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Implementation of the Astrov Method for Measuring the ME_E Effect with the Use of a Vibrating-Coil Magnetometer

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Abstract—A setup is developed for measuring the ME_E effect by fixing the amplitude of magnetization oscillations upon the repolarization of a sample, caused by the application of ac voltage to the sample plates. The temperature dependence of the ME_E effect in a $Ga_{2-x}Fe_xO_3$ single-crystal sample is measured in external fields from 0.25 to 1 kOe at temperatures from 77.4 to 280 K. It is established that the effect disappears when the Curie temperature is attained. The hysteresis of the magnetoelectric effect related to the magnetization hysteresis is measured.

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INTRODUCTION

In recent years, much attention has been focused on multiferroic materials, especially $BiFeO_3$ thin films, due to their potential for application [1–3]. Most of the techniques for studying the magnetoelectric behavior of multiferroics are based on the ME_H effect [4], i.e., the change in polarization ΔP upon a variation in the external magnetic field H and/or temperature T [5, 7]. Since in magnetoelectric materials the polarization and magnetization of a sample are interrelated, one can measure not only the polarization variation versus the external magnetic field, $\Delta P(T, H)$, but also the magnetization variation versus the electric field, $\Delta M(E)$, i.e., the ME_E effect [4]. However, there is a lack of published data on this measurement approach, despite its simplicity, which allows the abandonment of pulse techniques, thus simplifying data interpretation and enhancing measurement accuracy.

In study [8], Astrov proposed a method for measuring the ME_E effect on the basis of magnetization variation in an applied electric field, $\Delta M = aE$, where a is the linear magnetoelectric effect tensor. In study [9], the Astrov method was implemented with the use of a SQUID magnetometer. It was shown that such measurements can be implemented also with the use of a vibrating magnetometer. The advantage of this approach is the possibility of measuring in two modes. The magnetometer allows the total sample magnetization to be measured, which comprises two components: $M(H, E) = M(H) + M(E)$. The first term is the magnetization of a crystal caused by an applied magnetic field H and the second term is the ME_E effect. Comparing magnetization with and without an applied electric field E, one can extract the magnetoelectric-effect component $M(E) = M(H, E) - M(H, 0)$. Measurements can be performed by the Astrov method.

METHOD FOR MEASURING THE ME_E EFFECT

At the strong magnetic-fields lab, Kirensky Institute of Physics, a setup based on the vibrating magnetometer developed in 1985 was assembled [10]. The setup is intended for measuring the ME_E effect, i.e, magnetic-moment variation ΔM in the sample due to a change in the external electric field E.

As is known, in measurements of the magnetic moment on a vibrating-coil magnetometer, a sample vibrates in the center of a balanced system of coaxial removable coils. By relocating the sample from the vibration center to the center of one of the removable coils, one can measure the voltage induced by magnetic-moment variation ΔM in a sample due to the magnetoelectric effect without vibration. In fact, measurements according to the method described in [8] are performed.

A schematic circuit of the circuit is shown in Fig. 1. The sample *1* with deposited plates *2* is connected to a circuit with an ac generator *3*. When the generator is switched on, the sample's polarization continuously reverses. Since, in magnetoelectric materials, polarization is related to magnetization, polarization variation ΔP in the sample leads to magnetic-moment variation ΔM. The sample is placed at the center of one of the removable coils *4* in which magnetization reversal of the sample induces ac voltage U which is the output signal. The coil *5* induces an external dc magnetic field H. The sample is a planar capacitor; therefore, the electric-field strength in it increases with a decrease in

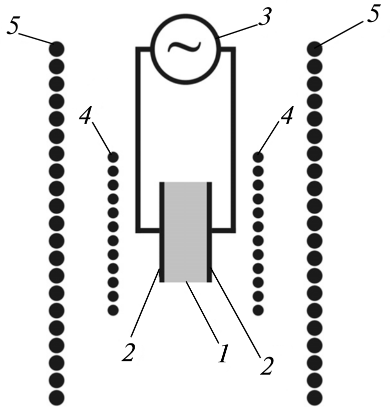

Fig. 1. Schematic of the $\Delta M(T)$, $\Delta M(U)$, and $\Delta M(H)$ measurements.

