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Ferromagnetic resonance in Co–Nb/Pd multilayers

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Abstract. Co–Nb(3.6 nm)/Pd(d_{Pd} nm) multilayers were prepared by the rf sputtering method. The polarization of Pd layers and the interlayer coupling through Pd layers were studied via magnetic and ferromagnetic resonance measurements. Magnetic measurement shows that the saturation magnetization of Co–Nb/Pd multilayers oscillates periodically when the Pd layer thickness increases, which is caused by the oscillatory polarization of the Pd layers. The spin-wave excitation indicates that a ferromagnetic interlayer coupling can exist until the thickness of the Pd layers is about 7 nm. An oscillatory variation between 2.00 and 2.12 of the effective g-factor, g_{eff}, with the thickness of Pd layers was observed for the first time. The oscillatory period of g_{eff} is about 1 nm. A similar oscillatory behaviour of the effective anisotropy, K_e, was also obtained. This oscillatory behaviour of g_{eff} and K_e was interpreted in terms of a model of two exchange-coupled sublattices: one sublattice is that of the Co–Nb magnetic layers, and the other is that of the polarized Pd layers. This model indicates that the oscillatory behaviour of g_{eff} and K_e mainly originates from the oscillation of the polarization of the Pd layers.

1. Introduction

The polarization of Pd atoms and the interlayer coupling in Fe/Pd and Co/Pd multilayers have stimulated great interest. Although free Pd atoms are non-magnetic, because the Stoner factor of Pd atoms is very large and the intra-atomic exchange interactions between 4d electrons are important, an enhanced magnetic susceptibility of the Pd metal can result, and additional ferromagnetism can be induced when Pd atoms form Pd-based diluted alloys containing Co, Fe, or Ni [1, 2]. Because the polarization of Pd atoms contributes to the increase of the magnetic moment per magnetic atom in the diluted alloys, the effective moment per magnetic atom is larger than that of bulk magnetic metals. The same phenomenon of ferromagnetic polarization of Pd atoms at the interfaces was observed in Fe/Pd [3, 4] and Co/Pd [4–6] multilayers. Furthermore, experiments revealed that Fe/Pd/Fe trilayers showed ferromagnetic coupling between Fe layers through Pd spacers up to 11 atomic monolayers [3, 7]. For more than 12 Pd atomic monolayers, a marginally small antiferromagnetic coupling was presented. No other experiments revealed evidence of antiferromagnetic coupling between magnetic layers through Pd spacers in multilayers. Experimental [5, 8] and theoretical [9–11] results indicated that the oscillatory variation of the saturation magnetization of the Pd-based magnetic multilayers was caused by the oscillatory dependence of the polarization of Pd atoms on the Pd layer thickness. It was supposed that both the 3d–4d interaction and the RKKY interaction played a role in the polarization of Pd atoms and the interlayer coupling between magnetic layers [10].

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Many studies of multilayers consisting of Pd and magnetic transition metals have been reported, but few have dealt with multilayers consisting of Pd and amorphous magnetic alloys. Since the polarization of Pd atoms and the interlayer coupling through Pd layers are very sensitive to the lattice constants of Pd layers and the detailed structures of the multilayers [3, 11], in this paper we have studied the polarization and interlayer coupling in the multilayers consisting of amorphous Co–Nb alloy and Pd metal, by using a vibrating-sample magnetometer (VSM) and ferromagnetic resonance (FMR) spectroscopy. FMR experiments are very sensitive to the magnetization and its distribution [12], the anisotropy [13, 14], and especially the interlayer coupling in the multilayers and sandwiches [13–15]. Therefore, for Pd-based multilayers, the FMR spectrum can be strongly affected by the polarization of Pd layers and the interlayer coupling. This has made FMR a very powerful tool for studying Pd-based multilayers.

2. Experiments

Co–Nb/Pd multilayers were prepared by an rf sputtering system with two targets which were made of amorphous Co–Nb alloy and Pd metal. The substrates were glass slides 0.2 mm thick. The targets and the sample holder were cooled by water. The chamber was first evacuated to about 2×10^{-6} Torr. Then 99.999%-pure Ar gas was introduced, and the Ar pressure was controlled at 5 mTorr during the sputtering process. The composition of the Co–Nb layers determined by electron-microprobe analysis was $Co_{90}Nb_{10}$. The deposition rates of Co–Nb and Pd were 0.1 nm s^{-1} and 0.25 nm s^{-1}, respectively. The thickness of each layer was controlled by controlling the exposure time. The thickness of the Co–Nb layers was fixed at 3.6 nm, and the thickness of the Pd layers was changed from 0.5 to 7 nm. The total number of bilayers was 20.

