Understanding types of magnetic coupling between magnetic layers in bilayer magnetic thin film system: Simulation

B. Tech. mini project report (PH312) submitted for the partial fulfilment of the requirement for the Degree of

Bachelor of Technology

by

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Acknowledgement

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Sincerely,
Shlok Bum

1 Introduction

Magnetization dynamics is a process in which the material acts as a magnet upon exposing it to an external magnetic field. Paramagnetic materials have a weakly induced magnetization in a magnetic field which fades away when the field is removed. Ferromagnetic and Ferrimagnetic materials have strongly induced magnetization and can remain as a permanent magnet. Magnetic multilayers usually have more than one ferromagnetic layers separated by a non-magnetic layer. The ferromagnetic layers interact through the spacer and align either parallel(same direction), anti-parallel(opposite direction) or biquadratic(90^o orientation) depending on the nature of the interlayer exchange coupling.

1.1 Interlayer exchange coupling

Interlayer exchange coupling in bilayer systems has generally two types - Bilinear and Biquadratic coupling depending on the direction of moment. The non-magnetic layer plays an important role in changing the interaction between the layer.

1.1.1 Bilinear Coupling

Let us assume that the thickness and magnetisation are same for both the above ferromagnetic layers.

When a sufficient magnetic field is applied both the layers respond together, and therefore they get saturated. As we approach towards zero and magnetic field in negative polarity the direction of magnetisation for both layers turns in opposite direction, responding together. These two magnetic layers are said to have an interaction of Bilinear Coupling.

It can be represented as $J_1(m_1.m_2), J_1$ is called bilinear coupling constant between

magnetisation m_1 and m_2.

If J_1 is positive we've ferromagnetic coupling. If J_1 is negative we have antiferromagnetic coupling. In antiferrormagnetic coupling the total magnetisation at zero magnetic field is zero as both the layers have opposite magnetisation. At sufficient magnetic field both the layers are saturated. When the magnetic field is close to zero, the antiferromagnetic state remains very stable called artificially constructed multilayer antiferromagnetic state.

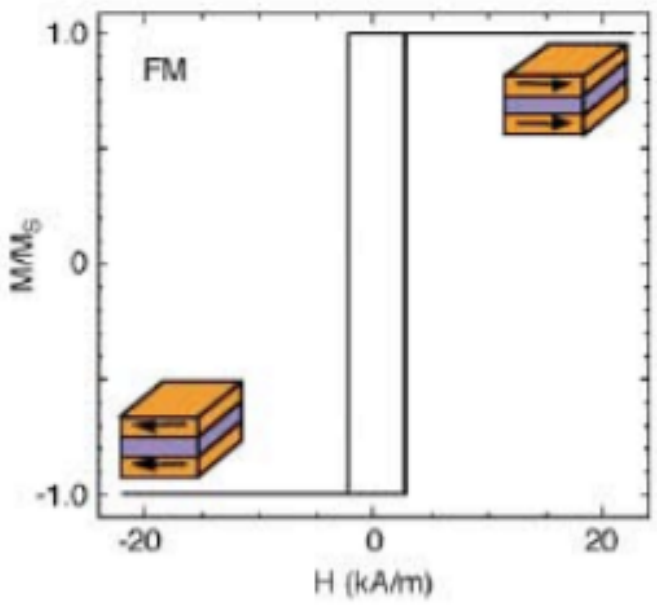

Figure 1.1: The bilinear coupling exhibiting the ferromagnetic coupling between the ferromagnetic layers

1.1.2 Biquadratic Coupling

Let us consider that the thickness are not same, but magnetisation maybe similar. When sufficient magnetic field is applied, the layers are saturated positively or negatively. But near zero magnetic field, the second layer's magnetisation rotates by 90^o. This is called 90^o coupling or biquadratic coupling represented by $J_2(m_1.m_2)^2$

