LOCAL SPIN-WAVE REGIONS IN A SUPERLATTICE CONSTRUCTED FERRO- AND ANTIFERROMAGNETIC SEMICONDUCTORS MATERIALS

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The s-d (or s-f) interaction model is used to study the local spin-wave excitations in a superlattice constructed by alternating layers of simple-cubic Heisenberg ferromagnetic and antiferromagnetic semiconductors materials. The spin-wave regions for local spin waves propagating in a general direction in the superlattice are derived by the Green function method. The results are i1lustrated numerically.

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INTRODUCTION

Magnetic layered structures constructed by different materials have received increasing interest during the last decade. Studies on artificial magnetic superlattices, either experimental or theoretical have been a subject of growing interests, because these structures are realizable in laboratories, whose characteristics may be much different from those of its component materials [1-5]. The spin waves spectrum, which is the signature of the periodicity, has been intensively studied in multilayered magnetic materials. The materials with periodic magnetic structure can be refereed to as magnonic crystals. Many physical properties of layered magnetic systems may be explained by the spin wave energy gap [6,7].

There have been considerable theoretical studies of spin excitations in the long-wavelength limit and in the short-wavelength limit, where the exchange coupling is dominant [8-10]. Most of these studies have been devoted experimental research of the superlattice properties consisting of two different ferro- or antiferromagnetic materials. However, little attention been paid on theoretical study of superlattice constructed by different type magnetic materials. Spin-wave excitations of ferro- and antiferromagnetic superlattice were studied in Ref [11]. In this paper we will study spectrum of the local spin waves in the superlattice constructed by alternating layers of simple-cubic Heisenberg ferromagnetic and antiferromagnetic semiconductors materials using Green function technique.

MODEL AND FORMALISM

We consider a Heisenberg model for ferro-and antiferromagnetic semiconductors superlattice with a simple cubic lattice. A schematic diagram of the superlattice model in which the atomic layers of ferromagnetic semiconductors material alternate with atomic layers of antiferromagnetic semiconductors materials is illustrated in fig.1. Elementary unit cell of the superlattice consist of two layers, spins labeled with a and b belong antiferromagnetic semiconductors layer, spins c and d belong ferromagnetic semiconductors layer. Each atomic layers is assumed to be the [001] planes. Lattice constant of the superlattice in x-y plane is a.

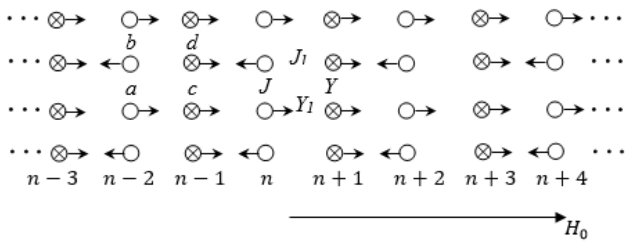

Fig.1. A superlattice model constructed by alternating layers of simple-cubic Heisenberg ferromagnetic and antiferromagnetic semiconductors materials. The lattice parameter a is assumed for both the materials.

Our total Hamiltonian H may be expressed as the sum of four terms:

$$H = H_{FM} + H_{FE} + H_{AFM} + H_{AFE}, \tag{1}$$

where H_{FM} is the Heisenberg Hamiltonian for the ferromagnetically ordered localized spins (of d or f type)

$$H_{FM} = -\frac{1}{2}\sum_{i,j} Y_{ij}\left(\vec{S}_i\,\vec{S}_j\right) - \sum_i g\mu_B\left(H_0 + H_{FM,i}{}^{(A)}\right)S_i^z \tag{2}$$

Hamiltonians H_{FE} and H_{AFE} representing an s-d (or s-f) ineraction for ferromagnetic and antiferromagnetic semiconductors materials, respectively

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$$H_{FE} = -\sum_i I_i \left(\vec{S}_i \, \vec{s}_i\right), \quad H_{AFE} = -\sum_i K_i \left(\vec{S}_i \, \vec{s}_i\right) \tag{3}$$

