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The effect of Pd doped in Ru layer on the interlayer coupling in Co/RuPd multilayers*

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2.0nmCo/$t$nm$Ru_{1-x}Pd_x$ multilayers with x=0, 0.05, 0.08, 0.24, 0.39 and 0.48 were prepared by magnetron sputtering. The spacer layer thickness of both Ru (before doping Pd) and RuPd (after doping Pd) varies from 0.2nm to 1.6nm. Two effects have been investigated: (1) the dependence of the interlayer coupling on the thickness of $Ru_{1-x}Pd_x$ as a function of x and (2) the dependence of the interlayer coupling on Pd doping density, x, as a function of thickness of $Ru_{1-x}Pd_x$. Our results indicate that the interlayer coupling is strongly dependent on the doping density and the spacer layer thickness. The saturation field H_s increases when very low concentration of Pd doped in the Ru layers and a suitable spacer thickness are adopted.

Keywords: interlayer antiferromagnetic coupling, magnetic recording, doping effect
PACC: 7550S, 7550R, 7560E, 7570F

1. Introduction

Parkin *et al* found the oscillatory antiferromagnetic coupling (AFC) in metallic superlattice structure Co/Ru in 1990.[1] This oscillatory antiferromagnetic coupling between Co layers is dependent on the thickness of the spacer layer of Ru and the antiferromagnetic coupling between Co layers appears when the spacer Ru layer thickness is around 0.8nm. Such an effect possesses a great potential application because recording medium composed of AFC layers is a promising approach to extension of the areal density of longitudinal media.[2] AFC media are made up of two (or three) ferromagnetic layers separated by Ru layer whose thickness can be adjusted to couple the layers antiferromagnetically. For such a structure, the effective areal moment density $M_r t_{\rm eff}$ of the composite structure is given by the difference between the remanence-thickness products of the magnetic layers, i.e. $M_r t_{\rm eff}$ =($M_{\rm r1}t_1$-$M_{\rm r2}t_2$). Here $M_{\rm r1}, t_1$ and $M_{\rm r2}, t_2$ are the remanence and thickness of the top layer (recording layer) and those of the bottom layer (stabilization layer) respectively, which allows AFC media to maintain thermal stability even for low $M_r t_{\rm eff}$ value due mainly to the interlayer AFC effect. Experimental realization of this concept has been achieved using CoPtCrB alloy layers separated by Ru. In recent years, much attention has been paid to the AFC magnetic structure and it has been demonstrated that the thermally stable low $M_r t_{\rm eff}$ media are suitable for a high recording density of 100 Gbit/in^2 and even higher.[3−14]

The oscillatory exchange coupling between ferromagnetic layers separated by a nonmagnetic metal spacer layer, which was first observed on rare-earth and transition metal multilayers (MLs), has been shown to be a fairly common behaviour.[15] One possible origin of the exchange coupling with spacer layer thickness is some sort of Ruderman–Kittel–Kasuya–Yosida (RKKY) coupling mediated by spin polarization of spacer layer.[16] In fact, any change of polarization in spacer can exert an influence on the interlayer exchange. The significant change in the oscillatory exchange coupling in Co/CuNi(110) has been found.[17] Moreover, one has found the oscillation of polar Kerr rotation with the variation of the doping concentration of Cu in the spacer layer of PtCu for the PtCu/Co MLs and the significant change of the interlay coupling in PtNi/Co and PdFe/Fe MLs.[18−20]

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In this paper, we report the effect of Pd doped into Ru layer on the interlayer exchange coupling in Co/RuPd MLs. Co/Ru MLs possess great potential application in data recording as mentioned above and the entrance of Pd into Ru layers may bring about a change of the interlayer coupling. On the basis of these considerations, the effect of Pd doping on the interlayer coupling in Co/Ru MLs has been investigated. Our results show that Pd polarization indeed changes the interlayer coupling which originally exists in Co/Ru MLs.