Therefore the interlayer exchange energy can be written as

$$J_1(m_1.m_2) + J_2(m_1.m_2)^2 \tag{1.1}$$

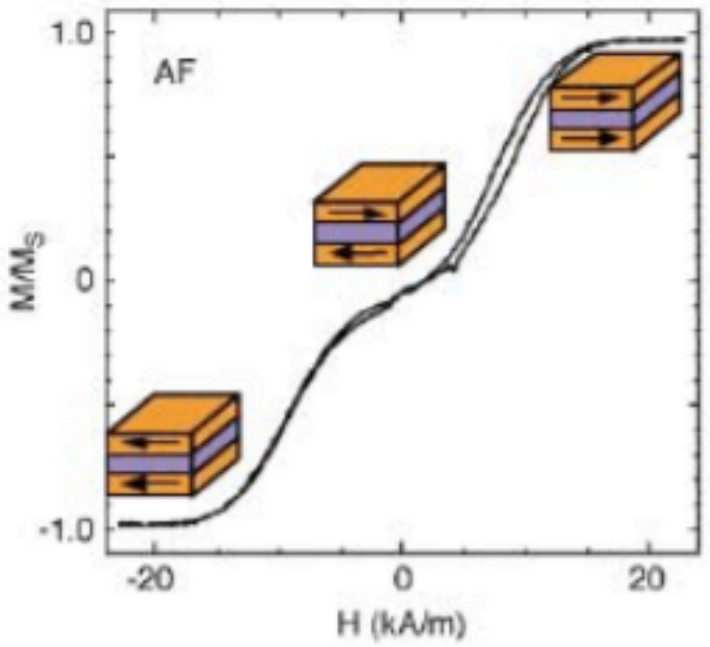

Figure 1.2: The bilinear coupling exhibiting the antiferromagnetic coupling between the ferromagnetic layers

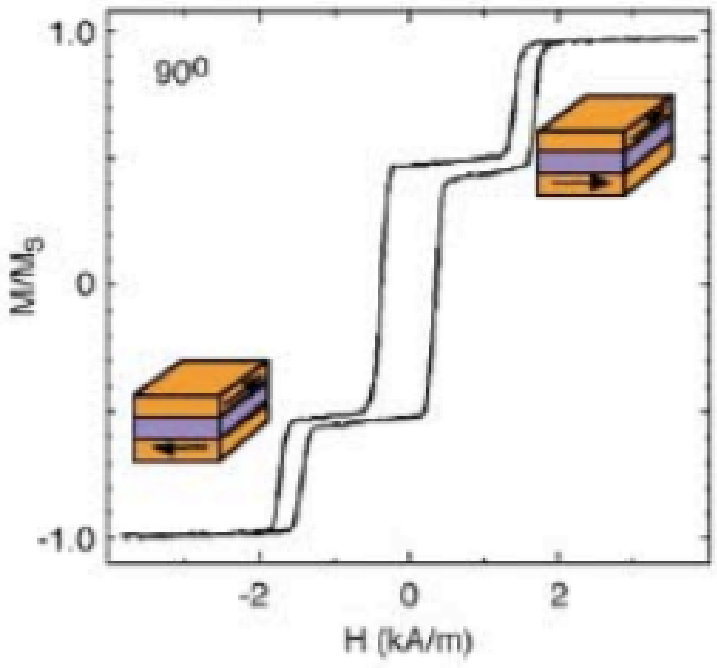

Figure 1.3: The biquadratic coupling exhibiting the 90^o coupling between the ferromagnetic layers.

2 | Simulation

2.1 Extraction of experimental points

The initial objective was to locate atleast 100 pixel coordinates of the experimental data points from the given graph to obtain the experimental data set for the M-H loops. To obtain the pixel coordinates, using image of the graph, each position of the mouse on the plot corresponds to a particular pixel location, which can be converted to x-y coordinates depending on the pixel location of the origin in cartesian coordinates. Further scaling is done to match the data set. These points were then converted to general x-y coordinates and scaled accordingly. MM-H loops are simulated using a numerical simulation model based on three major energy expressions namely magnetic anisotropy Energy (E_K), exchange coupling energy (E_J) and Zeeman energy (E_Z) as

$$E_T = E_K + E_J + E_Z \tag{2.1}$$

where

$$E_K = K_a t_a sin^2\alpha cos^2\alpha + K_b t_b sin^2\beta cos^2\beta \tag{2.2}$$

$$E_J = -J_1 cos(\alpha - \beta) - J_2 cos^2(\alpha - \beta) \tag{2.3}$$

$$E_Z = -M_a t_a H cos\alpha - M_b t_b H cos\beta \tag{2.4}$$

Here K is first order cubic magnetocrystalline anistropy constant, M is saturation magnetisation, t is thickness of CoMnSi layers.

H is the applied magnetic field, a and b represent top and bottom CMS layers, α and β is the angle between the direction of H and M in the bottom and top layers respectively.

