Theoretical studies of the magnetic multivalued recording in coupled multilayers

Lei Zhou, Ning Xie, and Shengyu Jin
T. D. Lee Physics Laboratory and Department of Physics, Fudan University, Shanghai 200433, People's Republic of China

Ruibao Tao
Center for Theoretical Physics, Chinese Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China and Department of Physics, Fudan University, Shanghai 200433, People's Republic of China

(Received 12 June 1996; revised manuscript received 9 September 1996)

In this paper, we discuss the possibilities of realizing the magnetic multivalued (MMV) recording in a magnetic coupled multilayer. The hysteresis loop of a double-layer system is studied analytically, and the conditions for achieving the MMV recording are given. The conditions are studied from different respects, and the phase diagrams for the anisotropic parameters are given in the end. [S0163-1829(97)04906-0]

I. INTRODUCTION

Many efforts have been devoted to the studies of magnetic multilayers because there have been lots of fascinating behaviors displayed in such systems.[1–4] One of the important applications of magnetic multilayers in technology is that they can be used as recording media for memory devices. In such materials, the hysteresis loop of one domain should be rather rectangular in order that two messages can be recorded in the ''spin-up'' and ''spin-down'' states, respectively. Recently, much attention has been paid to increase the density of the recording media. One of the proposals is to diminish the sizes of the domains. However, the recording density will eventually come to a limit following this way, so that one must try to find new approaches. A simple idea is that if more (than two) messages can be recorded in one domain, the recording density will be highly improved even though the domain's size remains the same. This is just the idea of the magnetic multivalued (MMV) recording which is believed to be the next strategy of high density recording and has attracted much attention from both experimental and theoretical sides. The MMV recording requires that more (than two) metastable phases which are stable enough to record messages must exist in the system; therefore, the hysteresis loop for such material should contain more (than one) sharp steps. Experimentally, the MMV recording was first confirmed by the field modulation method on disks of bilayers[3] or island on thin layers.[4] However, the theoretical origin is not yet clear.

More recently, a quantum theory of the coercive force[5] has been established for magnetic systems on the basis of some previous works.[6–8] The quantum approach enables one to study the hysteresis behaviors of a magnetic system from a micromagnetic view, and some interesting effects in double-film structures had been discussed by this method.[5]

The present paper is devoted to proposing a theoretical possibility of achieving the MMV recording in magnetic multilayers. The main idea is to find more metastable states in such systems. In the next section, we will briefly outline the quantum method and the model Hamiltonian studied. The stabilities of both the aligned and the canted spin states are discussed in Sec. III, and Sec. IV is devoted to the conditions for realizing the MMV recording. Finally, we compare the quantum method with the classical one in Sec. V, and summarize the main results in the last section.

II. MODEL HAMILTONIAN AND THE METHOD

In this paper, a double-layer system will be investigated analytically. The Hamiltonian can be given by

$$H=-\frac{1}{2}\sum_{m,m'}\sum_{\mathbf{R},\mathbf{R}'} I_{m,m'}(\mathbf{R},\mathbf{R}')\mathbf{S}_m(\mathbf{R})\cdot\mathbf{S}_{m'}(\mathbf{R}') - h\sum_{m,\mathbf{R}} S_m^z(\mathbf{R}) - \sum_m \sum_{\mathbf{R}} D_m[S_m^z(\mathbf{R})]^2, \tag{1}$$

where the subscripts m,m' are the number of the layers, and $\mathbf{R},\mathbf{R}'$ are the vectors of lattices on the x-y plane. $I_{m,m'}(\mathbf{R},\mathbf{R}')$ are the exchange parameters and only the nearest neighbor interaction is considered. The single-ion anisotropy is the ''easy axis'' case ($D_m>0$), and the ''easy-axis'' is perpendicular to the film. The spins and the anisotropies in different layers are different. It is supposed that $S_1>S_2$ without losing any generality.

Following Refs. 5 and 8, we will introduce the local coordinates (LC) system $\{\hat{x}_m,\hat{y}_m,\hat{z}_m\}$. The spin components in the LC system will have the following relations with those in the original one: $S_m^x=\cos\theta_m S_m^{x_m}+\sin\theta_m S_m^{z_m}, S_m^y=S_m^{y_m}$, $S_m^z=\cos\theta_m S_m^{z_m}-\sin\theta_m S_m^{x_m}$. In order to study the ground state properties and the low-lying spin-wave excitations, one can apply the usual spin-Bose transformation such as Holstein-Primakoff (HP) (Ref. 9) or the complete Bose transformations[10] (CBT's) to the spin operators in the LC system $\{S_m^{x_m},S_m^{y_m},S_m^{z_m}\}$. In a harmonic approximation, the HP transformation and the CBT's yield the same results. Then, after the LC transformation and the Bose transformation, the Hamiltonian becomes