2. Experiments

Multilayers of 2.0nmCo/$t$nm($Ru_{1-x}Pd_x$) with x=0, 0.05, 0.08, 0.24, 0.39 and 0.48 for different thickness of $Ru_{1-x}Pd_x$, t_{RuPd}, were prepared by magnetron sputtering at an Ar pressure of 0.93Pa. The substrate was of 0.2mm-thick glass covered by a 10-nm thick Ru layer. A Ru layer with 5nm thick was deposited on the surface of each sample as a protective layer. The background vacuum was about 6.7×10^{-5} Pa. The thickness of each sublayer was controlled by the sputtering time through a preset computer programming. The number of period of the samples is 20. The addition of Pd to Ru layer was carried out by means of increasing the area ratio of Pd to Ru on a composite target. The Pd concentration in the Ru layer was determined by energy dispersive x-ray (EDX). Small- and large-angle x-ray diffractions (XRD) were utilized to measure the modulated characteristics and the crystal structures of the multilayers, respectively. The hysteresis loop was determined by a vibrating sample magnetometer and superconducting quantum interference device magnetometry.

3. Results and discussion

The Ru film deposited on the glass substrate was found to have a thickness of 0.14μm and (002), (101) and (100) x-ray diffraction peaks. The Co film deposited on the glass substrate was observed to be 0.37μm thick and has (002) and (100) peaks. As for the multilayer structure, two small-angle XRD peaks can be clearly seen from the XRD measurement. Figure 1 gives an example for the 2.0nmCo/1.0nm$Ru_{1-x}Pd_x$ MLs with x=0, 0.24, 0.38 and 0.48, respectively. The period of the MLs determined by the small-angle XRD is consistent with the design. Figure 2 gives the large XRD pattern for the 2.0nmCo/1.0nm$Ru_{0.52}Pd_{0.48}$ MLs, as an example. Notice that the strongest x-ray diffraction (002) peaks appearing in the pure Ru and Co films do not appear in the Co/RuPd MLs. The other peaks in Ru and Co films and Pd(111) peak can be seen in the deposited Co/RuPd MLs.

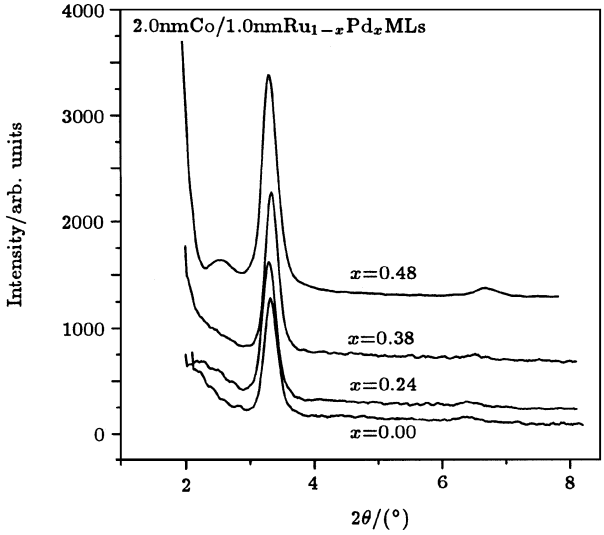


Fig.1. Small-angle XRD patterns for the 2.0nmCo/1.0nm$Ru_{1-x}Pd_x$ MLs with x=0, 0.24, 0.38, and 0.48, respectively.

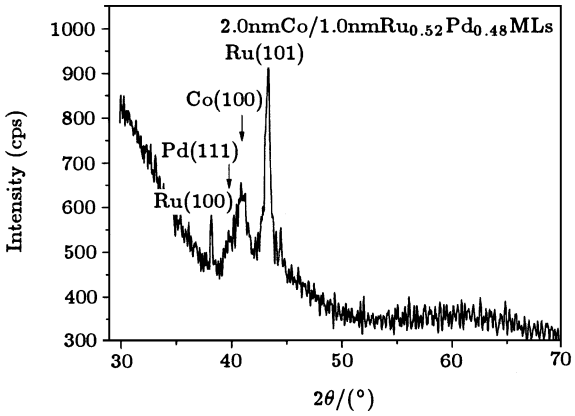


Fig.2. Large-angle x-ray diffraction patterns for the 2.0nmCo/1.0nm$Ru_{0.52}Pd_{0.48}$.

