Simple Analysis Of The Photoemmision From Quantum Wells, Wires And Dots Of Non-Linear Optical Materials

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Abstract

We study the photoemission from quantum wells (QWs), quantum well wires (QWWs) and quantum dots (QDs) of non-linear optical materials on the basis of a newly formulated electron dispersion law considering the anisotropies of the effective electron masses, the spin-orbit splitting constants and the presence of the crystal field splitting within the framework of ***k. p*** formalism. It has been found taking quantum confined $CdGaAs_2$ and $Hg_{1-x}Cd_xTe$ as an examples that the photoemission exhibits quantized variations with incident photon energy. The photoemission is the greatest for QDs and the least for QWs.

INTRODUCTION

In recent years, the importance of QWs, QWWs and QDs are already well known in the whole field of nanoscience and technology. Although many new effects associated with quantum confinement have already been reported, nevertheless it appears from the literature that the photoemission from quantum confined materials has been relatively less studied [1]. Therefore it would be of interest to study the photoemission from quantum-confined non-linear optical, optoelectronic and related materials respectively**.** In this context it is noted that Kildal [2] proposed the energy spectrum of the conduction electrons in non-linear optical materials under the assumptions of isotropic momentum matrix element and isotropic spin orbit splitting respectively, although the anisotropies of the aforementioned band parameters are the significant physical features of the said compound. Besides, the III-V optoelectronic compounds finds extensive application in distributed feedback lasers and infrared photodetectors. In what follows, we shall study the photoemission in quantum confined $CdGeAs_2$ on the basis of a newly formulated electron dispersion law by considering the aforementioned anisotropies of the energy bands constants together with the inclusion of crystal field splitting constant respectively. We shall take $Hg_{1-x}Cd_xTe$ as examples of optoelectronic materials which forms a special case of our generalized analysis.

Theoretical Background

The dispersion relation of the conduction electrons in bulk specimens of non-linear optical materials within the framework of **k.p** formalism can be expressed as [3]

$$\gamma(E) = f_1(E)k_x^2 + f_2(E)k_z^2 \tag{1}$$

where the notations are defined in the above reference.

The use of Equation (1) leads to the expressions of the photoemission from QW, QWW and QDs of nonlinear optical materials as

$$J_{2D} = \frac{\alpha_o.q}{h.d_z}\sum_{n_{z\min}}^{n_{z\max}}\Theta_1\left(E_{n_z}\right)\left[T_1(E_F,n_z)+T_2(E_F,n_z)\right] \tag{2}$$

$$J_{1D} = \frac{4\alpha_o q}{h d_y d_z}\sum_{n_y=1}^{n_{y\max}}\sum_{n_{z\min}}^{n_{z\max}}\Theta_1\left(E_{n_z}\right)\left[t_1\left(E_F,n_y,n_z\right)+t_2\left(E_F,n_y,n_z\right)\right] \tag{3}$$

and

$$J_{0D} = \frac{\alpha_o q}{2}\sum_{n_x=1}^{n_{x\max}}\sum_{n_y=1}^{n_{y\max}}\sum_{n_z=1}^{n_{z\max}}\frac{2}{\hbar}\Theta_1\left(E_{n_z}\right)\frac{2}{d_x d_y d_z}F_{-1}(\eta) = \frac{2\alpha_o q}{\hbar d_x d_y d_z}\sum_{n_x=1}^{n_{x\max}}\sum_{n_y=1}^{n_{y\max}}\sum_{n_{z\min}}^{n_{z\max}}\Theta_1\left(E_{n_z}\right)F_{-1}(\eta) \tag{4}$$

It appears than that the evaluation of the photoemission requires an expression of carrier statistics which can be written under the conditions of quantum confinement as

$$n_o = \frac{1}{2\pi d_z}\sum_{n_z=1}^{n_{z\max}}\left[T_1(E_F,n_z)+T_2(E_F,n_z)\right] \tag{5}$$

$$n_o = \sum_{n_y=1}^{n_{y\max}}\sum_{n_z=1}^{n_{z\max}}\int_{E'}^{\infty}N_{1D}(E)\,f(E)dE = \frac{2}{\pi}\sum_{n_y=1}^{n_{y\max}}\sum_{n_z=1}^{n_{z\max}}\left[t_1\left(E_F,n_y,n_z\right)+t_2\left(E_F,n_y,n_z\right)\right] \tag{6}$$

$$n_o = \frac{2}{d_x d_y d_z}\sum_{n_x=1}^{n_{x\max}}\sum_{n_y=1}^{n_{y\max}}\sum_{n_z=1}^{n_{z\max}}F_{-1}(\eta) \tag{7}$$

Under the condition $\Delta_{\square} = \Delta_{\perp} = \Delta$ (the isotropic spin orbiting constant), $\delta = 0$, $m_{\square}^* = m_{\perp}^* = m*$ (the isotropic effective electron mass at the edge of the conduction band), the Eq. (1) assumes the form

$$\frac{\hbar^2 k^2}{2m^*} = I(E), \tag{8}$$

$$I(E) \equiv \frac{E\left(E+E_g\right)\left(E+E_g+\Delta\right)\left(E_g+\frac{1}{3}\Delta\right)}{E_g\left(E_g+\Delta\right)\left(E+E_g+\frac{2}{3}\Delta\right)} \tag{9}$$

The Eq. (9) describes the dispersion relation of the conduction electrons in III-V, ternary, and quaternary materials and is well known in the literature as the three-band model of Kane, which should in turn be used as such for studying the electronic properties of such compounds where the spin orbit splitting constant is of the order of band gap [4].

