INTERBAND ELECTRON RAMAN SCATTERING IN SIZE-QUANTIZED FILMS OF INVERSE SEMICONDUCTORS

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The interband electronic Raman scattering in size-quantized films of semiconductor with inverted band structure within the scope of the two band Kane model is studied theoretically. Both the resonance and nonresonance cases are considered in detail. Calculations show, that the spectra of the scattered light exhibit sharp peaks due to the size-quantization. The polarization rules are established. The magnitude of the cross sections suggests that it is possible to observe this effect in an experiment.

The investigation of the low-dimensional systems is of widening interest because of their large possibilities of application in micro- and optoelectronics [1-3]. Typical representatives of such systems are the quantum-confined low-dimensional semiconductor systems. The size decreasing lead to the reconstruction of the electron spectrum what mares possible to fabricate new systems with different electronic and optical properties [2].

It is established that the inelastic light scattering is the sensible method of the investigation of elementary excitations of low-dimensional electron system [4]. It turned out that also as in the three-dimensional case one could separate the one particle excitation from the collective one. This peculiarity gives a possibility of study of energy level structure and collective electron-electron interactions.

The resonance Raman scattering of light involving the electron transitions between the discrete size-quantized levels was observed in $GaAs$-$Ga_{1-x}Al_xAs$ heterostructure [4-6]. In [7] the interband electron Raman scattering (IERS) in inverse layer of MDS structure is considered. In [8] IERS involving the valence size subbands as intermediate states in size-quantized thin semiconductor films with the simple band structure is investigated. It should be noted that the scattered light energy changes in the narrow interval that is equal to the difference of two nearest subbands. However the account of the realistic band structure and wave functions of the semiconductor can lead to many quantitatively new processes with the different frequency intervals for the scattered light [9,10].

Lately the great success are achieved in technology of the thin layers and structures with two-dimensional electron gas based on narrow gap semiconductors as well as semiconductors with inverted band structure [11]. The unique properties have an spin superlattices [12]. In these structures one can manage the energy intervals by different ways. The investigations of Raman scattering on two-dimensional electron gas in above mentioned structures are great interest both the theoretical and practical.

In the present paper the IERS on size-quantized levels in the semiconductors with inverse band structure is investigated (for simplicity the thin films case is considered). It is shown, that owing to the size-quantization the peaks appear in the spectrum of IERS and the scattered light frequency changes in large interval.

In fig.1 the band structure of α-Sn type inverse semiconductors near the Γ point of the Brillouin zone in the case of size-quantization and possible IERS process are shown. The incident photon of frequency of ω_o excites the electron from the light hole subband *(1)* to the conduction subband *(c)*. Simultaneously the electron from the heavy hole subband *(h)* drops back to the hole created by the first transition in the subband *(1)* and emits the photon of frequency of ω_1. The frequency shift $\omega=\omega_o-\omega_1$ is equal to the excitation energy of the particle-hole pair created in the scattering process.

