If, further, we apply Eq. (2) to an electrical conductor such as sodium, at room temperature we find $K_{\text{latt}}\simeq 8\times 10^{-3}$ cals/cm °C sec, which is about 2 percent of the observed thermal conductivity of the metal. This is consistent with the usual assumption that the lattice conductivity in such metals is practically negligible in comparison with that due to the free electrons.

In the case of beryllium, the effective number of conduction electrons is sufficiently low that the intrinsic lattice conductivity can be observed experimentally. Powell[8] finds that the data may be expressed by

$$K_{\text{latt}}=[(64/T)-0.036]\ \text{cal/cm °C sec}, \qquad (3)$$

valid between 320°K and 700°K. Because of the high characteristic temperature of beryllium (estimates vary between $\sim$650°K and $\sim$1040°K), this temperature-region cannot be considered as fully classical and this may account for the particular form of Eq. (3). However, if we take a value for α appropriate to classical behavior, Eq. (2) gives

$$K_{\text{latt}}\simeq(68/T)\ \text{cal/cm °C sec}. \qquad (4)$$

The close agreement with the dominant term of Eq. (3) must be regarded as fortuitous.

The ideal subjects for experimental investigation would seem to be the heavier inert gas solids. It is hoped to carry out experiments before long on such solids in our laboratories.

Note added in proof.—Two other recent articles of interest are: G. Leibfried and E. Schlömann, Gött. Nachr. IIa, 71 (1954); A. W. Lawson, "On the relation between thermal expansion and thermal conductivity in one-dimensional lattices" (unpublished).

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[8] R. Powell, Phil. Mag. 44, 645 (1953).

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Magnetization Reversal in Thin Films*

R. L. Conger
U. S. Naval Ordnance Laboratory, Corona, California

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An experiment has been performed which indicates that magnetization reversal in evaporated films of 80 percent Ni, 20 percent Fe, 2×10^{-5} cm thick takes place by domain rotation rather than by the motion of 180° domain walls.

The magnetization reversal in single crystals with dimensions of the order of a centimeter has been investigated by Williams[1] and others. They have shown that the reversal takes place by the motion of 180° domain walls and that the wall velocity is controlled by eddy current effects. Magnetization reversal in most polycrystalline materials probably takes place by this process. However, if a ferromagnetic film is too thin to support domain walls, the magnetization reversal would be expected to take place by a different mechanism.

The thickness at which a thin ferromagnetic film ceases to support domain walls has been calculated by Kittel.[2] For a material with an anisotropy energy of 5×10^{5} ergs/cm^3 and a wall energy of 3 ergs/cm, this thickness is 3×10^{-5} cm. Films thinner than this will tend to be single domain structures. Materials with anisotropy energy less than 5×10^{5} ergs/cm^3 will have a poly-domain to single-domain transition thickness greater than 3×10^{-5} cm.

We have prepared ferromagnetic films 2×10^{-5} cm thick which should be single domain structures and have observed the magnetization reversal of these films. During the reversal process there is a large component of the magnetization perpendicular to the direction of the applied field in the plane of the film. This perpendicular component was not observed with thicker sheets of ferromagnetic material.

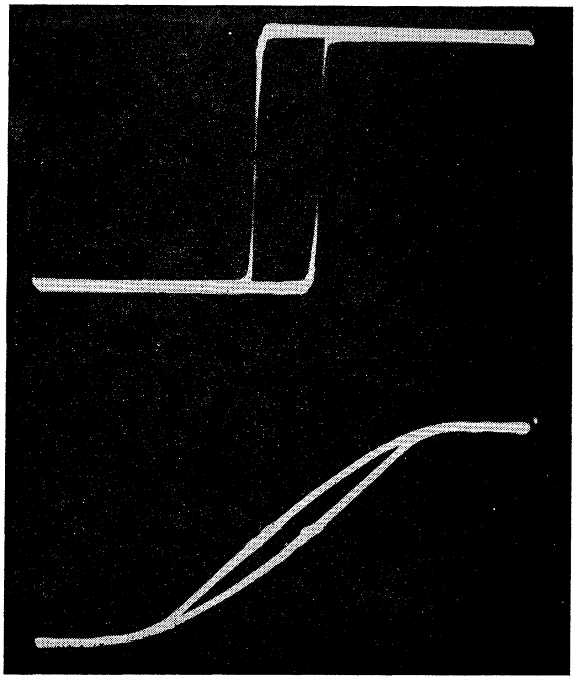

FIG. 1. Hysteresis loops of evaporated film.

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* This work was supported by the Office of Naval Research.

[1] Williams, Shockley, and Kittel, Phys. Rev. 80, 1090 (1950).

[2] C. Kittel, Phys. Rev. 70, 965 (1946).

