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Influence of V and Mn doping on the electrical transport properties of a Cr + 1.2 at.% Ga alloy

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Abstract

Measurements of the electrical resistivity (ρ) of a Cr + 1.2 at.% Ga alloy doped with V or Mn, are reported in the temperature range 6–900 K. These measurements were complimented with thermal expansion (α) measurements for the undoped Cr + 1.2 at.% Ga alloy in the temperature range 77–450 K. The measurements show interesting behaviour with dopant concentration in that the residual resistivity (ρ_{residual}) does not vary smoothly with dopant concentration as expected. On the contrary, ρ_{residual} shows three peaks as a function of dopant concentration. This behaviour is ascribed to impurity resonant scattering effects which are included in a theoretical model used to explain the observed temperature dependence of the resistivity for these alloys. The resistivity and thermal expansion coefficient of the Cr + 1.2 at.% Ga alloy behaves anomalously close to the ISDW–CSDW phase transition temperature (T_{IC}). The temperature derivative of the resistivity shows a minimum while the α–T curve shows a peak at T_{IC} in contrast to what is expected. The magnetic phase diagram of the (Cr + 1.2 at.% Ga)(V, Mn) alloy system is constructed from the results of the measurements.

Keywords: Magnetically ordered materials; Electronic transport; Spin-density-waves

1. Introduction

The electrical resistivity, ρ, of spin-density-wave (SDW) antiferromagnetic Cr alloys has received attention recently [1–11]. Much of this attention was driven by the model of resonant impurity scattering of conduction electrons, proposed by Volkov and Tugushev [12] to explain the observed low temperature anomalous resistivity behaviour of dilute Cr alloys. The model was used [1,2,4,7,8] successfully to explain the maxima observed in the residual resistivity of Cr–Fe, Cr–Si and Cr–Co alloys on adding V or Mn.

Local impurity levels are formed [6] within the SDW energy gap of Cr alloys and resonant scattering of the conduction electrons occurs when the Fermi level coincides with the impurity level. The Fermi level can be tuned through the impurity level of a binary Cr alloy by doping with Mn, to increase the electron concentration (e_{A}), or by V to decrease e_{A}. Such a tuning gives rise to distinct peaks occurring in the residual resistivity as a function of Mn or V concentration [1,2,4,7,8].

The resonant scattering component of the resistivity can have relatively large effects on the total resistivity at low temperatures. This component consists of two terms [13], the one being temperature independent and the other has a negative temperature dependence. The latter term gives rise to a minimum in the measured ρ–T curve at low temperatures, while the first term is responsible for the peaks in the residual resistivity as the Fermi level is tuned through the impurity level.

The resonant impurity scattering mechanism behaves differently in incommensurate (I) and commensurate (C) SDW Cr alloys. In the commensurate case the alloy has two discrete resonant local impurity levels in the SDW energy gap. These can be situated either symmetrically or asymmetrically around the center of the gap [13]. On the other hand, the local impurity levels in the SDW gap of an incommensurate SDW alloy are not discrete, but rather include a cluster of

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levels that may be spread over the entire energy gap [7,13]. This difference of behaviour is expected to give rise to narrow sharp peaks in the residual resistivity as a function of Mn or V dopant concentration in binary CSDW alloys, and to a broad peak for the ISDW case. Contrary to this expectation, some ISDW Cr alloys also show [7] narrow peaks in ρ on tuning the Fermi energy by doping.

Effects of resonant impurity scattering have been studied on the electrical resistivity of Cr–Fe, Cr–Si and Cr–Co alloys as the Fermi level is tuned by Mn or V doping [1,2,4,6,7]. The main features of the resistivity of these alloy systems are successfully explained using the resonant scattering model. Many finer aspects of the observations remain however unanswered. Amongst these are explanations for the narrow resistivity peaks observed in some ISDW alloys and the fact that both peaks lie on the V-dopant side of the system, contrary to expectation. As suggested previously [7], resonant impurity scattering effects in other Cr alloy systems should also be studied for a better understanding of the complex behaviour observed in the above-mentioned alloy systems.

Resonant impurity scattering effects are also expected [1,5,11] to be important in the Cr–Ga alloy system. A detailed study of such effects on the electrical resistivity of a Cr + 1.2 at.% Ga alloy, doped with V and Mn to tune the Fermi level, is reported here. The specific Ga concentration was chosen to allow for studying resonant scattering effects in both ISDW and CSDW phases of the system. This is possible since the magnetic phase diagram of binary Cr–Ga alloys contains a triple point at $c_t = 0.6$ at.% Ga and $T_t = 285$ K, where the ISDW, CSDW and paramagnetic phases coexist. As $c > c_t$ for the Cr + 1.2 at.% Ga alloy, doping with Mn to increase the electron concentration will drive the alloy deeper into the CSDW phase region of the phase diagram. Doping with V, on the other hand, will drive the alloy towards the ISDW phase region. It is believed [4] that doping with Mn and V does not result in the formation of their own impurity states, since the rigid band model works well for both these impurities in Cr.

