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Measurement of magnetocaloric effect in pulsed magnetic fields with the help of infrared fiber optical temperature sensor

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ABSTRACT

We present a new technique for experimental study of kinetics of phase transitions (PTs) and direct measurement of the magnetocaloric effect (MCE) in pulsed magnetic fields by using the fast response temperature probe with infrared fiber optical (IRFO) sensor. As demonstration of the new technique, the results are presented of MCE measurements for Gd near Curie point: $\Delta T_{ad} = 21.3$ K under pulsed magnetic field $\mu_0 H = 12.7$ T; and inverse MCE for $Fe_{48}Rh_{52}$ sample at initial temperature 305.1 K: $\Delta T_{ad} = -4.5$ K under pulsed magnetic field $\mu_0 H = 8.5$ T. Also, the energy losses on magnetization near the 1st order PT were calculated from the results of direct measurements of magnetization versus time for $Fe_{48}Rh_{52}$ sample: W = 45 J/kg.

1. Introduction

In recent years, all around the world, a large number of new magnetically ordered compounds are created and studied with magnetic, metamagnetic and magnetostructural phase transitions (PTs) of the 1st and 2nd orders, which are accompanied by the strong anomalies of magnetic, thermal and mechanical properties [1,2]. But, despite the fact that the PTs in magnetic substances are studied for a long time both theoretically and experimentally, at the moment there is no sufficiently deep understanding of the kinetic phenomena, accompanying PTs. By conventional theoretical approach, the growth of the new phase at PT of the 1st order is described by the kinetic equation of the Fokker-Planck. The relaxation processes near PT of the 2nd order is described by the Landau-Khalatnikov equation [3]. However, the applicability of these equations for the magnetic PTs has not been tested experimentally still yet.

The problem of the rate of PTs requires immediate solution also because it is crucial for the creation of the new technologies based on "giant" effects in the vicinity of PTs in solid state magnetic functional materials. For example, the magnetocaloric effect (MCE) reaches maximum near the PTs in magnetically ordered solids [1]. So, study of PT's rate is necessary for creation of a new technology of magnetic refrigeration at room temperature with high cooling power of a sold state working body [4]. The rate of PT limits the frequency of thermodynamic cycles. Accordingly, the power of refrigeration will depend on the frequency of cycles, and it is difficult to judge the competitiveness of this machine without determining the fundamental restrictions on the parameter of specific cooling power of the prospective MCE materials [5]. The comparative study of the kinetics of PTs of the prospective magnetic functional materials such as Heusler alloys [6–8], Fe-Rh [9–11] and MnFe-based [12] alloys is very important for creation of the novel devices based on MCE [13].

The purpose of the present work is to present a new technique for experimental study of kinetics of PTs and direct measurement of MCE in pulsed magnetic fields by using the infra red fiber optical (IRFO) temperature probe with the fast response and the high noise immunity. It comprises the infra red optical fiber which is transparent in IR wavelength range 5–15 μm, and the semiconductor photoresistor which is sensitive in the same range.

2. Experimental technique

For direct measurements of MCE in pulsed magnetic field the new device was designed using pyrometric principal. The device consists of

