Journal of Magnetism and Magnetic Materials 454 (2018) 78–84

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

# Nanoscale control of perpendicular magnetic anisotropy, coercive force and domain structure in ultrathin *Ru/Co/W/Ru* films

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A R T I C L E I N F O

*Article history:*
Received 16 January 2018
Accepted 22 January 2018

*Keywords:*
Perpendicular magnetic anisotropy
Coercive force
Domain structure
Dzyaloshinskii-Moriya interaction
Interface quality
Inversion symmetry

A B S T R A C T

Development of fast and energy-efficient spintronic devices requires novel nanoscaled materials with controllable magnetic properties. Here we show 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 dramatically reduce the coercive force and size of magnetic domains. We find that the *Ru/Co/W/Ru* films with up to 0.35 nm of the nominal thickness of *W* have robust PMA. The observed formation of a dendritic domain structure with small domains having homochiral Néel domain walls is an indicator of the interfacial Dzyaloshinskii-Moriya interaction appearing in trilayers with asymmetrical interfaces. The inversion-symmetry-broken *Ru/Co/W/Ru* films are a potential host for nucleation and manipulation of non-trivial spin textures like chiral domain walls and skyrmions.


## 1. Introduction

Recently, in perpendicularly magnetized heterostructures with "ferromagnet/heavy metal" (*FM/HM*) interfaces a number of novel spin-orbit effects, which are prospective for spintronic applications, has been observed [1–3]. Strong spin-orbit coupling between *FM* and *HM* atoms induces spin-Hall effect-driven spin-orbit torque (SOT) [4,5], anisotropic chiral damping [6], spin-wave canting [7], indirect exchange coupling and Dzyaloshinskii-Moriya interaction (DMI) [8,9]. These spin orbital effects are promising for non-volatile memory and artificial intelligence applications [10], like SOT-MRAM [11,12], racetrack memory [13,14], and neuromorphic computing [15–17]. The interfacial DMI (iDMI), an anti-symmetric exchange arising on *FM/HM* interfaces, stabilizes the homochiral Néel domain walls, cycloidal spin spirals and topologically protected spin textures, like skyrmions and merons [3,18,19].

In case of a trilayer system, like $HM_1/FM/HM_2$, iDMI arising on the top and bottom interfaces can lead to its cancelation or enhancement in dependence on the interaction sign. The complete compensation of iDMI has to be observed in films with the ideally symmetrical interfaces. However, quasi-symmetrical trilayers, like Pt/Co/Pt, possess a non-zero iDMI due to the different quality of the top and bottom interfaces [20–22]. Recently, the impact of the breaking of the structural inversion symmetry on the interfacial DMI has been studied in a wide range of systems: Pt/Co/$AlO_x$ [23], Pt/CoFeB/$AlO_x$ [24], Ir/Co/$AlO_x$ [25], Pt/Co/MgO [26], Pt/CoFeB/MgO [27], Ta/CoFeB/$TaO_x$ [28], Au/Co/W [29], Ir/Co/Pt [25,30], Ir/Fe/Co/Pt [31], Pt/Co/Ni/Ta [4]. Nowadays, the most promising interface engineering approach is based on the incorporation of an ultrathin metallic or non-metallic interlayer, called a dusting layer, into an interface between a ferromagnet layer and a heavy metal or an oxide capping: Pt/Co/*Ir*/Pt [32], Pt/Co/*Cu*/$AlO_x$ [33], Pt/Co/(*W,Ta,Pd*)/Pt [34], Pt/*Cu*/Co/Pt [35], MgO/Co/*Cu*/Pt/Ta [36], Pt/Co/*C*/Ta [37].

In our previous paper [38] we demonstrated magnetic properties of quasi-symmetrical *Ru/Co/Ru* trilayers and unveiled the layer composition in order to get strong perpendicular magnetic anisotropy (PMA), which value can be tuned by the thickness of the *Ru* buffer. However, our preliminary study has showed that this structure has weak spin-Hall effect ($\theta_{SH} \approx 0.005$), because in a symmetric structure, complete compensation of interfacial spin-orbit effects from opposite interfaces is expected. To avoid this compensation, it is necessary to break the symmetry of the structure. In connection with this, we propose to use the ultrathin interlayer of a heavy metal with the opposite to *Ru* signs of $\theta_{SH}$. This interlayer has to be introduced into the top *Co/Ru* interface, because the bottom

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https://doi.org/10.1016/j.jmmm.2018.01.056
0304-8853/

*Ru/Co* interface induces the out-of-plane magneto-elastic anisotropy and has to be preserved from any structural modification. The most suitable material for our task is tungsten (*W*), because it has the negative spin Hall angle ($\theta_{SH} = -0.14$) [39]. Our preliminary results have showed that the complete substitution of the *Ru* capping by *W* led to the vanishing of PMA and decreasing of saturation magnetization. To keep PMA and enforce the structural asymmetry, we introduce into the *Co/Ru* interface a dusting interlayer of *W* with nominal thickness $t_w$ ranging from 0 to 0.4 nm.

In this paper, we study the influence of the *Co* and *W* layers of various thicknesses on the magnetic properties, magnetization reversal and domain structure in the modified *Ru/Co/W/Ru* films.