Two or three peaks of the low-angle x-ray diffraction showed that all of the samples had good composition modulation structures. The modulation wavelengths measured by low-angle x-ray diffraction were in good agreement with the designed values within the errors of 5%. High-angle x-ray diffraction indicated that the Co–Nb layers were in an amorphous state, and that the Pd layers thicker than 1.5 nm had fcc (111) crystal structure. The magnetic properties of Co–Nb/Pd multilayers were measured by the VSM. The magnetic field was applied in the film plane. The magnetic background signals of the substrate and the sample holder were considered. A commercial homodyne EPR spectrometer with a TE102 cavity in the X band (9.78 GHz) was used to detect the FMR spectra at room temperature. The angle, Φ_H, between the film normal and the applied magnetic field varied from 0° to 90°. The first derivative of the absorbed power for the samples with respect to the magnetic field $P'(H)$ was recorded. The resonance field H_r was determined from $P'(H) = 0$, and the linewidth ΔH_r was defined as the field difference between the maximum and the minimum of $P'(H)$.

3. Results and discussion

The polarization of Pd atoms and the interlayer coupling in Co–Nb/Pd multilayers were first studied by VSM measurements. The Co–Nb layers (3.6 nm) are thick enough to eliminate the influences of the dimensional effect of the magnetism but thin enough to expose obviously various phenomena of the polarization of Pd atoms and the interlayer coupling. Figure 1 shows the dependence of the saturation magnetization M_0 at room temperature on the Pd layer thickness d_{Pd}. The saturation magnetization M_0 (measured by

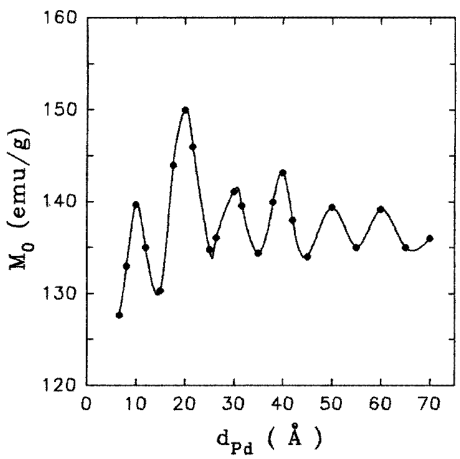

Figure 1. The dependence of the saturation magnetization M_0 at room temperature on the thickness of the Pd layers, d_{Pd}.

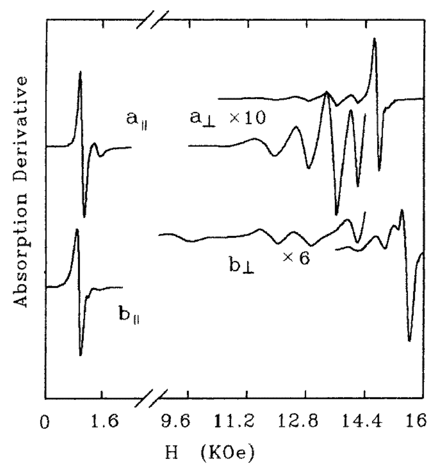

Figure 2. Some typical derivative spectra of the FMR at room temperature. The thickness of the Pd layers is (a) 1.5 nm, and (b) 4 nm. The signs ∥ and ⊥ denote the parallel and perpendicular configurations, respectively.

the VSM) is defined as the measured total magnetic moments divided by the total mass of Co–Nb layers in a multilayer. In figure 1, an oscillatory behaviour of M_0 is observed when d_{Pd} increases. When d_{Pd} is about 1, 2, 3, 4, 5, and 6 nm, M_0 is at the maximum positions; when d_{Pd} is about 1.5, 2.5, 3.5, 4.5, and 5.5 nm, M_0 is at the minimum positions. The oscillation period of M_0 is about 1 nm. When $d_{Pd} > 6.5$ nm, M_0 approaches a constant. On the other hand, the hysteresis loops of all of the samples indicate that no antiferromagnetic interlayer coupling exists in the Co–Nb/Pd multilayers.

