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MAGNETIZATION OF DİLUTED MAGNETIC SEMICONDUCTOR II TYPE SUPERLATTICES WITH IMPURITIES Mn (manganese) IONS

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ABSTRACT

In this paper, the magnetization of diluted magnetic semiconductor superlattices with a magnetic impurity of manganese is studied. It was found that the magnetization of a quasi-two-dimensional electron gas, depending on the degree of filling of the miniband superlattices, the molar concentration of the impurity, the exchange interaction constant and the spin splitting factor, changes sign and in a strictly two-dimensional case becomes positive. In a magnetic field, magnetization oscillates, and in strong magnetic fields the oscillations weaken, and their amplitude and frequency decrease. The contribution of the impurity to the magnetization is calculated. In a relatively weak magnetic field the magnetization associated with the impurity increases linearly and at a certain condition to the depending on the magnitude of the exchange constant and the impurity concentration changes its sign.

НАМАГНИЧЕННОСТЬ ПОЛУМАГНИТНЫХ ПОЛУПРОВОДНИКОВЫХ СВЕРХРЕШЕТОК II ТИПА С ПРИМЕСЯМИ ИОНОВ Mn (марганца)

АННОТАЦИЯ

В данной работе исследуется намагниченность полумагнитных полупроводниковых сверхрешеток с магнитной примесью марганца. Найдено, что намагниченность квазидвумерного электронного газа в зависимости от степени заполнения минизоны сверхрешеток, молярной концентрации примеси, постоянной обменного взаимодействия и фактора спинового расщепления меняет знак и в строго двумерном случае становится положительной. В магнитном поле намагниченность осциллирует, причем в сильных магнитных полях осцилляции ослабевают, и их амплитуда и частота уменьшаются. Вычисляется вклад примеси в намагниченность. В относительно слабом магнитном поле намагниченность, связанная с примесью, возрастает линейно и при определенном условии в зависимости от величины обменной константы и концентрации примеси меняет знак.

Ключевые слова: полумагнитный полупроводник, сверхрешетки II рода, квазидвумерный электронный газ, магнитная примесь, намагниченность, обменное взаимодействие.

MANQAN İONLARI İLƏ AŞQARANMIŞ II NÖV YARIMMAQNİT YARIMKEÇİRİCİ İFRATQƏFƏSLƏRİN MAQNİTLƏNMƏ ƏMSALI

XÜLASƏ

İşdə manqan ionları ilə aşqaranmış yarımmaqnit yarımkeçirici ifratqəfəslərin maqnit xassələri tədqiq edilir. Tapılmışdır ki, minizonanın dolma dərəcəsindən, aşqarın molyar konsentrasiyasından, mübadilə qarşılıqlı təsir sabitindən və spin parçalanması faktorundan asılı olaraq kvaziikiölçülü elektron qazının maqnitlənmə əmsalı işarəsini dəyişir və ikiölçülü halda müsbət olur. Xarici maqnit sahəsində maqnitlənmə əmsalının ossilyasiya etdiyi təyin olunmuşdur. Belə ki, güclü sahələrdə bu ossilyasiyalar zəifləyərək onların amplitudu və tezliyi azalır. Maqnitlənmə əmsalına maqnit aşqarının verdiyi pay da hesablanmışdır. Göstərilmişdir ki, zəif maqnit sahəsində aşqarla bağlı olan maqnitlənmə əmsalı xətti olaraq artır və müəyyən şərtdə mübadilə qarşılıqlı təsir sabitindən və aşqarın molyar konsentrasiyasından asılı olaraq işarəsini dəyişir.

Açar sözlər: yarımmaqnit yarımkeçirici, II növ ifratqəfəslər, kvaziikiölçülü elektron qazı, maqnit aşqarı, maqnitlənmə əmsalı, mübadilə qarşılıqlı təsir.

