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Magnetic field tunability of quantum dot infrared photodetectors

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Abstract

The effect of external magnetic field on the photoresponse of quantum dot photodetectors is studied numerically. Application of an external in-plane magnetic field results in frequency shift of the absorption lines of a photodetector and the appearance of new absorption peaks. The positions of the new peaks and their relative strengths depend on the type of optical transitions and on the size of quantum dot in the active region of the photodetector.

1. Introduction

Infrared photodetectors (IP) based on the quantum properties of nanostructures have been the subject of both experimental and theoretical research [1]. The active regions of such photodetectors consist of quantum wells [1], quantum dots [2, 3], or their combinations [4, 5]. The optical transitions between the levels of dimensional quantization of nanoscale active regions of IPs determine their optical response. Due to discrete nature of energy levels of quantum nanosystems the infrared photodetectors are sensitive only to fixed discrete frequencies of external illumination. These frequencies depend on the design of active region of IP. At the same time in many applications it is very important to have tunable photodetector, when the response frequency of a given configuration of photodetector can be tuned by external factors. One of the ways to tune the photoresponse frequency of infrared photodetectors is to apply an electric field, i.e. bias voltage, in the growth direction of the IP structure. In this approach the bias voltage not only shifts the relative positions of energy levels in active region of IP and correspondingly the response frequencies, but also affects the photocurrent.

Here we consider another approach to the problem of tuning photoresponse frequencies. This approach is based on application of external magnetic field to an infrared photodetector. Below we consider only in-plane (parallel) magnetic field, which is perpendicular to the growth direction, i.e., to the direction of photocurrent. The effects of magnetic field on the optical and transport properties of quantum well structures has been studied extensively for different systems [6, 7]. The main effect of parallel magnetic field is the momentum shift of the electron dispersion. This fact can strongly influence the processes, such as tunneling and optical transitions, where conservation of two-dimensional momentum is involved. In optics this results, for example, in the shift of quantum cascade laser lines and its broadening [8], although the disorder can suppress the effect of the parallel magnetic field [9].

To cover the different types of optical transitions in infrared photodetectors we study dot-in-a-well photodetectors [4]. In these photodetectors the quantum dot layer is grown within quantum wells. The structure is shown schematically in figure 1. The photodetector shows the response to three different wavelength corresponding to three different types of optical transitions (absorptions). All transitions occur from the ground state of the dot, where the electrons stay without illumination. The different optical transitions are:

(i) transitions from the ground to the excited states of the same quantum dot, where due to optical selection rules the transitions mainly occur into the first excited state of the dot;
(ii) transitions from the ground state of the quantum dot into continuous states of quantum well;
(iii) transitions from the ground state of the dot into 3D continuous states of the active region.

Below we study the effect of magnetic field only on the first two types of optical transitions. For these optical transitions the photoresponse of the infrared photodetectors is determined by two main processes: the first one is the optical transition of an electron from the ground state into the excites states and the second one is the escape of the electron from the excited states into 3D continuous states. The magnetic field should modify the rates of both processes. Below we study the magnetic field effects on the photoabsorption rate only. The escape process usually has the tunneling nature, i.e. under

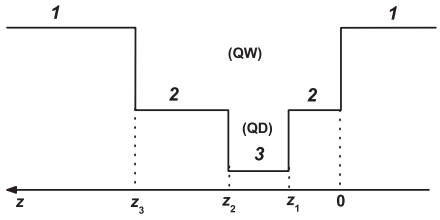

Figure 1. Infrared photodetector with dot-in-well geometry is shown schematically. The structure is shown along the growth direction. The numbers 1, 2, and 3 stand for GaAs, $In_xGa_{1-x}As$ (quantum well), and InAs (quantum dot), respectively. For concreteness we choose $x = 0.15$. The direction of axis z is the growth direction.

applied bias voltage the electron tunnels through the potential barrier into the continuous states. The parallel magnetic field introduces additional potential barrier, which should suppress the tunneling and correspondingly the escape rates [10]. For some parameters of photodetectors the main channel of the tunneling escape is a phonon-assisted tunneling. In this case the emission of phonons suppresses the potential barrier due to a magnetic field and tunneling rate has weak dependence on the magnetic field [10].

