5-16-2005

Temperature dependence of the magnetic anisotropy and magnetostriction of Fe100−xGax (x = 8.6, 16.6, 28.5)

A. E. Clark
Clark Associates

M. Wun-Fogle
United States Navy

J. B. Restorff
United States Navy

Kevin W. Dennis
Iowa State University, dennis@ameslab.gov

Thomas A. Lograsso
Iowa State University, lograsso@ameslab.gov

See next page for additional authors

Temperature dependence of the magnetic anisotropy and magnetostriction of Fe100−xGax (x = 8.6, 16.6, 28.5)

Abstract

The temperature dependence of the lowest order magnetic anisotropy constant K_1 and the lowest order saturation magnetostriction constant, $(3/2)\lambda_{100}$, were measured from 4 K to 300 K for $Fe_{91.4}Ga_{8.6}$,$Fe_{83.4}Ga_{16.6}$, and $Fe_{71.5}Ga_{28.5}$ and were compared to the normalized magnetization power law, $m^{l(l+1)/2}$. $Fe_{91.4}Ga_{8.6}$ maintains the magnetostriction anomaly of Fe $(d\lambda_{100}/dT>0)$ and K_1 is a reasonable fit to the $m^{l(l+1)/2}$power law with $K_1(0\text{ K}) \cong 90\text{ kJ/m}^3$. $Fe_{83.4}Ga_{16.6}$ does not show a magnetostriction anomaly, but fits the power law remarkably well. $Fe_{71.5}Ga_{28.5}$ possesses a small $K_1(\sim 1\text{ kJ/m}^3)$ at all temperatures and a large temperature dependent magnetostriction, reaching ~ 800 ppm at low temperature.

Keywords

iron alloys, gallium alloys, ferromagnetic materials, magnetic anisotropy, magnetostriction, magnetoelastic effects

Disciplines

Condensed Matter Physics | Metallurgy

Comments

The following article appeared in *Journal of Applied Physics* 97 (2005): 10M316 and may be found at http://dx.doi.org/10.1063/1.1856731.

Authors

A. E. Clark, M. Wun-Fogle, J. B. Restorff, Kevin W. Dennis, Thomas A. Lograsso, and R. William McCallum

Temperature dependence of the magnetic anisotropy and magnetostriction of $Fe_{100-x}Ga_x$ (x=8.6, 16.6, 28.5)

A. E. Clark
Clark Associates, Adelphi, Maryland 20783

M. Wun-Fogle[a] and J. B. Restorff
Naval Surface Warfare Center, Carderock Division, West Bethesda, Maryland 20817-5700

K. W. Dennis, T. A. Lograsso, and R. W. McCallum
Ames Laboratory USDOE, Iowa State University, Ames, Iowa 50010

(Presented on 8 November 2004; published online 16 May 2005)

The temperature dependence of the lowest order magnetic anisotropy constant K_1 and the lowest order saturation magnetostriction constant, $(3/2)\lambda_{100}$, were measured from 4 K to 300 K for $Fe_{91.4}Ga_{8.6}$, $Fe_{83.4}Ga_{16.6}$, and $Fe_{71.5}Ga_{28.5}$ and were compared to the normalized magnetization power law, $m^{l(l+1)/2}$. $Fe_{91.4}Ga_{8.6}$ maintains the magnetostriction anomaly of Fe ($d\lambda_{100}/dT>0$) and K_1 is a reasonable fit to the $m^{l(l+1)/2}$ power law with $K_1(0\text{ K})\cong 90\text{ kJ/m}^3$. $Fe_{83.4}Ga_{16.6}$ does not show a magnetostriction anomaly, but fits the power law remarkably well. $Fe_{71.5}Ga_{28.5}$ possesses a small $K_1(\sim 1\text{ kJ/m}^3)$ at all temperatures and a large temperature dependent magnetostriction, reaching ~800 ppm at low temperature. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1856731]

I. INTRODUCTION

Previous studies have revealed the existence of two anomalous peaks in the magnetostriction (λ_{100}) of Fe–Ga alloys.[1] The first peak, occurring near $Fe_{82}Ga_{18}$, has been attributed to an increase in the magnetoelastic coupling, b_1, with the onset of short range Ga ordering. On the other hand, the second peak, occurring near $Fe_{72}Ga_{28}$, does not appear to be due to magnetoelastic effects, but due to a softening of the shear modulus, $c' \equiv (c_{11}-c_{12})/2$. This paper presents the temperature dependence of the magnetic anisotropy and magnetostriction in the region of these anomalous magnetostriction peaks and relates the results to a magnetization dependence model.[2]

