GIANT MAGNETO-IMPEDANCE BEHAVIOUR IN FERRO-MAGNETIC MATERIALS

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ABSTRACT

The ferromagnetic amorphous and nanocrystalhne materials exhibited a new phenomenon called Giant magneto-impedance (GMI). In this phenomenon these materials exhibited a sensitive change in an AC voltage with the application of a small DC magnetic field. GMI properties were investigated for four different compositions of amorphous and nanocrystalline ferromagnetic alloys for ribbon and wire samples. The impedance behaviour was strongly affected by magnetostriction of the materials. In nearly zero magnetostrictive amorphous wires about 100% change per Oe of magnetic field was observed.

Key Words : Water-quenching, Magneto-impedance, Nano-crystalline, Magneto-resistive.

INTRODUCTION

Magnetoresistive (MR) sensor have been widely used in the intermediate range of field (10^{-6} - 10^{2} Gauss). The thin film magnetosresistive sensor was first discovered in 1971 by evaporation of 80/20Ni-Fe films deposited on non-magnetic substrate [1]. The low resistance change ratio of 2-3% for a field of 20-40 Gauss restricts application of thin film MR sensor till the discovery of giant magnetoresistance (GMR) in multilayers in 1988 [2]. The nominal values of resistance change of the multilayer system is very large and of the order 50-70% [3-5]. However, the magnetic saturation field for the GMR material is high and the sensitivity to the field is very low (~ 1% per Gauss). Besides, there are hysteresis and temperature instability problems in GMR materials.

During the progress in GMR materials, the development of magnetic sensor material covered a significant milestone with the discovery of a phenomenon called Giant-magneto-impedance (GMI). The Giant magneto-impedance effect has been recently observed in soft ferromagnets [6]. This effect is explained by classical electromagnetic theory, according to which the impedance (Z) of a sample depends on its effective transverse magnetic permeability (am), and Ml effects result from change in μm due to the application of an external magnetic field (H_{ex}). The observed variation in magneto-impedance was found to be of the order of 10 to more than 100 per Gauss external field depending on the material composition, shape and the frequency of the applied current [7-8]. Such large change in magneto-impedance value at the application of external dc magnetic field made the amorphous and nanocrystalline materials as a promising candidate for the development of micro magnetic sensor [9].

In this paper, we will focus on the preparation procedure of the Fe-based materials and their GMI characteristics. Their potential sensing applications of GMI materials will also briefly be described here.

MATERIAL PREPARATION

The measurement of Giant magneto-impedance was conducted on amorphous materials of two different shapes - one is in the form of ribbon and other is in the form of wire. The materials were prepared by rapid solidification technique. The ribbon shaped sample with nominal composition $Fe_{70.8}Nb_{3.7}Cu_1Al_{2.7}Mn_{0.7}Si_{13.5}B_{7.6}$ was prepared by single roller technique whereas the wires were prepared by in-water quenching system as shown in figure 1. Wires of diameter 125μm having three different chemical compositions $Fe_{77.5}Si_{7.5}B_{15}$, $Co_{72.5}Si_{12.5}B_{15}$ and $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ have been used for the GMI measurements.