The term H_{AFM} in (1) describes antiferromagnetically ordered localized spins:

$$H_{AFM} = \sum_{i,j} J_{ij} \left(\vec{S}_i \, \vec{S}_j\right) - \sum_i g\mu_B \left(H_0 + H_{AFM,i}{}^{(A)}\right) S_{ia}^z - \sum_i g\mu_B \left(H_0 - H_{AFM,i}{}^{(A)}\right) S_{ib}^z \tag{4}$$

H_0 in (2) and (4) is the internal magnetic field, which is assumed to be paralle1 to the z axis and $H_{FM(AFM),i}^{(A)}$ anisotropy field with simple uniaxial anisotropy. $\vec{S}$ and $\vec{s}$ are localized and conduction electron spins operator, respectively. There are both ferro- and antiferromagnetically spin arrangements between spins of the two atomic layers at each interface as shown in fig.1. The exchange constant between constituents are Y_1 when ferromagnetically, and J_1 antiferromagnetically arrangements between spins of the two atomic layers at each interface. In order to obtain the solutions Green function equation, we define eight type Green functions in the random phase approximation:

$$G_{i,j}^{(a)}(\omega) =<< S_{i,(a)}^+; S_{j,(a)}^- >>_\omega, \qquad G_{i,j}^{(b)}(\omega) =<< S_{i,(b)}^+; S_{j,(a)}^- >>_\omega,$$
$$G_{i,j}^{(c)}(\omega) =<< S_{i,(c)}^+; S_{j,(a)}^- >>_\omega, \qquad G_{i,j}^{(d)}(\omega) =<< S_{i,(d)}^+; S_{j,(a)}^- >>_\omega.$$
$$g_{i,j}^{(a)}(\omega) =<< s_{i,(a)}^+; S_{j,(a)}^- >>_\omega, \qquad g_{i,j}^{(b)}(\omega) =<< s_{i,(b)}^+; S_{j,(a)}^- >>_\omega,$$
$$g_{i,j}^{(c)}(\omega) =<< s_{i,(c)}^+; S_{j,(a)}^- >>_\omega, \qquad g_{i,j}^{(d)}(\omega) =<< s_{i,(d)}^+; S_{j,(a)}^- >>_\omega.$$

Furthermore, to emphasize the layered structure we shall use the following two-dimensional. Fourier transformation [11,12]

$$G_{i,j}^{(\alpha)}(\omega) = \frac{1}{N} \sum_{k_{||}} G_{n,n'}^{(\alpha)}(\omega, k_{||})\, exp[\, ik_{||}(r_i - r_j)], \quad (\alpha = a, b, c, d), \tag{5}$$

where $k_{||}$ is two-dimensional wave vector parallel to the xy- plane , n and n' indices of the layers to which r_i and r_j belong , respectively. Employing the equation of motion for the Green functions [13,14] one obtains the following set of equations after Fourier transform (5)

$$\begin{cases}
\lambda_a(\omega) G_{n,n'}^{(a)}(\omega, k_{||}) - \langle S_{n,a}^z \rangle \left[J\gamma(k_{||}) G_{n,n'}^{(b)}(\omega, k_{||}) - 0.5 Y_1 G_{n-1,n'}^{(c)}(\omega, k_{||}) - 0.5 Y_1 G_{n+1,n'}^{(c)}(\omega, k_{||}) \right] = 2\langle S_{n,a}^z \rangle \delta_{n,n'}, \\
\lambda_b(\omega) G_{n,n'}^{(b)}(\omega, k_{||}) - \langle S_{n,b}^z \rangle \left[J\gamma(k_{||}) G_{n,n'}^{(a)}(\omega, k_{||}) + J_1 G_{n-1,n'}^{(d)}(\omega, k_{||}) + J_1 G_{n+1,n'}^{(d)}(\omega, k_{||}) \right] = 0, \\
\lambda_c(\omega) G_{n+1,n'}^{(c)}(\omega, k_{||}) + \langle S_{n+1,c}^z \rangle \left[Y\gamma(k_{||}) G_{n+1,n'}^{(d)}(\omega, k_{||}) + Y_1 G_{n,n'}^{(a)}(\omega, k_{||}) + Y_1 G_{n+2,n'}^{(a)}(\omega, k_{||}) \right] = 2\langle S_{n+1,c}^z \rangle \delta_{n+1,n'}, \\
\lambda_d(\omega) G_{n+1,n'}^{(d)}(\omega, k_{||}) + \langle S_{n+1,d}^z \rangle \left[Y\gamma(k_{||}) G_{n+1,n'}^{(c)}(\omega, k_{||}) - 2J_1 G_{n,n'}^{(b)}(\omega, k_{||}) - 2J_1 G_{n+2,n'}^{(b)}(\omega, k_{||}) \right] = 0.
\end{cases} \tag{6}$$

