Magnetoresistance Coefficients and Their Temperature Dependence in Iron and Silicon-Steel*

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By using single-crystal strips of iron and silicon steel having the crystallographic orientations (001)−[100] and (1$\bar{1}$0)−[111], the magnetoresistance coefficients ρ_1, ρ_2, and their temperature dependence were measured below room temperature. The measurement of ρ_1 was accomplished by changing the domain structure in the demagnetized state by utilizing the magnetic field induced by the measuring current in the sample. It is found that both ρ_1 and ρ_2 are strongly dependent on temperature and composition, but it seems difficult to obtain a complete quantitative interpretation of the results.

A. INTRODUCTION

It is well established that the experimentally obtained magnetoresistance of a single magnetic domain of a ferromagnetic cubic crystal is given by the following expression[1]:

$$\left(\frac{\Delta R}{R}\right)=\rho_0+\rho_1\sum_{i=1}^{3}\alpha_i^2\beta_i^2+\rho_2\sum_{i,j=1}^{3}\alpha_i\alpha_j\beta_i\beta_j+\cdots,\quad(1)$$

where ρ_0, ρ_1, and ρ_2 are the temperature-dependent coefficients, the so-called magnetoresistance "constants," and α_i and β_i are direction cosines of the magnetic moment vector and the measuring-current vector, respectively, with respect to the cubic axes. Thus, in a case of a ferromagnetic substance whose easy direction of magnetization is [100] such as iron, only the ρ_1 term is dependent on the domain orientation and the ρ_2 term is only dependent on the rotation of the spontaneous magnetization in a domain.

It is, we see, theoretically possible to obtain the coefficients by measuring the difference in longitudinal magnetoresistance between the demagnetized and saturation bulk magnetized states for both the (001)−[100] and (1$\bar{1}$0)−[111] single-crystal strips, and such measurements were the fundamental purpose of this investigation.[2]

In these present experiments, measurements were made of the temperature dependence of ρ_1 and ρ_2 below room temperature using single-crystal strips of iron and silicon steel[3] having simple crystallographic orientation, that is, (001)−[100] and (1$\bar{1}$0)−[111]. The single-crystal strips, 0.5 mm×3 mm×50 mm for iron and 0.3 mm×3 mm×50 mm for silicon steel, were made with a special stress and anneal technique[4] by the author in his laboratory, Faculty of Science, Hiroshima University, Hiroshima, Japan.

B. MEASUREMENT OF ρ_2

For determining the coefficient ρ_2, the method of measuring the difference in longitudinal magnetoresistances suggested in the introduction is possible for the following reason. The easy direction of magnetization of both iron and silicon-iron is [100] so that neglecting the increase of resistance due to magnetostrictive lattice distortion caused by the configuration of the [100], [$\bar{1}$00], [010], [0$\bar{1}$0], [001], and [00$\bar{1}$] magnetic domains, the longitudinal magnetoresistance, $(\Delta R/R)_{\mathrm{demag}\cdot[111]}$, does not depend on the domain configuration, since the [111] direction is symmetric with respect to the cubic axes; that is,

$$(\Delta R/R)_{\mathrm{demag}\cdot[111]}=\rho_0+\tfrac{1}{3}\rho_1+\cdots.\quad(2)$$

The first subscript refers to the magnetic state and the second to the long axis of the crystal which is the current direction. In the case of bulk saturation magnetization,

$$(\Delta R/R)_{[111]\cdot[111]}=\rho_0+\tfrac{1}{3}\rho_1+\tfrac{2}{3}\rho_2+\cdots.\quad(3)$$

Here the first subscript refers to saturation in the [111] direction. The magnetoresistance obtained from the difference in resistance between the two above extreme cases $(\Delta R/R)_{\mathrm{demag}\to[111]\cdot[111]}$, is nearly equivalent to

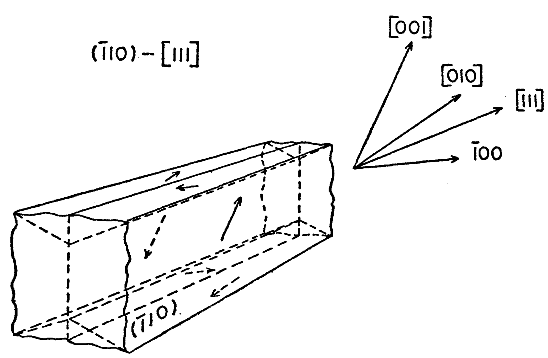

FIG. 1. Domain structure of a single-crystal strip having the (1$\bar{1}$0)−[111] crystallographic orientation.

