BULK SPIN-WAVE REGIONS IN A SUPERLATTICE FORMED FERRO- AND ANTIFERROMAGNETIC MATERIALS

V.A. TANRIVERDIYEV, V.S. TAGIYEV, S.M. SEYID-RZAYEVA
Institute of Physics of the National Academy of Sciences of Azerbaijan, Baku Az -1143, Baku, H.Javid ave. 33

Theoretical studies of superlattice formed from alternating layers of simple-cubic Heisenberg ferromagnetic and antiferromagnetic materials have been presented. The spin-wave regions for spin waves propagating in a general direction in the superlattice are derived by the Green function method. The results are illustrated numerically.

During the past decade, there has been growing interest in the magnetic properties of artificially layered structures. With the advance epitaxial growth technique, it is possible to grow very thin films of a several monolayers [1-3]. Various magnetic superlattices have been prepared in which magnetic and nonmagnetic layers alternate. They have applications in electronic information technology.

There have been many theoretical studies of spin wave dispersion in the long-wavelength or magnetostatic limit and in the short-wavelength limit, where the exchange coupling is dominant [4,5]. The different physical characteristics, such as spectrum of magnons, the temperature dependence of magnetization, magnetic susceptibility and others for magnetic layered structures are obtained using Green function method [6]. Most of the works have been devoted to the properties of superlattices composed of two different ferro- and antiferromagnetic materials [7–9]. In particularly bulk spin-wave regions in ferro- and antiferromagnetic superlattice are derived in Ref.[10,11]. The purpose of this paper is to explore the nature of the spectrum of the bulk spin waves in superlattice consisting of alternating layers of simple-cubic Heisenberg ferromagnetic and antiferromagnetic materials by the Green function method.

As indicated in fig.1 we consider a simple cubic superlattice model in which the atomic planes of ferromagnetic material alternate with atomic planes of antiferromagnetic material. Elementary cell of the superlattice consist of four type of spins those labeled with *a* and *b* belong antiferromagnetic material, spins c and d belong ferromagnetic material. Each atomic plane is assumed to be the [001] planes. Both materials are taken to be simple-cubic Heisenberg ferro- and antifermagnets, having exchange constant *Y* and *J*, respectively. 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. Lattice constant of the superlattice in x-y plane is a.

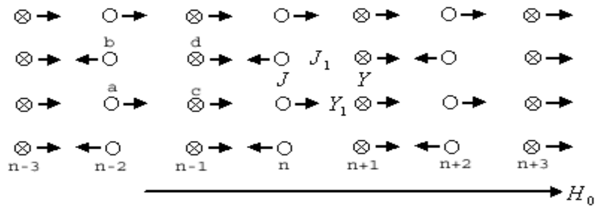

Fig.1. A superlattice model in which the atomic planes of ferromagnetic material alternate with atomic planes of antiferromagnetic material. The lattice parameter a is assumed for both the materials.

Our total Hamiltonian *H* may be expressed as

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

where H_{FM} is the Heisenberg Hamiltonian for the ferromagnetic order spins

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

The term H_{AFM} in (1) describes antiferromagnetic order spins:

$$H_{AFM} = \sum_{i,j} J_{ij}(\vec{S}_i\vec{S}_j) - \sum_i g\mu_B (H_0 + H_{AFM,i}{}^{(A)})S_{i,a}^z - \sum_i g\mu_B (H_0 - H_{AFM,i}{}^{(A)})S_{i,b}^z \tag{3}$$