1. Introduction

Diluted magnetic semiconductor superlattices (DMSS), consisting of alternating layers of two materials that combine electronic and magnetic properties are perspective, and appear attractive both from the point of view of fundamental physics and technology. This is connected with to fact that superlattices exhibit many new electronic and optical properties, unusual for bulk samples, due to the presence of an additional periodic potential whose period is larger than the original lattice constant. In diluted magnetic semiconductor superlattices, it is possible to change the electronic potential after making the superlattice structure using external parameters such as the external magnetic field and temperature. Exchange interactions in such materials give rise to new spin-dependent phenomena, including giant spin band splitting and large Faraday rotation [2]. Due to the fact that in recent years it has become possible to quite accurately determine the values of exchange integrals, theoretical studies of the DMSS physical properties have received significant development. Changing the composition and impurities concentration in DMSS, lead to alteration the parameters of the band structure, i.e., magnetic impurities affect the properties of the semiconductor matrix; they also exhibit behavior characteristic of the paramagnetic and ferromagnetic phases with a change in the impurity concentration. The interaction between localized magnetic moments of an impurity and conduction electrons leads to a number of new properties, for example, the giant negative magnetoresistance at the semiconductor-semimetal transition [1]. All these effects have a common origin; they are caused by $sp-d$ exchange interactions. Many of theoretical and experimental works has been devoted to the study of the spin-dependent transport of charge carriers due to the reciprocity influence of transport and magnetic properties in DMS [2]. In recent years, using the MBE method, it has been possible to create layer systems with quantum wells and superlattices of good quality. However, there are significantly less studies in which low-dimensional systems are studied in the presence of a magnetic field and magnetic impurities [3-5]. As an example, we give heterostructures $GaAs/AlGaAs$ [6], where the impurity is manganese. The influence of the impurity localized magnetic moments is also manifested in the properties of two-dimensional electron gas in the DMS by changing the g factor. The magnitude of the g factor is affected by exchange interactions and temperature. Spin splitting reduces the g factor and changes the sign [7]. In this work, the DMSS thermodynamic properties, namely, magnetization, are studied, since statistical characteristics significantly affect the magnetic and transport properties of low-dimensional systems in the presence of a magnetic impurity. Impurity localized magnetic moments is also displayed in the properties of two-dimensional electron gas in the DMS by changing the g factor [8]. The magnitude of the g factor is affected by exchange interactions and temperature. Spin splitting reduces the g factor and changes the sign. In this work, the DMSS thermodynamic properties, namely, magnetization are studied, since statistical characteristics significantly affect the magnetic and transport properties of low-dimensional systems in the presence of a magnetic impurity.

2. Energy spectrum and density of states of DMSS

The possibility to create thin films, superlattices, and heterostructures of diluted magnetic semiconductors using molecular beam epitaxy in combination with the appearance of new properties of these materials makes low-dimension diluted magnetic semiconductors very important from the point of view of both basic research and applied sciences. In the $Cd_{1-x}Mn_xTe$ and $Hg_{1-x}Mn_xTe$ compounds, the exchange interaction between conduction electrons and $3d^5$ impurity electrons Mn is carried out in the mean-field approximation. For electrons in a given external magnetic field and for a given state of magnetic ions systems, in the case where the electron wave function is sufficiently delocalized and the influence of electrons on each of the magnetic ions can be neglected, the Hamiltonian has the form:

$$H = H_0 + H_B + H_C + H_{ex}, \tag{1}$$

where H_0 is the Hamiltonian of the electron in an ideal crystal; the term H_B describes the influence of the magnetic field on the electron's state this is responsible for Landau quantization and spin splitting; H_C describes the Coulomb interaction of carriers with impurities; and the term H_{ex} corresponds to the exchange interaction between carriers and ions.

