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**Electrical Resistivity and Thermal Expansion Anomalies
of Ferromagnetic CoS_2**

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The resistivity of CoS₂ having the pyrite structure was measured between 4.2 K and 300 K under pressure up to 18 kbar and under magnetic field up to 45 kOe. The hump anomaly just below the Curie temperature (T_c) was found to become sharper with decreasing T_c by pressure and to become sluggish with increasing T_c by field. The magnetization (M) dependence of both the hump anomaly below T_c and a positive magnetoresistance above T_c was empirically analyzed, which resulted in M^2 dependent effective mass. The spontaneous and induced volume-strictions were also measured near T_c up to 45 kOe, the latter of which was found to vary as M^2 for small M . These anomalies can be qualitatively understood through the variations of M and T_c in a unified way including the effect of impurity-doping.

§1. Introduction

Anomalous electrical resistivity near the Curie temperature ($T_c \approx 120$ K) of a narrow-band ferromagnet CoS₂ with the pyrite structure has been first reported by Ogawa *et al.*^{1,2)} The anomaly is a hump just below the T_c , which is similar to antiferromagnetic metals Cr, Dy, etc.,³⁾ and is a unique feature which has not yet been observed in any other ferromagnetic metals such as Ni, Fe, Gd etc.³⁾ The origin of the hump anomaly in CoS₂ has not been clarified to date, although some possibilities were suggested,^{1,2)} which are related to a correlation effect or an ordering of orbital states. Electrons which dominate electrical conduction and magnetic properties^{2,4)} appear to be those in the same energy band which has mainly an e_g like character.^{5,6)} The variations of the anomalous temperature dependence in the resistivity with making solid solutions of CoS₂ have been reported for Fe_xCo_{1-x}S₂ and Co_{1-x}Ni_xS₂ by Ogawa *et al.*,^{2,7)} and recently for Co(S_{1-x}Se_x)₂ by Adachi *et al.*⁸⁾ The doping of Fe makes the hump anomaly sluggish with increasing T_c , whereas the doping of Ni makes it sharper with decreasing T_c . By doping Se, the hump anomaly in the resistivity,⁸⁾ thermal expansion anomaly⁸⁾ and a magnetization curve⁸⁻¹⁰⁾ below T_c become sharper and almost discontinuous with decreasing T_c . A change of the nature of the transition from second order in pure CoS₂ to first order in Se-doped CoS₂ is interesting. The

effect of Fe-doping is considered to narrow the band width,¹¹⁾ and the effect of Se-doping is to broaden the band width by increasing covalent mixing.^{10,12)} However, making solid solutions inevitably increases an atomic potential disorder and causes an interpretation of the results complex.¹⁰⁾

The hump anomaly below T_c seems to be related to the occurrence of spontaneous magnetization.²⁾ Then similar anomalous behaviour should be expected in case of magnetization induced by magnetic field. Recently, a positive magnetoresistance of CoS₂ above T_c was found by Adachi *et al.*^{3,8)} This is peculiar since such a positive magnetoresistance in the paramagnetic state of ferromagnetic metals has not been reported both experimentally and theoretically. It is not clear how the anomalous magnetoresistance above T_c is related to the hump anomaly below T_c . Moreover, there have been reported a hump-like spontaneous volumetric contraction below T_c ¹³⁾ and a positive H^2 -dependent forced volumetric contraction above T_c ,¹⁴⁾ but a mutual relation between them is not clear.

The purpose of this work is firstly to remove the effect of disorder and clarify the volume dependence of the hump anomaly in the resistivity by exploring high pressure experiments for CoS₂. Secondly, the effect of magnetic field on the resistivity and the volume is investigated in order to make clear a relation between the anomalous behaviour due to spontaneous and induced magnetization. Finally, it is tried to

understand the changes of the anomalies by various parameters, such as pressure, magnetic field and concentrations, in a unified way through a variation of the magnetization and the T_c .

§2. Experimental Method

2.1 Sample

The polycrystalline specimens of CoS_2 were supplied by Dr. S. Ogawa of Electrotechnical Laboratory, Tanashi, Tokyo. The samples were prepared by sintering the powders of CoS_2 and cut into rectangular shape. The packing factor²⁾ of the sample was 0.81. The details of the sample preparation are described in ref. 2.