H_0 in (1) and (2) is the internal magnetic field, which is assumed to be paralle1 to the *z* axis and $H^{(A)}_{FM(AFM),i}$ anisotropy field with simple uniaxial anisotropy. $\vec{S}$ is localized spin operator. There are both ferro- and antiferromagnetic spin arrangements between spins of the two atomic layers at each interface as shown in fig.1. Therefore we define four type Green function in real space

$$\begin{aligned} G^{(a)}_{i,j}(t,t') &= \langle\langle S^{+}_{i,(a)}(t); S^{-}_{j,(a)}(t')\rangle\rangle , \qquad G^{(b)}_{i,j}(t,t') = \langle\langle S^{+}_{i,(b)}(t); S^{-}_{j,(a)}(t')\rangle\rangle , \\ G^{(c)}_{i,j}(t,t') &= \langle\langle S^{+}_{i,(c)}(t); S^{-}_{j,(a)}(t')\rangle\rangle , \qquad G^{(d)}_{i,j}(t,t') = \langle\langle S^{+}_{i,(d)}(t); S^{-}_{j,(a)}(t')\rangle\rangle . \end{aligned} \tag{4}$$

Furthermore, to emphasize the layered structure we shall use the following the frequency and two-dimensional. Fourier transformation [2]

$$G^{(\alpha)}_{i,j}(t,t') = \frac{1}{N}\sum_{k_\parallel} \exp[ik_\parallel(r_i - r_j)]\frac{1}{2\pi}\int G^{(\alpha)}_{n,n'}(\omega,k_\parallel)\exp[i\omega(t-t')], \quad (\alpha = a,b,c,d), \tag{5}$$

where $k_{\parallel}$ is two-dimensional wave vector across to the xy-plane , ω is spin-wave frequency, 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 (4) one obtains the following set of equations after two-dimensional Fourier transformation [5]

$$\begin{cases} (\omega-\lambda^a)G^{(a)}_{n,n'}(\omega,k_{\parallel})-\langle S^z_{n,a}\rangle\left[4J\gamma(k_{\parallel})G^{(b)}_{n,n'}(\omega,k_{\parallel})-0.5Y_1G^{(c)}_{n-1,n'}(\omega,k_{\parallel})-0.5Y_1G^{(c)}_{n+1,n'}(\omega,k_{\parallel})\right]=2\langle S^z_{n,a}\rangle\delta_{n,n'}\,, \\ (\omega-\lambda^b)G^{(a)}_{n,n'}(\omega,k_{\parallel})-\langle S^z_{n,b}\rangle\left[4J\gamma(k_{\parallel})G^{(a)}_{n,n'}(\omega,k_{\parallel})+J_1G^{(d)}_{n-1,n'}(\omega,k_{\parallel})+J_1G^{(d)}_{n+1,n'}(\omega,k_{\parallel})\right]=0\,, \\ (\omega-\lambda^c)G^{(c)}_{n+1,n'}(\omega,k_{\parallel})+\langle S^z_{n+1,c}\rangle\left[4Y\gamma(k_{\parallel})G^{(d)}_{n+1,n'}(\omega,k_{\parallel})+Y_1G^{(a)}_{n,n'}(\omega,k_{\parallel})+Y_1G^{(a)}_{n+2,n'}(\omega,k_{\parallel})\right]=2\langle S^z_{n+1,c}\rangle\delta_{n+1,n'}\,, \\ (\omega-\lambda^d)G^{(d)}_{n+1,n'}(\omega,k_{\parallel})+\langle S^z_{n+1,d}\rangle\left[4Y\gamma(k_{\parallel})G^{(c)}_{n+1,n'}(\omega,k_{\parallel})-2J_1G^{(b)}_{n,n'}(\omega,k_{\parallel})-2J_1G^{(b)}_{n+2,n'}(\omega,k_{\parallel})\right]=0\,. \end{cases} \quad (6)$$

where $\lambda^a=g\mu H^{(A)}_{AFM}+4J\langle S^z_{AFM}\rangle+Y_1\langle S^z_{FM}\rangle\,,\qquad \lambda^b=-g\mu H^{(A)}_{AFM}-4J\langle S^z_{AFM}\rangle-2J_1\langle S^z_{FM}\rangle\,,$

$\lambda^c=g\mu H^{(A)}_{FM}+2Y\langle S^z_{FM}\rangle+Y_1\langle S^z_{AFM}\rangle\,,\qquad \lambda^d=g\mu H^{(A)}_{FM}+2Y\langle S^z_{FM}\rangle+2J_1\langle S^z_{AFM}\rangle\,,$

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

$\langle S^z_{FM}\rangle$ and $\langle S^z_{AFM}\rangle$ are average meaning of *z*-spins components in ferro- and antiferomagnetic sublattices.

