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Magnetization Reversal In Transition Metal Doped ZnO Nanoparticles
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Abstract

We report magnetic properties of transition metal (TM) doped ZnO nanoparticles and compare the doping effects of different transition metal ions into the ZnO matrix. Stoner–Wohlfarth model has been used to study the switching behavior of magnetic moments by observing energy diagram and hysteresis. Low magnetic anisotropy in Zn$_{1-x}$M$_x$O nanoparticles is observed where M=Fe, Co, Ni and x is the dopant amount. We have considered chemical precipitation technique for the preparation of Zn$_{1-x}$M$_x$O samples and have compared the reversal processes of magnetic moments with respect to time in the nanoparticles.

Keywords: Magnetization reversal, Diluted magnetic semiconductor, Transition metal, anisotropy, Stoner Wohlfarth model;

1. Introduction

Magnetization reversal process leads to 180° orientation of the magnetization vector from one orientation to the opposite direction. In magnetic data storage device, the information is recorded in the magnetic moments and can be manipulated using the reversal processes. Oxide diluted magnetic semiconductors (O-DMS) have attracted a great deal of interest in recent years in the field of magnetic recording and spintronic devices due to their wide bandgap and magnetic properties which can be induced by adding the dopants into the matrices [1, 2, 3, 4]. ZnO doped with 3d group elements exhibit room temperature ferromagnetic properties and has potential applications in magnetic recording storage devices [5, 6].

Stoner and Wohlfarth related the hysteresis with magnetic anisotropy in a coherent reversal model that quantitatively links the material parameters with the magnetization and its switching properties [7]. The total energy density of magnetic moments in Stoner-Wohlfarth (SW) model is the combination of anisotropy energy (magnetocrystaline and shape anisotropy energy) and Zeeman energy which can be written as [8]:

$$ E_\text{sw} = K_{\text{eff}} \sin^2(\phi - \theta) - \mu_0 M_s H \cos \theta $$

Where $\theta$ is the angle between the magnetization, $M$ and applied magnetic field, $H$ and $\phi$ is the angle between $H$ and the easy axis, $M_s$ is the saturation magnetization, $\mu_0$ is permeability in free space and $K_{\text{eff}}$ is the effective anisotropy energy density. SW model does not describe the reversal path (switching) of the magnetic moments. Time dependent magnetization $M(t)$ for a grain in presence of a damping parameter $\alpha$ is described by the Landau-Lifschitz-Gilbert (LLG) equation [9, 10, 11]:

$$ \frac{d\vec{M}}{dt} = \lambda (\vec{M} \times \vec{H}_{\text{eff}}) + \frac{\alpha}{M} (\vec{M} \times \frac{d\vec{M}}{dt}) $$

Where $\gamma$ is the gyromagnetic ratio.

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In this paper, the performance of magnetization reversal by coherent rotation of magnetic moments in singledomain magnets of transition metal ions (Fe, Ni, Co) doped ZnO nanosystems has been discussed. SW model was used to study the switching behaviour of magnetic moments by observing the energy diagram and hysteresis. The switching field ($H_s$) and the effective anisotropy energy density ($K_{eff}$) are compared for TM (Fe, Co, Ni) doped ZnO nanoparticles prepared by chemical precipitation technique.

2. MATERIALS AND METHODS

For SW model, the experimental values of $M_s$ and $H_c$ were obtained from the work of Anghel et al. where the samples are prepared by the chemical precipitation technique [12]. As the $M_s$ and $H_c$ values are only been reported for 2% of the dopants in the matrix, we have used the given parameters to evaluate the $H_c$ for 5% dopants as well. The details of these calculations shall be provided in the later sections. The reported and calculated $M_s$ and $H_c$ values are given in Tab. 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Amount</th>
<th>$M_s$ (A/m)</th>
<th>$H_c$ (A/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe:ZnO</td>
<td>2%</td>
<td>7.63</td>
<td>20.7(±0.02) X10^3</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>50.3</td>
<td>39.8(±0.02) X10^3</td>
</tr>
<tr>
<td>Co:ZnO</td>
<td>2%</td>
<td>2.4</td>
<td>2(±0.1) X10^3</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>1.336</td>
<td>33(±0.1) X10^3</td>
</tr>
<tr>
<td>Ni:ZnO</td>
<td>2%</td>
<td>1.336</td>
<td>4(±0.1) X10^3</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>4.453</td>
<td>15(±0.1) X10^3</td>
</tr>
</tbody>
</table>

3. RESULT AND DISCUSSION

3.1. Stoner-Wohlfarth model

The energy density as given in Eq. 1 can also be written as

$$E(\theta) = \sin^2(\varphi - \theta) - h \cos \theta$$

where $h=H/H_K$ is a dimensionless constant for a given $\varphi$ and $H_K$ is the anisotropy field. $K_{eff}$ can be obtained by the relation $K_{eff} = \frac{\mu_0 M_s}{2} H_K$.