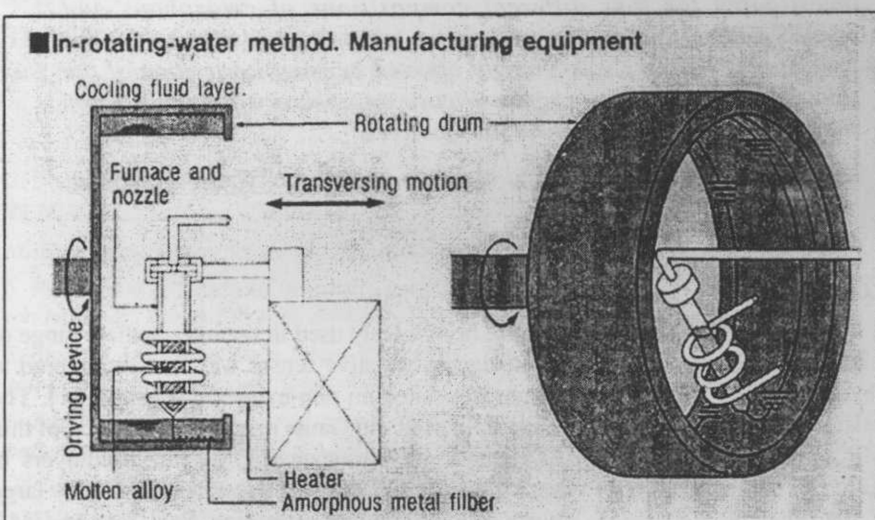


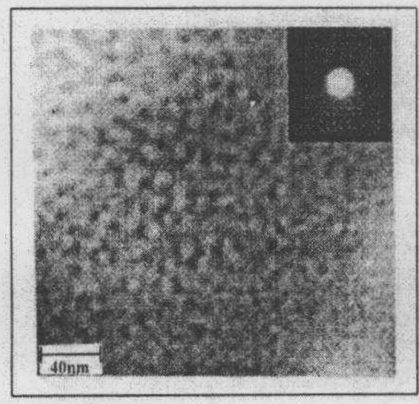
Fig. 1 : Schematic representation of in-water quenching system for the preparation of wire

PROPERTY EVALUATION

About 10cm long samples have been placed, along the axis of a Helmholtz coil for the magnetoimpedance measurement. The impedance was measured by four-probe technique where current at frequency in the MHz level was sent through the current probe and voltage across the voltage probe was measured by a signal analyser. For the alloy $Fe_{70.8}Nb_{3.7}Cu_1Al_{2.7}Mn_{0.7}Si_{13.5}B_{7.6}$ ribbons measurement was carried out for as-prepared as well as annealed samples. In the case of wire samples of $Fe_{77.5}Si_{7.5}B_{15}$, $Co_{72.5}Si1_{2.5}B_{15}$ and $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ alloys magnetoimpedance was measured only in the as-received state.

RESULTS AND DISCUSSIONS

The as-prepared ribbon sample was in amorphous state as observed from the TEM micrograph (Fig. 2a). Figure 3 shows the percentage change in impedance value for as-prepared and annealed $Fe_{70.8}Nb_{3.7}Cu_1Al_{2.7}Mn_{0.7}Si_{13.5}B_{7.5}$ against the applied d.c field along the direction of the current through the sample. Maximum change in impedance value for as-prepared sample was about 9%. However, the change in impedance decreased when the sample was annealed at 725K and 825K. The maximum change in impedance again increased to 18% when the material was annealed at 875K.



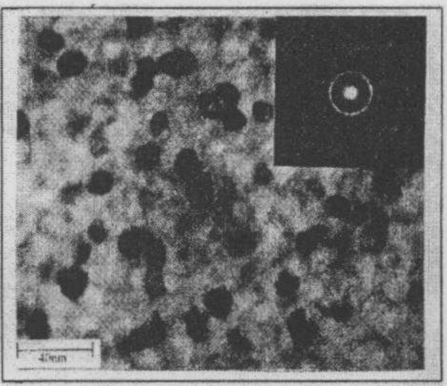


Fig 2 : TEM micrograph of (a) $Fe_{70.8}Nb_{3.7}Cu_1Al_{2.7}Mn_{0.7}Si_{13.5}B_{7.6}$ alloy ribbon and (b) annealed at 875K

The magnetoimpedance at the high frequency magnetising current was primarily caused by the interaction between the surface domain wall and the D.C. magnetising field. At the initial stage of annealing, the stress relaxation tpok place. As the material was positive magnetostrictive in nature in its amorphous state, there would be less perpendicular domains at the surface of the material and hence, the interaction between the applied magnetic field with the surface domain was less resulting in low impedance value. After annealing at higher temperature at 875K nanocrystalline Fe_3Si and Fe_3Al was formed and dispersed in amorphous matrix as shown in figure 2b. This improved the soft magnetic properties as well as decreased the magnetostriction constant as Fe_3Si is negative magnetostrictive material whereas, the amorphous matrix is positive magnetostrictive in nature. This microstructural modification at the surface resulted into more perpendicular domains at the surface and the sensitivity of the external film to the magnetoimpedance increased for 875K annealed sample (Fig. 3)

