Perpendicular magnetic anisotropy in Co$_2$Fe$_{0.4}$Mn$_{0.6}$Si

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We report perpendicular magnetic anisotropy (PMA) in the half-metallic ferromagnetic Heusler alloy Co$_2$Fe$_{0.4}$Mn$_{0.6}$Si (CFMS) in a MgO/CFMS/Pd trilayer stack. PMA is found for CFMS thicknesses between 1 and 2 nm, with a magnetic anisotropy energy density of $K_U = 1.5 \times 10^6$ erg/cm$^3$ for $t_{CFMS} = 1.5$ nm. Both the MgO and Pd layer are necessary to induce the PMA. We measure a tunable anomalous Hall effect, where its sign and magnitude vary with both the CFMS and Pd thickness.

A magnetic thin film will generally prefer to have its magnetic moment lying in the plane of the sample owing to the large demagnetizing field. New magnetic devices have made it desirable to fabricate thin magnetic layers which instead have an easy axis of magnetization directed perpendicular to the film plane, a condition known as perpendicular magnetic anisotropy (PMA). 1 In particular, spin-transfer-torque (STT) based devices require that a magnetic free layer can be easily flipped by a spin-polarized current while maintaining a high stability against thermal fluctuations. 2 Magnetic layers with PMA are well suited to optimize this trade-off for device applications.

In order to realize a high efficiency STT device, a high degree of spin-polarization in the magnetic layers is also desirable. CoFeB, with approximately 65% spin polarization, has been the most widely studied material so far, because it can be grown with PMA and incorporated into device structures with very large tunability against thermal fluctuations. 2 Efforts to induce PMA in the Heuslers have focused on compounds containing Fe on MgO (e.g. Co$_2$FeAl) 10,11. This was guided by earlier studies of CoFeB/MgO where the PMA is thought to have its origin in the Fe-O hybridization. 4 PMA has recently been reported in Co$_2$Fe$_{x}$Mn$_{1-x}$Si with $x \approx 0.4$ to be eminently promising for device applications with a low Gilbert damping parameter 8 and record 75% room temperature GMR ratio. 9

Efforts to induce PMA in the Heuslers have focused on compounds containing Fe on MgO (e.g. Co$_2$FeAl) 10,11. This is thought to have its origin in the Fe-O hybridization. 4 PMA has recently been reported in Co$_2$MnSi in CMS/Pd multilayer stacks on MgO, 12 and for Pd buffered Co$_2$Fe$_{x}$Mn$_{1-x}$Si on MgO, 13 but the details of the PMA and the contribution of the various interfaces remains unclear. Here, we demonstrate PMA in MgO/CFMS/Pd stacks, and show that both interfaces are important for this effect.

Samples were grown by DC magnetron sputtering in a Kurt J Lesker CMS-18 UHV system with a base pressure of $2 \times 10^{-8}$ Torr. Multilayer stacks consisting of MgO(2)/CFMS(t$_{CFMS}$)/Pd(2.5), where the number in parentheses is the nominal layer thickness in nm, were grown on $10 \times 10$mm Si/SiO$_2$ substrates at room temperature and post-growth annealed in-situ for 1 hour at 300°C with an in-plane magnetic field of 170 Oe. MgO was RF sputtered with 100 W power in 3 mTorr Ar, giving a growth rate of 0.05 Å/s. CFMS was DC sputtered at 100 W and 5 mTorr Ar, giving a growth rate of 0.43 Å/s, and Pd was DC sputtered at 175 W in 8 mTorr Ar, with a growth rate of 4.0 Å/s. Growth rates were calculated by growing a thick (> 50 nm) film and measuring the thickness with a Dektak profilometer. The composition of the Co$_2$Fe$_{0.4}$Mn$_{0.6}$Si target was verified by energy dispersive x-ray analysis in a SEM. Magnetization and Hall resistance measurements were done in a Quantum Design SQUID and PPMS respectively, at room temperature. The Hall measurements were made using sample holders from Wimbush Science & Technology, with spring-loaded contacts in a van der Pauw geometry.

In Figs. 1(a)-(d), magnetization measurements with the field applied parallel to the film plane and perpendicular to the film plane demonstrate PMA for CFMS films with thicknesses between 1 & 2 nm. Samples in this thickness range are easily magnetized out-of-plane, having a small saturation field ($H_s < 100$ Oe), and high remanence [Fig. 1(e)]. With the field applied in-plane, a larger applied field is required to saturate the magnetization, and the remanence is close to zero. Conversely, the magnetic behavior of a 3 nm thick CFMS film shown in Fig. 1(d) indicates an in-plane easy axis of magnetization.