2. Main system of equations

To calculate the photoabsorption rate we assume that the electric field, i.e. the bias voltage, is zero. Then we find numerically the energy spectra and corresponding wavefunctions of a single active region of photodetector in parallel magnetic and calculate the optical absorption rates from the ground state of the active region. The active region of photodetector is shown schematically in figure 1. It consists of $In_xGa_{1-x}As$ quantum well and InAs quantum dot in the quantum well. The Hamiltonian of an electron in the active region has the following form

$$\mathcal{H} = \left(\vec{p} + e\vec{A}\right)\frac{1}{2m^*}\left(\vec{p} + e\vec{A}\right) + V(\vec{r}) + \frac{1}{2}g\mu_B B\sigma_y, \quad (1)$$

where the charge of the electron is $-e$ and m^* is an effective electron mass, which takes the following values in different regions: $0.67m_e$ (GaAs), $0.06m_e$ (InGaAs), and $0.04m_e$ (InAs). The effective mass in InAs quantum dot takes into account the stain effects within the quantum dot region [11]. Here $\vec{A} = (Bz, 0, 0)$ is the vector potential corresponding to magnetic field applied in the $\hat{y}$ direction. The potential $V(x, y, z)$ in equation (1) is due to conduction band discontinuity and describes the quantum dot and quantum well structure. In our calculations we take the following values for discontinuity of conduction band: $V_{InGaAs} - V_{GaAs} = 477$ meV and $V_{GaAs} - V_{InGaAs} = 93$ meV. The last term in equation (1) describes the spin degrees of the freedom of electrons and results in the Zeeman splitting of the energy levels with different electron spin. We are interested only in a single electron picture and do not take into account spin–orbit coupling. Then the spin dynamics can be separated from the spatial motion. We also disregard the Zeeman term in equation (1) assuming that the direction of electron spin is always along axis y.

Below we assume that the quantum dot has a pyramidal shape with a square base and the sides of the base are parallel to the x and y axis. The size of the dot is characterized by the size of the base D and the height of the dot h. Below we take h to be equal to half of the size of the base D, $h = D/2$. In growth (z) direction the system is characterized by parameters z_1, $z_2 - z_1$ (region of QD), and $z_3 - z_2$, see figure 1. We take the following typical values of these parameters: $z_1 = 2$ nm and $z_3 - z_2 = 6$ nm. The size $z_2 - z_1$ is equal to the sum of the height of the dot and the width of the wetting layer, 1.24 ML. The width of GaAs layers introduces the finite size of the system. For both layers we take 10 nm. The size of the system in x–y plane is $D + 30$ nm in both x and y directions. We are using periodic boundary conditions in the x–y plane. As a next step we find numerically wavefunctions, $\psi_i(\vec{r})$, and energy spectrum, E_i, corresponding to Hamiltonian (1) for a finite size system replacing the derivatives by finite differences. The corresponding Hamiltonian matrix is sparse. To diagonalize the matrix we have used the Arnoldi–Lanczos algorithm. The maximum size of the matrix was $350\,000 \times 350\,000$.

With the known wavefunctions we calculate the optical absorption spectra from the following expression

$$I_\mu(\omega) \propto \sum_f \left| \int d\vec{r}\, \psi_i^*(\vec{r}) r_\mu \psi_f(\vec{r}) \right|^2 \delta\left(E_f - E_i - \hbar\omega\right), \quad (2)$$

where ψ_i and E_i are the wavefunction and the energy of the initial state, which is the ground state of the system; $\mu = x, z$ and $r_x = x$, $r_z = z$. In equation (2) we take into account that one of the main advantages of quantum dot photodetectors over the quantum well ones is that the quantum dot photodetectors are sensitive not only to z-polarized light but also to the in-plane polarization, for example, to x-polarized illumination. Therefore, for the quantum dot photodetector we need to study the effects of magnetic field on the absorption spectra for both polarizations of light.

