Magnetic studies of spin wave excitations in Fe/V multilayers


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Abstract

The magnetization of Fe(10 Å)/V(tV) (10 Å ≤ tV ≤ 40 Å) multilayers has been measured as a function of temperature. For Fe/V multilayers with fixed iron layer thickness of 10 Å, the magnetization decreases faster with temperature as the vanadium layers are made thicker. A simple theoretical model based on an anisotropic ferromagnetic system has been used to explain the temperature dependence of the magnetization and the approximate values for the bulk exchange interaction J0 and the interlayer coupling strength J1 for various Fe/V multilayers have been obtained.

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1. Introduction

Thin films and quasi-two-dimensional materials have many technological applications, including uses in electronics, data storage, and catalysis in the case of metal-on-metal films. Recent advances in film growth techniques such as molecular beam epitaxy (MBE) and in characterization methods such as the surface magneto-optical Kerr effect provide not only an opportunity for further technological application but also allow one to consider thin films as an important testing ground of our understanding of atomic interactions. The development of materials with characteristics tailored to a specific application requires a detailed understanding of their microscopic interactions, how these interactions are affected by factors such as composition and preparation, and how they determine the material properties. For example, the use of ultrathin magnetic films for data storage requires that the magnetization of the film be set and read with a high degree of accuracy and spatial resolution.

The discovery of coupled magnetic behaviour between layer components in various magnetic multilayers system [1–4] has led to an increased interest in two-dimensional (2D) systems. To understand how the interlayer exchange coupling between 2D ferromagnetic layers through non-magnetic layers affects the magnetic dynamics of such a coupled magnetic system, we carried out an investigation on a sputtered Fe/V multilayer system. By varying the V layer thickness, we were able to tune the interlayer exchange coupling strength.

From the effect of the thickness of the nonmagnetic spacer layers on the temperature behaviour one may obtain information about a possible interlayer coupling. The $M(T)$ behaviour and the Curie temperature $T_C$ will of course not only be determined by an interlayer coupling but by the interplay between anisotropy [5,6]. Furthermore, interdiffusion causing graded interfaces and disorder resulting in a distribution of exchange interactions, can play an important role. Especially when the magnetic layer thickness is in the monolayer regime the latter two factors might dominate the temperature dependence.

2. Experimental

The multilayers were deposited onto water-cooled glass and silicon substrates by RF diode sputtering. The chamber was first evacuated to a pressure of $1–2 \times 10^{-7}$ Torr using a turbomolecular pump. Argon of 5N purity was used as the sputter gas and its pressure was kept constant at $6 \times 10^{-3}$ Torr. The RF power density was 2.1 W/cm$^2$. The thickness was measured in situ using a pre-calibrated quartz monitor. All the samples were grown on V buffer layers 100 Å thick. The iron layer thickness $t_{Fe}$ was fixed at 10 Å and the vanadium layer thickness $t_V$ was varied in the range 2.5–40 Å. X-ray diffraction (XRD) profiles, taken in reflection geometry at both low ($2\theta < 10^\circ$) and high ($35^\circ < 2\theta < 60^\circ$) scattering angle, confirmed the modulated structure and shows a [1 1 0] texture. The magnetization was measured using a vibrating sample magnetometer in the temperature range 5–300 K.
3. Results and discussion

Fig. 1 shows the temperature dependence of spontaneous magnetization for the Fe/V multiplayers. First of all it is clear that the temperature dependence is affected by the thickness of V layers, yielding a decrease of the $T_C$ with increasing $t_V$. This may reflect a Fe interlaying coupling mediated by a V layers with increases with increasing V thickness. The interaction enhances, so to say, the ordering parameter of the layers at given temperature and induces a gradual cross from 2D to the 3D behavior. As $t_V$ is decreased, $M(T)$ changes from quasi-linear behaviour to more bulk-like behaviour. The magnetic coupling, whose strength is expected to be weak and depends on the $t_V$ layer thickness, effectively alters the magnetic properties of these multilayer films consisting of the 10 Å V layers which individually behave as 2D ferromagnets without the coupling.

To understand better how the magnetic coupling between neighbouring Fe layers affects the magnetic behavior of these films, we have used a simple model to describe these multilayer films. Suppose that each of the magnetic layer (1 1 0) films can be represented by $n$ spin-S 2D ferromagnetic planes with x, y, and z axes corresponding to the [0,0,1], [1,1,0], and [1,1,0] directions, and with in-plane exchange interaction $J_0$ and lattice parameter $a$. The coupling strength and separation between two adjacent planes are given by $J_1$ and $c$, respectively. This model is equivalent to a 3D anisotropic ferromagnetic whose spin-wave dispersion
relation is
\[ \varepsilon(\vec{k}) = \frac{k_B \theta_0}{6\pi S} \left\{ \frac{a^2}{4} [1 + m] k_x^2 + 2(k_z^2 + mk_z^2)] + \frac{1}{n A} [1 - \cos(k_y c)] \right\}, \tag{1} \]
where \( \theta_0 = 24\pi J_0 S^2 / k_B, m = 1 - 1/n, \Lambda = J_0 / J_1. \)