J_1 is the bilinear coupling constant, J_2 is the biquadratic coupling constant

Positive J_1 represents ferromagnetic coupling while negative J_1 and negative J_2 correspond to

180^o(antiferromagnetic) and 90^o(biqudratic) configurations respectively.The value of coupling parameters J_1 and J_2 are evaluated by comparing the simulation results with experimental M-H loops. The following are the original plots and the extracted plots-

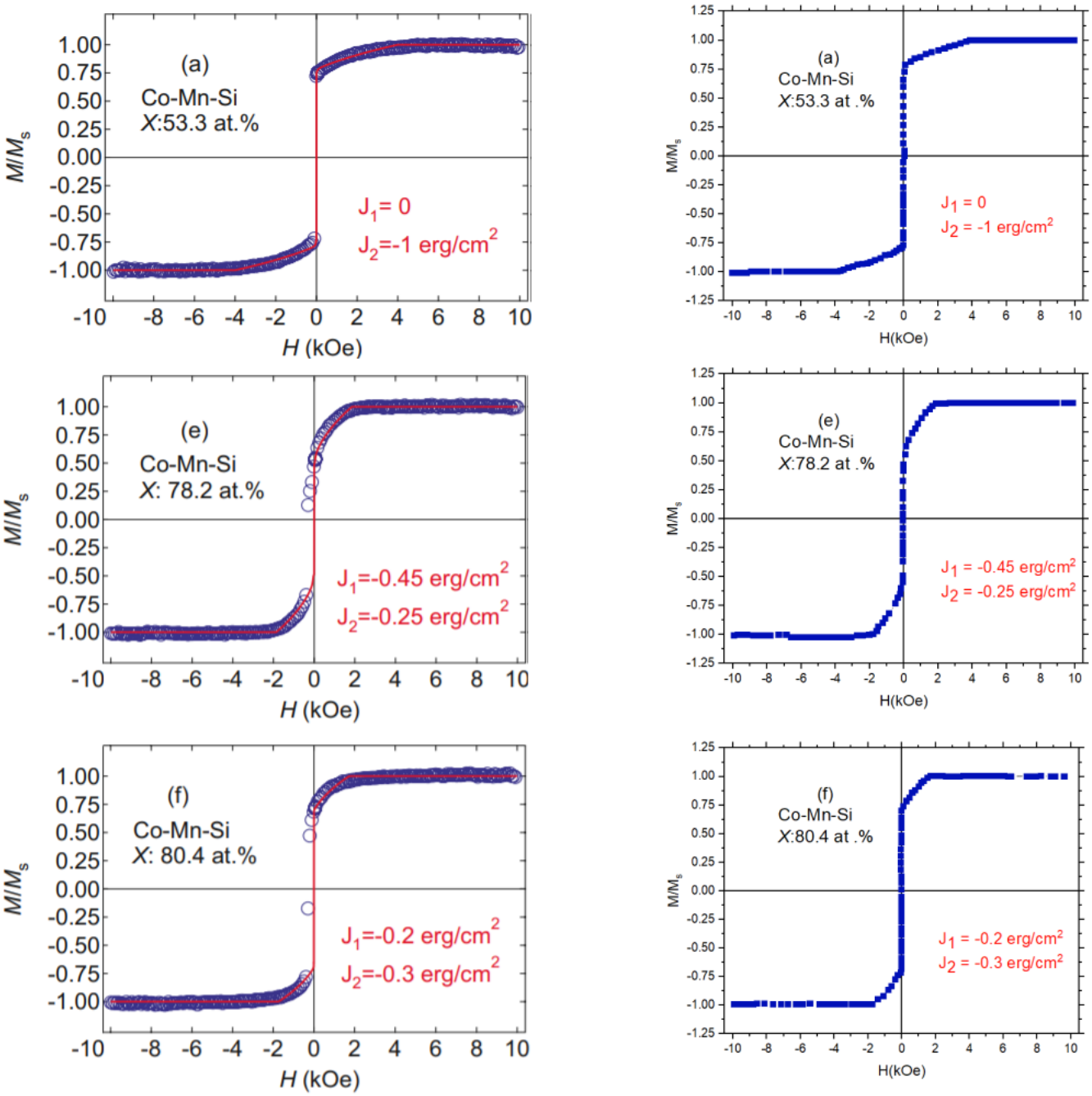

Figure 2.1: ***Left**: M-H loops of Co-Mn-Si(20nm)/Cr(1.2nm)/Co-Mn-Si(7nm) trilayers for top and bottom Co-Mn-Si, X: (a) 53.3 at %, (e) 78.2 at .%, (f) 80.4 at .%*
***Right**: Plot of extracted points*