The uniaxial magnetic anisotropy energy density $K_U$ is a quantitative measure of the PMA strength, and is determined from the difference in area under the out-of-plane and in-plane magnetization curves, where positive values correspond to PMA. $K_U$ is plotted as a function of t$_{CFMS}$ in Fig. 1(g), showing that the PMA is strongest for the $t_{CFMS} = 1.5$ nm film, having a value $K_U = 1.5 \times 10^6$ erg/cm$^3$. This is comparable to values found for other Heusler alloys, which are typically $1 - 3 \times 10^6$ erg/cm$^3$. 10,12-14

The decreasing $K_U$ with increasing film thickness and the transition to in-plane magnetic anisotropy (negative $K_U$) in Fig. 1(g) is a feature of magnetic thin films usually attributed to the competition between interface in-
duced PMA and the volume anisotropy, which tends to favor an in-plane easy axis.\textsuperscript{15} The uniaxial anisotropy is given by $K_U = K_V - 2\pi M_s^2 + K_S/t$, where $K_V$ and $K_S$ are the bulk and interface anisotropy terms respectively, and the term $2\pi M_s^2$ is the shape anisotropy. $K_U, t_{CFMS}$ is plotted against $t_{CFMS}$ in Fig. 1(h), where the intercept of the linear extrapolation indicates $K_S = 1.08$ erg/cm$^2$. The slope is equal to the effective volume contribution $K_{V_{eff}} = K_V - 2\pi M_s^2 = 5.3 \times 10^6$ erg/cm$^3$. The value of $K_S$ reported here is similar to that reported in Co$_2$FeAl\textsuperscript{10,16} ($K_S = 0.8 - 1.0$ erg/cm$^2$), but larger than what has been measured in Co$_2$MnSi stacks\textsuperscript{13} ($K_S = 0.5$ erg/cm$^2$) or multilayers\textsuperscript{12} ($K_S = 0.16$ erg/cm$^2$).

The Hall resistivity measured in a ferromagnetic material is empirically given by $\rho_{xy} = R_H H_z + R_{AHE} M_z$.\textsuperscript{17} It is the sum of the normal Hall effect, linear in applied field ($H_z$), and the anomalous Hall effect (AHE), which is proportional to the out-of-plane magnetization ($M_z$).

Therefore, measurements of the Hall effect can be used to probe PMA in thin films. The AHE in Figs. 2(a)-(e) confirms the PMA for CFMS film thicknesses 1 nm $\leq t_{CFMS} \leq$ 2 nm, which show 100 % remanence and a coercive field of around 25 Oe. The thicker 3 nm CFMS film in Fig. 2(e) shows an AHE characteristic of an in-plane easy magnetic axis, with a saturation field of about 3 kOe, in agreement with the magnetisation measurements in Fig. 1(d).

Data for the 0.75 nm CFMS film shown in Fig. 2(a) shows superparamagnetic behaviour, similar to observations in CoFeB thin films below the thickness threshold for PMA.\textsuperscript{18} A large, hysteretic AHE only becomes apparent at low temperature, as shown in Fig. 2(f). This is probably an indication that the film is not continuous, with the discontinuous regions of the film acting as superparamagnetic particles at room temperature.

PMA in magnetic thin films generally results from a modification of the orbital angular momentum due to hybridization of orbitals at the interfaces. In MgO/CoFeB, it is thought to be the Fe-O hybridization at the interface that leads to the PMA\textsuperscript{3} although a thin metallic capping layer, often Ta, has been shown to contribute also.\textsuperscript{19,20} PMA has also been observed and studied in Co/Pt and Co/Pd multilayers\textsuperscript{21} but in these cases, it is the Co 3d-(Pd, Pt) 5d hybridization that is understood to induce the PMA.\textsuperscript{22,23} While the data presented here indicate an interfacial origin of the PMA in CFMS thin films, samples with different interfaces were prepared in order to
The AHE coefficient is defined here as the zero-field extrapolation of the high-field Hall effect data for positive applied fields. For CFMS thin films in a MgO/CFMS/Pd stack, we observe a thickness dependent AHE, as shown in Fig. 2(g). There is a change in the sign of $R_{\text{AHE}}$ between $t_{\text{CFMS}} = 1.5$ and $t_{\text{CFMS}} = 2.0$ nm. This trend, and the sign change, appears independent of the magnetic anisotropy, which transforms from PMA to in-plane anisotropy between $t_{\text{CFMS}} = 2.0$ and $t_{\text{CFMS}} = 3.0$ nm. It is worth noting that this AHE sign change also occurs with a change in the Pd capping layer thickness, shown in Figs. 2(e-g). While further work is required to understand the origin of this effect, we note that the AHE depends on spin- and spin-orbit dependent scattering, and this system provides an opportunity to correlate these phenomena with the structural, magnetic and electronic properties of a highly spin-polarized magnetic material.

In conclusion, we have demonstrated PMA in Co$_2$Fe$_2$Mn$_{1-x}$Si with $x = 0.4$ for thin films in a MgO/CFMS/Pd trilayer stack. Both the MgO and the Pd layers are necessary to generate the PMA. This stack shows promise for incorporation into a spin-transfer-torque device with high thermal stability, low switching current, and high output power. The observation of a thickness-tunable AHE is an interesting, novel effect, and further work is required to elucidate its origin.

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