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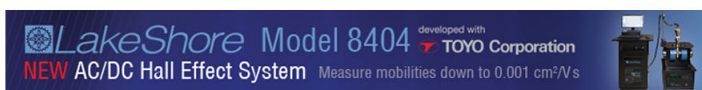
Tuning the interlayer exchange coupling between single perpendicularly magnetized CoFeB layers

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We experimentally study the tunability of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interlayer exchange coupling (IEC) in Pt/CoFeB/Pt/Ru/Pt/CoFeB/Pt stacks with perpendicular magnetic anisotropy (PMA). The perpendicular magnetization of a single Pt/$Co_{60}Fe_{20}B_{20}$/Pt (at. %) shows full remanence and square hysteresis loops for a CoFeB thickness range of 0.60–1.0 nm. By inserting a Pt layer between the Ru and CoFeB, the PMA of the ultrathin CoFeB layers is stabilized and the IEC can be tuned. In particular, we show that the IEC versus Pt thickness exhibits a simple exponential decay with a decay length of 0.16 nm. © *2012 American Institute of Physics.*
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The use of (perpendicularly magnetized) synthetic antiferromagnets (AFM) as already used for Magnetic-Random-Access-Memory (MRAM) applications, formed by ferromagnetic (FM) layers coupled anti-ferromagnetically, is highly suitable for a wide field of applications due to the high control achieved in the properties of these artificial structures, combined with their low net moment. Specifically, these synthetic-AFMs have a high potential to be used in spintronic devices.[1] A full understanding of the reversal of such structures under external fields and currents is therefore of high interest. In particular, the perpendicularly magnetized archetypal $[[Pt/Co]_X/Ru]_N$ with X,N > 1 system has been studied extensively due to its excellent properties for data storage applications and fundamentally for the nanoscale phase-formations it exhibits.[2,3] However, for applications where superlattices (N ≫ 1) with an accurate control of the switching-field of the layers within the superlattice is required, it is these phase-formations which render the material useless as the control of single layer switching is lost. The magnetostatic energy stored in a uniformly perpendicularly magnetized configuration increases linearly with total thickness (increasing X, N). At a certain thickness, the system can lower the total energy stored by forming perpendicular domains at the expense of domain wall energy (typically forming a labyrinth domain state). The total superlattice thickness at which this happens can be tuned by balancing the total magnetic moment per unit area ($M_s t$), the IEC-energy J, and PMA.[2] Furthermore, for perpendicular magnetized layers where the PMA is dominated by the Co/Pt interface, reducing X to 1 is not an option due to the loss of perpendicular magnetization (especially when $N > 1$ as there will be Co layers without a Pt interface) and is commonly solved by using FM coupled multilayered $[Pt/Co]_X$ blocks increasing the total superlattice thickness.[2,4] To circumvent the loss of PMA at non-Co-Pt interfaces in exchange biased PMA systems using IrMn or FeMn, the insertion of a thin Pt spacer was shown to increase the exchange bias field.[5] This was explained by an increased PMA and Pt acting as a diffusion boundary.[6,7]

In this letter, we experimentally study a basic building block of such a superlattice: a bi-layer of a single ultrathin perpendicularly magnetized $Co_{60}Fe_{20}B_{20}$ (at. %) layer, exchange coupled through Pt/Ru/Pt via the Ruderman-Kittel-Kasuya-Yosida (RKKY)-mechanism. By using $Co_{60}Fe_{20}B_{20}$, we reduce the magnetic moment per layer compared to Co ($M_s = 1200$ vs 1400 kA/m, respectively, for bulk). Inserting Pt at the Ru interfaces stabilizes the PMA of the single CoFeB, directly omitting the use of multilayered (X > 1) FM-blocks, which further reduces the magnetic moment per layer. In addition, by varying the Pt thickness, the IEC can be tuned.

We use the magneto-optical Kerr effect in a polar configuration (pMOKE) to study the magnetization configuration in (i) a single CoFeB layer sandwiched between Pt and (ii) exchange coupled CoFeB/Pt/Ru/Pt/CoFeB layers where we have inserted a Pt layer between the Ru and CoFeB. All samples are grown at room temperature on Si substrates with a native oxide and a Ta(2.4)/Pt(10) buffer layer (BL) (thickness given in nm) and capped with a capping layer (CL) of 2 nm Pt to prevent oxidation using RF (Ta) and DC (Pt, CoFeB, Ru) magnetron sputtering at an Ar pressure of 10 mTorr. The base pressure of the sputter chamber is 10^{-7} Torr. The thicknesses are calculated using the calibrated growth rate as obtained by atomic force microscopy. Using the confocal design of our sputtering system, wedge-shaped layers (constant thickness) with a 1.5% thickness change per mm can be grown when the substrates are oriented at an angle (rotated) relative to the sputter source. During all pMOKE measurements, the magnetic field is applied along the surface normal at a constant field-sweep rate of 150 Oe/s, with a laser spot estimated to be 300 μm wide, so that the layer thickness change in wedge-shaped samples within the laser spot can be neglected.