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

$$G^{(\alpha)}_{n+2,n'}(\omega,k_{\parallel})=\exp[ik_zd]\,G^{(\alpha)}_{n,n'}(\omega,k_{\parallel}),\quad G^{(\alpha)}_{n-1,n'}(\omega,k_{\parallel})=\exp[-ik_zd]\,G^{(\alpha)}_{n+1,n'}(\omega,k_{\parallel}),\quad \alpha=a,b,c,d. \quad (7)$$

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

$$\begin{pmatrix} \omega-\lambda^a & -4J\langle S_{AFM}\rangle\gamma(k_{\parallel}) & 0.5Y_1\langle S_{AFM}\rangle T^* & 0 \\ 4J\langle S_{AFM}\rangle\gamma(k_{\parallel}) & \omega-\lambda^b & 0 & J_1\langle S_{AFM}\rangle T^* \\ 0.5Y_1\langle S_{FM}\rangle T & 0 & \omega-\lambda^c & 2Y\langle S_{FM}\rangle\gamma(k_{\parallel}) \\ 0 & -J_1\langle S_{AFM}\rangle T & 2Y\langle S_{FM}\rangle\gamma(k_{\parallel}) & \omega-\lambda^d \end{pmatrix}\cdot\begin{pmatrix} G^{(a)}_{n,n'}(\omega,k_{\parallel}) \\ G^{(b)}_{n,n'}(\omega,k_{\parallel}) \\ G^{(c)}_{n+1,n'}(\omega,k_{\parallel}) \\ G^{(d)}_{n+1,n'}(\omega,k_{\parallel}) \end{pmatrix}=\begin{pmatrix} 2\langle S^z_{AFM}\rangle\delta_{n,n'} \\ 0 \\ 2\langle S^z_{FM}\rangle\delta_{n+1,n'} \\ 0 \end{pmatrix} \quad (8)$$

where $T=1+\exp(ik_zd)$ and T^* is the complex conjugate of T. The Green functions are obtained by solving the equations (8). The poles of the Green functions occur at energies, which are the roots of the following bulk-spin wave dispersion equation for the superlattice under consideration:

$$\begin{aligned} &64J^2Y^2\langle S_{FM}\rangle^2\langle S_{AFM}\rangle^2\gamma^4(k_{\parallel})-(\omega-\lambda^a)(\omega-\lambda^b)(\omega-\lambda^c)(\omega-\lambda^d)+\left(0.5J_1Y_1\langle S_{FM}\rangle\langle S_{AFM}\rangle TT^*\right)^2+ \\ &+4\gamma^2(k_{\parallel})\left[Y^2\langle S_{FM}\rangle^2(\omega-\lambda^a)(\omega-\lambda^b)-4J^2\langle S_{AFM}\rangle^2(\omega-\lambda^c)(\omega-\lambda^d)-2JYJ_1Y_1\langle S_{FM}\rangle^2\langle S_{AFM}\rangle^2TT^*\right]+ \\ &+\langle S_{FM}\rangle\langle S_{AFM}\rangle TT^*\left[0.25Y_1^2(\omega-\lambda^b)(\omega-\lambda^d)-J_1^2(\omega-\lambda^a)(\omega-\lambda^c)\right]=0 \end{aligned} \quad (9)$$

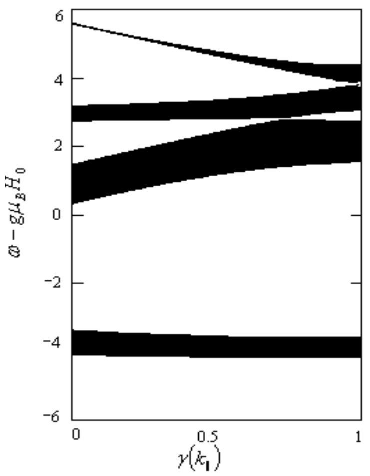

Fig.2. The bulk spin–wave regions in the superlattice as a function of transverse components of wave vectors. The values of parameters are following: *J/Y=0.5*; *J_1/Y=1.5*; *Y_1/Y=2;* $g\mu_BH^{(A)}_{FM}/Y\langle S^z_{FM}\rangle=0.1$; $g\mu_BH^{(A)}_{AFM}/Y\langle S^z_{FM}\rangle=0.5$; $\langle S^z_{AFM}\rangle/\langle S^z_{FM}\rangle=0.5$

