Domain Structure as Affected by the Uniaxial Ferromagnetic Anisotropy Induced in Cubic Solid Solutions

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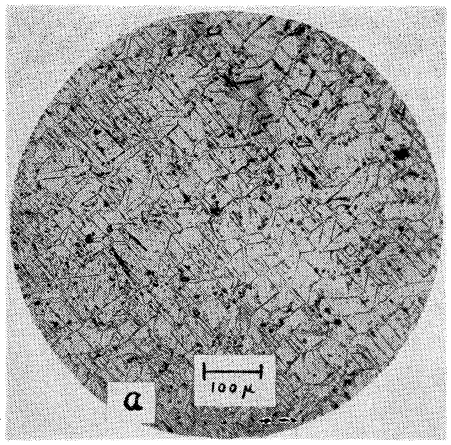
We have found that the domain structure of a 40% cobalt-nickel single crystal is very small-scaled and complicated in the annealed state as compared with that of ordinary ferromagnetic substances but it becomes simpler and larger after quenching from above the Curie temperature, indicating that the domain structure of a cubic solid solution can be affected by the induced uniaxial anisotropy. It is shown that these findings, together with the results of considerations reported previously, lead us to the conclusion that the Perminvar-type magnetic properties are due to the stabilization of domain walls by the induced uniaxial anisotropy in face-centered cubic solid solutions and in body-centered cubic solid solutions with negative cubic anisotropy constants.

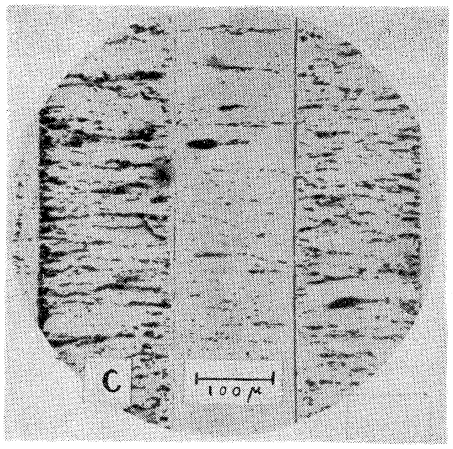
RECENTLY we[1] and, independently, Néel[2] have interpreted the uniaxial ferromagnetic anisotropy induced by magnetic annealing in cubic solid solutions as being due to an anisotropic distribution of atoms. According to this idea, when a ferromagnetic solid solution is cooled slowly from above its Curie temperature in the absence of an externally applied magnetic field, the uniaxial anisotropy may be induced along the directions of magnetization vectors distributed in compliance with the domain structure, and thus domain walls may be stabilized since the rotation of a magnetization vector from its original stabilized direction accompanies an increase in induced uniaxial anisotropy.

