**Study of the long-range exchange coupling in Nd-Fe-B/Ti/Fe multilayered structure**

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**1-Calculation of the film thickness of FM layers:**

Fabrication of the thickness of each FM layer of multilayered structure to achieve a zero magnetization while possessing net spin while FM layers interact with each other completely antiferromagnetically from RKKY theory is calculated in the following by calculating and magnetization of Nd-Fe-B layer, ideally for Nd2Fe14B crystalline structure and Fe layer. The spin of the thin film is considered a macroscopic bulk spin in the whole thin film. Orbital angular momentum and spin angular momentum for both Nd2Fe14B and Fe are calculated. In the Nd2Fe14B, the Nd atom with an electronic configuration of [Xe]4f46s2 carries the orbital angular momentum of L=6 and a net spin of 2. Also, while Fe as a transition metal with an electronic configuration of [Ar}4s23d6 carries orbital angular momentum of zero (L=0), it has a net spin of 2. So, the total magnetic moment of Nd2Fe14B will be 2 × M (Nd) + 14 × M (Fe) = 2 × 4 + 14 × 2 = 36 µB. For 2 neighbor Fe atoms in a BCC crystalline structure, the net orbital angular momentum will be 4 µB. To have the total magnetization of the Fe layer to quenched magnetization of the Nd-Fe-B layer we need to choose the correct proportion of these two layers. On a multilayered structure, both layers have the same area, so by controlling the thickness of FM layers we should be able to achieve this. If we assume the total magnetization of Nd2Fe14B and Fe should be equal to cancel each other, then we can write:

$$M\_{Nd\_{2}Fe\_{14}B}\_{ }\left(\frac{V\_{Nd\_{2}Fe\_{14}B}}{v\_{Nd\_{2}Fe\_{14}B}}\right)=M\_{Fe}\_{ }\left(\frac{V\_{Fe}}{v\_{Fe}}\right)$$

From the above $M\_{l}\_{Nd\_{2}Fe\_{14}B}=36 µ\_{B}$ and $M\_{l}\_{Fe}=4 µ\_{B}$ and also a unit crystalline cell of Nd2Fe14B and Fe are $v\_{Nd\_{2}Fe\_{14}B}=236 Å^{3}$ and $v\_{Fe}= 23.7 Å^{3}$. As mentioned, in the multilayered thin film structure both FM layers will have the same area, so for the volume of each FM layer we can write V = A × T, which A is are of the thin film and T is the thickness of it. By replacing the above parameters in the formula, we will have:

$$\left(\frac{T\_{Fe}}{T\_{Nd\_{2}Fe\_{14}B}}\right)=\left(\frac{M\_{l}\_{Nd\_{2}Fe\_{14}B}}{M\_{l}\_{Fe}}\right) × \left(\frac{v\_{Fe}}{v\_{Nd\_{2}Fe\_{14}B}}\right)= \left(\frac{36 µ\_{B}}{4 µ\_{B}}\right) × \left(\frac{23.7 Å^{3}}{236 Å^{3}}\right) \~ 0.9$$

So, if the ratio of Fe to Nd-Fe-B is 0.9, the total magnetization of the multilayered structure will be zero if FM layers completely interact with antiferromagnetically from RKKY interaction. For this purpose, we choose the thickness of the Nd-Fe-B layer 300 nm and for Fe layer 270 nm. Considering the total spin for Nd2Fe14B to be s=24 (4 total spins angular momentum from two Nd atoms will be subtracted from 28 total spins angular momentum of fourteen Fe atoms.). Therefore, we have $100\%-\left(\frac{20}{28}\right)\%\~29\% $uncompensated spin left.