$$H=U_0+H_1+H_2+\cdots, \tag{2}$$

H_2 can be written in the momentum $\mathbf{k}$ space for the x-y plane as follows:

$$H_2=\sum_{m,m'}\sum_{\mathbf{k}} F_{m,m'}(\mathbf{k},\theta)a_m^+(\mathbf{k})a_{m'}(\mathbf{k}) + \sum_{m,m'}\sum_{\mathbf{k}} G_{m,m'}(\mathbf{k},\theta)[a_m^+(\mathbf{k})a_{m'}^+(-\mathbf{k}) + a_m(\mathbf{k})a_{m'}(-\mathbf{k})], \quad (3)$$

in which the coefficients $F_{m,m'}$ and $G_{m,m'}$ are defined by

$$F_{m,m}(\mathbf{k},\theta)=I_{m,m}ZS_m(1-\gamma_k)-D_m\left(S_m-\frac{1}{2}\right)(\sin^2\theta_m - 2\cos^2\theta_m)+\sum_{m'} S_{m'}I_{m,m'}\cos(\theta_m-\theta_{m'}) + h\cos\theta_m, \quad (4)$$

$$F_{m,m'}(\mathbf{k},\theta)=-\frac{1}{2}I_{m,m'}\sqrt{S_mS_{m'}}[1+\cos(\theta_m-\theta_{m'})], \quad (5)$$

$$G_{m,m}(\mathbf{k},\theta)=-\frac{1}{4}\sqrt{2S_m(2S_m-1)}D_m\sin^2\theta_m, \quad (6)$$

$$G_{m,m'}(\mathbf{k},\theta)=\frac{1}{4}I_{m,m'}\sqrt{S_mS_{m'}}[1-\cos(\theta_m-\theta_{m'})]. \quad (7)$$

Here, $\gamma_k=(1/Z)\Sigma_\delta\exp(i\mathbf{k}\cdot\delta)$ where the summation δ runs over the Z nearest neighbors of a given site in the x-y plane.

In a first-order approximation, the spin configuration $\{\theta_m\}$ can be obtained by minimizing the ground state energy U_0: $\delta U_0/\delta\theta_m=0$, which yields the following equations:

$$\sum_{m'} I_{m,m'}S_{m'}\sin(\theta_m-\theta_{m'})+h\sin\theta_m+D_m(2S_m - 1)\sin\theta_m\cos\theta_m=0. \quad (8)$$

The equations above are just the same as the condition of $H_1=0$. The harmonic part of Hamiltonian can be exactly diagonalized by a generalized Bogolyubov transformation:

$$\alpha_m^+(\mathbf{k})=\sum_n U_{m,n}(\mathbf{k})a_n^+(\mathbf{k})+\sum_n V_{m,n}(\mathbf{k})a_n(-\mathbf{k}), \quad (9)$$

$$\alpha_m(-\mathbf{k})=\sum_n U_{m,n}(\mathbf{k})a_n(-\mathbf{k})+\sum_n V_{m,n}(\mathbf{k})a_n^+(\mathbf{k}), \quad (10)$$

so that we finally get

$$H=U_0'+\sum_k \epsilon_m(\mathbf{k})\alpha_m^+(\mathbf{k})\alpha_m(\mathbf{k})+\cdots, \quad (11)$$

where the magnon excitation energy $\epsilon_m(\mathbf{k})$ in Eq. (11) and the coefficients $(U_{m,n},V_{m,n})$ in Eqs. (9) and (10) can be obtained from the eigenvalues and the eigenvectors of the following matrix:

$$\hat{\mathcal{H}}(\mathbf{k})=\begin{pmatrix} \hat{\mathcal{F}}(\mathbf{k}) & i2\hat{\mathcal{G}}(\mathbf{k}) \\ i2\hat{\mathcal{G}}(\mathbf{k}) & -\hat{\mathcal{F}}(\mathbf{k}) \end{pmatrix}. \quad (12)$$

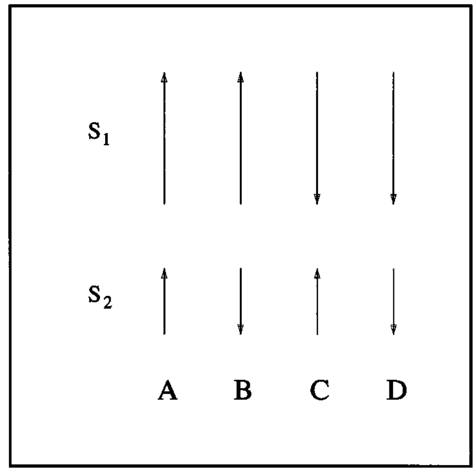

FIG. 1. Aligned spin configurations in a double-layer magnetic system.

