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# Magnetic anisotropy and Dzyaloshinskii–Moriya interaction of Pd/Co/Ta thin films

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**Abstract:** In this work, we experimentally studied the structure and magnetic properties of epitaxially grown ultrathin Pd/Co/Ta films. We have studied the effect of Ta on the structural and magnetic properties of Pd/Co epitaxial films. The deposition of a Ta layer on an epitaxial Co layer leads to a decrease in the saturation magnetization of the film due to strong magnetic disordering and the formation of a dead magnetic layer with a thickness of about 0.5 nm. Perpendicular magnetic anisotropy is observed for Co layer thicknesses less than 1.3 nm. The volume and surface components of magnetic anisotropy are determined. Additionally, the Dzyaloshinskii—Moriya interaction (DMI) is observed in epitaxial films with perpendicular magnetic anisotropy, with a DMI field value of about 30 mT.

**Keywords:** epitaxial thin films, perpendicular magnetic anisotropy, Dzyaloshinskii-Moriya interaction

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# Магнитная анизотропия и взаимодействие Дзялошинского-Мории в тонких пленках Pd/Co/Ta

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**Аннотация.** В данной работе экспериментально исследовались структура и магнитные свойства ультратонких пленок Pd/Co/Ta выращенных эпитаксиально. Мы исследовали влияние Ta на структурные и магнитные свойства эпитаксиальных пленок Pd/Co. Осаждение пленки Ta на эпитаксиальный слой Co приводит к понижению намагниченности насыщения пленки за счет сильного магнитного разупорядочения и формирования магнитомертвого слоя, толщиной около 0,5 нм. При толщине слоя Co меньше 1,3 нм наблюдается перпендикулярная магнитная анизотропия. Определены вклады объемной и поверхностной анизотропии. Также в эпитаксиальных пленках с перпендикулярной магнитной анизотропией наблюдается взаимодействие Дзялошинского-Мории (ВДМ) с величиной поля ВДМ примерно 30 мТл.

**Ключевые слова:** тонкие эпитаксиальные пленки, магнитная анизотропия, взаимодействие Дзялошинского-Мории

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## Introduction

As advances are made in spintronics, there is an ongoing search for new nanostructured materials with potential applications in controllable magnetic processes for creating skyrmionium racetrack memory, logic devices etc. Trilayer magnetic structures comprising heavy metal (1)/ferromagnet/heavy metal (2) are very promising for developing spintronics devices. Ultrathin epitaxial magnetic films (~1 nm) have exhibited anisotropy properties, which lead to a series of interface effects: enhanced perpendicular magnetic anisotropy (PMA), interfacial Dzyaloshinskii–Moriya interaction (DMI), spin-Hall effect etc. These effects are used for forming, stabilizing and controlling spin textures. The goal of this paper is to study the prospects of using thin epitaxial films with a Ta layer to create structures with a high DMI. This metal is currently the most interesting, because it is effective in experiments with other magnetic effects. For example, multilayer structures with tantalum have shown large values of the spin-orbit torque effect, as well as the ability to produce high-density skyrmion lattices [1].

## Materials and Methods

The epitaxial films were deposited by molecular beam epitaxy in an ultrahigh vacuum chamber with a base pressure of 3Ч10-11 Torr, (Omicron Nanotechnology). We used intrinsic undoped Si(111) substrates with the resistivity of 20–40 $k\Omega\times$cm with a Cu (2.1 nm) buffer layer. Before deposition, the substrates were flash-heated by direct current at 1200 °C a few times and slowly cooled down to room temperature. Cu, Pd and Co films were deposited by effusion cells, and deposition rates were controlled by quartz crystal microbalance and were 1 nm/min for Cu, 0.3 nm/min for Pd, and 0.1 nm/min Co, respectively. Deposition rates measured by quartz crystal microbalance were calibrated using reflection high-energy electron diffraction (RHEED, STAIB Instruments) based on intensity oscillations of specular beam reflection measured during layer deposition. The Cu 2.1 nm buffer layer prevents the intermixing of Pd with Si and protects from formation of amorphous silicide. A value of 2 nm Pd thickness was chosen because the lattice parameter reaches the bulk value, while the roughness parameter is small for the selected thickness [2]; moreover, we varied the thickness of the Co layer from 0.75 nm for inducing strong PMA for deposition on Pd [3, 4] to 4.5 nm. The temperature of the substrate was about 75 °C during Cu deposition and increased up to 110 °C for Pd and Co deposition. Ta (2 nm) layers were deposited by the electron-beam evaporation technique. Finally, films were covered with a Pd (3 nm) protection layer to prevent oxidation of the structure. Magnetization reversal processes and the effective PMA energy were estimated by hysteresis loops, measured by a vibrating-sample magnetometer (VSM, LakeShore 7410). Domain structure images were observed with a magnetooptical Kerr-effect microscope (Evico Magnetics) equipped with an in-plane electromagnet and custom-made out-of-plane electromagnet coil. Investigation of the DMI was performed using the observation of domain walls (DWs) displacement in a combination of IP and OP magnetic fields. The value of the internal Dzyaloshinskii–Moriya interaction field (HDMI) was determined by the minimum in the domain wall velocity dependencies on in-plane magnetic fields [5].

