Temperature Dependence of Magnetoresistance in Iron*

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Longitudinal and transverse magnetoresistance has been measured in iron single crystals at 300, 77, and 4.2°K in fields up to 50 kOe. For most field and current directions the magnetoresistance reverses sign between 300 and 4.2°K in both high and low fields. At 300°K the magnetoresistance shows an initial positive region connected with the magnetization process, while at high fields it shifts to a negative slope. At low temperatures the low-field magnetoresistance becomes negative and at 4.2°K the longitudinal and transverse magnetoresistance reach minimum values at 400–1000 Oe and 1–6 kOe, respectively. Both the transverse and longitudinal magnetoresistance show hysteresis within the negative region, and the decrease in resistance depends on the development of a net magnetization in the direction of the applied field. The negative magnetoresistance does not seem to be a sensitive function of domain configuration. The high-field magnetoresistance at 4.2°K is typical of a compensated metal and corresponds to $\omega_c\tau>1$, where ω_c is the cyclotron frequency and τ the relaxation time. Iron whiskers 180–400 μ in diameter with axes along ⟨100⟩ and ⟨111⟩ directions have been used for the experiments and have resistance ratios $\rho_{300°K}/\rho_{4.2°K}$ that vary from 200 to 2000.

INTRODUCTION

MEASUREMENTS of the transverse and longitudinal magnetoresistance in iron single crystals have been carried out at 4.2, 77, and 300°K. Iron whiskers 180–400 μ in diameter have been used for the experiments and are thick enough to approach the properties of bulk crystals. Whiskers less than 100 μ in diameter begin to show size effects and these will be reported in a later paper. The whiskers were grown by the hydrogen reduction of $FeCl_2$ at 700°C and grow with low index axes along ⟨100⟩, ⟨111⟩, and ⟨110⟩ directions. The detailed crystallography and zero-field domain structure have been reported previously by Coleman and Scott,[1,2] Isin and Coleman,[3] and de Blois and Graham.[4,5] Magnetic fields up to 50 kOe have been used for experiments at 4.2°K and up to 27 kOe for experiments at 77 and 300°K.

The measurements reported in this paper indicate that at low fields the magnetoresistance at all three temperatures measured is influenced by the domain changes occurring during magnetization while at high fields the magnetoresistance is observed to approach a behavior characteristic of the intrinsic electronic structure of iron. Similar observations have been reported by Semenenko and Sudovtsov[6,7] using high-purity iron specimens.

The magnetoresistance in both the low-field and high-field regions shows a marked dependence on temperature and in fact for most orientations and fields reverses sign between room temperature and 4.2°K. In high fields this is accounted for by the increase in mean free path at low temperatures. In low fields the interpretation of the results requires a detailed knowledge of the volume domain structure in zero field as well as in the applied fields.

The zero-field domain structure in iron whiskers has been well-established in the experiments reported in Refs. 1–5. These studies have shown that the zero-field domain structure in well-oriented whiskers is the simplest possible one to the extent that it can be determined by powder patterns on the surface. The proposed zero-field domain structures for the ⟨100⟩ and ⟨111⟩ axial whiskers are shown in Fig. 1. The volume domain structure indicated for the ⟨100⟩ axial whisker is undoubtedly the correct one since observations on all sides of the whisker are consistent with such a structure. In addition, domain motion observed during longitudinal magnetization as reported by Scott and Coleman[8] can only

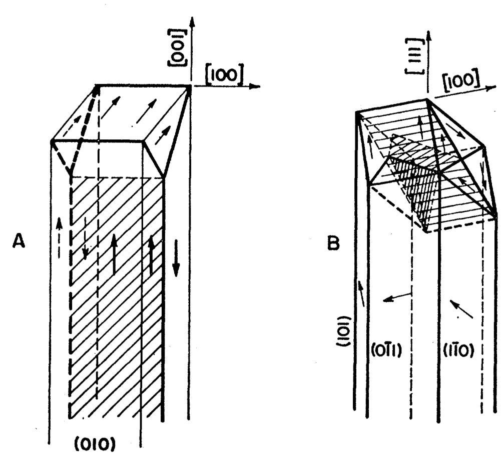

FIG. 1. Domain structures in iron whiskers deduced from powder-pattern studies at room temperature.

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[6] A. M. Sudovtsov and E. E. Semenenko, Z. Eksperim. i Teor. Fiz. 35, 305 (1958) [English transl.: Soviet Phys.—JETP 8, 211 (1958)].
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[8] G. G. Scott and R. V. Coleman, J. Appl. Phys. 28, 1512 (1957).