The elements of the sub-matrices $\mathcal{F}(\mathbf{k})$ and $\mathcal{G}(\mathbf{k})$ in matrix $\mathcal{H}(\mathbf{k})$ are $F_{m,m'}(\theta,\mathbf{k})$ and $G_{m,m'}(\theta,\mathbf{k})$ defined in Eqs. (4)–(7), respectively.[5]

Following Ref. 5, the minimum value of the magnon excitation energy $\epsilon_m(\mathbf{k})$ is defined as the gap $\Delta(h)=\min[\epsilon_m(\mathbf{k})]$.

Equation (8) may have many solutions corresponding to various possible spin configurations. For every solution of Eq. (8), one can calculate the magnon excitation gap $\Delta(h)$ following the method described above. According to Ref. 5, if the gap $\Delta(h)$ is positive, the state described by such a solution is a metastable one since a variation from this state must cost energy. However, when the gap comes to zero or is even negative at a field h_c, such a state will no longer be metastable and a transition from this state to another metastable one will take place. Thus, in the case that there are many metastable states existing in the system, the MMV recording is possible to take place.

Equation (8) has two kinds of solutions: the trivial solutions (i.e., $\theta_m=0$ or, π, $m=1,2$) which correspond to the aligned spin states; the nontrivial solutions (i.e., $\theta_m\neq 0$ or, π, $m=1,2$) to the canted spin states. Subsequently, we will discuss both the aligned spin states and the canted spin states, and discuss which state the system will transit to if the current state is unstable.

The following notations will be used. $I_{m,m}(\mathbf{R},\mathbf{R}')=J$, $I_{m,m'}(\mathbf{R},\mathbf{R})=I$ and $D_m(2S_m-1)=\widetilde{D}_m$. The exchange interaction within a layer should be the ferromagnetic type $(J>0)$. However, both the ferromagnetic and the antiferromagnetic types of interlayer exchange coupling will be discussed (i.e., $I>0$ or $I<0$).

III. METASTABLE STATES

A. The aligned spin states

In such a system, four aligned states are possible. They are illustrated in Fig. 1. For configuration A, we have $\theta_1=0,\theta_2=0$. From Eqs. (4)–(7), we obtain

$$\hat{\mathcal{F}}(\mathbf{k})=\begin{pmatrix} IS_2+\tilde{D}_1+h+JZS_2(1-\gamma_k) & -I\sqrt{S_1S_2} \\ -I\sqrt{S_1S_2} & IS_1+\tilde{D}_2+h+JZS_1(1-\gamma_k)\end{pmatrix}, \quad (13)$$

and

$$\hat{\mathcal{G}}(\mathbf{k})=0. \quad (14)$$

According to Eqs. (11) and (12), we find that the excitation energy $\epsilon_m(\mathbf{k})$ are just the eigenvalues of the matrix $\hat{\mathcal{F}}(\mathbf{k})$. Thus we obtain

$$\Delta_A(h)=h+\frac{1}{2}[\tilde{D}_1+\tilde{D}_2+IS_1+IS_2 - \sqrt{(IS_2-IS_1+\tilde{D}_1-\tilde{D}_2)^2+4I^2S_1S_2}]. \quad (15)$$

From the discussions above, it follows that the system in configuration A will be stable only in the case that

$$h \geqslant h_c^0, \quad (16)$$

where

$$h_c^0=\frac{1}{2}[-IS_1-IS_2-\tilde{D}_1-\tilde{D}_2 + \sqrt{(IS_2-IS_1+\tilde{D}_1-\tilde{D}_2)^2+4I^2S_1S_2}]. \quad (17)$$

It is similar for configuration B. The stable region for configuration B is

$$h_c^2 \leqslant h \leqslant h_c^1, \quad (18)$$

where

$$h_c^1=\frac{1}{2}[IS_2-IS_1+\tilde{D}_2-\tilde{D}_1 + \sqrt{(\tilde{D}_1+\tilde{D}_2-IS_1-IS_2)^2-4I^2S_1S_2}], \quad (19)$$

$$h_c^2=\frac{1}{2}[IS_2-IS_1+\tilde{D}_2-\tilde{D}_1 - \sqrt{(\tilde{D}_1+\tilde{D}_2-IS_1-IS_2)^2-4I^2S_1S_2}]. \quad (20)$$

Considering the symmetry between states A,B and states C,D, it is very easy to understand that the stable region of states C and D are $[-h_c^1,-h_c^2]$ and $(-\infty,-h_c^0]$, respectively.