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[1] W. Doring, Ann. Physik 32, 259 (1938).
[2] The notation (001)−[100] refers to a flat strip with its length in a [100] direction and with a (001) plane for its top face.
[3] Commercial silicon-steel sheet, having the following composition (weight percent): C 0.07%, Si 1.08%, Mn 0.18%, S 0.038%, and Cu 0.21%.
[4] T. Fujiwara and E. Tatsumoto, J. Sci. Hiroshima Univ. Ser. A, 13, 235 (1940).

the difference between

$$(\Delta R/R)_{[111]\cdot[111]} \quad \text{and} \quad (\Delta R/R)_{\text{demag}\cdot[111]},$$

as the *change* of R in the denominator can be neglected; that is,

$$(\Delta R/R)_{\text{demag}\to[111]\cdot[111]} = \tfrac{2}{3}\rho_2 + \cdots. \tag{4}$$

The subscript demag→[111] refers to the difference while the second [111] refers still to the long axis. Thus, a value for ρ_2 can be obtained by this straightforward measurement.

According to the Bitter figures of the $(1\bar{1}0)-[111]$ single-crystal strips observed by the author,[5] the domain structure is very simple as shown in Fig. 1. The increase in resistance due to the configuration of domains mentioned above, therefore, must be negligibly small. This is the reason why single-crystal strips having the (110)−[111] crystallographic orientations are used in this experiment.

C. MEASUREMENT OF ρ_1

It is, in general, difficult to obtain the coefficient ρ_1 for the reason that the magnetoresistance in the demagnetized state depends not only on the increase in resistance due to magnetostrictive lattice distortion caused by the domain configuration, but in addition on the domain configuration itself. If it were possible to set all domains perpendicular to the [100] direction, the direction of measurement, in the demagnetized state, the longitudinal magnetoresistance would be given by

$$(\Delta R/R)_{\text{demag}\cdot[100]} = \rho_0 + \cdots, \tag{5}$$

and the case of saturation bulk magnetization would be given by

$$(\Delta R/R)_{[100]\cdot[100]} = \rho_0 + \rho_1 + \cdots. \tag{6}$$

Then, just as in the case of the $(1\bar{1}0)-[111]$ samples, one magnetoresistance obtained from the difference in resistance between the two extreme cases,

$$(\Delta R/R)_{\text{demag}\to[100]\cdot[100]},$$

is equivalent to the difference between

$$(\Delta R/R)_{[100]\cdot[100]} \quad \text{and} \quad (\Delta R/R)_{\text{demag}\cdot[100]}.$$

That is,

$$(\Delta R/R)_{\text{demag}\to[100]\cdot[100]} = \rho_1 + \cdots. \tag{7}$$

Fortunately, such a demagnetized state as is conceived above can exist if a circular magnetic field be present in the sample, and such a field will always be present provided a sufficient measuring current is flowing through the sample. The domain structure thus obtained may be assumed to have the form shown in Fig. 2.

As a consequence of this analysis, the difference in magnetoresistance between the demagnetized and the case of saturation bulk magnetization should attain a constant value above a certain current density. In Figs. 3 and 4, this effect is shown for iron and silicon steel samples, respectively, at different temperatures as a function of current.

