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Magnetocaloric effect in nanogranular glass coated microwires

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Thermal dependences of the magnetic susceptibility of the glass-coated microwires with compositions Fe_3P and SnMn prepared by the Taylor–Ulitovski method have been determined. Direct measurements of the adiabatic temperature change revealed ΔT_{ad} of 0.04 K in the SnMn and ΔT_{ad} of 0.02 K in the Fe_3P microwires on the field change of 12 kOe. Temperatures of the peak values of MCE were found to be of ~215 K and ~320 K respectively. The variation of magnetic properties of the Fe_3P wires with the change of their diameters was observed.

1 Introduction In the last years the research on magnetism and magnetic materials has emerged as major fields of activity, which have got profound influence in the industry and day-to-day life of common man. Magnetic materials are being used more and more in applications such as permanent magnets, memory devices, sensors and transducers, etc. [1, 2]. A relatively new entrant to this list is the magnetic refrigeration, which uses new magnetic materials with promising magnetocaloric effect (MCE) [3, 4].

The magnetocaloric effect in magnetic materials, discovered by Warburg [5], has been widely used for attaining very low temperatures by applying a magnetic field isothermally and removing it adiabatically. The origin of MCE was explained independently by Debye and Giauque [6, 7], who also suggested the first practical use of MCE, that is the adiabatic demagnetizing of paramagnets to reach temperatures lower than 4.2 K. As it is well known, in general an isothermal application of a magnetic field decreases the configurational entropy of the ferromagnetic or paramagnetic spin system. A subsequent adiabatic demagnetization reduces the degree of the spin order, absorbing the thermal energy provided by the phonon bath of the isolated sample. It results in the decreasing of its temperature. A few machines using MCE for room-temperature refrigeration purposes have been demonstrated recently [8].

Magnetic refrigeration is considered as an innovative, energy saving and environmentally friendly technology. The working body of the system is a solid magnetic substance. It leads to higher amount of heat absorption/extraction per volume than in the conventional gas based systems. However it takes a large heat transfer area to provide high heat exchange efficiency. Number of working prototypes utilized gadolinium in the form of small spheres to resolve this technical issue. Meanwhile extension of the surface promotes chemical reactions of solid refrigerant with liquid coolant used to transfer heat inside the system.

On the other hand, ferromagnetic glass-coated microwires have a number of attractive features that make them strong candidates for use as a sensing element in high performance magnetic field or stress sensors, magnetic labels, and micro machines [9, 10]. Although the research on magnetic microwires is well established, it was only very recently proposed to utilise them within artificially structured materials. As a new example we propose in this work the use of magnetic glass-coated microwires of Fe_3P and SnMn composition as magnetocaloric materials to engineer magnetic functionality of advanced materials, for example, for exhibiting significant magnetic entropy changes around the Curie temperature (T_C) associated to MCE due to magnetic wire actuating performance. Therefore, a type of a smart material is proposed exhibiting MCE and coated with chemically inactive layer.

2 Experimental Two Fe_3P and SnMn thin glass coated microwires with different total diameters of 14–34 μm were produced by the Taylor–Ulitovski method [11, 12]. The master alloy of the composition was prepared by arc melting of the pure elements in Ar atmosphere. Subsequently, when the metallic alloy and the Pyrex glass coating were simultaneously molten, the so-formed microwire was drawn and rolled onto a rotating cylinder and quenched to room temperature. The samples obtained were in the form of a tiny metallic wire with the dimensions above mentioned.

The surface magnetic domain structure of the as-cast Fe_3P glass-coated microwires was characterized by optical microscopy Bitter technique, after removing the glass coating of the microwires by chemical etching in a HF (24 vol%) solution during 20–30 min [13]. The Bitter technique discloses the surface domain pattern, delineating the domain wall boundaries between the magnetic domains; even it cannot infer the magnetization direction in these domains. This method consists of the application of a colloidal aqueous solution of Fe_3O_4 nanoparticles over the sample surface. The magnetic nanoparticles of the ferrofluid are attracted to the Bloch domain walls due the stray magnetic field at the walls, which spreads out above the entire sample surface, revealing the intersection of every domain wall with the sample surface [14]. Commercial Ferrofluid EMG 408 (Ferrotec Corp., USA), with about 10 nm in nanoparticles size and low coercivity (60 G), was used for this purpose. Both, the demagnetized state and the result of when a constant applied magnetic field of 350 Oe was perpendicularly applied to the wire axis were investigated by employing a metallographic microscope.

