Evolution of ferromagnetic and spin-wave resonances with crystalline order in thin films of full-Heusler alloy Co$_2$MnSi

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We report the evolution of magnetic moment as well as magnetic anisotropy with crystalline order in Co$_2$MnSi thin films grown on (100) MgO by pulsed laser deposition. The films become more ordered as the annealing temperature ($T_A$) increases from 400 to 600 °C. The extent of $L_2_1$ ordering in the films annealed at 600°C is ≈96%. The static magnetization measurements by vibrating sample magnetometry shows a maximum moment of 4.95 $\mu_B$ per formula unit with low coercivity ($H_C$ ≈ 65 Oe) in the films annealed at 600°C. A rigorous analysis of the azimuthal and polar angle dependent ferromagnetic resonance (FMR) measured at several temperatures allows determination of various anisotropy fields relevant to our system as a function of $T_A$. Finally, we have evaluated the exchange stiffness constant down to 100 K using spin wave modes in FMR spectra. We have also estimated the exchange energies as well as stiffness constant by ab initio calculations using the Korringa-Kohn-Rostoker method.

I. INTRODUCTION

The Co-based Heusler alloys, which possess high magnetic moment and also high Curie temperature ($T_C$) along with theoretically predicted half metallic character, are potentially important for spintronics devices. However, due to atomic and/or antisite disorder, the values for spin polarization in epitaxial films of these alloys are found to be smaller than that obtained from various band structure calculations. Understanding the effect of structural disorder on the extent of spin splitting of the conduction band of Heusler alloys remains a challenging problem. Various groups have already reported the successful deposition of thin films of full-Heusler alloys, such as Co$_2$MnZ (Z: Si, Sn, Ge) on Al$_2$O$_3$,$^1$ Co$_2$FeSi on MgO (Ref. 2) and SrTiO$_3$,$^3$ Co$_2$MnSi on MgO (Ref. 4) and Al$_2$O$_3$. The full-Heusler alloy Co$_2$MnSi (CMS) has attracted much attention because of its large energy bandgap of 0.4 eV for minority-spin band$^6$ and a high $T_C$ ≈ 985 K.$^7$ The effect of annealing temperature ($T_A$) on magnetic properties of CMS thin films and bulk samples has been studied very well but the obtained value of moment is still smaller than the theoretically predicted moment of 5.00 $\mu_B$ per formula unit (f.u.) for bulk $L_2_1$ ordered CMS.$^8$ The measurements by Raphael et al.$^{9,10}$ on single crystals, arc melted polycrystals and $L_2_1$ ordered polycrystalline thin films of CMS on glass show a moment which is the same as the theoretical value, in spite of a large ($\approx$14%) Mn and Co site disorder in the latter two catagories of the samples. The site disorder also decreases the residual resistivity ratio from 6.5 (for single crystal) to a value of 1.4 for thin films. Several groups have used CMS as electrodes for magnetic tunnel junctions and obtained a spin polarization of 61% at 10 K,$^{11}$ and 89% at 2 K.$^{12}$ By using point contact Andreev reflection spectroscopy the spin polarization was found to be 55% at 4.2 K for CMS.$^{13}$ However these values of spin polarization are still smaller than the theoretically predicted value.$^{8,14}$

Other than spin polarization, the properties, such as magnetic anisotropy, magnetic exchange interactions, and damping, must also be characterized to make use of these Heusler alloys as memory devices with high frequency response. A powerful, non-destructive technique which allows the measurement of the amplitude, dynamics, and anisotropy of magnetization vector $\mathbf{M}$ and individual spins, is microwave spectroscopy. Through the measurement of ferromagnetic resonance (FMR), one can get information about magnetic anisotropy, magnetic inhomogeneities, domain sizes, and magnetization relaxation processes. The FMR spectroscopy has been used to study different Heusler alloys, such as Co$_2$MnGe,$^{15}$ Co$_2$MnGa,$^{16}$ Co$_2$FeSi,$^{17}$ and manganites like La$_{0.7}$Sr$_{0.3}$MnO$_3$.$^{18}$ The magnetic properties like the anisotropy constants and damping constant were studied by FMR spectroscopy of CMS thin films on SiO$_2$ (Ref. 19) and MgO (Ref. 20) substrates. A quantitative understanding of the magneto-dynamic properties of the magnetic metals or alloys can be made by density functional theory (DFT) calculations. The ab initio calculations on CMS have been done extensively by several groups to understand the magnetic excitations, spin-wave stiffness, and variation of the Curie temperature. However, the effect of strain produced by substrate on the various physical properties still needs thorough investigations.

