Temperature-dependent Magnetic Transitions in CoCrPt-Ru-CoCrPt Synthetic Ferrimagnets

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Abstract

The magnetic orientations and switching fields of a CoCrPt-Ru-CoCrPt synthetic ferrimagnet with perpendicular magnetic anisotropy have been studied in the temperature range from 2K to 300K. It was found that two sets of magnetic transitions occur in the CoCrPt-Ru-CoCrPt ferrimagnet across this temperature range. The first set exhibits three magnetic transitions in the 50K – 370K range, whereas the second involves only two transitions in the 2K and 50K range. The magnetic hysteresis curves of the synthetic ferrimagnet are assessed using the energy diagram technique developed by Koplak et al. [1] which accurately describes the competition between exchange energy, Zeeman energy, and anisotropy energy in the system. This energy diagram analysis is then used to predict the changes in the magnetic hysteresis curves of the synthetic ferrimagnet at 200K and 370K which represent potential operation temperature extrema that a synthetic ferrimagnet could be expected to operate at, were it to be utilized as a free layer in a memory spintronic device.

Keywords Synthetic ferrimagnet, Magnetic films, CoCrPt, Interlayer exchange coupling, Perpendicular magnetic recording, Magnetic switching, spintronics, magnetic tunnel junctions

Introduction

Synthetic ferrimagnet (SFM) trilayers consist of two antiparallel ferromagnetic (FM) films separated by a thin non-ferromagnetic metallic interlayer. For the case of identical FM layers, if the films are dissimilar in thickness, the SFM structure will exhibit a net magnetic moment (uncompensated ferrimagnet). The exchange coupling of the SFM varies with the interlayer thickness in an oscillatory fashion [2] and it has been attributed to various physical processes that include dipolar magnetostatic interactions and Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling. First observed by Grünberg et al. [3], films exhibiting antiferromagnetic coupling were utilized shortly thereafter in magnetic sensor devices based on the giant magnetoresistance (GMR) observed in Fe/Cr antiferromagnet structures [4][5]. More recently, synthetic ferrimagnets and antiferromagnets
have been utilized in magnetic tunnel junctions (MTJs) to provide exchange bias to the recording layer (free layer) or as the recording layer itself. When utilized in an MTJ device the strength of coupling can determine if the SFM is acting as a reference or free layer. The coupling strength is derived from measuring the magnetic field required for overcoming the exchange coupling energy which renders the magnetization orientation of the individual layers to be parallel. SFM structures that act to replace single FM recording layers in MTJs have demonstrated low critical switching currents without dramatically affecting thermal stability [6][7]. Additionally, we have proposed that SFM free layers can exhibit ultrafast switching speeds down to the picosecond time regime [8].

Most MTJ devices utilize CoFeB as the FM electrode due to high tunneling magnetoresistance measured when used with MgO tunneling barriers [9]. However, the maximum thickness of CoFeB exhibiting perpendicular magnetic anisotropy (PMA) is limited to around 1.5 nm [10]. The magnetization of CoFeB is also relatively high, which increases the charge current needed for spin-transfer torque switching. CoCrPt is a material of interest for MTJ applications due to its low magnetization and its large anisotropy [11], resulting in lower switching currents, improved thermal stability, and the use of thicker FM layers with concomitant process control improvements. In addition, the SFM configuration circumvents the materials-restrictive low magnetic damping requirement for selection of the FM thin film for MTJ devices [8].

It is essential to tailor the exchange energy and switching properties of the SFM structure for use in memory devices. However, the magnetic properties of the SFM are temperature dependent, and memory devices could be expected to operate under extreme conditions within the range of 200K to 370K. In this paper the exchange coupling of CoCrPt-Ru-CoCrPt trilayer structures has been investigated from 2K to 300K. It has been observed by Koplak et al. [1] that with decreasing temperature, the hysteresis loops of SFMs vary dramatically, and these authors developed a formalism to describe the observed changes in the hysteresis loop as a function of temperature in a CoFeB-Ta-CoFeB antiferromagnet. They employ an energy balance approach that includes the Zeeman energy, the exchange coupling energy, and energy barriers for switching arising from the effective magnetic anisotropy energy. It was found that the two main parameters controlling the switching behavior with decreasing temperature is the ratio of the magnetic moments of the two constituent ferromagnetic layers as well as the energy barrier for switching of each film, which is temperature dependent. In this paper the energy diagram technique introduced by Koplak et al. is used to describe the magnetic transitions measured in a CoCrPt-Ru-CoCrPt SFM as a function of temperature. This is compared with their results on the CoFeB-Ta-CoFeB SFM structure. Predictions are also made for the magnetic transitions of the CoCrPt-Ru-CoCrPt SFM at 200K to 370K to
exemplify the practical use of the energy diagram technique for assessing the robustness of a potential sensor device employing a SFM read layer.

