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Oscillatory interlayer coupling in Co/Pt multilayers with perpendicular anisotropy

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Interlayer coupling in several series of $[\mathrm{Co/Pt}]_N$ multilayers with perpendicular anisotropy and Pt thicknesses from 3 to 79 Å has been investigated using magnetometry measurements at temperatures from 293 K down to 8 K. Oscillatory interlayer coupling with a ferromagnetic background as a function of the Pt thickness was observed in every multilayer series. This oscillation of interlayer coupling can be attributed to the Ruderman-Kittel-Kasuya-Yosida interaction. Unusual temperature dependence of the coercivity and the saturation magnetization suggests that the polarization of Pt atoms by the adjacent Co layers is responsible for the ferromagnetic interlayer coupling in Co/Pt multilayers and the magnetic polarization of Pt atoms extends further into the Pt layers as the temperature decreases.

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The discoveries of oscillatory interlayer coupling in multilayers composed of ferromagnetic (FM) and nonmagnetic (NM) metals in 1986[1] and giant magnetoresistance in Fe/Cr multilayers in 1988[2] spurred great interest in this field.[3–13] A large variety of systems have been investigated and oscillations in interlayer coupling have been found in many systems, including FM/NM multilayers with noble metals, such as Cu,[4–7] Ag,[8] Au,[8–11] and transition metals, such as Cr (Refs. 3 and 12) and Ru.[13] The magnetization of the adjacent FM layers oscillates between ferromagnetic and antiferromagnetic alignments as the NM layer thickness varies.[14]

To date, most of the systems that exhibit oscillatory interlayer coupling have in-plane magnetic anisotropy. In recent years, multilayers consisting of Pd, Pt, and ultra-thin FM layers, typically Co, have attracted considerable attention. These multilayers exhibit perpendicular magnetic anisotropy which has potential applications in ultrahigh density perpendicular recording. The perpendicular anisotropy originates from the dominating interfacial anisotropy when the FM thickness is very small (e.g., 4 Å Co).[15,16] The ultra-thin Co layers are coupled together by the intervening Pd or Pt layers and behave as a single ferromagnet. Despite intensive studies on these multilayers, the mechanism of the interlayer coupling remains unclear. Previously, using hysteresis measurements, Parkin showed that there was no antiferromagnetic coupling in FM/NM multilayers with Pt or Pd;[13] while ferromagnetic resonance studies have found an oscillatory behavior superimposed on a FM background in Fe/Pd/Fe trilayers with in-plane anisotropy.[17] It is highly interesting to see if oscillatory interlayer coupling exists in multilayers with Pt and in systems with perpendicular anisotropy. Very recently, oscillation in interlayer coupling across a single Pt layer was reported for Pt thickness larger than 28 Å when the FM layers sandwiching the Pt are only weakly coupled.[18] In this paper, we report a systematic study of the interlayer coupling in Co/Pt multilayers with perpendicular anisotropy. $[\mathrm{Co/Pt}]_N$ multilayers with repetition N from 2 to 30 and Pt thicknesses from 3 to 79 Å were investigated using magnetometry measurements at various temperatures (T). Oscillatory interlayer coupling with a FM background between the Co layers has been observed and can be attributed to the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling similar to that in other FM/NM multilayers, such as Co/Cu. The temperature dependence of the interlayer coupling suggests that the Pt atoms are magnetically polarized by the Co layers. The magnetic polarization of Pt atoms extends further into the Pt layers as the temperature decreases. The magnetized Pt atoms are responsible for the FM coupling between the adjacent Co layers. This result indicates that both RKKY coupling and the polarization of Pt play important roles in the interlayer coupling in Co/Pt multilayers with perpendicular anisotropy.

Several series of $[\mathrm{Co/Pt}]_N$ multilayered samples with repetition N from 2 to 30 were fabricated using a ultrahigh vacuum magnetron sputtering system with a base pressure of 1×10^{-9} torr or better. Ultra-pure Ar gas of 4 mTorr was used for sputtering. The deposition rates of Co and Pt are 0.78 and 0.84 Å/s, respectively. 50 mm long Si wafers with a native oxide layer were used as the substrates. A 100 Å Pt buffer layer was first deposited on each wafer, followed by the deposition of Co/Pt multilayers. Each Co layer is uniform with a thickness of 4 Å and each Pt layer is a wedge with thickness t_{Pt} from 0 to 80 Å. Finally, a 30 Å Pt layer was deposited on top as the capping layer. Every Si substrate was cut into 40 pieces of 1.25 mm wide strips. Each strip has a thickness variation of 2 Å and t_{Pt} refers to the average thickness of each strip. For comparison, a single Co layer with a uniform thickness of 4 Å sandwiched between a 100 Å Pt buffer layer and a 30 Å Pt capping layer was also fabricated. Hysteresis loops were measured with a magnetic field (H) perpendicular to the film plane using a LakeShore vibrating sample magnetometer at temperatures between 293 and 8 K.