Recently, Victora and MacLaren [9] calculated the spin polarization in Co/Pd multilayers by using the layer Korringa–Kohn–Rostoker (KKR) method, and Miura *et al* [10] calculated it by using the X_α cluster method. They revealed that the oscillatory variation of the saturation magnetization was caused by the oscillatory dependence of the polarization of the Pd atoms on the Pd layer thickness. When the Pd layer is three atomic monolayers thick, all of the Pd atoms have a ferromagnetic polarization, and this produces a maximum of magnetization as a function of Pd layer thickness. In this case, the d–d interaction between Pd atoms and Co atoms is dominant. However, when the Pd layer is five atomic monolayers thick, the central Pd atomic monolayer has an antiferromagnetic polarization, and this produces a minimum of magnetization. In this case, the RKKY interaction rather than the d–d interaction between the central Pd atomic monolayer and the Co layers is dominant. Some experiments also showed a maximum of M_0 near the Co/Pd(0.9 nm) multilayer [7, 8] and a minimum of M_0 near the Co/Pd(1.4 nm) multilayer [10]. Our results are qualitatively in agreement with these results when d_{Pd} is less than 1.5 nm, but no experimental or theoretical data [7–11] showed that an obvious oscillation of M_0 could last even for $d_{Pd} > 6.5$ nm.

The ferromagnetic resonance technique was also used to study the polarization of Pd layers and the interlayer coupling in Co–Nb/Pd multilayers. Figure 2 shows some typical derivative spectra of the FMR at room temperature. For all of the samples, when the applied magnetic field is along the film normal ($\Phi_H = 0^\circ$, perpendicular configuration), 2–8 subsidiary resonance peaks below the main peak are observed. The resonance fields of the main peak and the subsidiary peaks decrease as the applied field rotates from the film normal, and most of the subsidiary peaks disappear at a critical angle. The critical angle is within 6° of the film normal for all of the samples. The disappearing peaks are spin-wave modes. Only when an interlayer coupling makes the multilayer behave as a single-layer film can spin-wave resonance be excited by microwaves [16]. The spin waves below the main peak can propagate through the Pd layers by means of the polarization of Pd atoms. This indicates that an obvious ferromagnetic interlayer coupling between Co–Nb layers exists in these samples. This is in agreement with the result from VSM measurements that no antiferromagnetic interlayer coupling exists in any sample.

When the applied field rotates to the film plane (the parallel configuration), one main peak and one very weak peak at higher field are found for the samples with the thickness of the Pd layers, d_{Pd}, less than 3.5 nm, and only one main peak is found for the samples with d_{Pd} thicker than 3.5 nm. The main peak is the uniform resonance mode of the Co–Nb/Pd multilayers. The very weak peak possibly originates from the interfaces of Co–Nb and Pd layers and/or from the polarized Pd layers with weak magnetization. The resonance linewidth of the main mode in the parallel configuration ($\Phi_H = 90°$) is narrow for all of the samples, and it increases approximately from 85 Oe to 200 Oe as the thickness of the Pd layers increases.

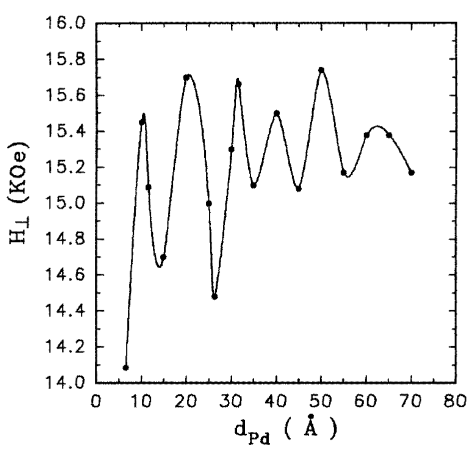

Figure 3. The dependence of the resonance field of the main uniform resonance mode in the perpendicular configuration, $H_\perp$, on the Pd layer thickness d_{Pd}.

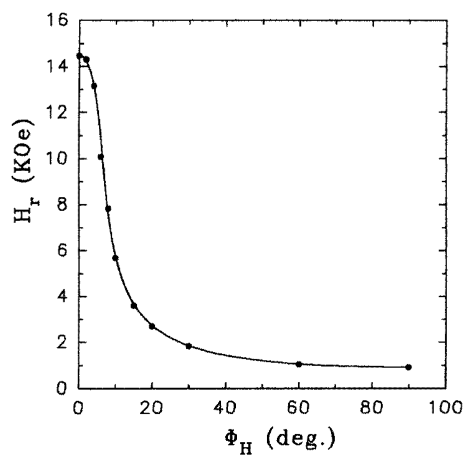

Figure 4. The Φ_H dependence of the resonance field H_r of the uniform resonance mode for Co–Nb(3.6 nm)/Pd(2.6 nm) multilayers. The circles represent experimental results, and the solid line represents the theoretical ones. The best-fitted g_{eff} is 2.10.

