

# Autostabilization of temperature in systems with combined magnetic and resistive transition under electric current flow

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It is shown that the active thermostabilization regime can be realized in systems based on materials exhibiting combined magnetic and resistive phase transition of first order, when the sample temperature under electric current is self-maintained about the threshold equal to  $T_c$  ( $T_c$  is the phase transition temperature). The dependences of the ferromagnetic phase fraction as well as the sample temperature on the electric and magnetic field have been calculated. The system working parameters necessary to realize the active thermostabilization regime have been determined. It is found that the magnetic field can effectively influence the system temperature under certain circumstances.

Показано, что на основе материалов с комбинированным резистивно-магнитным фазовым переходом первого рода может быть реализован режим активной термостабилизации, когда при протекании электрического тока в образце автоматически поддерживается температура вблизи порога  $T_c$  ( $T_c$  – температура фазового перехода). Рассчитаны зависимости доли ферромагнитной фазы и температуры в образце от электрического и магнитного полей. Определены рабочие параметры системы, при которых реализуется режим активной термостабилизации. Установлено, что при определенных условиях магнитное поле эффективно влияет на температуру системы.

## 1. Introduction

In recent years, the first order magnetic phase transitions in substituted perovskite manganites  $R_{1-x}A_x\text{MnO}_3$  ( $R$  – rare earth,  $A$  – alkaline or alkaline-earth element) are under a particular attention [1, 2]. The magnetic phase layering phenomenon observed in such materials is accompanied by the material separation into regions with different conductivities [3, 4]. So, the low-temperature ferromagnetic (FM) phase is characterized by high conductivity (as high as that of typical metals), while the conductivity of high-temperature paramagnetic (PM) phase is several orders lower [4, 5]. This unique combination of the peculiar features of different phases makes it possible to control the system conductivity by varying the external magnetic field. At the same time, there is a pos-

sibility to exert influence on the parameters of the phase domain structure by its heating under electric current [6, 7]. In this work, a mechanism is proposed to realize the active thermostabilization regime for the systems based on materials exhibiting combined magnetic and resistive phase transition of the first order.

## **2. Theoretical considerations**

Let the sample be assumed to be a film of the thickness  $L$ . The film can be either in FM or PM state depending on its temperature. At a certain temperature  $T_c$ , the values of thermodynamic potentials for FM and PM phases ( $\Phi_{FM}$  and  $\Phi_{PM}$ , respectively) become equal to one another; this means that under particular conditions, the phase coexistence is possible. This process is assumed to occur through the first-order phase transition, with both magnetization  $M$  and conductivity  $\sigma$  exhibiting discontinuous changes. In this case  $\sigma_{FM} \gg \sigma_{PM}$ .

As the FM phase is characterized by a high magnetization value, its response to external magnetic field and internal magnetostatic field will be appreciable. That is why the absolute value and the direction of the external field may affect the temperature at which the transition starts, as well as the nature of the phase transition itself.

Let the sample initial temperature be much lower than  $T_c$ , and the sample is in a single-domain state. This condition can be realized easily by applying an external magnetic field  $H$ . If the field is perpendicular to the film plane, the single-domain state is attained for  $H > 4\pi M$ .

Consider a case when the electric field  $\mathbf{E} = E_0 \mathbf{e}_x$  is applied to the film. An electric current starts to flow through the film. As only an insignificant fraction of electrons from the conduction band near Fermi energy  $\varepsilon_F$  takes part in the transfer processes, the electric current exerts no direct influence on the  $s-f$ ,  $s-d$  interband exchange which makes the system turn to the FM state below the phase transition point  $T_c$ .

At the same time, there is a mechanism of indirect influence of electric field on the magnetic subsystem, because the electric current flow is accompanied by heat release and the system heating.

When the sample temperature approaches  $T_c$ , the PM phase (i.e. regions of low conductivity) starts nucleating. A further heating results in the growth of the PM phase fraction which, in turn, causes the decreasing current density and deceleration of heat release process. The latter even can become negligibly small when the FM phase volume,  $V_{FM}$ , lowers under the percolation threshold  $V_p \sim 0.3 \cdot V$  ( $V$  – the sample volume). In this case, the FM phase is a system of isolated domains surrounded by the PM matrix.

As is shown in [8, 9], it is in the vicinity of the percolation threshold where the sharp conductivity and, correspondingly, the current density changes occur in a static regime.

To describe the system conductivity qualitatively, we use a series expansion of the effective conductivity  $\sigma_{eff}$  over the volume of FM phase near to the percolation threshold. Having neglected the conductivity of PM phase, we can write:

$$\sigma_{eff} = \begin{cases} 0, & V_{FM} < V_p \\ \sigma_0 \cdot (V_{FM} - V_p) / V, & \end{cases} \quad (1)$$

where  $\sigma_0$  – the expansion coefficient which is of the same order as  $\sigma_{FM}$ .