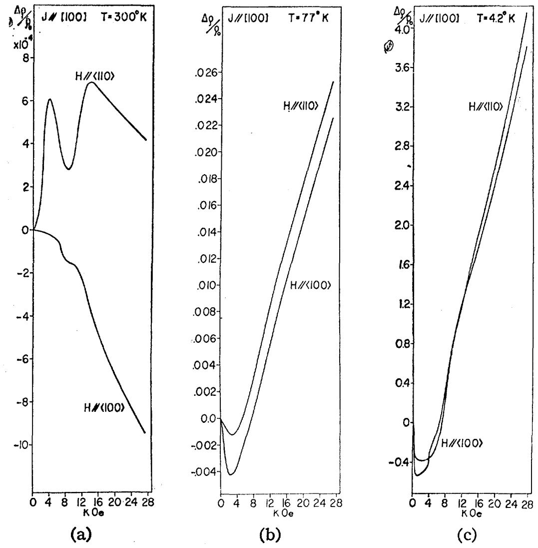

FIG. 2. (a) Transverse magnetoresistance measured at 300°K for a ⟨100⟩ axial whisker. (b) Transverse magnetoresistance measured at 77°K for a ⟨100⟩ axial whisker. (c) Transverse magnetoresistance measured at 4.2°K for a ⟨100⟩ axial whisker.

be interpreted in terms of this simple structure. The volume domain structure deduced for the ⟨111⟩ axial whiskers is less certain due to the initially more complicated structure as well as the more complicated longitudinal magnetization process. Measurements have been made on a number of ⟨100⟩ and ⟨111⟩ axial whiskers in both the transverse and longitudinal orientation. The data shown in the figures has been selected from the same whisker whenever possible for comparison purposes. However, the major features observed in any of the curves shown are characteristic of all the specimens measured.

TRANSVERSE MAGNETORESISTANCE

Measurements of the magnetoresistance have been made for currents along ⟨100⟩ and ⟨111⟩ with corresponding transverse field directions along the low-index directions ⟨100⟩, ⟨110⟩, and ⟨112⟩ as well as many higher index directions. Experimental curves recorded at the three temperatures are shown in Figs. 2 and 3. The curves in Fig. 2 correspond to ⟨100⟩ and ⟨110⟩ field directions and were measured for a ⟨100⟩ axial whisker 240 μ in diameter. The curves for the ⟨110⟩ and ⟨112⟩ field directions in Fig. 3 were measured for a ⟨111⟩ axial whisker 300 μ in diameter. The resistance ratios $\rho_{RT}/\rho_{4.2°}$ were 200 and 268 for the ⟨100⟩ and ⟨111⟩ axial whiskers, respectively.

At low fields the room-temperature transverse magnetoresistance is positive for all field directions except the easy direction of magnetization ⟨100⟩ for which it is negative for all field values up to 27 kOe. The positive magnetoresistance observed for other field directions exhibits either one or two maxima as shown in Fig. 2(a) and 3(a). In high fields above magnetic saturation all field dependence curves shift to a negative slope and for most field and current directions the magnetoresistance becomes negative before the maximum field of 27 kOe is reached.

The positive maxima observed for most field directions are consistent with additional resistance introduced by a more complicated domain structure developing during magnetization. Studies of powder patterns during transverse magnetization[1,2] indicate a complicated development of dagger domains and parallel domain walls in higher fields. This is particularly true for fields applied along hard directions of magnetization.

In the case of field along ⟨100⟩ and current along ⟨100⟩ no positive contribution to the magnetoresistance is observed, although surface domain patterns indicate that some domain structure develops. However, it is considerably less complicated than that observed for hard directions of magnetization. It seems quite probable that the domains in the main body of the whisker switch to the transverse ⟨100⟩ easy directions in very low fields and that the surface domains are due to the large demagnetizing field in the transverse orientation. The main contribution is negative in sign and probably due to the same mechanism that causes the negative slope at high fields. The absence of any positive contribution to the magnetoresistance for the ⟨100⟩ field direction is quite sensitive to field orientation. Slight misalignments of the applied field will introduce an initial positive maximum in the field dependence curve similar to that observed for non-easy field directions. The two maxima observed for the ⟨110⟩ field direction in Fig. 2(a) are associated in some way with the detailed variation in domain structure and are observed consistently in {100} ⟨100⟩ whiskers for field along ⟨110⟩.