II. EXPERIMENTAL METHOD

The magnetic anisotropy of single crystal $Fe_{100-x}Ga_x$ (x=8.6, 16.6, and 28.5) prepared by Bridgman growth[1] was examined. Three methods were used to determine the magnetic anisotropy: magnetic torque, magnetic fields for saturation along the easy and hard directions, and areas between magnetization curves taken along the easy and hard directions. The magnetic torque measurements were made using a Lake Shore Model 7410 Vibrating Sample Magnetometer with vector coils. The sample torque (L) was determined at magnetic fields from 3 kOe to 19 kOe. L is the product of the magnetic field and the perpendicular magnetization as the samples were rotated in the (100) and (110) planes. Values of the anisotropy constant, $K_1(H)$, were calculated at each field using standard procedures.[3] The value of K_1 for the alloy was determined by extrapolating $K_1(H)$ to infinite fields using $K_1=K_1(H)(1-a/H)$. This method was employed for Fe–8.6%Ga and Fe–28.5%Ga. The difference in area method[3] was used in various instances to corroborate the values of K_1 obtained from the torque method. For Fe–16.6%Ga, the anisotropy was calculated from the fields for saturation using the expression $K_1=H_{110}M_s/2$, where H_{110} is the field for saturation along the hard ⟨110⟩ direction and M_s is the saturation magnetization.[3] All measurements of the saturation magnetostrictions were made using conventional strain gage techniques at 15 kOe.

[a]Electronic mail: wunfoglem@nswccd.navy.mil; Phone: 301-227-5968; Fax: 301-227-5434.

III. RESULTS

Figure 1 compares the temperature dependences of the magnetostriction constant, $(3/2)\lambda_{100}$, K_1, and M_s, of $Fe_{91.4}Ga_{8.6}$ with those of Fe.[4,5] The temperature dependence of the magnetostriction of Fe is very unusual, having a peak near 200 K.[4] Unlike the magnetostriction, the magnetic anisotropy and magnetization of both Fe and Fe–8.6%Ga decrease with increasing temperature over the entire temperature range. For Fe–8.6%Ga, the magnetization is about 2 T at all temperatures and the values of K_1 increased to approximately 80 kJ/m^3. *The magnetostriction of Fe-8.6% was found to increase fourfold to ~110 ppm above that of Fe, however the magnetostriction still retains an Fe anomalous increase in value with temperature with an apparent peak near room temperature (RT).* Surprisingly the magnetic anisotropy nearly doubles that of Fe to ~90 kJ/m^3 at low temperatures to ~70 kJ/m^3 at RT. The large value at RT is consistent with the value of ~65 kJ/m^3 reported by Rafique *et al.*[6] for Fe–5%Ga. The magnetization has decreased about 10% below that of Fe in agreement with the early work of Kawamiya *et al.*[7] at higher Ga content.

Figure 2 describes how $(3/2)\lambda_{100}$, K_1 and M_s of $Fe_{83.4}Ga_{16.6}$ decrease with temperature. The magnitude of the anisotropy has fallen from the large values at 8.6%Ga revealing a peak between Fe and Fe–16.6%Ga. This alloy possesses a large magnetostriction (~360 ppm) and values that