RESULTS AND DISCUSSION

Using the appropriate equations and taking the parameters [5] $E_g = 0.57eV$, $\Delta_{\square} = 0.30eV$, $\Delta_{\perp} = 0.36eV$, $\alpha_o = 1$, $m_{\square}^* = 0.034m_o$, $m_{\perp}^* = 0.039m_o$, $\delta = -0.21eV$ and $T = 4.2K$, we have plotted in Fig.1 the normalized photoemission from QWs, QWWs and QDs of n-$CdGeAs_2$ as shown by the curves *(a)*, (a') and (a'') respectively as a function of the incident photon energy where the plots *(b)*, (b') and (b'') exhibits the same dependence for quantum confined $Hg_{1-x}Cd_xTe$ in accordance with the three-band model of Kane which is a special case of our generalized analysis and where the band constants are given by $E_g = \left(-0.302 + 1.93x + 5.35\times10^{-4}(1-2x)T - 0.810x^2 + 0.832x^3\right)eV$, $m^* = 0.1m_o E_g(eV)^{-1}$, $T = 4.2K$ and $\Delta = \left(0.63 + 0.24x - 0.27x^2\right)eV$.

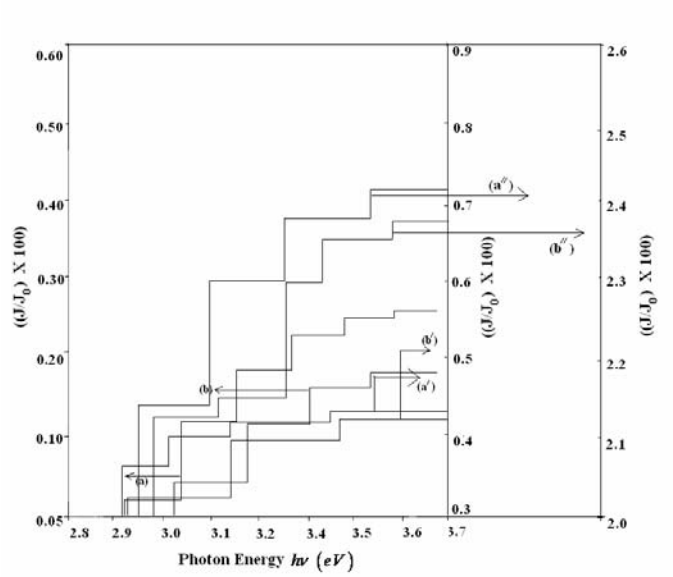

Fig1. The plots of the normalized photoemission as a function of incident photon energy in QWs *(a)*, QWWs (a') and QDs (a'') of $CdGeAs_2$. The plots of QWs *(b)*, QWWs (b') and QDs (b'') of $Hg_{1-x}Cd_xTe$ exhibit the same dependence as shown for quantum confined $CdGaAs_2$.

The appearance of the humps of the Fig.1 is due to the redistribution of the electrons among the quantized energy levels when the size quantum number corresponding to the highest occupied level changes from one fixed value to the others. With varying electron concentration, a change is reflected in the photoemission through the redistribution of the electrons among the size-quantized levels. It may be noted that the quantum dots lead to the discrete energy levels, somewhat like atomic energy levels, which produce very large changes. This follows from the inherent nature of the quantum confinement of the electron gas dealt with here. In quantum dots, there remain no free electron states in between any two allowed sets of size-quantized levels unlike that found for QWs and QWWs where the quantum confinements are 1D and 2D,

respectively. Consequently, the crossing of the Fermi level by the size-quantized levels in quantum dots would have much greater impact on the redistribution of the electrons among the allowed levels, as compared to that found for QWs and QWWs respectively. Although the photoemission varies in various manners with all the variables in all the limiting cases, the rates of variations are totally band-structure dependent.

The Fig.1 illustrates the dependence of the photoemission from quantum-confined materials on the incident photon energy. The electrons create a net emission current comprising a number of ladderlike steps. The quantum oscillations of the photocurrent in QDs exhibit greater numerical magnitudes as compared to the same from QWs and QWWs. From Fig.1, we observed that the photoemission exhibits plateaus as a function of incident photon energy, which is important from an experimental point of view, analogous to the same type of plateaus, which have been observed in quantum Hall effect in the variation of quantizing magnetic field. The reason for such an observation in quantum Hall effect is well known in the literature. The basic physics of 3D quantization in quantum Hall effect is radically different from the quantum confinement of our present paper, although the existence of the same type plateaus in both the radically different systems. The detailed experimental investigations with respect to this point will uncover the phenomena.

It must be mentioned that a direct research application of the quantum confinement of materials is in the area of band structure [6]. By mapping, the discrete quantum state energies as a function of film thickness is a given crystal direction, information about the effective masses and the dispersion relations may be derived[6]. Finally, it may be noted that the basic aim of this article is not solely to demonstrate the influence of quantum confinement on the photoemission from non-linear optical materials but also to formulate the appropriate electron statistics in the most generalized form, since the transport and other phenomena in semiconductors having different band structures and the derivation of the expressions of many important electronic properties are based on the temperature-dependent electron statistics in such materials.

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