AVERAGE ENERGY AND MAGNETIC SUSCEPTIBILITY OF DMS QUANTUM DOT

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In this paper, we investigated the average energy, specific heat, entropy and magnetic susceptibility of the cylindrical DMS quantum dot with respect to a change in magnetic field. The corresponding Schrodinger equation of a quantum dot was solved within the effective mass approximation. The resulting energy spectrum was used to find the corresponding expression for the average energy, specific heat, entropy and magnetic susceptibility. Then, the graphs of the average energy, specific heat, entropy and magnetic susceptibility as a function of the magnetic field were constructed. According to the results obtained, the average energy decreases nonlinearly with increasing magnetic field. And the magnetic susceptibility at small values of the magnetic field has a maximum that decreases and tends to zero with increasing magnetic field. With the increase of magnetic field, specific heat and entropy increase non-linearly.

Keywords: Diluted magnetic semiconductor, quantum dot, thermodynamic properties.
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INTRODUCTION

As is known, low-dimensional quantum systems depend on the external and internal parameters of their physical properties. These quantum systems are divided into 3 different systems according to the number of dimensions. These are known as quantum well, quantum wire and quantum dot. Quantum dot is a zero-dimensional structure and the length of all three dimensions is smaller than the De Broglie wavelength. In quantum dot, the movement of the electron is restricted in all three dimensions. As a result, the energy of the electron is quantized. Today, quantum dots with cylindrical, spherical, pyramidal and ellipsoidal geometries can be created with MBE and similar methods. Quantum dots are formed in the combined regions of semiconductors with different band energy values. In these regions, the electron is trapped in the potential field. The geometry and size of the potential field affect the physical properties of the electron such as optical, thermodynamic, magnetic and electrical [1], [2] .

As a result of adding a certain amount of magnetic atoms to the semiconductor, a semiconductor structure with magnetic properties called diluted semimagnetic semiconductor (DMS) is obtained. In these structures, an exchange interaction occurs between the sp band of the semiconductor and the d band of the magnetic atom (usually Mn atom). As a result of this interaction, a splitting occurs in the electron band structure of these structures, which is called the giant Zeeman splitting in the literature [3].

In this study, the changes in parameters such as average energy, specific heat, entropy and magnetic susceptibility of the DMS cylindrical quantum dot with respect to the magnetic field are investigated.

THEORY

In this part of our study, the energy spectrum of a single-electron diluted semimagnetic semiconductor cylindrical quantum dot is calculated. The potential of the quantum system we consider is defined as

$$V\left(\rho,\phi,z\right)=\frac{\mu\omega_{\rho}^{2}\rho^{2}}{2}+\frac{\mu\omega_{z}^{2}z^{2}}{2}. \tag{1}$$

Here

$$\omega_{\rho}=\frac{\hbar}{\mu R_{0}^{2}},\omega_{z}=\frac{\hbar}{\mu L_{0}^{2}} \tag{2}$$

and R_0 is the radius of the cylinder, L_0 is the height of the cylinder. When a magnetic atom is added to a dilute semiconductor, an interaction occurs between the sp electron band of the semiconductor and the d electron band of the magnetic atom.

We can write this interaction mathematically as

$$H_{DMS}=\frac{1}{2}xN_{0}\alpha\left\langle S_{z}\right\rangle\sigma_{z}. \tag{3}$$

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Here α is a constant, x is the concentration of the magnetic atom and $\langle S_z \rangle$ is a variable that depends on the Brillouin function. Taking into account the expressions we defined above, the Hamiltonian of the quantum system can be written as follows:

$$H = \frac{1}{2\mu}(\mathbf{p} + e\mathbf{A})^2 + V(\rho, \phi, z) + \frac{1}{2} g \mu_B B_z \sigma_z + H_{DMS} . \tag{4}$$

