**Effect of Magnetic Field on the Energy of Light Holes at the Valence Band Ceiling of A Narrow-Gap Quantum Well**

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**Abstract:** In this paper develops a method for determining the dependence of the allowed bands ,  of narrow-gap quantum well semiconductors on the magnetic field *B* and temperature *T*, and uses this method to determine the dependence of the forbidden zone width of the narrow-gap quantum well on the magnetic field *B* and temperature *T*. For this purpose, the effect of the magnetic field on the energy of light holes at the valence band ceiling of the narrow-gap quantum well, the effect of the magnetic field on the energy of free electrons at the bottom of the conduction band of the narrow-gap quantum well, the dependence of the two-dimensional energy density of states in the allowed bands of the narrow-gap quantum well on temperature and magnetic field, and the dependence of the forbidden band width of the narrow-gap quantum well on temperature and magnetic field were studied.

**Keywords:** semiconductor, quantum well, magnetic field, temperature, forbidden zone, energy.

**INTRODUCTION**

The main fundamental physical quantity of bulk and small-sized semiconductor structures is the band gap , the energy width of which allows us to predict the operational parameters of a semiconductor-based device. Therefore, determining and (if the band gap of newly created materials is not known) is one of the main tasks of semiconductor heterostructure technology. In addition, another important feature of *Eg* is its strong susceptibility to external influences, and even a change in *Eg* as a result of this influence radically changes the physical and chemical properties of a semiconductor device. There are a number of methods for determining the dependence of the band gap of semiconductors on external factors. In particular, in a number of works, a method for determining *Eg(T)* from the temperature dependence model of the surface density of states has been developed. In addition, a mechanism for explaining *Eg(T)* was created by the temperature change of the density of states, through the penetration of its “tail” into the bandgap. However, in these works, the effect of the quantizing magnetic field was not studied. In some works, the dependence of the bandgap of bulk and quantum-scale semiconductors on temperature, magnetic field, and hydrostatic pressure was studied. In particular, in works [1-5], the was calculated theoretically by changing the allowed bands of bulk semiconductor structures with temperature and magnetic field. In these works, it was proven that when the  condition is met, it turns into , that is, classical methods. This theory is mainly suitable for wide-bandgap 3D materials. In works [6-9], a model for quantum well semiconductors obeying the parabolic dispersion law was developed. A mechanism for the change of the bottom of the conduction band and the ceiling of the valence band (the boundaries of the allowed bands) of a rectangular quantum well with magnetic field and temperature was developed. As a result of the penetration of the tail of and into the , the model was proposed. In this case, quantum well semiconductors with wide bandgap were also determined.

In addition, in works[10-15], the dependence of the energy density of states of the conduction band of narrow-gap semiconductor materials on magnetic field and temperature was theoretically determined. In this work, an analytical expression for the nonparabolic dispersion law was derived. The experimental results were interpreted for different T using the obtained theoretical reports. However, in these works, a perfect mathematical model for determining , was not developed.

The main aim of this research work is to develop a method for determining the dependence of the allowed bands of narrow-gap quantum well semiconductors on the magnetic field B and temperature T, and to determine the dependence of the forbidden band width of the narrow-gap quantum well on the magnetic field B and temperature T using this method.

**METHODS**

This problem is solved by the three-band approximation. This approximation is a convenient solution of the equation for semiconductors with narrow bandgap quantum wells. In the considered approximation, the 8 X 8 interaction matrix can be written using and *H1* as follows [1]

 (1)

Here,

 (2)

The right-hand column in the matrix (2) represents the energy states associated with H.

If we calculate the initial energy with the bottom of the conduction band of the quantum well, (Ec=0), then the following equation is obtained:

 (3)

Here, .

From the formula (3) it is known that for k=0 the function E`(k) has four eigenvalues: E1=0; E2= E3= -Eg; and E4=- Eg-Δ. The condition E1=0 means that the counting starts from the bottom of the conduction band. The energies E2 and E3 denote the ceilings of the valence bands of heavy (Ev1) and light (Ev2) holes. The energy E4 indicates the spin orbital effect on the ceiling of the valence band.

To solve the problem, we use the following approximations:

1. Ignoring the spin orbital effect on the allowed bands of a narrow-gap semiconductor.

2. Ignoring the interaction with heavy holes, since the effective masses of light holes are close to the effective masses of free electrons.

In this case, Eg>>Δ and according to, the energy of light holes is determined as follows:

 (4)

It can be seen from expression (4) that *k2p2* (a P-matrix element, which is equal to ) is considered as the energy, since the condition that the term is a dimensionless quantity must be met. In this case, taking into account the above matrix element formula and the dimensionless quantities , (4) can be written as follows:

 (5)

In expression (5), the energy of light holes in narrow-gap bulk semiconductors at the valence band ceiling depends mainly on the effective masses and wave numbers of the light hole in the XYZ axes. In this case, the band gap (*Eg*) of the narrow-gap bulk semiconductor is considered constant. From formula (5), natural questions arise:

1. How to use (5) if the material under the influence of the magnetic field is a quantum-enclosed narrow-gap, heterostructure semiconductor?