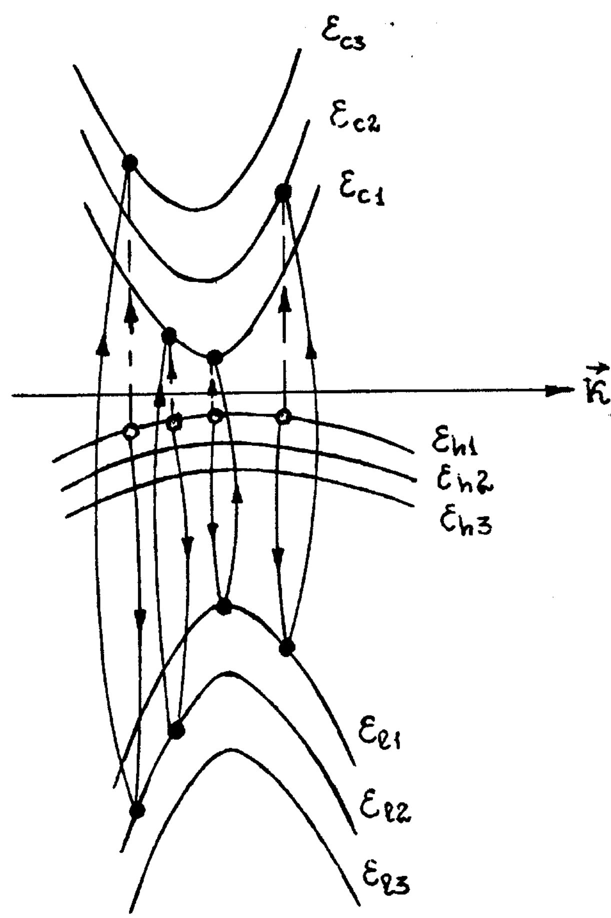

Fig.1. The band structure of zero gap semiconductor near the Γ point in the case of size quantization and possible IERS process.

This process first has been considered by Burstein, Mills and Wallis in bulk inverted semiconductors [10].

The general expression for the differential cross section (DCS) per unit frequency, per unit solid angle can be written in the form:

$$\frac{d^2S}{d\Omega d\omega} = r_0^2 \frac{\omega_1}{\omega_0} \sum_{i,f} |A_{fi}|^2 \hbar\delta(\hbar\omega - E_f + E_i), \quad (1)$$

$$A_{fi} = \frac{1}{m_0}\sum_r \left[\frac{\langle f|\vec{e}_1\vec{p}|r\rangle\langle r|\vec{e}_0\vec{p}|i\rangle}{E_i - E_r + \hbar\omega_0} + \frac{\langle f|\vec{e}_0\vec{p}|r\rangle\langle r|\vec{e}_1\vec{p}|i\rangle}{E_i - E_r - \hbar\omega_1} \right] \quad (2)$$

Here $r_0 = e^2/m_0c^2$ is the classical radius of electron; $\vec{p}$ is its momentum in crystals; i, r, f refer to the initial, intermediate and final states of electron; E_i, E_r, E_f are the corresponding electronic energies; $\vec{e}_0, \vec{e}_1$ and ω_0, ω_1 are, respectively, the polarization vector and frequency of the incident and scattered radiation's.

For rather thick films, when the number of crystalline layers is large, one can calculate the spectrum and wave functions of band electrons in $\vec{k}\vec{p}$ approach [8,13]. In the model of an infinitely deep potential well at the two-band approximation we have [14]:

$$E_{\nu n_\nu}(\vec{k}\perp) = E_{0\nu} + \frac{\hbar^2 k_\perp^2}{2m_{n_\nu}^{(\nu)}} + E_\nu^0 n_\nu^2, \qquad n_\nu = 1,2,3,\ldots \ll N, \quad (3)$$

$$E_\nu^0 = \frac{\hbar^2\pi^2}{2m_\nu d^2}, \qquad \nu = (c,h,1), \qquad \vec{k}_\perp = (k_x, k_x, 0), \quad (4)$$

where

$$\frac{1}{m_n^{(c)}} = \frac{1}{m_c}\left(1 + \frac{3\beta^{1/2}}{\pi n}\frac{(-1)^n - ch(\pi n\beta^{-1/2})}{sh(\pi n\beta^{-1/2})}\right)$$

$$\frac{1}{m_n^{(h)}} = \frac{1}{m_h}\left(1 + \frac{3\beta^{-1/2}}{\pi n}\frac{(-1)^n - ch(\pi n\beta^{1/2})}{sh(\pi n\beta^{1/2})}\right)$$

$$\frac{1}{m_n^{(1)}} = \frac{1}{m_1}, \quad \beta = \frac{m_c}{m_h}.$$

Here d is the thickness of the film, $E_{\nu o}$ is the difference of energies between the extreme of conduction and valence subbands, m is the algebraic effective mass that is $(+)$ for the conduction band and $(-)$ for the valence band.

