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Effects of Electrical Current and Tensile Stress on the Domain Structure in Polycrystalline Grain-Oriented 3.25% Silicon Steel*

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A Kerr magneto-optic apparatus has been used to observe the effects of an electrical current and tensile stress on the domain structure in commercial, 3.25% silicon steel. It is noted that a current density of 0.27 A/mm² produces almost complete saturation in a favorably oriented grain. This effect of current should be considered in elastoresistance and low-field magnetoresistance experiments. Upon application of a tensile stress of only 0.57 kg/mm², a domain pattern resembling the 'lozenge' pattern is shown to occur in certain grains. This indicates that the lozenge pattern is associated with stress and will probably not occur in a completely strain-free crystal. The corresponding strain-free pattern is identified here as a 'chevron' pattern.

* The complete paper, including Kerr photographs, has been submitted for publication in the *Journal of Applied Physics*.

New Method to Measure Directly the 180° Bloch Wall Energy

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Using the Bitter technique, the traces of a single 180° Bloch wall are observed by a device composed of two microscopes, one on each side of the sample. The wall is twisted by an inhomogeneous magnetic field. The measured displacements of the wall traces are related to the surface energy γ_0 of the Bloch wall which in turn is related to the Heisenberg exchange constant A .

In an iron-silicon alloy with 3% Si we find $\gamma_0 = 1.48$ ergs/cm² and $A = 1.48 \times 10^{-6}$ ergs/cm at room temperature, in fair agreement with the value $A \sim 1.7 \times 10^{-6}$ ergs/cm derived from Bloch's law and spin-wave theory at 0°K.

I. INTRODUCTION

FROM the value of the Bloch wall surface energy it is easy to obtain the Heisenberg exchange energy. Hence the unquestionable interest of surface energy, for which, however, only a few measurements have been undertaken (on Permalloy by Bean and deBlois¹ and Bates and Davis²). Quite recently, it has been called to our attention that our different method³ had already been propounded, thirteen years ago, in a paper by Williams and Shockley.⁴ As far as we are concerned these author's experimental results have never come to our knowledge. Furthermore, in their formulation an important term is lacking which not only drastically changes the magnitude of the effect, but also introduces a discontinuity of the wall displacement which is an essential feature of our method.

II. PRINCIPLE OF THE MEASUREMENT

Consider an iron-silicon alloy (010) plate, shaped in a parallelepiped, all of its surfaces being perpendicular to the easy axes of the crystal. The elementary Weiss domains then form alternate layers separated by (100) orientation plane 180° Bloch walls. When an electric

current, with a uniform density I , is sent through the crystal in a direction parallel to the (100) axis, the magnetic field due to the current twists the wall, without displacing it.

The experiment consists in measuring the wall deformation vs the current density I by means of a device consisting of two microscopes with the same optical axis (Fig. 1) and using the Bitter technique.

III. CALCULATIONS OF THE WALL DEFORMATION

Let ($Oxyz$) be a system of rectangular coordinate axes, parallel to the fourfold axes of the crystal, the origin O being equidistant from the two sides of the plate (Fig. 1). The Bloch wall is supposed to be a perfect cylindrical surface, its generating lines being parallel to Oz , which means that we neglect all closure domain effects. Let us call γ the wall energy per unit of surface area and ϕ the angle between the wall and the Oy axis.

In the absence of an external magnetic field the wall is plane and $\phi = 0$. When we apply a weak magnetic field parallel to Oz , the equilibrium condition is³

$$2H_z J_s + (\gamma + \partial^2 \gamma / \partial \phi^2) \cos \phi (d\phi/dy) = 0. \quad (1)$$

We have then used either Néel's⁵ formula where J_s is the saturation magnetization:

$$\gamma = \gamma_0 \{ 1 + [\lambda(1-\lambda)^{-1}] \ln[(1 + (1-\lambda)^{-1})\lambda^{-1}] \}, \quad (2)$$

¹ C. P. Bean and R. W. de Blois, *Magnetic Properties of Metals and Alloys* (American Society for Metals, Cleveland, Ohio, 1958).

² L. F. Bates and P. F. Davis, *Proc. Phys. Soc. (London)* **74**, 170 (1959).

³ L. Néel, *Compt. Rend.* **254**, 2891 (1962).

⁴ H. J. Williams and W. Shockley, *Phys. Rev.* **75**, 178 (1949).

⁵ L. Néel, *Cahiers Phys.* **25**, 1 (1944).

FIG. 1. Schematic arrangement.

with $\lambda = \frac{1}{4} \sin^2 2\varphi$ (γ_0 being the value of γ for $\varphi=0$) or the similar expression obtained by considering simultaneously, in the anisotropy energy, the constants K_1 and K_2 . Some recent measurements, not yet published, having shown that K_2/K_1 equals almost $8 \cdot 10^{-3}$ at room temperature. The results obtained from these two expressions are not appreciably different.

A suitable development of γ vs $(\sin \varphi)$ enables us to obtain the relative displacement X/L (in which L is a half the thickness of the crystal) as a function of $4\pi J_s I / \gamma_0$, shown in Fig. 2, the γ_0 parameter being fitted with respect to the experimental results. An essential point of interest lies in the fact that a discontinuity exists for $4\pi J_s I L^2 / \gamma_0 = 1.118$ and $X/L = 0.202$, where the Bloch wall, for a sufficient current, suddenly passes into the $0xz$ plane.

IV. EXPERIMENTAL RESULTS

Our experiments have been carried out on several iron-silicon alloy samples carefully annealed in pure hydrogen, with a composition between 3 and 3.2% Si. Some were cut in the shape of a frame, some in the shape of a parallelepiped of about $10 \times 10 \times 0.2$ mm.

The expected discontinuity is shown on the plot, Fig. 2, by a sudden change of slope at a point which can be situated with accuracy at $X/L = 0.25$ and $IL^2 = 8.2 \times 10^{-4}$ A. Thus, in four different experiments on crystals varying from 0.14 to 0.40 mm in thickness, the value of IL^2 ranges from 7.91 to $8.26 \cdot 10^{-4}$ Å.

Hysteresis phenomena do not appear to cause any difficulty. The first part of the curve can be followed in

FIG. 2. The twist of the Bloch wall, dashed line: calculated values; heavy line: measured values.

both directions, within experimental accuracy. But after the discontinuity, the walls are displaced to such an extent that our assumptions are no longer valid.

V. CALCULATIONS OF THE WALL ENERGY

With $4\pi J_s = 20\,200$ G we find $\gamma_0 = 1.48$ ergs/cm².⁶ The value predicted by Néel in 1944 was $\gamma_0 = 1.4$ ergs/cm². This result was obtained from a value of the anisotropy constant K larger than the values usually admitted for the iron silicon alloys. With $K = 3.70 \times 10^5$ ergs/cm³ we find an exchange constant $A = \gamma_0^2 / 4K = 1.48 \times 10^{-6}$ ergs/cm. This value is obtained at room temperature, whereas the Bloch law gives the constant A at 0°K. The assumed deviation between these two values being 4.4 %, this would give for 0°K: $A = 1.55 \times 10^{-6}$ ergs/cm. Lifschitz's calculations on the thermal variation of J_s , revised by Kittel,⁷ give $A = 1.7 \times 10^{-6}$ ergs/cm. The agreement between these two values is satisfactory.

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⁶ The present value is slightly different from the value reported by R. Aléonard and P. Brissonneau, *Compt. Rend.* **254**, 2934 (1962).

⁷ C. Kittel, *Rev. Mod. Phys.* **21**, 541-83 (1949).