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Magnetic structure of bilayer systems of thin films Pt/Co/(CoO)

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Abstract. Effect of oxidation ferromagnet Co layer on magnetic parameters of thin polycrystalline bilayers Pt/Co/(CoO)/Pt films have been studied. Films was obtained by magnetron sputtering. It is established that the oxidation of the cobalt layer leads to an increase in perpendicular magnetic anisotropy (PMA) in comparison with non-oxidized system also the order of oxidation layer is important. Heat treatment causes a decrease in PMA and an increase in magnetization, which is explained by interlayer diffusion and the formation of a Pt-Co alloy. Structural XRR-analysis showed that oxidation increases the thickness of the Co/CoO layer and reduces the roughness of the adjacent layers. The dependence of the coercive force and anisotropy on the oxidation sequence of the layers is found, which indicates the importance of the structural organization for controlling magnetic properties. The results demonstrate the promise of controlled oxidation in PMA tuning and exchange interaction in Pt/Co systems, which can be used in spintronic devices, including skyrmion memory and elements controlled by spin orbital momentum.

Keywords: perpendicular magnetic anisotropy, Pt/Co multilayer structures, cobalt oxidation, spin-orbit interaction, X-ray reflectometry, domain structure

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Материалы конференции
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Магнитная структура двуслойных систем тонких пленок Pt/Co/(CoO)

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Аннотация. Исследовано влияние окисления слоя ферромагнетика Co на магнитные параметры тонких поликристаллических двуслойных пленок Pt/Co/(CoO)/Pt. Образцы были получены методом магнетронного распыления. Установлено, что окисление слоя кобальта приводит к увеличению перпендикулярной магнитной анизотропии (ПМА) по сравнению с неокисленной системой, а также что порядок окисленного слоя существенно влияет на магнитные характеристики. Нагрев такой системы приводит к уменьшению

ПМА и увеличению намагниченности, что объясняется интерфейсной диффузией и образованием сплава Pt-Co. Рентгенографический анализ показал, что окисление увеличивает толщину слоя Co/CoO и уменьшает шероховатость соседних слоев. Обнаружена зависимость коэрцитивной силы и анизотропии от последовательности окисления слоев, что указывает на важность структурной организации для управления магнитными свойствами. Результаты демонстрируют перспективность контролируемого окисления при настройке ПМА и обменного взаимодействия в системах Pt/Co, которые могут быть использованы в устройствах спинтроники, включая скирмионную память и элементы, управляемые спин-орбитальным моментом.

Ключевые слова: перпендикулярная магнитная анизотропия, многослойные пленки, оксидирование кобальта, спин-орбитальное взаимодействие, рентгеновская рефлектометрия, доменная структура

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Introduction

Pt/Co and Pt/Co/MOx thin films (where M is an oxidizable metal such as Gd [1], Al [2], or Ni [3], etc.) have attracted considerable attention in spintronics research due to their unique interfacial magnetic properties. These systems exhibit perpendicular magnetic anisotropy (PMA) [4], efficient spin-orbit torque (SOT) generation via the spin Hall effect [5], and a pronounced Dzyaloshinskii-Moriya interaction (DMI) [6], all of which are crucial for next-generation magnetic devices.

The origin of PMA in Pt/Co interfaces stems from the hybridization of Pt's 5d electrons (which possess strong spin-orbit coupling) with the 3d electrons of the ferromagnetic Co layer [7]. This interaction leads to preferential out-of-plane magnetization, a key requirement for high-density spintronic applications. Further enhancement of PMA and DMI can be achieved through controlled oxidation of the ferromagnetic layer, as evidenced by studies on Pd/Co/CoO systems [8–9]. Additionally, oxidation can introduce exchange bias effects at low temperatures [10], which may be exploited for stabilizing magnetic configurations in device architectures.

While the Pt/Co/CoO presents a promising platform for investigating interfacial magnetic phenomena. The potential to tune PMA, DMI, and exchange coupling in this system makes it a candidate for advanced spintronic applications, including skyrmion-based racetrack memory [11], ultra-sensitive magnetic sensors [12] and other emerging spintronic devices that rely on precise control of magnetic interactions at metal/oxide interfaces.

