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STARK EFFECT IN P-TYPE DELTA-DOPED QUANTUM WELLS

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Abstract—In this work tight binding calculations in Be δ-doped GaAs quantum wells with an electric field applied along the [001] growth direction are presented. The Stark shifts of the hole electronic states for different impurity concentrations and electric field strengths are calculated. The δ-potential is treated as an external potential following the approach described earlier. A comparison with Stark effects in rectangular and graded-gap quantum wells is made.

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1. INTRODUCTION

For over a decade the properties of single and multiple δ-doped GaAs structures have been extensively studied both theoretically and experimentally [1–8]. The planar doping is used in devices to give rise to quantum confinement of carriers. For understanding the operating principles of these devices it is necessary to study the effect of the external constant electric field on the intersubband transitions [9], i.e., quantum confined Stark effect (QCSE).

The purpose of this paper is to describe the QCSE in p-type Be δ-doped GaAs quantum wells (QWs). The calculations are conducted by using the empirical tight binding (TB) method. Similar TB calculations have been already performed to treat electric field effects on the electronic and optical properties of various nanostructured materials [10–12]. To the best of our knowledge, there are no TB calculations of the Stark effect in Be δ-doped GaAs systems. The Stark effect in these systems have been studied mainly in the effective mass approximation [1–4, 6, 7].

2. MODEL AND METHOD

Numerical calculations of hole energy states and their spatial distributions are presented. We consider Be δ-doped GaAs QW with two-dimensional impurity concentration p_{2D} from 2×10^{12} to $10 \times 10^{12}\,\text{cm}^{-2}$ with a step of $1 \times 10^{12}\,\text{cm}^{-2}$ and from 10×10^{12} to $90 \times 10^{12}\,\text{cm}^{-2}$ with a step of $10 \times 10^{12}\,\text{cm}^{-2}$. The width of the inhomogeneous Be δ-doped finite region (the genuine V-shaped δ-doped QW) is 250 monolayers (MLs) and it is matched with two semi-infinite homogeneous GaAs barriers. We use the sp^3s^* spin dependent semi-empirical TB model and the surface Green function matching method [13]. The calculations are performed at the center of the 2D Brillouin zone for the GaAs [001] growth direction. The δ-potential is treated as an external potential in the Thomas-Fermi approximation [5, 8]. The external constant electric field F is applied to the QW in the growth direction. We add the effect of F as a second external potential to all diagonal elements of the Hamiltonian matrix in each atomic layer n [11, 12]. The external potential is zero outside the QW. The TB parameters determined in [14] are used. The calculations are made in the low temperature limit. The electric field value has been varied from $0\,\text{kV/cm}$ to $-25\,\text{kV/cm}$ with a $1\,\text{kV/cm}$ step. The zero value of the energy is at the top of the bulk GaAs valence band.

3. RESULTS AND DISCUSSION

We present here only the results for the negative electric fields. Such electric field direction moves up the right side of the δ-doped GaAs QW edge. Fig. 1 represents the effective confining Be δ-potential profile of the QW for acceptor concentration $p_{2D} = 5 \times 10^{12}\,\mathrm{cm}^{-2}$ and for different applied electric fields. The δ-potential is deeper for larger acceptor concentrations.

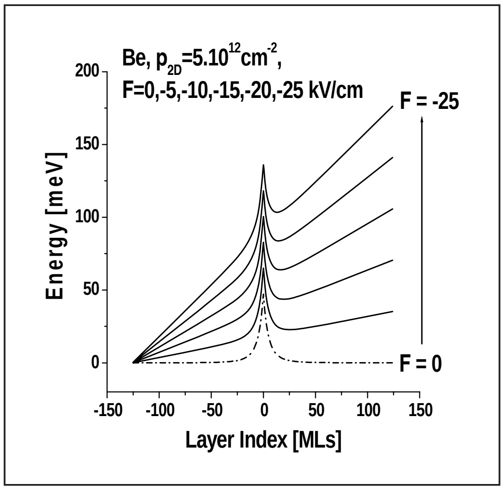

Figure 1. The effective Be δ-potential profile for $p_{2D} = 5.10^{12}\,\mathrm{cm}^{-2}$ at zero electric field (dot line) and under the applied electric fields $F = -5$, -10, -15, -20 and $-25\,\mathrm{kV/cm}$ from bottom to the top (full curves).