The hysteresis loop of 2.0nmCo/0.8nmRu MLs is shown in the inset in Fig.3. We can see from the loop that the remanence is zero. It means that the moments between the adjacent Co layers in the MLs are completely anti-parallel at H=0, namely an antiferromagnetic coupling is formed between Co layers. The saturation field H_s indicated by the arrow equals about 8.8×10^5A/m and it is defined as the field that makes Co moments in all the adjacent Co layers in the MLs orient to the same direction. The curve of H_s as a function of Ru thickness, t_{Ru}, is shown in Fig.3. The symbols of circle and square stand for our experimental results. As mentioned before, H_s is obtained from

hysteresis loop and we can acquire the ratio of M_r/M_s from the same hysteresis loop. Therefore, each H_s will have a corresponding ratio of M_r/M_s. The circle symbols show that the ratio is lower than 0.05 in the Ru thickness range of 0.4–1.0nm (see Fig.4). In other words, these MLs possess basically an interlayer anti-ferromagnetic coupling. The solid line in Fig.3 represents the experimental results from Parkin *et al*[1] and we can see that our results are in good agreement with theirs although our t_{Ru} is terminated at 2.4nm. Moreover, we added the data to the curve of H_s vs. t_{Ru} between t_{Ru}=0.2 and t_{Ru}=0.7nm.

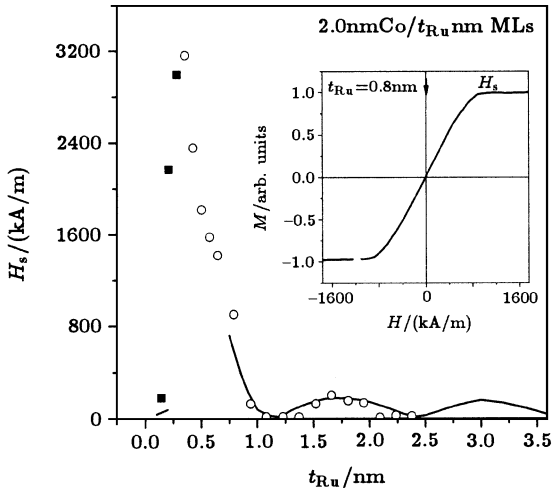


Fig.3. H_s as a function of t_{Ru} for the 2.0nmCo/t_{Ru}nm MLs. Our experimental data are indicated by the symbols of square and circle and the solid line is taken from Parkin *et al*;[1] the insert shows the hysteresis loop for the 2.0nmCo/0.8nm MLs.

Figure 4 gives the remanence ratio, M_r/M_s, as a function of $t_{Ru(RuPd)}$ for the 2.0nmCo/$t$nmRu$_{1-x}$Pd$_x$ MLs with x=0, 0.05, 0.08, 0.28 and 0.48, respectively. For the Co/Ru MLs without any Pd doping, the curve of M_r/M_s vs. t_{Ru} shows a concave shape and M_r/M_s=0 when t_{Ru}=0.8nm. In the case of x=0.48, the interlayer anti-ferromagnetic coupling is quenched in a given Ru thickness region. As for the medium doping of Pd (x=0.28), the dependence of interlayer coupling on Ru thickness in Co/Ru MLs can be still observed, but the interlayer anti-ferromagnetic coupling is modulated to a great extent. For x=0.05, $M_r/M_s \approx 0$ can be found at t_{RuPd}=0.8nm. These data indicate that the entrance of Pd into Ru layer results in an increase of remanence unless the doping is very small and t_{RuPd}=0.8nm.