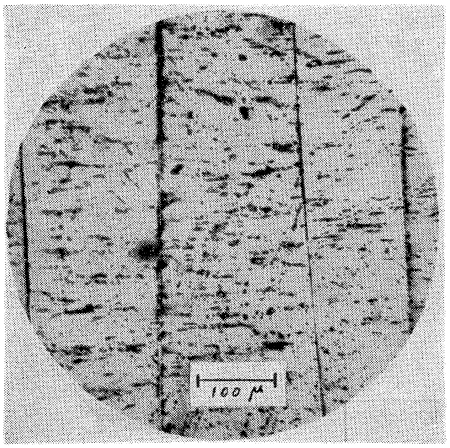
We have calculated[3] the restoring force acting on such a stabilized domain wall as a function of its displacement, using the theoretical results of our previous paper[1] and a method of calculation similar to that employed by Néel[4] in his theory of the magnetic after-effect due to the diffusion of interstitial atoms in a body-centered cubic lattice. Our calculation shows that, in a face-centered cubic (f.c.c.) solid solution with a cubic anisotropy constant, K, of any sign and in a body-centered cubic (b.c.c.) solid solution with a negative K, each of the substitutional type, the restoring force for the non-180° wall displacement increases almost linearly at first and eventually reaches a finite value, while that for the 180° wall displacement also increases almost linearly at first but finally tends to zero. Accordingly, for these solid solutions in which the induced uniaxial anisotropy is so large[5] that the displacements of domain walls in low fields may be controlled mainly by the restoring force, we have the following conclusions: (1) When cooled slowly from above the Curie temperature without magnetic field, both 180° and non-180° walls are displaced from their originally stabilized positions almost linearly and reversibly; thus a constant permeability is realized, in the initial range of the order of several oersteds of the applied effective magnetic field, which is given approximately by Ω_0/I_s, where Ω_0 is the induced uniaxial anisotropy constant and I_s is the saturation magnetization. (2) When the applied magnetic field is reduced to zero in the annealed state, every non-180° wall inevitably returns to its original stabilized position, while such is not always the case for 180° walls; this indicates that the contribution of non-180° wall displacements to the remanence is null. (3) When cooled rapidly from above the Curie temperature, the domain walls may not be stabilized and so the initial permeability rises while the coercive force decreases as compared with the annealed state. (4) Magnetic annealing is naturally effective. These properties comprise most, though not all, of the characteristics of perminvar (f.c.c. Fe-Ni-Co alloys),[6] and we are naturally led to suppose that all of the so-called perminvar-type magnetic properties are due to the stabilization of domain walls by the induced uniaxial anisotropy. In order to verify this supposition, however, it is necessary and sufficient to interpret, further, the very low remanence as well as the observed order of magnitude of the initial permeability in the annealed state of f.c.c. solid solutions and of b.c.c. solid solutions with $K<0$.

When we take into consideration the above-mentioned second conclusion, the very low remanence implies that non-180° walls are numerous in the domain structure. An initial permeability of the observed order, on the other hand, can be obtained by assuming that the mean total surface area of domain walls per unit volume, $\bar{S}$, is about ten times larger than that in ordinary ferromagnetic substances. This follows since, according to our calculation,[3] the initial susceptibility

[1] S. Taniguchi and M. Yamamoto, Sci. Repts. Research Inst. Tôhoku Univ. **A6**, 330 (1954); S. Taniguchi, Sci. Repts. Research Inst. Tôhoku Univ. **A7**, 269 (1955).
[2] L. Néel, J. phys. radium **15**, 225 (1954).
[3] M. Yamamoto and S. Taniguchi, J. Japan Insts. Metals (Sendai) **19**, 127 (1955) (in Japanese); S. Taniguchi, Sci. Repts. Research Insts. Tôhoku Univ. (to be published).
[4] L. Néel, J. phys. radium **12**, 339 (1951); **13**, 249 (1952).
[5] The uniaxial ferromagnetic anisotropy induced by magnetic annealing amounts to about 4×10^3 erg/cm³ for 60% nickel-iron alloy [S. Chikazumi and T. Oomura, J. Phys. Soc. Japan **10**, 842 (1955)] and to about 7×10^3 erg/cm³ for 50% nickel-cobalt alloy [T. Nagashima *et al.* (unpublished data)].
[6] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), p. 160.







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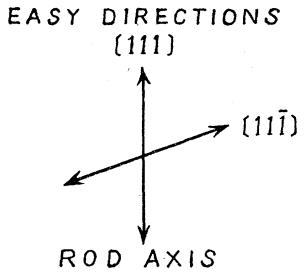

(d)

FIG. 1. Domain patterns observed on (1$\bar{1}$0) surfaces of a 40% cobalt-nickel alloy single crystal subjected to various heat treatments: (a) annealed, (b) air-quenched from 850°C, (c) cooled from 850°C with an external magnetic field applied along the rod axis.

due to the displacements of domain walls against the restoring force is of the order of $I_s^2 d_0 \bar{S}/\Omega_0$, where d_0 is the width of the domain walls. Thus, if our supposition is correct, it may be expected that the domain structure in the annealed state of f.c.c. solid solutions and of b.c.c. solid solutions (with $K<0$) should be fine and complicated as compared with that of ordinary ferromagnetic substances. Indeed, such a fine and complicated domain structure was previously observed by Bozorth and Walker[7] with an annealed single crystal of 60% (f.c.c.) cobalt-nickel alloy, which shows well-defined perminvar characteristics.[8] They suggested that such a fine domain structure might be due to the peculiarity in material constants, such as the cubic anisotropy, wall energy, etc., of this alloy, but this explanation is not clear to us and has been contradicted by our experiment as shown later.