In Fig. 1(a), the coercivity (H_c, left y-axis) and remanence (right y-axis) of a single CoFeB layer sandwiched between Pt layers as a function of CoFeB thickness t_{CoFeB} is shown. The CoFeB has a well-defined perpendicular magnetic configuration between 0.60 and 1.0 nm thickness, where a square hysteresis loop with 100% remanence is observed. For $t_{CoFeB} < 0.6$ nm, we approach the percolation limit, i.e., the layer has not formed a continuous film and a
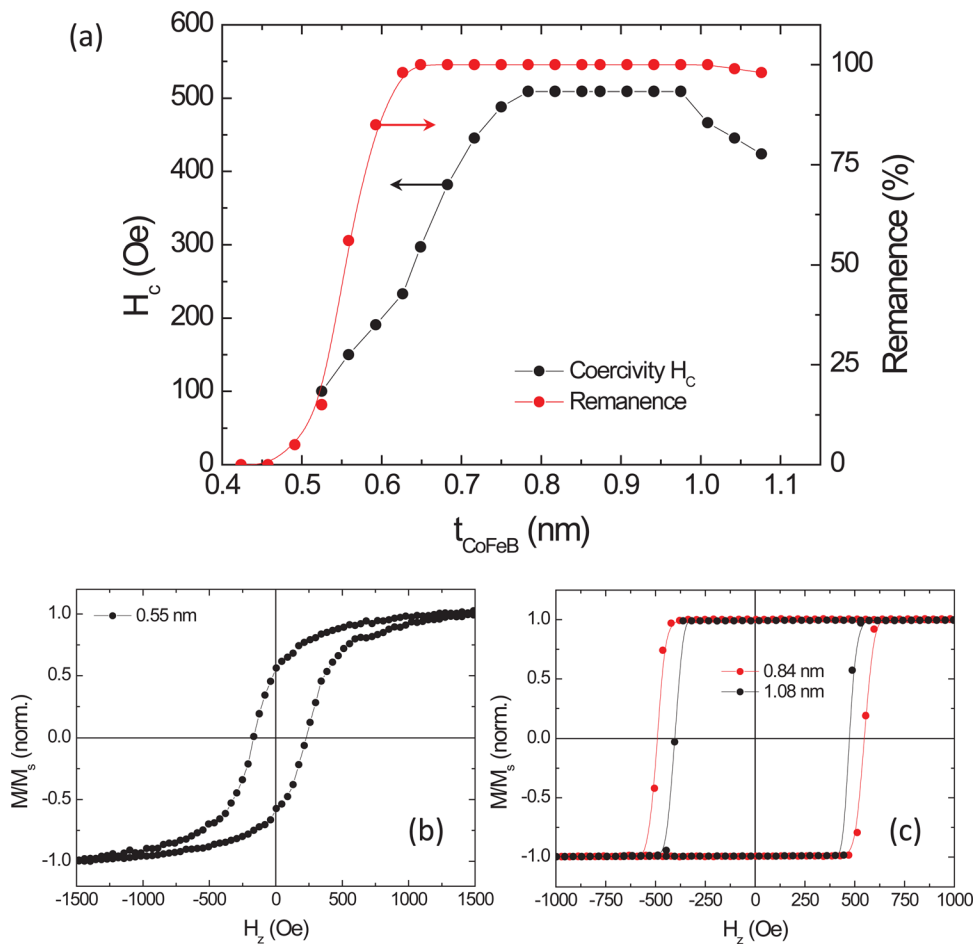
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FIG. 1. (Color online) (a) Coercive field (H_c, left y-axis) and remanence (right axis) of a BL/CoFeB(t_{CoFeB})/CL sample as a function of CoFeB thickness obtained from hysteresis loops as shown in (b) for $t_{CoFeB} = 0.55$ nm and (c) $t_{CoFeB} = 0.84$ nm and 1.08 nm. The lines are a guide to the eye.

