XMCD study of Ru/Co/W/Ru films with strong Dzyaloshinskii-Moriya interaction.

A.S. Samardak[1], A. Kolesnikov[1], A. Ognev[1], M. Platunov[2,3] and A. Rogalev[2]

1. School of Natural Sciences, Far Eastern Federal University, Vladivostok, Russian Federation; 2. European Synchrotron Radiation Facility (ESRF), Grenoble, France; 3. Kirensky Institute of Physics, Krasnoyarsk, Russian Federation

An enhancement of the spin-orbit effects arising on an interface between a ferromagnet (*FM*) and a heavy metal (*HM*) is possible through the strong breaking of the structural inversion symmetry in the layered films. We have found that the introduction of an ultrathin W interlayer between Co and Ru in Ru/Co/Ru films enables to preserve perpendicular magnetic anisotropy (PMA) and simultaneously induce a large interfacial Dzyaloshinskii-Moriya interaction (iDMI). We find that the Ru/Co/W/Ru films have PMA up to 0.35 nm of the nominal thickness of W (t_W). The study of the spin-wave propagation in the Damon-Eshbach geometry by Brillouin light scattering (BLS) spectroscopy reveals the drastic increase of the iDMI value with the rising t_W. The maximum iDMI of -3.1 erg/cm^2 is observed for t_W=0.24 nm, which is 10 times larger than the latter for the quasi-symmetrical Ru/Co/Ru films [1]. Our polycrystalline Ru/Co/W/Ru films were prepared by magnetron sputtering on the SiO_2 substrates at room temperature. The base pressure in the chamber was 10^{-8} Torr. The working pressure of Ar^+ was 10^{-4} Torr. In order to precise control the thickness of layers, we used low sputtering rates: *V(Ru)*=0.011 nm/s, *V(Co)*=0.018 nm/s, *V(W)*=0.02 nm/s. The Co thickness (t_{Co}) was varied from 0.7 to 1.5 nm. The thickness of the buffer and capping Ru layers (t_{Ru}) was 10 and 2 nm, correspondingly. The W thickness (t_W) was taken in the range from 0 to 0.4 nm. Polarization dependent X-ray spectroscopy measurements at the Co *K*- (7709 eV), W L_3- (10207 eV) and W L_2- (11544 eV) edges on the Ru(10nm)/Co(1nm)/W(*x*)/Ru(2nm) structures were performed at the ESRF ID12 beamline. Four different samples have been measured with *x*=0, 0.21, 0.25 and 0.29, where *x* is the thickness of the layer in nm. The APPLE-II undulator and a Si(111) double crystal monochromator were used to collect the spectra. Circular polarization rate of monochromatic x-rays was in excess of 95% at the W $L_{3,2}$-edges. Magnetic field of 0.27 T generated by an electromagnet was applied in the film plane and nearly parallel to the X-ray beam direction. This filed was sufficient to reach magnetic saturation of the samples at room temperature. In order to detect x-ray absorption spectra from our samples, we had to use an energy resolved detector - Si drift diode with an active area of 10 mm^2. To avoid saturation of the detector with fluorescence of Ru and of Si as well as Compton scattering from SiO_2 substrate a 50 μm Al filter was inserted between sample and the diode. The XMCD spectra were recordered by flipping the direction of applied magnetic field two times at every energy point of the x-ray absorption spectra. To make sure that XMCD signal is free of experimental artefacts, we checked that the sign of XMCD was reverted when it was recorded with opposite x-ray helicity. It should be underlined that the attenuation length for tungsten $L_{3,2}$ edges is about 4 orders of magnitude larger than the total thickness of W in the samples. We plotted normalized x-ray absorption spectra at the *K*-edges of Co in Ru/Co/W/Ru trilayers in comparison with a sample without W. Comparison of our normalized XANES spectra recorded at the *K*-edge of cobalt with published results [2,3] clearly shows that in all studied samples Co has *hcp* structure and practically not affected by the deposition of tungsten. We reproduced normalized XANES and XMCD spectra recorded at the $L_{3,2}$-edges of W in Co/W/Ru trilayers in comparison with those measured on bulk Co_3W alloy [4]. For the XANES spectra the ratio of the tungsten L_3/L_2 was taken equal to 2.19/1. The normalized intensities of XMCD signals is about 1% and evidence that 5*d* states of W carry a magnetic moment for all measured samples. This induced magnetic moment is antiparallel to applied field and therefore to the 3*d* magnetic moment of Co. Due to a rather high level of noise it is very difficult to discuss the orbital magnetic moment and its sign. We can only give its estimate, it is about 10 times weaker than the spin magnetic moment. Integrating the $\langle l_Z \rangle$ and $\langle 2s_Z \rangle$ spectra and taking x-ray absoprtion cross-section per hole from [4], we found $m_L < \pm 0.002$ and $m_S \sim -0.023 \pm 0.004$ for all three studied samples. Similar values were also obtained in [4]: $m_L < \pm 0.004(1)\ \mu_B$ and $m_S \sim -0.023(2)\ \mu_B$ for W on bulk Co_3W alloy. What has attracted our attention is some visible difference in the absorption white-line intensities at W $L_{3,2}$ edges for three samples that can result from variation of the 5*d* DOS above the Fermi level. Specifically, L_3 absorption edge reflects both $5d_{3/2}$ and $5d_{5/2}$ DOS whereas only the $5d_{3/2}$ band is probed at the L_2-edge as given by the dipolar selection rules for corresponding optical transitions: $2p_{3/2} \rightarrow 5d_{3/2}$ and $5d_{5/2}$ at the L_3-edge and $2p_{1/2} \rightarrow 5d_{3/2}$ at the L_2-edge. Surprisingly, Co(1nm)/W(0.21nm) and Co(1nm)/W(0.29nm) show nearly the same structures whereas an increase of the number of W $5d_{3/2}$ empty states for Co(1nm)/W(0.25nm) sample is clearly observed. This is a clear difference, eventhough quite minor, in population of spin-orbit split 5*d* states between these three samples. In summary, we show that there is an induced spin magnetic moments of about -0.02 μ_B per atom for W for all studied samples with a much weaker orbital contribution. The magnetic moment of W is antiferromagnetically coupled with the Cobalt moment in agreement with other studies on 3*d*/W systems [4,5]. Small changes in the population 5*d* spin-orbit split bands for different thicknesses of tungsten were observed.

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