Materials and Methods

The samples were prepared using magnetron sputtering under high vacuum conditions, with the SiO_2 substrate rotating at a speed of 40 rpm. The layer structure consisted of an initial 5 nm Pt layer, followed by a 1 nm Co layer, a 2 nm intermediate Pt layer, and a 3 nm Pt capping layer. The Co layer was oxidized in the magnetron load chamber under a constant pressure of $P = 1\times10^{-3}$ Torr for two minutes. As a result, 6 samples were obtained (two single-layer and four bilayer films, thicknesses are given in brackets in nanometers, molar volume ratio CoO/Co $k \approx 1.74$):

1. SiO_2/Pt(5)/Co(1)/Pt(3)
2. SiO_2/Pt(5)/Co($1-x$)/CoO($k\times x$)/Pt(3)
3. SiO_2/Pt(5)/Co(1)/Pt(2)/Co(1)/Pt(3)
4. SiO_2/Pt(5)/Co($1-x$)/CoO($k\times x$)/Pt(2)/Co(1)/Pt(3)

5. SiO_2/Pt(5)/Co(1)/Pt(2)/Co(1–*x*)/CoO(*k*×*x*)/Pt(3)
6. SiO_2/Pt(5)/Co(1–*x*)/CoO(*k*×*x*)/Pt(2)/ Co(1–*x*)/CoO(*k*×*x*)/Pt(3)

The films were heated in a vacuum oven under working pressure $P = 2\times10^{-3}$ Torr for 10 minutes at $T = 300$ °C.

The magnetic properties (magnetic moment, anisotropy field, coercive force) were determined by analyzing hysteresis loops measured using a vibrating sample magnetometer (VSM by LakeShore). Additionally, domain wall motion dynamics were studied using Kerr microscopy (EvicoMagnetics), and layer roughness was evaluated based on X-ray reflectometry (XRR) spectra.

Results and Discussion

All samples exhibited perpendicular magnetic anisotropy (PMA), as confirmed by the hysteresis loops in Fig. 1, *a*. The strength of the anisotropy was found to scale with the number of oxidized layers, suggesting that interfacial oxidation plays a crucial role in enhancing PMA, likely due to increased interfacial spin-orbit coupling and structural modifications at the Co/CoO interface.

After heating (Fig. 1, *b*, red dots), a noticeable reduction in PMA was observed, accompanied by a significant increase in magnetization. This behavior can be attributed to interfacial diffusion and structural relaxation. Heating likely promotes intermixing at the Pt/Co interface, leading to the formation of a Pt-Co alloy, which alters magnetic interactions. The displacement of the CoO layer and possible reduction of oxygen vacancies may weaken the anisotropy while enhancing magnetization due to improved ferromagnetic ordering.

