JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **12** No 4, 04039(3pp) (2020)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **12** № 4, 04039(3cc) (2020)

Short Communication

Peculiarities of Magnetocaloric Effect in Ferromagnetic Cylindrical Nanowires with a Domain Wall

A.B. Shevchenko[1], M.Yu. Barabash[2,*]

[1] *G.V. Kurdyumov Institute for Metal Physics of the N.A.S. of Ukraine, 36, Academician Vernadsky Boulevard, 03142 Kyiv, Ukraine*
[2] *Technical Center, N.A.S. of Ukraine, 13, Pokrovs'ka St., 04070 Kyiv, Ukraine*

(Received 06 June 2020; revised manuscript received 15 August 2020; published online 25 August 2020)

It is established that in a weak magnetic field significantly lower than $2\pi M$, where M is the magnetization of a ferromagnetic cylindrical nanowire, the entropy of the latter increases due to the thermal motion of the domain wall comprised in it. As a result, a negative magnetocaloric effect emerges in this system. This phenomenon has a nanoscale nature and disappears with moving to bulk materials. It is shown that the established effect is in accordance with the fundamental Le Chatelier-Brown principle for the self-regulating thermodynamic systems. The obtained result is of significant interest in the context of the development of new methods to achieve precise temperature values on the low dimensional magnetic nanostructures. In turn, in strong magnetic fields of the order of the magnetic field generated by the movement of electrons in atoms (~ (1-10) kOe) a positive magnetocaloric effect takes place, i.e. the temperature of the ferromagnetic nanowire increases with increasing amplitude of the magnetic field. For the diameter of the nanowire, an estimate is given at which the transition from the longitudinal domain wall to the domain wall in the form of a Bloch point occurs.

Keywords: Ferromagnetic nanowire, Domain wall, Entropy, Magnetocaloric effect.

DOI: 10.21272/jnep.12(4).04039 PACS numbers: 75.30.Sg: 75.75. + a: 75.60.Ch

1. INTRODUCTION

Due to their unique magnetic and thermal properties, ferromagnetic nanowires (FNs) are widely used in various nanotechnologies (e.g., see monographs [1, 2] and the bibliography therein). Their increasing application is directly related to the study of physical phenomena in them caused by the interaction of various systemic factors of these nanomaterials. One of the processes which bind the magnetic and thermodynamic properties of magnetically active materials is the magnetocaloric effect (MCE). This phenomenon allows studying the magnetic ordering in a sample during the adiabatic change of entropy of magnetic subsystem of the sample in an external magnetic field. Besides, the data on MCE provide useful information on magnetic phase transitions, as the MCE is most pronounced exactly under the conditions of these transformations.

It should also be noted that by means of MCE it is possible to regulate the temperature of a magnet, reaching its extremely low values. The MCE is characterized by the sign: when the temperature of the material decreases with the external magnetic field, it corresponds to a negative MCE, and in the opposite case a positive MCE occurs.

It should be noted that a significant contribution to the thermodynamic properties of an FN, comparable by magnitude with the entropy and heat capacity of its phonon, magnon, and electron subsystems, can be induced by the thermal motion of a domain wall (DW) [3, 4] whose average velocity is determined by the temperature of the FN. It is natural to assume that the factor of DW also influences the MCE in FN. The features of this effect in cylindrical nanowires with DWs are studied in the present work.

2. PROBLEM SOLVING AND RESULT DISCUSSION

Let us consider a FN with magnetic structure characterized by a longitudinal-type DW [1] formed as a result of competition between the exchange and magnetostatic energies of the nanowire. The entropy S_{DW} due to the thermal motion of the DW along the long axis of the nanowire (OZ-axis) in the magnetic field $h_Z = H/2\pi M << 1$, according to the results of [3], can be written as follows:

$$S_{DW} = Nk_B \frac{c}{2\delta} e^{-a} \Big((1+a)(1+\ln D - 0.5\ln a + \\ + \ln\big(\mathrm{sh}(ah_z)/ah_z\big)) + 1.5 - ah_z\,\mathrm{cth}(ah_z)\Big) , \qquad (1)$$

where N is the number of phonons, k_B is the Boltzmann constant, c is the lattice parameter of the magnetic material, $\delta = (A/\pi M^2)^{1/2}$ is the effective width of the DW, A is the exchange constant, $a = \pi d^2 A / \delta k_B T$, d is the diameter of the nanowire, T is the temperature, $D = \pi d^2 A^{1/2} / \gamma h\sqrt{2}$, $\gamma = 2\cdot 10^7\ \mathrm{Oe}^{-1}\cdot\mathrm{s}^{-1}$ is the gyromagnetic ratio, h is the Planck constant, $S_{DW} \to 0, d \to \infty$.