Taking into account the electron spin $\mu_z B$ leads to an additional term in the Hamiltonian, where is $\mu_z = \mu_B(\sigma_z/\sigma)$ the projection of the intrinsic magnetic moment onto the field direction associated with the electron spin, σ_z - spin operator with eigenvalue $\pm 1/2$, $\mu_B = e\hbar/2m_0$ - Bohr magneton, B - magnetic field induction. Since the spin operator commutes with the Hamiltonian, its zth component is preserved, and in the Schrödinger equation, the spin and coordinate variables are separated. Therefore, the complete eigenfunctions of the electron, taking into account the spin, are obtained by multiplying the wave functions without spin by the spin wave functions corresponding to certain values of the spin projection $\sigma = \pm 1/2$ In this case, an additional term is added to the energy eigenvalues, corresponding to the energy of the eigenmoment in the magnetic field. The difference from a non-magnetic semiconductor is the presence of exchange interaction. For exchange interaction, the Heisenberg spin model:

$$H_{ex} = -\sum J(\vec{r} - \vec{R}_n) S_n \sigma, \tag{2}$$

n-number of the magnetic $J(\vec{r} - \vec{R}_n)$ ion, exchange integral between conduction band electrons and impurity electrons, σ - spin of mobile electrons with $\vec{r}$ radius vector, S_n - spin of magnetic impurity R_n localized at a site (for manganese $S_n = 5/2$). When the magnetic field is directed along z, then in H_{ex}, all manganese spin operators are replaced by their mean values, and for the conduction band, we have:

$$\langle \psi_c | H_{ex} | \psi_c \rangle = \begin{vmatrix} 3A & 0 \\ 0 & 3A \end{vmatrix}. \tag{3}$$

Here

$$A = -\frac{1}{6} N_0 \alpha \langle |S_z| \rangle x, \tag{4}$$

where N_0 is the number of cells per unit volume, the modification of the band structure caused by the *s-d* interaction will be described by a constant α equal to $\alpha = -\langle S|J|S \rangle / \Omega$, x - the molar concentration of the impurity. In the Schrödinger equation, in the effective mass approximation, the exchange potential mixes the orbital and spin degrees of freedom, which can lead to the scattering of electrons from one orbital state to another with a spin flip. The solution to the Schrödinger equation with Hamiltonian (1) taking into account (3) for the energy spectrum of semimagnetic semiconductor superlattices in a strong magnetic field parallel to the axis directed perpendicular to z the layers, which quantizes the motion of the electron in the plane of the layer and removes the spin degeneracy for the energy spectrum, will have the form:

$$\varepsilon(N,\sigma,k_z) = (2N+1)\mu B + \varepsilon_0(1-\cos ak_z) + g^*\sigma\mu_B B + 3AS\,. \tag{5}$$

Where $N = 1,2,...$ are the Landau quantum numbers, k_z is the quasi-momentum component along the axis z, $\mu = (m_0/m_\perp)\mu_B$, m_0 is the mass of a free electron, $m_\perp$ is the mass of the electron in the plane of the layer, ε_0 is the half-width of the conduction band in the direction k_z, a is the superlattice period in the direction z, g^* is the factor that is determined from the band structure, and the rest are standard constants. It can be seen that each Landau level is distributed into two spin sublevels, and the magnitude of the distribution of the *N*th level is the same and equal to $\Delta\varepsilon = g^*\mu_B B$. In this work, manganese ions with spin 5/2 are taken as impurities, and then the energy spectrum (5) takes the form:

$$\varepsilon = (2N+1)\mu B \pm \frac{1}{2} g\mu_B B \mp \frac{5}{2}\alpha\, x\, f(B,T) + \varepsilon_0(1-\cos ak_z)\,. \tag{6}$$

x - molar concentration of manganese, $f(B,T) = \frac{2}{5} B_{5/2}\left(\frac{g_{Mn}\mu_B B}{k_0 T}\right)$, where

$$B_S(x) = \frac{2s+1}{2} cth\frac{2s+1}{2} - \frac{1}{2} cth\frac{x}{2}$$

- Brillouin function (at strong fields and low temperatures, this function tends to unity).

