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DOMAIN STRUCTURE IN ISING FERROMAGNET SmNi₅

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Abstract. – The domain structure in SmNi₅ single crystals has been studied at 5 K by means of the oxygen cryocondensation method. The domain wall energy has been estimated to be 0.7 erg/cm². The calculations of the Ising domain wall energy have been performed. Consistence between experimental and theoretical values has been found.

1. Introduction

Systematic studies of the narrow domain walls have started in the early seventies, when several groups (see [1] for references) recognized the unusual magnetization processes in highly anisotropic ferromagnets. It has been shown that under certain conditions the domain walls in these materials can become very narrow (even "monoatomic" or "ferroelectric"), so that the traditional continuum description of the domain walls should not be adequate for such ferromagnets. The consequence of the domain wall narrowness is the dependence of the domain wall energy on the wall position with respect to the crystal lattice, which gives rise to the intrinsic coercive field. Up to now, only narrow domain wall models with the magnetic moment rotating inside the wall were considered. These models are not valid, however, for Ising ferromagnets. The SmNi₅ system analysed in the present paper is an hexagonal ferromagnet (lattice constants: \(a = 4.95 \, \text{Å}, \ c = 3.97 \, \text{Å}\)) with a Curie temperature \(T_c = 27.5 \, \text{K}\). As it has been shown recently [2], in SmNi₅, the curve of primary magnetization along the orthohexagonal \(c\)-axis exhibits a very sharp jump at about 3 kOe, and then the magnetization increases slowly. In the magnetic field directed perpendicularly to the \(c\)-axis the dependence of the magnetization on the field intensity is completely different, similar to that of Van Vleck paramagnets. This suggests that SmNi₅ should be considered as a good three-dimensional Ising system. The values of the crystal field and molecular field parameters determined in [2] strongly confirm this suggestion. Therefore, in SmNi₅, one should expect narrow domain walls with linear, Ising-like distribution of magnetization inside the walls rather than Bloch-like walls.

The main purpose of this paper is to analyse the domain structure in SmNi₅ single crystals in order to determine the domain wall energy and the character of magnetization distribution inside the walls.

2. Experiment

Single crystals of SmNi₅ have been prepared by the Czochralski method in an induction furnace. The domain structure has been investigated at 5 K on the surface perpendicular to the \(c\)-axis. Since the crystals are opaque and the magnetooptical Kerr effect is too small to be used for domain structure observation, we have applied the oxygen cryocondensation method [3] to make the domain structure visible. In the oxygen technique the sample is located into the chamber containing gaseous helium and cooled to the chosen low temperature \((T < 35 \, \text{K})\). At this temperature the gaseous \(\text{He} – \text{O}_2\) mixture is introduced into the chamber. The introduced oxygen solidifies in the form of many fine particles, which are attracted by stray fields to the domain walls due to the positive magnetic susceptibility of oxygen. As the example, the oxygen pattern of the domain structure obtained on the SmNi₅ single crystal is presented in figure 1.

It has been found that the domain structure appearing in SmNi₅ is typical for uniaxial highly anisotropic materials. At the sample surfaces perpendicular to the \(c\)-axis the characteristic undulatory domain walls and numerous spike and star-like surface domains have been observed. For the analysis of the obtained domain structure patterns the Bodenberger-Hubert approach

Fig. 1. – Magnetic domain pattern on the basal plane of SmNi₅ single crystal, obtained by means of the oxygen cryocondensation method.
[4] has been used. Bodenberger and Hubert showed that the average surface domain width in a thick plate cut perpendicularly to the easy axis is given by:

\[ w_1 = \beta \frac{4\pi}{M_0^2} \gamma, \]

where \( \gamma \) is the domain wall energy density, \( M_0 \) is the magnetization and \( \beta \) is a geometrical factor depending on the type of surface structure. According to [4] \( \beta \) is equal to 0.31 for SmCo5 and for similar magnetic materials of high magnetocrystalline anisotropy. In the frame of the method [4] the value \( \gamma = (0.7 \pm 0.05) \) erg/cm\(^2\) has been obtained for SmNi5 (for saturation magnetization \( m = 0.7 \mu_B/\text{SmNi}_5 \) [2]).

3. Discussion

To test the validity of the Ising domain wall model for SmNi5 the wall energy calculations for different wall positions with respect to the crystal lattice and for different values of wall width have been performed. In the calculations the standard Ising Hamiltonian has been used:

\[ \mathcal{H} = -2J \sum_{i \neq j} S_i^z S_j^z, \]

where \( J \) is the exchange integral (\( J = 0.51 \times 10^{-16} \) erg [2]), \( S_i^z \) denotes the \( z \)-th spin component of the \( i \)-th ion; the sum extends over all pairs of nearest neighbours in the crystal. The values of the thermal average \( \langle S^z \rangle \) have been calculated taking into account not only the ground multiplet of the \( \text{Sm}^{3+} \) ion (\( ^6H_{5/2} \)) but also two excited multiplets (\( ^6H_{7/2} \) and \( ^6H_{9/2} \)). Finally the following expression for the Ising domain wall energy has been obtained:

\[ \gamma = \frac{1}{2R} \left\{ \sum_i \sum_j -2J \left[ \langle S_i^z S_j^z \rangle - \langle S^z \rangle^2 \right] + \right. \]
\[ \left. - \sum_i k_B T \left[ F \left( \frac{S_i^z}{\langle S^z (T = 0 \text{ K}) \rangle} \right) - F \left( \frac{\langle S^z \rangle}{\langle S^z (T = 0 \text{ K}) \rangle} \right) \right] \right\}, \]

where

\[ F(x) = \ln 2 - \frac{1}{2} (1 + x) \ln (1 + x) - \frac{1}{2} (1 - x) \ln (1 - x), \]

\( R \) is the wall surface, \( k_B \) – the Boltzmann constant, \( T \) – temperature; index \( i \) enumerates all magnetic atoms in the sample, index \( j \) – all neighbours of the \( i \)-th atom.

The results of the calculations are summarized in figure 2, where the domain wall energy density \( \gamma \) as a function of the domain wall width \( \delta \) is presented for four differently positioned walls. Two curves denoted as A-0 and A-2 have been obtained for walls perpendicular to the \( a \)-axis with wall centres at the points (0, 0, 0) and (1/4, 0, 0), respectively. Two other curves (B-0 and B-2) describe the walls perpendicular to the orthohexagonal \( b \)-axis, with the wall centres at the points (0, 0, 0) and (0, 1/4, 0), respectively. The domain wall energies calculated for center positions mentioned above are limited and the values obtained for all other positions lie between them.

As it is seen in figure 2, at the temperature of 5 K the “ferroelectric” wall (the wall in which two neighbouring atomic layers have antiparallel oriented spins) perpendicular to the \( b \)-axis has the lowest energy. This energy does not depend on the wall position with respect to the atomic lattice, so the intrinsic coercive field in SmNi5 should be rather small. This conclusion is consistent with the magnetization measurements [2]. Also the calculated value of the domain wall energy is in agreement with that obtained experimentally.