As follows from Eq. (1), the effective conductivity increases sharply as the volume fraction of FM phase exceeds the percolation threshold. This effect can be used to develop the active thermostabilization regime for the system.

The task will be solved in two steps.

## **3. The film phase layering in a perpendicular field**

When solving the problem of phase layering for the film in a perpendicular field, let us assume that the film thickness  $L$  exceeds considerably the domain structure period  $P$ :

$$L \gg P \tag{2}$$

This allows us to make two important simplifications. On the one hand, such assumption will make it easier to determine the dependence of the FM phase volume on temperature and external field. On the other hand, it will allow us to neglect the nonuniformity in the temperature distribution within the film plane when we solve the problem of heat exchange between the film and the surrounding medium.

As follows from Eq. (1), in the vicinity of the percolation threshold, the system conductivity heavily depends on the FM phase fraction. That is why we will concentrate attention on the determination of the  $V_{FM}/V$  dependence on the system temperature and external field.

That dependence can be obtained from the condition of energy minimum for a magnetic subsystem, which is given by the following expression in the case under consideration [10, 11]:

$$\Delta E = \int_{V_{FM}} dv (\varepsilon - \mathbf{M} \cdot \mathbf{H} - \mathbf{M} \cdot \mathbf{H}_m / 2) + \Sigma \cdot S, \tag{3}$$

where  $\varepsilon = \Phi_{FM} - \Phi_{PM}$  – is the difference of the thermodynamic potentials for FM and PM phases, respectively, which can be presented in the vicinity of the phase transition point as a series expansion over temperature:  $\varepsilon = k(T - T_c)$ . Here,  $k$  – is the expansion coefficient (a phenomenological parameter);  $T_c$ , the temperature at which the thermodynamic potentials of the phases become equal to one another;  $\mathbf{M} = M \cdot \mathbf{e}_z$ , the magnetization of FM phase;  $\mathbf{H} = H \cdot \mathbf{e}_z$ , the external magnetic field directed perpendicular to the film plane;  $\mathbf{H}_m$ , magnetostatic field of the sample;  $\Sigma$ ,  $S$ , the surface energy density and the total area of the phase interfaces, respectively. Integration in expression (3) is carried out over the volume of FM phase. The form of the expression (3) implies that the crystallographic anisotropy is neglected.

For a system, a fragment of which is shown in Fig. 1, the magnetostatic field is about  $\mathbf{H}_m \approx -4\pi \langle \mathbf{M} \rangle = -4\pi M \cdot (V_{FM}/V) \mathbf{e}_z$ , when the condition  $L \gg P$  is met. As a result, the integral (3) can be easily calculated:

$$\frac{\Delta E}{V} \approx -(MH - k(T - T_c)) \frac{V_{FM}}{V} + 2\pi M^2 \left( \frac{V_{FM}}{V} \right)^2 + \Sigma \cdot S. \tag{4}$$

The total interface area depends on the characteristic period of domain structure rather than on the FM phase volume. Therefore, the  $V_{FM}/V$  value can be easily determined from the condition of the system magnetic energy minimum (see Eq. (4)):

$$\frac{V_{FM}}{V} = \frac{HM - k(T - T_c)}{4\pi M^2}. \tag{5}$$

Since the FM phase relative volume varies from zero to unity, the system temperature in the phase separation regime lies within the range:

$$T_c - T_M + MH/k < T < T_c + MH/k. \tag{6}$$

Here, to make the expression more explicit, a temperature parameter  $T_M = 4\pi M^2/k$  is introduced. This parameter determines the width of the temperature interval where the FM and PM phases coexist.

The  $k$  parameter value can be determined in an indirect way, for example, using the experimental results from [8, 9]. According to these data, for the Ca-substituted perovskite manganites with  $M \sim 320$  G and  $T_c \sim 240$  K, the percolation onset temperature rises with the magnetic field increase at an average rate of 0.8 K/kOe. This corresponds to the value of  $k \sim 4 \cdot 10^5$  erg·cm<sup>-3</sup>·K<sup>-1</sup>.

So, for the material considered in [9], the temperature interval of the phase coexistence should be  $T_M \sim 2.5$  K. However, the experimentally observed value is several times larger than that es-

timated in the above way. This effect, at least in part, may originate from the inhomogeneous Ca ion distribution over the sample volume. As a result,  $T_c$  displays a considerable space dispersion.