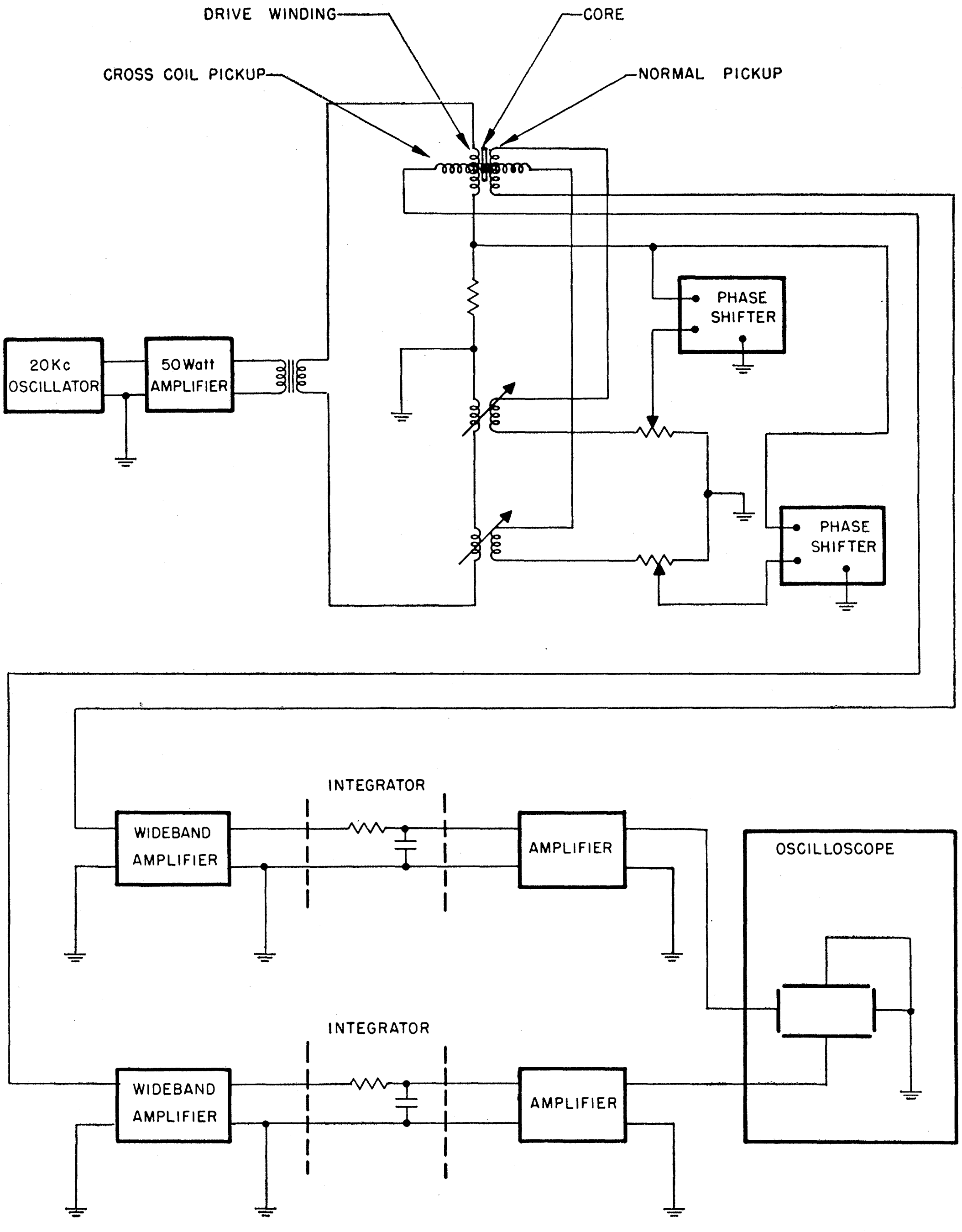

FIG. 2. *M* loop core tester.

The thin films used in this experiment were prepared by evaporating in a vacuum an iron-nickel alloy onto a heated glazed ceramic substrate. The films were in the form of circular disks about 1.5 cm in diameter and 2×10^{-5} cm thick. They had a mirror-like surface. Electrical conductivity measurements showed that the films were continuous layers.

The films had a composition of 80 percent Ni and 20 percent Fe. This alloy was chosen because its low anisotropy energy (about 10^4 erg/cm^3) would increase the tendency of the films to be single domain structures. Chemical composition and thickness of the films were determined by colorimetric chemical analysis using a spectrophotometer.

In order to align the crystals in the film, a magnetic field of several hundred oersteds was applied to the films during their deposition. Figure 1 shows two 60-cycle hysteresis loops for one of the films. The top loop

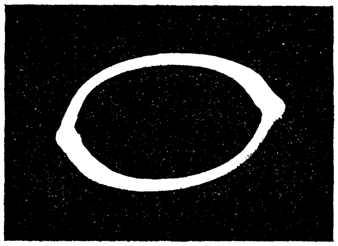

FIG. 3. M loop without bias.