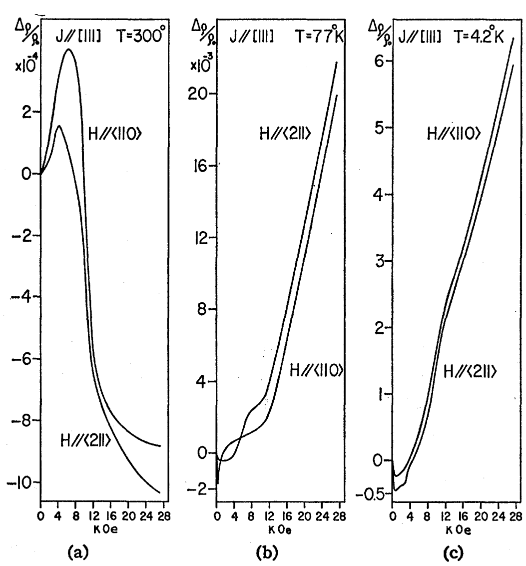

FIG. 3. (a) Transverse magnetoresistance measured at 300°K for a ⟨111⟩ axial whisker. (b) Transverse magnetoresistance measured at 77°K for a ⟨111⟩ axial whisker. (c) Transverse magnetoresistance measured at 4.2°K for a ⟨111⟩ axial whisker.

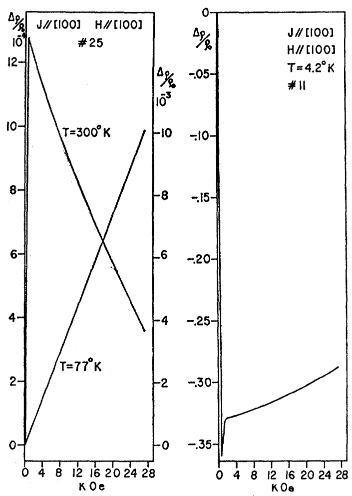

FIG. 4. Longitudinal magnetoresistance for ⟨100⟩ axial whiskers at 300, 77, and 4.2°K.

The resistance change observed during magnetization at room temperature represents only about 0.1% of the total resistance. Therefore, the mechanism contributing to the low-field structure need only have a small effect on the total scattering. Domain boundary scattering could therefore contribute even though the mean free path is about 10^{-3} times smaller than the average domain size. However, in the case of the ⟨100⟩ longitudinal magnetoresistance at room temperature, a rapid initial rise of magnetoresistance is observed even though this should correspond to the simplest domain development.[8a] This would indicate that domain boundary scattering is not playing a significant role. Volume effects due to the changing direction of magnetization in the various domains relative to current and crystal axis could also produce effects of this order. Smit[9] has expressed the resistance tensor (referred to the cubic axes of the crystal) in terms of the direction cosines of the magnetization as follows:

$$\rho_{11}=\rho_0 C_1\alpha_1^2+C_3(\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2+\alpha_1^2\alpha_2^2)+C_5\alpha_2^2\alpha_3^2, \quad (1)$$
$$\rho_{12}=C_2\alpha_1\alpha_2+C_4\alpha_1\alpha_2\alpha_3^2.$$

The C's are constants and terms higher than fourth order have been omitted. In the case of iron, Smit found this to be a 0.5% effect at room temperature.

The linear decrease of the magnetoresistance observed at room temperature in high fields for all orientations is characteristic of other observations on ferromagnetic metals.[9,10] The negative slope has been explained on the basis of a decrease in the scattering of electrons from $4s$ states to $3d$ states using the model of s-d scattering in ferromagnetic metals due to Mott.[11,12] The decrease in resistance with increasing field is interpreted as a decrease in the s-d scattering caused by a reduction in the density of $3d$ states at the Fermi surface parallel to the field. This argument has been discussed in some detail by Smit.[9]

At low temperatures the behavior of the magnetoresistance in both the low-field and high-field regions changes substantially due to the large increase in mean free path of the conduction electrons. At liquid-nitrogen temperatures, the initial low-field magnetoresistance for most orientations of field shows a negative region extending up to several kilo-oersted while at high fields the magnetoresistance becomes positive rising rapidly with field and described by $\rho(B)/\rho_{(0)}=\text{const}\times B^m$ where $1\leq m\leq 2$. Curves measured at nitrogen temperature are shown in Figs. 2(b) and 3(b). At helium temperature the behavior is similar except for an order of magnitude increase of $\Delta\rho$ for the low-field negative magnetoresistance and a more rapid rise (larger values of m) of the high-field positive magnetoresistance. Curves measured at helium temperature are shown in Figs. 2(c) and 3(c), and are similar to measurements previously reported by Isin and Coleman[3] and Reed and Fawcett.[13] For certain special field directions the field dependence curves also show positive maxima as well as negative regions. These field directions are those that correspond to maxima in the low-field rotation diagrams and examples have been shown in Ref. 3.