Now, in order to verify our expectation mentioned above, we have made the observation of domain structure and its change due to heat treatment on a single crystal of 40% (f.c.c.) cobalt-nickel alloy which also shows well-defined perminvar characteristics.[8] The single crystal has been grown from the melt *in vacuo* and shaped into the form of a rectangular rod of about 1.5×0.5×0.3 cm^3, the rod axis being along the [111] direction, namely a direction of easy magnetization, and the largest side surfaces being (1$\bar{1}$0) planes. The domain pattern observed after annealing at 1200°C for an hour without magnetic field is shown in Fig. 1(a), which shows a fine domain structure connected in a complicated manner by 71°, 109°, and 180° walls; this pattern is similar to that of a 60% cobalt-nickel single crystal observed previously by Bozorth and Walker.[7] When quenched from 855°C above the Curie temperature on a water-cooled copper plate in vacuo, however, a very simple and large-scale domain structure, connected mainly by 180° walls lying along the length of the specimen crystal [Fig. 1(b)], is found to cover almost all parts of the (1$\bar{1}$0) surfaces, as may be expected from the shape of the specimen crystal. These observations indicate that the fine domain structure in the annealed state [Fig. 1(a)] may not be due

[7] R. M. Bozorth and J. G. Walker, Phys. Rev. **79**, 888 (1950).
[8] M. Yamamoto, Sci. Repts. Research Insts. Tôhoku Univ. **A4**, 14 (1952); Yamamoto, Taniguchi, and Hoshi, Sci. Repts. Research Insts. Tôhoku Univ. **A6**, 539 (1954); M. Yamamoto and S. Taniguchi, J. Japan Inst. Metals (Sendai) **19**, 645, 648 (1955) (in Japanese).

to imperfections in the specimen crystal or may not be explained by the suggestion of Bozorth and Walker,[7] but may be characteristic of the annealed state of these alloys. The domain pattern obtained after cooling at the rate of about 200 centigrade degrees/hr from 855°C with an external magnetic field of about 550 oersteds applied along the length of the specimen crystal [Fig. 1(c)] is also shown for comparison. Thus our expectation that the domain structure in the annealed state of f.c.c. solid solutions and of b.c.c. solid solutions (with $K<0$) should be fine and complicated, and accordingly our supposition that the perminvar-type magnetic properties are due to the stabilization of domain walls by the induced uniaxial anisotropy, has been verified, and it may be said that these properties are really common to the annealed state of such solid solutions.

Finally, the above considerations and observations seem to indicate, further, that in general the domain structure of a ferromagnetic crystal may be fine and complicated at temperatures immediately below the Curie temperature, and it grows larger and becomes simpler with decreasing temperature. However, in the solid solutions concerned, the growth of domains may be suppressed appreciably at high temperatures since their domains can grow only by an accompanying redistribution of atoms by diffusion, and the domain structure is fixed strongly at lower temperatures by the induced uniaxial anisotropy.

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Slow Surface Reaction on Germanium

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An experimental study of the long decay time levels has shown that the reaction between the levels and the bulk germanium depends on the number of carriers in the germanium, on the oxygen pressure, and exponentially on the temperature. It is therefore suggested that the rate-limiting process is electron transfer over a surface barrier. A simplified model, based on this mechanism, yields adequate agreement with the present results and also with those obtained by Kingston.

I. INTRODUCTION

THE field effect, i.e., the change of conductance of a semiconducting filament of germanium when an electric field is applied normal to the surface, has been studied by many investigators.[1–4] In the present work, we have been concerned more with the "polarization" of the field effect, a phenomenon which has to date been studied mainly by Kingston and McWhorter[5] and by Low.[4] If a field, E, is applied normal to the surface of a flat filament, an excess charge will be induced on the surface and the conductance along the specimen will therefore change (field effect). However, if the field is maintained, the conductance will in time return to its initial value (polarization of the field effect). This latter effect has been the subject of the present investigation. It is ascribed to a reaction which involves the transfer of the induced charge into nonconducting surface states. The reaction is reversible.

