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Abstract. Electrical resistivity measurements on a Cr + 0.3 at.% Ru alloy single crystal are reported as a function of temperature. The first-order incommensurate–commensurate spin density wave magnetic transition is accompanied by a small resistivity anomaly, showing a large hysteresis effect on heating and cooling. A well defined resistivity anomaly without hysteresis, characteristic of a second-order transition, is observed at the commensurate spin density wave to paramagnetic transition. The spin-flip transition is not resolved in the resistivity measurements on the single crystal.

Three magnetic phases appear on the magnetic phase diagram of dilute Cr–Ru alloys: an incommensurate (I) spin density wave (SDW) phase, a commensurate (C) SDW phase and a paramagnetic (P) phase [1]. There exists a triple point near $c = 0.2$ at.% Ru and 325 K where these three phases co-exist [2]. For $c < 0.2$ at.% Ru only the ISDW phase is found below the Néel point, T_N, down to 0 K, while the order of the phase changes for $c > 0.2$ at.% Ru on increasing the temperature from 0 K to above T_N, is from ISDW to CSDW to P.

Studies on polycrystalline dilute Cr–Ru alloys show that the ISDW–P and CSDW–P phase transitions are characterized by magnetic anomalies in the temperature dependence of nearly all physical properties of these alloys. In the case of the electrical resistivity (ρ), for instance, anomalies are observed in all published studies on ρ–T curves for both the ISDW–P and CSDW–P transitions [2–4]. For the ISDW–CSDW phase transition occurring at temperature T_{IC}, however conflicting data appear in the literature for alloys with $c > 0.2$ at.% Ru. Jayaraman and co-workers [4] who studied the effects of high pressure on the magnetic transition temperatures of polycrystalline dilute Cr–Ru alloys, did not detect any anomaly in their ρ–T curves that could be associated with the ISDW–CSDW phase transition for $c > 0.2$ at.% Ru. This prevented them from obtaining the ISDW–CSDW phase line on the pressure–temperature magnetic phase diagram of the Cr–Ru system. In contrast to the work of Jayaraman and co-workers [4], Butylenko and Nevdacha [2] did however observe a small ρ-anomaly while heating their polycrystalline alloys ($c > 0.2$ at.% Ru) at a rate of 4–5 K min^{-1} through T_{IC}. Unfortunately, neither of the above-mentioned papers report on the purity of their starting material or on the quality of their alloys, making proper assessment of the conflicting reports difficult. In this regard it may be mentioned that the measurements of Butylenko and Nevdacha [2] gives $d\rho/dT \simeq 0.02\,\mu\Omega\,\mathrm{cm\,K^{-1}}$ at $T > T_N$ for pure Cr and for their Cr–Ru alloys which is rather low, compared to $d\rho/dT \simeq 0.04\,\mu\Omega\,\mathrm{cm\,K^{-1}}$ obtained by Arajs and co-workers [5] and Yakhmi and co-workers [6] for pure Cr. For the magnetoelastic properties, elastic constants and thermal expansion, T_{IC} is also clearly marked [7] by well defined anomalies for polycrystalline alloys with $c > 0.2$ at.% Ru.

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The nesting between the electron and hole Fermi surface sheets of ISDW Cr is improved by adding Ru. This forces the SDW to become commensurate with the lattice when $c > 0.2$ at.% Ru [1]. One therefore expects a larger truncation of the Fermi surface in the CSDW than in the ISDW phase, giving rise to a ρ-anomaly at T_{IC}. This effect results for instance in a ρ-anomaly at T_{IC} for single crystalline Cr + 0.45 at.% Mn and Cr + 0.70 at.% Mn which show first-order ISDW–CSDW transitions [8]. In this regard it may be noted that a ρ-anomaly at T_{IC} is observed in single crystal Cr-Mn alloys but not in polycrystals of this alloy system [8].