Numerically calculated bulk spin-wave regions in the superlattice as a function of the quantity $\gamma(k_{\|})$ for a particular choice of parameters is presented in figure 2, that corresponds to $-1 \leq \cos k_z d \leq 1$ range. The calculations shows that roots of dispersion equation (9) have tree positive and a negative frequencies. The analysis of the results shows that the width of the bulk-spin wave regions in the superlattice formed from ferro- and antiferromagnetic materials depends on transverse components of wave vectors and exchange interaction.

[1] *J. J. Chen, G. Dresselhaus, M.S. Dresselhaus, G. Sprinhoulz, C. Picher, G. Bauer.* Phys. *Rev*., 1996, B54, 4020.

[2] *C. A. Ramos, D. Lederman, A.R. King, V. Jaccarino* Phys. Rev. Lett., 1990, 65, 2913.

[3] *T. M. Giebultowicz, P. Klosovski, N. Samarth, H. Lou, J. K. Furdyna.* J. J. Rhyne, Phys. Rev., 1993, B48, 12817.

[4] *D. H. A. L. Anselmo, E.L. Albuquerque, M.G. Cottam.* J. Appl. Phys., 1998, 83, 6955.

[5] *V.A.Tanriverdiyev, V.S.Tagiyev, S.M.Seyid-Rzayeva*. Phys. Stat. Sol. (b), 2003, 240, 183.

[6] *D.N. Zubarev* UFN LXXI, 1, 1960.

[7] *Feng Chen and H.K.Sy.* J. Phys. Condens. Matter., 1995, 7, 591.

[8] *E.L.Albuquerque. Fulko, E.F.Sarmento, D.R.Tilley.* Solid State Commun., 1986, 58, 41.

[9] *L.L.Hincey and D.L. Mills*. Phys. Rev.,1986, B 33, 3329

[10] *V.A.Tanriverdiyev, V.S.Tagiyev, M.B. Guseynov*. Transaction. Azerbaijan Academy of Sciences,2000, 20, 2.

[11] *V.S.Tagiyev, V.A.Tanriverdiyev, S.M.Seyid-Rzayeva, M.B.Guseynov*. Fizika, Baku,2000, 1.

V.Ə. Tanrıverdiyev, V.S. Tağıyev, S.M. Seyid-Rzayeva

FERRO- VƏ ANTİFERROMAQNİT MATERİALDAN HAZIRLANMIŞ İFRATQƏFƏSDƏ HƏCM SPİN DALĞA ZONASI

İki sadə kubik Heyzenberq ferromaqnit və antiferromaqnit materialın atom laylarının növbələşməsindən alınmış ifratqəfəs tədqiq olunur. Qrin funksiyası metodu ilə ifrat qəfəsin oxu boyunca yayılan həcm spin dalğaları üçün spin dalğa zonası təyin edilib. Nəticə kəmiyyətcə təsvir edilir.

В.А. Танрывердиев, В.С. Тагиев, С.М. Сеид-Рзаева

ЗОНЫ ОБЪЕМНЫХ СПИНОВЫХ ВОЛН В ФЕРРО- И АНТИФЕРРОМАГНИТНЫХ СВЕРХРЕШЕТКАХ

В настоящей работе рассмотрена сверхрешетка, состоящая из чередующихся одноатомных слоев гейзенберговских кубических ферромагнитных и антиферромагнитных материалов. Методом функций Грина определены зоны объемных спиновых волн,распростроняющихся вдоль оси сверхрешетки. Полученные результаты численно интерпретированы.

Received: 16.10.06