Materials and Methods

All films were deposited without substrate heating or bias in a magnetron sputter system with a base pressure < 10^{-7} Torr. The films were grown on oxidized silicon (100) substrates. The thin film structure consisted of the following: Ta(5 nm)/Ru(10 nm)/CoCrPt(x nm)/Ru(y nm)/CoCrPt(z nm)/Ru(5 nm). The CoCrPt sputtering target has a nominal composition of Co_{70}Cr_{18}Pt_{12}. The Ta/Ru seed layer was used to promote CoCrPt growth with its basal (002) plane parallel to the thin film plane (c-axis out of plane). Magnetic hysteresis loops were collected using a Quantum Design MPMS-3 superconducting quantum interference device (SQUID) magnetometer with 10^{-8} emu sensitivity. All magnetic hysteresis loops presented in this work were performed with the substrate aligned perpendicular to the direction of the applied magnetic field.

Results and Discussion

![Schematic representation of the film stack cross-section and hysteresis curves of the SFM structures with two different Ru interlayer thicknesses measured at 300K.](image)

As shown in Fig. 1, the exchange energy of the CoCrPt-Ru-CoCrPt SFM can be tailored by varying the Ru interlayer thickness. The exchange energy per unit area of a SFM with dissimilar FM layers was estimated by Koplak et al. using the expression: \( J_{EX} = -H_B m_2/S \). Here \( H_B \) is the bias field.
which indicates the center of the outer loop. In Fig. 2a-b, \( H_B \) is labeled and measured by finding the center of the outer loops at which point the SFM becomes saturated. At 2K (Fig. 2c), there is no outer loop unlike in Fig. 2a-b. In this case a minor loop must be taken to locate the \( H_B \) field, which is shown by the red curve in Fig. 2c. In the \( J_{\text{EX}} \) equation, \( m_2 \) is the magnetic moment from the thinner magnetic layer (\( m_1 \) being the moment from the thicker layer), and \( S \) is the surface area of the film. In Fig. 1, the exchange energy is calculated to be -0.070 erg/cm\(^2\) and -0.0305 erg/cm\(^2\) for SFMs with 0.5 and 0.8 nm Ru interlayers, respectively. Generally, higher exchange coupling strength is desirable for memory applications, including novel devices such as a double MTJ containing two SFM reference layers and a SFM free layer discussed in [8] which is predicted to switch in ps time scales.

Figure 2) Hysteresis curves of CoCrPt(1.7)/Ru(0.8)/CoCrPt 1.3) SFM at a) 300K, b) 50K, and c) 2K. The switching behavior from 50-300K includes three magnetic transitions while two transitions are observed at 2K. In Figs. 2a and b), the center of the outer loops is indicated by \( H_B \). In Fig. 2c), the \( H_B \) indicates the center of the minor loop (red curve) associated with the switching of the thinner magnetic layer.

A SFM has four possible magnetic configurations \((\uparrow\uparrow, \uparrow\downarrow, \downarrow\uparrow, \downarrow\downarrow)\), where the left and right arrows indicate the bottom (thicker) and top (thinner) FM layers, respectively as shown in Fig. 2. The number of transitions found in the hysteresis loop at a given temperature depend on the exchange-coupling energy, the Zeeman energy, and the energy barrier for magnetic reversal. From the literature, it is also evident that the magnetic field sweeping rate influences the magnetic switching behavior [12]. However, in this work each data point of the hysteresis curve is collected once the applied field has stabilized. Also, each hysteresis curve is collected once the sample temperature has fully stabilized.

