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TRANSPORT AND MAGNETIC PROPERTIES OF $(Fe_{100-x}V_x)_{75}$ $P_{15}C_{10}$ AMORPHOUS ALLOYS

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ABSTRACT

$(Fe_{100-x}V_x)_{75}P_{15}C_{10}$ (x = 0, 5, 10 and 15) amorphous alloys in the form of ribbon were prepared by the standard melt spinning technique and studied their transport and magnetic properties. The resistivity follows 'Mooij correlation' at low temperature (300 - 93) K. The Hall resistivity and the magnetoresistance (MR) were measured in an applied magnetic field up to 0.6T at room temperature (RT = 300 K). Anomalous Hall effect was observed in the Hall resistivity measurement and MR was found to vary 0 - 8%. The saturation magnetization gradually decreased with the increase of V in the alloys at RT.

Key words: Resistivity, Mooij correlation, Hall resistivity, Magnetoresistance, Saturation magnetization

INTRODUCTION

Fe-based glassy alloys have been used in many electrical devices such as magnetic wires, sensors, band-pass filters, magnetic shielding and energy-saving electric power transformers (Szewieczek *et al.* 2007, Inoue *et al*. 2000, Schwarz *et al.* 2004) due to their satisfactory soft magnetic properties. Isotropic and anisotropic spin scattering mechanism should contribute to the resistivity and anomalous Hall effect in magnetically ordered amorphous metals (Heinemann *et al.* 1987, Cote *et al.* 1981, Sinha 1971, Kaul *et al.* 1986). For the scattering centers magnons, magnetic impurities and topological spin disorder had been proposed (Kaul *et al.* 1986, Kaul 1979).

In many cases, the structural disorder of the atomic sites was projected into the spin lattic (Cote *et al.* 1981, Erle *et al.* 1988) thus introducing a magnetic scattering contribution to the resistivity aside from thermal excitations. However, this contribution was found to be small in most cases (Jen *et al.* 1988); apparently, anisotropic scattering was a much more sensitive tool to identify spin scattering contributions in amorphous metals. Mooij (Mooij 1973) pointed out a correlation of the electrical resistivity (ρ) and its temperature coefficient of resistivity (TCR = $1/\rho \times d\rho/dT$) at low temperature in metallic alloys. Mooij (Mooij 1973) observed that TCR changes sign in a relatively narrow range of resistivity (i.e., the critical resistivity for which TCR = 0, $\rho_c \approx 100$ - 160 $\mu\Omega$-cm).

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For $\rho > 160$ μΩ-cm, the ρ usually decreases as temperature increases, in contrast to the normal metallic behavior seen for lower ρ systems. Most theoretical approaches to the Mooij correlation are based on quantum mechanical coherence effects, namely the incipient Anderson localization (Anderson 1958). It has been argued that the breakdown of the adiabatic approximation, leads to phonon-assisted tunneling and, therefore, to a negative TCR.

The effect arises from the Lorentz force acting on a moving charge in a magnetic field that curves its trajectory away from its straight line path. This causes charge to accumulate on one side of a conductor and create a potential difference across the opposite sides of a conductor. Other origins for the Hall effect which included the asymmetric scattering (known as skew scattering) from impurities with spin-orbit coupling. There are indeed two different manifestations of spin-orbit scattering contributing to the additional Hall effects (called the anomalous Hall effect). The first is skew scattering (Kondo 1962) and the second is the side jump (Berger 1970), which arises not only from spin-orbit scattering of impurities, but also from ordinary scattering when the electron conduction wave functions have their spin and orbit coupled together.

These mechanisms have been investigated in relation to certain (spin) scattering centers, such as spin waves (Kondo 1962) or spin impurities (Berger *et al.* 1979), but apparently other possible spin scattering centers have not been covered as yet. All metals show some MR, but up to only a few per cent. Nonmagnetic metals such as Au, exhibits small MR, but the magnitude is somewhat greater (up to 15%) in ferromagnetic metals such as Fe and Co. The semimetal Bi also shows ~ 18% MR in a transverse field of 0.6T which rises to a 40-fold change at 24T (Pippard 1984). Cu is more typical in the same very powerful field (24T) gives rise to change of only ~ 2% at RT. This is the classical positive magnetoresistance that varies as B^2 (B = applied magnetic field) in metallic ferromagnet such as CrO_2, Fe_3O_4 (Watts *et al.* 2000). It is absent in the free electron gas (Ashcroft *et al.* 1976) but appears when the Fermi surface is non spherical. This MR originates from the impact of the Lorentz force on the moving charge carriers similar to the Hall effect.