## 2. Experimental

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. The structural and magnetic properties of the quasi-symmetrical *Ru/Co/Ru* were systematically studied in [38].

Magnetic properties of films were investigated with vibrating sample magnetometer (7410 VSM, LakeShore). Kerr microscopy (Evico Magnetics) was used to study domain structure and its field driven dynamics. The crystal structure and interface quality were studied by X-ray diffraction (XRD) and X-ray reflectivity (XRR) measurement techniques (SmartLab, RIGAKU) at CuKα radiation wavelength (1.54 Å). The fitting of XRR spectra were performed with GenX software [40].

## 3. Perpendicular magnetic anisotropy

The main purpose of our study is to significantly enhance the structural inversion asymmetry and, consequently, iDMI, simultaneously keeping PMA in the films. Our previous results on

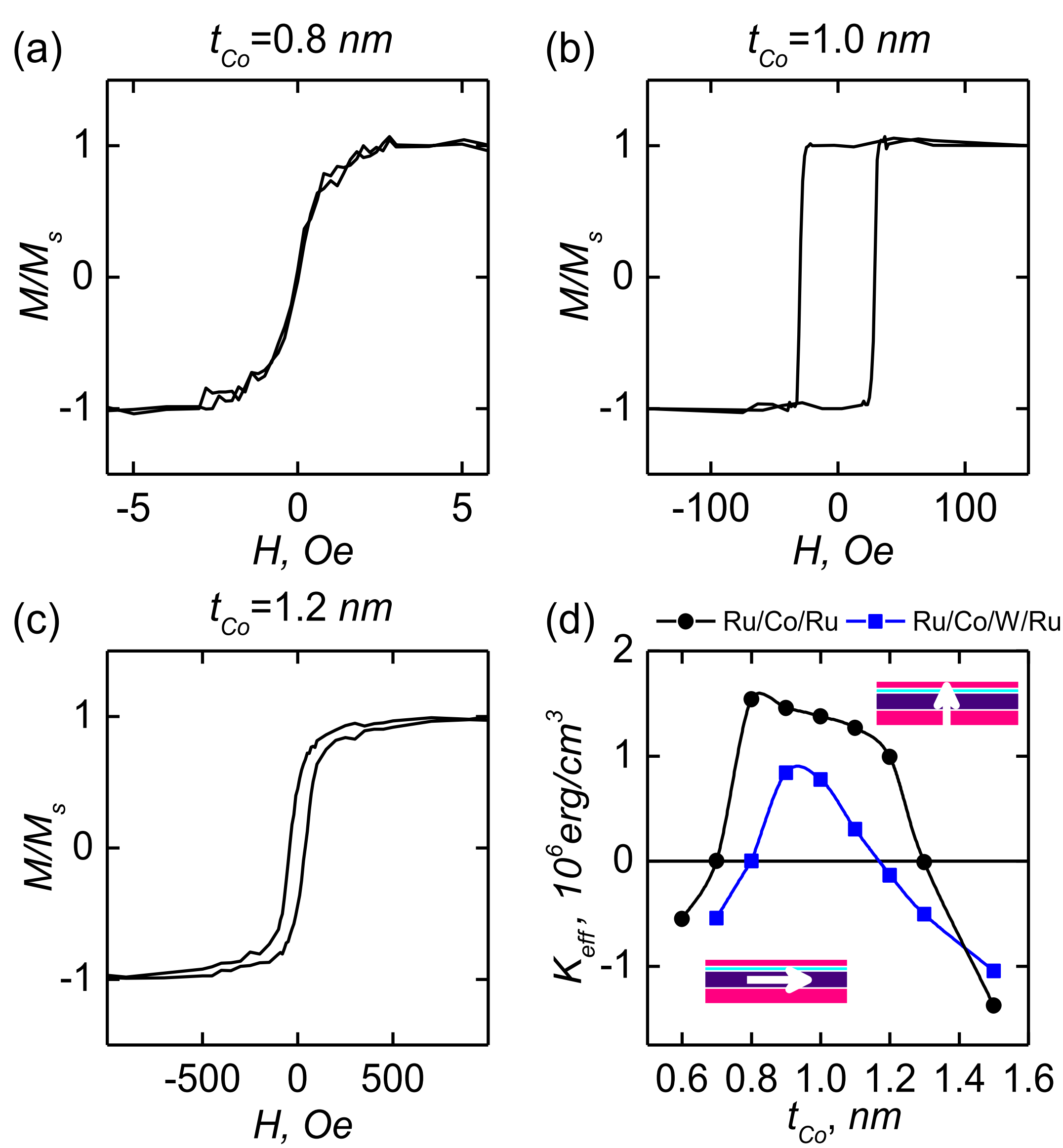


**Fig. 1.** Magnetic hysteresis loops measured by VSM in the out-of-plane geometry for *Ru(10)/Co($t_{Co}$)/W(0.23)/Ru(2)* (thicknesses in nm) films with the different *Co* thicknesses: (a) $t_{Co}$ = 0.8 nm, (b) 1.0 nm, (c) 1.2 nm. (d) Dependences of the effective magnetic anisotropy energy $K_{eff}$ on the Co layer thickness for *Ru/Co/Ru* (black curve) and *Ru/Co/W/Ru* (blue curve) films. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)