2.2 High pressure experiments at low temperatures

Pressure was generated in a piston-cylinder apparatus using a Teflon cell technique.¹⁵⁾ The inner diameter of the cylinder was 12.7 mm and pressure medium was a solution of kerosene and transformer oil in the ratio of 1:1. Sample dimension was about 0.9 mm $\times$ 1.5 mm $\times$ 8 mm and a distance between potential leads was about 2.8 mm. Electrical resistance was measured by the dc four-probe method. A sensitivity of the measurements was 0.1 $\mu\Omega$ for a current of 100 mA. Temperature was measured by a Chromel-Alumel thermocouple which was calibrated in each run using the boiling points of helium and nitrogen.* Temperature variation keeping the pressure constant was carried out in a high pressure cryostat which was described in ref. 17. In our experiments, pressure was generated at room temperature, and during the temperature variation the applied load was kept constant within ± 0.05 ton which corresponds to ± 0.03 kbar. Pressure calibration was made using a manganin gauge and Bi I-II phase transition at 25.5 kbar¹⁸⁾ at room temperature within ± 0.3 kbar, and using a superconducting transition of Pb ¹⁹⁾ at helium temperatures to an accuracy of $\pm 4\%$.

2.3 Measurements under magnetic field

Magnetic field was generated up to 45 kOe

using a superconducting solenoid. Temperature was measured by a copper-constantan thermocouple. A cryostat and a mechanism of sample rotation were the same as that described in ref. 20. Electrical resistance was measured by the four-probe method for a sample with dimension of 1.4 mm $\times$ 2.2 mm $\times$ 12 mm.

Thermal expansion and volumetric contraction were measured by the strain gauge method for a sample of 1.4 mm $\times$ 2.2 mm $\times$ 8 mm. A foil strain gauge* was cemented on the sample in a direction parallel to the sample length. A dummy gauge was cemented on a copper plate of 5N purity. All the gauges in this study were taken from the same lot. The active gauge on the sample and the dummy gauge on the copper plate were placed parallel within $\pm 2^\circ$ on a copper disk. A relative resistance change in the gauges due to strain was measured by the ac bridge method with a frequency of 5.5 kHz. A sensitivity of the strain measurements was 1×10^{-7} . The linear coefficient of thermal expansion of the reference material copper was taken from ref. 21 in the temperature range from 30 K to 300 K, and fitted to a polynomial to the 9th order with a standard deviation of $0.6 \times 10^{-8}/\text{K}$. The gauge factor at room temperature is 2.01 ± 0.02 and increases with decreasing temperature by about 4% at 100 K, the data of which were supplied by the manufacturer.

From the measurements of a magnetoresistance effect of the strain gauges, it was estimated above 100 K that an incomplete field compensation by a dummy gauge is of the order of 10^{-7} at 45 kOe, including the effect of a demagnetization field of CoS_2 . The temperature dependence of the demagnetization field also causes an error in the thermal expansion coefficient. The error is of the order of $10^{-8}/\text{K}$, which is small compared with the errors due to incomplete temperature compensations of the gauges and leads, which amount at most to the order of $1 \times 10^{-6}/\text{K}$.

§3. Experimental Results

3.1 Effect of pressure on the electrical resistivity

The temperature dependence of the resis-

and Chu.¹⁶⁾

* The thermo-electromotive force of the Chromel-Alumel thermocouple at the liquid helium and nitrogen fixed points was found to be unchanged by pressure within $\pm 0.1 \mu\text{V}$ and $\pm 0.3 \mu\text{V}$ up to 18 kbar, respectively. This is consistent with the result by Diatschenko

* The strain gauges were KFL-02-C-11 (120.0 ohm) and adhesive was CC-15 A, both of which were made by Kyowa Electronic Instruments Co., Ltd.

tivity at constant pressure is shown in Fig. 1, and also in Fig. 2. The pressure coefficient of the electrical resistivity at room temperature was found to be about $-4.5 \times 10^{-3}/\text{kbar}$. A correction due to the dimension change of the sample would give 7% larger absolute value, assuming that the distance between the potential leads exactly follows a change of sample length. Resistance values at room temperature for each run at constant pressures were normalized to resistivity values using the above coefficient and an atmospheric value of the resistivity which was determined for a single crystal by Ogawa.^{1,2)}