Koplak et al. found for the CoFeB-Ta-CoFeB SFM three types of hysteresis loops over the temperature range studied. In the 180K-300K range, three magnetic transitions were observed for Type I hysteresis \((\uparrow\uparrow\downarrow\downarrow, \uparrow\downarrow\uparrow\uparrow, \downarrow\uparrow\downarrow\downarrow)\). Two transitions are present between 120K-170K for Type II hysteresis \((\uparrow\uparrow\downarrow\downarrow, \uparrow\downarrow\uparrow\downarrow)\) and 2K-110K \((\uparrow\uparrow\uparrow\uparrow, \uparrow\uparrow\downarrow\downarrow)\) for Type III hysteresis. These transitions are
observed when the applied magnetic field is swept from positive to negative. The reverse transitions are encountered when the field is swept from negative to positive. In the case of the CoCrPt-Ru-CoCrPt system, we observe three transitions (↑↑↓↓, ↑↓↑↓, ↓↑↓↓) in the 300K to 50K range (Fig. 2a-b). Whereas the number of magnetic transitions reduces to two when the sample is cooled down to 2K (Fig. 2c), (↑↑↓↓, ↑↓↓↓) similar to the hysteresis loop measured in the 120K-170K range in the CoFeB-Ta-CoFeB system. The third set of magnetic transitions (↑↑↓↓, ↑↓↓↓) that are reported for the CoFeB-Ta-CoFeB SFM (Type III hysteresis) are not observed for the CoCrPt-Ru-CoCrPt SFM. Table 1 summarizes the types of hysteresis curves observed in both the CoCrPt-Ru-CoCrPt and the CoFeB-Ta-CoFeB SFMs as a function of temperature.

| Hysteresis Type and Magnetic Transitions | CoCrPt-Ru-CoCrPt SFM | CoFeB-Ta-CoFeB SFM |
|-----------------------------|----------------------|---------------------|
| Type I Hysteresis           | 50 - 300 K           | 180 - 300 K         |
| ↑↑↑↑↓↓, ↑↓↓↓↑, ↓↑↓↓↑   |                      |                     |
| Type II Hysteresis          | 2 - 40 K             | 120 - 170 K        |
| ↑↑↑↓, ↑↓↓↓↑            |                      |                     |
| Type III Hysteresis         | -                    | 2 - 110 K          |
| ↑↑↓↑, ↓↑↓↓↓           |                      |                     |

Table 1) Comparison of the hysteresis types and the associated magnetic transitions observed in the CoCrPt-Ru-CoCrPt and CoFeB-Ta-CoFeB SFM by Koplak et al. [1]. The indicated magnetic transitions occur when the magnetic field is swept from positive saturation to negative saturation. The bold arrows represent the magnetic moment, $m_1$, of the thicker magnetic layer. The temperature range where each type of hysteresis curve is observed are provided under the heading of the different SFM structures.

Here we analyze the magnetic transitions exhibited by the SFM with a 0.8 nm Ru spacer (Fig. 1) using the energy diagram technique. This technique relies on a simple energy balance (Eq. 1) which contains the exchange energy ($E_{EX}$), Zeeman energy ($E_Z$), and the potential barriers $E_{eff1}$ and $E_{eff2}$ (corresponding to the 1.7 nm and 1.3 nm CoCrPt, respectively).

$$ \text{Eq. 1) } E_{Total} = E_{EX} + E_{Z} + E_{eff1} + E_{eff2} $$

The exchange energy, $E_{EX}$, is proportional to the surface area of the sample and can be estimated from $|E_{EX}| = H_B \cdot m_z$. Here $H_B$ represents the bias field, which is measured by locating the center of the minor loop of the softer magnet as previously described. In the case of the first type of switching shown in Figs. 3a) and 3b), there are three loops: the center field of the outer loops is $H_B$
and indicates the strength of exchange coupling. The potential energy barriers arise due to the effective magnetic anisotropy energy of each magnetic layer. Notably the hysteresis curves are measured along the easy-axis, therefore, $E_{\text{eff1}}$ and $E_{\text{eff2}}$ are not equal to the anisotropy energy determined from the hard axis hysteresis. In a hysteresis loop with three transitions (Figs. 3a) and 3b), $E_{\text{eff1}}$ can be estimated from the coercive field of the outer loops as $H_{C-\text{outer}} = \frac{E_{\text{eff1}}}{2m_1}$. Then $E_{\text{eff2}}$ can be calculated from the coercive field of the inner loop expressed by $H_{C-\text{inner}} = \frac{E_{\text{eff1}}+E_{\text{eff2}}}{2(m_1-m_2)}$. These estimates arise from the equations derived by Koplak et al. describing the possible magnetic transitions. The Zeeman energy, $E_Z$, is proportional to the applied magnetic field and can be expressed as $E_Z = -(m_1 + m_2) \cdot H$.