Two quasi-continuous determines one quantum state in a magnetic field (k_y, k_z), three discrete quantum numbers: N,σ,S and the density of states is determined by the formula:

$$g_B(\varepsilon) = \frac{1}{2(\pi R)^2 a}\sum_{N\sigma}(2\varepsilon_0\varepsilon_z - \varepsilon_z^2)^{-1/2} = \frac{1}{2(\pi R)^2 a\varepsilon_0}\sum_{N\sigma}\sin^{-1}(ak_z)\,, \tag{7}$$

Here $R = (\hbar/eB)^{1/2}$ - magnetic length, $\varepsilon_z = \varepsilon(N,\sigma,k_z) - (2N+1)\mu B - g^*\sigma\mu_B B - 3AS$,

$$Z(\varepsilon) = a\,k_z = \arccos\left(1 - \frac{\varepsilon - \varepsilon_z}{\varepsilon_0}\right).$$

From (7) it is clear that the density of states has a feature every time the energy coincides with one of the Landau levels $\varepsilon = \varepsilon_N = (2N+1)\mu B$, i.e. oscillates with changing magnetic field.

In the case of a degenerate electron gas, the density of states depends significantly on the relationship between the Fermi level and the width of the one-dimensional conduction band in the k_z direction. Taking spin splitting into account significantly affects the behavior of the density of state, and at large values of the g^* factor there is a linear dependence of the density of state on the magnetic field.

3. Magnetization

The magnetization of an electron gas M, using the Gibbs method, can be found based on the explicit form of the grand thermodynamic potential $\Omega=\Omega(T,V,\zeta,B)$:

$$M=-\frac{1}{V}\left(\frac{\partial\Omega}{\partial B}\right)_{T,V,\zeta}, \tag{8}$$

where the grand thermodynamic potential in a quantizing magnetic field has the form:

$$\Omega=-k_0T\sum_{N\,k_y k_z S\,\sigma}\ln\left(1+e^{\frac{\zeta-\varepsilon(N,k_z,S,\sigma)}{k_0T}}\right). \tag{9}$$

For a grand thermodynamic potential $\Omega=\Omega(T,V,\zeta,B)$ we have:

$$\Omega=-k_0T\frac{V}{2a(\pi R)^2}\sum_N\int_0^{Z_0}\ln(1+e^{\eta^*+\varepsilon_0^*\cos Z})\,dZ, \tag{10}$$

Where $\eta^*=\zeta^*-\varepsilon_N^*-\varepsilon_0^*$, $\zeta^*=\zeta/k_0T$, $\varepsilon_N^*=\varepsilon_N/k_0T$, $\varepsilon_0^*=\varepsilon_0/k_0T$ and the upper bound of the integral is defined as:

$$Z_0=\begin{cases}\pi, & \varepsilon>2\varepsilon_0\\ \arccos\left(1+\dfrac{\mu B+g\mu B/2-5\alpha x f(B,T)/2-\varepsilon}{\varepsilon_0}\right), & \varepsilon<2\varepsilon_0\end{cases}. \tag{11}$$

If we move in (10) from integration over dZ to integration over $d\varepsilon$ energy, then for Ω we obtain [7]:

$$\Omega=\frac{k_0TV}{2(\pi R)^2}\sum_{N\,S\,\sigma}\int_{\varepsilon_N}^{\infty}\frac{dk_z(\varepsilon,N)}{d\varepsilon}\ln\left(1+\exp\left(\frac{\zeta-\varepsilon}{k_0T}\right)\right)d\varepsilon. \tag{12}$$

The expressions are valid for any value of the magnetic field and the degree of degeneracy of the electron gas.