Moreover, the resonance field of the main uniform resonance mode in the perpendicular configuration, $H_\perp$, is strongly dependent on the Pd layer thickness d_{Pd}. Figure 3 shows the dependence of $H_\perp$ on the Pd layer thickness d_{Pd}. It is very interesting that $H_\perp$ oscillates periodically with increasing Pd layer thickness (figure 3) as the saturation magnetization M_0 does (figure 1). The oscillatory phase and period of $H_\perp$ are the same as those of M_0.

Here we mainly focused on the main uniform resonance mode. The Landau–Lifshitz equation of motion for a magnetic system with a magnetization M is given by

$$-\frac{1}{\gamma}\frac{\partial \boldsymbol{M}}{\partial t} = \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} \qquad (1)$$

where $\boldsymbol{H}_{\text{eff}}$ includes the applied magnetic field, the demagnetization, and the anisotropy ones. The dispersion relation of the uniform resonance mode for multilayers with perpendicular uniaxial anisotropy can be written as follows [17]:

$$(\omega/\gamma)^2 = [H_r \cos(\Phi - \Phi_H) - 4\pi M_{\text{eff}} \cos^2\Phi + H_{K_2} \sin^2 2\Phi] \times [H_r \cos(\Phi - \Phi_H) - 4\pi M_{\text{eff}} \cos 2\Phi + 4H_{K_2}(\sin^2 2\Phi - \sin^2\Phi)]. \tag{2}$$

According to the equilibrium equations for the magnetization M_S, we have the following equation:

$$H_r \sin(\Phi - \Phi_H) - 2\pi M_{\text{eff}} \sin 2\Phi + 4K_2 \sin^3\Phi \cos\Phi = 0 \tag{3}$$

where H_r is the resonant field, Φ_H is the angle between the applied magnetic field and the film normal direction, Φ is the angle between the direction of the saturation magnetization M_S of the multilayer and the film normal direction, $4\pi M_{\text{eff}} = 4\pi M_S - 2K_1/M_S$ is the effective magnetization which is introduced by the demagnetization field, K_1 is the first-order perpendicular uniaxial anisotropy, $H_{K_2} = K_2/M_S$ is the second-order anisotropy field, $\omega = 2\pi f$ ($f = 9.78$ GHz) is the microwave angular frequency, $\gamma = g_{\text{eff}}e/(2mc)$ is the gyromagnetic factor, and g_{eff} is the effective g-factor of the multilayers.

According to equations (2) and (3), in perpendicular geometry ($\Phi_H = 0$), $\Phi = 0$, $H_r = H_\perp$, and

$$\omega/\gamma = H_\perp - 4\pi M_{\text{eff}} \tag{4}$$

and in parallel geometry ($\Phi_H = 90°$), $\Phi = 90°$, $H_r = H_\parallel$, and

$$(\omega/\gamma)^2 = H_\parallel(H_\parallel + 4\pi M_{\text{eff}} - 4H_{K_2}). \tag{5}$$

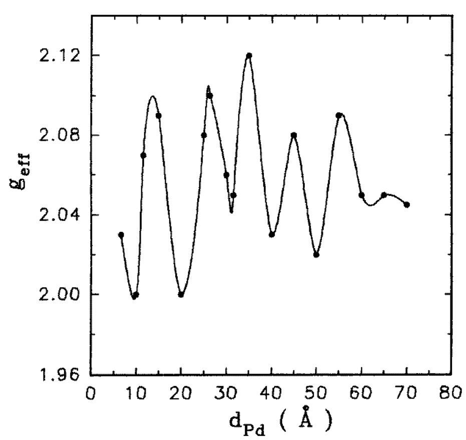

Figure 5. The dependence of the best-fitted g_{eff} on the Pd layer thickness, d_{Pd}.

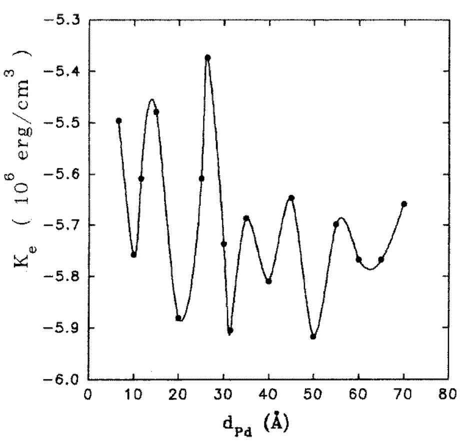

Figure 6. The dependence of the effective magnetic anisotropy K_e on the thickness of the Pd layers, d_{Pd}.