It will be shown that two other disturbances, namely temporary illumination and temporary changes in temperature, cause a similar reaction to occur. In both cases the equilibrium charge density in surface states is displaced. Upon removing the stimulus, a return to equilibrium is observed which shows itself as a slow change in *dark* conductance.

II. EXPERIMENTS ON THE FIELD EFFECT

The sample used for most of the measurements had a p-type impurity density of the order of 10^{13} cm^{-3}, which implies intrinsic conduction above about -16°C. The sample dimensions were $0.2\times2\times10$ mm, the capacity between the field effect probe and the sample was the order of 2 $\mu\mu$f. At all temperatures the surface was p-type, as determined from the sign of the field effect.[2] The measurements of conductance were made using the potentiometer probe technique. The sample was etched with 10% HF, 90% HNO_3, and was aged for four weeks in air, to promote the formation of a stable oxide, before measurements were made.

Results of measurement on the field effect and its polarization as a function of temperature are shown in Fig. 1. The field is applied at time zero. The value of the equilibrium conductance was determined by measurements on a thick filament of germanium, cut from the same crystal to match the characteristics of the sample

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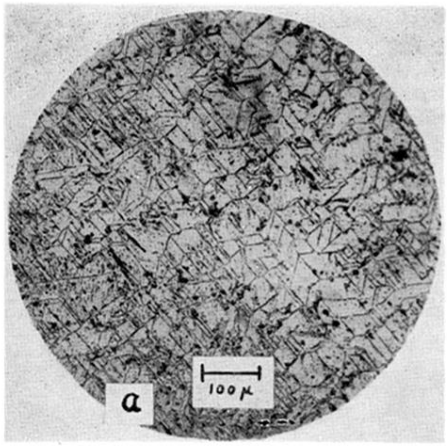
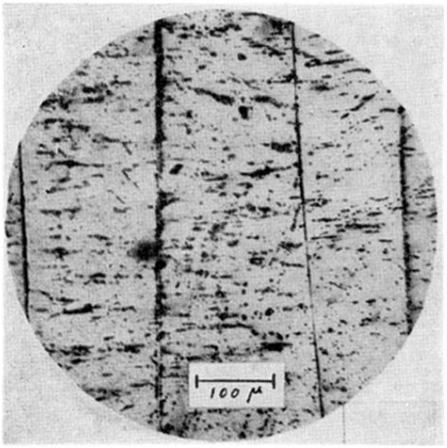
[1] W. Shockley and G. L. Pearson, Phys. Rev. **74**, 231 (1948).
[2] J. Bardeen and S. R. Morrison, Physica **20**, 873 (1954).
[3] H. C. Montgomery and W. L. Brown, Phys. Rev. **98**, 1565(A) (1955).
[4] G. G. E. Low, Proc. Phys. Soc. (London) **68**, 10 (1955).
[5] R. H. Kingston and A. L. McWhorter, Phys. Rev. **98**, 1191(A) (1955); A. L. McWhorter, Phys. Rev. **98**, 1191(A) (1955); A. L. McWhorter, thesis, Massachusetts Institute of Technology, May, 1955 (unpublished).





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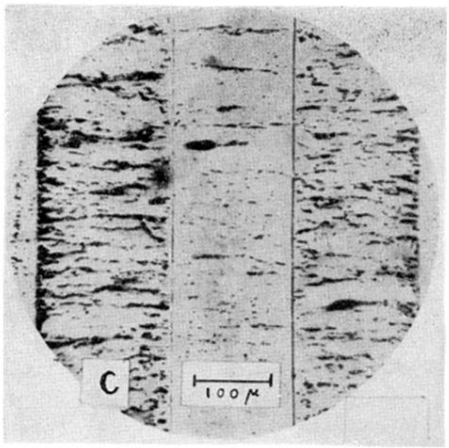

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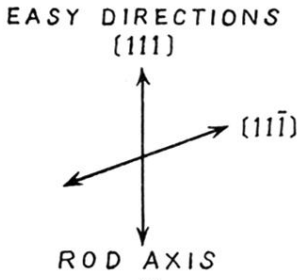

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