In these figures, the crosses indicate the difference in magnetoresistance between the state demagnetized by a gradually decreasing alternating field in the presence of a direct measuring current and that of saturation bulk magnetization; and the circles the same difference except that there, the demagnetized state is attained with zero measuring current in the sample. In both cases, as is seen in Figs. 3 and 4, the magnetoresistance

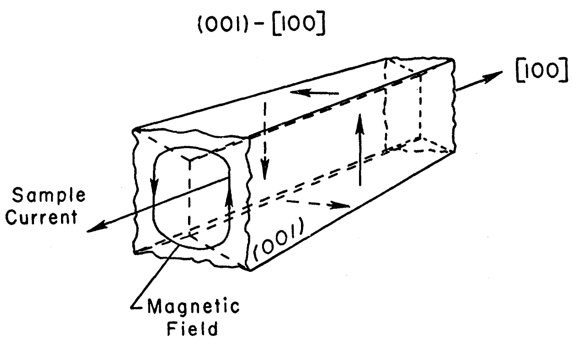

FIG. 2. Domain structure of a single-crystal strip having the (001)−[100] crystallographic orientation in the presence of a sufficiently large sample current.

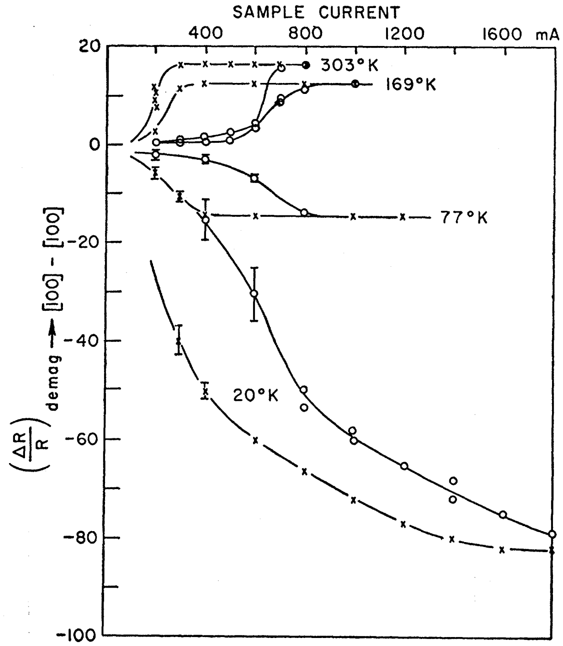

FIG. 3. Difference in magnetoresistance *vs* sample current for iron at different temperatures. The crosses correspond to measurements made on samples demagnetized with finite sample current, and the circles correspond to measurements made on samples demagnetized with zero sample current.

[5] These have been described at the meeting of the Physical Society of Japan but not yet published.

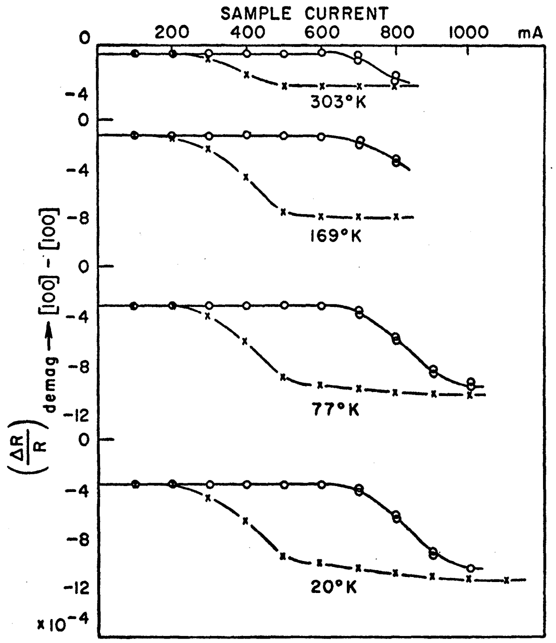

FIG. 4. Difference in magnetoresistance *vs* sample current for the (||) (001)−[100] specimen of silicon steel at different temperatures. Crosses and circles have the same significance as in Fig. 3.

does attain the same constant value above a certain current density as was predicted. There is, however, a difference in the minimum current *density* required to saturate the magnetoresistance, in other words, sufficient to change the domain structure to that shown in Fig. 2. This difference implies that there is an activation energy necessary to change the initial domain structure, in the presence of zero current, to the more stable one shown in Fig. 2, which is expected when the current is sufficiently large.

