Magnetocrystalline Anisotropy Constants of Iron at Room Temperature and Below

C. D. GRAHAM, JR.

General Electric Research Laboratory, Schenectady, New York

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The anisotropy constants of iron have been determined from torque measurements on a {110} single-crystal disk in fields up to 15 000 oersteds or higher and at temperatures of 77, 195, and 300°K. The values of K_1 at the three temperatures are $(520\pm10)\times10^3$, $(505\pm10)\times10^3$, and $(480\pm10)\times10^3$ ergs/cm^3; the value of K_2 at all three temperatures is $(0\pm50)\times10^3$ ergs/cm^3. The anisotropy decreases as the fourth power of the saturation magnetization over the temperature range studied.

INTRODUCTION

EXPERIMENTAL determinations of the crystal anisotropy constants of iron have been tabulated by Bozorth.[1] The room temperature values of K_1 range from 400×10^3 to 525×10^3 ergs/cm^3, and the values of K_2 from -170×10^3 to $+290\times10^3$. There are two published values for K_1 at liquid nitrogen temperature[2,3]: 575×10^3 and 520×10^3 ergs/cm^3. There is a need for better information.

Most of the determinations of anisotropy constants have been made from measured magnetization curves of single-crystal samples, but more recent work has tended to favor the use of torque measurements.[4-9] The values reported here are based on torque measurements at maximum fields four to five times higher than those used in previous investigations of iron.

EXPERIMENTAL PROCEDURE AND RESULTS

The sample was prepared from a single crystal of Armco iron, grown by the Virginia Institute for Scientific Research, Richmond, Virginia. The total impurity content of this material is stated to be about 0.2%, with the major impurity about 0.1% Cu. Since the crystal anisotropy does not appear to be sensitive to small composition changes, this material may be regarded as pure iron for the purpose of this experiment. The final sample was in the form of an approximately ellipsoidal disk, 0.327 inch in diameter by 0.031 inch thick, weighing 0.242 g. This corresponds to a volume of 0.0308 cm^3 if the density is taken as 7.86 g/cm^3.

The plane of the disk was within 1° of a {110} plane, as determined by x-rays. After machining, the sample was annealed for several hours at 870°C in dry hydrogen. No included grains were visible after etching the prepared sample.

Torque measurements were made with a torque magnetometer which uses a helical spring as the measuring element. The sample is held at the end of a rigid shaft rotating in fixed bearings; this design permits the magnetometer to be calibrated with a simple weight and pulley arrangement, and also permits the sample to be immersed in a cooling bath without affecting the rest of the instrument. Two calibrations made during the course of the measurements gave spring constants of 189 and 190 dyne-cm per degree of deflection. Friction in the bearings limited the accuracy of an individual reading to about $\frac{1}{2}$ degree, which for the sample used corresponds to about 3×10^3 ergs/cm^3. The low-temperature baths were liquid nitrogen and dry ice in acetone.

Torque measurements were made at 5° intervals over a full 360° rotation of the disk, with additional readings at 1° intervals at the torque peaks and at certain of the torque zeros. Complete torque curves were taken at fields from 2000 to 20 000 oersteds at room temperature, and from 2000 to 15 000 oersteds at the low temperatures, where the container for the cooling bath increased the spacing between the electromagnet pole pieces. Repeat runs were made at a number of fields at all temperatures after the sample had been removed from its holder and then replaced. Figure 1 shows two
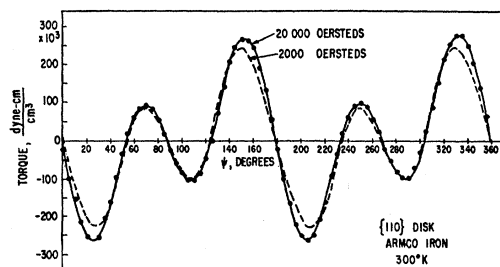
[1] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), p. 567.

[2] R. M. Bozorth, J. Appl. Phys. **8**, 575 (1937); also reference 1, p. 568.