At equilibrium, magnetization points along a direction defined by particular $\theta$ that minimizes the energy for which $\theta = \varphi$ for which total energy density is minimum. For certain values of applied magnetic field, two energy minima $\theta_1$ and $\theta_2$ are obtained which are further used to plot hysteresis curves. The critical field (switching field) for which the magnetization value jumps from one energy minimum to another is denoted by $H_s$[8]:

$$H_s = \frac{H_K}{(\sin^{2/3} \varphi + \cos^{2/3} \varphi)^{3/2}}$$

Analogous to the thin-films, we assume that in these systems also the dipolar energy minimizes with the perpendicular magnetic anisotropy in the system [13]. However for $\varphi=90^\circ$, no magnetic hysteresis was observed. Therefore, the maximum $\varphi=85^\circ$ is considered in order to reproduce the experimental hysteresis curves in this article.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$H_K$(A/m)</th>
<th>$H_s$(A/m)</th>
<th>$K_{eff}$(J/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe:ZnO(5%)</td>
<td>23.3X10^4</td>
<td>17.8 X10^4</td>
<td>7.37</td>
</tr>
<tr>
<td>Co:ZnO(5%)</td>
<td>18.2 X10^4</td>
<td>13.9 X10^4</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Ni:ZnO(5%)  

8.4 X10^4  

6.4 X10^4  

0.24

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\Delta H_{pp}(G)$</th>
<th>$M_s(A/m)$</th>
<th>$a$</th>
<th>Reversal time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe:ZnO(5%)</td>
<td>1074.54</td>
<td>50.3</td>
<td>3.4X10^4</td>
<td>0.00150</td>
</tr>
<tr>
<td>Co:ZnO(4%)</td>
<td>238.8</td>
<td>1.3</td>
<td>29.2 X10^3</td>
<td>0.00002</td>
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<tr>
<td>Ni:ZnO(5%)</td>
<td>801.38</td>
<td>4.3</td>
<td>28.3 X10^3</td>
<td>0.00025</td>
</tr>
</tbody>
</table>

Figure 1: Hysteresis curve of Zn$_{1-x}$O (x=0.05) where M=Fe(dotted line), Co(filled circle) and Ni(open circle).

In Fig. 1 Fe doped ZnO gives highest $H_c$ value 39.8(±0.02)10$^3$ whereas Ni doped ZnO gives rise to the lowest $H_c$. Because of high $H_c$ Fe is the most effective dopant for producing ferromagnetism in nanoparticles of ZnO at 5% as seen in figure 1. Fast switching of magnetization the switching field should be low. The Table 2 shows that Ni containing ZnO is suitable for better magnetic recording purpose because of its lowest switching field. The anisotropy energy density ($K_{eff}$) of transition metals doped ZnO is found to be very low (10$^{-1}$-10$^1$J/m$^3$) as compared to that of the bulk metals (10$^2$.J/m$^3$).

Figure 2: Magnetization reversal path with time in (a)Fe:ZnO, (b) Co:ZnO and (c) Ni:ZnO for 5% dopant. For clarity break has been shown in time scale.

Table 3: Damping constant of transition metal doped ZnO
3.2. Time Evolution of Magnetic Moment Orientation

To evaluate the time dependent magnetic moments, Landau-Lifshitz-Gilbert equation [11, 14] is been used. The magnetic damping constant $\alpha$ is also known as Gilbert damping constant and is given by $4\pi v/\gamma M_s$ where, $v$ is the relaxation frequency, $\gamma$ is the gyromagnetic ratio and $M_s$ is the saturation magnetization [15]. Large values of $\alpha$ are required for ferromagnetic materials in order to achieve high-speed magnetization switching. The value of $\alpha$ for transition metal doped in ZnO has not been reported so far. We evaluate relaxation frequencies using the linewidth of EPR signal ($\Delta H_{pp}$) for Zn$_{1-x}$M$_x$O [16, 17]. The calculated value of $\alpha$ and the reversal time is reported in the Table 3. Co containing ZnO has the larger value of damping constant ($\alpha \approx 29 \times 10^3$). It is observed for lower applied magnetic field, reversal time of magnetic moment is lowest in Co:ZnO (Fig. 2). As there is not large difference in $\alpha$ value of Co and Ni doped ZnO, reversal time of magnetic moment in Ni doped ZnO is close to the value for Co:ZnO. In case of Fe:ZnO the $\alpha$ value is lowest and the switching time is found to be very high.

It is known that both spin-orbit and s-d interactions are the major causes of magnetic damping for ferromagnetic materials [14, 18]. However, at present, we cannot evaluate how much each interaction contributes to the damping parameter due to lack of detailed investigations, both experimentally and theoretically.

4. CONCLUSION

The results suggest that the dopant type plays an important role in the magnetic properties of Zn$_{1-x}$M$_x$O nanoparticles. The anisotropy constant $K_{eff}$ is smaller in these samples than those reported for the bulk metals. Time evolution of magnetic moment is observed for Fe, Co, Ni containing ZnO nanosystems. In Co doped ZnO, switching of magnetic moments are faster as compared to Ni and Fe doped ZnO. Because of low damping parameter and longer relaxation time for Fe, it is not a suitable dopant for magnetic recording in ZnO matrices.

Acknowledgements

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References

magnetization, bandgap, and lattice volume of transition metal (M = Cr, Mn, Fe, Co, or Ni) doped Zn$_{1-x}$M$_x$O nanoparticles. J. Appl. Phys., 107, 09E314.