The exothermic pleaks in DSC plots indicated that the wire samples were amorphous in the as-received state. Figure 4 shows the variation of magnetoimpedance with applied D.C. field for three wire samples $Fe_{77.5}Si_{7.5}B_{15}$, $Co_{72.5}Si_{12}B_{15}$ and $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ which were positive, negative and nearly zero (but negative) magnetostrictive materials respectively. The maximum change in magnetoimpedance observed for $Fe_{77.5}Si_{7.5}B_{15}$ was about 22% and the impedance value decreased almost linearly with the increase of applied D.C. field. In case of $Co_{72.5}Si_{12.5}B_{15}$ alloy the maximum 85% change in impedance was

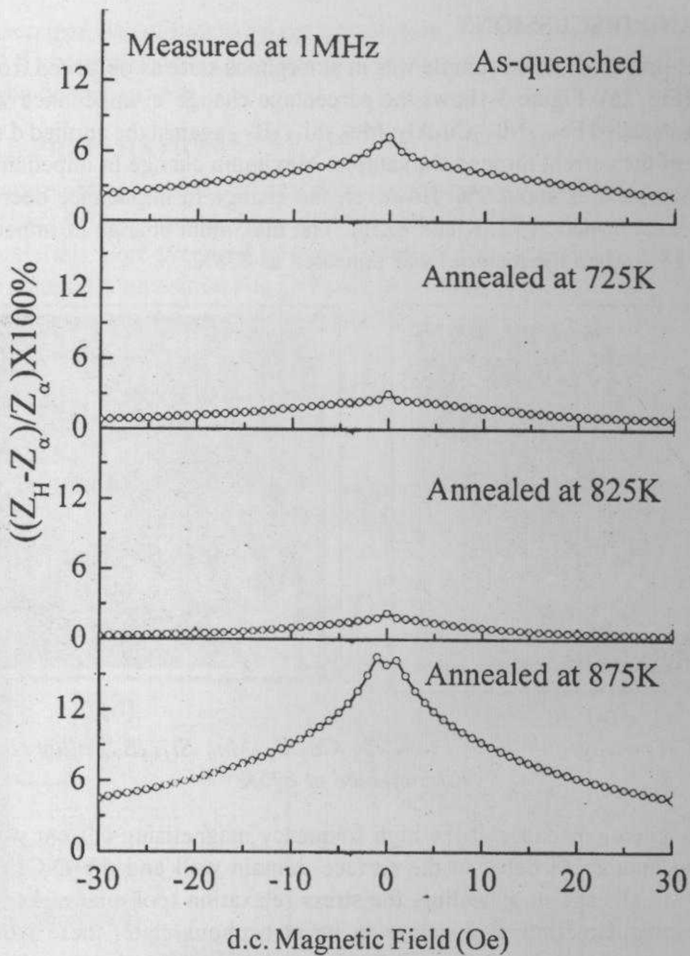


Fig 3 : Magnetoimpedance behaviour of various annealed $Fe_{70.8}Nb_{3.7}Cu_1Al_{2.7}Mn_{0.7}Si_{13.5}B_{7.6}$ ribbons

observed. Impedance decreased sharply up to 3Oe of field and remained constant up to 18Oe of field and then decreased linearly with the field. The maximum change in magnetoimpedance value was found in $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ alloy which was about 350% At the initial stage (<1 Oe), sharp increase in impedance value was observed followed by an exponential decrease with the application of D.C. field.

The variation of magnetoimpedance for the wire samples of three alloys can be explained from their variation in magnetostriction constant resulting in different domain structure. During the preparation of wires by in-water quenching, the outer surface of the wire solidifies first and then the inner surface thereby leading to a shrinkage. Owing to this differential cooling process, a unique stress distribution occurs resulting in two distinct anisotropy in the magnetostrictive material. In the case of positively magnetostrictive