An inflection point at the hump anomaly corresponds to the T_c .²²⁾ The T_c decreases with increasing pressure with an initial slope of $dT_c/dP = -0.64 \pm 0.04 \text{ K/kbar}$, as shown by closed circles in Fig. 8. This value is in good agreement with a value -0.64 K/kbar reported by Menyuk *et al.*²³⁾ who used a helium gas as a pressure medium, but is larger in magnitude than -0.55 K/kbar by Bindloss²⁴⁾ and smaller than -0.86 K/kbar by Sato *et al.*²⁵⁾ Furthermore, our experimental value agrees with $-0.61 \pm 0.05 \text{ K/kbar}$ which we estimated from the Ehrenfest relation using the data of specific heat by Ogawa^{26,27)} and thermal expansion coefficient by us described later. A reason for the disagreement with the values by Bindloss and Sato *et al.* may be a difference in pressure calibration at low temperatures. Detailed comparison is difficult, since the calibration procedures are not described in the papers by these authors.

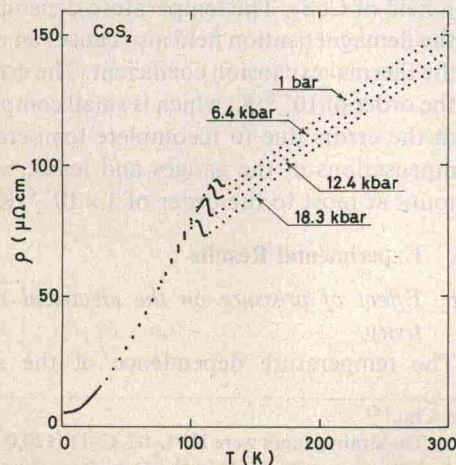


Fig. 1. Electrical resistivity of CoS_2 at high pressures.

In the paramagnetic phase, the temperature dependence is almost unchanged by pressure. However, it is noted that the effect of short range order above T_c , by which we mean a departure from a linear temperature dependence extrapolated from the high temperature resistivity, is suppressed by pressure, that is, it ranges about 25 K above T_c at atmospheric pressure and zero field but only about 7 K at 18.3 kbar, as seen in Fig. 2. The hump anomaly at T_c becomes sharper and larger with increasing pressure. This is associated with a fairly small pressure effect on the resistivity in the ferromagnetic phase compared with that in the paramagnetic phase.

3.2 Effect of magnetic field on the electrical resistivity

In Fig. 2, the temperature dependence of the resistivity near T_c at constant magnetic fields is also shown up to 45 kOe, in which the fields were perpendicular to the current direction of the sample (transverse magnetoresistance). The position of the hump shifts to higher temperature with increasing magnetic field. This fact indicates an increase of T_c by the magnetic field, as the inflection point is plotted by open squares in Fig. 8. As is seen in Fig. 2, the hump becomes sluggish with increasing magnetic field, in contrast to the pressure effect. In the paramag-

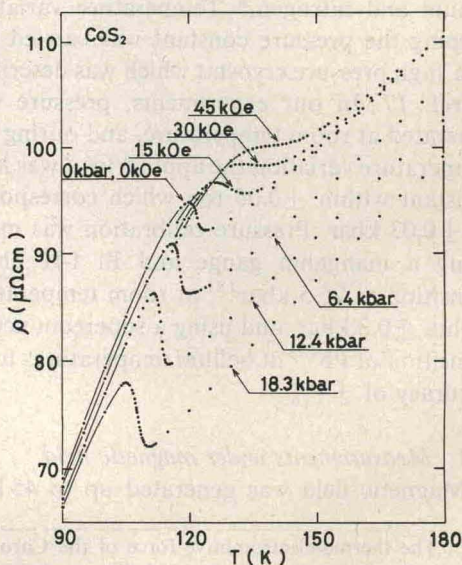


Fig. 2. Electrical resistivity of CoS_2 under magnetic field and under pressure near T_c . The magnetic field is transverse to a current direction.

netic phase, the transverse magnetoresistance increases as H^2 with increasing magnetic field H at constant temperatures between 150 K and 170 K, as shown in Fig. 3(a). The coefficient A of the H^2 dependence varies as the inverse of $(T - T_c)^2$, as plotted in Fig. 3(b); it suggests a divergence in magnetoresistance toward the T_c . In fact, if we plot the initial slopes of the data below 150 K in Fig. 3(a) which saturate at higher fields, they are on the same line as that above 150 K in Fig. 3(b). At 236 K and 295 K, the change of the resistivity was so small compared with the experimental accuracy that any clear power law dependence in H could not be determined.