In this paper, we present the measurements of static magnetization and angular dependence of FMR to establish magnetic anisotropy in CMS films deposited on (100) MgO by pulsed laser ablation at 200 °C. We have optimized the growth of pure phase of CMS with structural and magnetic properties which are nearly equal to those of bulk by subsequently annealing the films at various temperatures. The increase in

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the post-deposition annealing temperature \( T_A \) increases the magnetic moment as well as \( L_2 \) ordering parameter. The FMR approach also permits us to observe spin-wave resonance (SWR) spectra which are direct evidence of low energy excitations. By assuming the asymmetrical pinning state, we calculate the temperature dependent spin-wave stiffness constant of CMS films down to 100 K for the first time. The spin-wave stiffness constant, which illustrates the strength of the various exchange interactions within the sample, is an important quantity from the application point of view. The aim of this paper is to examine the static and dynamic magnetic properties of the CMS thin films. The structure of this paper is as follows: Sec. I, which covers the Introduction, has been presented already. Section II deals with details of the sample preparation and measurement procedures. All the results and their interpretation are given in Sec. III, which is further divided into subsections. The basic theory of FMR and how the FMR response can be used to calculate anisotropy and spin-wave stiffness is presented in Sec. III A. The X-ray diffraction and dc magnetization measurements are summarized in Sec. III B, and the experimental results of FMR are presented in Sec. III C. Finally, the \textit{ab initio} calculation of exchange interactions and spin-wave stiffness constant by using the Korringa-Kohn-Rostoker (KKR) method are given in Sec. III D. In Sec. IV, we presented the conclusions drawn from these measurements and theoretical calculations.

II. EXPERIMENTAL DETAILS

The epitaxial CMS thin films of 40 nm and 70 nm thickness were grown on single crystal (100) MgO substrate by pulsed laser ablation (laser fluency \( \approx 3 \text{ J cm}^{-2} \)) of a stoichiometric target of CMS made by arc melting. These films were deposited in an all-metal-seal high vacuum chamber equipped with a Ti-getter pump, and an ultrahigh vacuum compatible substrate heater which could heat the samples to \( \approx 850 \text{ °C} \). We used a growth temperature of 200 \text{ °C} followed by 1 h annealing at \( T_A = 400, 500, \) and 600 \text{ °C} in high vacuum to enhance crystallization and ordering in the films. In subsequent discussion, these samples will be identified as \( S(t/T) \), where \( t \) and \( T \) refer to thickness in nm and the annealing temperature in °C, respectively.

The crystallographic structure of the films was characterized using a PANalytical X’Pert PRO X-ray diffractometer equipped with a CuK\( \alpha_1 \) source in 0-2θ and φ modes. For static magnetization measurements at room temperature with both in-plane \((\hat{H}^\parallel)\) and out-of-plane field \((\hat{H}^\perp)\) orientations, we have used a vibrating sample magnetometer (VSM) with a maximum field of 1.7 T. The FMR measurements were performed down to 100 K with a fixed microwave frequency \( \approx 9.75 \text{ GHz} \), in a Bruker A 300 EPR spectrometer. The films for these measurements were mounted in the microwave cavity such that the applied static magnetic field could be aligned in the \((\hat{H}^\parallel)\) and \((\hat{H}^\perp)\) geometries by rotating the sample rod with a stepper motor. A diode detector measures the absorbed microwave power \( P \) by monitoring the reflected power from the cavity. In a standard FMR measurement, the external field is swept to make the magnetic sample go through the resonance condition, at which the microwave losses in the sample reach the peak. A modulation of amplitude 6 Oe and frequency 100 kHz was imposed on the static field to allow lock-in detection of the resonance condition. The recorded signal, which is proportional to the field derivative of the absorbed microwave power, is measured as a function of applied field.

III. RESULTS AND DISCUSSION

A. Anisotropy constants and spin wave modes

The dynamics of magnetization vector \( \mathbf{M} \) under the influence of the microwave and static magnetizing field \( \mathbf{H} \) can be described with the help of Fig. 1. We have used a spherical polar geometry where \( \theta_M \) and \( \phi_H \) are the polar coordinates. The azimuthal angles are \( \varphi_M \) and \( \varphi_H \), respectively. The angle \( \varphi_u \) defines the angle that in-plane anisotropy axis \( \mathbf{H}_u \) makes with the \( x \)-axis.