Recent elastic constant [9, 10] measurements on a Cr + 0.3 at.% Ru single crystal also show a first-order ISDW–CSDW phase transition. It is accompanied by nearly discontinuous changes in the elastic constants at T_{IC} and by large hysteresis effects. This anomaly in the elastic constants was recently used [11] to determine $\mathrm{d}T_{\mathrm{IC}}/\mathrm{d}P$ and $\mathrm{d}T_{CI}/\mathrm{d}P$ for a Cr + 0.3 at.% Ru single crystal, something that could previously not be obtained by Jayaraman and co-workers [4] for polycrystalline Cr–Ru due to the absence of ρ-anomalies at the ISDW–CSDW phase transition. One would also expect a similar behaviour as that obtained for the elastic constants, in the other physical properties of dilute Cr–Ru alloy single crystals. In trying to solve the conflicting reports concerning a ρ-anomaly at the ISDW–CSDW phase transition of polycrystalline Cr–Ru alloys, it should therefore be more appropriate to look for such anomalies in good quality Cr–Ru single crystals. We report detailed ρ-T measurements on a good quality Cr + 0.3 at.% Ru single crystal in which both ISDW–CSDW and CSDW–P phase transitions are present.

The Cr + 0.3 at.% Ru crystal was cut from the same single crystal boule as that used in the magnetoelastic studies [9–12]. We have also completed neutron diffraction studies on this crystal [13], verifying its quality and the first-order nature of the ISDW–CSDW transition. Furthermore, electron microprobe analyses and the rather sharp first-order ISDW–CSDW transition observed in the magnetoelastic measurements on the crystal, verify that it is of good homogeneity. Electrical resistivity was measured using a standard four-probe DC method for both forward and reverse current directions in order to eliminate thermal EMF. A sample of length about 6 mm and cross sectional area about 1.3 mm^2, with the longest axis along [110], was spark cut from the crystal. Current was applied along the long axis and data were recorded during both cooling and heating runs. During heating runs measurements were recorded at $\simeq 0.05$ K intervals while heating the sample slowly at $\simeq 0.09\ \mathrm{K\,min^{-1}}$. The cooling rate was $\simeq 0.13\ \mathrm{K\,min^{-1}}$ and data were recorded at $\simeq 0.07$ K intervals in this case.

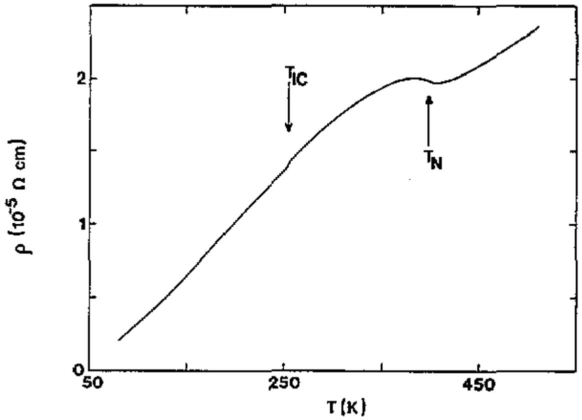

Figure 1. Electrical resistivity along [110] as a function of temperature for a Cr + 0.3 at.% Ru alloy single crystal. Data were recorded at 0.05 K intervals on heating the sample slowly at $\simeq 0.09\ \mathrm{K\,min^{-1}}$.

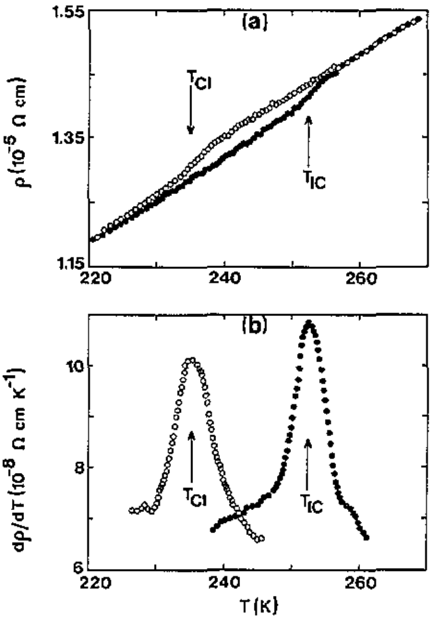

Figure 2. (*a*) Electrical resistivity (ρ) as a function of temperature near T_{CI} (on cooling ○) and T_{IC} (on heating •). Only every tenth measured point is plotted for clarity. (*b*) $\mathrm{d}\rho/\mathrm{d}T$ near T_{CI} (on cooling ○) and T_{IC} (on heating •). Only every tenth data point is plotted for clarity.

