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INVESTIGATION OF FACTORS AFFECTING THE RADIATION INTENSITY OF QUANTUM WELLS

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Abstract

We study the possibilities of increasing the light-emission intensity of quantum wells. We describe the influence of the quantum-well width and the effective mass of charge carriers on the radiation intensity. Since the formation of negatively charged layers near the quantum well can increase the photon emission, we propose to form the charged layers with the use of ion implantation. The results of the study can be implemented in the field of quantum-size light-emitting structures and sensors.

Keywords: light-emitting structure, quantum well, photon emission, Coulomb interaction, electron energy levels.

1. Introduction

Quantum well light-emitting solid-state structures have well-known advantages over the structures of wide (classical) active region [1–5]. Changing the quantum-well width is accompanied with shifting of radiation frequency, because changing of photons energy with narrowing of the active region yields in a shorter radiation wavelength of quantum-well structures. This effect provides wide opportunities for managing properties of light-emitted structures. In quantum wells, the number of inverse-populated states is smaller than that in a double heterostructure of thick active layer [1]. Therefore, the threshold current of quantum-well lasers is much lower than the threshold current of a thick-layer double heterostructure. In addition, photon generation in quantum-well lasers is possible not only at room temperature [6–8] but also at higher temperature up to 310 K [7].

An influence of different factors on quantum-well features is the subject of many theoretical and experimental studies [9–14]. As shown in [11], the laser emission from quantum well takes place at a lower photon energy than the lowest energy of confined particle transition. That occurs due to discrete character of the energy structure and density function of electron states in quantum wells. Luminescence with the photon energy below the exciton-transition energy also observed in periodic quantum wells due to the tunneling phenomenon [12]. Light-emitting structures of a quantum-well type were studied in [13], using scanning tunneling microscopy; it was revealed that photons are emitted at higher energy than that of tunneling electrons. As noted in [13], two-electron processes can cause quantum-well transitions and corresponding light emission. Quantum wells in semiconductor structures can generate terahertz

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electromagnetic dipole radiation [14]. This indicates the existence of charge oscillations in semiconductors associated with wave-packet dynamics.

Analysis of factors influencing on the radiation intensity and finding of attainable ways to increase light emission are the main tasks of our work. Aspects of the quantum-well model examined in our study are as follows: (i) the selection rule in connection to the light-emitting phenomenon; (ii) evaluation of the radiation intensity dependence on physical parameters of the two-dimensional quantum structure; (iii) estimation of the radiation intensity in the classical limit; (iv) the influence of the charge layers on the radiation.

2. Characterization of the Photon Emission Intensity of Quantum Wells

In this section, we study the influence of parameters of the quantum well on the radiation intensity; the parameters under our investigation are the width of the quantum well and the effective mass of charge carriers, which is a function of the band structure of the solid matter.

Due to the spatial quantization of the spectra of charge carriers, the light-emission generation frequency is determined by the space between the energy levels of electrons and holes in a quantum well not only by the band gap width. In semiconductor quantum wells, a thin ($5-20$ nm) compound layer of low-band gap energy is placed between two layers of high-band gap energy. Thus, the potential well for electrons is formed near the valence band, while for holes it is formed near the conduction band. The movement of electrons and holes in the thin structure is restricted, and the width of the quantum well is comparable to the de Broglie wavelength of charge carries. Therefore, the quantum size effect takes place.

Spontaneous and stimulated transitions of electrons in quantum wells are described by the Einstein formula

$$B_{nm} = B_{mn} = A_{nm}\frac{\pi^2 c^3}{\hbar\omega^3}, \tag{1}$$

where A and B are the Einstein coefficients accounting for the probabilities of the spontaneous and stimulated emission, ω is the photon frequency, c is the speed of light in vacuum, and $\hbar$ is the Planck constant. The probability of spontaneous transitions is expressed by an element of the transition matrix

$$A_{nm} = \frac{q^2\omega^3}{3\pi\varepsilon_0 c^3\hbar}|\mathbf{r}_{nm}|^2, \tag{2}$$