Thus, it is seen that ρ_1 can be obtained by the straightforward method mentioned above; that is, by obtaining the magnetoresistance by measuring the difference in

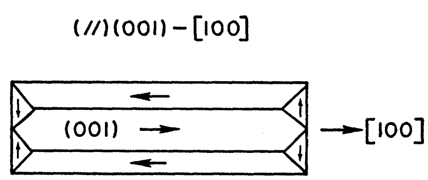

FIG. 5. Domain structure of the (||) (001)−[100] single-crystal strip of silicon steel.

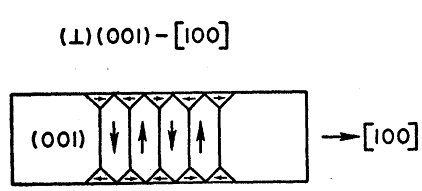

FIG. 6. Domain structure of the (⊥) (001)−[100] single-crystal strip of silicon steel.

resistance between the state which has the domain structure as shown in Fig. 2 and the case of the bulk saturation magnetization.

D. DOMAIN STRUCTURE AND MAGNETO-RESISTANCE EFFECT

In the case of silicon steel, two different sample types were measured, the following notation being used to identify them: (||) (001)−[100] and (⊥) (001)−[100]; where the indices (||) and (⊥) indicate that the single-crystal sample was made from a strip cut parallel or perpendicular to the rolling direction of the silicon-steel sheet. The domain structures of the (||) and (⊥) samples in the ordinary demagnetized state are different, as shown in Figs. 5 and 6.[6] Therefore, the behavior of the magnetoresistance is quite different between the (||) (001)−[100] and the (⊥) (001)−[100] samples in the low-current region as is seen in

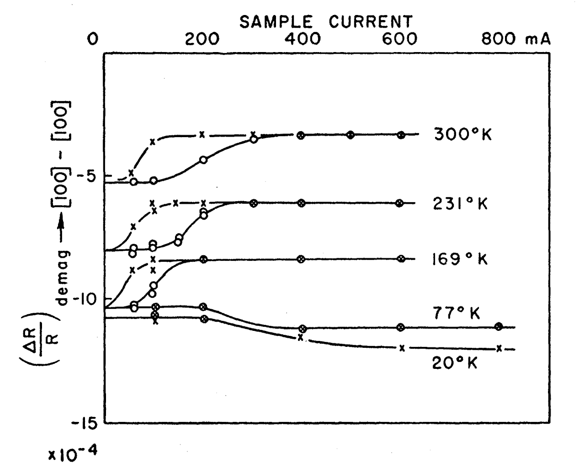

FIG. 7. Difference in magnetoresistance *vs* sample current for the (⊥) (001)−[100] specimen of silicon steel at different temperatures. Crosses and circles have the same significance as in Fig. 3.

Fig. 4 and Fig. 7. But in both sample types, and at the same temperature, almost equal saturation magnetoresistance, $(\Delta R/R)_{\mathrm{demag}\to[100]\cdot[100]}$, was obtained with high currents as expected.

In the case of iron, the theoretical domain structure of the (001)−[100] sample in the ordinary demagnetized state is just that of the (||) (001)−[100] sample of silicon steel. This is verified by the behavior of the magnetoresistance at the various sample currents and shown in Fig. 3.

E. EFFECT OF MEASURING CURRENT ON DOMAIN STRUCTURE

As has been described so far, in the measurement of magnetoresistance, the intensity of the current in the sample must be carefully controlled because the domain

[6] E. Tatsumoto, J. Sci. Hiroshima Univ. Ser. A **17**, 229 (1953).

structure might well be changed by the magnetic field itself, induced by the current.

In the case of the $(1\bar{1}0)-[111]$ sample, the effect of the current is negligibly small as shown in Fig. 8. This can be easily understood because in this case the magnetic field induced by the current mainly causes rotation of the magnetic moment of the main domains (shown in Fig. 1), but this is difficult since the anisotropy energy is large.