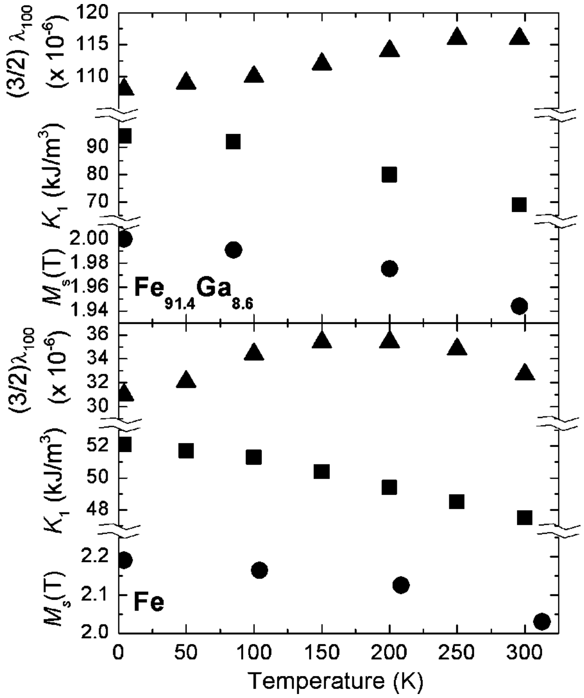

FIG. 1. Magnetostriction, $(3/2)\lambda_{100}$, magnetic anisotropy, K_1, and magnetization, M_s, of (a) $Fe_{91.4}Ga_{8.6}$ and (b) Fe (see Refs. 4,5).

slightly decrease with temperature. The anomalous temperature dependence ($d\lambda_{100}/dT > 0$) of the magnetostriction observed at low concentrations of Ga has now disappeared.

Figure 3 shows the magnetostriction and the magnetization near the 28%Ga peak as a function of temperature. The temperature dependent magnetostriction is extraordinary, reaching peak values near 800 ppm at 4 K. *While the RT magnetostriction is large and comparable to those near the 18%Ga peak, the low temperature value is nearly double in value*. The magnetic anisotropy in the region of the 28%Ga peak is very small. For $Fe_{71.5}Ga_{28.5}$, the magnitude of K_1 was found to be only a few kJ/m^3 over the entire temperature range.

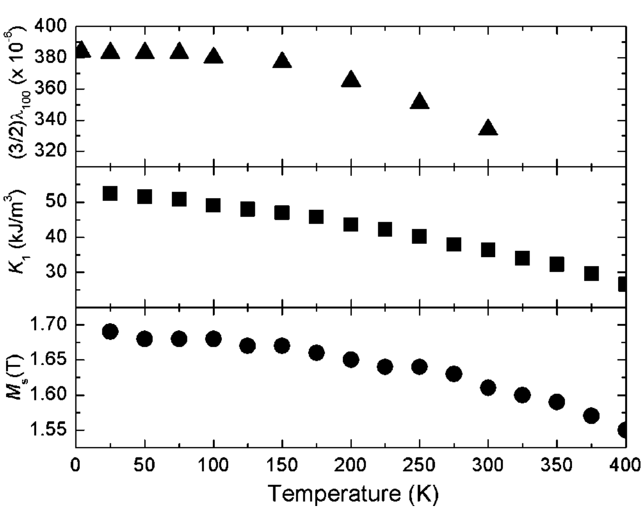

FIG. 2. Magnetostriction, $(3/2)\lambda_{100}$, magnetic anisotropy, K_1, and magnetization, M_s, of $Fe_{83.4}Ga_{16.6}$.

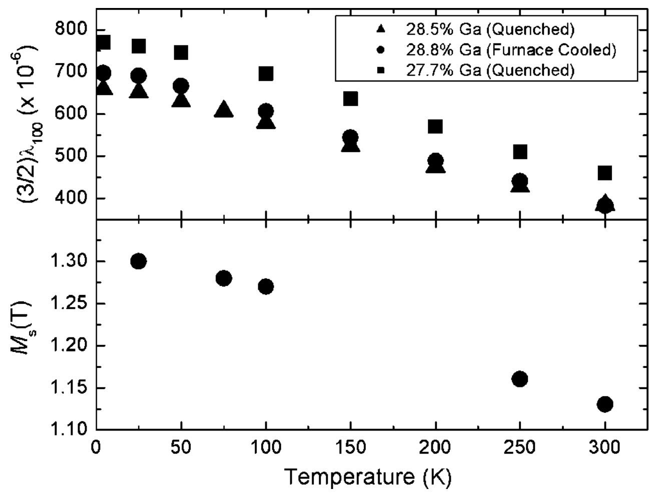

FIG. 3. Magnetostriction, $(3/2)\lambda_{100}$, for $Fe_{71.5}Ga_{28.5}$ (quenched), $Fe_{71.2}Ga_{28.8}$ (furnace cooled), and $Fe_{72.3}Ga_{27.7}$ (quenched) and magnetization, M_s, for $Fe_{71.5}Ga_{28.5}$ (furnace cooled).