Thermal dependence of the ac-magnetic susceptibility of the different glass coated microwires studied in this work has been determined from 78 K to 400 K. Adiabatic temperature change, originated from MCE has been measured directly on the special set-up created in Department of Physics of MSU. The thermo-couple was utilized for continuous registration of the temperature on the magnetic field change from 0 kOe to 12 kOe at certain temperatures. During the measurements the sample has been placed in the chamber evacuated up to the 10^{-3} Torr to maintain the adiabatic conditions. The estimated error due to the heat leakage was found to be of 5×10^{-3} K.

3 Results and discussion Figure 1(a)–(c) show the pictures of the surface magnetic domain structure corresponding to Fe_3P microwire. Fig. 1(a) was obtained without colloid for checking the microwire dimensions. Figure 1(b) and (c) represent the surface maze domain structure, which consists of the domain walls of the radial closure domains, for a zone near the end of the Fe_3P microwire (magnification of this part can be seen in Fig. 1(c)), and near the border of the Pyrex glass-coating respectively. The observed domain walls thickness is about 1.4–1.9 μm.

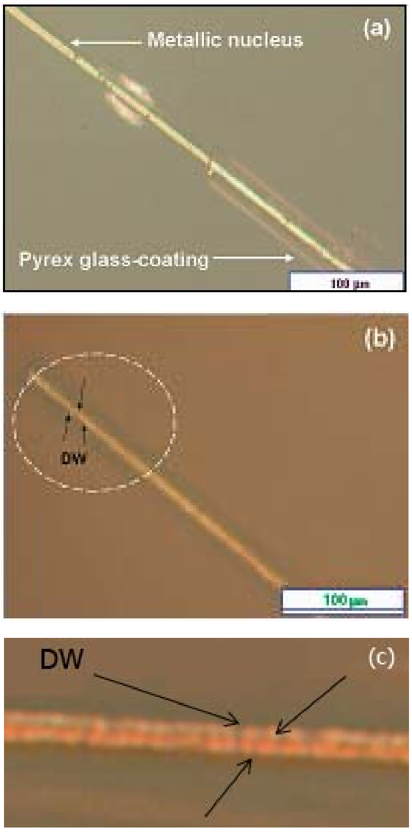

Figure 1 (online colour at: www.pss-a.com) Domain pattern pictures for a zone of Fe_3P glass-coated microwires obtained by means of the Bitter technique: (a) microwire dimensions; (b) amorphous state without applied field, (c) with a perpendicular applied field of 350 Oe.

In order to magnify the closure domains on the microwire's surface, a magnetic field of 350 Oe, provided by a permanent magnet, was perpendicularly applied to the microwire axis, as it has been done for the case of Fig. 1(c). The temperature dependence of ac-susceptibility of SnMn microwire is shown in the Fig. 2. The second order phase

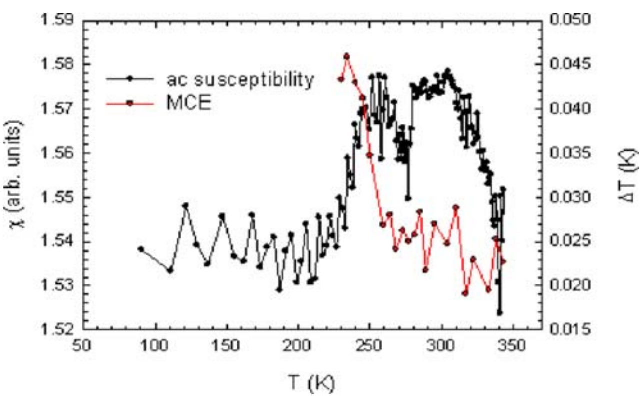

Figure 2 (online colour at: www.pss-a.com) Ac-susceptibility and MCE in the SnMn as a function of the temperature.

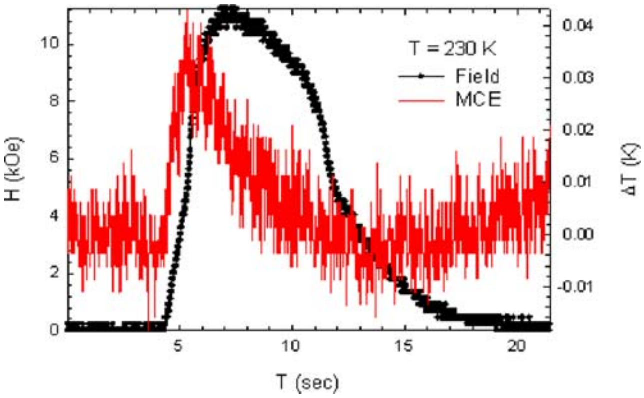

Figure 3 (online colour at: www.pss-a.com) Temporal dependence of the MCE in SnMn.