B. The canted spin states

For every trivial solution, nontrivial solutions can be bifurcated from them at some fields. Around the bifurcation points, the variations of the angles from the trivial solution should be very small. Thus, it is reasonable to linearize the nonlinear equations (8) to study the behaviors of the nontrivial solutions around the bifurcation point. Taking configuration A as an example, we have $\sin\theta_m \sim \theta_m$. Then around the bifurcation point, Eqs. (8) will be linearized as

$$IS_2(\theta_1-\theta_2)+h\theta_1+\tilde{D}_1\theta_1=0, \quad (21)$$

$$IS_1(\theta_2-\theta_1)+h\theta_2+\tilde{D}_2\theta_2=0, \quad (22)$$

which can be rewritten as

$$\begin{pmatrix} -\tilde{D}_1-IS_2 & IS_2 \\ IS_1 & -\tilde{D}_2-IS_1\end{pmatrix}\begin{pmatrix}\theta_1\\ \theta_2\end{pmatrix}=h\begin{pmatrix}\theta_1\\ \theta_2\end{pmatrix}. \quad (23)$$

The matrix on the left side of the above equation can be diagonalized with the following two eigenvalues:

$$\lambda_1=\frac{1}{2}[-IS_1-IS_2-\tilde{D}_1-\tilde{D}_2 + \sqrt{(IS_2-IS_1+\tilde{D}_1-\tilde{D}_2)^2+4I^2S_1S_2}], \quad (24)$$

$$\lambda_2=\frac{1}{2}[-IS_1-IS_2-\tilde{D}_1-\tilde{D}_2 - \sqrt{(IS_2-IS_1+\tilde{D}_1-\tilde{D}_2)^2+4I^2S_1S_2}]. \quad (25)$$

Thus, if $h=\lambda_1$ or λ_2, the linearized equations (21) and (22) or Eq. (23) has nonzero solutions. If we put this solution as a ''guessed solution'' into the nonlinear equations (8), we can finally get a nontrivial solution step by step. The nontrivial solutions bifurcated from other trivial solutions can be studied similarly.

Noting $\lambda_1>\lambda_2$, it is easy to understand that the nontrivial solution cannot exist when $h>\lambda_1$. It is interesting to find that $\lambda_1=h_c^0$. Thus the canted spin state can appear only in the case that the aligned spin state is not stable.

In order to study whether the canted spin state can be stable or not, one should study the magnon excitation gap $\Delta(h)$ in the vicinity of the critical point h_c^0 for the nontrivial solution. Since the angles θ_1,θ_2 are very small in this case, it is reasonable to adopt a first-order approximation when calculating the magnon excitation gap. From Eqs. (4)–(7), the elements of the matrix $\hat{\mathcal{H}}(h_c^0,\mathbf{k})|_{\mathbf{k=0}}$ in a first order approximation can be given as

$$F_{m,m'}=F^0_{m,m'}+\delta F_{m,m'}, \quad (26)$$

$$G_{m,m'}=G^0_{m,m'}+\delta G_{m,m'}, \quad (27)$$

where $F^0_{m,m'},G^0_{m,m'}$ have been defined in Eqs. (13) and (14) by setting $\mathbf{k}=0$. $\delta F_{m,m'}$ are found to be

$$\delta F_{1,1}=-\frac{1}{2}IS_2(\theta_1-\theta_2)^2-\left(\frac{1}{2}h_c^0+\frac{3}{2}\tilde{D}_1\right)\theta_1^2, \quad (28)$$

$$\delta F_{2,2}=-\frac{1}{2}IS_1(\theta_1-\theta_2)^2-\left(\frac{1}{2}h_c^0+\frac{3}{2}\tilde{D}_1\right)\theta_2^2, \quad (29)$$

$$\delta F_{1,2}=\delta F_{2,1}=-\frac{1}{4}\sqrt{I^2S_1S_2}(\theta_1-\theta_2)^2. \quad (30)$$

Since θ_1,θ_2 can be substituted by the solution of the linearized equations (21) and (22) in the critical point h_c^0 in a first-order approximation, they must have the following relation:

$$\frac{\theta_1}{\theta_2}=\frac{IS_2}{IS_2+\widetilde{D}_1+h_c^0}=\frac{IS_2}{F_{1,1}^0}. \tag{31}$$