Knowing the perpendicular resonance field $H_\perp$, $H_\parallel$, and g_{eff} (or γ), we can obtain $4\pi M_{\text{eff}}$, H_{K_2}, and the Φ_H dependence of the resonance field H_r from equations (2)–(5). It was found that the calculated Φ_H dependence of H_r fitted very well with the experimental results for all of the multilayers if a suitable g_{eff} was selected for them. The best-fitted g_{eff} was obtained in this way for all of the samples. H_{K_2} is found to be about two or even more orders of magnitude smaller than $4\pi M_{\text{eff}}$. Figure 4 shows the dependence of the resonance field H_r on Φ_H for Co–Nb(3.6 nm)/Pd(2.6 nm) multilayers ($g_{\text{eff}} = 2.10 \pm 0.01$). The circles in figure 4 represent experimental results, and the solid line represents the theoretical ones. Figure 5 shows the dependence of the best-fitted $g_{\rm eff}$ on the Pd layer thickness $d_{\rm Pd}$. When $d_{\rm Pd}$ increases from 0.5 nm, the value of $g_{\rm eff}$ oscillates between 2.00 and 2.12. The oscillatory period in $g_{\rm eff}$ is about 1 nm. When $d_{\rm Pd} > 6$ nm, $g_{\rm eff}$ approaches a constant of 2.05. This is the first observation of the oscillation of the effective g-factor in multilayers.

Table 1. The thickness of the Pd layers $d_{\rm Pd}$ (designed thickness), the parallel resonance field $H_\parallel$, and perpendicular resonance field $H_\perp$ (experimental values), the best-fitted $g_{\rm eff}$, the effective magnetization $4\pi M_{\rm eff}$, and the second-order perpendicular uniaxial anisotropy field H_{K_2} (obtained from $H_\parallel$, $H_\perp$, and equations (2)–(5)), the saturation magnetization M_0 measured by the VSM, and the scaling parameter β defined by equation (19).

$d_{\rm Pd}$ (nm)	$H_\parallel$ (Oe)	$H_\perp$ (Oe)	$g_{\rm eff}$	$4\pi M_{\rm eff}$ (G)	H_{K_2} (Oe)	M_0 (Oe)	β (10^{-2})
0.66	990	14 085	2.03	11 408	109	127.7	3.00
1.0	910	15 450	2.00	11 951	−134	139.7	12.66
1.16	912	15 090	2.07	11 641	4.6	135	8.87
1.5	950	14 700	2.09	11 373	136	130.3	5.08
2.0	930	15 700	2.00	12 207	4.7	150	22.42
2.5	912	15 000	2.08	11 641	46	134.8	8.71
2.65	920	14 480	2.10	11 153	11.3	136.1	9.76
3.0	910	15 300	2.06	11 908	45	141.1	13.79
3.16	880	15 664	2.05	12 256	−14.8	139.6	12.58
3.5	850	15 100	2.12	11 804	−30	134.4	8.39
4.0	920	15 500	2.03	12 059	26.8	143	15.32
4.5	920	15 080	2.08	11 721	9.5	134	8.06
5.0	900	15 740	2.02	12 282	−26.7	139.4	12.42
5.5	900	15 170	2.09	11 827	78.5	135	8.87
6.0	880	15 380	2.05	11 972	−85	139.2	12.26
6.5	920	15 380	2.05	11 972	67.6	135	8.87
7.0	950	15 170	2.04	11 745	88	136	9.68

The effective magnetic anisotropy K_e of the Co–Nb/Pd multilayers can be given by the effective magnetization $4\pi M_{\rm eff}$ as follows:

$$K_e = -4\pi M_{\rm eff} M_S/2 \simeq -4\pi M_{\rm eff} M_{\rm Co}/2. \qquad (6)$$

However, we cannot obtain M_S for a CoNb/Pd multilayer from just the FMR data. On the other hand, because we do not know the distribution of the polarized magnetic moments of the Pd layers, we cannot know M_S for a Co–Nb/Pd multilayer from just the VSM measurements, to which the FMR responds. As an approximation, the saturation magnetization M_S of a CoNb/Pd multilayer is replaced by the saturation magnetization $M_{\rm Co}$ of a thick Co–Nb layer ($M_{\rm Co} = 124$ emu g^{-1} = 964 emu cm^{-3} at room temperature) in equation (6). Figure 6 shows the dependence of K_e on the thickness of the Pd layers, $d_{\rm Pd}$. K_e is calculated according to equations (4)–(6), where $H_\perp$ and $H_\parallel$ are obtained from the FMR data, and γ is obtained from the best-fitted $g_{\rm eff}$. The line in figure 6 is a guide to the eyes. The magnetic anisotropy K_e oscillates periodically with increasing $d_{\rm Pd}$. The oscillatory phase and period of K_e (figure 6) are the same as those of $g_{\rm eff}$ (figure 5). Table 1 shows some experimental and theoretical fitted results.