slanted hysteresis loop is observed (see Fig. 1(b)). For $t_{CoFeB} > 1.0$ nm, the Pt/CoFeB interface anisotropy is not sufficient to sustain a perpendicular magnetization configuration and a gradual spin-reorientation-transition to in-plane occurs as indicated by a decrease of H_c (see Fig. 1(c), $t_{CoFeB} = 1.08$ nm). This behavior is commonly observed for Pt/Co/Pt (Refs. 8 and 9) and shows that the Pt/Co$_{60}$Fe$_{20}$B$_{20}$/Pt system also exhibits a well-defined perpendicular magnetization configuration with sharp hysteresis loops in a certain thickness range.

In Fig. 2, hysteresis loops of an exchange coupled sample BL/CoFeB(0.84)/Pt(0.31)/Ru(t_{Ru})/Pt(0.31)/CoFeB(0.84)/CL are shown at four different Ru thicknesses. For thick Ru thickness $t_{Ru} > 1.75$ nm (see Fig. 2(a)), a sharp hysteresis loop with a single switch is observed indicating ferromagnetic (FM) coupling, i.e., both CoFeB layers switch at the same coercive field. For lower Ru thicknesses, an increasingly slanted loop (spin-flop) is observed with a sudden sharp switch (spin-flip). This indicates an anti-ferromagnetic (AFM) coupling between the bottom and top CoFeB layer through the Pt/Ru/Pt layers. The saturation field increases with thinner Ru indicating an increasing IEC. For very thin Ru thickness $t_{Ru} < 0.5$ nm (not shown), FM coupling is found. The absence of an AFM state for $t_{Ru} < 0.5$ nm may indicate high roughness of the Ru layer which can lead to FM bridges between the two CoFeB layers (pinholes) and/or very local IEC strength variations.[10–12] For $t_{Ru} > 1.75$ nm up to 6 nm, we only observe FM coupling. This behavior is typi-

cal of oscillatory IEC via the RKKY-mechanism as observed, for instance, in [[Pt/Co]$_X$/Ru] $_N$ systems.[2]

The slanted parts of the loops indicate a spin-flop behavior (canted magnetization configuration) of the two CoFeB layers (IEC > PMA);[4,13] when coming from negative saturation to positive field, the spins gradually turn towards the AFM state (see arrows in Fig. 2(d)). At a certain point, the Zeeman energy is enough to switch the spins to the other AFM state (note that due to the finite skin depth of the pMOKE, we probe the top CoFeB layer more sensitively); with increasing field, the spins spin-flop into the other fully-parallel configuration. We measured the PMA of a Ta(2.4)/Pt(10)/Co(0.84)/Pt(2) sample to be $K_U = 4.8 \pm 0.1$ Merg/cm^3 using a $M_S = 850$ emu/cm^3 measured by vibrating sample magnetometry and anomalous Hall effect.[14] This gives an effective perpendicular anisotropy field of $H_k = 2K_U/M_S - 4\pi M_S = 620 \pm 200$ Oe. This H_k is an upper limit estimate for the bi-layer sample discussed here since the Pt inserted at the Ru interface is thin $t_{Pt} = 0.31$ nm compared to the Pt layers in the reference sample preventing it from forming a closed layer (RMS roughness measured by AFM.35 nm). We believe that this is the reason for the observed gradual transitions even for low IEC (thick Ru), and we will return to this issue when discussing Fig. 4. Whether the transition happens through the formation of a multidomain state (nucleation and domain wall motion) or coherent-rotation is at this moment unclear and will need further investigation. If no Pt is inserted between the CoFeB and Ru, the switching is
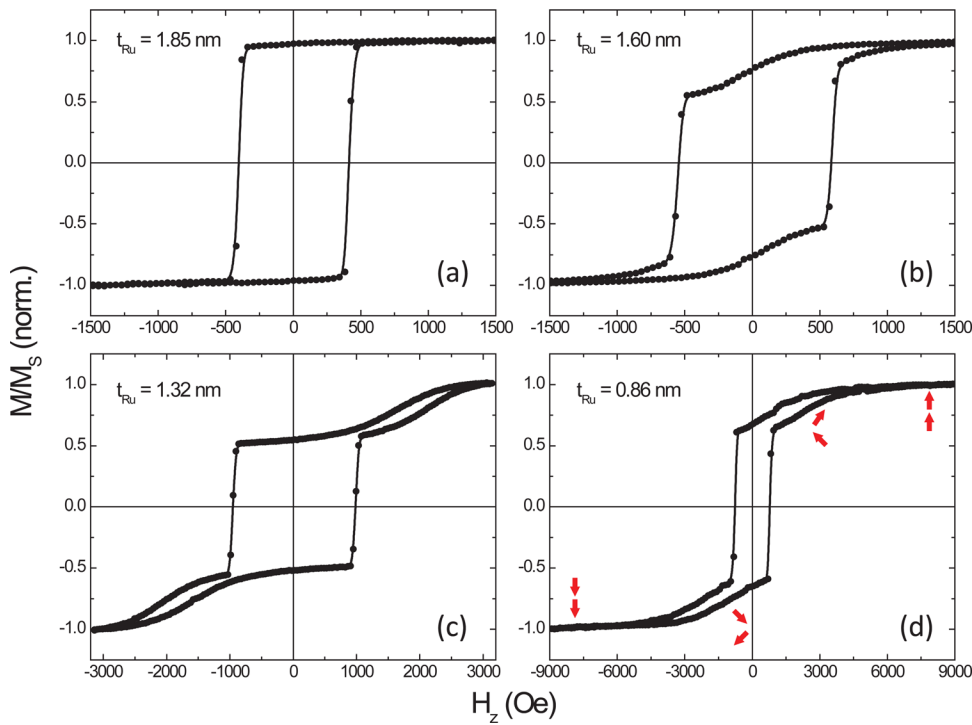
FIG. 2. (Color online) Hysteresis loops as obtained on BL/CoFeB(0.84)/Pt(0.31)/Ru(t_{Ru})/Pt(0.31)/CoFeB(0.84)/CL, where t_{Ru} is indicated in the graphs. (d) We have indicated the magnetic configuration by the arrows. A clear transition from FM to AFM IEC is observed. Note the different x-axis scale in (c) and (d). The lines are a guide to the eye.