The rapid increase in resistance at higher fields is the expected behavior resulting from the Lorentz force on the electrons when the mean free path is sufficiently long so that $\omega_c\tau\geq 1$, and is not of ferromagnetic origin except for the contribution to B from the internal magnetization. ($\omega_c=eH/mc$ = cyclotron frequency, τ = relaxation time.) The room temperature to helium temperature resistance ratios vary from 200 to 2000 for the whiskers measured and at low temperatures $\omega_c\tau\geq 1$ is satisfied in high fields. The high-field magnetoresistance observed at helium temperature is typical of that observed for compensated metals and has been discussed in detail by Lifshitz *et al.*[14] and Fawcett and Reed.[15] In addition,

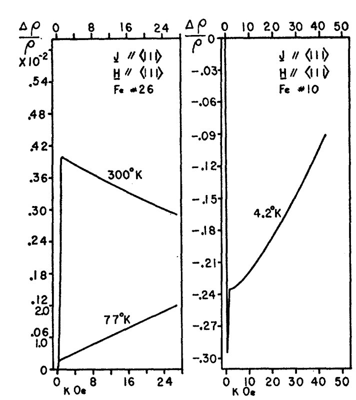

FIG. 5. Longitudinal magnetoresistance for ⟨111⟩ axial whiskers at 300, 77, and 4.2°K.

[8a] *Note added in proof.* Additional experiments have shown that this initial rise as shown in Fig. 4 is not observed in exactly oriented ⟨100⟩ specimens.
[9] J. Smit, Physica **16**, 612 (1951).
[10] Velio A. Marsocci, Phys. Rev. **137**, A1842 (1965).
[11] N. F. Mott, Proc. Roy. Soc., London **A153**, 699 (1936).
[12] N. F. Mott, Advan. Phys. **13**, 325 (1964).
[13] W. A. Reed and E. Fawcett, Phys. Rev. **136**, A422 (1964).
[14] I. M. Lifshitz, M. Ya. Azbel, and M. I. Kaganov, Z. Eksperim. i Teor. Fiz. **30**, 220 (1955); **31**, 63 (1956) [English transls.: Soviet Phys.—JETP **3**, 143 (1965); **4**, 41 (1957)].
[15] E. Fawcett and W. A. Reed, Phys. Rev. **131**, 2463 (1963).

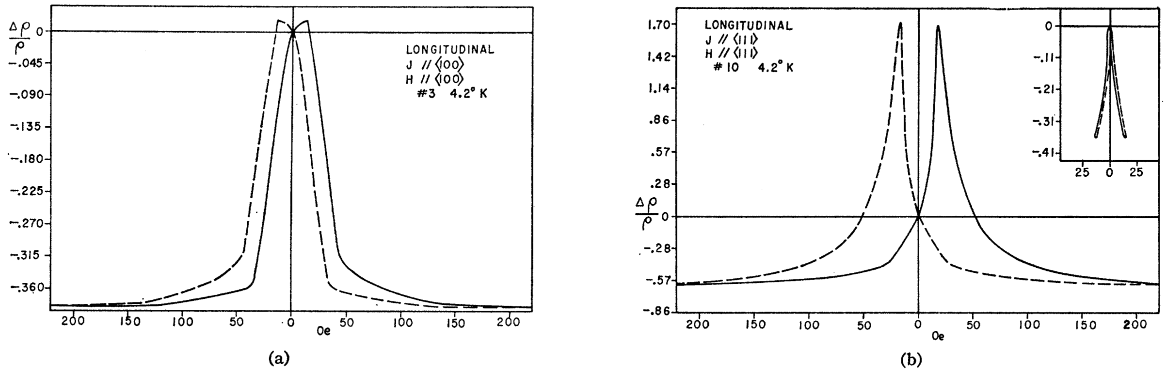

FIG. 6. (a) Hysteresis at 4.2°K in the longitudinal magnetoresistance of a ⟨100⟩ axial whisker. (0–250 Oe).
(b) Hysteresis at 4.2°K in the longitudinal magnetoresistance of a ⟨111⟩ axial whisker. (0–250 Oe).

transverse rotation curves taken in fields up to 100 kOe along with field dependence curves indicate that open orbits are supported by the Fermi surface of iron in ⟨100⟩ and ⟨110⟩ directions. These results have been re-reported in Refs. 3 and 13.

The low-field negative magnetoresistance observed at low temperatures is difficult to understand in detail. Additional interpretation will be given in the section on negative magnetoresistance and hysteresis.