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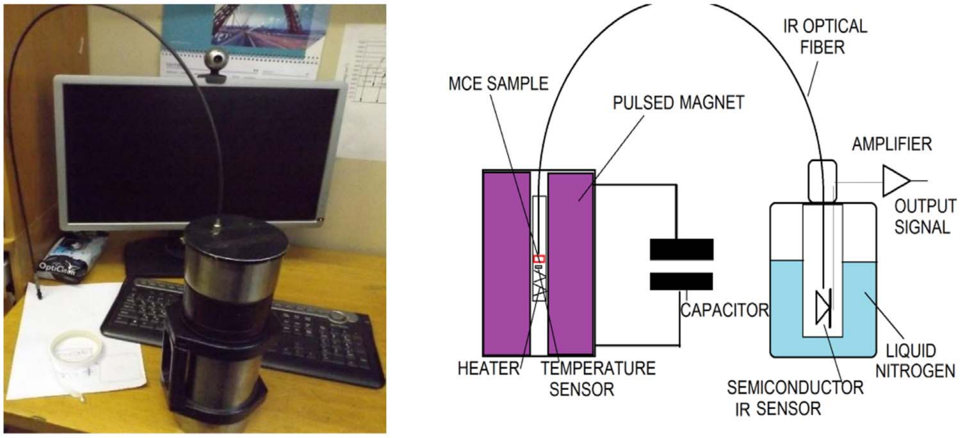
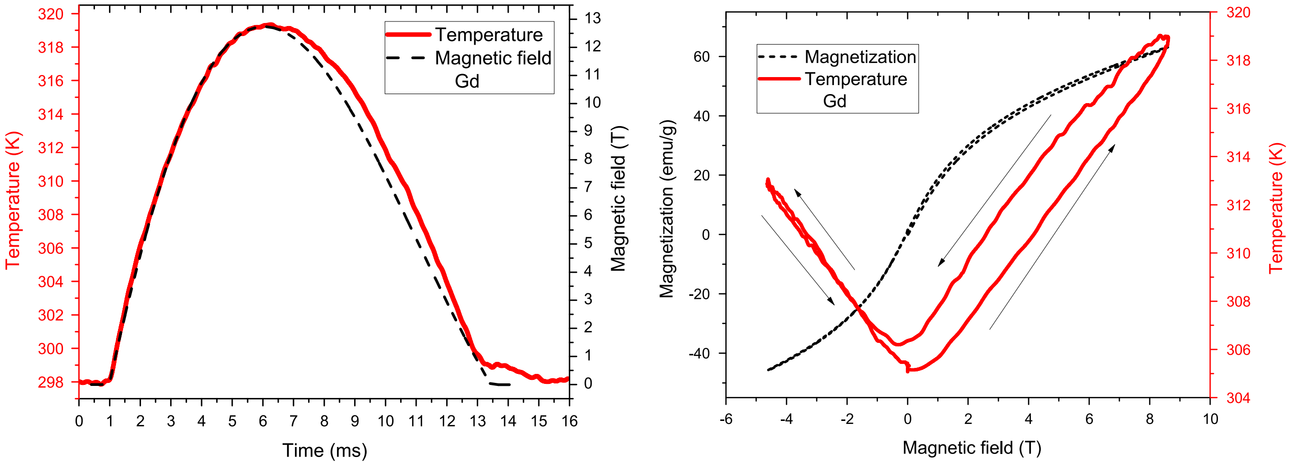


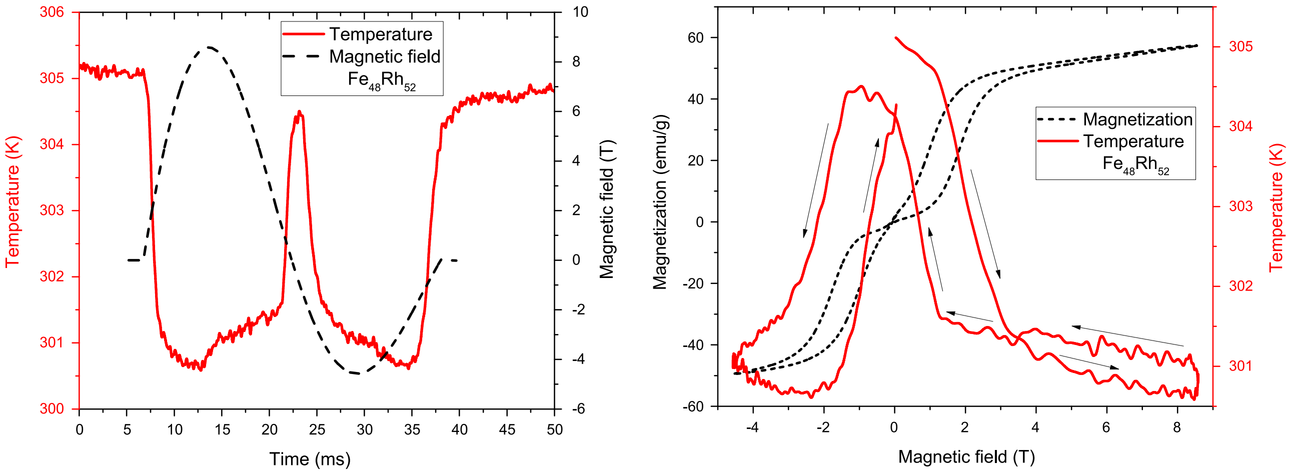
(a) (b)

Fig. 1. (a) The general view of the IRFO temperature probe. (b) The scheme of infrared fiber optical temperature probe.



(a) (b)

Fig. 2. Measurements of MCE by the IRFO temperature probe on Gd sample. (a) Time dependence of temperature (solid) and magnetic field (dash). (b) Temperature and magnetization vs. magnetic field at two consistent impulses with different directions, arrows show direction of magnetic field change.