It should be noted that formula (1) was obtained for a DW in a nanowire with no random fluctuations of local crystallographic anisotropy and inhomogeneity at its surface. These defects can result in pinning of the DW [5].

---

[*] mbarabash@nasu.kiev.ua

In our case, the thermodynamic relation connecting the change in temperature and magnetic field under the conditions of considered adiabatic process is the following:

$$\frac{\Delta h_z}{\Delta T} = -\frac{c_{V,h_z}/T}{\left(\partial S_{DW}/\partial h_z\right)_{V,T}} . \qquad (2)$$

In equation (2), the heat capacity c_{V,h_z} of the system contains also the corresponding contribution of the thermal motion of DW.

From the expression (2) it follows that the sign of MCE is determined by the dependence $S_{DW}(ah_z)$, the analysis of which involves knowledge of the parameters of FN. Without limiting the generality, we will consider a ferrite-garnet nanowire, and then summarize the results. Assuming $A \sim 10^{-7}$Erg·cm^{-1}, $c \sim 1.23 \cdot 10^{-7}$ cm, $M \sim 50$ Gs, $d \sim 5 \cdot 10^{-7}$cm and using (1), the ratio S_{DW}/S_{DW}^0 (where $S_{DW}^0 = \lim_{h_z \to 0} S_{DW}$) is plotted in Fig. 1.

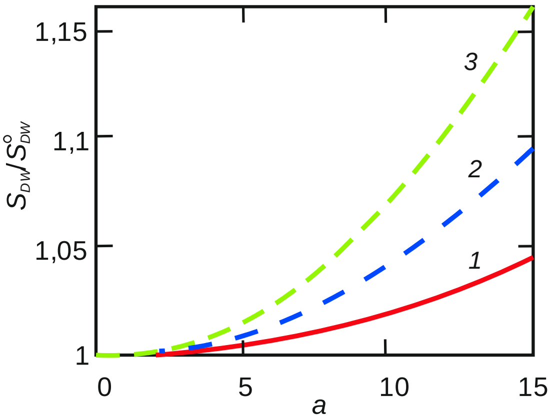

Fig. 1 – Dependencies S_{DW}/S_{DW}^0 for various magnetic fields: 1 – $h_z = 0.1$; 2 – $h_z = 0.15$; 3 – $h_z = 0.2$

It is easy to see that the entropy associated with thermal motion of the DW increases when the amplitude of the external magnetic field increases. This result is consistent with the fact that the field h_z, shifting the center of DW in a unit cell of the phase space by a small distance (see the derivation of formula (1) in [3]), increases the number of its microstates, i.e. the entropy of DW. Therefore, $(\partial S_{DW}/\partial h_z)_{V,T} > 0$, and correspondingly $\Delta h_z/\Delta T < 0$ (see (2)), which indicates a negative sign of MCE in the system. It should be taken into account that the first order of the expansion on the magnetic field of the thermodynamic potential of the system of FN magnons can contribute to the denominator of formula (2) [6]. As the study of this issue shows, taking into account the above factor leads to a weakening of the MCE with increasing nanowire diameter.

It is worthwhile to note that this result is consistent with the fundamental Le Chatelier-Brown principle for the self-regulating thermodynamic systems. Indeed, an increase in the magnitude of the magnetic field leads to an increase of the FN magnetostatic energy due to the nanowire magnetization (in the fields $h_z > 1$ the magnetostatic energy also increases due to the deformation of DW magnetic structure). In this case, according to (1), it is easy to find an expression for the average magnetization of the FN: $\bar{M}_{h_z} = 2M\bar{n}L(ah_z)$, where $\bar{n}$ is the average number of phase cells filled with DW and $L(x)$ is the Langevin function. As the above energy increases, the system is trying to compensate it by reducing the internal energy, i.e. by lowering its temperature. At the same time, in magnetic fields $h_z > 1$ the wire is completely magnetized along the direction h_z, and a further increase in the field amplitude does not lead to a change in the magnetostatic energy of the FN. In these objects, in strong magnetic fields of the order of the magnetic field generated by the movement of electrons in atoms, i.e. ~ (1-10) kOe, the alignment of electron spins occurs along the field h_z as its amplitude increases. This means a decrease in the exchange energy, and the system, in accordance with the Le Chatelier-Brown principle, tries to compensate it by increasing its internal energy, i.e. the positive MCE takes place.