[3] *American Institute of Physics Handbook*, edited by Dwight E. Gray (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 5, p. 221.

[4] L. P. Tarasov, Phys. Rev. **56**, 1224 (1939).

[5] L. P. Tarasov, Phys. Rev. **56**, 1231 (1939).

[6] J. S. Kouvel and C. D. Graham, Jr., J. Appl. Phys. **28**, 340 (1957).

[7] D. A. Langford, Report No. 5077, Metropolitan-Vickers Electric Company, Ltd., Research Department, Manchester, England, March, 1956 (unpublished).

[8] H. Shenker, NAVORD Report No. 3858, U. S. Naval Ordnance Laboratory, White Oak, Maryland, February, 1955 (unpublished).

[9] R. C. Hall, WADC Report No. 58–21, ASTIA No. 142293, Westinghouse Electric Corporation, January, 1958 (unpublished).

FIG. 1. Room-temperature torque curves of {110} iron disk at 2000 and 20 000 oersteds. ψ is angle from $\langle100\rangle$ direction to direction of applied field. Experimental points omitted from the low-field curve for clarity.
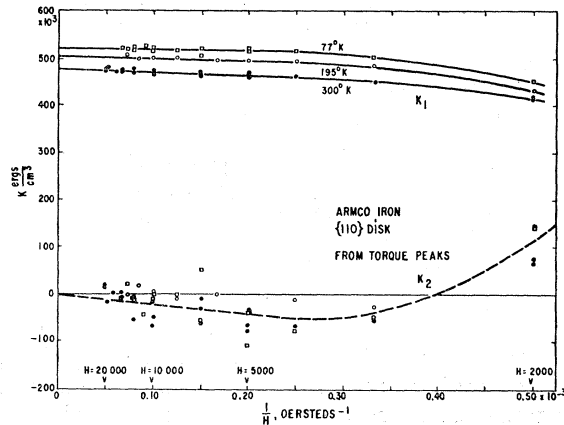
FIG. 2. Increase of apparent anisotropy with increasing field. Data from torque peaks, plotted against $1/H$.

of the measured torque curves, indicating the changes which occur as the field is increased.

Anisotropy constants were deduced from the torque curves by two independent methods, one involving the measured torque peaks and the other involving the measured torque slopes at zero torque. In all cases, the average value of all the equivalent peaks or slopes of a complete torque curve was used in computing the constants. Values of the anisotropy constants were computed from the torque peak data by Shenker's method[8]; this is a simple graphical procedure for fitting the measured peaks to the peaks of a theoretical curve calculated for two constants K_1 and K_2. The method of torque slopes was devised by Kouvel, and has been previously applied to an iron-silicon alloy.[6] The method allows a choice of the particular torque slopes to be used; in this work only the slopes taken in the easy directions (where the slopes are negative) were used, since they could be determined with the greatest accuracy. The method of torque peaks gave results with considerably less scatter.

Tarasov first pointed out that the apparent anisotropy constant deduced from a torque curve increases with increasing fields of measurement.[4,5] He used an
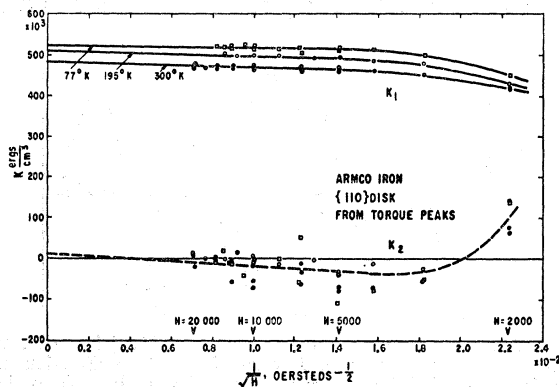

FIG. 3. Same as Fig. 2, plotted against $1/\sqrt{H}$.

extrapolation against $1/H$ to find the anisotropy constant at infinite field. However, Tarasov's measurements extended only from 2000 to 3500 oersteds; recent torque measurements carried to fields of 15 000 to 20 000 oersteds have shown that an extrapolation against $1/\sqrt{H}$ may be preferable.[6,7] Both extrapolations are empirical.

