FMR studies of half metallic ferromagnetic thin films 
Co$_2$MnSn and Co$_2$MnGe

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Abstract. Thin films of Heusler alloys Co$_2$MnSn and Co$_2$MnGe prepared on sapphire $a$-plane substrates by RF-sputtering have been investigated by ferromagnetic resonance (FMR) technique. The magnetic anisotropies of the Co$_2$MnSn and Co$_2$MnGe thin films have been probed and the effective magnetization values have been extracted. Weak in-plane anisotropies observed for the Co$_2$MnGe sample indicate a textured growth of the films. Non-uniform (spin-wave and interface/surface) modes have been observed and the exchange stiffness constants for the Co$_2$MnSn and Co$_2$MnGe films have been estimated.

1. Introduction

The spin polarization of the conduction electrons is the most important parameter determining the performance of various spintronic devices [1]. For that reason, half-metallic Ferro magnets, which have completely spin-polarized electrons at the Fermi level, are very attractive for the spintronic applications. However in order to construct the multilayered MTJ device one need to know in details the magnetic anisotropies of a thin film material to tailor them in a desirable way. Besides any effects of surfaces/interfaces and bulk in-homogeneities should be studied thoroughly to understand physics involved and realize in practice a half-metallic MTJ device.

It is well known that ferromagnetic resonance (FMR) is a very efficient technique to study the nanoscale magnetic properties of various ferromagnetic materials. In this work thin films of various half metallic Heusler alloys Co$_2$MnSn and Co$_2$MnGe have been investigated using FMR technique.

2. Experimental procedures

Thin films of Co$_2$AlGe and Co$_2$AlSn (both with thickness of 100 nm) were prepared by RF-sputtering on sapphire $a$-plane substrates covered by a 5 nm thick V buffer layer and were finally capped by protecting overlayer of amorphous Al$_2$O$_3$ with thickness of about 5 nm, see details elsewhere [2,3].

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FMR spectra were recorded on Bruker EMX spectrometer (9.8 GHz) at room temperature. Angular dependences of EPR spectra were recorded with the magnetic field rotated either in the film plane ("in-plane" geometry) or in the plane which is perpendicular to the film plane ("out-of-plane" geometry). It should be noted that due to restrictions of the experimental setup in the in-plane geometry the microwave magnetic field is perpendicular to the film plane, while for the out-of-plane geometry this field is in the plane of film.

3. Experimental results and discussion

Splitting of the FMR signal due to excitation of non-uniform modes are observed (figure 1). Noticeable in-plane anisotropy for the Co$_2$MnGe film is evident from the angular dependence of FMR resonance fields $H_{res}$ (Figure 2), while in-plane angular dependence for the Co$_2$MnSn film having nearly the same magnitude is masked by very broad line-width in the parallel orientation (about 1 kOe).

A very high anisotropy is observed in the out-of-plane measurements, while the magnitude of the in-plane anisotropy (figure 2) is very small. Therefore, it is possible to extract the effective magnetization $M_{eff}$ from the out-of-plane dependences of $H_{res}$ (not presented) using in theoretical modelling only the shape anisotropy contribution. Here, the term "effective" means that $M_{eff}$ contains in general a small contribution due to various anisotropies, e.g. the surface or strain anisotropies. Computer simulations provide rather high values: $M_{eff} = 892$ emu/cm$^3$ for the Co$_2$MnGe film, and $M_{eff} = 790$ emu/cm$^3$ for the Co$_2$MnSn sample. Both results are very close to the bulk values, indicating an absence of sizable B2-type disorder [3, 4, 5], and in the excellent agreement with the saturation magnetization values, reported previously [6].

Discussing FMR results for Co$_2$MnGe Heusler film it should be noted that the sample is rather uniform magnetically as evident from narrow signal line-widths (about 30 Oe near the perpendicular position), while for the Co$_2$MnSn sample the FMR signal in the parallel orientation is very broad (up to 1 kOe). This indicates larger magnetic inhomogeneity of the Co$_2$MnSn film comparable with the Co$_2$MnGe sample.

![Figure 1](image1)

**Figure 1.** FMR spectra of Co$_2$MnGe and Co$_2$MnSn films for the DC magnetic field applied in parallel (left) and perpendicular (right) to the film plane.
Figure 2. In-plane angular dependence of resonance fields for Co$_2$MnGe film.