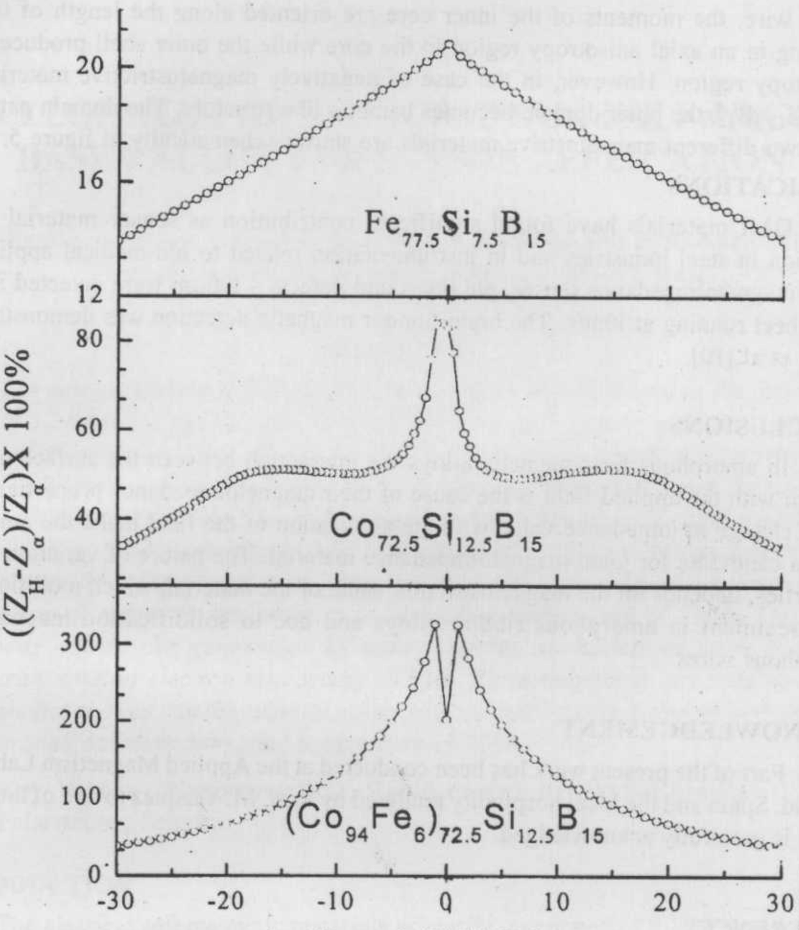


Fig 4 : Magnetoimpedance of different amorphous wires

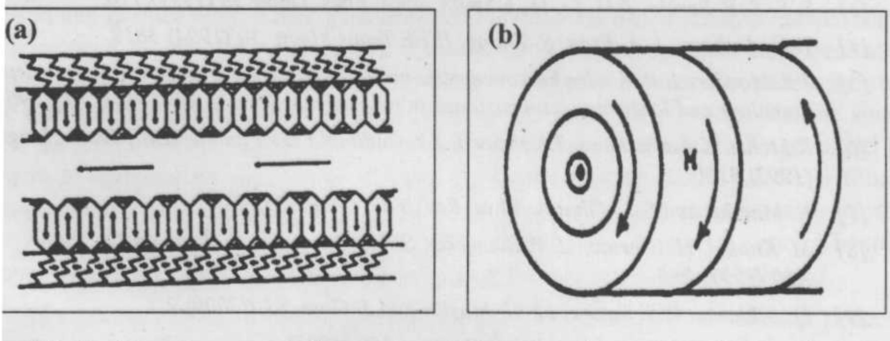


Fig 5 : Domain pattern of magnetostrictive wires (a) positive (b) negative

FeSiB wire, the moments of the inner core are oriented along the length of the wire resulting in an axial anisotropy region in the core while the outer shell produces radial anisotropy region. However, in the case of negatively magnetostrictive materials like $Co_{725}Si_{12.5}B_{15}$, the outer domain becomes bamboo like structure. The domain patterns of these two different magnetostrive materials are shown schematically in figure 5.

APPLICATIONS

GMI materials have found significant contribution as sensor material in flaw detection in steel industries and in instrumentation related to bio-medical applications. Using magnetoimpedance sensor, pin holes and defects ~ l00μm were detected in a thin steel sheet running at l0m/s. The brain tumour magnetic detection was demonstrated by Mohri et al.[10].

CONCLUSIONS

In amorphous ferromagnetic alloys the interaction between the surface magnetic domain with the applied field is the cause of their magnetoimpedance properties. About 300% change in impedance value with the application of the field make the amorphous alloy a candidate for giant magnetoimpedance material. The nature of variation of GMI properties, depends on the magnetostriction value of the material, which modifies due to heat-treatment in amorphous ribbon alloys and due to solidification mechanism in amorphous wires

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