(a) (b)

Fig. 3. Measurements of MCE by the IRFO temperature probe on $Fe_{48}Rh_{52}$ sample. (a) Time dependence of temperature (solid) and magnetic field (dash). (b) Temperature and magnetization vs. magnetic field at two consistent impulses with different directions, arrows show direction of magnetic field change.

optical fiber made of $AgCl_xB_{1\text{-}x}$ $(0 < x < 1)$ compound by vacuum extrusion through a die [14–18], and a photoresistor made of narrow-gap semiconductor Cd-Hg-Te, which is placed into cryostat with liquid nitrogen. The optical fiber is transparent in IR wavelength range 5–15 μm, the photoresistor is sensitive in the same range. One optical fiber end is connected to the photoresistor, the other optical fiber end is connected with a surface of the MCE sample (see Fig. 1). The sample with MCE under investigation is placed into a pulsed coil magnet with magnetic field up to 13 T and pulse duration of 12.5 ms at room temperature. The electronic part includes analog amplifier of a signal from the photoresistor, and analog-to-digital converter, connected to PC. The initial temperature of the sample was controlled by small thermostat with conventional Pt thermoresistor temperature sensor. The frequency response of electronic measurement system was 1 MHz.

The sensor was calibrated with the help of at heating of thin semiconductor film by short electrical impulses. The sensitivity of IRFO sensor is 0.7 mV/K, the accuracy is about ±0.1 K. The response time of the electronic circuit is 1 µsec. It was found that the emissivity of the samples affects the measurement insignificantly. The sample holder was made of textolite and does not affect the adiabatic conditions of the measurement due to short magnetic pulse time.

3. Results and discussion

The pure gadolinium was chosen [19–21] for the first test of the new technique. The samples had a disk shape with a diameter of 5 mm and a thickness of 1 mm, with the mass of 136 mg. As a preliminary demonstration of the possibility of the new technique for MCE measurements, the measured temporal dependences of magnetic field and change of temperature are plotted on Fig. 2a. It is found for gadolinium at initial temperature 298 K: ΔT_{ad} = 21.3 K under pulsed magnetic field $\mu_0 H$ = 12.7 T. Our data are in good correlation with results of the work [22]: ΔT_{ad} = 15.4 K under pulsed magnetic field $\mu_0 H$ = 7.5 T. However, the value of MCE, measured by the IRFO sensor, exceeds nearly by 10% the value obtained by a semiconductor diode temperature sensor in Bitter coil magnet for the Gd sample of the same series [20]. The 10% difference can be explained by the fact that the conditions are closer to adiabatic in the pulse experiment, and the use of non-contact temperature measurement method by IRFO sensor excludes additional heat loss provided by conventional sensor. Fig. 2b shows the MCE and magnetization dependence on the magnetic field at two consistent impulses with different directions.

The second was $Fe_{48}Rh_{52}$ sample, its magnetic properties were describe earlier in [10,11]. The mass of sample was 105 mg. The measured temporal dependences of magnetic field and change of temperature are plotted on Fig. 3a. The inverse MCE for $Fe_{48}Rh_{52}$ sample at initial temperature 305.1 K: ΔT_{ad} = −4.5 K under pulsed magnetic field $\mu_0 H$ = 8.5 T. Of course, this results are less results obtained in [9], but we used a little bit different composition of alloy. Fig. 3b shows the inverse MCE and magnetization dependence on the magnetic field at two consistent impulses with different directions. The magnetization curve has characteristic for the 1st order PT hysteresis loop. The energy losses on magnetization are irreversible work of magnetic field in cycle of magnetic cooling [21]. We can calculate this work as square of hysteresis loop $W = \int H dM$. From our experiments on $Fe_{48}Rh_{52}$ at $\mu_0 H$ = 8.5 T this value was obtained W = 45 J/Kg.

4. Conclusions

In summary, the following conclusions can be drawn from these studies. We report the first experimental results of direct measurement of the MCE in pulsed magnetic fields by using the fast response IRFO sensor. The value of MCE for gadolinium near Curie point (298 K) is found to be ΔT_{ad} = 21.3 K under pulsed magnetic field $\mu_0 H$ = 12.7 T. The inverse MCE for $Fe_{48}Rh_{52}$ sample at initial temperature 305.1 K: ΔT_{ad} = −4.5 K under pulsed magnetic field $\mu_0 H$ = 8.5 T. The energy losses on magnetization near the 1st order PT were calculated from the results of direct measurements of magnetization versus time for $Fe_{48}Rh_{52}$ sample: W = 45 J/kg. Knowledge of the energy losses plays an important role at the design of the refrigeration based on materials with MCE [21]. Signal-to-noise ratio of IRFO system is not less than 10:1. The new system demonstrates higher noise immunity than existing systems based on micro-thermocouples [23–26] and thin film thermoresistors [27–29]. Recently experiments on MCE in high pulsed and alternating magnetic fields attract growing attention [30]. The new measurement technique presented here can find the applications in these studies.

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