We measured the surface roughness of some Co/Pt multilayers using an atomic force microscope because the interface and surface quality is critical for the magnetic properties in multilayers. The peak-to-peak amplitude of the surface roughness is 2–3 Å with a wavelength of about 600 Å. The small roughness of the surface indicates the high quality of the multilayer interfaces, which is desirable for the investigation of interlayer coupling.

Perpendicular anisotropy has been obtained in all $[\mathrm{Co/Pt}]_N$ multilayers with N from 2 to 30 and t_{Pt} from 3 to

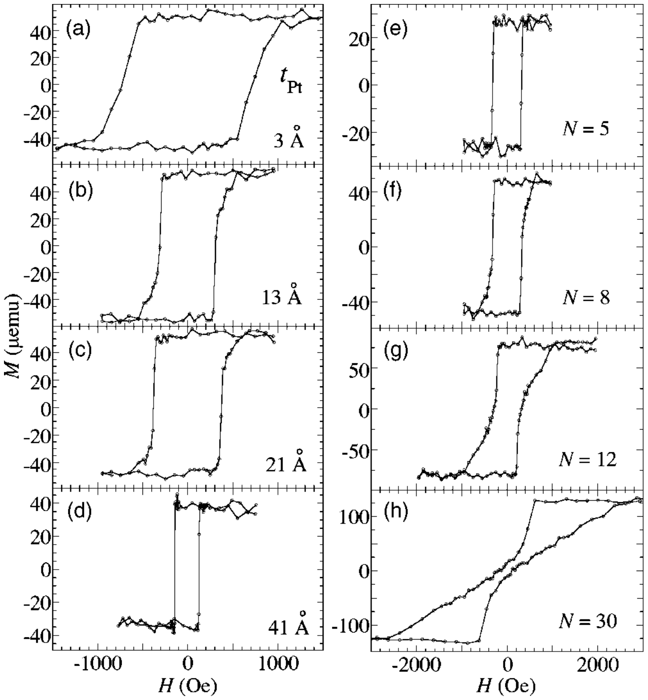

FIG. 1. Room temperature hysteresis loops of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_8$ multilayers with Pt layer thicknesses (t_{Pt}) of (a) 3 Å, (b) 13 Å, (c) 21 Å, (d) 41 Å, and of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(11\ \text{Å})]_N$ multilayers with (e) $N=5$, (f) $N=8$, (g) $N=12$, and (h) $N=30$.

79 Å. Examples of the hysteresis loops for $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_8$ multilayers with eight repetitions and $t_{\mathrm{Pt}}=3,13,21,41$ Å are shown in Figs. 1(a)–1(d). In this series, all the hysteresis loops are square except for $t_{\mathrm{Pt}}=3$ Å, which shows a more gradual switching than the others since the small Pt thickness (2 to 4 Å) cannot completely separate the adjacent Co layers. Therefore, the interfacial anisotropy, which is responsible for the perpendicular anisotropy, at Co/Pt interfaces for $t_{\mathrm{Pt}}=3$ Å is not as dominating as those with thicker Pt layers, resulting in the gradual transition in Fig. 1(a).