The magnetic properties of the transition elements are critically dependent on fine details of the electronic structure of the d-electrons. Within Stoner's model for ferromagnetism (Mizia *et al.* 2007), the effective moment of an iron atom in metallic iron and in iron alloys is mainly due to the effective spins of the 3d electrons. In general, the orbital moment of iron atoms is strongly quenched by the electric field. Alloying Fe with 3d elements affects the magnetic moments and also the saturation magnetization (Vincze *et al.* 1973, Wertheim *et al.* 1964). Although there was a wide consensus about this decrease theoretically (Hamada 1981, Moruzzi *et al.* 1992, Paja *et al.* 1979), the question has not been investigated in full detail experimentally. In the magnetically diluted

metallic systems the atomic moments are magnetically coupled via the RKKY (Mizutani 2003) type exchange interaction and ordered into a ferromagnetic domain structure for sufficiently low temperatures. In this study, authors will present the transport and magnetic behavior of a series of amorphous $(Fe_{100-x}V_x)_{75}P_{15}C_{10}$ (x = 0, 5, 10 and 15) alloys in detail.

MATERIALS AND METHODS

The $(Fe_{100-x}V_x)_{75}P_{15}C_{10}$ (x = 0, 5, 10 and 15) amorphous metallic ribbons were prepared from appropriate ratio of pure elements (Fe = 99.95%, V = 99.95%, P = 99.95% and C = 99.95%) by the standard melt spinning technique (Budhani *et al.* 1982) with wheel speed of ~ 6000 rev/min and cooling rate 1.8×10^6 °C/min. The XRD of the as prepared samples contains a broad peak within the 2θ values from 42 to 47° which confirms the samples are amorphous in nature (Karal *et al.* 2011). The ribbons used for measurements were ductile and had a width of 0.8 mm, a thickness of 25 μm and a length of 2 - 20 cm. The resistivity of the rectangular strip size samples was measured by conventional four point probe technique at RT and also at low temperature (300 - 93)K in a liquid nitrogen atmosphere. The Hall resistivity was measured using a conventional Hall geometry where the magnetic field applied to the perpendicular of the ribbon surface. A constant-current power supply (Model: Hewlett-Packard 6177C) and a digital nano-voltmeter (Model: Keithley 181) along with chromel constantan thermocouple were used in the measurement setup. When the resistance of a material changes with the applied magnetic field, the material is said to have the MR. MR is calculated by the following equation (Cullity 1972).

$$MR\% = \frac{R(B) - R(0)}{R(0)} \times 100\% \quad (1)$$

where, R(B) is the resistance in presence of magnetic field and R(0) is the resistance in absence of magnetic field. The magnetization was measured using a vibrating sample magnetometer (VSM) at RT and a magnetic field from 0 to 1.172 kG, as described in detail elsewhere (Karal 2011).

RESULTS AND DISCUSSION

Resistivity at RT

Fig. 1 shows the resistivity with V content at RT. The resistivity increases with the increase of V in the system as addition of V sites creates new spin scattering centers for the conduction electrons. Increase of V in the system also creates topological disorder adding to the resistivity. Thus the resistivity enhancement is assumed to be a cumulative effect of the additional spin scattering centers and the topological disorder.

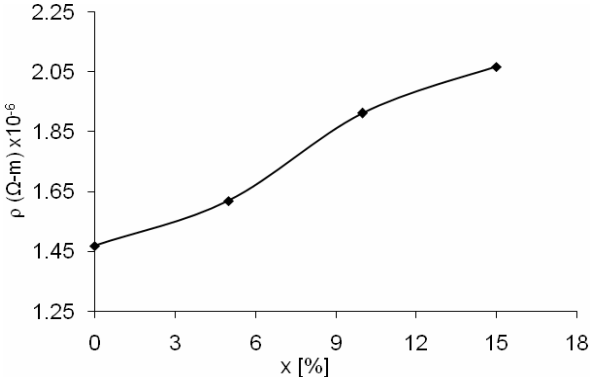

Fig. 1. Resistivity as a function of x [%].

Resistivity at low temperature (300 - 93) K

Fig. 2 shows the temperature dependent of normalized resistivity of the samples. The normalized resistivity decreases with the decrease in temperature for samples x = 0 and 5 that may be happening due to the decrease of incoherent electron-magnon scattering. For samples x = 10 and 15 the normalized resistivity increases with the decrease in temperature due to the structural topological scattering. For the samples x = 0 and 5 the measured ρ at RT were 141 μΩ-cm and 160 μΩ-cm respectively that shows positive TCR.