Thus all the terms in Eqs. (28)–(30) can be obtained after extracting a common parameter θ_2^2 through use of Eq. (31). For example,

$$\delta F_{1,1}=\left[-\frac{1}{2}IS_2\left(1-\frac{IS_2}{F_{1,1}^0}\right)^2-\left(\frac{h_c^0}{2}+\frac{3}{2}\widetilde{D}_1\right)\left(\frac{IS_2}{F_{1,1}^0}\right)^2\right]\theta_2^2. \tag{32}$$

So, based on the perturbation theory, the magnon excitation gap $\Delta(h_c^0)$ of the canted spin state at the critical point h_c^0 in the first-order approximation can be presented as

$$\Delta(h_c^0)\simeq\delta F_{1,1}+\delta F_{2,2}-\frac{1}{F_{1,1}^0+F_{2,2}^0}[(\delta F_{1,1}-\delta F_{2,2})(F_{1,1}^0-F_{2,2}^0)+4\sqrt{I^2S_1S_2}\,\delta F_{1,2}]. \tag{33}$$

$\Delta(h_c^0)/\theta_2^2$ must now be a definite value determined by the parameters. The nontrivial spin state which is bifurcated from configuration B can be studied similarly, and the magnon excitation gap $\Delta(h_c^2)$ for such a canted spin state can also be derived following the same procedure.

IV. THE CONDITIONS FOR MMV RECORDING

We have studied both the aligned spin state and the canted one. In order to realize the MMV recording, the four aligned spin states must be overlapping with each other. Thus, it is required that

$$h_c^2<h_c^0<h_c^1. \tag{34}$$

On the other hand, to be used for recording, the hysteresis loop should be as sharp as possible. Otherwise, it may cause difficulty to distinguish two messages. Thus, the canted spin states should not exist:

$$\Delta(h_c^0)<0, \quad \Delta(h_c^2)<0. \tag{35}$$

Equations (34) and (35) are just the conditions for realizing the MMV recording in a double-layer structure. The conditions are the complicated relations between the single-ion anisotropy parameters (D_1,D_2), the exchange interaction parameter (I), and the spins (S_1, S_2). We will study them from different respects.

First, we study what the requirement is for the interlayer exchange parameter I if the two magnetic layers are determined. The following model will be investigated:

model 1: $S_1=3$, $S_2=1$, $D_1/D_2=2.0$.

The critical fields h_c^0, h_c^1, h_c^2 have been shown together as functions of I/D_2 in Fig. 2 . One may find that the exchange parameter should satisfy $I_c^1<I<I_c^2$ for condition (34). If the exchange coupling is the ferromagnetic case and is very strong $(I>I_c')$, the B and C states cannot be stable at all since the two magnetic layers are unwilling to antiparallel with each other (Fig. 2). In Fig. 3, $\Delta(h_c^0)$ is shown with respect to I/D_2 in order to study the stabilities of the canted spin state bifurcated from configuration A. One may find that only when the interlayer coupling is the antiferromagnetic case and is stronger than a critical value $(|I|>|I_c^3|)$, could

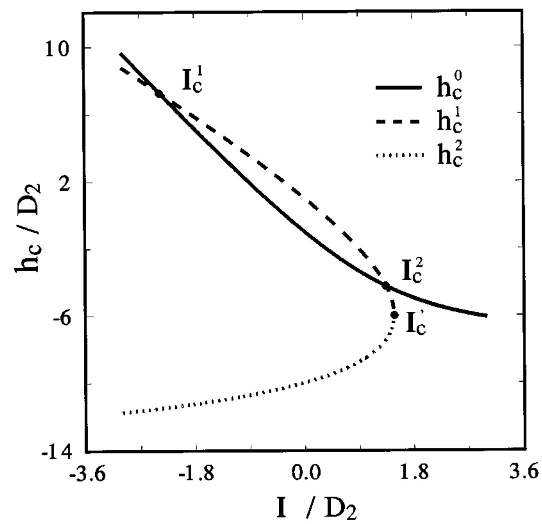

FIG. 2. Critical fields h_c^0, h_c^1 and h_c^2 as functions of the interlayer coupling constant for the double-layer system.

this canted spin state appear. If the coupling is the ferromagnetic case, this canted spin state is not able to be metastable. $\Delta(h_c^2)$ has also been studied for model 1, and it is always negative. In all, the exchange coupling should not be very strong compared to the anisotropy in order to realize the MMV recording. An example has been shown in Fig. 4 where $I/D_2=0.5$. The multistep shape of the hysteresis loop can be clearly observed.