Figure 1 shows ρ as a function of temperature on heating between 77–500 K and figure 2(*a*) shows the behaviour in the vicinity of the ISDW–CSDW transition for both heating and cooling runs. Two anomalies are observed in figure 1, the higher temperature one, which is relatively large, occurs near T_{N}, the CSDW–P transition, while the weaker low temperature one is associated with T_{IC}. The anomaly at T_{N} in figure 1 is rather well defined compared to the flatter and broader anomaly observed in polycrystalline Cr + 0.3 at.% Ru by Butylenko and Nevdacha [2]. Furthermore, for $T > T_{\mathrm{N}}$ the results in figure 1 give $\mathrm{d}\rho/\mathrm{d}T \simeq 0.04\,\mu\Omega\,\mathrm{cm\,K^{-1}}$ which corresponds well with the value obtained for pure Cr by Arajs [5] and Yakhmi [6]. As is usually done in determining T_{N} for dilute Cr alloys, this temperature is taken at the temperature of the $\mathrm{d}\rho/\mathrm{d}T$ minimum in figure 1, giving $T_{\mathrm{N}} = (394 \pm 1)$ K. This compares reasonably well with the value (402 ± 5) K obtained [12] during elastic constant measurements. Heating and cooling runs through T_{N} show no hysteresis effect as is representative of a second-order CSDW–P transition at T_{N}.

The spin-flip transition temperature, where the ISDW phase changes from a transverse ISDW to a longitudinal one on cooling, is $T_{\mathrm{sf}} = 85$ K [12] for this crystal. Although T_{sf} is well resolved by clear anomalies in the elastic constants [12], it is not resolved in the ρ–T measurements of figure 1. Most previous ρ-measurements on dilute Cr alloys, including Cr–Ru, were done on polycrystalline material. As far as we can ascertain, the spin-flip transition is not resolved in any of these measurements, except in those of Arajs [14] on polycrystalline pure Cr. Measurements by Muir and Ström-Olsen [15] on a Cr single crystal however fail to reveal the ρ-anomaly observed in polycrystalline Cr. They suggested that the anomaly observed in the latter case was probably induced by strains, connected with a change in lattice parameter at T_{sf}, in the polycrystalline material. The general trend seems to be an absence of ρ-anomalies at T_{sf} in Cr and dilute Cr alloys. This is in a sense not too surprising as the spin polarization direction of the ISDW state turns through 90° at T_{sf} without changing the nature of the SDW state itself.

Figure 2(*a*) clearly depicts well defined anomalies in the ρ–T curves at T_{IC} (on heating) and at T_{CI} (on cooling). A large hysteresis effect of width $\Delta T = 18$ K is observed (figure 2(*a*)) for the ISDW–CSDW transition, comparable to that ($\Delta T = 22\,\mathrm{K}$) observed during elastic constant measurements [10]. Figure 2(*b*) shows $\mathrm{d}\rho/\mathrm{d}T$ in the vicinity of T_{IC} and T_{CI}. Maxima are observed on heating or cooling. T_{IC} (heating) and T_{CI} (cooling) were defined at these maxima. We obtain $T_{\mathrm{IC}} = (252.7 \pm 0.5)\,\mathrm{K}$ and $T_{\mathrm{CI}} = (235 \pm 1)\,\mathrm{K}$ which compare reasonably well with the values $T_{\mathrm{IC}} = 255.6\,\mathrm{K}$ and $T_{\mathrm{CI}} = 238.6\,\mathrm{K}$ obtained [10] during the elastic constant measurements on the Cr + 0.3 at.% Ru crystal.

In conclusion, electrical resistivity measurements on a good quality Cr + 0.3 at.% Ru single crystal reveal clearly distinguishable magnetic anomalies at the ISDW–CSDW transition as well as hysteresis effects, expected for this first-order transition. We can only speculate on reasons for the absence of this anomaly in the measurements of Jayaraman and co-workers [4] on polycrystalline Cr–Ru alloys with $c > 0.2$ at.% Ru. As the anomaly observed in the single crystal is relatively small, it may easily be smeared out by sample inhomogeneities. Unfortunately, the previous studies [2, 4] on polycrystalline Cr–Ru alloys give no indication of the homogeneity or quality of the alloys used.

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