At a given F value, which depends on p_{2D} a secondary QW appears on the right side of the δ-doped QW. That value of F depends on p_{2D} as follows: $p_{2D} = 2$, $F = -1$; $p_{2D} = 20$, $F = -2$; $p_{2D} = 50$, $F = -6$; $p_{2D} = 90$, $F = -17$. With increasing F the δ-doped QW becomes narrower and shallower, while the secondary QW gets wider and deeper. As a result the bound states spatial distributions increasingly penetrate in the secondary well. After a given F value the system represents an asymmetric double QW with corresponding bound states. In this paper we consider only the hole energies which are not influenced by the presence of this secondary QW.

Figure 2 shows the energies of the heavy hole ground (hh0) and first excited (hh1) states and of the light hole ground state (lh0) calculated for four different two-dimensional Be concentrations p_{2D}(20, 40, 70 and 90) versus the electric field intensity. Here and further the impurity concentration p_{2D} is given in units $10^{12}\,\mathrm{cm}^{-2}$. The electric field effects on the hole energy levels are similar for all impurity concentrations. With increasing F the hole energies increase. These dependencies are almost linear, but their slopes are different. The changes in the hole energies with F are more pronounced for the ground states hh0 and lh0 (a, b), than for the next heavy hole level hh1 (c).

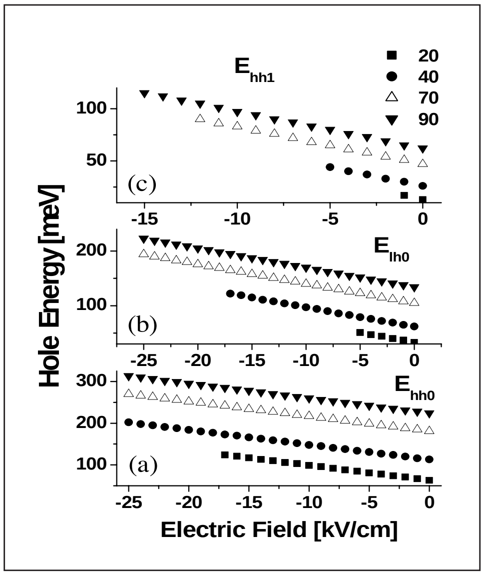

Figure 2. The dependence of the hole energy levels E_{hh0} (a), E_{lh0} (b) and E_{hh1} (c) on the applied electric field intensity as a function of the acceptor concentration p_{2D}, for a p-type Be δ-doped GaAs QW. The acceptor concentrations in units $10^{12}\,\mathrm{cm}^{-2}$ are $p_{2D} = 20$ (rectangles), $p_{2D} = 40$ (circles), $p_{2D} = 70$ (open triangles), $p_{2D} = 90$ (full triangles).

Figure 3 shows the probability density spatial distributions of some hole states at given values of the acceptor concentration p_{2D} and of the applied electric field F, as indicated on the figure. At zero field all spatial distributions are symmetrically situated around the center of the QW. With increasing F the states get slightly displaced from the center to the right. The influence of F on spatial distributions is more pronounced for smaller acceptor concentrations. For example the displacement of the lh0 distribution is well seen for $p_{2D} < 10$ but it is less pronounced for larger p_{2D} (compare Figs. 3(a) and (c)). At $p_{2D} > 40$ even high F values do not result in substantial displacement of the hh0, lh0 and hh1 distributions. (see Fig. 3(b) and (c)).