However, there remains a question. At the field h_c^0 where spin configuration A is no longer stable, B and D spin states are both stable. Why will the system transit to spin configuration B instead of configuration D (Fig. 4)? This question can be answered by studying the magnon excitation spectrum. According to Eqs. (9)–(12), one can get the concrete forms of the Bose operators $\alpha_m(\mathbf{k})$. We only study the lowest mode of spin wave, so that $\mathbf{k}=0$. Suppose $m=1$ without losing generality, thus

$$\epsilon_1(\mathbf{k}=0,h_c^0)=\Delta(h_c^0)=0, \tag{36}$$

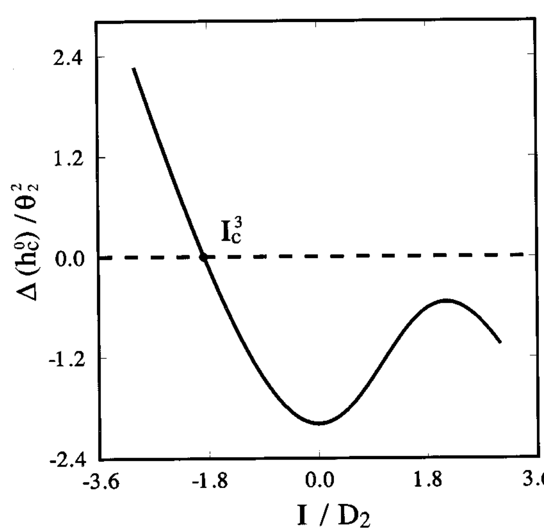

FIG. 3. $\Delta(h_c^0)/\theta_2^2$ as the function of the interlayer coupling constant for the double-layer system.

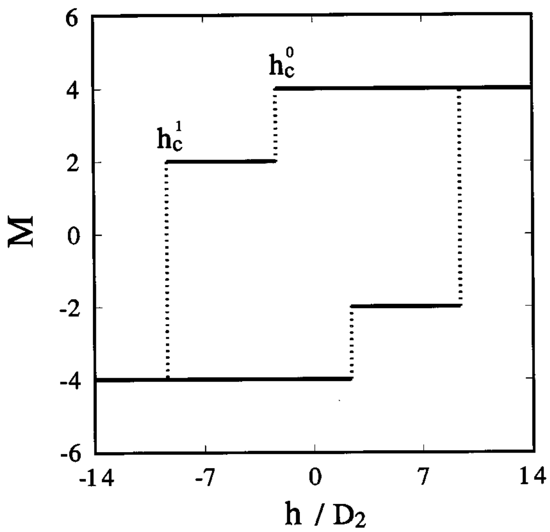

FIG. 4. Hysteresis loop of a double-layer magnetic system with a ferromagnetically interlayer coupling constant $I/D_2=0.5$.

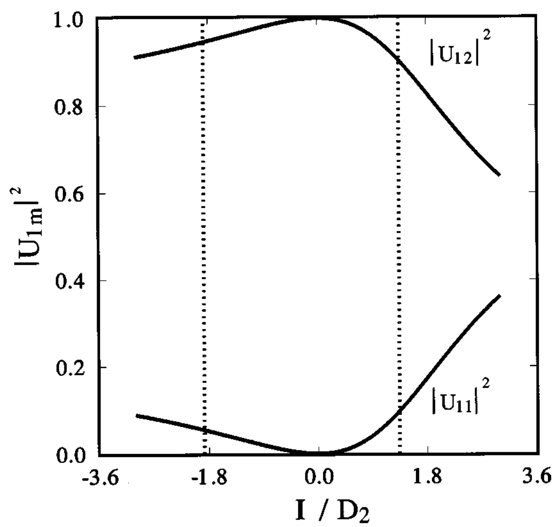

FIG. 5. The possibilities for the two magnetic layers to turn flipping ($|U_{1,1}|^2$, $|U_{1,2}|^2$) as functions of the interlayer exchange parameter.

$$\alpha_1(\mathbf{k})=U_{1,1}(\mathbf{k})a_1(\mathbf{k})+U_{1,2}(\mathbf{k})a_2(\mathbf{k}), \tag{37}$$

where

$$U_{1,1}(\mathbf{k}=0)=\frac{I\sqrt{S_1S_2}}{\sqrt{(IS_2+h_c^0+\tilde{D}_1)^2+I^2S_1S_2}}, \tag{38}$$

$$U_{1,2}(\mathbf{k}=0)=\frac{IS_2+h_c^0+\tilde{D}_1}{\sqrt{(IS_2+h_c^0+\tilde{D}_1)^2+I^2S_1S_2}}. \tag{39}$$