Spin-wave (exchange) modes are observed for both Co$_2$MnGe and Co$_2$MnSn samples, that allows us to estimate the exchange stiffness constant D. Our estimations similar to the procedure applied in ref. [5] result in $D = 1.5 \times 10^{-9}$ Oe cm$^2$ for the Co$_2$MnSn sample, while for Co$_2$MnGe sample the estimations are very rough ($D = 0.8 \pm 1.8 \times 10^{-9}$ Oe cm$^2$) due to overlapping between the SWR and magneto-static modes. It is remarkable that the above values are close to our estimation of $D = 1.9 \times 10^{-9}$ Oe cm$^2$ for Co$_2$MnSi system [5]. Besides, for the Co$_2$MnGe thin film the multiple magneto-static (or "magneto-exchange") modes (figure 1) are revealed in FMR spectra. These modes may appear, for instance, as result of exchange decoupling at grain boundaries, as proposed in refs. [7, 8].

The only main mode at higher field is observed in the parallel orientation of the out-of-plane geometry, while an additional lower-field mode is revealed in the in-plane geometry (figure 1). The first one is the bulk mode with nearly uniform spin precession, while an appearance of the additional mode is attributed to the "unconventional" in-plane geometry with non-uniform radiofrequency field distribution through the sample. Therefore, this mode is apparently some kind of non-uniform precession of magnetization (e.g. surface/ interface mode). Remarkably, there is a difference between the in-plane behaviour of the low- and high-field modes (figure 2). The low-field mode possesses dominant two-fold behaviour, which is attributed to a growth induced uniaxial anisotropy due to the stepped surface of the a-plane sapphire substrate [2, 3]. However, the main mode exhibits the dominant cubic anisotropy with symmetry expected for the DC field rotated in the (110) crystalline plane (some small uniaxial term is probably due to interface-induced anisotropy). We estimated the cubic anisotropy term ($K_1/M_S$) to be about ~10 Oe. A weak cubic anisotropy for this mode points to a partial in-plane (110) texture for the Co$_2$MnGe film. Formation of out-of-plane (110) texture for Co$_2$MnGe and Co$_2$MnSn films grown on V buffer has been reported previously in ref. [6].

Figure 3 shows the both experimental and theoretical angular dependence of resonance field results in the in-plane (a) and out-of-plane (b) geometry of Co$_2$MnGe film obtained at 35K. We observed contribution of both four-fold and two-fold anisotropies effect for Co$_2$MnGe film at low temperature, uniaxial anisotropy is much higher. We also attributed $M_{\text{eff}}$ value for the Co$_2$MnGe film as 1000 emu/cm$^3$, at 35 K.

In conclusion, we have shown that Co$_2$MnGe and Co$_2$MnSn films grown on a-plane Al$_2$O$_3$ substrate reveal weak in-plane anisotropies. Rather large magnetic in-homogeneity of the Co$_2$MnSn film comparing with the Co$_2$MnGe sample has been observed. Cubic symmetry of the in-plane anisotropy for the Co$_2$MnGe sample indicates a partially textured growth of this film. The effective
magnetization values and the exchange stiffness constants for the Co$_2$MnSn and Co$_2$MnGe films have been estimated.

Figure 3. In-plane (a) and out-of-plane (b) angular dependences of resonance fields of FMR spectra recorded at 35K for Co$_2$MnGe film. The open circles and squares denote the experimental results in the in-plane and out-of-plane geometries, respectively. Continuous lines represent the theoretical fitting results.

4. References
[1] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, von Molnar S, Roukes M L, Chcthelkanova A Y and Treger D M 2001 Science 294 1488
[2] Verdujin E A and Westerholt K 2006 J. Appl. Phys. 99 084502
[3] Geiersbach U, Bergmann A and Westerholt K 2002 J. Magn. Magn. Mater. 240 546
[4] Ziebeck P J and Webster K R A 1986 Landolt-Börnstein New Series III/19c
[5] Rameev B, Yildiz F, Kazan S, Aktas B, Gupta A, Tagirov L R, Rata D, Buergler A, Gruenberg P, Schneider C M, Kammerer S, Reiss G and Hutten A 2006 Phys. stat. sol. (a) 203 1503
[6] Geiersbach U, Bergmann A and Westerholt K 2003 Thin Solids Films 425 225
[7] Rameev B Z, Gupta A, Anguelouch A, Xiao G, Yildiz F, Tagirov L R and Aktas B 2004 J. Magn. Magn. Mater. 272-276 1167
[8] Bergmann A, Grabis J, Toperverg B P, Leiner V, Wolff M, Zabel H and Westerholt K 2005 Phys. Rev. B 72 214403