LONGITUDINAL MAGNETORESISTANCE

The longitudinal magnetoresistance in iron whiskers also shows a strong dependence on temperature and exhibits low-field behavior connected with domain changes during magnetization. At room temperature in longitudinal fields the resistance of both the ⟨100⟩ and ⟨111⟩ axial whiskers shows an initial increase with field followed by saturation and a decrease of resistance in high fields. The resistance versus field curve approaches a constant negative slope in high fields. These results are consistent with the high temperature behavior reported by Smit,[9] and also by Semenenko and Sudovtsov[6,7] for longitudinal fields up to 800 Oe. Wagner[16] has also observed similar curves for carbon-nickel at room temperature.

At low temperatures the longitudinal magnetoresistance shows a general behavior similar to that observed for transverse fields. This consists of an initial sharp decrease in resistance followed by increasing resistance in high fields. In the longitudinal case at 4.2°K, the entire decrease in resistance occurs in the first few hundred oersted of applied field and is of the same order of magnitude as the decrease observed in transverse fields, although for a given whisker the longitudinal decrease is greater than the transverse. In addition, the increase of resistance in high fields up to 50 kOe is not sufficient to produce a positive magnetoresistance. The entire curve from 0 to 50 kOe corresponds to a negative magnetoresistance for both the ⟨100⟩ and ⟨111⟩ axial whiskers, although the slope indicates that the magnetoresistance will become positive between 50 and 100 kOe. Longitudinal magnetoresistance curves for the ⟨100⟩ and ⟨111⟩ axial whiskers are shown in Figs. 4 and 5 for the three temperatures measured.

NEGATIVE MAGNETORESISTANCE AND HYSTERESIS

The rapid decrease in resistance observed in low applied fields at helium temperature has been studied in detail for both longitudinal and transverse fields. The results obtained in longitudinal fields from 0 to 250 Oe are shown in Figs. 6(a) and 6(b) for the ⟨100⟩ and ⟨111⟩ axial whiskers, respectively. Curves have been drawn for fields both parallel and antiparallel to the current, values of **H** on the right correspond to the parallel orientation of **J** and **H**. The curves are drawn for two complete cycles of the field in which the field starts at the maximum value in one direction, decreases

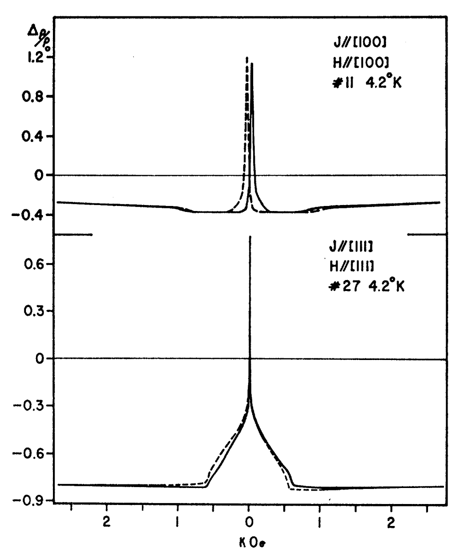

FIG. 7. Hysteresis curves for longitudinal magnetoresistance of ⟨100⟩ and ⟨111⟩ axial whiskers. (0–2500 Oe). Sweep rate is ten times faster than those used to obtain Fig. 6.

[16] Von Paul Wagner, Ann. Physik 32, 665 (1938).

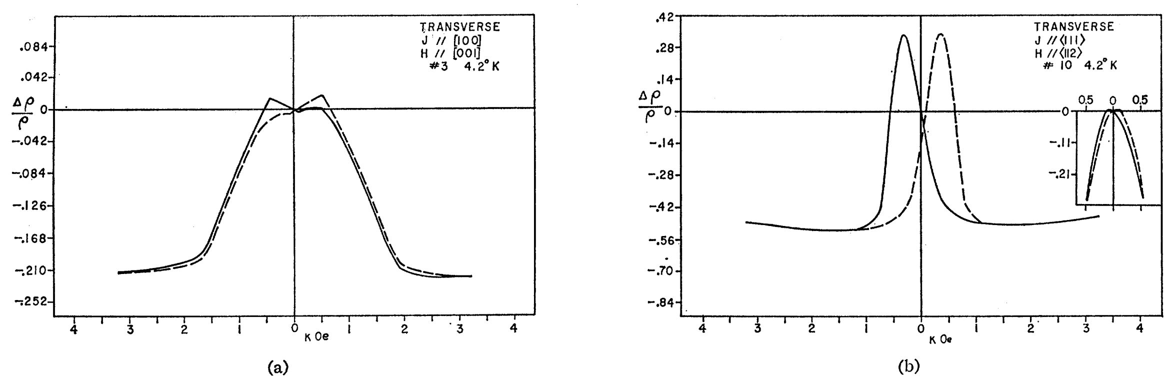

FIG. 8. (a) Hysteresis in the transverse magnetoresistance observed at 4.2°K for a ⟨100⟩ axial whisker. (b) Hysteresis in the transverse magnetoresistance observed at 4.2°K for a ⟨111⟩ axial whisker.