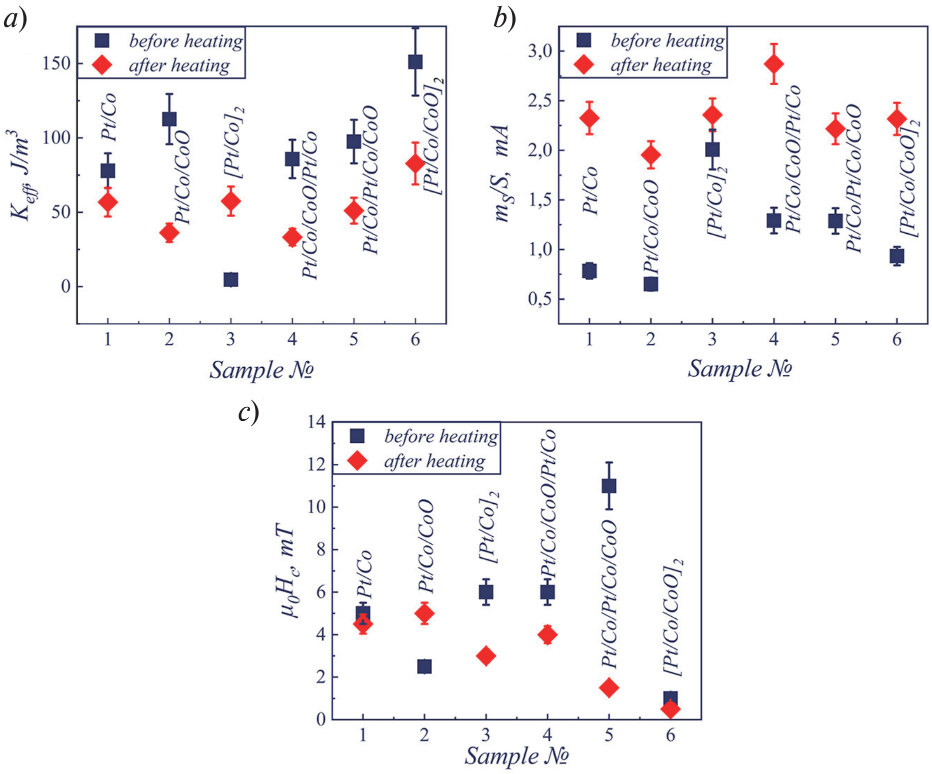

Fig. 1. Magnetic parameters of samples after and before heating (*a*) anisotropy field, (*b*) saturation magnetization per area, (*c*) coercive force

The magnetic properties of the samples varied not only with the number of oxidized layers but also with the sequence of oxidation (whether the first or second Co layer was oxidized). This dependence implies that the stacking order of oxidized and non-oxidized layers influences interfacial spin interactions and strain distribution. Such variations may arise from differences in:

- Crystal structure distortion: oxidation modifies the local coordination of Co atoms, affecting magnetocrystalline anisotropy.
- Interfacial roughness and strain as seen in Fig. 2, *a*, the order of oxidation impacts the structural morphology, which in turn alters magnetic coupling.

The coercivity of the samples was also sensitive to oxidation conditions (Fig. 1, *c*), likely due to the redistribution of defects that act as pinning sites for domain walls. An increase in defect density typically leads to higher coercivity, whereas annealing may reduce it by promoting defect annihilation or recrystallization.

Structural characterization (Fig. 2, *b*) revealed that oxidation leads to an expansion of the Co/(CoO) layer beyond its initial nominal thickness (1 nm), consistent with the incorporation of oxygen and the formation of a graded interface. Additionally, Fig. 2, *c* demonstrates that the presence of the oxide layer reduces the roughness of the adjacent Pt layer, suggesting that oxidation induces interfacial smoothing, possibly due to stress relaxation or atomic rearrangement.

The magnetic domain structure, imaged by Kerr microscopy (Fig. 3), displayed small, irregular domains with jagged walls, indicative of strong pinning effects.