Experimental (open circles) and simulated (line) M-H loops for different samples with different Co content are plotted together in Figure 2.2 to justify the quality of the fitting and thereby evidently extracting the coupling parameters. *Plotted using Origin Pro Lab*

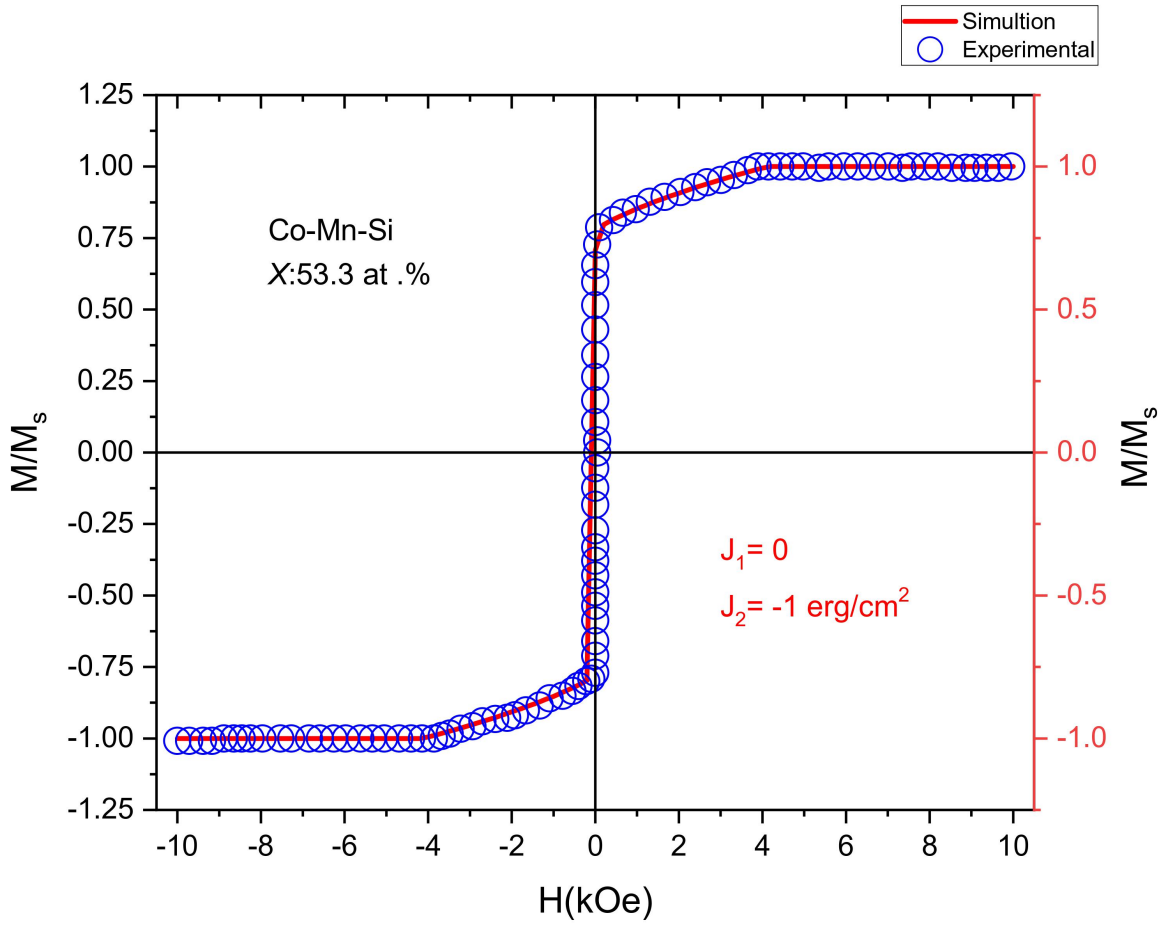

Figure 2.2: *Experimental and simulated M-H loops for Co-Mn-Si/Cr/Co-Mn-Si with Co content as 53.3 at .%. The values of* $M_s(emu/cm^3) = 950$, $t_a(cm) = 2e-06$, $t_b(cm) = 7e-07$, $K_a = K_b(erg/cm^3) = -30000$ *are taken for calculations.*