The second type of hysteresis curve shown in Fig. 3c) has no outer loops, which are needed to estimate $E_{\text{EX}}$. However, one can still calculate $H_B$ and thus $E_{\text{EX}}$ by measuring the minor loop as shown in Fig. 2c. This is obtained by switching the softer, thinner $m_2$ magnetic layer after the SFM has been saturated [13]. $H_B$, labeled in Fig. 2c, was determined to be -1798 Oe. The minor loop in Fig. 2c is measured by saturating the SFM to the $\uparrow\uparrow$ orientation, sweeping the magnetic field to just beyond the $\downarrow\downarrow - \uparrow\uparrow$ magnetic transition, and then saturating the SFM back to the $\downarrow\downarrow$ orientation. This indicates an exchange coupling strength of -0.11 erg/cm$^2$ for the SFM at 2K. After $E_{\text{EX}}$ is obtained, $E_{\text{eff1}}$ and $E_{\text{eff2}}$ can be calculated using equations $H_{\uparrow\uparrow-\downarrow\downarrow} = \frac{2|E_{\text{EX}}|-E_{\text{eff2}}}{2m_2}$ and $H_{\uparrow\downarrow-\downarrow\downarrow} = -\frac{2|E_{\text{EX}}|+E_{\text{eff1}}}{2m_1}$, respectively. The resulting energy diagram (Fig. 3c) is consistent with the transition fields of the minor loop and the saturated hysteresis loop. $E_{\text{eff1}}$ and $E_{\text{eff2}}$ are plotted at each temperature in Fig. 5a. Notably, $E_{\text{eff1}}$ is larger than $E_{\text{eff2}}$ until the temperature is lowered to 2 K. Similar behavior was observed in Koplak et al. (Figure 3) Energy diagrams of the CoCrPt(1.7)/Ru(0.8)/CoCrPt(1.3) SFM at a) 300K, b) 50K, and c) 2K. The solid lines indicate the total energy, excluding the energy barriers, while the dashed lines include the temperature-dependent energy barriers. The hysteresis curves are shown in each pane with corresponding magnetic moments on the secondary axis. The red hysteresis loop in c) displays
the minor loop measured to determine \( H_B \). Dashed arrows indicate the energies associated with the minor loop and the corresponding transitions.

The energy diagrams shown in Fig. 3 describe the magnetic transitions occurring for each temperature. Solid lines indicate the energy of the SFM system with zero \( E_{\text{eff}} \), i.e. when there are no energy barriers to overcome. The solid lines are thus, the addition of the Zeeman energy and the Exchange energy, with a y-intercept equal to the exchange energy. The dashed lines represent the total energy of the system after the \( E_{\text{eff1}} \) and \( E_{\text{eff2}} \) are included, as described by Eq. 1. As the magnetic field is swept, the magnetic orientation present is the one with the lowest energy. Shown in Fig. 3a), the blue solid line represents the \( \uparrow\uparrow \) orientation as the field is lowered from +2 T. If the energy barrier for reversal of each layer is zero, the \( \uparrow\uparrow\downarrow\downarrow \) will occur at the intersection of the blue solid line and the orange solid line representing the total energy of the \( \uparrow\downarrow \) orientation. At 300K, the \( E_{\text{eff}} \) energies for \( m_1 \) and \( m_2 \) are negligibly low such that the magnetic transitions occur approximately at the solid line intersections.

The potential barriers become larger as temperature is decreased down to 2K (Fig. 5a). Since the \( E_{\text{eff}} \) terms are not field-dependent, they shift the dashed lines up along the y-axis. For a magnetic transition to occur, the magnetic field must be changed such that the energy barrier between the solid and dashed line is crossed. As seen in Fig. 3b, the \( \uparrow\uparrow\downarrow\downarrow \) transition no longer occurs at the intersection of the solid blue and orange lines, but at the point where the potential barrier of another orientation energy is crossed. As the potential barriers increase with lower temperature, certain transitions are prohibited from occurring due to the existence of lower energy states from other magnetic orientations. At 2K (Fig. 3c), the \( \downarrow\downarrow\uparrow\uparrow \) transition does not occur as it does at 300K and 50K (Fig. 3a-b) since the potential barrier of the \( \downarrow\downarrow \) state is lower in energy than the \( \uparrow\uparrow \) state.