2. It is known that the Eg of narrow-gap bulk or small-sized semiconductors is very sensitive to external factors. In this case, how are and determined?

3. How does a change in affect the energy density of states in the valence band of the quantum-enclosed?

To solve these problems, it is necessary to create a new mathematical model.

By applying expression (5) to narrow-gap semiconductors with quantum wells, the following expression is obtained:

 (6)

Formula (6) is the energy of light holes in a narrow-gap quantum well at the valence band ceiling.

Here, *nz* is the number of quantum wells, *d* is the thickness of the narrow-band quantum well, and *m\** is the effective mass of the light well.

As can be seen from formula (6), the light well energy at the valence band ceiling of the quantum well depends on the quantum well thickness, the light well effective mass, and the number of quantum wells.

Now, let us consider the effect of a strong magnetic field on a narrow-band quantum well. In particular, let the direction of the magnetic field induction vector  be along the Z axis and perpendicular to the XOY plane. This is called the longitudinal quantizing magnetic field. In this case, according to Landau theory and the laws of the quantizing magnetic field, the  terms of the free light well at the valence band ceiling of the quantum well are replaced by the  term.

Here *NLv* is the number of Landau levels in the valence band of a narrow-band quantum well, *ɷcv* is the cyclotron frequency of light holes.

It follows that formula (6) under the influence of a longitudinal quantizing magnetic field takes the following form:

(7)

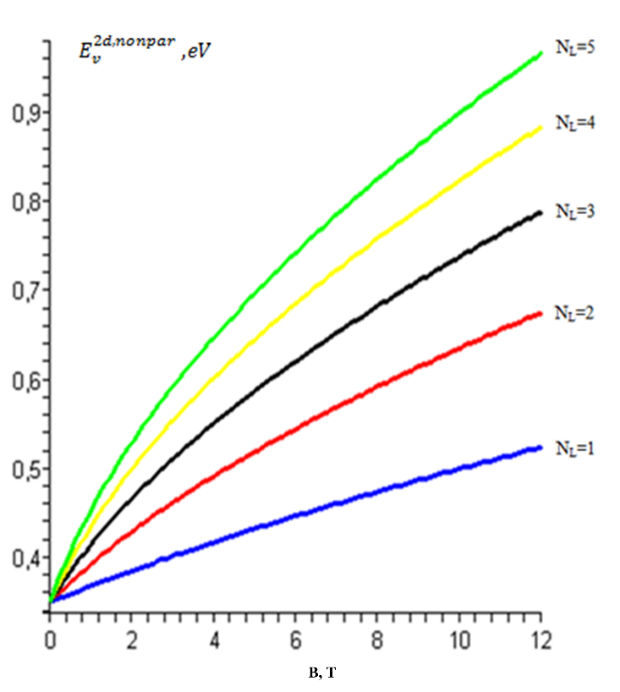
From the derived formula (7) it is clear that the light hole energy at the valence band ceiling of the quantum well is transformed into discrete energy levels in all directions. This, in turn, makes the light hole energy analogous to the quantum dot energy. However, it is also necessary to consider another important physical quantity, Eg, which depends on *B* and *d*. The reason is that the change in the function *Eg(B,d)* is considered monotonically. From this, the function  becomes . In this case, the formula takes the following form:

 (8)

The obtained formula (8) expresses the dependence of the light hole energy in the valence band gap of a quantum well on the magnetic field, the band gap width, the thickness of the quantum well, and the number of dimensional levels. Let us analyze expression (8) numerically and graphically. In works [13], the Joseph oscillations of a narrow-gap InAs quantum well semiconductor were determined. Here, the InAs quantum well thickness *d*=4 nm, B=0÷12 Tl, Eg(0)=0.35 eV, and *nz* were taken as.

By substituting these experimental values ​​into (8), we can obtain a graph of . Fig.1 shows the dependence of the energy of light holes in the vacancy ceiling of an InAs quantum well on the magnetic field for different Landau levels. As can be seen from this figure, the curve of the graph is reflected in the non-quadratic dispersion law of a narrow-gap InAs quantum well.

In addition, using formula (8), it is possible to calculate the two-dimensional energy density of states in the valence band of a narrow-gap quantum well.



**FIGURE 1.** The dependence of the energy of light holes in the valence ceiling of an InAs quantum well on the magnetic field for Landau levels.

**CONCLUSION**

In the process of carrying out this research work, the following conclusions were reached:

1. A mathematical model was developed to determine the dependence of the light hole energy at the valence band ceiling of a narrow-gap quantum well and the free electron energy at the bottom of the conduction band of the quantum well on the magnetic field, the band gap width, the quantum well thickness, and the number of dimensional levels.
2. A method was proposed to determine the dependence of the allowed bands , of narrow-gap quantum well semiconductors on the magnetic field *B* and temperature *T*.
3. Using this method, the dependence of the band gap width of a narrow-gap quantum well on the magnetic field *B* and temperature *T* was determined.

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