The time derivative of the magnetization around its equilibrium position is described by the Landau-Lifshitz-Gilbert equation as \(^{21}\)

\[
d\mathbf{M}/dt = -\gamma [\mathbf{M} \times (\mathbf{H} + \mathbf{H}_{\text{eff}})] + \alpha \left( \mathbf{M} \times \frac{d\mathbf{M}}{dt} \right) .
\]

Here \( \gamma \) is the Gilbert damping constant and \( \gamma = g\mu_B/\hbar \), the gyromagnetic ratio with \( g \) the spectroscopic splitting factor.

The total magnetic energy density \( F \) of the film can be expressed as \(^{32}\)

\[
F = -M_s H \sin \theta_M \sin \theta_H \cos(\varphi_M - \varphi_H) + \cos \theta_M \cos \theta_H
- (2\pi M_s^2 - K_\perp) \sin^2 \theta_M - K_u \cos^2(\varphi_M - \varphi_u) \sin^2 \theta_M \\
- \frac{1}{8} [3 + \cos 4(\varphi_M - \varphi_H)] K_4 \sin^4 \theta_M .
\]

where the first term is Zeeman energy, the second term the demagnetizing contribution, and the remaining two are the anisotropy energies. Here \( M_s \) is the saturation magnetization, whereas \( K_u, K_4, \) and \( K_\perp \) are the in-plane uniaxial, the fourfold and perpendicular anisotropy constants, respectively, with corresponding anisotropy fields \( H_a = K_u/M_s, H_4 = 4K_4/M_s, \) and \( H_\perp = 2K_\perp/M_s, \) respectively. The resonance frequency \( \omega_r \) of the uniform precession mode obtained from the energy density is given by.

FIG. 1. (Color online) Schematic diagram of relevant vectors in spherical polar coordinates. The azimuthal angles \( \varphi_M, \varphi_H \) are the in-plane angle between \( \mathbf{M}, \mathbf{H} \) and the \( x \)-axis, respectively. The angles \( \theta_M, \theta_H \) are the polar angles between \( \mathbf{M}, \mathbf{H} \) and the \( z \)-axis, respectively. The \( \varphi_u \) is the angle that in-plane anisotropy axis \( \mathbf{H}_u \) makes with the \( x \)-axis.
\[ \omega_n = \frac{\gamma}{M \sin \theta_M} \left[ \frac{\partial^2 F}{\partial \theta^2} \frac{\partial^2 F}{\partial \varphi_M^2} - \left( \frac{\partial^2 F}{\partial \theta \partial \varphi_M} \right)^2 \right]^{1/2}. \]  

Here all the derivatives are evaluated at the equilibrium positions of \( M \) and \( H \). When the applied field is in the plane of the film, the resonance frequencies for uniform mode are given by,

\[ \left( \frac{\omega}{\gamma} \right)^2 = \left| H^1 \cos(\varphi_H - \varphi_M) + 4\pi M_{\text{eff}} \right| + \left( \frac{K_4}{2M_S} [3 + \cos 4(\varphi_M - \varphi_4)] + \frac{2K_4}{M_S} \cos^2(\varphi_M - \varphi_4) \right] \times \left| H^1 \cos(\varphi_H - \varphi_M) + \frac{2K_4}{M_S} \cos 4(\varphi_M - \varphi_4) \right| + \frac{2K_4}{M_S} \cos 2(\varphi_M - \varphi_4), \]  

where \( 4\pi M_{\text{eff}} = 4\pi M_S - 2K_\perp/M_S \) is the effective magnetization. For the out-of-plane applied magnetic field, the resonance frequencies are given by,

\[ \left( \frac{\omega}{\gamma} \right)^2 = \left[ H^1 \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos 2\theta_M \right] \times \left[ H^1 \cos(\theta_M - \theta_H) - 4\pi M_{\text{eff}} \cos^2 \theta_M \right]. \]  