The coercivity (H_C) of the hysteresis loops in Figs. 1(a)–1(d) decreases with increasing t_{Pt}, but not monotonically. For example, the loop for $t_{\mathrm{Pt}}=21$ Å in Fig. 1(c) is wider than that for $t_{\mathrm{Pt}}=13$ Å in Fig. 1(b). The coercivity for the entire series of multilayers ($3\leqslant t_{\mathrm{Pt}}\leqslant 79$ Å) with $N=8$, which exhibits an oscillatory behavior with a clear peak at $t_{\mathrm{Pt}}=23$ Å, is shown in Fig. 2(b). In order to make sure that this oscillatory dependence of H_C on t_{Pt} is intrinsic to Pt, we measured H_C for multilayers with $N=5$, 12, 20, and 30, as shown in Figs. 2(a), 2(c), 2(d), and 2(e), respectively. All five series in Fig. 2 exhibit similar t_{Pt} dependence of H_C with a clear peak at $t_{\mathrm{Pt}}\approx 23$ Å. For each series of samples, the sample-to-sample variation of quality, such as substrate roughness, density of defects, interface roughness, and impurity level, is minimal across the whole range. The only variable within each series is the Pt thickness, which increases linearly from 3 to 79 Å for the 39 strips. Thus, the consistency of the oscillatory dependence of H_C on t_{Pt} must be intrinsic to Pt since other factors either give no dependence on t_{Pt} (e.g., substrate quality, interface roughness, impurity) or monotonic dependence on t_{Pt} (e.g., grain size).

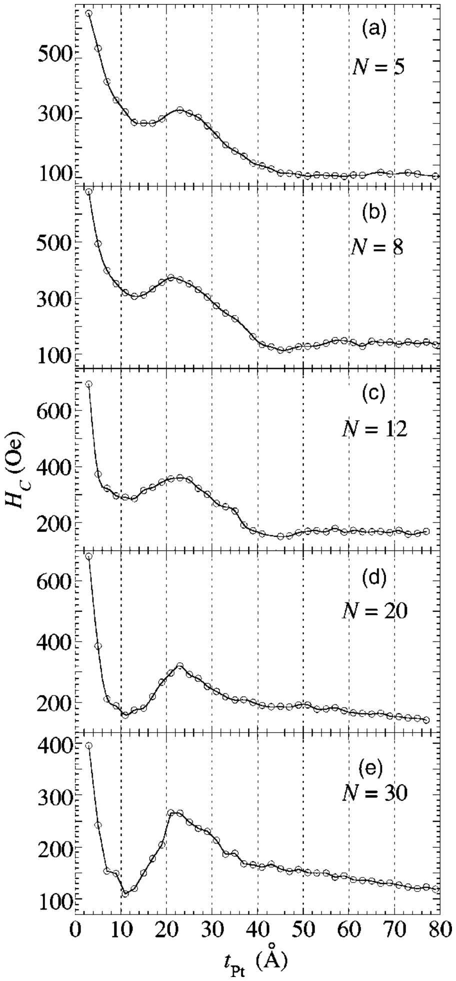

FIG. 2. Room temperature coercivity (H_C) of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_N$ multilayers with repetition N of (a) 5, (b) 8, (c) 12, (d) 20, and (e) 30 for t_{Pt} between 3 and 79 Å.

For Co/Pt multilayers with perpendicular anisotropy, we have the advantage of understanding the interlayer coupling from H_C, although not quantitatively. Figure 3 shows the coercivity of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(11\ \text{Å})]_N$ multilayers which are the sixth strips cut from wedged wafers with repetition N from 2 to 12. As a comparison, the coercivity of a single ($N=1$) Co layer is also shown in Fig. 3. From $N=2$ to 5, H_C shows a

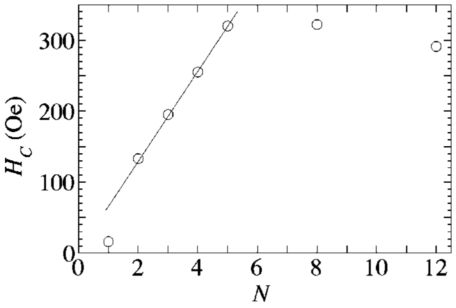

FIG. 3. Coercivity of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(11\ \text{Å})]_N$ multilayers with N from 1 to 12 at room temperature. The point for $N=1$ is from a single Co layer.