The third set of magnetic transitions (\( \uparrow\downarrow\uparrow\uparrow \), \( \downarrow\uparrow\downarrow\downarrow \)), or Type III hysteresis, occurs when the condition \( E_{\text{eff1}} < E_{\text{eff2}} \cdot \frac{m_1}{m_2} - 2|E_{\text{EX}}| \cdot \frac{m_1-m_2}{m_2} \) is satisfied [1]. The CoCrPt-Ru-CoCrPt SFM studied does not meet this requirement and does not show this set of transitions even down to 2K. Compared to the CoFeB-Ta-CoFeB SFM reported by Koplak et al. [1], which has an exchange energy at 300K of \( E_{\text{EX}}/S = -0.01 \text{ erg/cm}^2 \), the CoCrPt-Ru-CoCrPt SFM has an exchange energy at 300K of \( E_{\text{EX}}/S = -0.04 \text{ erg/cm}^2 \). The CoFeB-Ta-CoFeB SFM and the CoCrPt-Ru-CoCrPt SFM have \( m_1/m_2 \) ratios of 1.38 and 1.79, respectively. At 300K the effective anisotropy energy barriers for both systems are: \( E_{\text{eff1}}/S = 4.0 \times 10^{-3} \text{ erg/cm}^2 \) and \( E_{\text{eff2}}/S = 2.5 \times 10^{-3} \text{ erg/cm}^2 \) for CoFeB-Ta-CoFeB, \( E_{\text{eff1}}/S = 1.7 \times 10^{-3} \text{ erg/cm}^2 \) and \( E_{\text{eff2}}/S = 7.3 \times 10^{-3} \text{ erg/cm}^2 \) for the CoCrPt-Ru-CoCrPt. The energy barriers for the CoCrPt-Ru-CoCrPt are lower for \( E_{\text{eff1}} \) and \( E_{\text{eff2}} \) by a factor of 2.3 and 3.4, respectively. This disparity in \( E_{\text{eff}} \) causes the
right side of the inequality to be lower, which explains why the third set of magnetic transitions are absent in the CoCrPt-Ru-CoCrPt SFM.

Figure 4 illustrates the dependence of the left and right sides of the inequality $E_{\text{eff}1} < E_{\text{eff}2} \cdot \frac{m_1}{m_2} - 2|E_{\text{EX}}| \cdot \frac{m_1 - m_2}{m_2}$ on the exchange coupling energy for both the CoCrPt and CoFeB SFM systems. The plot shows the energies calculated at 100K, since CoFeB-Ta-CoFeB shows the third set of magnetic transitions at this temperature. At a given exchange energy, the third set of magnetic transitions should be observed when the right side of the equation is larger than $E_{\text{eff}1}$. When plotted as a function of $E_{\text{EX}}$, the right side of the inequality is a line whose slope is determined by the $m_1/m_2$ ratio and the intercept by the product of $E_{\text{eff}2}$ and $m_1/m_2$. The dependence of the right side of the inequality on $m_1/m_2$ is also illustrated in Fig. 4a-b. As $m_1/m_2$ approaches 1, the slope and the y-axis intercept of the right side of the inequality is lowered. Since it has been shown that fast spin transfer torque switching can be achieved with a low $m_1/m_2$ ratio [8], this analysis is important in understanding the type of hysteresis curves that will be present in the SFM when tailoring the ratio of magnetic moments. It is evident from Fig. 4a that the magnetic switching behavior of the CoCrPt-Ru-CoCrPt SFM will not exhibit the third type of magnetic switching for either stronger or weaker exchange energy as the intercept of the right side of the inequality is lower than $E_{\text{eff}1}$.