IV. DISCUSSION

The temperature dependence of the magnetic anisotropy and magnetostriction is often related to the temperature dependence of the magnetization. Callen and Shtrickman[2] have shown that the temperature dependence can be expressed in terms of the reduced magnetization, $m = M(T)/M(0)$, for a number of theories. They found that properties which depend upon the second power ($l=2$) of the direction cosines of the magnetization with respect to the crystal axes, such as the lowest order magnetostriction, λ_{100}, should follow the $m^{l(l+1)/2} = m^3$ power law at low temperatures. Likewise those that depend upon the fourth power ($l=4$) of the direction cosines, such as K_1, follow the $m^{l(l+1)/2} = m^{10}$ power law at low temperatures. In the following we show that: (1) the magnetostriction anomaly exhibited by Fe becomes weaker as Fe is partially substituted by Ga, (2) for concentrations of Ga near both magnetostriction peaks, the temperature dependencies of the magnetostrictions are close to the $m^{l(l+1)/2}$ power law, and (3) unlike the magnetostrictive behavior, the $m^{l(l+1)/2}$ power law agrees fairly well to the temperature dependence of K_1 at the dilute Ga concentration as well as near the low Ga concentration magnetostriction peak. (At the higher Ga concentration magnetostriction peak, the values of $|K_1|$ were too low to validate the $m^{l(l+1)/2}$ power law.)

Figure 4 shows the temperature dependencies of the normalized magnetostriction, magnetic anisotropy, and the third and tenth powers of the normalized magnetization for Fe–8.6%Ga. The m^{10} fit for the anisotropy is close to the experimental K_1 results. The magnetostriction, on the other hand, has a positive temperature dependence and cannot easily be explained. Clearly, the anomalous magnetostriction temperature dependence of Fe extends to at least 8.6%Ga.

Figure 5 illustrates a similar fit for the Fe–16.6%Ga sample. Again the m^{10} law fits reasonably well with the K_1 experimental data. At this concentration of Ga, the magnetostriction anomaly is removed and m^3 is an excellent fit to the data. Note, since c' has a weak temperature dependence,[1] the magnetoelastic energy $b_1 \equiv -3\lambda_{100}c'$, becomes a fair fit.

The elastic and magnetoelastic phenomena at Fe–

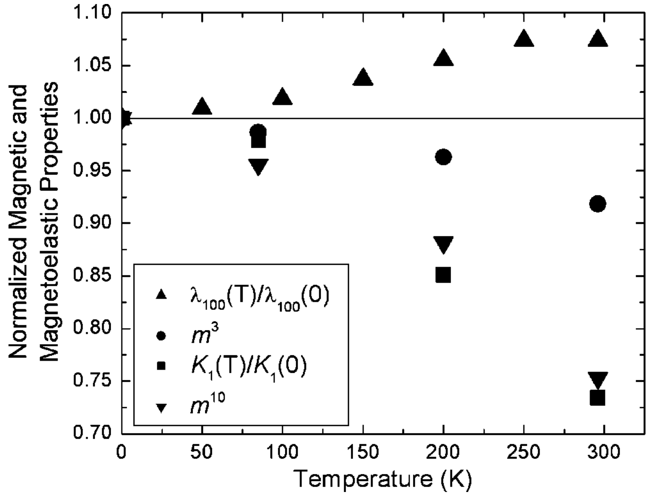

FIG. 4. $\lambda_{100}(T)/\lambda_{100}(0)$, m^3, $K_1(T)/K_1(0)$, and m^{10} as a function of temperature for $Fe_{91.4}Ga_{8.6}$.