Since the excitation energy of this mode is zero, if there are any kinds of fluctuations, the bosons at this mode must be greatly excited without costing energy. The current spin configuration will be completely destroyed because of the excitations. Noting α_1 is a linear combination of a_1,a_2, the quantities $|U_{1,m'}|^2$ may be understood as the possibilities of the bosons in the mth layer to be excited, thus they must be considered as the possibilities of the spins in the mth layer to turn flipping. In Fig. 5, the two quantities $|U_{1,m'}|^2$ are shown together as functions of I/D_2 for model 1. One may find that in the region where the MMV recording is permitted, $|U_{1,1}|^2\sim 0$ while $|U_{1,2}|^2\sim 1$. Thus, at the field h_c^0 where the configuration A is not able to be stable, the spins in the second layer are most likely to turn flip while those in the first layer are not likely to do so. So, in this case, the system will transit to configuration B instead of configuration D. One may also find that if the interlayer exchange is the ferromagnetic case and is very strong ($I\gg D_2$), the two quantities will be close. Thus, the two magnetic layers are willing to turn flip together because of the strong interlayer coupling. The MMV recording is not able to be realized then. By the way, if there is no coupling between the two magnetic layers ($I=0$), we find that $|U_{1,1}|^2=0$ and $|U_{1,2}|^2=1$. This is easy to understand. Because the two layers are not coupled, they can be treated independently. In this case, one may find that h_c^0 and h_c^2 are just the coercive forces of the two layers. So, when the external field reaches h_c^0, the second layer will turn over while the first layer will not.

Finally, we study what kinds of materials can be used for MMV recording. Suppose $S_1=S_2=S, D'_m=(2S-1)D_m/|I|S$, the phase diagrams for the D'_1-D'_2 plane are given in a ferromagnetic case (Fig. 6) and in antiferromagnetic case (Fig. 7), respectively. The two cases are quite different. To realize the MMV recording, the anisotropies for the two materials cannot be very close ($D'_1\sim D'_2$) if the exchange is the ferromagnetic case (Fig. 6), while there is no such restriction for the antiferromagnetic case (Fig. 7). However, a common requirement in the two cases is still a weak interlayer exchange interaction.

V. COMPARISON WITH THE CLASSICAL METHOD

Before the quantum method is developed, the classical method is popularly used to discuss the magnetic configurations and other properties in magnetic layered structures.[1,11] The method can be briefly described as follows.[11] Treating the spins as classical vectors, one can write out the energy function $U(\{\theta_m\})$ after the LC transformation. The spin configuration $\{\theta_m\}$ is obtained by minimizing the energy function, and a given configuration is metastable only if any fluctuation will raise the corresponding energy: $U(\{\theta_m+\delta\theta_m\})>U(\{\theta_m\})$. Since $U(\{\theta_m+\delta\theta_m\})$ can be expanded to series of $\delta\theta_m$ at the point $\{\theta_m\}$,

$$U(\{\theta_m+\delta\theta_m\})=U(\{\theta_m\})+\frac{1}{2}\sum_{m,m'}\frac{\partial^2 U}{\partial\theta_m\partial\theta_{m'}}\delta\theta_m\delta\theta_{m'} +\cdots, \tag{40}$$

it can be easily derived that a configuration is stable only when all the eigenvalues of the following matrix $\mathcal{M}$ are positive. The elements of the matrix are defined as

$$M_{m,m}=\sum_{m'}S_mS_{m'}I_{m,m'}\cos(\theta_m-\theta'_m)+hS_m\cos\theta_m +D_mS_m^2\cos 2\theta_m, \tag{41}$$

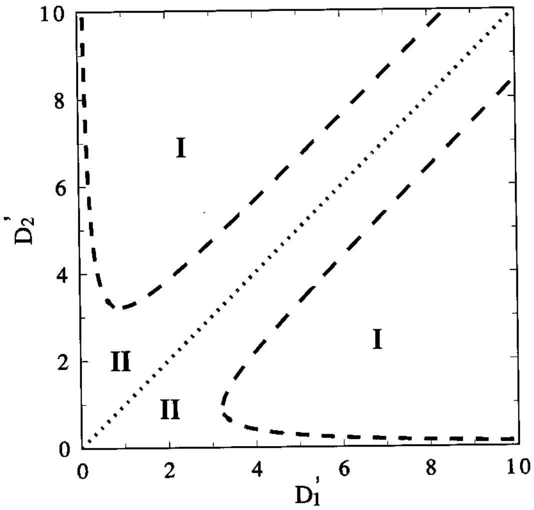

FIG. 6. Permitted values of the two anisotropies for realizing the MMV recording in the ferromagnetic coupling case. One can achieve the MMV recording in region I, and cannot do so in region II.