where $\lambda^a(\omega) = \omega - K\langle s^z \rangle - \frac{K^2 \langle S_{AFM}^z \rangle \langle s^z \rangle}{\omega - g_e\mu_B H_0 - K\langle S_{AFM}^z \rangle} - g\mu H_{AFM}^{(A)} - 4J\langle S_{AFM}^z \rangle - Y_1 \langle S_{FM}^z \rangle$,

$$\lambda^b(\omega) = \omega + K\langle s^z \rangle - \frac{K^2 \langle S_{AFM}^z \rangle \langle s^z \rangle}{\omega - g_e\mu_B H_0 + K\langle S_{AFM}^z \rangle} + g\mu H_{AFM}^{(A)} + 4J\langle S_{AFM}^z \rangle + 2J_1 \langle S_{FM}^z \rangle ,$$

$$\lambda^c(\omega) = \omega - I\langle s^z \rangle - \frac{I^2 \langle S_{FM}^z \rangle \langle s^z \rangle}{\omega - g_e\mu_B H_0 - I\langle S_{FM}^z \rangle} - g\mu H_{FM}^{(A)} - 2Y\langle S_{FM}^z \rangle - Y_1 \langle S_{AFM}^z \rangle ,$$

$$\lambda^d(\omega) = \omega - I\langle s^z \rangle - \frac{I^2 \langle S_{FM}^z \rangle \langle s^z \rangle}{\omega - g_e\mu_B H_0 - I\langle S_{FM}^z \rangle} - g\mu H_{FM}^{(A)} - 2Y\langle S_{FM}^z \rangle - 2J_1 \langle S_{AFM}^z \rangle ,$$

$$\gamma(k_{||}) = 2(cos\, k_x\, a + cos\, k_y\, a) ,$$

$\langle S_{FM}^z \rangle$ and $\langle S_{AFM}^z \rangle$ are average meaning of z-spins components in ferro - and antiferromagnetic sublattices, respectively.

The system is also periodic in the z direction, which lattice constant is d=2a. According to Bloch's theorem, we introduce the following plane waves [15, 16]:

$$G^{(\alpha)}_{n+2,n'}(\omega,k_{||}) = exp[ik_z d]\ \ G^{(\alpha)}_{n,n'}(\omega,k_{||})\ ,$$

$$G^{(\alpha)}_{n-1,n'}(\omega,k_{||}) = exp[-ik_z d]\ \ G^{(\alpha)}_{n+1,n'}(\omega,k_{||}),\quad \alpha = a,b,c,d. \tag{7}$$

Using (7) the system of equations (6) may be written the following matrix form:

$$\begin{pmatrix} \lambda_a(\omega) & -J\langle S_{AFM}\rangle\gamma(k_{||}) & 0.5Y_1\langle S_{AFM}\rangle T^* & 0 \\ J\langle S_{AFM}\rangle\gamma(k_{||}) & \lambda_b(\omega) & 0 & J_1\langle S_{AFM}\rangle T^* \\ Y_1\langle S_{FM}\rangle T & 0 & \lambda_c(\omega) & Y\langle S_{FM}\rangle\gamma(k_{||}) \\ 0 & -2J_1\langle S_{AFM}\rangle T & Y\langle S_{FM}\rangle\gamma(k_{||}) & \lambda_d(\omega) \end{pmatrix} \cdot \begin{pmatrix} G^{(a)}_{n,n'}(\omega,k_{||}) \\ G^{(b)}_{n,n'}(\omega,k_{||}) \\ G^{(c)}_{n+1,n'}(\omega,k_{||}) \\ G^{(d)}_{n+1,n'}(\omega,k_{||}) \end{pmatrix} =$$

