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일축이방성 $4f-3d$ 화합물의 부격자이방성에 관한 반도식적 분석법

한국표준과학연구원 김윤배
吉林大學 金漢民

A semi-graphical method to analyze the sublattice anisotropy of $4f-3d$ compounds with uniaxial magnetocrystalline anisotropy

KRISS Y.B. Kim
Jilin University Jin Han-min

1. Introduction

A graphical method solving directly the anisotropy constants was firstly applied to Co single crystal by Sucksmith and Thompson [1]. The authors of this paper [2] extended the method to higher order anisotropy constants and applied to analyze the anisotropy of $Pr_2Fe_{14}B$ at 290 K. These are, however, based on the rigid coupled magnetization model, and give no ideal solution for the magnetization behaviour of $4f-3d$ compounds at low temperature. At low temperature near 4.2 K, the $4f-$ anisotropy becomes strong and an additional energy for the exchange interaction is needed to describe the magnetization state. In this paper, we suggest a semi-graphical method to analyze the anisotropy of two sublattice system with uniaxial anisotropy.

2. Analyzing procedures

In order to simplify the calculation, let us consider a tetragonal $4f-3d$ compound with easy magnetization $c-$axis in which the anisotropy of $3d$ sublattice is well described by K_1. If we assume an external field $\vec{H}$ is applied perpendicular to $c-$axis and all the sublattice moments rotate on the plane made by $c-$axis and $\vec{H}$, the free energy of the compound is expressed as follows ;

$$\begin{aligned} E = & K_{1(3d)}\sin^2\theta_{3d}+K_{1(4f)}\sin^2\theta_{4f}+K_{2(4f)}\sin^4\theta_{4f}+K_{3(4f)}\sin^4\theta_{4f}\cos 4\varphi_{4f} \\ & +K_{4(4f)}\sin^6\theta_{4f}+K_{5(4f)}\sin^6\theta_{4f}\cos 4\varphi_{4f}-M_{3d}H\sin\theta_{3d}-M_{4f}H\sin\theta_{4f} \\ & +N_{4f3d}M_{3d}M_{4f}(\sin\theta_{3d}\sin\theta_{4f}+\cos\theta_{3d}\cos\theta_{4f}) \end{aligned} \tag{1}$$

Here, the notation θ is the inclination angle of sublattice magnetic moments from [001] axis, and φ is the angle from [100] of the projection of sublattice moments (or $\vec{H}$) on basal plane.

If $\vec{H}$ is parallel to [100] ro [110], from equilibrium conditions of free energy and the relations $\sin\theta_{3d}=m_{3d}/M_{3d}$, $\sin\theta_{4f}=m_{4f}/M_{4f}$ and $m=m_{4f}+m_{3d}$, following equations are obtained ;

$$2K_{1(3d)}\frac{m-m_{4f}}{M_{3d}}-M_{3d}H+N_{4f3d}M_{3d}M_{4f}\left\{\frac{m_{4f}}{M_{4f}}-\frac{m-m_{4f}}{M_{3d}}\frac{\pm\sqrt{1-(m_{4f}/M_{4f})^2}}{\sqrt{1-(m-m_{4f})^2/M_{3d}^2}}\right\}=0 \tag{2}$$

$$2K_{1(4f)}\frac{m_{4f}}{M_{4f}}+4\left(\frac{m_{4f}}{M_{4f}}\right)^3(K_{2(4f)}\pm K_{3(4f)})+6\left(\frac{m_{4f}}{M_{4f}}\right)^5(K_{4(4f)}\pm K_{5(4f)})-M_{4f}H$$
$$+N_{4f3d}M_{3d}M_{4f}\left\{\frac{m_{3d}}{M_{3d}}-\frac{m_{4f}}{M_{4f}}\frac{\sqrt{1-(m_{3d}/M_{3d})^2}}{\pm\sqrt{1-(m_{4f}/M_{4f})^2}}\right\}=0 \quad (3)$$

Here, m , m_{4f} and m_{3d} represents the magnetization observed in measurement direction, the component of $3d$−sublattice and $4f$−sublattice, respectively. The " ± " sign for $\pm\sqrt{1-(m_{4f}/M_{4f})^2}$ is positive for ferromagnetic coupling $(0<\theta_{4f}<\pi/2)$) and negative for antiferromagnetic coupling $(\pi/2<\theta_{4f}<3\pi/2)$ of $4f-3d$ sublattices.

If we know the value of $K_{1(3d)}$, the sublattice magnetizations at a given H can be calculated numerically by applying the experimental value of m and H into equation (2). The $4f$−sublattice anisotropy constants, then, can be determined by graphically by applying the sublattice magnetizations into equation (3) according to the following procedures ; At first, make a plot of $-M_{4f}H+N_{4f3d}M_{3d}M_{4f}\left\{\frac{m_{3d}}{M_{3d}}-\frac{m_{4f}}{M_{4f}}\frac{\sqrt{1-(m_{3d}/M_{3d})^2}}{\pm\sqrt{1-(m_{4f}/M_{4f})^2}}\right\}$ vs. $2\frac{m_{4f}}{M_{4f}}$. Since high power terms of m_{4f}/M_{4f} ($K_{2(4f)}\pm K_{3(4f)}$ and $K_{4(4f)}\pm K_{5(4f)}$ terms) are neglectable at low field region, the plot should be linear at the low field region, and $K_{1(4f)}$ can be determined by the negative slope of the plot. (The $K_{1(4f)}$ also can be determined from the initial susceptibility of hard magnetization curve [3]). Secondly, apply the value of $K_{1(4f)}$ determined by above mentioned process into equation (3) and make a plot of $2K_{1(4f)}\frac{m_{4f}}{M_{4f}}-M_{4f}H+N_{4f3d}M_{3d}M_{4f}\left\{\frac{m_{3d}}{M_{3d}}-\frac{m_{4f}}{M_{4f}}\frac{\sqrt{1-(m_{3d}/M_{3d})^2}}{\pm\sqrt{1-(m_{4f}/M_{4f})^2}}\right\}$ vs. $4\left(\frac{m_{4f}}{M_{4f}}\right)^3$. This plot shall show a linear relation again up to higher field region in which the $\left(\frac{m_{4f}}{M_{4f}}\right)^5$ term is neglectable. Then, the negative slope of the linear portion is $K_{2(4f)}\pm K_{3(4f)}$. Finally, put again the values of $K_{1(4f)}$ and $K_{2(4f)}\pm K_{3(4f)}$ into equation (3), and make the plot of $2K_{1(4f)}\frac{m_{4f}}{M_{4f}}-M_{4f}H+4\left(\frac{m_{4f}}{M_{4f}}\right)^3\{K_{2(4f)}\pm K_{3(4f)}\}+N_{4f3d}M_{3d}M_{4f}\left\{\frac{m_{3d}}{M_{3d}}-\frac{m_{4f}}{M_{4f}}\frac{\sqrt{1-(m_{3d}/M_{3d})^2}}{\pm\sqrt{1-(m_{4f}/M_{4f})^2}}\right\}$ vs. $6\left(\frac{m_{4f}}{M_{4f}}\right)^5$. Then, the $K_{4(4f)}\pm K_{5(4f)}$ can be determined by the negative slope of the linear plot. If experimental data is out of linear relation at high field region, it may be due to the effect of higher order anisotropy constants or the leaving of magnetic moments from original rotation plane. If it is due to higher order anisotropy constants, they can be determined by applying the same procedure to higher order anisotropy constants. The indivisual anisotropy constants can be calculated from the results obtained from magnetization curves of [100] and [110] directions.

References

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