Such a dispersion can no doubt influence significantly the course of the phase transition. However, the account for this effect is beyond the scope of this work. In what follows, we will concentrate on the development of the approach for a hypothetical, ideally homogeneous material.

The Eq. (5) links the sample phase composition with the system temperature and magnetic field. As the main task of this work is to describe the active thermostabilization regime, we should supplement the system of equations by those of a heat balance with the surrounding medium.

#### 4. Temperature distribution and heat balance conditions

When determining the equilibrium distribution of phases (see Eq. (5)), we assumed that the sample temperature is the same over its whole volume. In practice, such a condition can be satisfied only under a certain approximation.

For the system shown fragmentarily in Fig. 1, the temperature distribution inhomogeneities originate from a spatial inhomogeneity of conductivity resulting from the phase separation, as well as from a permanent heat exchange with the surrounding medium across the film surface. However, for some particular relationships between physical and geometrical parameters of a magnetic film and thermo-insulating layer, the temperature distribution inhomogeneity can be neglected.

To derive the equation of thermal balance and determine the condition when the temperature field can be considered as homogeneous, let us consider the heat conduction equation:

$$c\rho \frac{\partial T}{\partial t} - \nabla(\kappa(x,y) \cdot \nabla T) = \sigma(x,y) \mathbf{E}^2, \tag{7}$$

where  $\kappa(x,y)$ ,  $\sigma(x,y)$  – are the film heat conduction coefficient and conductivity, modulated in the  $xOy$  plane;  $c$ ,  $\rho$ , the material heat capacity and density being practically independent of whether the film is in a phase separated state or not;  $\nabla = e_i \partial/\partial x_i$ ; the right part of Eq. (7) takes into account the power of heat sources in a sample.

Let us solve the problem of the temperature distribution determination in a simplified way, assuming the thermostat temperature to be constant and equal to  $T_e$ . Under such conditions, the system will eventually achieve a thermal balance with  $\partial T/\partial t = 0$ .

At a stationary regime, the latent heat of a phase transition present in dynamics and accompanying the changes in the sample phase distribution is also insignificant. This allows us to exclude the temporal part of the task and concentrate attention on the study of the spatial temperature distribution.

It should be noted that for the regime settled, the heat conduction problem will include two dimensional parameters, the domain structure period  $P$  in the film plane and the film thickness  $L$ . To simplify the form of the expressions, we introduce the variables:  $\boldsymbol{\rho} = (xe_x + ye_y)/P$ ,  $\zeta = z/L$ . The heat conduction equation takes the form:

$$\frac{\partial}{\partial \boldsymbol{\rho}} \left( \kappa(\boldsymbol{\rho}) \cdot \frac{\partial T}{\partial \boldsymbol{\rho}} \right) = \left( \frac{P}{L} \right)^2 \cdot \left( -\kappa(\boldsymbol{\rho}) \frac{\partial^2 T}{\partial \zeta^2} - \sigma(\boldsymbol{\rho}) \mathbf{E}^2 L^2 \right). \tag{8}$$

As follows from expression (2), the right part of Eq. (8) is a correction squared with respect to the small parameter  $P/L$ . Thus, the solution of Eq. (8) can be written as a series expansion over  $(P/L)^2$ :

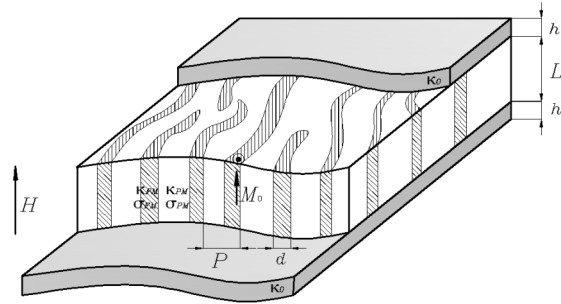


Fig. 1. A fragment of the sample with the ferro-magnetic phase domains (schematic view).

$$T(\boldsymbol{\rho}, \zeta) = T_0(\zeta) + (P/L)^2 \cdot T_1(\boldsymbol{\rho}, \zeta) + \dots \quad (9)$$

The unknown function  $T_0(\xi)$  should be fitted to satisfy the Fredholm alternative for a non-uniform equation:

$$\frac{\partial}{\partial \boldsymbol{\rho}} \left( \kappa(\boldsymbol{\rho}) \cdot \frac{\partial T_1}{\partial \boldsymbol{\rho}} \right) = -\kappa(\boldsymbol{\rho}) \frac{\partial^2 T_0(\zeta)}{\partial \zeta^2} - \sigma(\boldsymbol{\rho}) \mathbf{E}^2 L^2. \quad (10)$$

In our case, the necessary and sufficient condition for obtaining a non-trivial solution of this equation is that the average value of the right part of Eq. (10) is zero in the  $xOy$ -plane:

$$\frac{\partial^2 T_0(\zeta)}{\partial \zeta^2} = - \frac{\overline{\sigma(\boldsymbol{\rho}) E^2}}{\overline{\kappa(\boldsymbol{\rho})}} \cdot L^2. \quad (11)$$

Here, the overbars mean averaging over the film plane.