In the case of the $(001)-[100]$ sample, as mentioned previously, the effect of the current on the domain structure is very marked, but in the case of a (||) $(011)-[100]$ sample[5] it is quite small as shown in Fig. 9. This behavior is also well understood. In the case of the $(001)-[100]$ sample, as the perpendicular direction to the current vector is also magnetically easy and since there will be no demagnetizing effect opposing the field induced by the current, even a small field is sufficient to change the domains formerly parallel to the current vector to ones perpendicular to it as shown in Fig. 2. In the case of the (||) $(011)-[100]$ sample, the domain structure[5] is very like that of the (||) $(001)-[100]$ sample, but as the perpendicular direction to the current vector is magnetically hard, there will be no variation in domain configuration expected, except around both edges of the sample.

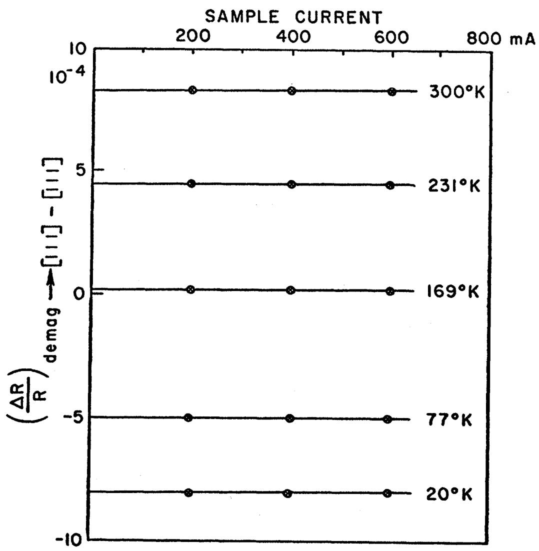

Fig. 8. Difference in magnetoresistance *vs* sample current for the (||) $(1\bar{1}0)-[111]$ specimen of silicon steel at different temperatures. Crosses and circles have the same significance as in Fig. 3.

For both the (||) $(001)-[100]$ and $(011)-[100]$ samples, a small magnetoresistance was observed even at small measuring current, although theoretically no magnetoresistance is expected. It may be inferred that this magnetoresistance is mainly due to magnetostrictive lattice distortion occurring around the many small domains embedded in the main domains, especially near both ends of the specimen in the demagnetized state. The same influence on the observed magnetoresistance should also appear in the results for the (⊥) $(001)-[001]$ sample. In this sample, the magnetostrictive lattice distortion occurring around the closure domains at both edges of the samples (shown in Fig. 6) is the principal effect and is quite large. As is seen in Fig. 4 and Fig. 7, this effect also changes with temperature. While a detailed discussion of the magnetoresistance *vs* current and *vs* temperature for both sample types may be possible, any such analysis must be postponed until crystallographic data, obtained by a

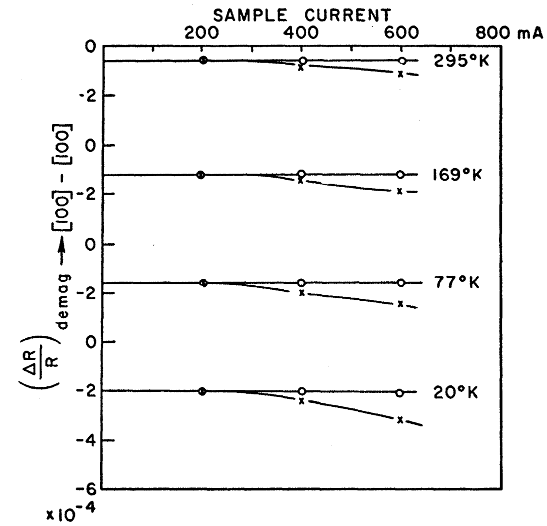

Fig. 9. Difference in magnetoresistance *vs* sample current for the (||) $(110)-[100]$ specimen of silicon steel at different temperatures. Crosses and circles have the same significance as in Fig. 3.