Using the spectrum (3) and found wave functions for arbitrary $\vec{k}$ for the complicated matrix element (2) in the zz polarization case (when the incident and scattered radiations are polarized parallel to the z axis) we have the following expression:

$$|A_{fi}|^2 = \frac{\pi m_0^2 P^4}{3\hbar^2}\left\{ |A_{hh} + B_{hh}|^2 \frac{k_\perp^4}{k_c^4}\delta_{n_c n_h} + 4\frac{k_\perp^2}{k_h^2}\frac{T_{n_c n_h}^2}{k_c^2 d^2}|A_{hh} + B_{hh}|^2 \right\} \quad (5)$$

where

$$A_{hh} = \left[\varepsilon_g + \hbar\omega_0 + \frac{\hbar^2 k_\perp^2}{2\mu_-} + \varepsilon_0\left(n_c^2 - \frac{m_c}{m_h}n_h^2\right)\right]^{-1},$$

$$B_{hh} = \left[\varepsilon_g - \hbar\omega_0 + \hbar\omega + \frac{\hbar^2 k_\perp^2}{2\mu_-} + \varepsilon_0\left(n_c^2 - \frac{m_c}{m_h}n_h^2\right)\right]^{-1} \quad (6)$$

$$T_{n_c n_h} = \left[1 - (-1)^{n_c - n_h}\right]\frac{2n_c n_h}{n_c^2 - n_h^2}, \qquad k_c^2 = \frac{m_c}{m_{n_c}^{(c)}}k_\perp^2 + \frac{\pi^2 n_c^2}{d^2},$$

$$k_h^2 = \frac{m_h}{m_{n_h}^{(h)}}k_\perp^2 + \frac{\pi^2 n_h^2}{d^2},$$

Substituting (5) and (6) in to (1) for the DCS we get finally:

$$\frac{d^2S_{zz}}{d\Omega d\omega} = \sum_{n_c,n_h} D_0^{(n_c)}\left\{\left|A_{hc}^0 + B_{hc}^0\right|^2 D_1^2\delta_{n_cn_h} + 4\cdot\left|A_{hh}^0 + B_{hh}^0\right|^2 D_2\right\}\theta(D_1) \quad (7)$$

$$\theta(D_1) = \begin{cases}0, & D_1 < 0\\ 1, & D_1 > 0\end{cases};\quad D_1 = 1 - \varepsilon_0\left(n_c^2 + \frac{m_c}{m_h}n_h^2\right)\Big/\hbar\omega,\quad \varepsilon_0 = \frac{\hbar^2\pi^2}{2m_cd^2},$$

$$D_0^{(n_c)} = \frac{3r_0^2m_0^2\varepsilon_g^2}{32\pi\hbar m_{n_c}^{(c)}}\cdot\frac{\omega_1}{\omega_0},\qquad D_2 = \frac{T_{n_cn_h}^2}{\pi^2}\cdot\frac{\varepsilon_0}{\hbar\omega}\left(1 - \frac{\varepsilon_0n_c^2}{\hbar\omega + \varepsilon_0\left(n_h^2 - n_c^2\right)}\right)$$

$$A_{hh}^0 = \left[\varepsilon_g + \hbar\omega_0 + \hbar\omega + \varepsilon_0\left(n_h^2 - n_c^2\right)\right]^{-1},$$
$$B_{hh}^0 = \left[\varepsilon_g - \hbar\omega_0 + 2\hbar\omega + \varepsilon_0\left(n_h^2 - n_c^2\right)\right]^{-1}$$

$$A_{hc}^0 = A_{hh}^0\cdot\delta_{n_cn_h},\quad B_{hc}^0 = B_{hh}^0\cdot\delta_{n_cn_h},\quad A_{h1}^0 = A_{hh}^0\cdot\delta_{n_1n_h},\quad B_{h1}^0 = B_{hh}^0\cdot\delta_{n_1n_h},$$
$$\frac{1}{\mu_\pm} = \frac{1}{m_{n_c}^{(c)}} \pm \frac{1}{m_{n_h}^{(h)}},\quad H_{hc}^0 = A_{hc}^0 + B_{hc}^0,\quad H_{hh}^0 = A_{hh}^0 + B_{hh}^0$$

A like the bulk case, when two different geometries take place (the cubic symmetry is supposed) [9], in the thin film case there are four geometries: xx, xy, xz, zz.