A spin-off from the electrical resistivity measurements on the $Cr_{98.8}Ga_{1.2}$(V, Mn) alloys, is the construction of the magnetic phase diagram of the system in the temperature–electron concentration plane. This gives a further opportunity to test itinerant electron theories in this regard.

2. Experimental methods

One binary $Cr_{1-x}Ga_x$ alloy series, with nominal range $0 \le x \le 0.025$ (eight alloys) and two ternary alloy series, $(Cr_{0.988}Ga_{0.012})_{1-y}Mn_y$ and $(Cr_{0.988}Ga_{0.012})_{1-z}V_z$, with nominal ranges $0 \le y \le 0.04$ (10 alloys) and $0 \le z \le 0.04$ (6 alloys), were prepared from 99.999% pure Cr, Ga, V, and 99.99% Mn starting materials by arc melting in a purified argon atmosphere. Due to the closeness of the boiling point of Mn to the melting point of Cr, some Mn was lost during the melting procedure. The ingots were homogenized for three days at 900 °C in sealed quarts ampoules, which were partially filled with ultra high purity argon gas after evacuation. Electron microprobe and X-ray fluorescence analyses were used to determine the actual alloy concentrations. For the ternary alloy series the actual Ga content do not differ by more than 12% from the nominal value of 0.012 in the alloy formula, giving an average concentration of 1.06 ± 0.07 at.% Ga for the ternary alloy samples studied. This variation in the Ga content is of the same order as previously [1] also found for the Fe content in a similar study on ternary $(Cr_{0.973}Fe_{0.027})_{1-y}Mn_y$ and $(Cr_{0.973}Fe_{0.027})_{1-z}V_z$ alloy systems.

Electrical resistivity was measured using a standard four-probe DC method for both forward and reverse current directions in order to eliminate thermal emfs. The sample lengths were about 7 mm and the cross sectional area about 1.5 mm^2. Data were recorded during heating runs for the ternary alloys in the temperature range 6–900 K, except for $(Cr_{0.988}Ga_{0.012})_{1-z}V_z$ with $z = 0.0012$, 0.0021, 0.0073, 0.0107, 0.0220 and 0.0415, in which case measurements were done only up to 450 K. For the latter samples the upper limit of 450 K was high enough for the purpose of the study, as this series does not show magnetic phase transitions above 350 K. In the case of the binary Cr–Ga series measurements were done from 6 K only up to 85 K, which is adequate for the present investigation. Measurements were recorded at 0.2 K intervals while slowly heating the samples at a rate of approximately 0.3 K/min. The experimental error in the absolute values of the resistivity is about 2%, which is mainly due to the uncertainty in the distance between the voltage contact wires, of thickness 0.2 mm, spot welded to the sample.

3. Results

Fig. 1 shows typical examples of ρ–T curves for the binary Cr–Ga series on heating between 6 and 85 K. In this and subsequent ρ–T curves the data points are represented

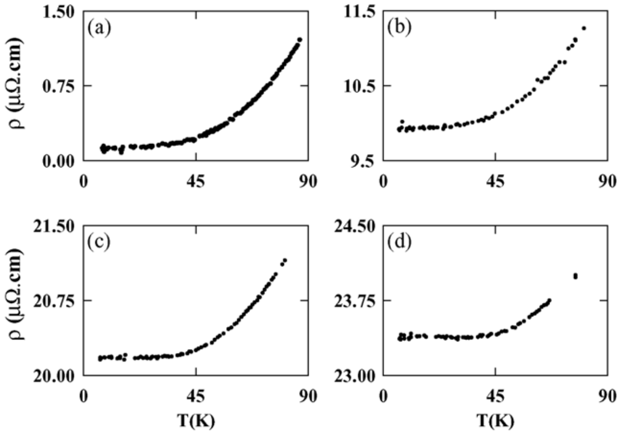

Fig. 1. Typical examples of the electrical resistivity, ρ, as a function of temperature for the binary $Cr_{1-x}Ga_x$ series, with (a) $x = 0$, (b) $x = 0.0065$, (c) $x = 0.0140$ and (d) $x = 0.0168$. The data points were obtained during heating runs.