Here $\mathbf{p} = -i\hbar\nabla$ is the momentum operator, $\mathbf{A} = \left(0, \frac{B\rho}{2}, 0\right)$ is the vector potential, μ is the effective mass, e is the electron charge, g is the Lande coefficient, μ_B is the Bohr magneton, B is the magnetic field and σ_z is the Pauli matrix. Taking into account the Hamiltonian we defined, we find an energy spectrum expression of the form

$$E = \frac{\hbar\omega_c m}{2} + \hbar\omega_z\left(n + \frac{1}{2}\right) + \hbar\Omega\left(n_\rho + \frac{|m|+1}{2}\right) + \frac{1}{2}\sigma\mu_B B\left(g + \frac{xN_0\alpha\langle S_z \rangle}{\mu_B B}\right) \tag{5}$$

as a result of the solution of the Schrödinger equation [4]. Here

$$\omega_c = \frac{eB}{\mu}, \qquad \Omega = \sqrt{\omega_\rho^2 + \omega_c^2} \tag{6}$$

and $n_\rho = 0,1,2,...$; $n = 0,1,2,...$; $m = 0,\pm1,\pm2,...$, $\sigma = \pm1$ are quantum numbers that determine the energy state of an electron.

By writing the energy spectrum expression we found in the

$$Z = \sum_{n,n_\rho,m,\sigma} e^{-\beta E_{n,n_\rho,m,\sigma}} \tag{7}$$

distribution function, we obtain the

$$Z = \frac{1}{2}\frac{\cosh\left(\frac{1}{2}g^*\mu_B B\beta\right)\operatorname{csch}\left(\frac{1}{2}\omega_z\hbar\beta\right)\operatorname{csch}\left(\frac{1}{2}\Omega\hbar\beta\right)\sinh\left(\frac{1}{2}\Omega\hbar\beta\right)}{\cosh\left(\frac{1}{2}\Omega\hbar\beta\right) - \cosh\left(\frac{1}{2}\omega_c\hbar\beta\right)} \tag{8}$$

expression. Using this expression,

$$U = -\frac{\partial \ln Z}{\partial \beta} \tag{9}$$

the average energy,

$$C_v = k_B\beta^2\frac{\partial^2 \ln Z}{\partial \beta^2} \tag{10}$$

specific heat,

$$S = k_B \ln Z - k_B\beta\frac{\partial \ln Z}{\partial \beta} \tag{11}$$

entropy and

$$\chi = -\frac{\partial^2 F}{\partial B^2} \tag{12}$$

magnetic susceptibility expressions are found.

RESULTS

In this section, numerical calculations of the average energy and magnetic susceptibility changes with respect to the magnetic field are given. $Cd_xMn_{1-x}Te$ compound is considered as an example sample. $\mu_0 = 9.1*10^{-31}kg$, $\mu_e = 0.096\mu$ [5], $g_e = -1.04$ [6], $\alpha N_0 = 0.22eV$ [3] values were used in the calculations.

The graph of the change of average energy with respect to the magnetic field is given in Figure 1. As can be seen from the figure, the value of the average energy decreases with the increase of the magnetic field in the $R_0 = 10nm$ and $L_0 = 20nm$ dimensions of the cylinder. The graph of the change of magnetic susceptibility with respect to the magnetic field is given in Figure 2. As can be seen from the figure, the magnetic susceptibility approaches zero with the increase of the magnetic field. The magnetic susceptibility is equal to zero at the $B = 40T$ value of the magnetic field. In addition, the graphs of the change of specific heat and entropy with respect to the magnetic field are given in Figure 3 and Figure 4. As can be seen from the graphs, the specific heat and entropy increase nonlinearly with the increase of the magnetic field.

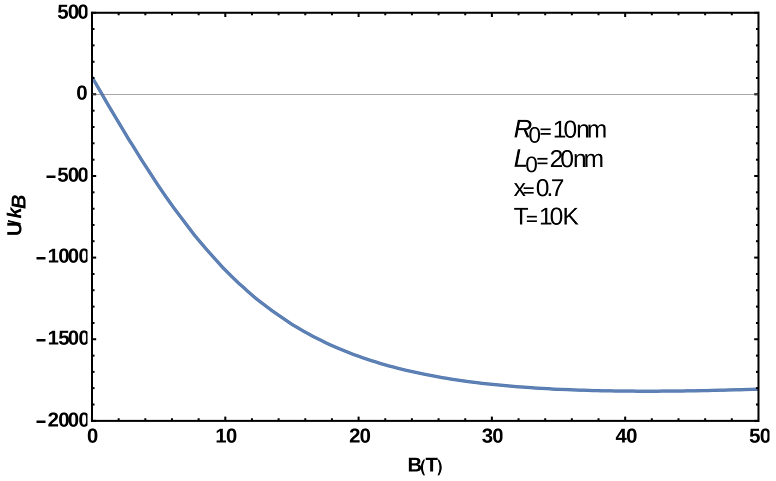

Fig. 1. Graph of average energy against magnetic field.

