The $PbTiO_3$ shifts are much larger than those in $BaTiO_3$, but this might be expected from the greater lattice distortion and high polarizability of the Pb ion.

Excellent single crystals for this investigation were furnished by Dr. Kohman of the Bell Telephone Laboratories, Dr. Karan of International Business Machines in Poughkeepsie, Dr. Lefkowitz of the Glenco Corporation, and Dr. Jaffe of the Brush Development Company. The research has been supported jointly by the Brookhaven National Laboratory and contracts with the U. S. Atomic Energy Commission and the Signal Corps Engineering Laboratories.

† Under the auspices of the U. S. Atomic Energy Commission.
* Now a guest at Brookhaven from the Westinghouse Research Laboratories.
‡ Present address: Department of Physics, The Pennsylvania State University, University Park, Pennsylvania.

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Magnetic Domains in Thin Films of Nickel-Iron*

CHARLES A. FOWLER, JR., AND EDWARD M. FRYER
Department of Physics, Pomona College, Claremont, California
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CONSIDERABLE attention has been given recently to the problem of the magnetic behavior of thin ferromagnetic films.[1–5] Measurements of certain of the magnetic properties have seemed to indicate that domain configurations in general depend upon the thickness and the constants of the films in the manner predicted by Kittel,[6] namely, a single domain parallel to the film when the thickness is less than a critical value and domains oriented normal to the film surface when this value is exceeded. Direct observation of the domain structure in films has apparently been unsuccessful, although an indirect observation by optical transmission through very thin films has been reported by König.[7]

By employing the longitudinal Kerr magneto-optic method of domain observation, previously described,[8] we have succeeded in photographing the domain structure of an evaporated NiFe film (80% nickel) 5000 angstroms thick, measuring 1 in.$\times 1\frac{1}{4}$ in. on the surface. Figure 1(A) is a composite photograph of the several portions of the complete film surface, the composite being necessary because of the rather limited photographic field of our Kerr setup. The pattern consists of a number of antiparallel, gently curving domains several millimeters wide and separated near certain of the film edges by dagger-like domains of various lengths. There is no evidence of closure domains at any of the film edges. By photographing through the microscope cover glass which serves as a backing for the evaporated alloy, the Kerr technique has revealed the domain configuration on the reverse side of the film, and this proves to be a mirror image of the front side when the film has been turned over about a longitudinal axis [see Fig. 1(B)]. Thus it follows that each domain extends completely through the film, as expected.

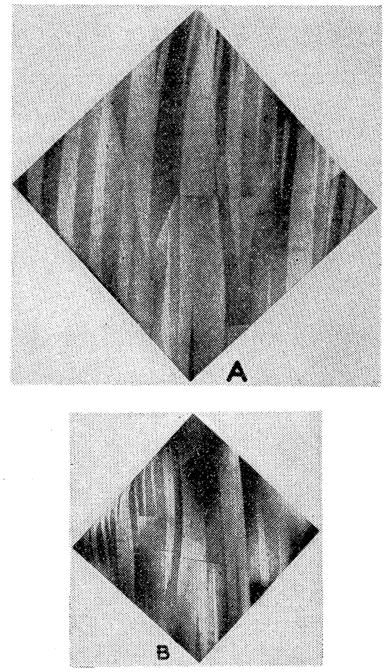

FIG. 1. Composite photographs of the domain configurations in the top (A) and the bottom (B) surfaces of a NiFe film 5000 A thick. The specimen was turned over about an axis connecting the top and bottom corners of the pictures.

The domains are exceedingly sensitive to external magnetic fields. Figure 2 illustrates their behavior in a portion of the surface as the S pole of a small compass needle is brought up to the edge of the film and then withdrawn. These three photographs are part of a longer sequence which indicates that the changes caused by the small field of the perturbing pole occur by movement of the domain walls. When the pole is replaced by an unmagnetized steel needle, a smaller but still significant domain shift is observed. We have even observed changes in domain configuration to occur overnight, presumably caused by small stray fields in the laboratory.

Investigation of two other films of this material but with thicknesses of 10 000 angstroms and 20 000 angstroms, respectively, showed no evidence of surface domains. It is possible that these thicker films contain the predicted normal domains, perhaps very much smaller in surface area than those of Fig. 1. We are now attempting to photograph or otherwise detect these as a part of a systematic experimental study of the domain behavior in films of this thickness down to those of 100 angstroms or less, in a controlled uniform magnetic field.

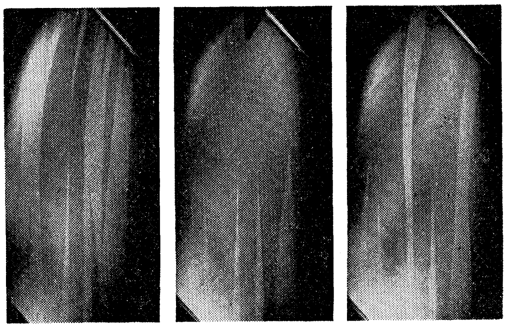

FIG. 2. Domain behavior in a portion of the film as the S pole of a small compass needle is brought up to the film edge and then removed. The needle end can be seen at the top of (B).

The authors are indebted to Dr. R. L. Conger and his group at the Naval Ordnance Laboratory, Corona, California for furnishing us with the thin film specimens and for discussions concerning their magnetic behavior.