On the other hand, a measurement was done

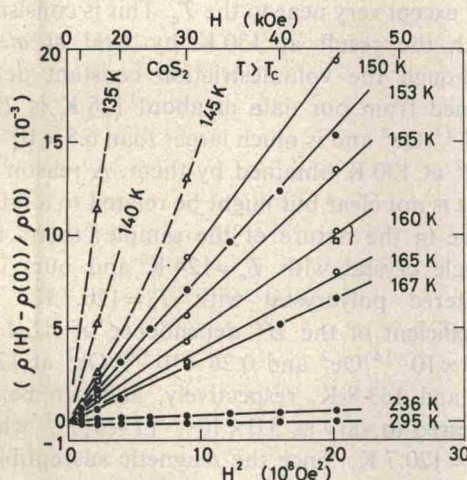


Fig. 3(a). Magnetoresistance of CoS_2 above T_c as a function of the square of magnetic field. ●: Transverse magnetoresistance measured in a constant-temperature condition. ○ and △: Transverse magnetoresistance replotted from constant-field data of Fig. 2. □: Longitudinal magnetoresistance.

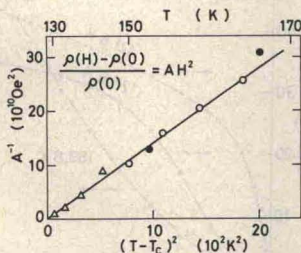


Fig. 3(b). Inverse coefficient of the H^2 dependence of the transverse magnetoresistance above T_c as a function of the square of $T - T_c$, where $T_c = 122$ K. Below 145 K, initial slopes in Fig. 3(a) are plotted. The symbols indicate the same meaning as in (a).

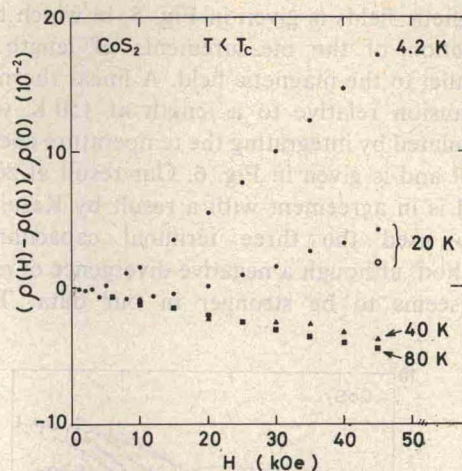


Fig. 4. Magnetoresistance of CoS_2 below T_c . Only an open circle is a longitudinal data and the others are transverse data.

in the same temperature range as in Fig. 2 at 45 kOe with a field direction parallel to the current direction (longitudinal magnetoresistance). The resistivity value and the temperature dependence was almost the same as the transverse data in Fig. 2, for example smaller only by an amount 0.05% at 160 K as an open square in Fig. 3(a), and the difference at the other temperatures was at most of the order of 0.1%. This fact indicates that the positive magnetoresistance above T_c and the associated change of the hump anomaly by magnetic field are due to isotropic origin.

In the ferromagnetic phase as shown in Fig. 4, the transverse magnetoresistance shows a composite effect of a negative contribution and a positive one, which are demonstrated typically in the data at 80 K and 4.2 K, respectively. The negative contribution is considered to be due to a spin orientation effect by H , which is linear in H .²⁸⁻³⁰⁾ The positive contribution increases rapidly as the temperature lowers and a difference between the transverse and longitudinal data is large as seen at 20 K. This is considered to be due to the Lorentz force magnetoresistance effect which should vary as B^2 in a simple case, where B is a magnetic flux.

3.3 Effect of magnetic field on the thermal expansion anomaly near T_c and the forced volumetric contraction above T_c

The temperature dependence of the linear coefficient (α) of thermal expansion at various

magnetic fields is given in Fig. 5, in which the direction of the measurements of length is parallel to the magnetic field. A linear thermal expansion relative to a length at 150 K was calculated by integrating the temperature coefficient and is given in Fig. 6. Our result at zero field is in agreement with a result by Kasai¹³⁾ who used the three terminal capacitance method, although a negative divergence of α at T_c seems to be stronger in our data. The