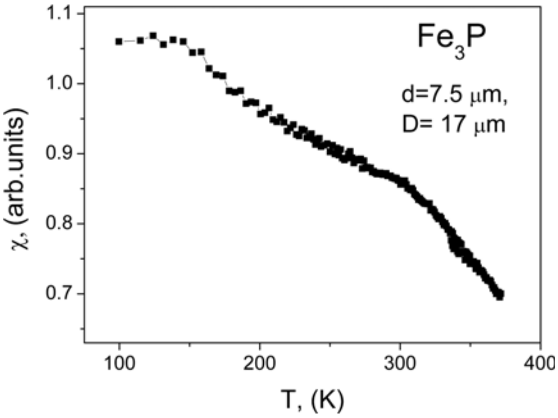

Figure 4 Ac-susceptibility of Fe_3P sample no. 1.

transition from ferromagnetic to paramagnetic state is accompanied with the peak of the ac-susceptibility. However in the ordered state, the temperature dependence of the ac-susceptibility is a complex function of the magnetization saturation, anisotropy and coercive field. The non-monotonic variation of the susceptibility of SnMn implies that the characteristic peak near the phase transition is overlapped with the peak originated from the peculiarities of the domain structure and can not be properly distinguished. Nevertheless in the paramagnetic state susceptibility decreases according to Curie–Weiss law and the inflection point on the temperature dependence of the ac-susceptibility can be used as an estimation of the interval of the phase transition. The Curie temperature of the sample, defined as a temperature of the maximum $|d\chi/dT|$, was found to be of ~340 K.

A plot of temporal dependence of the adiabatic temperature change collected on the field change of 12 kOe is shown on the Fig. 3. Application of the magnetic field gives rise to the ΔT_{ad} of 0.04 K clearly seen on the figure. A set of field dependences of the ΔT_{ad} was utilized to produce a curve of the temperature dependence of MCE presented on the Fig. 2. The largest value of ΔT_{ad} was observed well below the Curie temperature implying that the transformation of the domain structure and rotation of the magnetic moment due to the magnetization in SnMn give rise to the larger values of the MCE than the change of the magnetization saturation itself, which is proportional to $|dI/dT|$ and reaches the maximum at the Curie temperature [8].

The diameters of the internal metallic cores and the total diameters of two Fe_3P microwires are presented in the Table 1. The temperature dependences of the ac-susceptibility are shown in the Figs. 4 and 5 respectively. Both curves consist of peaks placed slightly below the Curie temperature of ~360 K, followed by a gradual rise of the susceptibility with decreasing temperature. The observed elevation of the χ on the cooling probably originated from the complex domain structure of the samples. The change of diameters doesn't shift the Curie temperatures but affects the dynamics of magnetization giving rise to the difference in the cusps of the χ. The MCE in both samples were found to be less than in SnMn attaining the largest value of 0.02 K in the vicinity of the Curie temperature.

Table 1 Dimensions of Fe_3P microwires.

	D_{tot} (μm)	d_{int} (μm)
no.1	14–20	6.5–8.5
no.2	28–34	15.5–16.6

4 Conclusion

The measurements of the ac-susceptibility of three glass coated metallic microwires have been performed for fast screening of their magnetic properties. The subsequent direct measurements of the adiabatic temperature change originated from the MCE have been done in the range of the temperatures covering the locations of the extremum of ac-susceptibility. The observed values of ΔT_{ad} are rather small being of ~0.04 K in the SnMn and ~0.02 K in both Fe_3P samples. However up to our knowledge it is the first direct measurements of the MCE in this kind of objects. The magnetic glass coated microwires are flexible substances readily available in the wide range of chemical compositions capable of easy variation of their properties. Hopefully these investigations will become a new direction in the development of the magnetocaloric materials.

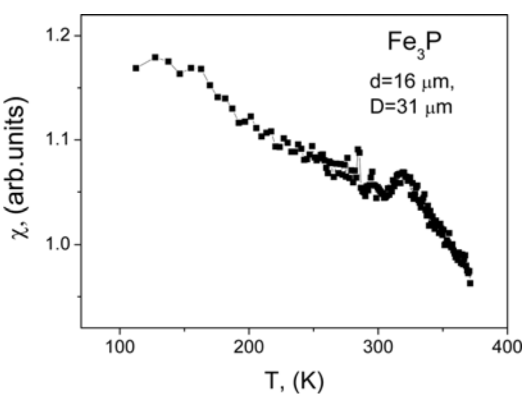

Figure 5 Ac-susceptibility of Fe_3P sample no. 2.

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