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Observation of Quantum Effects in Cyclotron Resonance

R. C. FLETCHER, W. A. YAGER AND F. R. MERRITT
Bell Telephone Laboratories, Murray Hill, New Jersey
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NEW cyclotron resonance lines associated with the valence band of germanium have been resolved. These are believed to be the experimental confirmation of the predictions of Luttinger and Kohn,[1] who showed that, when a crystal band edge is degenerate, a quantum mechanical treatment of the cyclotron resonances predicts a nonuniform spacing between the lower energy levels. Thus, if these levels can be preferentially populated by going to low enough temperatures, new cyclotron resonances should appear.

Measurements were made at 23.5 kMc/sec at temperatures from 4.2 to 1.3°K. For this latter temperature the Boltzmann factor, $e^{h\nu/kT}$, is 2.5, which should be large enough to provide a significant population of the lower levels. Carriers of both signs were introduced into the germanium lattice by illumination with white tungsten light. In order to study holes in the presence of much larger electron resonances, a circular cavity was used which gave circular polarization. A series of measurements was made on three slices cut from a single-crystal ingot (8×10^{12} cm^{-3} excess donors) in the three principal directions. Final alignment of the sample in the magnetic field was accomplished by rotating the sample until the appropriate electron resonances merged.

In Fig. 1 there is displayed a reproduction of the heavy-hole resonance at both 4.2°K and 1.3°K for the three directions. These reproductions represent a smoothed-out composite of a number of recorder tracings for each case. All the curves are normalized to unity at their maximum. As can be seen, new resonances appear at 1.3°K which are not present at 4.2°K in all three directions. In two instances [$m^*=0.332$ in the (111) direction and 0.262 in the (110) direction] the extra resonances were also seen at 4.2°K. The reason why these have escaped detection previously is presumably a combination of too high a microwave power (possibly raising the average electron energy to the high-energy levels) and too short mean-free-time (broad lines).

The resonances with question marks are somewhat uncertain because of proximity to other lines or because of residual electron lines arising from imperfect circular polarization. This latter also causes an appreciable effect on the shape and position of the strong line at $m^*=0.360$ in the (110) direction. The extra line in the (100) direction at $m^*=0.593$ is unmistakable at 1.3°K but vanishes at 4.2°K. No comparable line was found in the other directions.

The light-hole resonance did not display the same kind of structure. It was measured to have the values

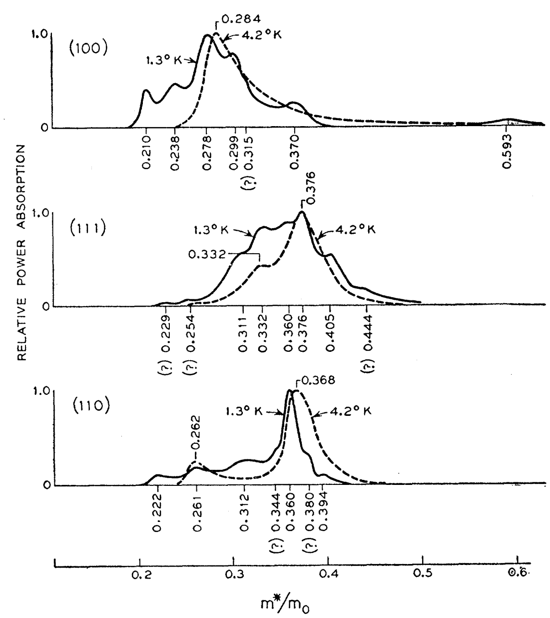


FIG. 1. Heavy-hole resonances at 4.2°K and 1.3°K in the three major crystal directions using circular polarization. The appearance of extra resonances at the lower temperature is believed to be the quantum effect.

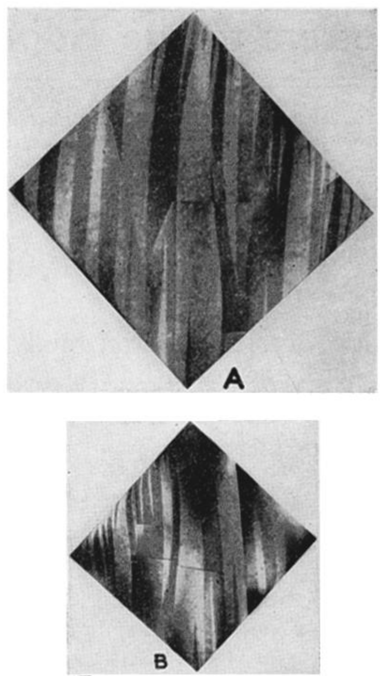
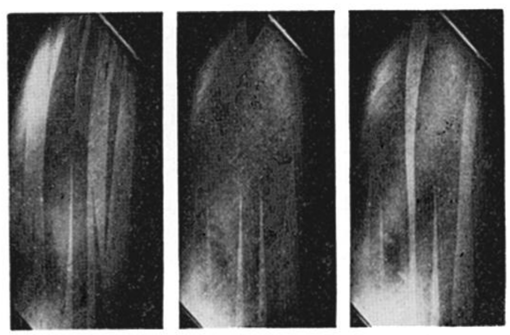


FIG. 1. Composite photographs of the domain configurations in the top (A) and the bottom (B) surfaces of a NiFe film 5000 A thick. The specimen was turned over about an axis connecting the top and bottom corners of the pictures.



(A) (B) (C)

FIG. 2. Domain behavior in a portion of the film as the S pole of a small compass needle is brought up to the film edge and then removed. The needle end can be seen at the top of (B).