Figures 4(a), (b) and (c) displays the electric field dependence of the intersubband transitions energies E_{hh0}–E_{lh0} and E_{hh0}–E_{hh1}, repectively for three different acceptor concentrations: $p_{2D} = 10$, $p_{2D} = 20$ and $p_{2D} = 90$. Two interesting features are observed. First, with increasing p_{2D} the (hh0–lh0) transition energy increases. Second, the transition energies do not depend on the applied F. The dependence shows some fluctuations but they are not greater than 1 meV and can be due to calculation errors.

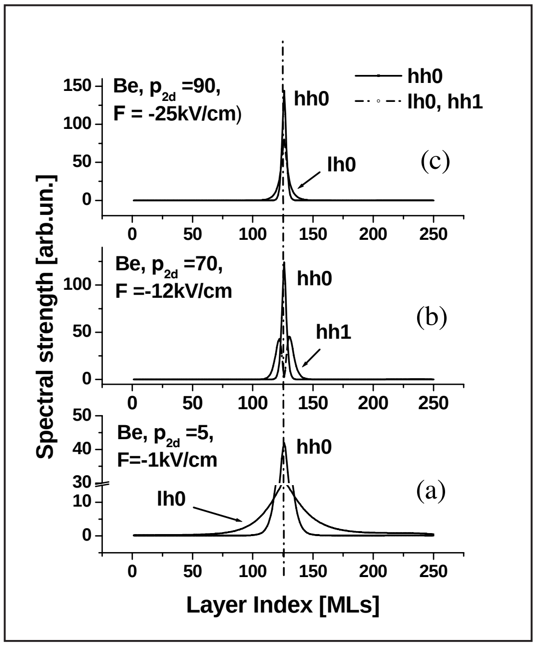

Figure 3. Spectral strength spatial distributions of the hole states hh0 (solid lines) and lh0 and hh1 (dot lines) as a function of the acceptor concentration p_{2D} and of the applied electric field F, for a Be δ-doped GaAs QW. (a) $p_{2D} = 5$, (b) $p_{2D} = 70$, (c) $p_{2D} = 90$.

Comparing the present study with our previously obtained results for rectangular and graded-gap QWs [11, 12], we can say that the most important points are the following ones: (1) the hole energies depend on the Be concentration and the applied electric field; (2) the transition energies between hole states depend on the Be concentration, however they show practically zero Stark shift; (3) The spatial overlap between the states is significant at low F and in general it is larger compared to that in the rectangular and the graded-gap QWs from [11, 12].

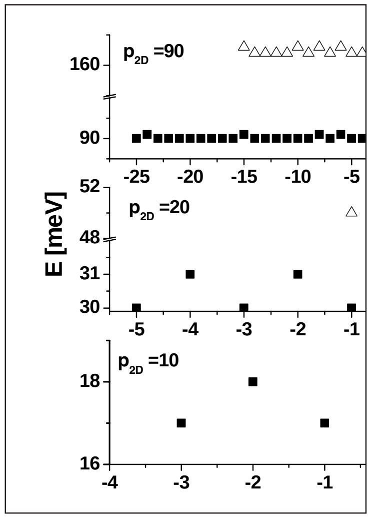

Figure 4. The dependence of the transition energy ΔE in meV between the hole states hh0–lh0 (squares), and hh0–hh1 (triangles) on the applied electric field F as a function of p_{2D} (in units $10^{12}\,\mathrm{cm}^{-2}$) for the QW under study. (a) $p_{2D} = 10$, (b) $p_{2D} = 20$, (c) $p_{2D} = 90$.

4. CONCLUSIONS

The first TB calculation of the QCSE in Be δ-doped GaAs QWs is presented. We have studied in details the Stark shifts of the hole states and their spatial distributions, the subband spectra and intersubband transitions of holes. The results give insight into the physics of the δ-doping QWs with different impurity densities subjected to an electric field with different magnitudes. Such investigations are very promising in looking for δ-doped structures for potential applications in devices based on the hole intersubband and intrasubband transitions e.g., photodetectors and optical modulators. The results demonstrate that the TB method can be used to investigate the Stark effect in a double asymmetric QW system, which is interesting for coherent intraband radiation applications.

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