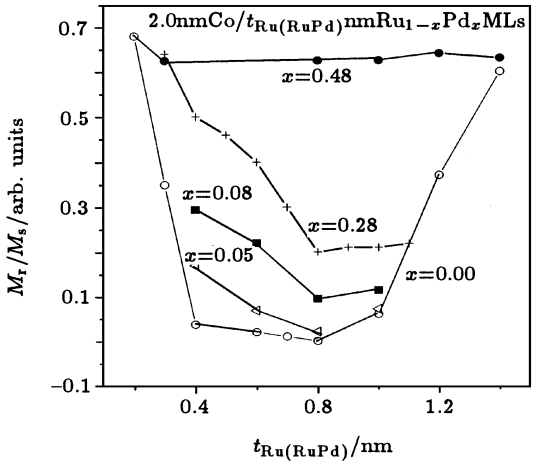


Fig.4. The remanence ratio M_r/M_s vs. $t_{Ru(RuPd)}$ as a function of Pd doping concentration x, for the 2.0nmCo/1.0nmRu$_{1-x}$Pd$_x$ MLs with x=0, 0.05, 0.08, 0.38, and 0.48, respectively.

Figure 5 shows the hysteresis loops of the 2.0nmCo/0.8nmRu$_{1-x}$Pd$_x$ MLs for x=0, 0.05, 0.28 and 0.48, respectively. For x=0.28 and 0.48, the loops possess the hysteresis characteristics and the hysteresis loop for x=0.48 is given in the inset in Fig.5. As compared to the curve with x=0, the curve with x=0.05 possesses also a near-zero remanence, but its H_s (1.6×10^6A/m) is larger than the value of H_s (8.8×10^5A/m) for x=0.

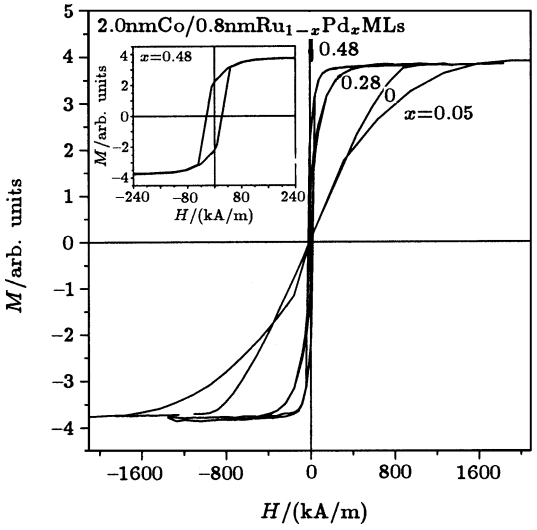


Fig.5. Hysteresis loop for the 2.0nmCo/0.8nmRu$_{1-x}$Pd$_x$ MLs with x=0, 0.05, 0.28 and 0.48, respectively. The inset shows the loop of the MLs with x=0.48.

Figure 6 shows the relationships of H_s vs. x for t_{RuPd}=0.4, 0.6 and 0.8nm, respectively. It can be obviously seen that each H_s reaches its maximum at x=0.05, and then decreases with the increase of x. But for t_{RuPd}=1.0nm, H_s does not show any increase at x=0.05 and this curve is not given in Fig.6. As

mentioned above, the magnitude of H_s reflects the strength of the antiferromagnetic coupling between Co layers. The increase of H_s means that the antiferromagnetic coupling increases at x=0.05 for the t_{RuPd}=0.4, 0.6 and 0.8nm.