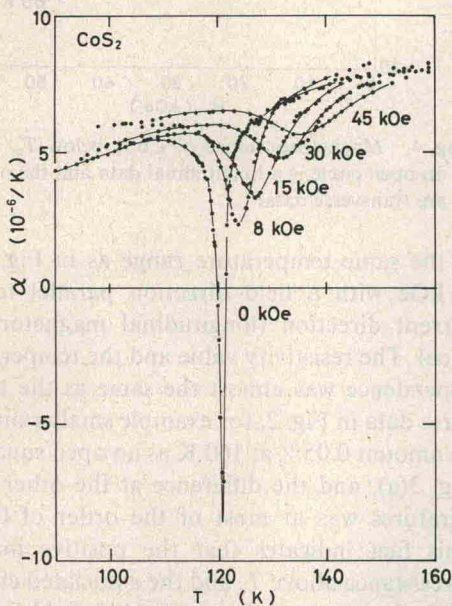


Fig. 5. Linear coefficient of thermal expansion of CoS_2 under magnetic field parallel to a sample length.

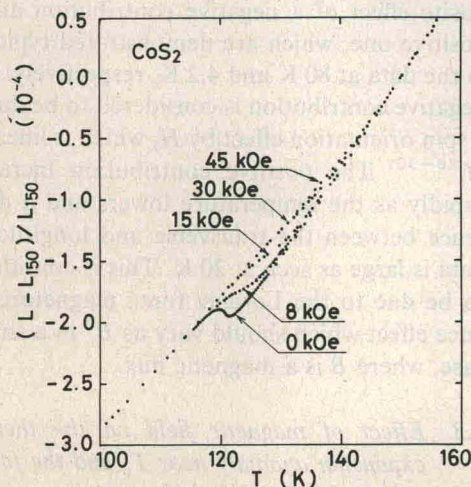


Fig. 6. Linear thermal expansion of CoS_2 relative to a length at 150 K under magnetic field. The data other than that of 0 kOe are plotted only near T_c .

divergence of α is suppressed by the magnetic field, which is parallel to a direction of the measurement, and the volumetric anomaly in the thermal expansion at T_c becomes sluggish as in Fig. 6 with increasing T_c . The T_c was determined from a minimum of α and is plotted by open triangles in Fig. 8. The effect of magnetic field on the temperature dependence of α did not change, when the thermal expansion was measured in a direction perpendicular to the magnetic field, within $\pm 0.3 \times 10^{-6}/\text{K}$ which is close to the experimental error. This fact indicates that the effect is intrinsic and due to a change in the volume magnetostriction.

On the other hand, a field induced magnetostriction $\Delta L/L_0$ was measured above T_c , as shown in Fig. 7. At low fields, $\Delta L/L_0$ varies as H^2 except very near to the T_c . This is consistent with the result at 130 K by Arai *et al.*,¹⁴⁾ although the volumetric constant determined from our data at about 128 K is $25 \times 10^{-14}/\text{Oe}^2$ and is much larger than $6.8 \times 10^{-14}/\text{Oe}^2$ at 130 K obtained by them. A reason for this is not clear but might be related to a difference in the nature of the sample; theirs is a single crystal with $T_c = 124$ K and ours is a sintered polycrystal with $T_c = 120.7$ K. The coefficient of the H^2 dependence of $\Delta L/L_0$ is $8.3 \times 10^{-14}/\text{Oe}^2$ and $0.26 \times 10^{-14}/\text{Oe}^2$ at 127.6 K and 163.8 K, respectively, and can be expressed to vary as $5.0 \times 10^{-12}(T - T_c)^{-2}$ where $T_c = 120.7$ K. Since the magnetic susceptibility of CoS_2 varies as $\chi(\text{emu/g}) = 0.57 \times 10^{-2}(T - T_c)^{-1}$ below about 350 K²⁾ and induced magnetization is $M = \chi H$, the induced magnetostriction varies as $\Delta L/L_0 = 2.5 \times 10^{-4}(M/M_0)^2$, where M_0 is the magnetization at 0 K

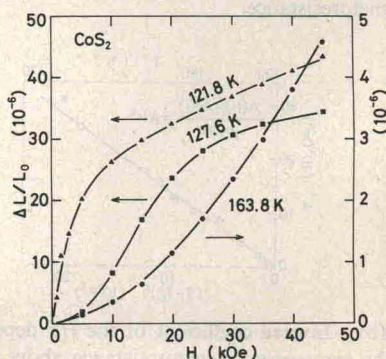


Fig. 7. Magnetostriction of CoS_2 above $T_c (=120.7$ K). Circles and squares are longitudinal data and triangles are transverse data.