As mentioned earlier, the SFM can be used as a replacement for a single FM layer in a memory device. Such devices are expected to operate successfully over a wide range of temperatures. Therefore, it is important to predict the behavior of the SFM at any temperature. The energy diagram technique can be used to predict the transition fields of the SFM if the temperature dependence of $E_{\text{eff}}$, $E_{\text{EX}}$, and the magnetization, $m$, are known. Figure 5a-c shows the temperature dependence of $E_{\text{eff}}$, $E_{\text{EX}}$, and $m$, respectively. $E_{\text{eff}}$, $E_{\text{eff}1}$, and $E_{\text{eff}2}$ are proportional to $m^{\frac{n(n+1)}{2}}$ at lower temperatures (<150K), while at higher temperatures the potential energy barriers are proportional to $m^n$ similar to the temperature dependence of the magnetic anisotropy observed for other materials [14, 15]. Here, $m$ is the magnetic moment and $n$ is the exponent of the magnetic anisotropy function ($n=2$ is typical for uniaxial anisotropy). Fig. 5a) shows the fit for $E_{\text{eff}2}$ based on the $m^{\frac{n(n+1)}{2}}$ proportionality. Good agreement is seen with the fit until around 150K, at higher temperatures, $E_{\text{eff}2}$ is proportional to $m^n$. The parameters $E_{\text{EX}}$ and $m$ change linearly in this temperature range. Fitting the trends seen in Fig. 5 allows one to predict the behavior at 200K and 370K, the temperature extrema that a spintronic sensor could potentially expected to operate reliably. The energy diagrams for the CoCrPt(1.7)/Ru(0.8)/CoCrPt(1.3) SFM at these two temperatures are shown in Fig. 6. These energy diagrams are constructed using the fitted parameters from Fig. 5. Both energy diagrams in Fig. 6a)
and 6b) show magnetic transitions corresponding to the type I regime [1]. The transition field for $\uparrow \uparrow \uparrow \downarrow$ (where $m_1$ reversal occurs) is predicted to be 1400 Oe and 950 Oe at 200 K and 370 K, respectively. In Fig. 6a the hysteresis diagram measured at 200K is shown and agrees with the predicted transitions from the energy diagram.

The CoCrPt-Ru-CoCrPt SFM system can provide potential advantages over CoFeB-Ta-CoFeB due to its low magnetization and its large magnetic anisotropy [11]. The anisotropy in CoCrPt is largely determined by magnetocrystalline anisotropy as opposed to interface anisotropy for the case of CoFeB. Therefore, CoPtCr films exhibit PMA for film thicknesses up to 15 nm. Thus, the $m_1/m_2$ ratio in the films can be controlled more precisely, allowing for more tunability of the SFM properties. This is of particular interest for the implementation of ps magnetic switching employing SFM structures as proposed by Camsari et al. [8].

Figure 4) The left and right sides of the inequation $E_{eff1} < E_{eff2} \cdot \frac{m_1}{m_2} - 2|E_{EX}| \cdot \frac{m_1 - m_2}{m_2}$ plotted as a function of $E_{EX}$ for the a) CoCrPt-Ru-CoCrPt and b) CoFeB-Ta-CoFeB SFM. The black solid and dashed lines labeled “Right – $m_1/m_2$” represents the right side of the inequality at different magnetic ratios. The left side of the inequality is represented by the red curve and is labeled $E_{eff1}$. The black squares shown in a) represent the observed exchange energy of the CoCrPt-Ru-CoCrPt SFM at 100K.
Figure 5) a) $E_{\text{eff}1}$, $E_{\text{eff}2}$, and $E_{\text{eff}}$ (Total) plotted versus temperature. b) $|E_{\text{EX}}|$ plotted versus temperature. c) The magnetic moments, $m_1$ and $m_2$ of the 1.7nm and 1.3nm thick CoCrPt layers, respectively, plotted versus temperature.

Figure 6) The energy diagram for the CoCrPt(1.7)/Ru(0.8)/CoCrPt(1.3) SFM at 200K and 370K, calculated from fitted parameters in Fig 5. The transition fields are indicated by the vertical dashed lines. The hysteresis curve measured at 200K is shown in a).

Conclusions

The energy diagram technique has been applied to describe the magnetic transitions of CoCrPt-Ru-CoCrPt SFM as a function of temperature. Two types of hysteresis curves are observed, one above 50K with three subloops and the other at 2K with two magnetic transitions. Type III hysteresis is not seen in this SFM system due to the large $E_{\text{eff}1}$ seen in the CoCrPt SFM which prevents the $E_{\text{eff}1} < E_{\text{eff}2} \cdot \frac{m_1}{m_2} - 2|E_{\text{EX}}| \cdot \frac{m_1-m_2}{m_2}$ inequality from being satisfied. This is large $E_{\text{eff}1}$ constant corresponds to the high anisotropy present in the CoCrPt film. The calculation of the potential barriers of the SFM at 2K was possible by measuring the minor loop associated with the switching of the thinner $m_2$ layer. Utilizing this diagram technique for CoCrPt-Ru-CoCrPt allows for the
assessment and prediction of the different magnetic orientations present in the SFM system at any given temperature.

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