Magnetic structure of (Fe$_{0.97}$Cr$_{0.03}$)$_2$P

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Abstract. Magnetic behaviour of di-metal iron phosphide with a small substitution of iron by chromium, (Fe$_{0.97}$Cr$_{0.03}$)$_2$P, has been studied using SQUID magnetometry and powder neutron diffraction. It is paramagnetic at temperatures above ~180 K with persisting short range ferromagnetic (FM) order. At lower temperatures three different regions of magnetic behaviour are identified. FM order evolves in the region 180 K – 120 K but much more slowly and with much less magnetic moments than in Fe$_2$P. In the region 120 K – 50 K negative exchange interactions gain some importance leading to a loss of FM order. Below 50 K FM interactions again dominate. Pinning centres influence the behaviour at low temperature up to ~100 K.

Keywords. Magnetic structure; neutron diffraction; alloys.

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1. Introduction

The di-metal iron phosphide Fe$_2$P, crystallizing in a hexagonal C22 structure with P6$_2$2m ($D_{3h}^3$) space group, is a ferromagnet with a sharp transition to paramagnetic state at ~210 K [1]. It has a high uniaxial magnetic anisotropy with the magnetic moments aligned along [001] and exhibits a metal like electrical conductivity (resistivity ~10$^{-4}$ ohm cm [2]). The magnetic behaviour of the material has been extensively studied for the effect of pressure and metallic substitutions as well as vacancy substitutions [1–7 and references therein]. All these are known to exhibit strong influences. Thus, application of hydrostatic pressure reduces Curie temperature with pronounced anisotropy and above 5 kbar double metamagnetic transitions occur – first from ferromagnetic (FM) to metamagnetic and then to antiferromagnetic state in the sequence of decreasing temperature [e.g., 1 and references therein].
Metallic substitutions, the subject of the present paper, also lead to interesting changes. Small substitutions of Fe by Co, as also by Ni, strengthen the FM structure as revealed in the elevation of Curie temperature, e.g., from $\sim 210$ K in Fe$_2$P to $\sim 295$ K in 5% Ni substituted alloy [8]. On the other hand substitutions by Cr and Mn, tend to destroy the FM order; at as low a level of substitution as 3% of Mn, and also of Cr, the bulk magnetization is considerably reduced [9,10], as compared to that in Fe$_2$P.

In an earlier study on the title alloy, our group [10] reported magnetization measurements as a function of magnetic field (in fields $> 500$ Oe) and temperature. However, due to the use of liquid nitrogen, the low temperature range was limited to 80 K. Only one peak was seen in magnetization-temperature curve. It was surmised that ferromagnetic order does not exist but no further inference could be made about the magnetic behaviour. More recent studies by Srivastava et al [6] on an alloy formed of simultaneous substitutions by Cr and Ni in small proportions have shown the existence of re-entrant spin glass phase. This has lead to a greater interest in examining the magnetic behaviour of the Cr substituted alloy and this paper is an effort in that direction. Magnetization and neutron diffraction measurements have been performed on poly-crystalline sample of (Fe$_{0.97}$Cr$_{0.03}$)$_2$P in the temperature range 5 K–300 K. It is found that as the temperature is lowered from 300 K, it exhibits three different kinds of magnetic behaviour in three temperature ranges. The plan of the paper is as follows. The experimental details are given in the next section. Results and discussions are presented in the subsequent sections.

2. Experimental details

The alloy has been prepared by the method of solid state diffusion at $\sim 1000^\circ$C. The details of preparation are described elsewhere [10]. Phase identification was done with the help of X-ray diffraction patterns recorded on a Philips powder diffractometer (model PW 1840) using FeK$_\alpha$ radiation. All the observed reflections could be indexed using Fe$_2$P like hexagonal cell.

Magnetization measurements have been made using a SQUID magnetometer (quantum design model MPMS) for both zero field cooled (ZFC) as well as field cooled (FC) conditions covering a temperature range of 5 K to 300 K. In ZFC mode the sample was cooled under zero field from 300 K to 5 K, then a magnetic field was applied and magnetic moment of the sample was measured as a function of temperature ($T$) in the warming cycle. In FC mode the sample was cooled from 300 K to 5 K in the presence of field and $M$ vs $T$ was recorded during cooling cycle.

Magnetization has also been measured as a function of the external magnetic field at different sample temperatures. These measurements were made as follows. The sample was first cooled from 300 K (paramagnetic state) to 10 K under zero field. Then successively increasing fields were applied and magnetization was recorded at each field value. After thus completing the measurements at one temperature (10 K) the field was switched off and sample was warmed to 300 K. It was kept at 300 K for about half an hour and then cooled to the next temperature 30 K. The magnetization measurements were once again made under successively increasing fields. After the measurement the field was again switched off and the sample was warmed up to 300 K. This process was continued in the above manner going over different temperatures.