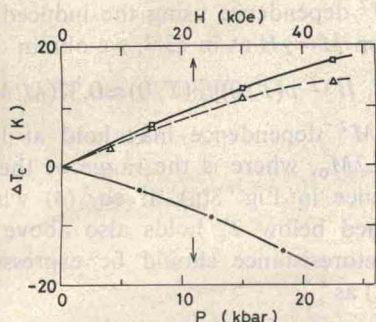


Fig. 8. Changes of the Curie temperature of CoS_2 with pressure and magnetic field determined from the resistivity (● and □) and the thermal expansion (Δ) measurements. The T_c 's at $P=0$ kbar and $H=0$ kOe for three samples are 121.9 ± 0.2 K for ●, 122.5 ± 0.5 K for □ and 120.7 ± 0.2 K for Δ.

and is 40.1 ± 0.5 emu/g.¹⁰⁾ Such an M^2 dependent magnetostriction has been expected³¹⁾ and observed³²⁾ for a weak ferromagnet. The H^2 dependence of $\Delta L/L_0$ holds for H smaller than that corresponds to $M \approx 0.2M_0$. Thus we expect that the above M^2 dependent relation holds roughly for $M \lesssim 0.2M_0$. If this relation is ap-

plied to spontaneous magnetization of such a small magnitude, it gives $\Delta L/L_0$ values similar to those observed in the spontaneous magnetostriction in Fig. 6.

§4. Analysis of the Electrical Resistivity

The resistivity can be expressed by a Drude formula $\rho = m^*/(ne^2\tau)$, where m^* is the effective mass of conduction electrons, n is the number of the carriers, e is the electron charge, and $1/\tau$ is a sum of the inverses of relaxation times for impurity scattering τ_0 , phonon scattering τ_p and magnetic scattering τ_m . Suppose

$$1/\tau_m(M(T, H)) = (1/\tau_{mp}) \{1 - a[M(T, H)/M_0]^2\}, \quad (1)$$

where a is a positive constant which will be assumed later to be unity, and M_0 is the saturation magnetization at 0 K, $M_0 = M(0, 0) \approx M(0, H)$. In case of CoS_2 , the conduction electrons are identical to magnetic electrons. Therefore, we generally expect that the m^* (or the effective value of n) also changes with increasing magnetic polarization of the band. Thus, we can express the resistivity as

$$\begin{aligned} \rho(T, H) &= \frac{m^*(M)}{ne^2} \left[\frac{1}{\tau_0} + \frac{1}{\tau_p(T)} + \frac{1}{\tau_{mp}} \left\{ 1 - a \left[\frac{M(T, H)}{M_0} \right]^2 \right\} \right] \\ &= \frac{m^*(M)}{m_0^*} \left[\rho_{p0} + \rho_p(T) + \rho_{mp} \left\{ 1 - a \left[\frac{M(T, H)}{M_0} \right]^2 \right\} \right] \\ &= [m^*(M)/m_0^*] \rho'(T, H), \end{aligned} \quad (2)$$

where $m_0^* = m^*(0)$. The $\rho'(T, H)$ is regarded as the resistivity which should be expected when m^* do not depend on M and can be calculated using the experimental data as below. The implication of the assumptions made here will be discussed briefly in §5.

We tried to find the magnetization dependence of m^* explicitly by analyzing the resistivity at 15 kOe, as shown in Fig. 9(a). Here, $\rho_p(T)$ is the ideal resistivity in a paramagnetic state and is taken to be equal to the resistivity of $\text{Co}_{0.7}\text{Ni}_{0.3}\text{S}_2$ reported by Ogawa *et al.*,²⁾ since the temperature coefficient of the resistivity of $\text{Co}_{0.7}\text{Ni}_{0.3}\text{S}_2$ is approximately equal to that of CoS_2 above T_c . The paramagnetic residual resistivity ρ_{p0} is estimated to be about $1/3.7$ of an observed ferromagnetic one $\rho_{F0} (= m^*(M_0)/(ne^2\tau_0))$, by comparing the observed residual resistivities of ferromagnetic and paramagnetic

solid solutions $\text{Co}(\text{S}_{1-x}\text{Se}_x)_2$ by Adachi *et al.*⁸⁾ The ρ_{mp} is about $49 \mu\Omega\text{cm}$, $M_0 = 40.1$ emu/g¹⁰⁾ and a is assumed to be 1.0. The temperature dependence of M at 15 kOe is taken from unpublished data by Ogawa above 118 K and that extrapolated from the data below 10 kOe by Johnson and Wold¹⁰⁾ below 118 K. In the extrapolation, an approximate empirical relation of high field susceptibility $\chi_{10\text{kOe}} = 1.02 M_{10\text{kOe}}^{-2.6}$ is used which we found from the above M - H data between 77 K and 124 K, where χ and M are in unit of emu/g.