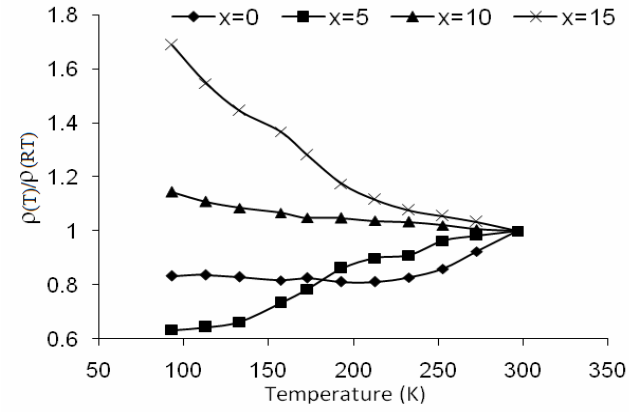

Fig. 2. Normalized resistivity as a function of temperature.

On the other hand, for the samples x = 10 and 15 the measured ρ at RT were 191 μΩ-cm and 206 μΩ-cm respectively that shows negative TCR. These results follow the Mooij-correlation of metallic glasses which was based on quantum mechanical coherence effects, namely incipient Anderson localization. Such transport phenomena deviates from

the conventional Boltzmann's transport. In the case of disorder metals, the wavelength of the conduction electron is comparable with the atomic distances which result in interference between scattering waves. The negative TCR is the result of reduction of interferences with temperature rises. Again, the gradual change from positive TCR to negative TCR with V content is accompanied by shortening of the mean free path down to an average atomic distance. An increase in ρ in this regime is due entirely to the mean free path effect and is free from the band structure effect.

Hall Resistivity at RT

Fig. 3 shows the Hall resistivity as a function of magnetic field upto 0.6 T at RT. The Hall resistivity has shown sharp increase initially with magnetic field. Once saturation is achieved, there is no domain motion as it has assumed a single domain. Hall resistivity increases with increase of V content and also the applied magnetic field.

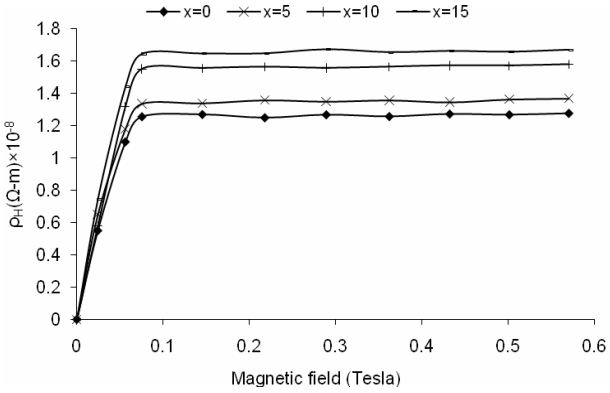

Fig. 3. Hall resistivity as a function of magnetic field.

One must consider the quantum mechanical side jump mechanism according to which the electrons a small transverse deflection at each scattering event. If this mechanism were dominant in the present alloys, ρ_H should be proportional to ρ^2. While the V content increase in the alloys, magnetic impurities and also topological spin disorder increases that may be responsible for the increase of Hall resistivity. One or more of the scattering processes i. e. impurity, phonon and spin disorder scattering give dominant contribution to the anomalous Hall effect in different filed which, in turn, are different for different samples. The anomalous Hall effect results from anisotropic scattering and this in turn comes from an interplay of internal polarization, (spin) scattering centers and spin-orbit coupling.

The internal polarization can be provided by the spontaneous magnetization inside a domain or by an induced magnetization. The non linear behavior of the ρ_H vs $\mu_0 H$ curve

decomposed into the normal Hall effect and anomalous Hall effect that can be written are as follows (Mizutami 2003).

$$\rho_H = R_0 \mu_0 H + R_s M_s \quad (2)$$

The first term, characterized by the ordinary Hall coefficient (R0) and the second term characterized by the extraordinary or anomalous Hall coefficient (Rs). From this figure authors have seen that there is a saturation in the ferromagnetic regime always, indicating that the anomalous Hall effect dominates. This is not found in equivalent crystalline materials. As elementary anisotropic scattering mechanisms, so far, the quasi-classical skew scattering (first order) and the quantum mechanical (second order) side jump have been proposed. Accordingly, the anomalous Hall constant, $Rs = c_1\rho + c_2\rho 2$ have been proposed, where c_1, c_2 are supposed to refer to the first order (skew) and second order (side jump) mechanisms. For amorphous systems often it is argued that because of the large number of scattering centers the quadratic term should dominate and since the side jump supposedly does not depend very much on the type of scattering potential, it has dealt with the same scattering situation in case of ρ and ρH and therefore $\rho H \sim \rho^2$ might be valid.