to 0, then increases in the opposite direction. The solid curve represents the first cycle and the dotted curve the second cycle. The curves show a clear hysteresis effect which indicates a close connection between the resistance and domain development. The hysteresis is completely symmetric about the zero-field point and indicates that the zero magnetization state of the crystal (complete flux closure domain configuration) corresponds to the maximum in the resistance. By careful cycling of the whisker the resistance maximum can be made to occur at zero applied field. The double-cycle process will then correspond to only negative magnetoresistance if the cycle is carried only to very low maximum fields as shown in the upper right hand corner of Fig. 6(b) for the ⟨111⟩ axial whisker. This means that the correct zero-field resistance corresponding to complete flux closure is the value of resistance at the maximum. The decrease of resistance, therefore, corresponds to about 84% of the total resistance of the crystal. Zero resistance would correspond to a $\Delta\rho/\rho=-1$.

The effect is similar in both the ⟨100⟩ and ⟨111⟩ axial whiskers, although the apparent positive magnetoresistance produced by the hysteresis in the ⟨111⟩ whisker is more pronounced. The field cycles shown in Figs. 6(a) and 6(b) were carried out very slowly and the resistance at each field value is constant in time. The curves shown are taken directly from an x-y recorder measuring voltage drop across the specimen on the x axis and solenoid current on the y axis.

Longitudinal field cycles up to 2500 Oe at 4.2°K have also been carried out and are shown in Fig. 7 for both ⟨100⟩ and ⟨111⟩ axial whiskers. In this case the field sweep is faster and the ⟨100⟩ axial whisker shows a greater hysteresis than was shown in Fig. 6(a) for the slow sweep rate. The flat minimum between 250–1000 Oe corresponds to the very sharp minimum observed in the high-field longitudinal curves of Fig. 4. The ⟨111⟩ axial whisker shows no appreciable change in hysteresis at the fast sweep rate and as shown in Fig. 7 the hysteresis peaks are unresolved on the field scale of the fast sweep. In addition, the longitudinal magnetoresistance of the ⟨111⟩ axial whisker reaches a minimum value more slowly than is the case for the ⟨100⟩ axial whisker. Both of these observations are consistent with the probable domain development during magnetization. In the ⟨100⟩ case the center domain wall moves to one side during initial application of the field and the main body of the whisker becomes magnetized along ⟨100⟩. Powder patterns also indicate that rapid removal of the field often leaves various combinations of 90° domain walls in the body of the whisker which may contribute to the increased hysteresis at the fast sweep rate. The domain structure in the ⟨111⟩ whisker at zero field is a less flexible arrangement and in low fields the magnetization will develop more slowly since there are no easy directions in the applied field direction. The fact that longitudinal hysteresis in the ⟨111⟩ whisker does not increase with sweep rate is also consistent with powder patterns which indicate that rapid removal of the applied field never modifies the zero field domain structure observed on the surface and indicated in Fig. 1.

The hysteresis in the negative region of the transverse magnetoresistance has been studied in fields up to 2500 Oe. Results for the ⟨100⟩ and ⟨111⟩ axial whiskers are shown in Figs. 8(a) and 8(b), respectively. Two cycles of the magnetic field are again shown, each cycle corresponding to starting at the maximum field value, decreasing to zero, and increasing to the maximum field in the opposite direction. For the ⟨100⟩ axial whisker the transverse field was applied in the ⟨100⟩ direction and in the ⟨211⟩ direction for the ⟨111⟩ axial whisker. As shown in Fig. 8(a) a very small hysteresis was observed for the ⟨100⟩ case. The symmetry of the ⟨100⟩ curve about the 0-field position was found to be extremely sensitive to the orientation of the applied field. Misorientations of 1° will shift the maximum of resistance substantially to the right or left of the 0-field position. Relative to the longitudinal case the transverse resistance minimum is also shifted to much higher field values. This may account for the shallower minimum in the transverse case since the $\omega_c\tau$ values will be higher at the minimum giving a greater positive contribution from the high-field magnetoresistance.