The FMR technique also allows us to study the spin-wave pattern formed by spin waves within the film. For a thin film of thickness \( d \), the frequencies of standing waves in the case of out-of-plane applied magnetic field are given by

\[ \left( \frac{\omega}{\gamma} \right) = H_n - 4\pi M_{\text{eff}} + \frac{D}{\gamma H} \left( \frac{n\pi}{d} \right)^2. \]  

Here \( H_n \) is the resonance field for the spin wave mode of order \( n \) and \( D \) is the spin-wave stiffness constant. The integer \( n \) corresponds to the number of half wavelengths of spin wave spectra within the thickness of the film. In the absence of SWR modes (i.e., \( n = 0 \)), Eq. (6) gives a uniform FMR mode. The spin-wave stiffness constant \( D \) can be calculated by considering two different spin-wave modes in Eq. (6).

### B. Structural and magnetic measurements

First of all, we have characterized the crystallographic structure of our CMS films with X-ray diffraction. The crystal structure of the ordered full-Heusler alloy consists of four fcc sublattices with Co atoms at (1/4, 1/4, 1/4) and (3/4, 3/4, 3/4), the Mn atom at (0, 0, 0), and the Si atom at (1/2, 1/2, 1/2) in Wyckoff coordinates. Figure 2(a) shows the \( \theta-2\theta \) diffraction profile of S(70/600), where the (200) and (400) reflections of the cubic phase of CMS are clearly seen. The intensities of these peaks increase with \( T_A \) indicating a better crystallinity for the films annealed at higher temperature. The X-ray peaks for the \( L_2_1 \) structure (space group \( F m \bar{3} m \)) should have two types of superlattice reflection, i.e., (111) and (200) in addition to (220) fundamental reflection. The intensity ratio \( I_{111}/I_{220} \) provides the measure of the \( L_2_1 \) atomic site ordering in the Heusler alloys. The \( \varphi \) scans for the (111) and (220) superlattices of the sample S(70/600) are shown in the upper and lower panel of the Fig. 2(b), respectively. This gives the direct evidence of crystalline growth of S(70/600) in \( L_2_1 \) structure with \( \approx\text{96}\% \) ordering. The \( \varphi \) values for the (111) and (220) planes of the CMS film are shifted by 45° with respect to those of the MgO planes. A similar epitaxiality with \( L_2_1 \) ordering is also observed in S(40/600). By reducing the annealing temperature, the extent of ordering decreases, and the films annealed below 400°C are amorphous.

The hysteresis loops of 70 nm films with different \( T_A \) measured at room temperature with in-plane magnetic fields are shown in Fig. 3. The magnetic moment of the CMS film increases on increasing the \( T_A \) due to increase in the \( L_2_1 \) ordering parameter. The inset of Fig. 3 shows the hysteresis loop of S(70/600) for both \( H^\parallel \) and \( H^\perp \) geometries, which clearly indicates it to be a soft magnet with in-plane easy axis and coercivity of \( \approx\text{65} \) Oe. The magnetic moment per f.u. for S(40/600) and S(70/600) is 4.78 \( \mu_B \) and 4.95 \( \mu_B \), respectively. These values are in reasonable agreement with the predicted value of 5.00 \( \mu_B /\text{f.u.} \) according to the Slater-Pauling rule.  

### C. Dynamic magnetic measurements

We can determine the values of anisotropy constants very precisely from the angular variation of the resonance fields by using Eqs. (4) and (5). The left-hand side of Fig. 4...
shows the room temperature FMR spectra of the 70 nm film annealed at different temperatures for $H^\parallel$ configuration while the data for $H^\perp$ are shown on the right-hand side. The observation of the sharp resonance peaks with narrow linewidth indicates excellent magnetic homogeneity of the samples, except for S(70/400) where spurious peaks appear at lower field for in-plane geometry. A noteworthy feature of $H^\perp$ data is the presence of well resolved SWR modes, which can be seen in the 40-fold magnified out-of-plane data of S(70/600) [Fig. 4(a)].