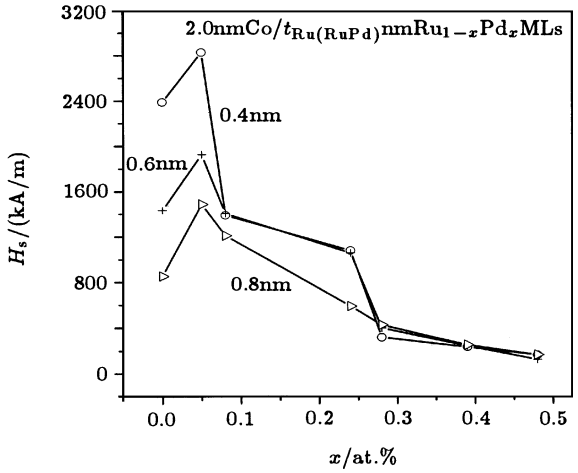


Fig.6. The saturation field H_s as a function of x for t_{RuPd}=0.4, 0.6 and 0.8nm, respectively.

Figure 7 gives the relationships of M_r/M_s vs. x for t_{RuPd}=0.4, 0.6 and 0.8nm, respectively. M_r/M_s obviously increases with x. However, M_r/M_s remains nearly zero when x is less than 0.05 and t_{RuPd}=0.8nm.

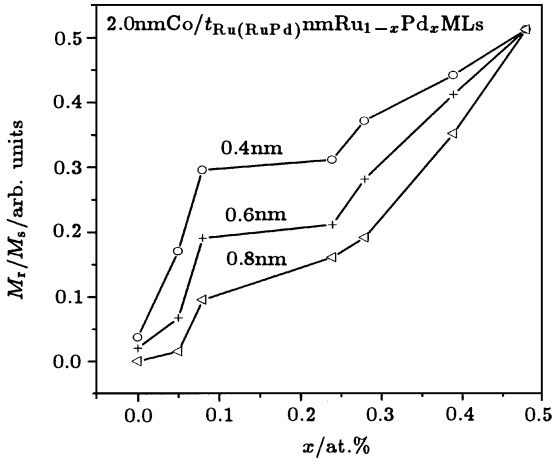


Fig.7. The remanence ratio M_r/M_s as a function of x for t_{RuPd}=0.4, 0.6 and 0.8nm, respectively.

In Co/Pd MLs, Pd atom is polarized by Co layers and each Pd atom at the interface possesses a maximal magnitude of about 0.3 bohr magnetron given by theoretical calculation.[21] The polarization of Pd atom in the spacer layer can be positive or negative and it is dependent on its position in spacer layer. Therefore, the strength of Pd atom polarization decreases with increase in distance in an oscillation manner (it follows the RKKY theory). When Pd is doped into Ru layer, we believe that Pd polarization happens; therefore Pd polarization may change the coupling between the adjacent Co layers. Pd polarization can be confirmed by theoretical calculation or measurement of saturation magnetization.[19,20] In our case, the contribution of the Pd polarization to the total magnetization saturation of the sample is very small due mainly to the use of a thick Co layer even if in the case of large Pd doping density. Therefore, we cannot give the polarization behaviour of Pd in Ru layers in this paper.

4. Conclusions

In summary, doping Pd into Ru spacer layer results in a significant change of the interlayer coupling. The interlayer anti-ferromagnetic coupling in Co/Ru MLs can be completely quenched as a large doping concentration is utilized (x=0.48). In this case, the saturation field H_s decreases, but the magnetic remanence increases. When the doping concentration is medium, the interlayer antiferromagnetic coupling is weakened. H_s could be increased only at a small doping concentration, x=0.05. The interlayer coupling is also closely dependent on the spacer thickness after doping Pd. It is clear that 0.8nm RuPd is a good thickness because a near-zero M_r appears in 0.8nm thick RuPd.

It is required that AFC material as a magnetic recording medium should have a large saturation field and a completely antiferromagnetic coupling between two magnetic layers as H=0. Our results indicate that Pd doping is effective on the increase of H_s when x=0.05 and t_{RuPd}=0.8nm. In our opinion, the use Co/RuPd MLs with a small Pd doping as an AFC recording medium is worthy of further study.

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