FIG. 4. M loop with bias.

was measured in the direction of this field and the bottom loop was measured perpendicular to this direction in the plane of the film. The two loops indicate that a high degree of orientation has been obtained. Later experiments showed that a field of 0.5 to 1.0 oersteds was enough to produce films with hysteresis loops like thos of Fig. 1. Hysteresis loops were determined with an apparatus similar to that used by Crittenden.[3]

These thin films were examined in an apparatus which made it possible to observe the magnetization change as a pattern on a cathode-ray oscilloscope screen. The film was placed inside a coil assembly which consisted of 3 coils of 20 turns each. Two of the coils, the driving coil and the M_z pickup coil, had a common axis. The axis of the third coil, the M_r pickup coil, intersected the axis of the other two coils at right angles. The center of the three coils coincided. The axes of the driving coil and the M_z pickup coil were always tangential to the surface of the film. The axis of the third coil could be either tangential or normal to the film surface.

A 20-kc/sec oscillator supplied enough power to the driving winding to produce an oscillating field inside the coil of about 20 oersteds peak to peak. The voltage induced in the M_r pickup coil was amplified, integrated, and displayed as a vertical deflection on a cathode-ray oscilloscope screen. The voltage induced in the M_z pickup coil was amplified, integrated, and displayed as a horizontal deflection on the scope. Decoupling techniques similar to those used in the hysteresis loop equipment were used to eliminate all coupling between the driving and pickup coils except that due to the ferromagnetic material. Figure 2 is a block diagram of the apparatus.

As a result of this decoupling, the voltage induced in the pickup coils was proportional to $d\mathbf{M}/dt$ in the direction of the pickup coil axis. After this voltage was amplified and integrated with respect to time, its magnitude was proportional to the component of **M** in the direction of the coil axis.

It was observed that when the axis of the M_r coil was normal to the surface of the ferromagnetic film, the voltage induced in the M_r coil was always very much smaller than when the axis of this coil was tangential to the surface of the film. This shows that the magnetization vector **M** stays in the plane of the film when the magnetization is reversed. Since the magnetization vector **M** remains in the plane of the film, the trace that is observed on the oscilloscope when the axes of the M_z and the M_r coils are tangential to the surface of the film represents the successive positions of the magnetization vector M as the direction of the magnetization is reversed.

Figure 3 shows such a trace of the **M** vector for one of the evaporated films. Then a small biasing field perpendicular to the direction of the driving field was applied by holding a small permanent magnet near the film. This changed the curve of Fig. 3 to that of Fig. 4. When the magnet was held near enough to the film to saturate it magnetically, the curve was reduced to a dot. These experiments showed that the curves were actually caused by the ferromagnetic material in the thin film, the only ferromagnetic material in the system.

These traces of the **M** vectors show that magnetization reversal in these evaporated films does not take place by the motion of 180° domain walls. If magnetization reversal took place by 180° wall motion, all the material in the film would be magnetized either in the direction of the driving field or in the opposite direction, except for the material inside the walls. For this case the trace of the **M** vector would be a straight line. When the thin evaporated film was replaced by a ferrite core, the trace of the **M** vector became such a straight line.

Figures 3 and 4 indicate that the magnetization reversal may take place by the rotation of a single domain. For this reversal mechanism, the trace of the **M** vector would be a circle or a semicircle. A steady magnetic biasing field could cause the **M** vector to move along a semicircular path, while with no biasing field present the vector could move on a circular path. Since Figs. 3 and 4 are approximately a circle and a semicircle, respectively, the single-domain rotation hypothesis will partly explain the shape of these curves.

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[3] Crittenden, Hudimac, and Strough, Rev. Sci. Instr. 22, 872 (1951).

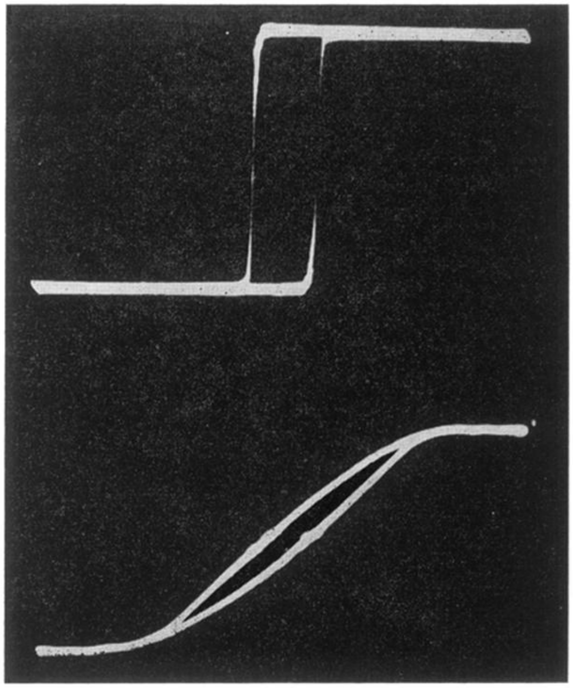

Fig. 1. Hysteresis loops of evaporated film.