MR% at RT

Fig. 4 shows the transverse MR as a function of magnetic field up to 0.6 T at RT. The initial large change in the MR occurs in the low field which is accompanied by growth of magnetic domain parallel to the direction of the magnetic field. Once the magnetic saturation is achieved there is no domain motion as it has assumed a single domain.

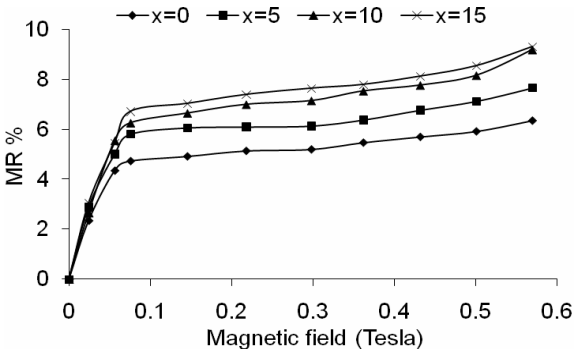

Fig. 4. MR% as a function of magnetic field.

The only contribution to the MR comes at this stage is from the conduction electron scattering due to the collision between themselves and hence the electron mean free-path is much longer in this stage. The physical origin of the MR effect lies in spin orbit coupling. As magnetic moment rotates, the electron cloud about each nucleus deforms slightly and this deformation changes the amount of scattering undergone by the

conduction electrons in their passage through the lattice. It is seen from the figure that MR% increases with increase of V content. If V content increases, the topological spin disorder increase in the system and hence MR% increases. The MR varies from 0 to 8% with the increase of V content and also with the applied magnetic field.

Saturation magnetization at RT

Fig. 5 shows the saturation magnetization as a function of V content at RT. It is found that the saturation magnetization gradually decreases with the increase of V content at RT. Magnetization as a function of magnetic field at RT was discussed elsewhere (Karal *et al.* 2011).

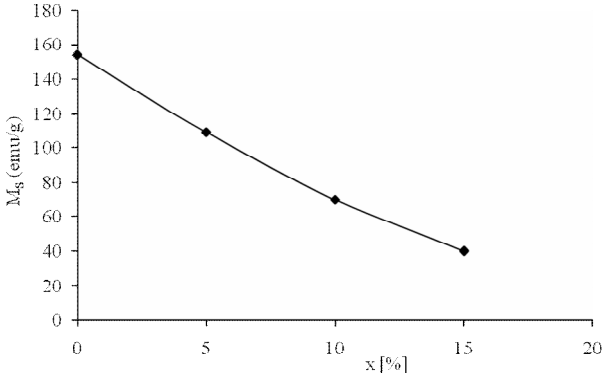

Fig. 5. Saturation magnetization as a function of x [%].

The saturation magnetization (M_s) and Bohr magneton (μ_B) per Fe atom of the as prepared ribbons at RT are shown in Table 1. Bohr magneton per formula of $(Fe_{100-x}V_x)_{75}P_{15}C_{10}$ (x = 0, 5, 10 and 15) samples can be obtained by using the following formula (Smit 1971).

$$\mu_B = \frac{M}{5585} \times Ms \tag{3}$$

where, M is the molecular weight of the substance and M_s is the saturation magnetization.

Table 1. Saturation magnetization and Bohr magneton of $(Fe_{100-x}V_x)_{75}P_{15}C_{10}$ (*x* = 0, 5, 10 and 15) ribbons at RT.

Samples, x	Saturation magnetization M_s (emu/g)	Bohr magneton (μ_B)
0	154	1.275
5	109	0.894
10	70	0.573
15	40	0.328

The decrease of saturation magnetization is due to the replacement of ferromagnetic Fe by paramagnetic V and also due to the reduction of the overall interatomic exchange interaction.

CONCLUSION

Transport and magnetic measurements were done on an amorphous Fe-V-P-C series ribbons. The resistivity increases with the increase on V content in the samples at RT. Positive TCR for the samples of x = 0, 5 and negative TCR for the samples of x = 10, 15 are observed in the low temperature (300-93)K resistivity measurement that follows Mooij correlation. Anomalous Hall effect is observed in the Hall resistivity measurement. MR varies from 0 to 8% with the applied magnetic field and also with the V content. The saturation magnetization gradual decreases with the increase of V content into the alloys.

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