In Fig. 9(b), a ratio of the observed $\rho(T, 15\text{kOe})$ to the $\rho'(T, 15\text{kOe})$ is plotted. This figure shows an enhancement of the resistivity, hence of the effective mass, with increasing magnetic order. In Fig. 10, a logarithmic plot is made for an excess resistivity $\Delta\rho(T, 15\text{kOe}) = \rho(T, 15\text{kOe}) - \rho'(T, 15\text{kOe})$ versus M . It is

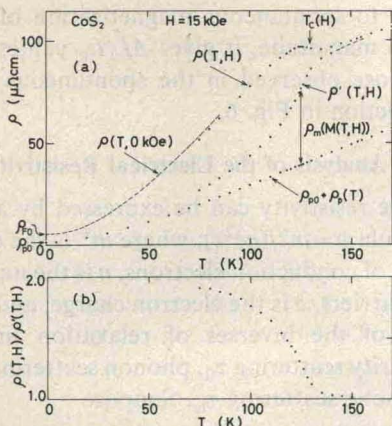


Fig. 9(a). $\rho(T, H)$; the observed resistivity. $\rho'(T, H)$; the resistivity without change in the effective mass by the magnetic ordering, composed of the paramagnetic residual resistivity ρ_{p0} , the phonon (or paramagnetic) contribution $\rho_p(T)$, and the magnetic contribution $\rho_m(M(T, H))$, for CoS_2 at $H=15$ kOe. (b) Ratio of $\rho(T, H)$ to $\rho'(T, H)$ at $H=15$ kOe.

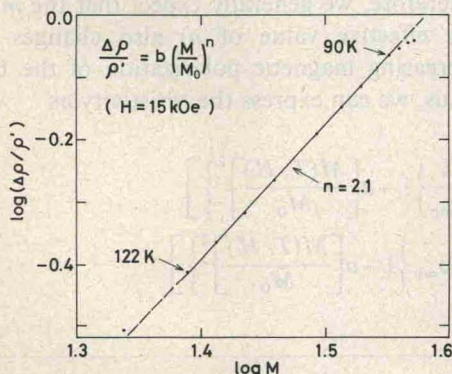


Fig. 10. Logarithmic plot of $\Delta\rho(T, H) = \rho(T, H) - \rho'(T, H)$ divided by $\rho'(T, H)$ versus $M(T, H)$ in unit of emu/g at $H=15$ kOe.

found from Fig. 10 that $\Delta\rho$ below T_c varies roughly as the square of the magnetization:

$$\Delta\rho/\rho' = b(M/M_0)^{2.1}, \quad (3)$$

between 90 K and 122 K with $b=1.09$. Thus, we can express the magnetization dependence of m^* roughly as

$$m^*(M) = m_0^*[1 + b(M/M_0)^2], \quad b=1.09. \quad (4)$$

On the other hand, we found the positive H^2 dependence in the magnetoresistance in the paramagnetic phase, as described in §3.2. From Fig. 3(b), the coefficient A of the H^2 dependence is expressed as $A(\text{Oe}^{-2}) = 0.72 \times 10^{-8}(T - T_c)^{-2}$, with $T_c = 122$ K. By rewriting

the H^2 dependence using the induced magnetization $M = \chi H$ as in §3.3, we obtain

$$[\rho(T, H) - \rho(T, 0)]/\rho(T, 0) \approx 0.37(M/M_0)^2. \quad (5)$$

This M^2 dependence may hold at least for $M \lesssim 0.2M_0$, where is the range of the H^2 dependence in Fig. 3(a). If eq. (4) which was obtained below T_c holds also above T_c , the magnetoresistance should be expressed from eq. (2) as

$$[\rho(T, H) - \rho(T, 0)]/\rho(T, 0) \approx \{b - [\rho_{mp}/\rho(T, 0)]a\}(M/M_0)^2, \quad (6 \cdot a)$$

where $\rho(T, 0) = \rho_{p0} + \rho_p(T) + \rho_{mp}$ and M^4 term is neglected. Since $\rho_{mp}/\rho(T, 0) \approx 0.5$ in the temperature range in Fig. 3, $b=1.09$ and $a=1.0$, we obtain

$$[\rho(T, H) - \rho(T, 0)]/\rho(T, 0) \approx 0.6(M/M_0)^2. \quad (6 \cdot b)$$

This is in good agreement with the experimental result eq. (5), considering the crudeness of our analysis. Thus, eq. (2) with eq. (4) explains the anomalous magnetoresistance in the paramagnetic phase as well as the resistivity anomaly in the ferromagnetic phase.