In conclusion, it is worthwhile to note that the longitudinal DW is realized in sufficiently thin nanowires. According to estimates, in nanowires with a diameter $d > 4\pi\delta$ the so-called Bloch point acts as a DW [1, 2]. The Bloch point is a singularity in the form of a "magnetic hedgehog," with higher symmetry of the magnetic structure as compared to the longitudinal DW. In this case, taking the "quasiparticle" approach to describe the properties of these objects (which is possible due to the effective mass), by analogy with the results of [7], one should expect a weaker manifestation of the MCE in the FN with a Bloch point.

3. CONCLUSIONS

It is found that in weak magnetic fields (significantly lower than those in the presence of a DW in ferromagnetic cylindrical nanowires) the DW factor causes a negative MCE. At the same time, in strong magnetic fields of the order of the intra-atomic magnetic field of electrons, a positive MCE occurs in a nanowire.

REFERENCES

1. E. Bruck, *Handbook of Magnetic Materials: Magnetic Nanowires and Nanotubes* (Elsevier: 2018).
2. R.P. Loreto, *Topological States Applied to Spintronics Devices* (Vicosa Minas Gerais: Brazil: 2018).
3. A.B. Shevchenko, M.Yu. Barabash, *Phys. B.: Cond. Matt.* **556**, 114 (2019).
4. A.B. Shevchenko, M.Yu. Barabash, I.M. Zabolotnyi, *Res. Phys.* **16**, 102988 (2020).
5. A.A. Ivanov, V.A. Orlov, *Phys. Solid State* **57**, 2204 (2015).
6. S.V. Vonsovsky, *Magnetism* (Nauka: Moscow: 1971) [In Russian].
7. A.P. Shpak, A.B. Shevchenko, A.B. Mel'nik, *Technical Physics (Zhurnal Tekhnicheskoi Fiziki)* **74** No 3, 81 (2004) [In Russian].

Особливості магнетокалорічного ефекту в феромагнітних циліндричних нанодротах, що містять доменну стінку

А.Б. Шевченко[1], М.Ю. Барабаш[2]

[1] *Інститут металофізики ім. Г. В. Курдюмова НАН України, бульвар Академіка Вернадського, 36, 03142 Київ, Україна*
[2] *Технічний центр НАН України, вул. Покровська, 13, 04070 Київ, Україна*

Встановлено, що в слабкому магнітному полі, істотно меншому за $2\pi M$, де M – намагніченість феромагнітного циліндричного нанодроту, величина ентропії останнього, обумовлена тепловим рухом доменної стінки, яка міститься в ньому, зростає. Внаслідок цього факту, у вказаній вище системі має місце від'ємний магнетокалорічний ефект. Дане явище має нанорозмірну природу та зникає при переході до об'ємних матеріалів. Показано, що встановлений ефект узгоджується із фундаментальним принципом саморегулюючих термодинамічних систем Ле Шательє-Брауна. Отриманий результат являє значний інтерес в контексті розробки нових методів досягнення прецезійно точних температур на низьковимірних магнітних наноструктурах. В свою чергу, в сильних магнітних полях порядку магнітного поля, спричиненого рухом електронів всередині атомів (~ (1-10) kOe), відбувається позитивний магнетокалорічний ефект, тобто, має місце збільшення температури феромагнітного нанодроту із збільшенням амплітуди магнітного поля. Приведено оцінку для діаметру нанодроту, при якому поздовжня доменна стінки трансформується у доменну стінку у вигляді точки Блоха.

Ключові слова: Феромагнітний нанодріт, Доменна стінка, Ентропія, Магнетокалорічний ефект.