## Results and Discussion

Crystalline structure of Si(111)//Cu(2.1)/Pd(2)/Co($d_{Co}$)/Ta(2)/Pd(3) films was studied *in situ* via RHEED. Detailed investigation of the growth processes of epitaxial Pd and Co was presented in our previous works [2, 4]. A RHEED image of the epitaxial fcc Co (1 nm) layer is presented in Fig. 1, *a*. The mismatch between the lattice parameters of Co (0.354 nm) and Ta (0.331 nm) is insignificant, amounting to about 6.6%. However, due to the difference in crystal symmetry (fcc Co vs bcc Ta), as well as the fact that Ta has a very high melting point (3017 °C), it exhibits a tendency toward amorphous growth, which is accompanied by the disappearance of diffraction stripes and an increase in the background level on the RHEED pattern, as shown in Fig. 1, *b*. Despite the strong disordering of the Ta layer, further deposition of the fcc Pd layer occurs in the (111) direction with the predetermined predominant crystallographic direction retained. This makes it possible to obtain multilayer films with the preservation of the epitaxial orientation.

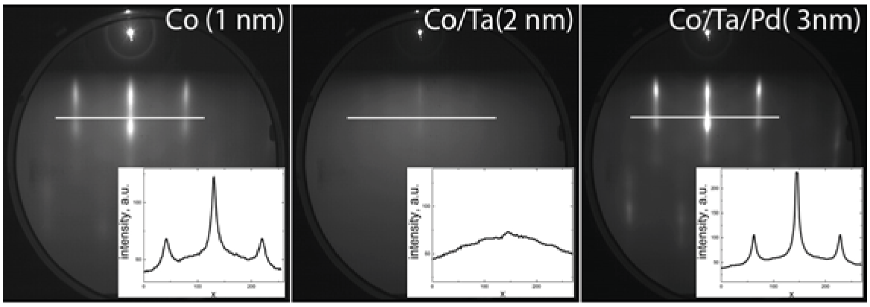


Fig. 1. RHEED images for different layers in Si(111)//Cu(2.1)/Pd(2)/Co(1)/Ta(2)/Pd(3) film

The magnetic properties of Si(111)/Cu/Pd/Co/Ta/Pd films were studied using the magnetic hysteresis loops obtained using VSM in magnetic fields, applied along the in-plane (IP) and out-of-plane (OP) directions. The saturation magnetization normalized to the thickness of the deposited Co layer in Pd/Co/Ta films demonstrates values below the magnetization of bulk single-crystal Co ($M_{s\,\mathrm{Co\,bulk}}$ = 1420 G). At a thickness of 0.75 nm of the ferromagnetic layer, $M_s$ is equal about 600 G, and with increasing thickness, Co increases sharply, however, even at a thickness of 4.5 nm, it does not reach the bulk value, as shown on the inset of fig.2(*a*). In this case $M_s$, determined by the slope of the line graph $(m_s/S) = f(d_{Co})$ is about 1440 G, this is less than epy saturation magnetization of Pd/Co/Pd films (Ms = 1520 G) which was investigated in our previous work [4], where the increase of saturation magnetization is related to the magnetic polarization Pd. It is known that magnetic polarization of the 4*d* Pd boundary layer is observed in Pd/Co/Pd films due to hybridization of 3*d* electrons of Co, which leads to an overall increase in the magnetic saturation moment. In Pd/Co/Ta films, the magnetic moment decreases linearly with decreasing Co thickness; however, the zero moment (the point of intersection of the graph with the abscissa axis) is expected at a nonzero positive value of $d_{Co} \approx 0.4$ nm (Fig. 2, *a*), which indicates the existence of a magnetically disordered ‘dead magnetic’ layer at the Co/Ta interface. Magnetic polarization at the Pd/Co interfaces shifts the intersection point to negative thicknesses [4] of −0.1 nm, and thus the dead layer thickness can be determined as the difference $d_{DL} \approx 0.4 - (-0.1) \approx 0.5$ nm, which is about 2.5 monolayers of Co(111).