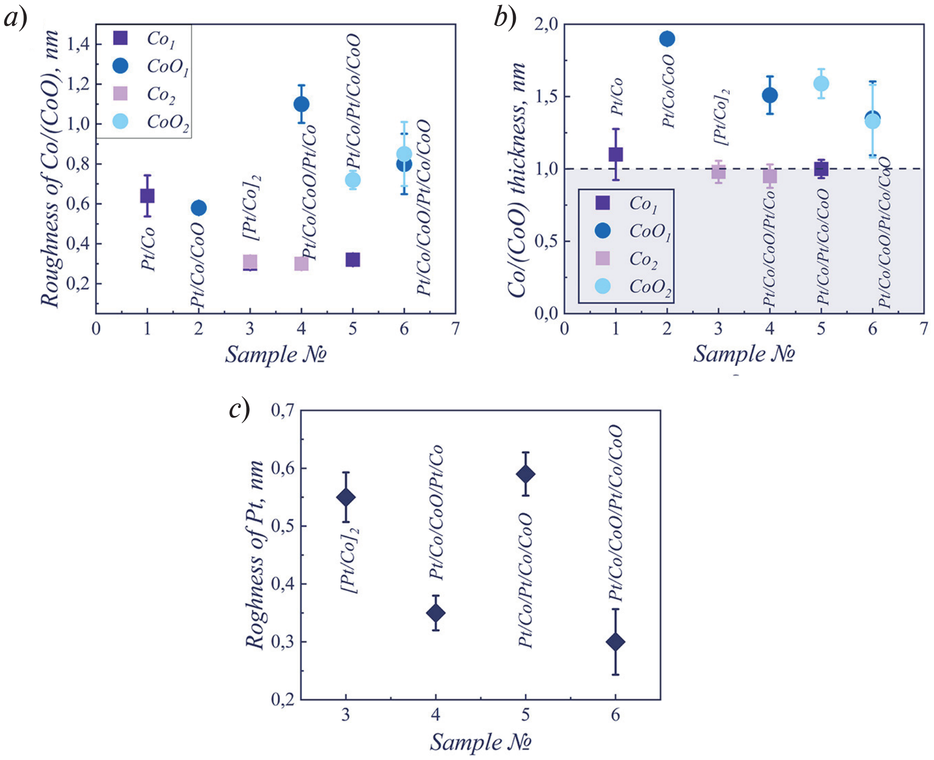

Fig. 2. XRR-measurements (*a*) roughness of Co/(CoO) layers, (*b*) thickness of Co/(CoO) layers, (*c*) roughness of Pt-interlayer in bilayers systems

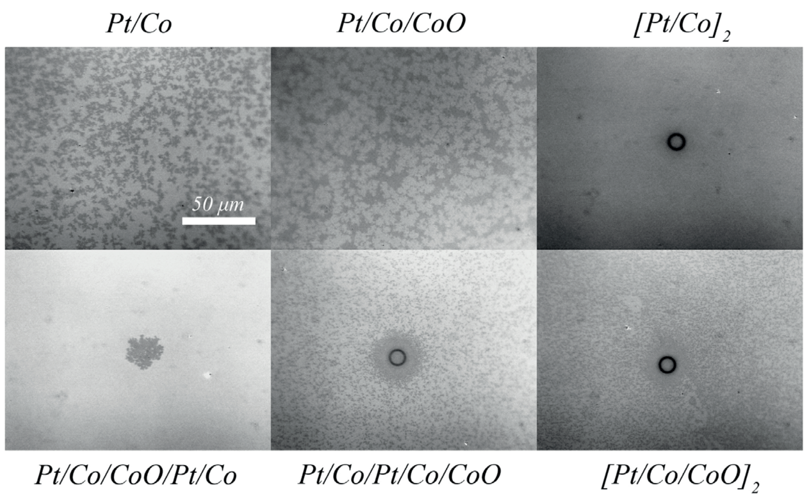

Fig. 3. Kerr-images of domain structure after the 0.2 ms pulse of perpendicular field Hz = 10.8 mT

Conclusion

The study of polycrystalline Pt/Co/(CoO)/Pt films, fabricated by magnetron sputtering, reveals a strong dependence of their magnetic properties on the structural organization of the layers. A critical finding is that the presence and order of oxidation in the CoO layer play a decisive role in modulating the interfacial magnetic interactions. These films exhibit pronounced perpendicular magnetic anisotropy (PMA), with the anisotropy field (Ha) increasing systematically as the number of oxidized layers grows, suggesting that controlled oxidation enhances spin-orbit coupling effects at the Pt/CoO interface.

Interestingly, while oxidation strengthens PMA, it also introduces competing effects: a reduction in magnetic anisotropy is observed alongside an increase in the film's net magnetic moment. This behavior is attributed to two interrelated factors – the displacement of the oxide layer, which alters interfacial hybridization, and the release of bulk metallic Co, which contributes to a stronger ferromagnetic response but reduces anisotropy contributions from the interface. Structural characterization via X-ray reflectometry (XRR) further supports these observations, confirming that the CoO layer thickness exceeds that of the metallic Co, indicating deep oxidation penetration and possible interfacial diffusion.

These findings highlight the delicate balance between oxidation depth, interfacial structure, and magnetic performance in Pt/Co-based multilayers. The ability to tailor PMA through controlled oxidation makes this system promising for advanced spintronic applications, including skyrmion-based memory and spin-orbit torque devices.

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