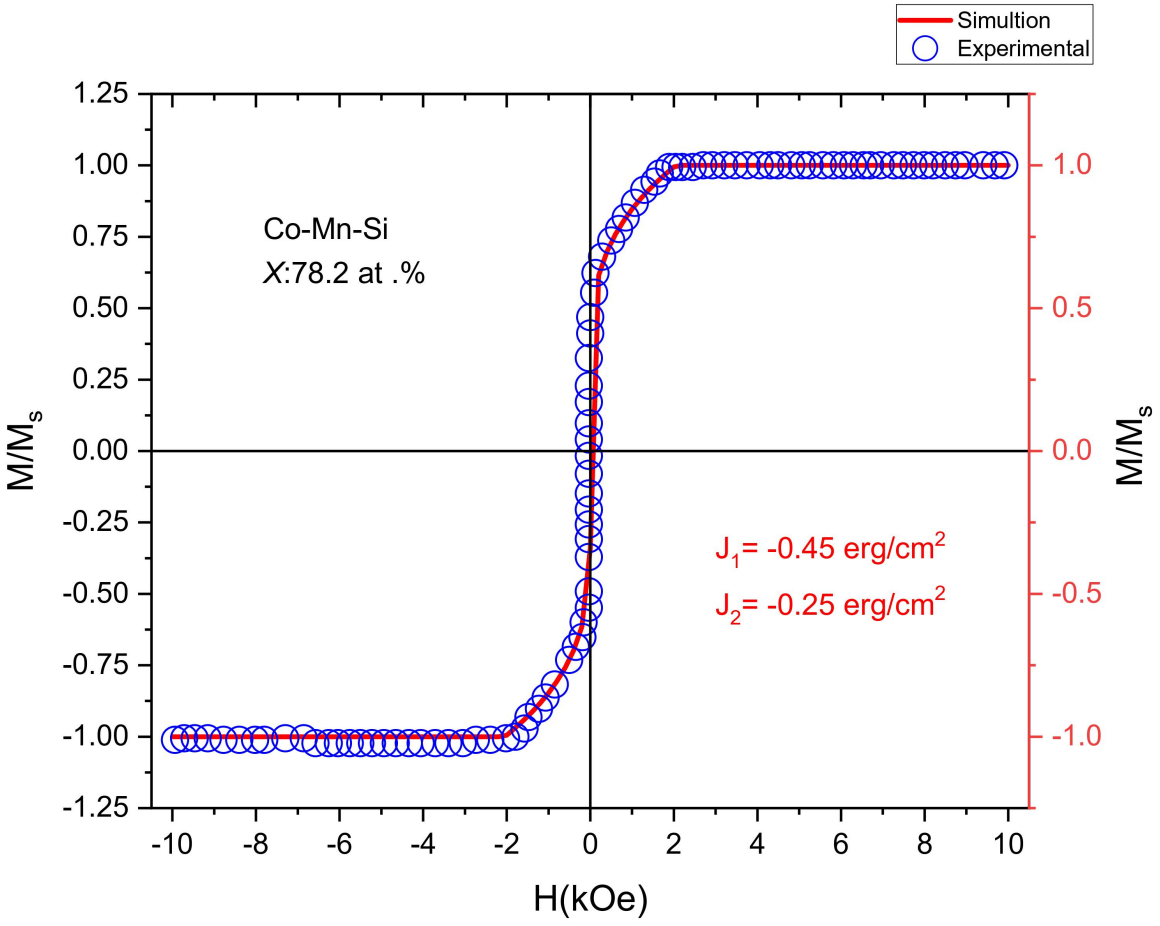

Figure 2.3: *Experimental and simulated M-H loops for Co-Mn-Si/Cr/Co-Mn-Si with Co content as 78.2 at .%. The values of* $M_s(emu/cm^3) = 950$, $t_a(cm) = 2e-06$, $t_b(cm) = 7e-07$, $K_a = K_b(erg/cm^3) = -56000$ *are taken for calculations.*