At temperatures well below the Curie temperature, the planar spin waves that can be excited are only those with long wavelengths defined by \( k_x a \ll 1, k_y a \ll 1 \) and \( k_z a \ll 1 \). The following magnetization temperature dependence can be obtained:
\[ m_z(T) = m_z(0) - \frac{V g \mu_B}{8\pi^3} \int \int \int \frac{1}{\phi(\vec{k}) / k_B T - 1} d^3 k, \tag{2} \]
where \( V \) is the total volume occupied by the magnetic substance.

In the two limiting temperature regimes, \( k_B T \ll 4s J_1 \) and \( k_B T \gg 4s J_1 \), the above equation reduces to
\[ M_z(T) \approx M_z(0) \left[ 1 - \zeta \left( \frac{3}{2} \right) \frac{3\sqrt{6\lambda S}}{2} \frac{m + (\sqrt{2}/n)(c/a)}{\sqrt{1 + m} \sqrt{m} + (1/n)(c/a)^2} (T/\theta_0)^{3/2} \right] \]
if \( 4J_1S \gg k_B T \), \tag{3}
and
\[ M_z(T) \approx M_z(0) \left[ 1 - \frac{3\sqrt{6\lambda S}}{2} \left( \frac{T}{\theta_0} \right)^{3/2} \frac{m + (\sqrt{2}/n)(c/a)}{(1 + m) \sqrt{m}} \sum_{v=1}^{\infty} \frac{e^{-[(c/n)(\theta_1/T)]}}{\nu^{3/2}} \right] \times \left\{ 1 + \left[ \frac{v \theta_1}{n T} \right] e^{-[(3\pi S/n)(c/a)^2 T/\theta_0]} \right\} \]
if \( 4J_1S \ll k_B T \), \tag{4}
where \( \theta_1 = 4J_1S/k_B \) and \( \zeta(x) \) the Riemann function is 2.612 for \( x = \frac{3}{2} \).

In the low-temperature regime \( (4J_1S \gg k_B T) \), when the significant contribution comes only from long-wavelength modes in all directions, the temperature dependence is that of a 3D system, i.e., \( T^{3/2} \). In the high-temperature regime \( (4J_1S \ll k_B T) \), the strong thermal excitation of spin waves along the perpendicular direction essentially decouples the 2D ferromagnetic planes. Consequently, these decoupled 2D ferromagnetic planes give rise to a quasi-linear \( T \) dependence for the magnetization. Therefore, as \( T \) is increased, the spin-wave excitation of the anisotropic ferromagnetic system undergoes a 3D–2D dimensional crossover. The characteristic crossover temperature, \( \theta_1 \), is related to the interlayer coupling through \( \theta_1 \).

Using Eqs. (3) and (4), satisfactory fits were obtained for the \( M(T) \) data for all of the Fe/V multilayer films. The \( M(T) \) theory curves obtained from the fits are shown in Fig. 1, well matching the experimental data points. The values of \( J_0 \) and \( J_1 \) obtained from the fits are listed in Table 1 for all films (taken \( S = 1 \)). The derived in-plane exchange interaction constants all consistently fall in the range expected for the bulk exchange interaction of Fe [7]. Compared to the in-plane coupling, however, the interlayer coupling is considerably weak. A decrease in the Pt layer thickness results
in an increase in the interlayer coupling, which in turn elevates the characteristic 3D–2D crossover temperature.

4. Conclusions

In conclusion, the temperature dependence of the magnetization of Fe(10 Å)/V(t_V) multilayers has been investigated for various V layer thicknesses. As the t_V is reduced, the onset of a relatively weak magnetic interaction between neighbouring Fe layers causes the spin-wave excitations to have a 3D character at low temperatures and then crossover to a 2D behaviour as the temperature is increased. A simple model calculation based on an anisotropic ferromagnetic system has allowed us to obtain numerical estimates for the interlayer coupling strength at various V layer thickness.

References


Table 1
The fitting results from Eqs. (5) to (6) for Fe(10 Å)/V(t_V)

<table>
<thead>
<tr>
<th>t_V (Å)</th>
<th>J_0/k_B (K)</th>
<th>J_1/k_B (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>103</td>
<td>21</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>0.7</td>
</tr>
<tr>
<td>40</td>
<td>110</td>
<td>0.03</td>
</tr>
</tbody>
</table>

J_0 is the in-plane exchange interaction between neighbouring Fe atoms and J_1 is the coupling strength between two neighbouring Fe planes.