From the above, we can see that very useful results for $g_{\rm eff}$ and K_e (or $4\pi M_{\rm eff}$) can be obtained from equations (2)–(6). However, equations (2)–(6) are too simple to indicate the real origin of the oscillations of $g_{\rm eff}$ and K_e. For Co–Nb/Pd multilayers, we can see that when $d_{\rm Pd}$ is about 1, 2, 3, 4, 5, and 6 nm, the polarization of the Pd layers is at a maximum (figure 1), which corresponds to the minima of g_{eff} and K_e in figure 5 and figure 6. In contrast, when d_{Pd} is about 1.5, 2.5, 3.5, 4.5, and 5.5 nm, the polarization of the Pd layers is at a minimum, which corresponds to the maxima of g_{eff} and K_e in figure 5 and figure 6. Therefore, we suppose that the oscillations of g_{eff} and K_e possibly originate from the oscillation of the polarization of Pd layers. A similar corresponding relationship between the oscillation of the anisotropy and the oscillation of the spin polarization of the Pd layers was also found for Fe/Pd multilayers [18]. The dependence of g_{eff} on the thickness of the Pt layers was also found in Pt/Co multilayers [19], but no explanation was given.

In order to prove our hypothesis, a complicated model must be adopted. We use a well-known model of exchange-coupled sublattices [20, 21]. One magnetic sublattice is that of the Co–Nb magnetic layers, and the other magnetic sublattice is that of the polarized Pd layers (mainly in the interfacial regions). Because the Co–Nb magnetic layers and the polarized Pd layers are strongly coupled at the interfaces, according to an analysis similar to that in reference [21], the uniform resonance mode (acoustic mode) can still be given by the effective single-layer resonance condition of equations (2) and (3), where all effective fields of the strongly exchange-coupled sublattices must be given by the scaling laws

$$H_{K_1} = (1-\alpha)2K_{1\mathrm{Co}}/M_{\mathrm{Co}} + \alpha\, 2K_{1\mathrm{Pd}}/M_{\mathrm{Pd}} \tag{7}$$

$$H_{K_2} = (1-\alpha)2K_{2\mathrm{Co}}/M_{\mathrm{Co}} + \alpha\, 2K_{2\mathrm{Pd}}/M_{\mathrm{Pd}} \tag{8}$$

$$4\pi M_{\mathrm{eff}} = (1-\alpha)4\pi M_{\mathrm{Co\,eff}} + \alpha\, 4\pi M_{\mathrm{Pd\,eff}} \tag{9}$$

$$\omega/\gamma = (1-\alpha)\omega/\gamma_{\mathrm{Co}} + \alpha\omega/\gamma_{\mathrm{Pd}}. \tag{10}$$

The general scaling law can therefore be written in the form

$$H_{\mathrm{eff}} = (1-\alpha)H_{\mathrm{Co\,eff}} + \alpha H_{\mathrm{Pd\,eff}} \tag{11}$$

where the bilayer scaling parameter α is given by

$$\alpha = \mu_{\mathrm{Pd}}N_{\mathrm{Pd}}/(\mu_{\mathrm{Co}}N_{\mathrm{Co}} + \mu_{\mathrm{Pd}}N_{\mathrm{Pd}}). \tag{12}$$

In equation (12), N_{Co} and N_{Pd} are the numbers of monolayers for Co–Nb and Pd layers, and μ_{Co} and μ_{Pd} are the magnetic moments per Co atom and per polarized Pd atom.