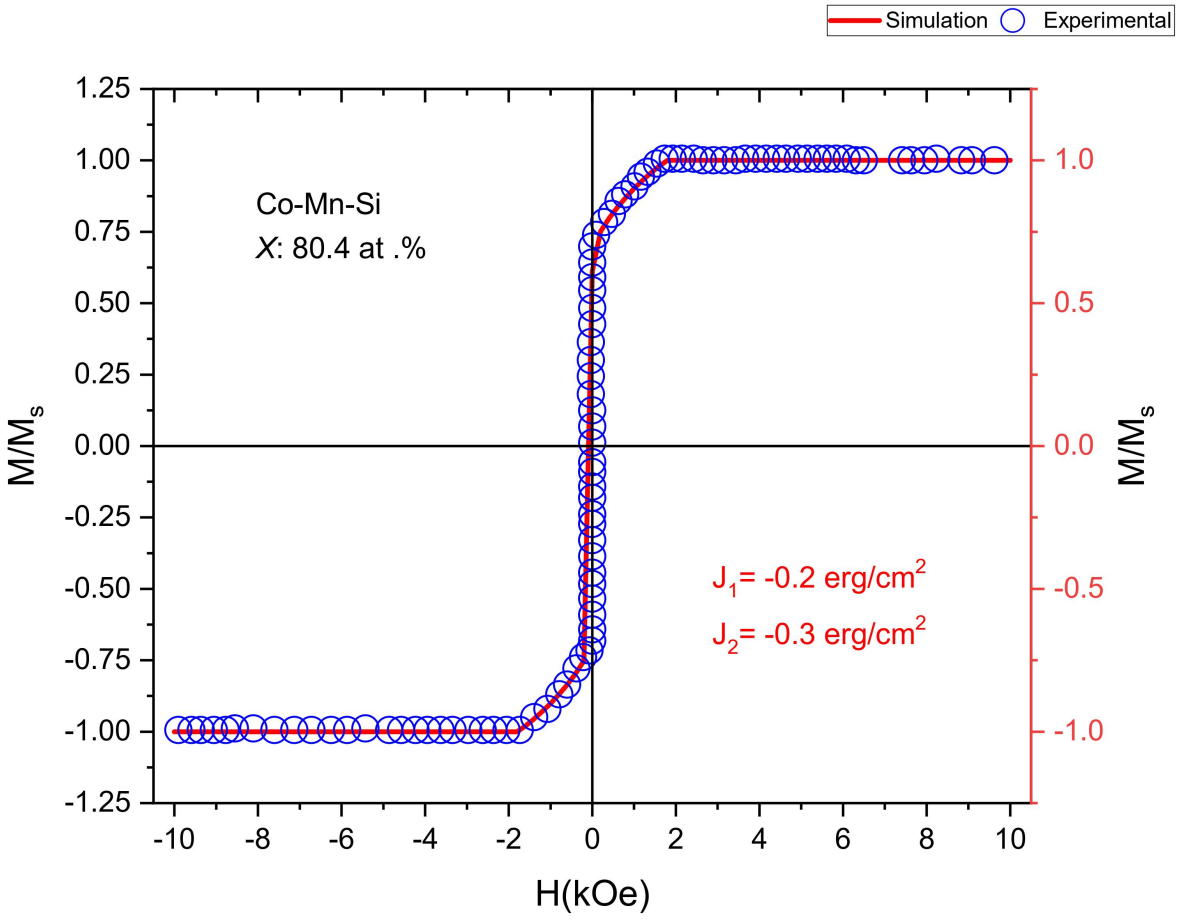

Figure 2.4: *Experimental and simulated M-H loops for Co-Mn-Si/Cr/Co-Mn-Si with Co content as 80.4 at .%. The values of* $M_s(emu/cm^3) = 880$*),* $t_a(cm) = 2e-06$*,* $t_b(cm) = 7e-07$*,* $K_a = K_b(erg/cm^3) = -6800$ *are taken for calculations.*

By observing the plots for different simulation conditions, we can confirm which coupling is the dominant one. If J_1 dominates then it is ferromagnetic coupling for positive J_1 and antiferromagnetic coupling for negative J_1. Similarly, if J_2 dominates and is negative, we get biquadratic or 90^o coupling which corresponds to perpendicular orientation of the magnetisation of both the ferromagnetic layers. In Fig 2.2 the remanence value of M/M_s is close to 0.74 indicating 90_o coupling. In Fig 2.4 the value is lesser than 0.74 but greater than 0.48 (indicating 180_o coupling) showing that both bilinear and biquadratic coupling are comparable. However in Fig 2.3, the value is much lesser than that in the case of Fig 2.4 indicating that bilinear coupling is more dominating. At Co concentration of almost 50%, biquadratic coupling dominates, but as it increases, bilinear coupling starts dominating in the range of almost 72% upto 78%. Any further increase in the concentration makes biquadratic coupling dominate again. The absolute value of K_a and K_b is highest when bilinear coupling dominates over biquadratic, while it is lowest when both bilinear and biquadratic coupling are comparable.

References

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[2] S Bosu et al. "Chemical ordering dependence of interlayer exchange coupling in Co-Mn-Si/Cr/Co-Mn-Si trilayer structures". In: *Physical Review B* 81.5 (2010), p. 054426.