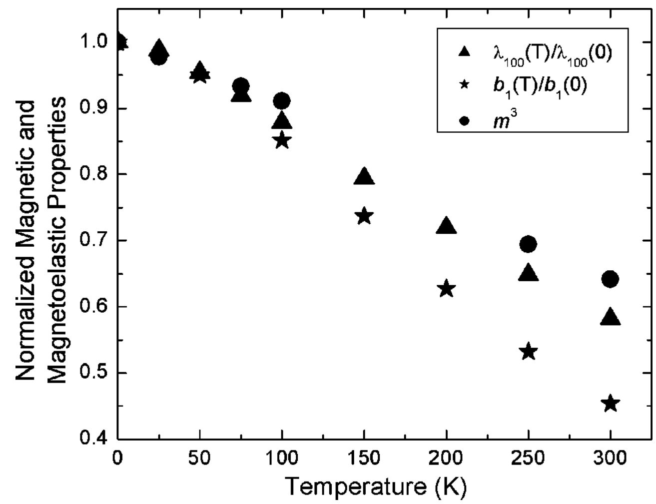

FIG. 6. $\lambda_{100}(T)/\lambda_{100}(0)$, $b_1(T)/b_1(0)$, and m^3 as a function of temperature for $Fe_{71.5}Ga_{28.5}$.

28.5%Ga is, in many ways, unrelated to the lower Ga concentrations: (1) the magnetic anisotropy was found to be 1–2 orders of magnitude smaller than the low concentration Ga alloys, and (2) the elastic constant c' decreases to about 0.1 of the Fe value and decreases by a factor of ~ 2 from 4 K to RT.[1] Figure 6 shows the fit of the temperature dependencies of both the magnetostriction and b_1 to the third power of the magnetization. Although the magnetostriction and the magnetization fall more strongly with temperature than those observed at the lower concentration alloys, m^3 remains a good fit to the normalized magnetostriction. Because of a rapidly decreasing c' with temperature,[1] however, m^3 no longer remains a satisfactory fit to the normalized magnetoelastic energy.

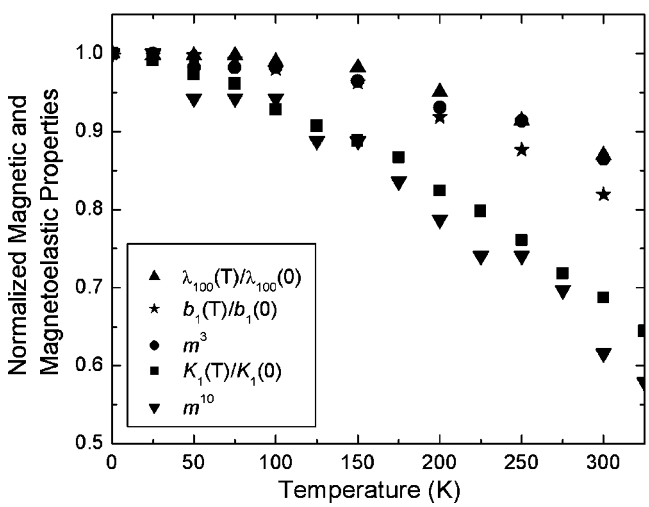

FIG. 5. $\lambda_{100}(T)/\lambda_{100}(0)$, $b_1(T)/b_1(0)$, m^3, $K_1(T)/K_1(0)$, and m^{10} as a function of temperature for $Fe_{83.4}Ga_{16.6}$.

ACKNOWLEDGMENTS

This work was supported by the U.S. Office of Naval Research, the In-House Laboratory Research Program at the Carderock Division of the Naval Surface Warfare Center and by Office of Basic Energy Science, Materials Science Division of the U.S. Department of Energy under Contract No. W-7405-ENG-82. The authors would like to thank K. McComber of MIT, Boston, MA for his measurements of the temperature dependent magnetostriction.

[1]A. E. Clark, K. B. Hathaway, M. Wun-Fogle, J. B. Restorff, V. M. Keppens, G. Petculescu, and R. A. Taylor, J. Appl. Phys. **93**, 8621 (2003).
[2]H. Callen and S. Shtrickman, Solid State Commun. **3**, 5 (1965).
[3]See, for example, D. B. Cullity, *Introduction to Magnetic Materials* (Addison–Wesley, Reading, MA, 1972), Chap. 7.
[4]E. Tatsumoto and T. Okamoto, J. Phys. Soc. Jpn. **14**, 1588 (1959).
[5]*AIP Handbook*, 3rd ed. (McGraw–Hill, New York, 1973), pp. 5–145, 5–206.
[6]S. Rafique, J. R. Cullen, M. Wuttig, and J. Cui, J. Appl. Phys. **95**, 6939 (2004).
[7]N. Kawamiya, K. Adachi, and Y. Nakamura, J. Phys. Soc. Jpn. **33**, 1318 (1972).