linear dependence on N, while for larger N, H_C deviates from the straight line and starts to decrease. The linearity of H_C versus N is directly related to the interlayer coupling of the Co layers. Previous, the magnetic switching in perpendicularly magnetized multilayers has been attributed to the domain wall nucleation and domain wall motion.[9] However, Fig. 3 indicates that for $N \leqslant 5$, the interlayer coupling determines the domain wall nucleation which initiates the magnetic reversal. Otherwise H_C would not be linear with N. Therefore, we can relate the amplitude of the interlayer coupling to H_C by the equation

$$H_C = H_{C0} + \frac{(N-1)J}{M_S t_{\mathrm{Co}}}, \tag{1}$$

where H_{C0} is the intrinsic coercivity of one Co(4 Å) layer, J is the exchange coupling per unit surface area between the adjacent Co layers, M_S is the saturation magnetization of Co, and t_{Co} is the thickness of a single Co layer (4 Å). The term $(N-1)J$ represents the total interlayer coupling strength per unit area for $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_N$ multilayers because there are $N-1$ intervening Pt layers. Equation (1) implies that H_C is linear with N, which is exactly what we have observed for multilayers with $2 \leqslant N \leqslant 5$. Because the domain wall nucleation also depends on other factors, J determined from H_C is not the actual coupling strength. Nevertheless, H_C represents the t_{Pt} dependence of interlayer coupling.

At $N \leqslant 5$, the hysteresis loops are square, while for $N > 5$, part of the loop becomes slanted [Figs. 1(f)–1(h)], resulting in the deviation of H_C from linearity in Fig. 3. For $N=8$, a tail appears in the magnetic switching in an otherwise square loop. The tail becomes more significant as N increases. The magnetic switching in Co/Pt multilayers is accomplished by the domain nucleation and domain wall motion.[9,19] At $N \leqslant 5$, once the nucleation process starts, the domain walls quickly move across the whole sample, giving a sharp switch. For multilayers with larger N, after the nucleation, the domain wall motion slows down as N increases, giving a more gradual transition. However, within the same series of multilayers, H_C still follows the t_{Pt} dependence of J, which allows us to investigate the interlayer coupling simply through H_C.

The oscillatory behavior of H_C in Fig. 2 can be attributed to the RKKY coupling of the Co layers through Pt. RKKY interaction is responsible for the oscillatory interlayer coupling in many FM/NM systems. Recently, oscillatory coupling between two stacks of Co/Pt multilayers separated by a single Pt layer with a thickness larger than 28 Å has been reported (with one peak at $t_{\mathrm{Pt}}=37$ Å), which was also due to the RKKY interaction.[18] In all of our Co/Pt multilayers with t_{Pt} between 3 and 79 Å, we observed an oscillatory interlayer coupling with a pronounced peak around $t_{\mathrm{Pt}}=23$ Å. At larger t_{Pt}, because of the weaker interlayer coupling, H_C is unable to reflect the oscillation of the interlayer coupling. The oscillatory behavior in H_C is likely to originate from the RKKY coupling of Co layers through Pt.

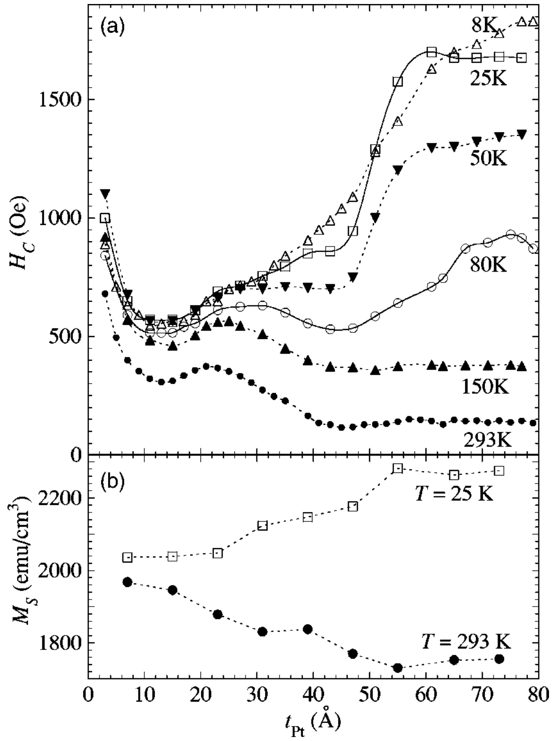

FIG. 4. (a) Coercivity (H_C) and (b) saturation magnetization (M_S) of $[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_8$ multilayers for t_{Pt} between 3 and 79 Å at temperatures of 293 K (solid circles), 150 K (solid up triangles), 80 K (open circles), 50 K (solid down triangles), 25 K (open squares), and 8 K (open up triangles).