Figures 5(a) and 5(b) show the azimuthal and polar angular dependence of the resonance field for S(70/600), respectively. Figure 5(a) shows a fourfold symmetry with easy axis along the [110] direction. An excellent fit to Eq. (4) of these data is found with $\phi_a$ and $\phi_4$ equal to 45° for the films annealed at 500 and 600 °C, whereas for S(70/400) we found $\phi_a = 17°$ and $\phi_4 = 45°$. This is in agreement with the X-ray measurements which show that the (100) plane of the CMS film is rotated by 45° with respect to the (100) plane of MgO. The fitting also gives the value of the in-plane anisotropy constants $K_u = 4.52 \times 10^4$ erg/cm$^3$ and $K_4 = 1.14 \times 10^5$ erg/cm$^3$, respectively, for S(70/600). These numbers are comparable with the earlier result obtained from Brillouin light scattering spectroscopy$^{23}$ and FMR technique$^{20}$ for the thin films of CMS. The in-plane anisotropy fields for all the films are summarized in the inset of Fig. 5(b). We note that the resonance fields are a strong function of $T_A$ and hence are related to the crystallite size, the extent of ordering, magnetostriction, and the stress due to epitaxy. Thus, the increase in the $T_A$ leads to an increase in the anisotropy constants, since the annealing improves the crystallinity and ordering of the $L_2_1$ structure. However, in all the films the easy axis remains along the [110] direction except 400 °C films.

The polar angular variation of FMR [see Fig. 5(b)] clearly shows the hard axis of magnetization to be along the [001] direction. A very strong field is needed to rotate M from the easy axis to the sample’s normal direction. The polar variation of the resonance field for S(70/600) is in good agreement with Eq. (5) with fitting parameters $g = 2.11$ and $4\pi M_{s} = 14.5$ kOe. The nearly same $g$ value is obtained for S(40/600) but with a slightly lesser value of $4\pi M_{s} (= 13.7$ kOe). Using the saturation magnetization determined from hysteresis loops in Fig. 3, we can calculate the perpendicular anisotropy field by the relation $4\pi M_{s} = 4\pi M_{s} - 2K_{4}/M_{s}$. We observe the $K_4$ to be negative for all the films, implying an in-plane easy axis. The anisotropy fields ($H_{4}$) are 1260 Oe for S(40/600) and 1610 Oe for S(70/600). These values
are a bit smaller than the previously reported value for Cr-buffered CMS films on MgO due to the excess tensile strain on CMS by MgO in our case. The variation of FMR linewidth ($\Delta H_{pp}$) for azimuthal and polar angular configuration for S(70/600) are shown in the inset of Fig. 6(a). The $\Delta H_{pp}$ values remain nearly constant for azimuthal angular variation, whereas for the case of polar angular variation it increases on decreasing the temperature. One important feature of the FMR spectra of thin magnetic films is the observation of satellite peaks on the lower field side of the main resonance similar to the peaks seen in Fig. 4(a). The origin of these peaks has been attributed to a nonuniform field seen by the spins as a function of film thickness. These peaks can be indexed by only odd or only even or both even and odd numbers. We have determined the conditions from SWR for both even and odd values to the spin-wave mode number for S(70/600) are shown in the inset of Fig. 6(a). The linewidths ($\Delta H$) values remain nearly constant for azimuthal angular variation, whereas for the case of polar angular variation it increases on decreasing the temperature.

D. Computational details and estimation of stiffness constant

The $ab$ initio calculations on CMS with cubic crystal structure (space group Fm3m), were carried out by using the Korringa-Kohn-Rostoker Green’s function method within the spin-polarized scalar-relativistic Hamiltonian. A 22 $\times$ 22 $\times$ 22 mesh (834 k-points) and 30 energy points on the complex energy path were used to obtain self-consistent ground-state potential with local spin density approximation. The interactions within a sphere of radius 3$a$ ($a$ is the lattice parameter of CMS) were considered for the calculation of exchange energies. The spin wave energy $E(q)$ is related to the exchange interaction as given below:

$$E(q) = \frac{4\mu_B}{m} \sum_{ij} J_{ij} [1 - e^{i \mathbf{q} \cdot \mathbf{R}_i}],$$

where $m$ is the magnitude of the local magnetic moment per atom and $J_{ij}$ is the exchange energy between $i$th and $j$th sites with $\mathbf{R}_{ij} = \mathbf{R}_i - \mathbf{R}_j$ the translation vector between site 0 and $j$ and $\mathbf{q}$, a vector in the corresponding Brillouin zone. For the cubic systems with small $\mathbf{q} \rightarrow 0$, we have $E(q) \approx D q^2$, where $q = |\mathbf{q}|$. Thus the spin-wave stiffness $D$ is given by the curvature of the spin-wave dispersion $E(q)$ at $q = 0$. We have calculated the spin-wave stiffness constant for CMS using the expression

$$D = \frac{2}{3} \sum_j |\mathbf{R}_j|^2 \frac{J_{0j}}{\sqrt{m_i m_j}} e^{-\eta R_{0j}/a}$$

in the limit $\eta \rightarrow 0$; where $\eta$ is the damping parameter.