Carrying out the similar calculations for the other geometries we have (as for as the quantitative behavior of DCS in xy geometry is similar to xx case, we give below the expressions only for xz and xx geometries):

$$\frac{d^2S_{xz}}{d\Omega d\omega} = \frac{1}{4}\sum_{n_c,n_h} D_0^{(n_c)}\left\{\left[\left(\left(B_{hc}^0\right)^2 + \frac{9}{2}\left(A_{hc}^0\right)^2\right)^2 D_1^2 + 2\cdot\left(\frac{A_{hc}^0D_1}{2} + 2D_3\right)^2\right]\delta_{n_cn_h} + \right.$$
$$\left. + 2\cdot\left[\left(A_{hc}^0 + B_{hc}^0\right)^2 + 2\cdot\left(B_{hh}^0\right)^2\right]D_2 + 8\cdot\left|D_3\right|^2_{n_c\neq n_h}\right\}\theta(D_1) \quad (7a)$$

$$\frac{d^2S_{xx}}{d\Omega d\omega} = \frac{1}{8}\sum_{n_c,n_h} D_0^{(n_c)}\left\{\left[\frac{13}{4}\left(H_{hc}^0\right)^2\cdot D_1 + \left(\frac{H_{hc}^0D_1}{2} - 2D_3\right)^2\right]\delta_{n_cn_h} + \right.$$
$$\left. + 2\cdot\left[5\cdot\left(H_{hc}^0\right)^2 + \left(H_{hh}^0\right)^2 - 2\cdot H_{hh}^0H_{hc}^0\right]\cdot D_2 + 4\cdot\left|D_3 + D_4\right|^2_{n_c\neq n_h}\right\}\theta(D_1), \quad (7b)$$

$$D_3 = \frac{\varepsilon_0}{\hbar\omega}\sum_{n_1}\frac{B_{h1}^0T_{n_cn_1}T_{n_1n_h}}{\pi^2\left[1 + \varepsilon_0\left(n_h^2 - n_c^2\right)/\hbar\omega\right]^{1/2}};\qquad D_4 = \frac{\varepsilon_0}{\hbar\omega}\sum_{n_1}\frac{A_{h1}^0T_{n_cn_1}T_{n_1n_h}}{\pi^2\left[1 + \varepsilon_0\left(n_h^2 - n_c^2\right)/\hbar\omega\right]^{1/2}}$$

It is seen from (7) that in the case of zz polarization there are both the process with $\Delta n=n_c-n_h=0$ and the processes with $\Delta n=n_c-n_h=1,3,5...$

In dependence on pump energy there are two cases: resonance $(\hbar\omega_0>\varepsilon_g)$ and nonresonance $(\hbar\omega_0<\varepsilon_g)$. For the both cases the scattering begins from the threshold $n_c=n_h=1$, that corresponds to the transition energy between first subbands of conduction and heavy hole bands

$$\omega_{th} = \hbar^2\pi^2/2\mu_+d^2 \quad (8)$$

In the nonresonance case DCS beginning from the threshold initially increases. Then having reached maximum DCS begins to fall till the value corresponding to the transition energy between second subbands of conduction and heavy hole bands. Next with tendency of further decrease the following peaks appear and for $\omega=\omega_0$ DCS is zero.

In the resonance case the different resonance frequencies correspond to the processes with $\Delta n=o$ and with $\Delta n\neq o$:

$$\hbar\omega_R(\Delta n = 0) = \left(\hbar\omega_0 - \varepsilon_g\right)/2 \quad (9)$$

$$\hbar\omega_R(\Delta n \neq 0) = \left[\hbar\omega_0 - \varepsilon_g - \varepsilon_0\left(n_h^2 - n_c^2\right)\right]/2 \quad (10)$$

The energy distance between this resonances is

$$\Delta\hbar\omega_R = \left|\varepsilon_0\left(n_h^2 - n_c^2\right)/2\right| \quad (11)$$

The condition (10) completely coincides with the resonance condition in the bulk case [10], that is the conse-