Figures 2 and 3 show the torque-peak results extrapolated in both ways. The curves for K_1 are so nearly horizontal that it is impossible to say which extrapolation is better. The quoted final values are in all cases the average of the values obtained by the two extrapolations. Figure 4 shows the room-temperature values as obtained from the torque slope measurements. The scatter is clearly greater than for the torque peak results, but the extrapolated value appears to be about the same. The torque slope measurements at low temperatures gave very closely the same results as the torque peak measurements, but with increased scatter.
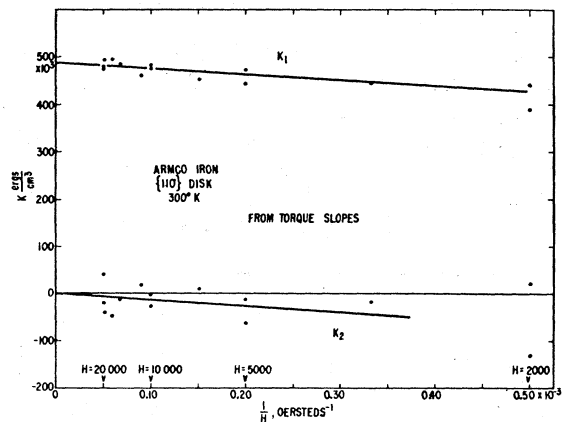

FIG. 4. Room-temperature data from torque slopes, plotted against $1/H$.

At all temperatures the scatter in the values of K_2 is quite large. This is because small changes in the ratio of the peak heights appear as large changes in the derived value of K_2, which is another way of saying that the measured torque properties of a crystal do not depend very strongly on the value of K_2. Nevertheless, all the values of K_2 except those at the lowest fields are fairly near zero, and it seems safe to conclude that K_2 is small compared to K_1 at room temperature and below.

The final values for the constants are tabulated in Table I. The values obtained from the torque slopes have not been used, because of the scatter in the results. However, in no case did the torque slope data indicate any real disagreement with the torque peak values—only a scatter around the torque peak values. The indicated errors are somewhat larger than the actual scatter in the torque peak results, and are intended to include the absolute errors in measurement as well as the error involved in the extrapolation. No

correction has been applied for the increase in density at low temperature; this amounts to about $\frac{1}{2}\%$ between room temperature and liquid nitrogen. The final average values are plotted against temperature in Fig. 5.

DISCUSSION

Since the measurements reported here extended to higher fields than were used in previous determinations of the anisotropy of iron, the values listed above should be more reliable than the older figures. The room temperature value of K_1 obtained here $(480 \times 10^3$ ergs/cm$^3)$ may be compared with a recent value of 460×10^3 reported by Hall for similar measurements on a similar sample,[9] and also with the value of 460×10^3 quoted in the Americal Institute of Physics Handbook.[3] A value near 420×10^3 has been often used in the literature as an average of the early results; it is clear that this figure is at least 10% too low.

One[2] of the two previously-reported low-temperature values for K_1 was derived from the magnetization curve of a single crystal rod with a known but not simple orientation, measured by Honda, Masumoto, and Kaya in 1928.[10] Values determined from such an indirect

TABLE I. Values of the anisotropy constants K_1 and K_2.

Temp. (°K)	Extra-polation	K_1, (ergs/cm^3)	Average K_1, (ergs/cm^3)	Average K_2, (ergs/cm^3)
77	$1/H$ $1/\sqrt{H}$	518×10^3 520×10^3	$(520 \pm 10) \times 10^3$	$(0 \pm 50) \times 10^3$
195	$1/H$ $1/\sqrt{H}$	502×10^3 509×10^3	$(505 \pm 10) \times 10^3$	$(0 \pm 50) \times 10^3$
300	$1/H$ $1/\sqrt{H}$	477×10^3 483×10^3	$(480 \pm 10) \times 10^3$	$(0 \pm 50) \times 10^3$

measurement should not be as reliable as those reported here. The other previous low-temperature value[3] agrees exactly with the figure obtained here $(520 \times 10^3$ ergs/cm$^3)$.