where q is the electron charge, ε_0 is the vacuum permittivity, and $\mathbf{r}_{nm}$ is the transition matrix element. For the one-dimensional motion, it can be expressed as

$$A_{nm} = \frac{q^2\omega^3}{3\pi\varepsilon_0 c^3\hbar}|x_{nm}|^2. \tag{3}$$

For an infinitely deep potential well, we have [15]

$$\psi_n(x) = \sqrt{\frac{2}{a}}\sin\left(\frac{\pi n}{a}x\right), \tag{4}$$

$$E_n = \frac{\pi^2\hbar^2}{2m_e a^2}n^2, \qquad n = 1,\, 2,\, 3, \ldots, \tag{5}$$

where m_e is the electron mass and a is the well width. The matrix element reads

$$x_{nm} = \int_0^a \psi_n^*(x)\, x\, \psi_m(x)\, dx. \tag{6}$$

From (6) we obtain the integral

$$x_{nm} = \frac{2}{a} \int_0^a \sin\left(\frac{\pi n}{a} x\right) \sin\left(\frac{\pi m}{a} x\right) x\, dx = 2a \int_0^1 \sin(\pi n \xi) \sin(\pi m \xi) \xi\, d\xi. \tag{7}$$

In view of (7), we define the following selection rule: n and m cannot be odd and even at the same time. In this case, the integral is simplified to

$$x_{nm} = -\frac{8anm}{\pi^2 (n^2 - m^2)^2}, \qquad n > m. \tag{8}$$

The photon emission intensity is

$$I_{nm} = \hbar\omega\, A_{nm} = \frac{q^2 \omega^4}{3\pi\varepsilon_0 c^3} |x_{nm}|^2 = \frac{64 q^2 \omega^4 a^2}{3\pi^5 \varepsilon_0 c^3} \left[\frac{nm}{(n^2 - m^2)^2}\right]^2; \tag{9}$$

here, the frequency can be eliminated. Using expression (5), we arrive at

$$\omega = \frac{\Delta E_{nm}}{\hbar} = \frac{\pi^2 \hbar}{2 m_e a^2} (n^2 - m^2). \tag{10}$$

Substituting (5) and (10) in (9), we obtain

$$I_{nm} = \frac{4}{3\varepsilon_0 a^6} \left(\frac{\hbar}{m_e}\right)^4 \left(\frac{\pi}{c}\right)^3 (qnm)^2, \tag{11}$$

where m_e is an effective mass value used for real materials [3]. Formula (11) reveals the dependence of the light-emission intensity on the electron transitions in the quantum well. In addition, it is worth clarifying an important point, namely, if we consider the radiation of a quantum harmonic oscillator, the quantum number can only change by one. Any transitions of electrons at $n > m$ from even levels to odd ones and from odd levels to even ones are allowed in a quantum well.

As follows from (11), there are three ways to increase the radiation intensity of quantum well: (i) to reduce the thickness of the two-dimensional structure; (ii) to decrease the electron effective mass; (iii) to use the high-energy levels. Narrowing of the active region down to several nanometers is achievable with the use of high-precision fabrication technologies, for example, molecular beam epitaxy. Extremely strong dependence of the light-emission intensity on the potential-well width (we derived the power function $I_{nm} \propto 1/a^6$) can be applied for the creation of sensors; capabilities of pressure sensors based on quantum wells were analyzed in [16, 17]. As for materials characterized by low effective mass of electrons, A_3B_5 compounds seem to be prospective, e.g., indium antimonide. We also note that the mobility of charge carriers is inversely proportional to their effective mass. Therefore, to create light-emitting structures, semiconductor materials with high mobility of charge carriers should be used. Finally, high-energy levels in light-emitting structures are realized with current pumping.