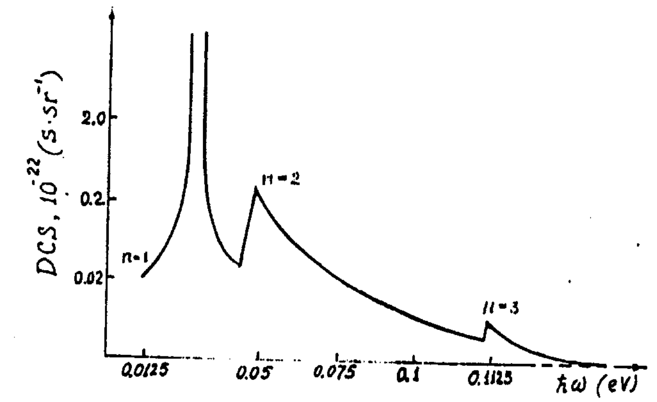

Fig.2. The dependence of DCS vs. $\hbar\omega$ in the resonance case ($\hbar\omega_0>\varepsilon_g$) .

quince of the use of two-band Kane model where $m_c=m_1$ and $(m_c/m_h)\to 0$. But condition (10) strongly depends on thickness, effective mass and subband numbers.

In fig.2 DCS vs. $\hbar\omega$ in the resonance case ($\hbar\omega_0>\varepsilon_g$) for the process with $\Delta n=0$ is shown. For parameters the following values a chosen: $\hbar\omega_0$=0.37 eV, ε_g=0.3 eV, $m_c=0.03m_o$, $m_h=0.4m_o$, d=200 Å. The dependence of DCS on $\hbar\omega$ for different thickness for the same process and for the same parameters is given in fig.3.

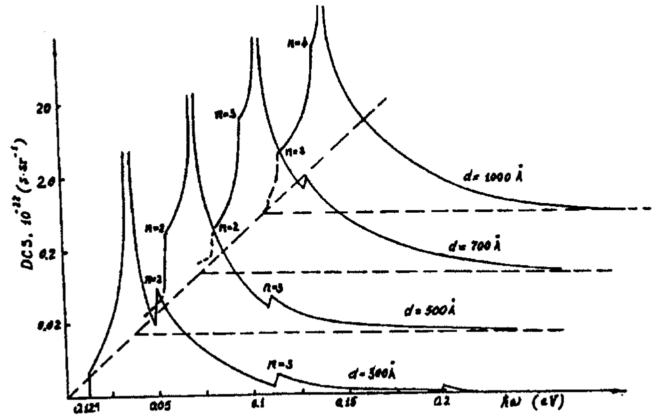

Fig.3. The DCS vs. $\hbar\omega$ for the different thickness in the resonance case.

As distinct from zz geometry the additional processes with $\Delta n=n_c-n_h=2,4,6...$ arise in xz and xx geometries.

It should be noted that the obtained results can be applied to two dimensional in double heterostructure [15] is a case in a point. The obtained expressions may be useful also for analyses of IERS spectra in superlattices.

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İNVERS ZONA QURULUŞLU YARIMKEÇİRİCİ NAZİK LÖVHƏLƏRDƏ İŞIĞIN ZONALARARASI KOMBİNASİYALI ELEKTRON SƏPİLMƏSİ

Məqalədə ikizonalı Keyn modeli çərçivəsində invers zona quruluşuna malik yarımkeçirici nazik lövhələrdə işığın zonalalarası kombinasion elektron səpilməsi nəzəri olaraq tədqiq edilmişdir. Göstərilmişdir ki, işığın səpilmə spektrində ölçü kvantlanması ilə əlaqədar kəskin maksimumlar (piklər) əmələ gəlir. Polyarizasiya asılılıqları müəyyənləşdirilmişdir. Diferensial effektiv kəsiyin tərtibi bu effektin eksperimentdə müşahidə olunmasının mümkünlüyünü göstərir.

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МЕЖЗОННОЕ ЭЛЕКТРОННОЕ КОМБИНАЦИОННОЕ РАССЕЯНИЕ СВЕТА В ТОНКИХ ПЛЕНКАХ ИНВЕРСНЫХ ПОЛУПРОВОДНИКОВ

В рамках двухзонной модели Кейна теоретически исследовано межзонное электронное Раман-рассеяние в размерно-квантованных пленках полупроводников с инверсной зонной структурой. Рассмотрены как резонансный, так и нерезонансный случаи. Показано, что спектр рассеянного света содержит резкие пики, обусловленные размерным квантованием. Установлены поляризационные зависимости. Порядок дифференциальных эффективных сечений указывает на возможность экспериментального наблюдения этого эффекта.

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