A recent measurement of K_2 gave (in ergs/cm^3) 71×10^3 at $300°K$ and 90×10^3 at $77°K$,[11] slightly higher than the upper limit suggested above.

One immediate use for the new results is to compare the temperature variation of the anisotropy of iron with the temperature variation of the saturation magnetization. Zener has derived a tenth-power relationship, $K_T/K_0 = (M_T/M_0)^{10}$, which should be valid at low temperatures.[12] He showed that this agreed with the anisotropy values as given in the literature at that time. The present results fit a fourth-power law: $K_T/K_0 = (M_T/M_0)^4$; Fig. 6 compares the two cases. Other theoretical discussions of the temperature
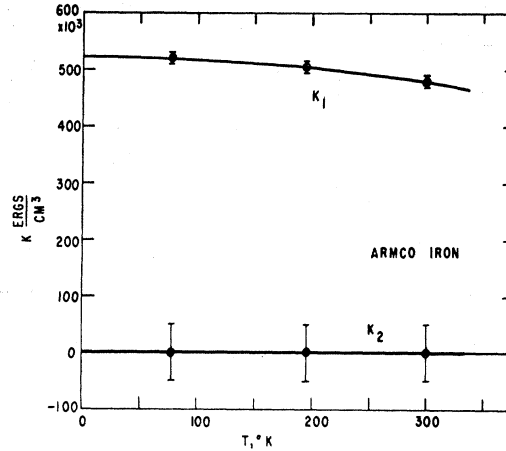
FIG. 5. Crystal anisotropy constants of iron as a function of temperature.

dependence of the anisotropy have been given by Keffer,[13] Van Vleck,[14] and Carr.[15]

After this paper was written, I learned from R. M. Bozorth of the Bell Telephone Laboratories that the data for iron given in reference 3 were taken from some unpublished measurements of his, made in 1952. The values were derived from torque measurements on a $\{100\}$ disk in fields up to about 20 000 oe. With Dr. Bozorth's kind permission, I quote his results here:

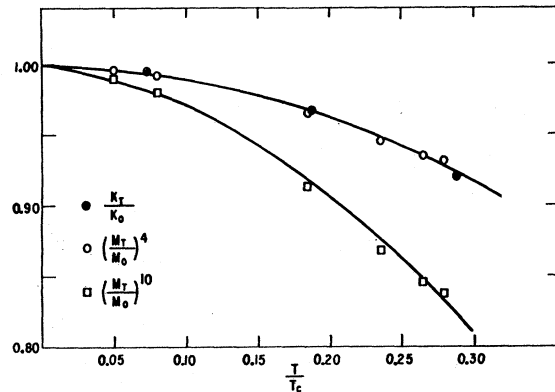| Temperature, °K	K_1, ergs/cm^3
297	469×10^3
275	476×10^3
195	498×10^3
77	518×10^3
0	(521×10^3).

FIG. 6. Comparison of tenth-power and fourth-power laws of variation of K_1 with M_s. Magnetization values from P. Weiss [Extr. Actes VII Cong. Int. Froid 1, 508 (1937)], as given by Bozorth (reference 1, p. 720). $T_c \equiv$ Curie point.

[10] Honda, Masumoto, and Kaya, Science Repts. Tôhoku Imp. Univ. 17, 111 (1928).

[11] H. Sato and B. S. Chandrasekhar, J. Phys. Chem. Solids 1, 228 (1957).

[12] C. Zener, Phys. Rev. 96, 1335 (1954).

[13] F. Keffer, Phys. Rev. 100, 1692 (1955).

[14] J. H. Van Vleck, Proceedings of the American Institute of Electrical Engineers, Conference on Magnetism and Magnetic Materials, Boston, 1957 (American Institute of Electrical Engineers), p. 6; Phys. Rev. 52, 1178 (1937).