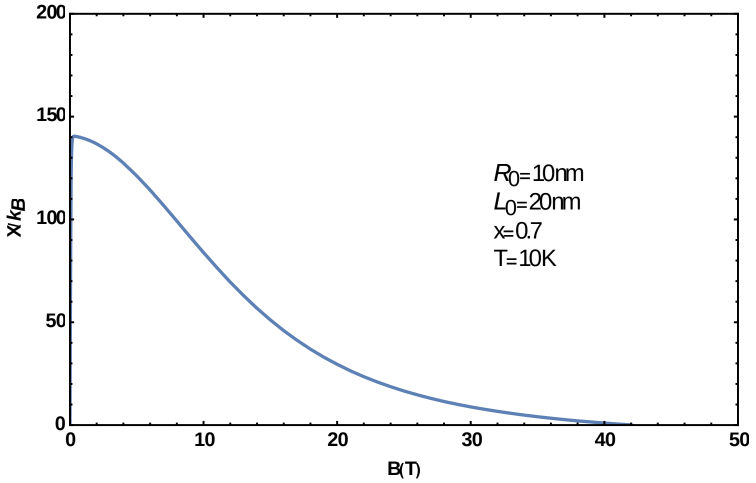

Fig. 2. Graph of magnetic susceptibility versus magnetic field.

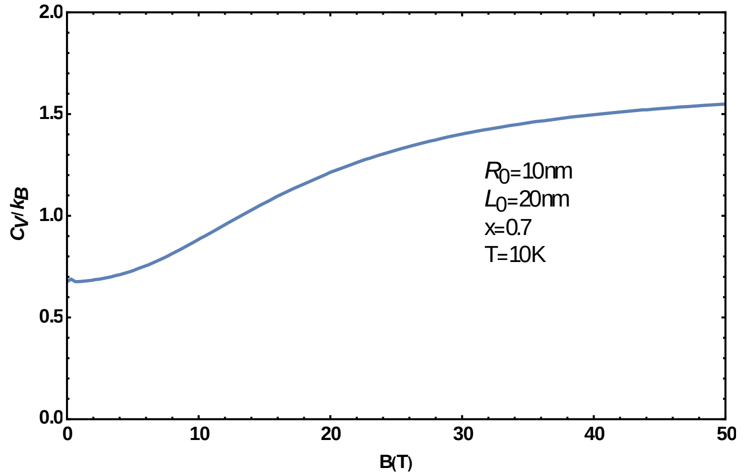

Fig. 3. Graph of specific heat against magnetic field.

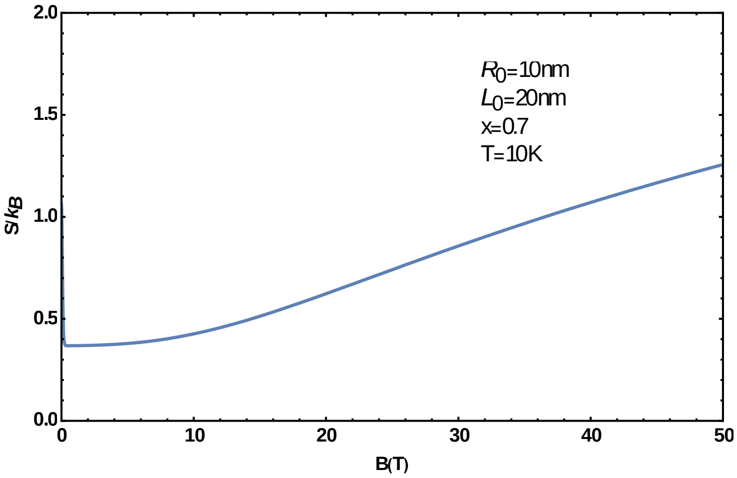

Fig. 4. Graph of entropy versus magnetic field.

CONCLUSION

In this study, the changes in the average energy, specific heat, entropy and magnetic susceptibility parameters of a single-electron diluted semimagnetic semiconductor cylindrical quantum dot with respect to the magnetic field were investigated. According to the results obtained, the values of the average energy and magnetic susceptibility decrease with the increase of the magnetic field. The specific heat and entropy increase with the increase of the magnetic field.

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