Figure 7(a) shows the variation of exchange energies of CMS as a function of distance ($R_{ij}/a$) with $a = 0.5655$ nm, the bulk $L2_1$ ordered CMS lattice parameter. The exchange interaction is calculated between Co1-Co1, Co1-Co2, Mn-Co, and Mn-Mn sublattices, where Co1 and Co2 are the two
types of Co atoms at different Wyckoff positions. The strongest interaction is found between the Mn-Co sublattices followed by the interaction between Co1-Co2 sublattices. The coupling between the nearest neighbor sites has the maximum contribution while all other interactions contribute negligibly. The strength of Co1-Co1 and Mn-Mn interactions are very small and nearly same in magnitude. Hence, the stability of ferromagnetism in CMS is mainly governed by Mn-Co interactions between the Mn atom and the eight nearest Co atoms. The interactions between Co-Co and Mn-Mn sublattices are of different signs for different distances between atoms due to Ruderman-Kittel-Kasuya-Yoshida oscillations as shown in Fig. 7(a).

We have calculated the spin-wave stiffness constant for CMS by using Eq. (9) for different pairs of sublattices on varying \( \eta \) values between 0.5 and 1.5 and then the corresponding \( D \) at \( \eta = 0 \) is estimated by taking the quadratic fit [see inset of Fig. 7(a)]. By summing the \( D(\eta = 0) \) values for above mentioned pairs, the value of \( D \) for CMS is found to be 5.23 meV nm\(^{-2}\), which is comparable to that obtained by Thoene et al.\(^{30}\) We have also investigated the effect of lattice parameter \( a \) of film on the magnetic properties of CMS, since the thin films grown MgO will have a larger value of \( a \) due to in-plane tensile strain. The calculated magnetic moments of individual sites as well as for total CMS unit cell are shown in Fig. 7(b). There is a significant increase in the moments of Mn sites which increases with \( a \), whereas on the other hand the moments for the Co site decreases as the value of \( a \) increases above the bulk value. These two site-specific moments (Co and Mn) balance each other so that the net magnetic moment remains unchanged. The total moment changes slightly with lattice constant but remains almost constant near a value of 5 \( \mu_B \) up to \( \pm 6\% \) change in the lattice parameter. Figure 7(c) shows the variation of \( D \) with lattice parameter. The value of \( D \) remains constant for the values of lattice constant larger than bulk because the system attains the full magnetization but for lower lattice constants it increases rapidly due to a stronger hybridization between the \( d \) orbitals of Co and Mn atoms as well as the increase in exchange interactions. This clearly shows that our experimental values of moment and spin-wave stiffness constant are close to the theoretically estimated ones even after considering the effect of strain on CMS.

IV. SUMMARY

We have addressed the magnetic state of CMS thin films having a different degree of \( L_21 \) ordering using static magnetization measurements and ferromagnetic resonance absorption in a microwave cavity. The magnetic moment (\( \approx 4.95 \mu_B/\text{f.u.} \)) of the well-ordered crystalline films is in agreement with the calculated value for this half-metallic ferromagnetic. Further, these films are magnetically soft with in-plane magnetic easy axis and coercive field \( H_C \approx 45-150 \text{ Oe} \). We have precisely determined the anisotropy parameters via in-plane and out-of-plane angular dependence of resonance fields. A good fit of all experimental data, using appropriate values of the magnetic coefficients which describe the free energy, is obtained. We found \( K_1 = -8.18 \times 10^4 \text{ erg/cm}^2 \), \( K_2 = 4.52 \times 10^4 \text{ erg/cm}^2 \), and \( K_4 = 1.14 \times 10^5 \text{ erg/cm}^3 \) for S(70/600). We have determined, for the first time, the temperature dependence of \( H_c \) for CMS, which follows a \( T^{5/2} \) dependence. The exchange energies as well as the \( D \) values have been obtained from first principle calculations. We have also calculated the effect of lattice parameter on the magnetic moment and \( D \), which is consistent with our experimental results for CMS film with tensile strain.

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