All of the expressions given as equations (7)–(11) describe effective fields, and hence the effective fields of individual layers form the set of natural variables of the magnetic multilayers. $K_{1\mathrm{Co}}$, $K_{2\mathrm{Co}}$, and M_{Co} ($K_{1\mathrm{Pd}}$, $K_{2\mathrm{Pd}}$, and M_{Pd}) are the first-order perpendicular uniaxial anisotropy, second-order perpendicular uniaxial anisotropy, and saturation magnetization of the Co–Nb magnetic layers (polarized Pd layers) respectively. $4\pi M_{\mathrm{Co\,eff}}$ and $4\pi M_{\mathrm{Pd\,eff}}$ can be written as

$$4\pi M_{\mathrm{Co\,eff}} = 4\pi M_{\mathrm{Co}} - 2K_{1\mathrm{Co}}/M_{\mathrm{Co}} \tag{13}$$

$$4\pi M_{\mathrm{Pd\,eff}} = 4\pi M_{\mathrm{Pd}} - 2K_{1\mathrm{Pd}}/M_{\mathrm{Pd}}. \tag{14}$$

For the polarized Pd layers, if we suppose that each Pd atom occupies a volume of the dimensions of $a_{\mathrm{Pd}}^2 \times c_{\mathrm{Pd}}$ (a_{Pd} is the dimension of the crystalline lattice in the film plane, and c_{Pd} is the interplanar distance between monolayers), and that m_{Pd} is the total polarized magnetic moment of the Pd layers in unit area of a CoNb/Pd multilayer consisting of N bilayers, then μ_{Pd} can be written as

$$\mu_{\mathrm{Pd}} = [m_{\mathrm{Pd}}/(c_{\mathrm{Pd}}N_{\mathrm{Pd}}N)](a_{\mathrm{Pd}}^2 c_{\mathrm{Pd}}). \tag{15}$$

For the amorphous Co–Nb magnetic layers, if we suppose that each Co atom occupies a volume like a crystalline cell of the dimensions $a_{\mathrm{Co}}^2 \times c_{\mathrm{Co}}$ (a_{Co} is the dimension of the 'crystalline lattice' in the film plane and c_{Co} is the 'interplanar distance' between monolayers), and that m_{Co} is the total magnetic moment of the Co–Nb layers in unit area of a Co–Nb/Pd multilayer consisting of N bilayers, then μ_{Co} can be written as

$$\mu_{Co} = [m_{Co}/(c_{Co}N_{Co}N)](a_{Co}^2 c_{Co}). \tag{16}$$

From equations (12), (15), and (16), we can obtain

$$\alpha = (m_{Pd}a_{Pd}^2)/(m_{Pd}a_{Pd}^2 + m_{Co}a_{Co}^2). \tag{17}$$

For the CoNb/Pd multilayers, the polarized Pd layers are mainly limited to the interfacial regions, and both the CoNb layers and the Pd layers will strain to match each other, especially at the interfaces. Therefore, as an approximation, we may suppose $a_{Co} \approx a_{Pd}$. Then equation (17) can be written as

$$\alpha \approx m_{Pd}/(m_{Co} + m_{Pd}) = (M_0 - M_{Co})/M_0. \tag{18}$$

In equation (18), M_0 is the saturation magnetization of a magnetic multilayer obtained by a VSM measurement, which is defined as the measured total magnetic moment divided by the total mass of Co–Nb layers in a multilayer. M_{Co} is the saturation magnetization of Co–Nb magnetic layers, which is supposed to be equal to the saturation magnetization of a thick Co–Nb layer. Thus, the scaling parameter α can be obtained from equation (18).

If we define another scaling parameter β as

$$\beta = m_{Pd}/m_{Co} = (M_0 - M_{Co})/M_{Co} = \alpha/(1-\alpha) \tag{19}$$

equation (10) can be written as

$$(1+\beta)/g_{eff} = 1/g_{Co\,eff} + \beta/g_{Pd\,eff}. \tag{20}$$

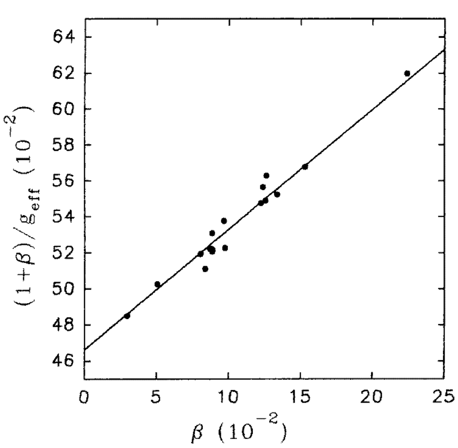

Figure 7. The dependence of $(1+\beta)/g_{eff}$ on the scaling parameter β.

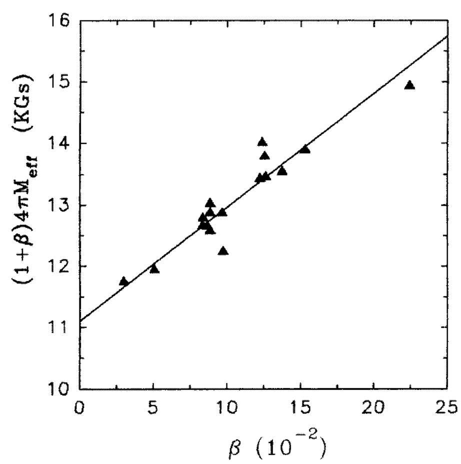

Figure 8. The dependence of $(1+\beta)4\pi M_{eff}$ on the scaling parameter β.