dominated by spin-flop (not shown), i.e., the IEC $\gg$ PMA. This is also due to the thin CoFeB layer; for a given Ru thickness, the IEC scales as J/t_{FM}, where J is the IEC-energy per unit area and t_{FM} the FM layer thickness, hence the coupling strength a layer feels can be "diluted" by increasing the thickness of the FM layer. As discussed before, for perpendicular magnetized layers where the PMA is interface-dominated, this is not an option due to the loss of Co/Pt interfaces, especially for $N > 1$. An example of the IEC "dilution" is shown in Fig. 3, where we show the hysteresis loops obtained on a BL/CoFeB(t_{CoFeB})/Pt(0.38)/Ru(1.53)/Pt(0.38)/CoFeB(t_{CoFeB})/CL sample, where we wedge the CoFeB thicknesses t_{CoFeB}. With decreasing t_{CoFeB}, a clear increase

in the IEC is observed as is apparent from the higher saturation field and increasing spin-flop behavior.

As is apparent from the results presented in Figs. 2 and 3, we cannot fine-tune the IEC/PMA ratio by varying the Ru and/or CoFeB thickness to obtain sharp switching layers. We, therefore, study the IEC as a function of Pt thickness t_{Pt} inserted at the interface between Ru and CoFeB.[15] The Pt at the interface will serve two purposes: first to stabilize the PMA of the single-CoFeB layer; second, it will attenuate the IEC, as the IEC through Pt in [Pt/Co] layers was shown to be FM for Pt thicknesses below 2.2 nm.[16–19] Typical hysteresis loops of a BL/CoFeB(0.84)/Pt(t_{Pt})/Ru(1.53)/Pt(t_{Pt})/CoFeB(0.84)/CL sample are shown in Figs. 4(a)–4(e), where we
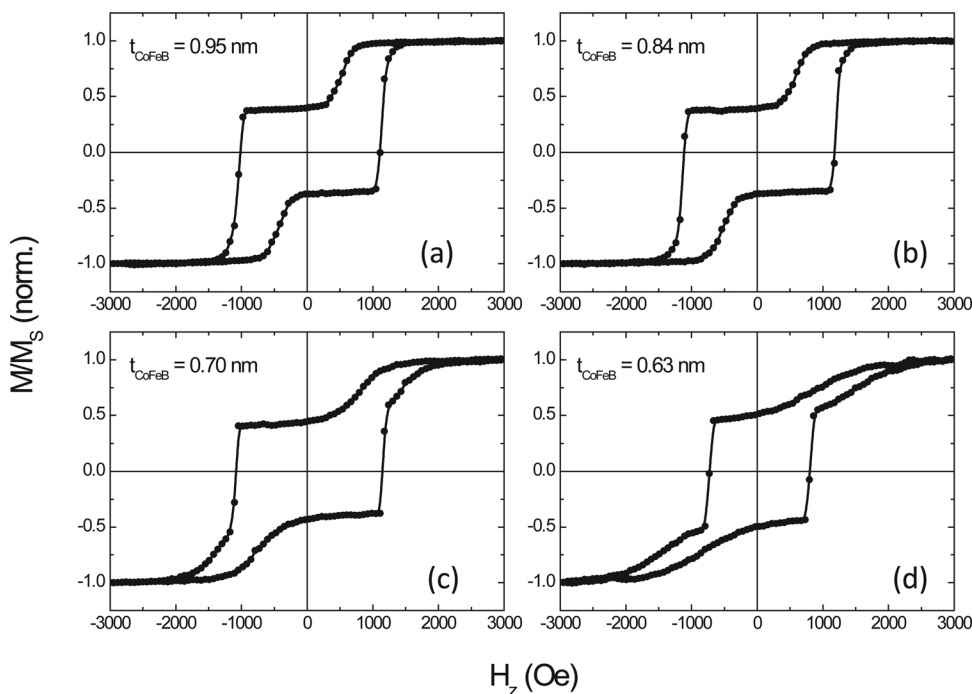