Taking into account (12) in (8), for magnetization, we obtain:

$$M=\frac{k_0T}{B}\frac{1}{2a(\pi R)^2}\left\{\sum_N\left[Z_0+\frac{\mu_B B(2N+1)}{\varepsilon_0\sin Z_0}\right]\ln\left[1+\exp\left(\frac{\zeta-\varepsilon}{k_0T}\right)\right]+\ +\frac{\varepsilon_0}{k_0T}\int_0^{Z_0}f_0 Z\sin Z dZ\right\}. \tag{13}$$

In the case of a degenerate electron gas, for magnetization in the quantum limit $(N=0)$ we have:

$$M=\frac{\varepsilon_0}{2a\pi^2R^2B}\left(\sin Z_0-2Z_0\cos Z_0-\frac{\mu B(1+\sigma g^*)+3AS}{\varepsilon_0}ctg\,Z_0\right), \tag{14}$$

here Z_0 is given by formula (11).

From (14) it follows that the magnetization of a quasi-two-dimensional electron gas, depending on the degree of filling of the miniband, the molar concentration of the impurity, the exchange interaction constant and the g factor, changes sign and in a strictly two-dimensional case becomes positive. In a magnetic field, the magnetization oscillates, and in strong In magnetic fields, oscillations weaken, and their amplitude and frequency decrease. At low degrees of miniband filling, the magnetization has the form:

$$M = -\frac{\mu e B}{2a\pi^2 \hbar Z_0} + M_{Mn}. \tag{15}$$

The second term in equation (15) describes the contribution of the diluted magnetic semiconductor superlattces magnetization.

For magnetization, M_{Mn} we get:

$$M_{Mn} = \frac{5}{2} N \frac{(\mu_B g_{Mn})^2 B}{k_0 T} + \frac{\mu_B g_{eff}}{2} th\left(\frac{\mu_B g^* B}{k_0 T}\right), \tag{16}$$

where $g_{eff} = g^* - \frac{5}{2}\frac{\alpha x N}{\mu_B B}$.

In strong magnetic fields at low temperatures $\left(\frac{\mu g^* B}{k_0 T} >> 1\right)$, we have:

$$M_{Mn} = \frac{5}{2} N \frac{1}{k_0 T} (\mu_B g_{Mn})^2 B + \frac{\mu_B g^*}{2}\left(1 - \frac{5}{2}\frac{\alpha x N}{\mu g B}\right). \tag{17}$$

Based on (17), it follows that with increasing magnetic field, the magnetization increases and then reaches saturation. At $\frac{\mu g^* B}{k_0 T} << 1$, i.e. at weak magnetic fields and high temperatures, the magnetization will be:

$$M_{Mn} = \frac{5}{2} N \frac{1}{k_0 T} (\mu_B g_{Mn})^2 B + \frac{(\mu_B g^*)^2 B}{4 k_0 T}\left(1 - \frac{5}{2}\frac{\alpha x N}{\mu g B}\right). \tag{18}$$

From (18) it is clear that in a relatively weak magnetic field the magnetization increases linearly and at a certain magnetic field, but at $B < \frac{5}{2}\frac{\alpha x N}{\mu g^*}$, i.e. depending on the exchange constant and the concentration of the impurity, the sign changes.

4. Conclusion

The magnetization of DMSS with a magnetic impurity of manganese is being studied. It was found that the magnetization of a quasi-two-dimensional electron gas, depending on the degree of filling of the miniband, the molar concentration of the impurity, the exchange interaction constant and the g factor, changes sign and in a strictly two-dimensional case becomes positive. In a magnetic field, magnetization oscillates, and in strong magnetic fields the oscillations weaken, and their amplitude and frequency decrease. The contribution of the impurity to the magnetization is calculated. It is shown that this contribution in a strong magnetic field and at low temperatures increases with increasing magnetic field, and then reaches saturation as a result of the alignment of the spin of electrons and magnetic impurities in the averaged external magnetic field and the exchange field of the magnetic ion. In a relatively weak magnetic field, the magnetization associated with the impurity increases linearly and, at a certain magnetic field, depending on the exchange constant and the concentration of the impurity, changes sign.

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