Unlike other FM/NM multilayers (e.g., Co/Cu) which show oscillations between ferromagnetic and antiferromagnetic coupling, the interlayer coupling is always ferromagnetic for all the Co/Pt multilayers we studied. Similar behavior has been observed in Fe/Pd/Fe trilayers.[17] The FM coupling of Co layers is because both Pt and Pd are transition metals of group 10 (same group as Ni) and are nearly ferromagnetic.[20,21] The Pd or Pt atoms in the vicinity of a FM layer can be polarized and carry magnetic moments.[22] The polarized Pt or Pd layers give the ferromagnetic coupling between the FM layers and eliminate the possibility of antiferromagnetic coupling such as that in Co/Cu multilayers. The FM coupling strength decreases monotonically with t_{Pt}. Reference 18 attributed the FM background of interlayer coupling across a Pt layer to the orange-peel coupling for perpendicular magnetization due to the relatively large surface roughness of 12 Å. In our Co/Pt multilayers, the surface roughness is 2 to 3 Å, and thus, the orange-peel coupling is unlikely.

Because the magnetic polarization of Pt atoms depends on temperature, the temperature dependence of H_C should reveal important information of interlayer coupling. We chose a series of Co/Pt multilayers with $N=8$ and measured H_C for t_{Pt} between 3 and 79 Å at temperatures of 8, 25, 50, 80, 150, and 293 K, as shown in Fig. 4(a). The t_{Pt} dependence of H_C shows little change when T drops from room temperature to 150 K except that the magnitude of H_C becomes larger. However, below 80 K, H_C exhibits significantly different t_{Pt} dependence, instead of decreasing at large t_{Pt}, H_C shows a considerable rise after $t_{\mathrm{Pt}}=40$ Å. The increasing H_C indicates that the interlayer coupling becomes stronger as t_{Pt} increases, while in most FM/NM systems, the interlayer coupling weakens as the adjacent FM layers are further apart. This unusual behavior can be interpreted as a result of the stronger polarization of Pt atoms at lower temperatures. As an example, we discuss the curve for $T=25$ K in Fig. 4(a). On top of the oscillation, H_C increases considerably up to $t_{\mathrm{Pt}}=60$ Å, after which H_C reaches saturation. First-principles calculations have found that magnetic polarization of Pd atoms extends several layers into the Pd layer in Fe/Pd/Fe trilayers at room temperature.[17] The same should exist in Co/Pt multilayers. At room temperature, the depth of the Pt polarization is only several layers. At large t_{Pt}, the adjacent Co layers are coupled through nonpolarized Pt and the coupling strength decreases with increasing t_{Pt}. However, at low temperatures, the depth of the Pt polarization becomes much larger. The adjacent Co layers are coupled together by polarized Pt layers, which are effectively FM layers. As t_{Pt} increases, more Pt atoms are polarized. The addition of polarized Pt atoms makes the whole multilayer a stronger ferromagnet, resulting in a larger H_C at larger t_{Pt}. From Fig. 4(a), we estimated that the polarization of Pt extends into the Pt layers for about 30 Å from each side at $T=25$ K. Thus, after $t_{\mathrm{Pt}}=60$ Å, H_C essentially saturates.

This explanation is supported by the total magnetization of the multilayers M_S in Fig. 4(b). At room temperature, M_S decreases with increasing t_{Pt} because the Pt atoms near one Co/Pt interface are less polarized by the Co layer on the other side of the Pt layer as t_{Pt} increases, resulting in the reduction of the total magnetic moment. The estimated depth of Pt polarization is about a few layers, consistent with previous reports.[17] At 25 K, M_S increases with increasing t_{Pt} until about 55 Å. This is a clear evidence that for thicker Pt layers, more Pt atoms are polarized, resulting in a stronger interlayer coupling at larger t_{Pt}. We also noticed that the oscillatory coupling with a pronounced peak at $t_{\mathrm{Pt}}=23$ Å essentially does not change with temperature, which is consistent with the RKKY coupling in other systems.

In conclusion, RKKY-type oscillatory interlayer coupling has been observed in $[\mathrm{Co}(4\text{ Å})/\mathrm{Pt}(t_{\mathrm{Pt}})]_N$ multilayers with N from 5 to 30 and t_{Pt} from 3 to 79 Å using hysteresis measurements. We found that the magnetic polarization of Pt atoms is responsible for the FM coupling between the Co layers. The FM coupling becomes stronger at low temperatures because the polarization of Pt atoms extends deeper into the Pt layers which, in turn, couples the Co layers more strongly.

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