Because $g_{Co\,eff}$ and $g_{Pd\,eff}$ can be regarded as constants, a linear relationship between $(1+\beta)/g_{eff}$ and β will be obtained. Figure 7 shows the dependence of $(1+\beta)/g_{eff}$ on the scaling parameter β. β is obtained from equation (19). We can see that the relationship between $(1+\beta)/g_{eff}$ and β can be fitted by a straight line. From the intercept of the fitted line, we obtained $g_{Co\,eff} = 2.15$. From the slope of the fitted line, we obtained $g_{Pd\,eff} = 1.50$. This clearly indicates that the oscillation of g_{eff} for CoNb/Pd multilayers is mainly caused by the oscillation of the polarization for Pd layers. $g_{Co\,eff}$ is close to the g-factor of bulk fcc Co

(2.18). However, $g_{\mathrm{Pd\,eff}}$ (1.50) is far away from $g = 2$. A possible explanation is that strong Co 3d–Pd 4d valence-band hybridization at the interfaces of Co–Nb/Pd multilayers affects the spin–orbit coupling of Pd, and therefore affects $g_{\mathrm{Pd\,eff}}$. Another possible explanation is that our approximations, such as $a_{\mathrm{Co}} \approx a_{\mathrm{Pd}}$, are too rough for the exact $g_{\mathrm{Pd\,eff}}$ to be derived.

From equations (9) and (19), we can obtain

$$4\pi M_{\mathrm{eff}}(1+\beta) = 4\pi M_{\mathrm{Co\,eff}} + \beta\, 4\pi M_{\mathrm{Pd\,eff}}. \tag{21}$$

If $4\pi M_{\mathrm{Co\,eff}}$ and $4\pi M_{\mathrm{Pd\,eff}}$ can be regarded as constants, a linear relationship between $(1+\beta)4\pi M_{\mathrm{eff}}$ and β will be obtained. Figure 8 shows the dependence of $(1+\beta)4\pi M_{\mathrm{eff}}$ on the scaling parameter β. We can see that the relationship between $(1+\beta)4\pi M_{\mathrm{eff}}$ and β can be fitted by a straight line. From the intercept of the fitted line, we obtained $4\pi M_{\mathrm{Co\,eff}} = 11.1$ kG. From the slope of the fitted line, we obtained $4\pi M_{\mathrm{Pd\,eff}} = 18.6$ kG. This clearly indicates that the oscillation of $4\pi M_{\mathrm{eff}}$ (or the effective anisotropy K_e) is mainly caused by the oscillation of the polarization of the Pd layers. Though $4\pi M_{\mathrm{Co\,eff}}$ and $4\pi M_{\mathrm{Pd\,eff}}$ may be dependent on the Co–Nb layer thickness and Pd layer thickness respectively, it is clearly indicated in figure 8 that both $4\pi M_{\mathrm{Co\,eff}}$ and $4\pi M_{\mathrm{Pd\,eff}}$ can be approximately regarded as constants when the Co–Nb layer thickness is fixed and only the Pd layer thickness is changed.

4. Conclusions

In conclusion, Co–Nb/Pd multilayers were prepared by the rf sputtering method. The polarization of Pd layers and the interlayer coupling through Pd layers were studied by magnetic and ferromagnetic resonance measurements. Magnetic measurement shows that the saturation magnetization of Co–Nb/Pd multilayers oscillates periodically when the Pd layer thickness increases; this is caused by the oscillatory polarization of the Pd layers. The spin-wave excitation indicates that the ferromagnetic interlayer coupling can exist until the thickness of the Pd layers reaches about 7 nm. An oscillatory variation between 2.00 and 2.12 of g_{eff} with the thickness of the Pd layers was observed for the first time. The oscillatory period of g_{eff} is about 1 nm. A similar oscillatory behaviour of K_e was also obtained. This oscillatory behaviour of g_{eff} and K_e was interpreted in terms of a model of two exchange-coupled sublattices; one sublattice is that of the Co–Nb magnetic layers, and the other is that of the polarized Pd layers. This model indicates that the oscillatory behaviour of g_{eff} and K_e mainly originates from the oscillation of the polarization of the Pd layers.

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