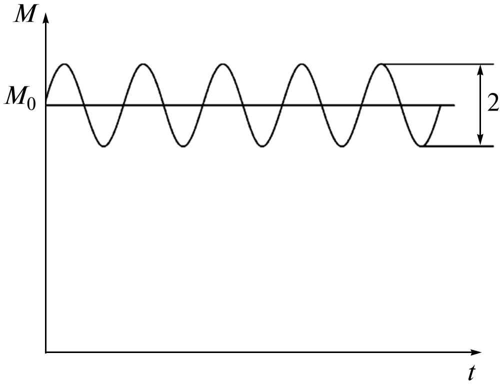

Fig. 2. Sample magnetization behavior during the measurements.

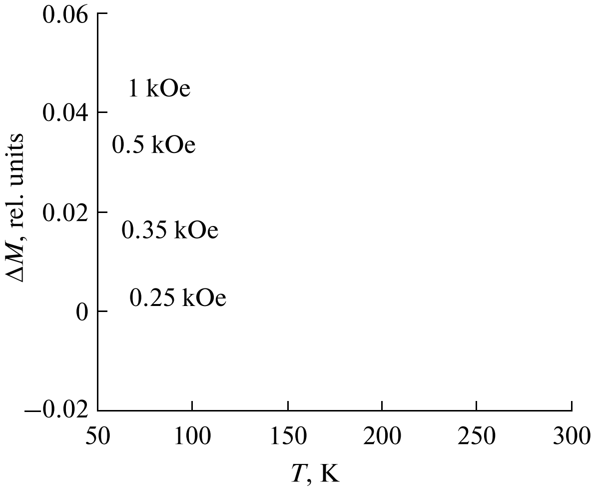

Fig. 3. Magnetoelectric effect ΔM vs temperature T in different magnetic fields.

the gap between the plates and measurements on thin samples (films) are the most sensitive.

Figure 2 shows the time dependence of the magnetic moment of the sample for an ac voltage applied to its plates. During the measurements, the magnetic moment of the sample oscillates relative to the constant value of M_0 caused by the dc magnetic field H with a frequency equal to that of the signal from the generator *3*. An ac electric voltage U applied to the sample plates leads to repolarization of the sample. Repolarization, due to magnetoelectric coupling, leads to a change in the magnetic moment. Thus, in removable coil *4* (Fig. 1), an ac voltage is induced, which is caused by the periodic variation in the sample magnetization. By measuring the induced ac voltage, one can obtain the magnetization reversal amplitude ΔM and by varying the external conditions, measure the field, temperature, and other dependences.

Since the method is based on measurements of the voltage induced in removable coil *4*, an increase in the frequency of the signal from the generator *3* leads to proportional growth of the output signal, which improves the signal-to-noise ratio but degrades the repolarization quasisteady-state condition.

Since the output signal is relatively small, we applied synchronous detection of the signal from the coil *4* using the reference signal of the generator *3* with the repolarization frequency. Thus, we retuned the magnetometer devices [10] to the repolarization frequency.

TEST MEASUREMENTS

We performed test measurements on the well-known magnetoelectric $Ga_{2-x}Fe_xO_3$ ($x = 1.3$) [4, 11, 12] with orthorhombic symmetry ($E \| b$, $H \| c$, ΔM fixed along the c axis). Figure 3 shows the temperature dependence of the magnetoelectric effect $\Delta M(T)$, where ΔM is the amplitude of the magnetization variation due to repolarization of the sample. The amplitude of the magnetization variation is given in relative units; to obtain absolute values, it is necessary to calibrate the setup. Data on the dependences $\Delta M(T, H)$ were detected automatically by a computer, as in [10].