The dependence of the effective magnetic anisotropy on the thickness is shown in Fig. 2, *b*. Epitaxial Pd/Co/Ta films demonstrate the perpendicular magnetic anisotropy at small thicknesses. Compared to epitaxial Pd/Co/Pd films, in which magnetic anisotropy is induced at the interfaces, mainly due to strong crystalline stresses, the energy of perpendicular magnetic anisotropy in Pd/Co/Ta films is significantly lower due to the disordered layer at the Co/Ta interface. Maximum value of effective anisotropy is $K_{eff} \times d_{Co} = 8\cdot10^{-5}$ J/m$^2$ in the range of perpendicular magnetic anisotropy observed at $d_{Co}$ = 1 nm. At the same thickness, there is also a maximum of coercive force $\mu_0 H_c$ = 13 mT. A decrease in the layer thickness leads to a decline of the coercive force, which may be due to a significant influence of dead layer $d_{DL}$ and nonzero roughness of the Pd/Co interface, which can lead to the appearance of sections of a ferromagnetically discontinuous layer. On the other hand, an increase in the thickness of the Co layer to 1.2 nm also leads to a decrease in the coercive force, which is associated with a decrease in the magnetic anisotropy.

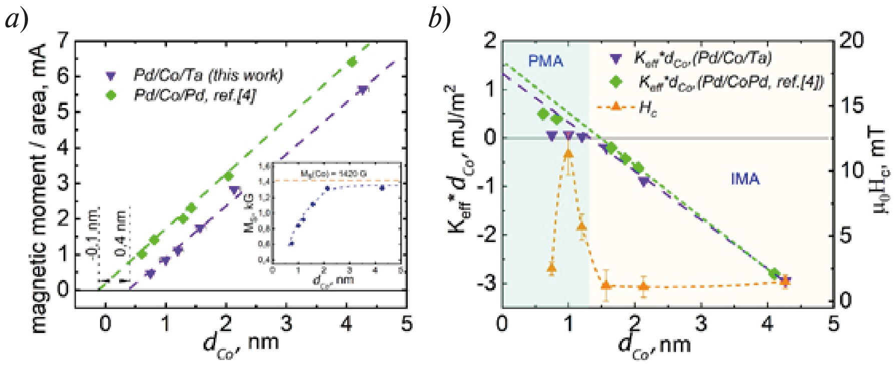


Fig. 2. Magnetic moment per unit of sample area ($a$), saturation magnetization (inset in ($a$)), effective magnetic anisotropy and coercive force ($b$) as a function of $d_{Co}$

The transition between perpendicular and in-plane anisotropy is observed at a thickness of about 1.3 nm; with a further increase in thickness in-plane magnetic anisotropy is observed at which the coercive force does not exceed the value of $\mu_0 H_c$ = 1–2 mT. Effective magnetic anisotropy may be determined as

$$K_{eff} \cdot d_{Co} = K_v + \frac{(2)K_s}{d_{Co}}.$$

The slope of the linear section of curve of the magnetic anisotropy was used to determine the volume contribution to the effective anisotropy $K_v$ = 1 MJ/m$^3$, and to determine the constant of surface anisotropy $K_s$ = 1.4 mJ/m$^2$.

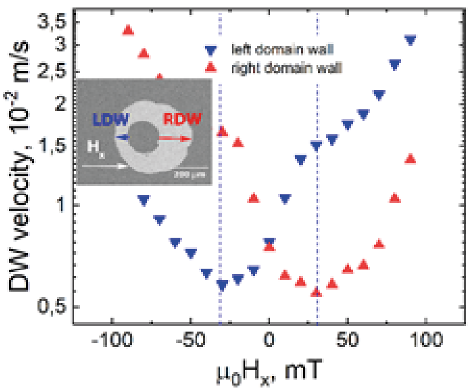


Fig. 3. Dependence of domain wall velocity on in-plane magnetic field $H_x$. Visualization of magnetic domains was carried out with magnetooptical Kerr microscopy A simple scheme of the experiment is presented in the inset