For the ⟨111⟩ axial whisker the transverse magnetoresistance shows a similar hysteresis effect to that observed for the ⟨111⟩ in longitudinal fields. The only es-

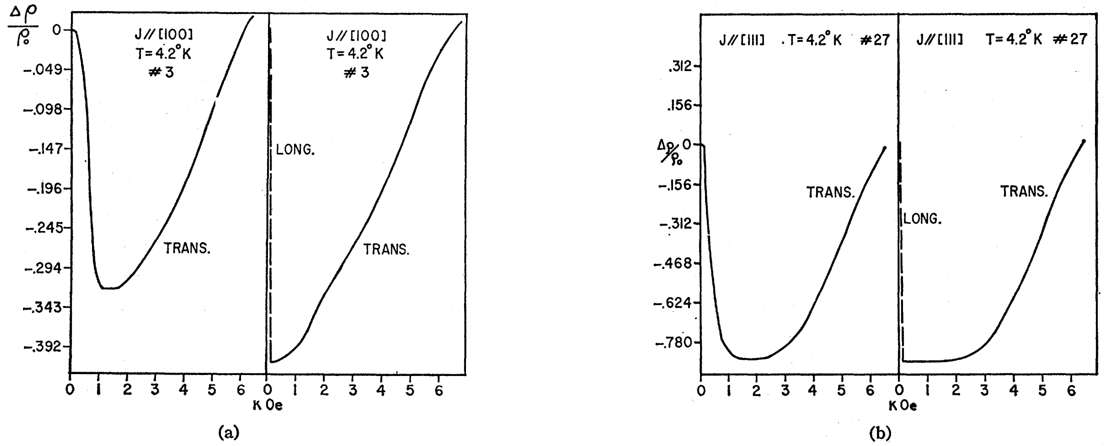

FIG. 9. Magnetoresistance curves obtained by applying both longitudinal and transverse magnetic fields. Curve on left is for purely transverse field. Curve on right is for successive application of a 100 Oe longitudinal field and a 6 kOe transverse field. (a) ⟨100⟩ axial whisker. (b) ⟨111⟩ axial whisker.

sential difference is a shift of the minimum to much higher fields. By careful cycling of the field the maximum can again be made to correspond to the 0-field position as shown in the insert of Fig. 8(b).

Experiments were also carried out in which both a longitudinal and a transverse field were applied to the crystal. Results are shown in Fig. 9(a) and 9(b). The curves labeled TRANS. correspond to the application of transverse fields while the dotted curves labeled LONG. correspond to application of longitudinal fields. The curves on the left show the usual negative minimum in magnetoresistance obtained for a purely transverse field. The curves on the right were obtained by first applying a longitudinal field of ~100 Oe and then applying the transverse field. In this case the entire decrease occurs during the application of the longitudinal field and subsequent application of the transverse field produces only an increase in resistance.

Hysteresis was also studied at room temperature and found to be a negligible effect for both longitudinal and transverse orientations. Hysteresis for a ⟨111⟩ axial whisker in a transverse field is shown in Fig. 10 and is very small relative to the large hysteresis of approximately 2 kOe observed at helium temperature. This may well be due to the thermal activation of domain boundaries which will be effectively frozen out at 4.2°K.

All of these results indicate that the low-field magnetoresistance is closely related to the domain development during magnetization. However, comparison of the ⟨100⟩ and ⟨111⟩ axial whiskers indicates that the negative region of magnetoresistance is connected more directly to the development of a net magnetization in the direction of the applied field than it is to the detailed geometry of the domain structure. For the ⟨100⟩ axial whisker, this conclusion is supported by the simple magnetization process which should occur in longitudinal fields. Domain development consists only of the gradual displacement of the central domain wall to one side of the whisker as has been demonstrated at room temperature by Scott and Coleman.[8] There will be a more complicated domain structure developing at the ends of the whisker due to the demagnetizing field, but this represents only a small volume of the whisker and is generally outside the potential leads. One therefore expects the domain structure in the body of the ⟨100⟩ whisker to remain extremely simple during longitudinal magnetization.

The behavior of the ⟨111⟩ axial whisker in a pure longitudinal field also indicates that the development of a net magnetization is the major factor in the negative magnetoresistance. The initial decrease in resistance is essentially the same as that observed for the ⟨100⟩ axial whisker. This occurs despite the fact that ⟨111⟩ is a hard direction of magnetization and that the initial zero-field domain structure corresponds to magnetization directions nearly perpendicular to the current (see Fig. 1). The longitudinal magnetization process also involves a much more complicated domain development consisting first of switching the domains to other easy directions of magnetization giving a net magnetization along the current direction followed by spin rotation in higher fields. The development of a complicated domain structure during longitudinal magnetization has been verified at room temperature using powder patterns. In

