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## GMR in intermetallics

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### **Abstract**

Typical examples of giant magnetoresistance effects observed in intermetallic compounds at various conditions are reviewed and some comparisons with the GMR magnetic multilayer systems are shown. The possibilities of tuning material parameters desired for applications are discussed in the context of present understanding of the mechanisms responsible for GMR in this class of materials.

### **I. INTRODUCTION**

The large application potential of magnetoresistive devices has recently motivated intensive investigations of resistivity changes accompanying the reorientation of magnetic moments in various materials when exposed to external magnetic field. Since the discovery of the giant magnetoresistance (GMR) in multilayers,<sup>1-4</sup> a massive research effort is focused on these artificially fabricated structures, in which the local magnetization directions can rotate in moderate magnetic fields. A typical material of this class can be schematically labeled as M<sub>m</sub>N<sub>n</sub>, which means a structure of piled up blocks of m atomic layers of a magnetic element M (e.g. Fe, Co) alternating with blocks of n atomic layers of a non-magnetic element N (e.g. Cu, Cr). Below certain temperature, the magnetic moments within one M-block are by rule ordered ferromagnetically. The RKKY-type exchange interaction mediated by the N-block can be for certain thickness of the block

antiferromagnetic which yields antiparallel (AP) coupling between two subsequent M-blocks. Application of a magnetic field sufficient to compensate the antiferromagnetic interaction breaks the antiparallel coupling leads the system to a forced parallel (P) alignment of all magnetic moments. This transition is usually continuous and frequently yields almost a linear response of the magnetization to the magnetic field. The electrical resistivity of such a multilayer system in zero field ( $\rho_{AP}$ ) is by rule considerably larger than in the field-aligned state ( $\rho_P$ ). If we define of the magnetoresistance as:

$$\Delta\rho/\rho = [\rho(B) - \rho(0\text{ T})]/\rho(0\text{ T}), \quad (1),$$

than we obtain for the magnetoresistance in the state of the parallel alignment of moments:

$$\Delta\rho = (\rho_P - \rho_{AP})/\rho_{AP} \quad (2),$$

This magnetoresistance is usually negative and when reaching values of the order of some tens %, the notion "Giant Magnetoresistance" is widely used. In fact, these magnetic multilayer structures and their transformations upon applied magnetic field resemble bulk crystalline materials with antiferromagnetic structures built up of antiferromagnetically coupled ferromagnetic layers. When inspecting literature we can find papers reporting sometimes decades ago<sup>5</sup> on magnetoresistance effects in such bulk materials being more sizeable than the "Giant Magnetoresistance" in the heterogeneous multilayer structures. In the present paper, we review some typical examples of bulk materials which exhibit considerable magnetoresistance phenomena and to discuss possible tuning material parameters desirable for applications.

## II. MAGNETORESISTANCE PHENOMENA IN BULK INTERMETALLICS

Although publications on systematic studies of the magnetoresistance in magnetic intermetallic materials are generally lacking (exceptions may be found in refs. 6 and 7), there exist relatively rich set of papers devoted to magnetoresistance phenomena in individual compounds or alloy systems. Basically the GMR effects are reported in two classes of materials, antiferromagnets on one hand and the spin fluctuators on the other. In compounds of the first family, much richer family we observe GMR accompanying usually

various metamagnetic transitions between two types of magnetic structures whereas the magnetic phase transitions in the other class of materials which cause sizeable magnetoresistance effects are connected with the stabilization (or better formation) of magnetic moments in systems of itinerant electrons.

#### **A. GMR on metamagnetic transitions in antiferromagnets**

An example of one of the largest magnetoresistance effects in regular-rare-earth intermetallic compounds is the antiferromagnet  $\text{NdGa}_2$ .<sup>8</sup> The sequence of metamagnetic transitions in this compounds yield  $\Delta\rho/\rho = -40\%$  in 2 T, where probably the "ferromagnetic" alignment of Nd magnetic moments is achieved. Similar a double metamagnetic transition process in  $\text{NdCu}_2$  is accompanied by  $\Delta\rho/\rho = -10\%$  in 3 T.<sup>9</sup> The GMR effects in this sort of compounds are confined to very low temperatures, because of the low value of  $T_N$ , which is a consequence of weak exchange interactions between rare-earth moments.

Higher ordering temperatures (and related extension of the temperature interval of appearance GMR) in rare-earth containing materials can be expected when some late transition metals are involved. In this respect,  $\text{SmMn}_2\text{Ge}_2$ , which is antiferromagnetic between 100 and 150 K and ferromagnetic outside this range,<sup>10,11</sup> should be mentioned when searching for materials which might be more attractive for applications. The transition from the antiferromagnetic state to a low-resistance "ferromagnetically" aligned state can be induced by moderate fields (below 1 T), but the reduction of the resistivity does not exceed 10%. A similar situation can be found in  $\text{Ce}(\text{Fe}_{1-x}\text{Co}_x)_2$ , with  $x > 0.1$ . This material becomes ferromagnetic below  $\sim 180$  K but when lowering temperature further a transition to the low-temperature antiferromagnetic state appears at about 80 K.<sup>12</sup> This transition manifests in a dramatic increase of the electrical resistivity.<sup>13</sup> The ferromagnetic (and presumably the low-resistance) state can be then recovered by application of a sufficient magnetic field.<sup>13</sup> Similar loss of ferromagnetism at low temperatures can be observed also for small substitutions of Fe in  $\text{CeFe}_2$  by some p-metals<sup>14</sup> or 4d and 5d transition metals,<sup>15-17</sup> which should also lead to large magnetoresistance effects.

## **B. GMR connected with band metamagnetism**

In certain class of compounds containing transition-metal elements like Co, considerable magnetoresistance effects can be connected with the suppression of spin fluctuations and subsequent moment formation. As characteristic energies of such fluctuations are as a rule large, available magnetic fields can be effective only if assisted by the action of another, e.g. rare-earth, sublattice, as in some  $R\text{Co}_2$  compounds. Thus although the related resistance variations are very large, they can be achieved only in a limited temperature range. For some of rare earths, the Co moments are formed from the highly susceptible matrix of the 3d states by the concerted action of ordered rare earth moments at the Curie temperature  $T_C$ , which thus becomes a first order transition. Above  $T_C$ , the large resistivity is affected not only by disordered rare-earth moments, but strong spin-fluctuations in the Co 3d-electron subsystem contribute, as well. The electron-spin fluctuation scattering is removed in the transition by a sudden drop of a considerable absolute value (e.g.  $80 \mu\Omega\text{cm}$  in  $\text{DyCo}_2$ ; similar effects can be observed also in  $\text{HoCo}_2$ ,  $\text{ErCo}_2$  and  $\text{TmCo}_2$ ).<sup>6,18</sup> The effect of exchange fields of the 4f subsystem on the 3d one can be naturally assisted by the external magnetic field, which shifts the transition towards higher temperatures. Thus, for a particular temperature from a limited range above  $T_C$ , the resistivity can be reduced drastically. Although present in compounds containing rare earths, the effect is clearly due to the onset of 3d magnetism in these cases.

## **III. PERSPECTIVES OF GMR IN INTERMETALLICS**

Concerning application perspectives of GMR effects in intermetallics, transition-metal based intermetallics, in particular, serve a wide field for further research. Since the direct exchange interactions between transition-metal atoms are strong, magnetic ordering and GMR phenomena in this class of materials may be obtained at room and higher temperatures.

Although many material parameters do not comply with the requirements for applications, we have shown that a systematic study of GMR in intermetallics may guide the search for suitable candidates in this class of materials.

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