$$= \begin{pmatrix} 2\langle S^z_{\mathrm{AFM}}\rangle\delta_{n,n'} \\ 0 \\ 2\langle S^z_{\mathrm{FM}}\rangle\delta_{n+1,n'} \\ 0 \end{pmatrix} \tag{8}$$

where $T = 1 + exp(ik_z d)$ and T^* is the complex conjugate of T. The Green function are obtained by solving the equations (8). The poles of the Green functions occur at energies, which are the roots of the following local spin wave dispersion equation for the superlattice constructed ferro- and antiferromagnetic semiconductors materials:

$$\langle S_{AFM}\rangle^2\langle S_{FM}\rangle\big[JJ_1YY_1\gamma^2(k_{||})TT^*(\langle S_{AFM}\rangle + \langle S_{FM}\rangle) - J_1^2Y_1^2\langle S_{AFM}\rangle(TT^*)^2 -$$

$$J^2Y^2\langle S_{FM}\rangle\gamma^2(k_{||})\big] + \langle S_{AFM}\rangle\lambda_d(\omega)\big[J^2\langle S_{AFM}\rangle\gamma^2(k_{||})\lambda_c(\omega) - 0.5Y_1^2\langle S_{FM}\rangle TT^*\lambda_b(\omega)\big] +$$

$$\lambda_a(\omega)\big[2J_1^2\langle S_{AFM}\rangle^2TT^*\lambda_c(\omega) + \lambda_b(\omega)\big(\lambda_c(\omega)\lambda_d(\omega) - Y^2\langle S_{FM}\rangle^2\gamma^2(k_{||})\big)\big] = 0 \tag{9}$$

CONCLUSION

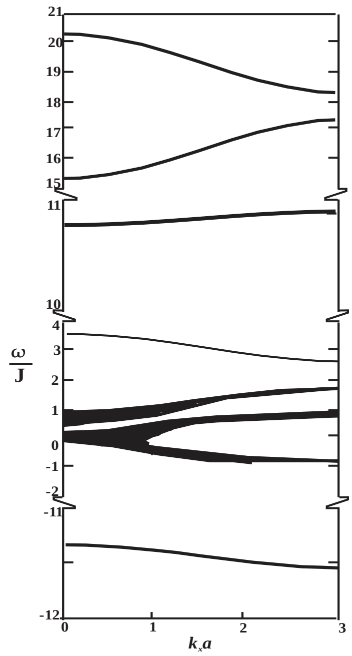

Fig. 2. The bulk spin–wave regions in the superlattice as a function of transverse components of wavevectors. The values of parameters are following: $J/Y = 0.5$, $J_1/Y = 0.5$, $Y_1/Y = 1.5$, $I/Y = 15$, $K/Y = 10$, $\langle S^z_{AFM}\rangle = \langle S^z_{FM}\rangle = \langle s^z\rangle = 0.5$, $g\mu_B H^{(A)}_{FM}/Y = 0.1$, $g\mu_B H^{(A)}_{AFM}/Y = 0.2$.

For the superlattice under consideration, the bulk spin-wave energy regions as a function of wave vector $k_x a$ for a particular choice of parameters is demonstrated in figure 2, that corresponds to $k_y a = 0$ and $-1 \le cosk_z d \le 1$ range.

The calculations show that roots of dispersion equation (9) have six positive and two negative frequencies. In addition, half of the spin-wave regions correspond to the small value of the frequency module, and half of the higher ones. The spin wave frequencies increase with increasing exchange coupling between localized spins and (s-d) or (s-f) exchange interaction of the conduction electrons spins.

The analysis of the results shows that the width of the bulk-spin wave regions in the superlattice formed ferro- and antiferromagnetic materials is depended on transverse components of wave vectors and exchange interaction.

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