The curves shown in Fig. 3 were obtained in magnetic fields H from 0.25 to 1 kOe at the same voltage applied to the plates $U = 100$ V and the frequency $n = 1400$ Hz. The curves qualitatively coincide with the data reported in [4]. It can be seen that in weak magnetic fields there is a sharp jump in the amplitude of the magnetoelectric effect after certain temperatures, which is, possibly, be related to a fast shift in charge ordering domain walls at these temperatures. It can also be related to the fact that at these temperatures the coercivity drops to a value at which the magnetization reversal of the sample is more effective. It can be seen in Fig. 4 that the fields at which the jump is observed correspond to the values at which the hysteresis loop has not collapsed yet. In addition, it can be seen that

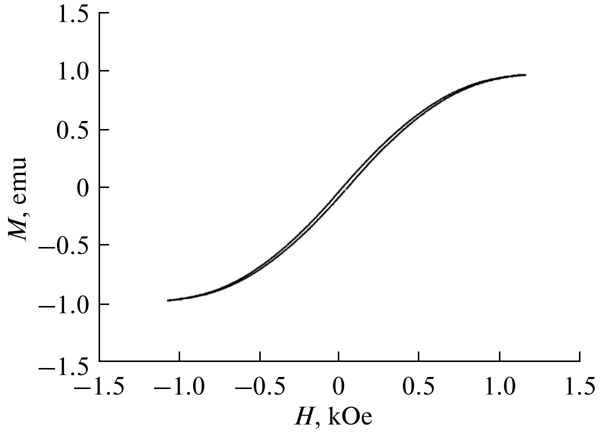

Fig. 4. Sample magnetization M vs applied field H at $T = 77.4$ K.

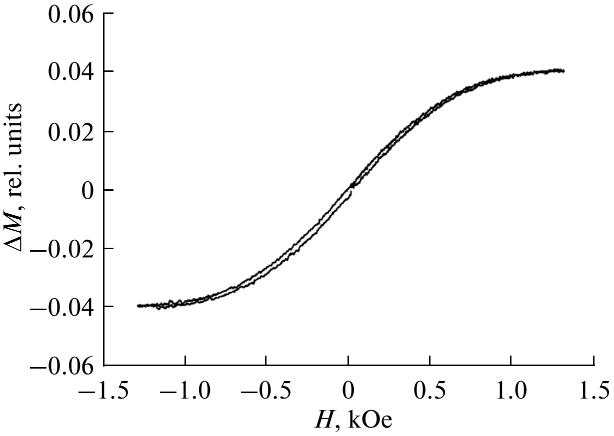

Fig. 5. Magnetoelectric effect M vs applied field H at $T = 77.4$ K.

when the Curie temperature $T_C = 272$ K is attained, the magnetoelectric effect disappears and right before the Curie temperature a peak occurs, which is apparently caused by the Hopkinson effect. The weaker the external magnetic field, the sharper the peak is.

In addition, we obtained the field dependence of the magnetoelectric effect $\Delta M(H)$ (Fig. 5). The hysteresis of the magnetoelectric effect is apparently due to the hysteresis of magnetization M of the sample (Fig. 4). Comparing Figs. 4 and 5, one can conclude that the value of the magnetoelectric effect is proportional to the magnetization of the sample, at least in the measuring magnetic-field range.

CONCLUSIONS

A setup for measuring the ME_E effect in the quasisteady-state mode was developed. In the measurements, the amplitude of the magnetization oscillations in the sample during its repolarization caused by an applied ac voltage is fixed. To test the technique, a $Ga_{2-x}Fe_xO_3$ single-crystal sample was chosen. The temperature dependence of the magnetoelectric effect for this sample was measured in external magnetic fields from 0.25 to 1 kOe at temperatures from 77.4 to 280 K. It was found that the effect disappears at the Curie temperature, which indicates the correctness of the method used. The field dependences $\Delta M(H)$ were obtained, which represent hysteresis related to the magnetization hysteresis. As a whole, the setup appeared sufficiently sensitive to measure the ME_E effect and allows many parameters of this phenomena to be determined.

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