We should expect the visible effect of magnetic field on the energy and optical spectra when the magnetic length, $l_B = (\hbar/eB)^{\frac{1}{2}}$, becomes comparable to the characteristic size of the system, such as width of the quantum well and the height of the quantum dot. For example, for $B = 5$ T the magnetic length is equal to $l_B \approx 11$ nm and around this value we should expect the manifestation of parallel magnetic field in photoresponse spectra of photodetectors.

3. Results and discussion

The results of calculations are shown in figures 2 and 3. In figure 2 we analyze the optical transitions from the ground state of the dot to the continuous states of the quantum well. The tendency is the same for all sizes of the quantum dot. In figure 2(a) the results for the quantum dot with the size of the base $D = 12$ nm are shown for different magnetic fields and for in-plane polarization of light. The transitions to the states of the quantum well are in the range of 200–230 meV. At zero magnetic field the optical absorption consists of a single peak at 220 meV, which is shown by a solid line. When we increase the magnitude of magnetic field the

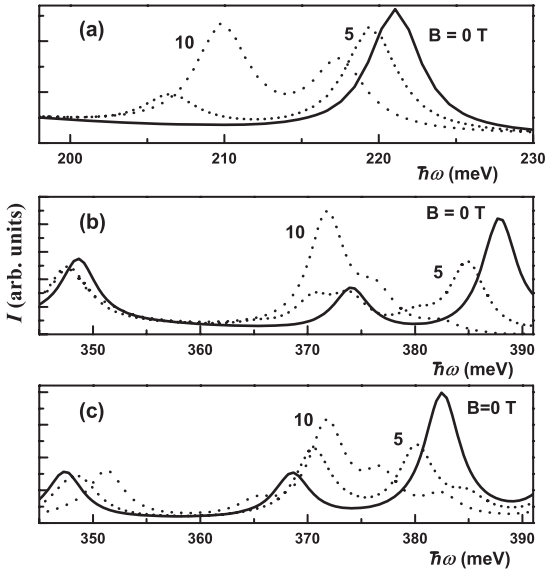

Figure 2. Absorption spectra corresponding to quantum dot–quantum well transitions are shown for different values of magnetic field, different sizes of quantum dot base and different light polarizations: (a) $D = 12$ nm and x-polarized light; (b) $D = 20$ nm and x-polarized light; (c) $D = 20$ nm and z-polarized light. Numbers by the lines are the values of magnetic field.

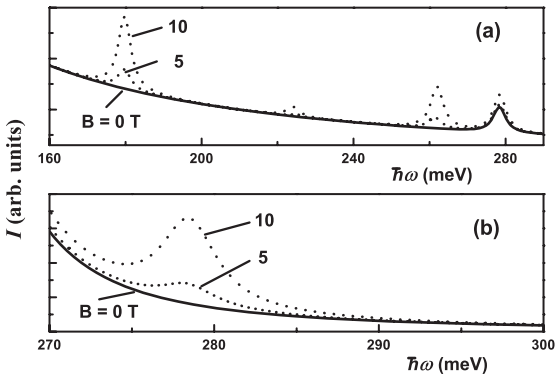

Figure 3. Absorption spectra corresponding to transitions within the same quantum dot are shown for different light polarizations and different magnetic fields: (a) x-polarized light; (b) z-polarized light. The size of the base of quantum dot is $D = 20$ nm. Numbers by the lines are the values of magnetic field. The strongest transition to the first excited state of the dot is not shown.

formation of a second peak at low frequency is clearly seen. At $B = 5$ T (dotted line) the second peak is at ≈207 meV. With increasing magnetic field the lower energy peak becomes blue-shifted, while the higher energy peak is red-shifted. Therefore, with increasing magnetic field the separation between the peaks decreases. At $B = 10$ T the peaks are separated by ≈8 meV. There is also redistribution of the intensity between the peaks. With increasing magnetic field the lower energy peak becomes stronger, while the higher energy peak becomes weaker. Summarizing the above behavior we can tell that with the application of parallel magnetic field the absorption line becomes red-shifted with additional internal structure.