FIG. 3. Hysteresis loops as obtained on a BL/CoFeB(t_{CoFeB})/Pt(0.38)/Ru(1.53)/Pt(0.38)/CoFeB(t_{CoFeB})/CL sample, where t_{CoFeB} is indicated in the graphs. The lines are a guide to the eye.
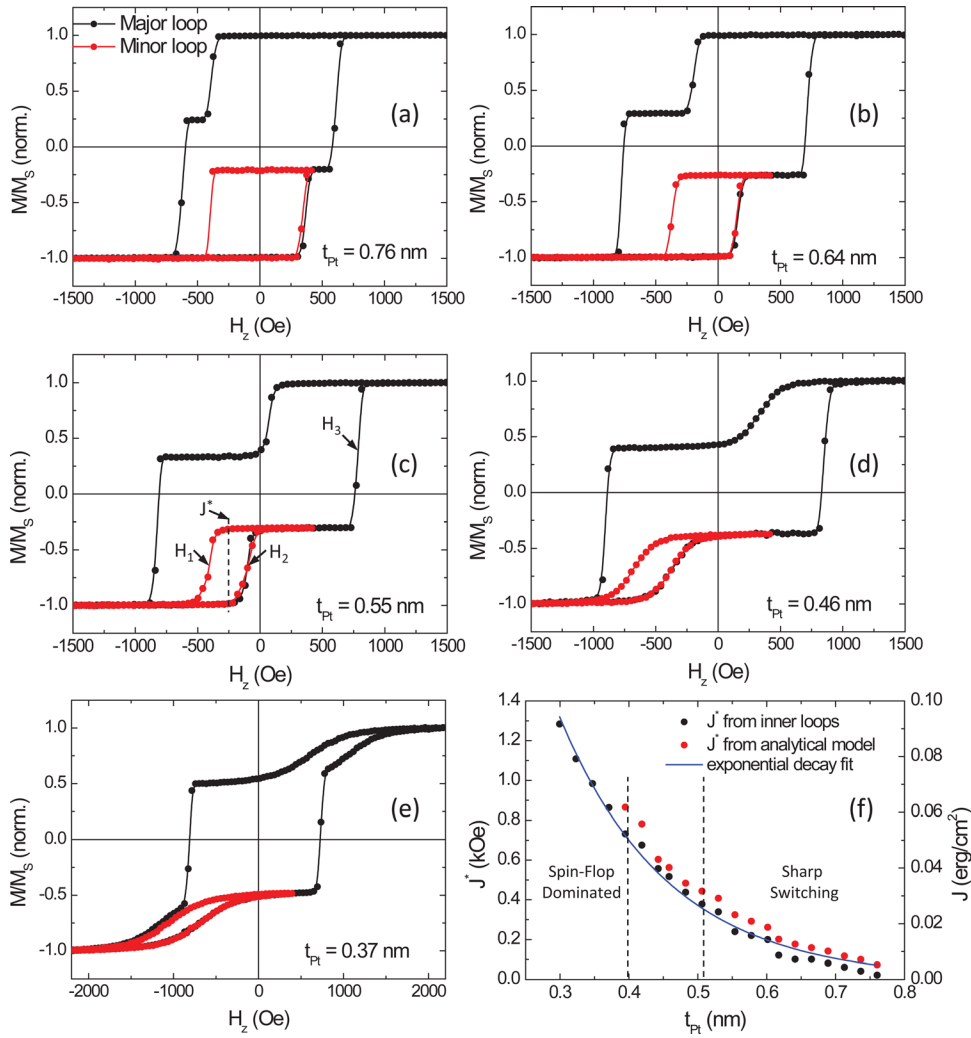
FIG. 4. (Color online) (a)-(e) Hysteresis loops as obtained on a BL/CoFeB(0.84)/Pt(t_{Pt})/Ru(1.53)/Pt(t_{Pt})/CoFeB(0.84)/CL sample, where t_{Pt} is indicated in the figures. The lines are a guide to the eye. (c) The fields used to determine J^* and J in (e) are indicated. (f) J^* as obtained from the minor loops and analytical model. A fit of J^* obtained from the inner loops to an exponential decay function is shown.