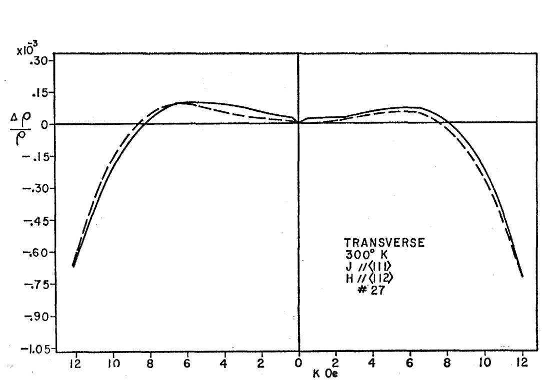

FIG. 10. Hysteresis curve measured for a ⟨111⟩ axial whisker in a transverse field at 300°K.

the ⟨111⟩ case the magnetization also switches from a state with magnetization in each domain approximately perpendicular to **J** to a state with magnetization parallel or antiparallel to **J** while in the ⟨100⟩ case magnetization is always parallel or antiparallel to **J**. This would indicate that the switching of magnetization from perpendicular to parallel orientations with respect to the current is not a major factor in the decrease of resistance. This effect has been previously suggested as a possible contribution to the negative magnetoresistance[7] and is known as the reverse galvanomagnetic effect.

The transverse negative magnetoresistance also indicates that the decrease in resistance follows the development of the net magnetization in the applied field direction. The negative region is similar to the longitudinal case except that the minimum occurs for field values an order of magnitude higher. This is completely consistent with the slower development of magnetization in the transverse orientation due to the large demagnetizing field. The transverse domain development is also much more complex than is the case for longitudinal fields, however, this does not seem to change the general features of the observed negative magnetoresistance from that of the longitudinal case.

CONCLUSIONS

Measurements of the room-temperature magnetoresistance in iron whiskers are consistent with previous experiments and in agreement with theory particularly in high fields where a negative slope is observed for all field dependence curves. The low-field transverse magnetoresistance shows structure connected with domain development during magnetization and is a sensitive function of the relative orientation of field, crystal axis, and current. The transverse magnetoresistance due to domain structure is positive at room temperature and exhibits maxima for field values in the range of 2–6 kOe. This positive contribution is very small relative to the total resistance and could be due either to domain boundary scattering or to anisotropies introduced by changes in the relative direction of magnetization and current.

At low temperatures effects due to the long mean free path of the electron become dominant and for most field directions this reverses the sign of the magnetoresistance as the temperature is lowered. At nitrogen temperature this is already the major contribution to the magnetoresistance and at helium temperature the effects of long mean free path are completely dominant. In high fields at helium temperature $\omega_c\tau > 1$ and the magnetoresistance behavior is consistent with the theory for a compensated metal.

The low-field magnetoresistance at helium temperatures is generally negative. The transverse magnetoresistance shows a negative minimum for field values of 1–6 kOe while the longitudinal magnetoresistance reaches a negative minimum in fields of 400–1000 Oe. Additional structure in the low field magnetoresistance can be observed for special field orientations where the domain structure changes in a complicated manner.

The negative magnetoresistance observed for most orientations of field, current, and crystal axes appears to be directly connected with the development of a net magnetization in the direction of the applied field. Specific domain structure development introduces some structure in the field dependence curves, but the main effect is an initial smooth decrease in the resistance. This smooth decrease is observed for a large number of field and current directions corresponding to both simple and complicated domain structure development. In the transverse case the minimum is probably shifted to higher fields due to the large demagnetizing field which will cause the net magnetization in the direction of the field to develop more slowly. The detailed mechanism causing the reduction in resistance when the net magnetization develops is not clear at present. The mean free path at helium temperature is on the order of or greater than the average domain dimension and the electron would be expected to pass through domain boundaries between collisions. The 90° or 180° rotation of the magnetization from one domain to the next might produce a substantial change in the contribution of a given electron orbit to the conductivity along the current direction. This change would depend on the detailed geometry of the Fermi surface and any analysis would require a better knowledge of the Fermi surface than is presently available. The existence of open orbits on the Fermi surface as reported in Refs. 3 and 13, would be expected to introduce substantial anisotropies in the resistance as a function of relative direction of magnetization, current, and crystal axes. These anisotropies are, of course, observed directly in high fields where the whisker is behaving as a single domain. In low fields the effects would be averaged in a complicated manner over all domains with field directions distributed over a number of ⟨100⟩ easy directions of magnetization. The result of the averaging process might then depend on the net average magnetization rather than on the detailed domain structure.

Domain boundary scattering may contribute to the detailed structure of the field dependence curves but does not account for the major negative magnetoresistance regions observed in low fields. These points have still to be verified in detail and iron whiskers offer specimens with high purity, simplified domain structure, and very few defects for carrying out studies of this type. Size effects may introduce some complications, but selected whiskers can be grown up to ~1 mm in diameter which should avoid this problem.

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