Similar behavior can be seen for larger quantum dots. In figures 2(b) and (c) the results are shown for quantum dot with the size of the base $D = 20$ nm. The transitions to the states of the quantum well now is in the range of 350–390 meV. In figure 2(b) the results for the in-plane polarization of light are shown. Similar to a smaller dot (figure 2(a)), at zero magnetic field there is one strong peak. But now we also have a small satellite. With increasing magnetic field the main peak becomes slightly red-shifted and its intensity decreases, while the intensity of the lower frequency peak increases. Finally, the total structure becomes red-shifted. We see the same behavior for z-polarized light (see figure 2(c)). With increasing magnetic field the absorption spectrum becomes red-shifted. In all cases the shift is about 10–20 meV.

In figure 3 we present the optical transitions within the quantum dot levels, i.e. the transitions from the ground state of the quantum dot into the excited states of the same dot. For small quantum dots there is only one excited state in the dot. We have found that in this case the effect of magnetic field on the optical absorption is very small for the magnetic field up to 10 T. For large quantum dots there are many excited states in the dot. The main transition is to the first excited state. At zero magnetic field transitions to the higher excited states are usually suppressed due to optical selection rules and due to different symmetries of the excited states of the dot. Application of parallel magnetic field results in the mixture of the states with the different in-plane symmetry. This mixture results in an increase of the intensity of transitions to the excited states of the dot. This behavior is illustrated in figure 3(a) for $D = 20$ nm and in-plane polarization of the external light. The main peak at ≈95 meV which corresponds to the transition to the first excited state is not shown in the figure. At zero magnetic field there is a small peak at ≈280 meV. With increasing magnetic field we can see the increase of the transition rates to other excited states. The positions of these peaks have weak magnetic field dependence, but the heights of the peaks increase with increasing magnetic field. The results for z-polarized light is shown in figure 3(b). In this case the magnetic field affects only a single high-frequency transition at energy ≈280 meV. With increasing magnetic field the intensity of this transition increases.

There were no direct experimental observations of the effect of the parallel magnetic field on the optical properties of the realistic quantum dots. In terms of the applications the possible experiments would be the measurements of the photoresponse of infrared quantum dot photodetector in a parallel magnetic field. We expect that the parallel magnetic field changes the response frequency of the photodetector. As we mentioned above the more interesting results should be expected for dot-in-a-well photodetectors [4]. In this case there are different types of optical transitions, which have different dependencies on the magnetic field.

The indirect experimental manifestation of the effects of the parallel magnetic field on the optical properties of the quantum dot has been observed by Blaser *et al* [8]. They studied the effect of the parallel magnetic field on the emission spectra of quantum cascade lasers. Although the active elements of the quantum cascade lasers are quantum wells the observed dependence of the emission spectra on

the magnetic field was different from what was expected for the optical transitions within quantum well states. For the intersubband optical transitions within quantum well the emission peak should be red-shifted with increasing magnetic field. The results of [8] showed a completely different behavior. Namely, with increasing the magnetic field strength the luminescence peak showed a small blue shift. Such a blue shift was explained theoretically [12] by considering the optical transitions between the electron localized states within the quantum well. Such localized states of the electron can be considered as the states of the quantum dot. Since the blue shift in the emission spectra corresponds to the red shift in the absorption spectra, then the results observed in [8] are consistent with the red shift of the absorption line illustrated in figure 2.

In conclusion, the response frequency of quantum dot infrared photodetectors can be tuned by applying a parallel magnetic field. The effect of magnetic field is different for different types of optical transitions. For the optical transitions within the same quantum dot the magnetic field results in additional absorption lines blue-shifted from the zero magnetic field line, while for the transitions from the quantum dot to the continuous quantum well states the magnetic field shifts the absorption line to a lower frequency. The typical shift of absorption lines is in the range 10–20 meV. Due to a larger size of the quantum well wavefunctions the transitions to the quantum well states are more sensitive to magnetic field than the transitions between the quantum dot states. The effect of magnetic field on the quantum dot–quantum well transitions should be observable already at $B = 2$ T.

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