The study of the Dzyaloshinskii–Moriya interaction was carried out based on the asymmetry of the propagation of domain walls in the creep mode for the Pd/Co(1)/Ta sample, since it demonstrates the highest perpendicular magnetic anisotropy. The necessary conditions for accurate measurement of the Dzyaloshinskii–Moriya interaction field are the following: stable nucleation of a domain in the same place, the absence of anisotropic macrodefects and roughness, a coercive force of less than 30 mT, and the absence of other domains in the field of view of the selected domain during its propagation. Using by the focused ion beam technique, an artificial defect was formed, which played the role of a stable center of domain nucleation The dynamics of domain wall propagation was studied using a magnetooptical Kerr microscope. On an artificial defect, using a short out-of-plane field ($H_z$) pulse, with duration of 2 ms, a domain was generated, after which a constant in-plane magnetic field ($H_x$) was switched on and after that, gave a second pulse of the out-of-plane magnetic field. Under the action of a displacing external in-plane field, the displacement of domain walls moving along the field and against the field occurs unequally (shown in the inset to Fig. 3). The domain wall velocity of movement is recorded from the shift of the left and right domain walls at a known $H_z$ pulse width. The minimum of domain wall velocity is observed at nonzero $H_x$ (Fig. 3). The in-plane displacement field is compensated by the action of the internal non-zero Dzyaloshinskii–Moriya interaction field (HDMI, which is oriented against the direction of the magnetic field), which displaces $H_{min}$, i.e., the field at which the domain wall velocity is minimal, relative to zero. The shape of the curves at low speeds is quite symmetrical and close to parabolic, suggesting that $\mu_0 H_{DMI} \approx \mu_0 H_{min}$ = 30 mT. Slight kinks on the curves indicate an insignificant damping component.

## Conclusion

We have studied the structure and magnetic properties of Si(111)/Cu/Pd/Co/Ta/Pd epitaxial films. The study of the layer growth process showed a disordered growth of Ta on the epitaxial Co layer, as well as a tendency to ordering with further deposition of Pd with the preservation of crystallographic symmetry. Ta, when deposited on the Co epitaxial layer, forms a magnetically disordered layer about 0.5 nm thick. The magnetically dead layer leads to a decrease in the perpendicular magnetic anisotropy in comparison with the previously studied symmetric epitaxial structures of the Pd/Co/Pd composition. For the Pd/Co/Ta system, the effective anisotropy components are determined: the volume anisotropy constant $K_v$ = 1 MJ/m$^3$, and the surface anisotropy constant $K_s$ = 1.4 mJ/m$^2$. It was expected that the violation of the symmetry of the structure by introducing the Ta layer would lead to an increase $H_{DMI}$, compared with Pd/Co/Pd films, but this did not happen, since Ta leads to a decrease in anisotropy compared to a symmetrical structure due to strong mixing at the interface. However, breaking of the film symmetry in this case leads to more symmetric velocity curves, which indicates a decrease in the contribution of chiral damping. Thus, despite the disordered growth of Ta and the relatively small $\mu_0 H_{DMI} \approx 30$ mT, it is possible to create DMI-enhanced ordered multilayer superlattices by increasing the number of layers based on the epitaxial films.


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## REFERENCES


1. **Wang L., Liu Ch., Mehmood N., Han G., Wang Ya., Xu X., Feng Ch., Hou Z., Peng Y., Gao X., Yu G.,** ACS Applied Materials & Interfaces 11, 12, (2019) 12098–12104
2. **Davydenko A.V., Kozlov A.G., Ognev A.V., Stebliy M.E., Chebotkevich L.A.,** Applied Surface Science. 384 (2016) 406–412.
3. **Davydenko A.V., Kozlov A.G., Stebliy M.E., Kolesnikov A.G., Sarnavskiy N.I., Iliushin I.G., Golikov A.P.,** Physical Review B 103, (2021) 094435.
4. **Davydenko A.V., Kozlov A.G., Ognev A.V., Stebliy M.E., Samardak A.S., Ermakov K.S., Kolesnikov A.G., Chebotkevich L.A.,** Physical Review B. volume 95, issue 6, 28 (2017) 064430.
5. **Je S.G., Kim D.H., Yoo S.C., Min B.C., Lee K. J., Choe S.B.,** Physical Review B, 88. (2013) 214401.


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