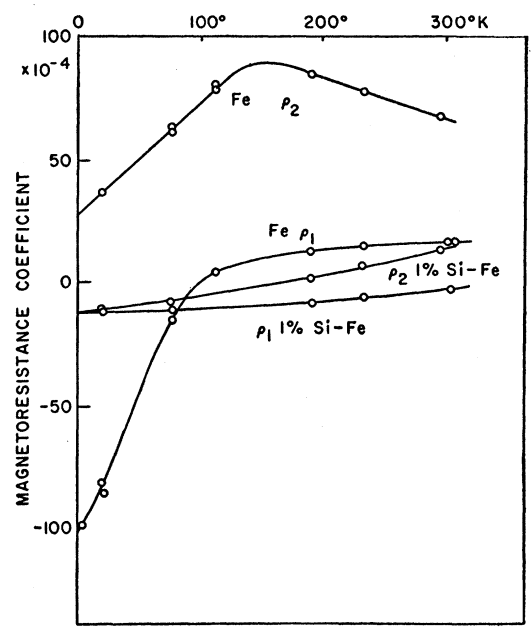

Fig. 10. Magnetoresistance coefficients ρ_1 and ρ_2 *vs* temperature for iron and silicon steel.

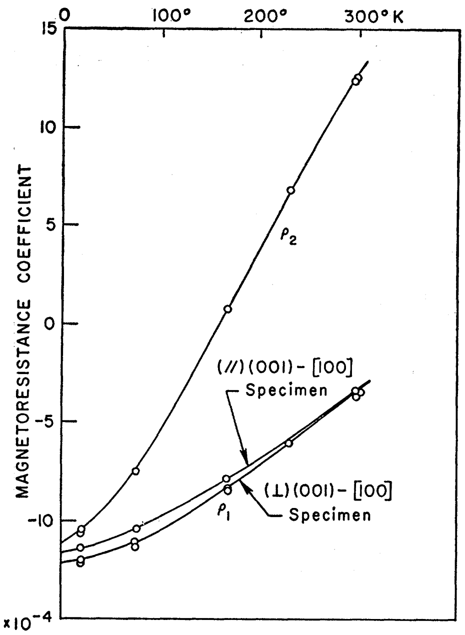

FIG. 11. Magnetoresistance coefficients ρ_1 and ρ_2 *vs* temperature for silicon steel on an expanded scale.

collaborator of the author, using x-ray, electron-diffraction, and electron-microscope techniques, is available.

F. TEMPERATURE DEPENDENCE OF ϱ_1 AND ϱ_2

In these measurements, two samples for each crystallographic orientation were used, except for (||) (001) −[100] of silicon steel, where only one sample was available. The measurements were made at room temperature and in constant temperature baths of liquid propane, ethylene, methane, nitrogen, hydrogen, and helium boiling at atmospheric pressure in contact with their vapors. At these temperatures, the resistance was measured by a null method (with a Leeds and Northrup type *K* potentiometer and galvanometer) by recording both the potential drop across a 45-mm length of the specimen (using pressure-contact probes) and the potential across a 0.1-ohm standard resistance in series with the sample current.

Finally, the temperature dependences of ρ_1 and ρ_2 obtained by the method previously described are shown in Fig. 10 and for silicon steel on an expanded scale in Fig. 11. The results thus obtained are of fundamental significance in the interpretation of the magnetoresistance effects in iron and in iron containing small amounts of silicon-like elements. As is seen in Figs. 10 and 11, there is a strong dependence of ρ_1 and ρ_2 on both temperature and composition. While it should be possible to interpret these data on the basis of electron transport theory of magnetoresistance, a simple picture does not immediately present itself. Moreover, it is desirable to have measurements of associated conduction-type phenomena available and it is proposed to undertake such measurements (of longitudinal and transverse magnetoresistances and Hall effect at all temperatures below the Curie point) as part of a systematic program of research on iron, silicon steel, and others in the author's laboratory in Japan in the near future.

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