Observation of Domains in the Antiferromagnetic Single Crystal NdS

V. I. MAKAROV, N. S. TERESHINA, O. N. OVCHARENKO, A. A. SANKOV, AND G. M. LOGINOV

Physico-technical Institute, Ukrainian Academy of Sciences

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The temperature dependence of the magnetic susceptibility of an NdS single crystal is measured at temperatures between 4.2 and 20.4 °K in fields up to 6000 Oe and for various crystallographic directions. It is found that the magnetic susceptibility of NdS in the antiferromagnetic state (for $T < T_N = 8.5$°K) does not depend on the crystal direction; this is ascribed to the presence of antiferromagnetic domains. The domain structure was observed visually by depositing highly dispersed iron particles (< 100 Å) at a temperature of 4.2 °K. The width of the domains is $\sim 2\times10^{-4}$ cm and that of the domain boundaries 2×10^{-5} cm.

THE magnetic properties of different chalcogenides have been investigated recently in a wide temperature interval. These compounds come in the form of either powders or fused polycrystals. A study of the magnetic susceptibility χ of polycrystalline NdS has shown that it goes over at T = 8°K from the paramagnetic state into the antiferromagnetic state.[1]

We have investigated the temperature dependence of single-crystal NdS[1)] in fields up to 6,000 Oe and at temperatures 4.2–20.4°, 77°, and 290°K for three different directions, [111], [110], and [100]. The initial purity of the metal was 99.7% and that of the sulfur better than 99.99%. NdS crystallizes in a cubic lattice of the NaCl type with a = 5.47 Å. The single crystal dimensions were $\sim 1.5\times1.5\times1.5$ mm. The magnetic structure of NdS is unknown.

The magnetic susceptibility was measured by the Faraday method using a balance with automatic compensation. The measurement accuracy was 1%. The temperature was measured with a carbon resistance thermometer accurate to 0.1°K. It was found that in the temperature interval 4.2–20.4°K the dependence of the magnetic moment of the NdS on the magnetic field was linear and no residual magnetic moment is observed in the entire temperature range within the limits of the experimental accuracy.

The temperature dependence of χ is shown in Fig. 1. We see that at $T_N = 8.4 \pm 0.1$°K the plot has a sharp minimum corresponding to the antiferromagnetic transition. At $T > T_N$ up to 20.4°K, the Curie-Weiss law is satisfied with $\Theta = -4$°K. Below T_N, a sharp increase of the reciprocal magnetic susceptibility is observed, with χ independent of the crystal orientation.

One of the causes of the observed isotropy at $T < T_N$ may be the formation of antiferromagnetic domains, which average χ over all the crystal directions. From this point of view, the most thorough investigations are performed on NiO, whose χ is also isotropic. The antiferromagnetic domains in NiO were observed visually by optical methods. The powder method developed for ferromagnets was not used, since NiO is an antiferromagnet without weak ferromagnetism, and the antiferromagnetic domain boundaries have no magnetic moment in this case.[2] It can be assumed that a weak

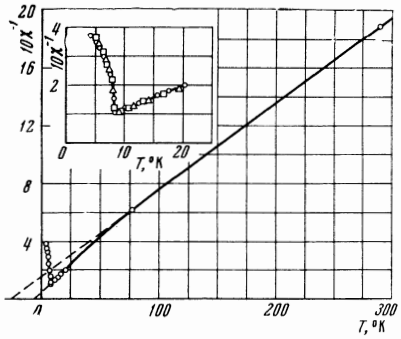

FIG. 1. Temperature dependence of the magnetic susceptibility of single-crystal NdS: ○–H ∥ [100], △–H ∥ [010], □–H ∥ [111].

magnetic moment can occur in the domain wall as a result of the boundary conditions on the surface of the metal or as a result of crystallographic defects that disturb the antiferromagnetic order of the spins as they turn from the direction of the antiferromagnetism axis in one domain to the direction of the axis in another. We have therefore undertaken an attempt to observe antiferromagnetic moments with the aid of minute iron particles (< 100 Å).[7]

We used a well known method of producing minute iron particles, namely evaporation in an inert-gas atmosphere.[3] This method is used for electron-microscope investigations of the magnetic structure of hard superconductors.[4] Minutely-dispersed iron particles were obtained by evaporating iron in a helium atmosphere at low pressure (1 mm Hg). The produced iron particles settle on the surface of the sample at the locations of the magnetic-field gradient.[5,6]

The domain structure was observed on the natural cleaved face (100) of the NdS single crystal, which was placed, together with a previously deposited carbon film of ~100 Å thickness, into the device for evaporating the iron at a temperature lower or higher than T_N, i.e., at 4.2 or 20.4°K. The iron was evaporated in the absence of an external magnetic field (there was no compensation for the earth's magnetic field). After the iron particles were deposited, a carbon film ~100 Å thick was again deposited on the surface. We thus obtained a carbon replica of the distribution of the finely-dispersed iron particles on the surface of the sample.

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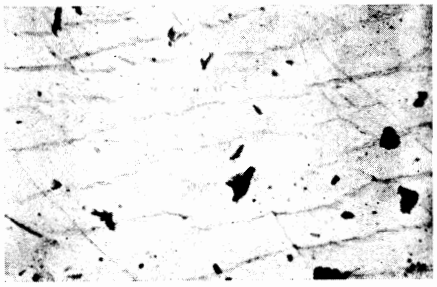

FIG. 2. Domain structure obtained by evaporating iron particles on the (100) plane of single-crystal NdS. Magnification 10^4 X.

The carbon replica was investigated in an electron microscope.[2)]

The experimental data have shown that the distribution of the iron particles on the surface of NdS crystal at 20.4°K (i.e., above T_N) constitutes a random picture, demonstrating the absence of magnetic gradients on the surface at this temperature. The photograph shows the distribution of the iron particles evaporated at 4.2°K, i.e., at $T < T_N$, obtained as a result of the presence of magnetic-field gradients on the NdS surface. The contours made up by the iron particles can be treated as boundaries of antiferromagnetic domains that carry a magnetic moment. The domain width is 2×10^{-4} cm and the width of the domain wall 2×10^{-5} cm. We see that the area of the domain boundaries on the surface of the crystal is quite large and amounts to ~10% of the total area. As already noted, measurements with accuracy up to 1% revealed no residual magnetic moment in these NdS single crystals. It can therefore be assumed that the carriers of the ferromagnetic moment are the traces of the domain boundaries on the crystal surface.

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