§5. Discussion

The analysis in a preceding section shows that the anomalous temperature and field dependence of the resistivity is determined mainly by a variation of the magnetization. In the analysis, the magnetization dependence assumed for $1/\tau_m$ in eq. (1) is that expected for the spin-disorder resistivity³³⁾ and a possible temperature dependence^{29,34)} of other quantities than that of M is neglected in this term. Moreover, the resistivity of $\text{Co}_{0.7}\text{Ni}_{0.3}\text{S}_2$ taken as $\rho_p(T)$ seems not only to contain the phonon scattering expressed by the Grüneisen-Bloch equation but also to include magnetic scattering due to spin fluctuations as calculated for an itinerant case by Ueda and Moriya.³⁴⁾ The ambiguity in the separation and meaning of these terms is due to a fact that 3d e_g electrons in CoS_2 are intermediate between localized and itinerant states.^{5,27)} Although we could express the anomaly by the variation of m^* with M , there remains a possibility of an extra M dependence in $1/\tau$ which might explain the anomaly, as has been treated for the impurity scattering.^{11,35)}

The origin of the variation of m^* with M is not clear at present. There has been no evi-

dence of magnetic superlattice which would cause an extra energy gap near the Fermi level. On the other hand, from the electronic-specific-heat coefficient γ of $\text{Fe}_x\text{Co}_{1-x}\text{S}_2$ by Ogawa,^{27,36)} we see that the density of state at the Fermi level *per Co atom* increases in the paramagnetic phase whereas it decreases in the ferromagnetic phase, with increasing Fe concentration, that is, with decreasing band width. This fact suggests that an electronic structure near the Fermi surface should be quite different in the paramagnetic and ferromagnetic phases. This may be a part of the reason for the different pressure effects on the resistivity in the paramagnetic and ferromagnetic phases, which was described in §3.1. Thus, it is interesting to distinguish whether such a change in the electronic structure near the Fermi surface originates from a possible special shape of the one-electron band or from an effect of electron correlation; this requires further theoretical studies.

The results of the effects of magnetic field by us and of Se-doping by Adachi *et al.*⁸⁾ on the resistivity and thermal expansion anomalies are similar to those effects on the M - T curve;⁸⁻¹⁰⁾ our result of the pressure effect on the resistivity and T_c is similar to the effects of Se-doping and Ni-doping and opposite to that of Fe-doping. For the variety of these parameters, we note that the anomalies in the resistivity and the thermal expansion are qualitatively determined by the magnetization behaviour and that the sharpness of the transition simply depends on T_c . As to the variation of the T_c , we get a correspondence of 1 kbar $\approx$ 0.10 at. %Se $\approx$ 0.11 at. %Ni $\approx$ -0.37 at. %Fe $\approx$ -1.4 kOe.

Finally, we comment on a relation of the magnetization dependence of the resistivity (eq. (2) with eq. (4)) to the critical exponents of CoS_2 below T_c . From eqs. (2) and (4) we obtain $d\rho/dT \propto M(dM/dT)$, neglecting M^4 term and the weak temperature dependence of $\rho_p(T)$. Thus we get $d\rho/dT \propto -|\varepsilon|^{2\beta-1} = -|\varepsilon|^{-0.50}$, where $\varepsilon = (T - T_c)/T_c$ and $M \propto |\varepsilon|^\beta$ with $\beta = 0.25 \pm 0.01$.²²⁾ The calculated exponent -0.50 of $d\rho/dT$ is close to the value -0.55 observed by Ogawa and Teranishi¹⁾ in the range $|T - T_c| \approx 0.2 \text{ K} \sim 4.8 \text{ K}$. It is interesting to distinguish whether this coincidence is an effect of the long range order expressed by eqs. (2) and (4), or rather an effect of possible band structure

fluctuations which was treated for antiferromagnetic metals by Ausloos.³⁷⁾

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