \omega_1 - E_g$ in the Fig. 1. The relative values of the cross section $d\sigma/d\Omega$ at the discrete spectrum were also given in the same figure.

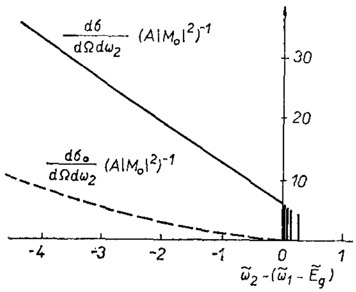

Fig. 1. Solid line: scattering cross section in the presence of the exciton effect (result of our work). Dashed line: scattering cross section when the exciton effect is neglected (Ref. [10]).

Note that in the final state there may be the exciton bound to a neutral donor, for example. Denote by $\varphi(\boldsymbol{r})$ the wave function of this exciton as a point-like particle in a potential field. It is easy to check that the cross section of the scattering process with the creation of an exciton bound to the donor is equal to that with the creation of a free exciton multiplied by a factor [12]

$$N = \frac{1}{V_0} \left| \int \varphi(\boldsymbol{r})\, d\boldsymbol{r} \right|^2 \simeq \frac{50\pi\, a_0^3}{V_0} ,$$

where V_0 is the elementary cell volume. For CdS:

$$V_0 = 5 \times 10^{-23}\, \text{cm}^3 , \quad a_0 = 2{\cdot}8 \times 10^{-7}\, \text{cm}$$

this factor equals

$$N \simeq 6{\cdot}9 \times 10^4 .$$

This means enhancement of the cross-section due to the existence of the exciton bound to the donor.

In conclusion we note that the exciton effect in the two photon absorption was considered in a series of papers [13–15]. The interband electronic Raman scattering in an electromagnetic field with the creation of an exciton was also considered in Refs. [16–17]. However, in these papers the authors did not compare the cross section in two different cases where the exciton effect is or is not taken into account.

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