Now we quantitatively compare the quantum-well radiation with the classical-dipole radiation. To do this, we calculate the radiation intensity of the quantum well in the classical limit, which takes place at high quantum numbers. For transitions between neighboring levels, we have $m = n - 1$. In this case,

$$I_{n,n-1} = \frac{64q^2\omega^4a^2}{3\pi^5\varepsilon_0c^3}\left[\frac{n(n-1)}{(2n-1)^2}\right]^2. \tag{12}$$

For large values of the quantum number, in the limit we obtain

$$I_c = \lim_{n\to\infty} I_{n,n-1} = \frac{4q^2\omega^4a^2}{3\pi^5\varepsilon_0c^3}. \tag{13}$$

To represent the dipole-radiation intensity, we use the well-known expression

$$I_c = \frac{q^2\omega^4a^2}{12\pi\varepsilon_0c^3}, \tag{14}$$

where a is the charge oscillation amplitude. Thus, we find that in the classical limit, the dipole-radiation intensity is noticeably greater than the photon-radiation intensity of a quantum well, namely,

$$\frac{I_c^{\mathrm{D}}}{I_c^{\mathrm{QW}}} = \frac{\pi^4}{9} \approx 10.823.$$

In the next section, we propose an effective way to increase the quantum-well radiation intensity.

3. Influence of Charge Layer on Electronic Spectrum

In this section, we consider the influence of static charges on the quantum-well features. In the simple case, we estimate the change in the energy spectrum of electrons under the influence of the Coulomb repulsion force from the side of one wall with the coordinate $x = 0$. The interaction potential is equal to $\dfrac{q^2}{4\pi\varepsilon_0x}$. Taking into account this potential in the first-order perturbation theory, we obtain

$$\Delta E_n^{(1)} = \frac{q^2}{4\pi\varepsilon_0}\int_0^a \frac{|\psi(x)|^2}{x}\,dx = \frac{q^2}{4\pi\varepsilon_0a}\int_0^a \frac{\sin^2(\pi nx/a)}{x}\,dx = \frac{q^2}{8\pi\varepsilon_0a}\left[\gamma + \ln(2\pi n) - \mathrm{Ci}\,(2\pi n)\right], \tag{15}$$

where $\gamma \approx 0.5772$ is the Euler–Mascheroni constant and $\mathrm{Ci}\,(x)$ is the cosine integral. The estimate value (15) is valid if the Coulomb interaction energy is significantly smaller than the kinetic energy of the particle. For sufficiently large n, we arrive at

$$E_n \approx \frac{\pi^2\hbar^2n^2}{2m\,a^2} + \frac{q^2}{8\pi\varepsilon_0a}[\gamma + \ln(2\pi n)]. \tag{16}$$

For simplicity, the cosine integral in (16) is omitted. Coulomb repulsion leads to "heating" of electrons in a potential well, since the distances between energy levels increase by $\dfrac{q^2\ln(n/m)}{8\pi\varepsilon_0a}$.

According to Eq. (9), the radiation intensity is related to the transition frequency (i.e., to the energy) as $I_{nm} \propto \omega^4$. Consequently, our estimate (16), where the magnitude and sign of charge near the well are taken into account, reveals the influence of charge on the radiation intensity. As a result, we draw the main conclusion: The creation of negatively charged layer near the potential well with electrons should enhance radiation. If there are two charged layers near the quantum-well walls, then estimate (15) should be multiplied by two. The decrease in energy levels due to the Coulomb attraction likely contributes to the Bose–Einstein condensation.

4. Summary

Summarizing, in this paper we discussed the main physical factors that affect the radiation intensity of quantum wells. We derived a new formula which allows one to take into account the effect of the quantum-well width and the effective mass of charge carriers on the radiation intensity. The selection rule for electronic transitions in a quantum well is obtained. The radiation intensity of a quantum well in the classical limit is calculated and the comparison with dipole radiation is made. We showed that the dipole radiation intensity is noticeably greater than the photon radiation intensity of the quantum well. The shift of electron energy levels in the presence of negative charges on quantum-well walls is estimated. It was revealed that formation of negatively charged layers near the quantum-well region should lead to increase in the light-emission intensity. The results obtained can be implemented in the design and technology of quantum-size light-emitting structures and sensors.

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