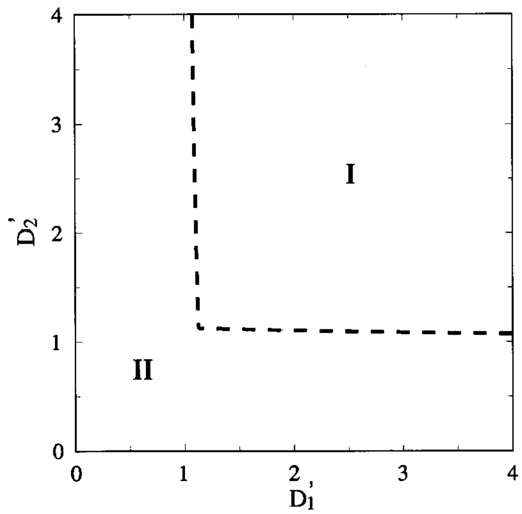

FIG. 7. Permitted values of the two anisotropies for realizing the MMV recording in the antiferromagnetic coupling case. One can achieve the MMV recording in region I, and cannot do so in region II.

$$M_{m,m'} = -I_{m,m'}\cos(\theta_m - \theta_{m'})S_m S_{m'}. \tag{42}$$

One can compare the two methods now. For a general spin system, when it is in an aligned state ($\theta_m = 0$ or π), it can be easily found that the matrix $\mathcal{M}$ is in fact equivalent to the matrix $\mathcal{H}(\mathbf{k})$ [Eq. (12)] when $\mathbf{k}=0$, provided that one may multiply every D_m term with a factor $(1-1/2S_m)$ in the matrix $\mathcal{M}$. Since the lowest spin-wave excitation is in the $\mathbf{k}=0$ subspace, we understand that for the aligned spin state, quantum fluctuations influence the final results only through deducting the effective value of the anisotropy D_m by a factor of $(1-1/2S_m)$.

However, things are different for the canted spin states. When $\theta_m \neq 0$ or π, quantum fluctuations are far more than the factor $(1-1/2S_m)$, and they may give some quantitative corrections to the final results. Numerical calculations show that quantum fluctuations always destroy the spin order *before* the classical fluctuations can do so.

By the way, we would like to point out that the quantum theory actually presents a basis for the classical theory for such spin systems. At the coercive field, we have $\mathbf{k}=0$ for the lowest mode of bosons, thus such bosons must be *infinitely* excited since they do not need energy and since they are bosons (not fermions). Because of $\mathbf{k}=0$, such an excitation must cause the spins within one layer to turn over together. From these arguments, one may find that the spins within a layer can be reasonably treated as a single vector so that a classical method can be applied.

VI. CONCLUSION

In conclusion, we have analytically studied the hysteresis loop of a double-layer magnetic system. We find that when the interlayer coupling and the anisotropies of the two materials satisfy some complicated conditions, more metastable states will be possible to appear, and the magnetic multivalued recording may be realized. The conditions are discussed from different respects, and the permitted values of the anisotropies for realizing the MMV recording are presented. Finally, we made a comparison between the quantum method used here with the classical method, and showed that the quantum fluctuations are nontrivial in the canted spin states.

ACKNOWLEDGMENTS

This research was partly supported by National Science Foundation of China and the National Education.

[1] R. E. Camley and R. L. Stamps, J. Phys. Condens. Matter **5**, 3727 (1993).
[2] S. Ohnuki, K. Shimazaki, N. Ohta, and H. Fujiwara, J. Magn. Soc. Jpn. **15**, 399 (1991).
[3] K. Shimazaki, M. Yoshihiro, O. Ishizaki, S. Ohnuki, and N. Ohta, J. Magn. Soc. Jpn. **19**, 429 (1995).
[4] S. Gadetsky, T. Suzuki, J. K. Erwin, and M. Mansuripur, J. Magn. Soc. Jpn. **19**, 91 (1995).
[5] Lei Zhou, Ruibao Tao, and Yoshiyuki Kawazoe, Phys. Rev. B **54**, 9924 (1996).
[6] X. Hu and Y. Kawazoe, J. Appl. Phys. **75**, 6486 (1994).
[7] X. Hu and Y. Kawazoe, Phys. Rev. B **49**, 3294 (1994).
[8] Ruibao Tao, Xiao Hu, and Yoshiyuki Kawazoe, Phys. Rev. B **52**, 6178 (1995).
[9] T. Holstein and H. Primakoff, Phys. Rev. **59**, 1098 (1940).
[10] Ruibao Tao, J. Phys. A **27**, 3621 (1994).
[11] Ning Xie, Lei Zhou, Shengyu Jin, and Ruibao Tao, Int. J. Mod. Phys. B **10**, 3627 (1996).