show the major and minor loops. In the minor loop, we first saturate the magnetization in the negative direction ($-M_s$) and increase the field until the bottom layer (in this case) switches and then reverse the field sweep direction. From the shift of the minor loop, the coupling field is found: $J^* = (H_1 + H_2)/2$ as shown in Fig. 4(c). Furthermore, J^* can also be obtained by using an analytical model using the two transitions in the major loop, H_2 and H_3 as $J^* = (H_3/N - H_2/O)/2$, where $N = 2\sqrt{M(1 + M)}$, $O = 2(1 - M)\sqrt{M/(1 + M)}$, and $M = (1 + H_3/H_2)/(H_3/H_2 - 1)$.[13] The values of J^* (left y-axis) and $J = J^* M_s t_{CoFeB}$ (right y-axis) versus t_{Pt} obtained in these ways are shown in Fig. 4(f). Note that t_{Pt} is inserted at both sides of the Ru layers so the total Pt inserted is $2t_{Pt}$. For $t_{Pt} > 0.5$ nm sharp switching is observed. The analytical model gives a good agreement with the shift of the inner loops albeit the overall value obtained is slightly higher by ~70 Oe. We believe that this is due to a different magnetization reversal dynamics of the switching layer in the major and the minor loop[20] but will need further investigation. For $t_{Pt} < 0.4$ nm, the analytical model is not valid anymore as the IEC ≫ PMA (Ref. 13) and can be seen from the dominant spin-flop behavior in Fig. 4(e). This is also close to the percolation limit of the Pt layer as discussed before resulting in a loss of PMA and was also observed to be a critical thickness in an exchange biased system.[5] Moreover, the increasingly gradual transition

observed for $t_{Pt} < 0.5$ nm correspond to the $H_k \approx J^* = 620 \pm 200$ Oe. In Fig. 4(f), we have included a fit of J^* obtained from the inner loops using an exponential decay function: $J^* = A \exp(-t_{Pt}/t_d)$ with $A = 8.7 \pm 0.2$ kOe the amplitude and $t_d = 0.16 \pm 0.01$ nm the decay length. The good agreement indicates that the Pt simply acts to attenuate the coupling strength as expected for this thickness range of Pt.[16] A slight deviation between the fit and experimental data is observed for $t_{Pt} > 0.65$ nm thickness, which we attribute to the aforementioned effects at low Pt thickness. Note that the amplitude would give an very high exchange energy of 0.62 erg/cm^2 at $t_{Pt} = 0$ nm, which will never be reached in these samples due to, among others, the loss of PMA at thin Pt thickness. The decay length may allow us to understand the induced magnetic polarization depth in the Pt by the CoFeB, but this is beyond the present study.[17,21]

In summary, we have investigated the IEC between single perpendicularly magnetized CoFeB layers coupled through Pt/Ru/Pt via the RKKY-mechanism. By inserting a Pt layer between the CoFeB and Ru, the PMA of the CoFeB layer could be stabilized and the strength of the IEC was tuned. The studied bi-layer system is the basic building block for superlattices, where accurate control over the switching field and sharp switching is required. We anticipate that by using a single Co$_{60}$Fe$_{20}$B$_{20}$ layer, the superlattice thickness

where a phase-transition to a multidomain structure occurs is greatly increased. Furthermore, our results will facilitate the design and fabrication of perpendicularly magnetized synthetic AFMs.

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