[15] W. J. Carr, Jr., J. Appl. Phys. 29, 436 (1958); Phys. Rev. 109, 1971 (1958).

The value at 0°K was extrapolated assuming $K_1 = a \times \exp(-bT^2)$.

These results agree with those shown in Fig. 5, within the experimental error. However, the decrease of K_1 with increasing temperature is slightly more rapid according to Bozorth's data than according to mine; his results are best fitted by a fifth-power law, $K_T/K_0 = (M_T/M_0)^5$.

Low-Energy Sputtering Yields in Hg†

GOTTFRIED K. WEHNER

Mechanical Division of General Mills, Incorporated, Minneapolis, Minnesota

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Further data on sputtering yields for normally incident Hg^+—ion bombardment in the energy range of 50 to 400 ev have been collected. Experimental data are used to determine the influence of atomic weight and heat of sublimation of the target material and to establish an empirical sputtering relation. Results provide strong support for a picture of sputtering which might be termed "playing three-dimensional billiards with atoms." The degree of filling of the inner shells, especially the d shells, determines how closely collisions approximate hard-sphere collisions. Energy is transferred most efficiently in metals with completely filled d shells. Accordingly, Cu, Ag, and Au have the highest sputtering yields. Results for Hg^+—ion bombardment support theories developed by Langberg and by Silsbee but disagree with a theory published by Henschke. Conditions may be different, however, for the case of bombardment with light ions such as hydrogen or helium.

The sputtering yields of alloys do not seem to differ substantially from those of their main constituents.

INTRODUCTION

THE present study is a continuation of previous work on low-energy Hg^+—ion sputtering.[1] The goal is and has been to measure sputtering yields of metals and semiconductors under normally incident Hg^+—ion bombardment primarily as a function of ion energy in the range 50 to 400 ev. Conditions necessary for obtaining reliable results, the measuring procedure, and the apparatus have been described in detail in the earlier paper to which reference should be made.

Targets to be sputtered are immersed in a low-pressure Hg vacuum arc tube like large negative Langmuir probes. Discharge data are as follows: 2.5 amp discharge current, 30 volts discharge voltage drop, Hg gas pressure ~ 1 micron, ion current density at target ~ 5 ma/cm^2, target temperature during sputtering ~ 400°C. Yields are determined by measuring the weight loss of the target after removal from the demountable tube. Yields are given in $S/(1+\gamma)$ atoms/ion where γ is the electron yield resulting from ion bombardment, a value which is of the order of 0.1 to 0.2 in our energy range.

SPUTTERING YIELD DATA

Titanium.—In recent experiments with Ti somewhat different yields were found than those previously reported. Upon re-examination of the original target material it was discovered that a stainless steel alloy had been measured instead of Ti. The correct curve for Ti is shown in Fig. 1. Occasionally considerably lower than normal yields were found and in these cases we suspected a small leak in the tube. In order to check this point, measurements were made with a controllable leak. It was found, indeed, that small traces of air reduced the sputtering rate of Ti very markedly. In the case of a Ge target, however, the yield was scarcely affected by a leak.

Chromium.—Previous measurements on Cr did not give very consistent results. Recently, samples of ductile Cr were obtained.[2] The yields of this material and of
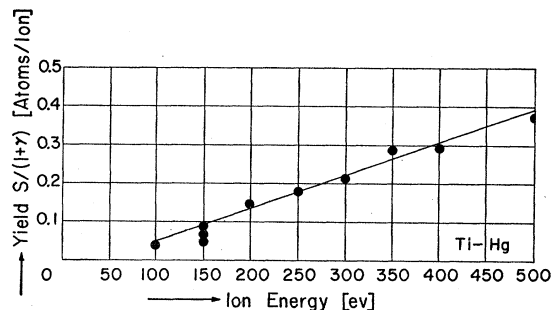

FIG. 1. Sputtering yield of Ti vs ion energy.

[1] G. K. Wehner, Phys. Rev. **108**, 35 (1957).

[2] Courtesy of Bureau of Mines, Albany, Oregon.