The calculation of  $\overline{\kappa(\boldsymbol{\rho})}$  is quite easy and results in

$$\overline{\kappa(\boldsymbol{\rho})} = \kappa_{eff} = \kappa_{PM} + (\kappa_{FM} - \kappa_{PM}) \cdot (V_{FM}/V).$$

However, the determination of the average power of heat sources,  $\overline{\sigma(\boldsymbol{\rho}) E^2}$ , is troublesome, because both the conductivity and local electric field intensity depend considerably on the state of the phase domain system. However, since the sharp discontinuities of the conductivity and heat producing are observed near the percolation threshold, let us use the phenomenological formula of the conductivity expansion (1) and introduce the average capacity of heat sources in the form:

$$\overline{\sigma(\boldsymbol{\rho}) E^2} = \begin{cases} \sigma_0 E_0^2 (V_{FM} - V_P)/V, & V_{FM} > V_P \\ 0, & V_{FM} < V_P \end{cases} \quad (12)$$

Now the solution of Eq. (8), symmetrical relative to the  $z = 0$  plane, can be presented as

$$T_0(z) = T_0(0) - \frac{\sigma_0 E_0^2 z^2}{2 \cdot \kappa_{eff}} \cdot \frac{V_{FM} - V_P}{V}, \quad (13)$$

where  $T_0(0)$  is the integration constant which is determined from the condition of the heat flux continuity in the direction perpendicular to the film surface:

$$\kappa_{eff} \frac{\partial T_0(z)}{\partial z} = \kappa_0 \frac{T_e - T_0(z)}{h} \Big|_{z=L/2}. \quad (14)$$

So, the temperature distribution within the film is determined by the expression:

$$T_0(z) = T_e + \Theta \cdot \frac{V_{FM} - V_P}{V} \cdot \left( 1 - \frac{\kappa_0}{\kappa_{eff}} \cdot \frac{(z - L/2)^2}{L \cdot h} \right), \quad (15)$$

where the designation  $\Theta = \frac{\sigma_0 E_0^2 L h}{2 \cdot \kappa_0}$  is introduced. It is this quantity that is an important heat parameter of the problem. It has the temperature dimensionality and characterizes the sample heating process resulted from the electric current. Its value grows with the increase in both the thermal isolation efficiency ( $h/\kappa_0$ ) and heat source intensity ( $\sigma_0 E_0^2$ ).

It follows from (15) that the increase in the thermo-isolating parameter  $\kappa_{eff}/\kappa_0$  gives rise to more homogeneous temperature distribution over the sample.

At this stage, we can formulate the condition that, being satisfied, enables us to consider the temperature distribution as a homogeneous one over the whole film volume. It is clear that the temperature modulation over the film thickness should be considerably less than the temperature interval of a magnetic phase transition:

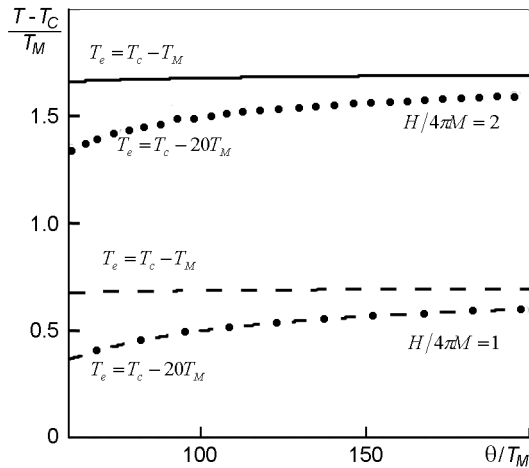


Fig. 2. Dependence of the sample temperature  $T$  on the heat parameter  $\Theta = \frac{\sigma_0 E_0^2 L h}{2 \cdot \kappa_0}$ . The two lower curves are plotted for magnetic field  $H = 4\pi M$ , and correspond to different values of the thermostat temperature  $T_e$ . The upper pair of curves is built for magnetic field  $H = 8\pi M$  for the same thermostat temperatures.

$$\frac{V_{FM} - V_P}{V} \cdot \frac{\kappa_0 L}{4\kappa_{eff} h} \ll \frac{T_M}{\Theta}. \tag{16}$$

Then, as follows from the expression (15), we can neglect the temperature changes within the film thickness and consider the sample temperature  $T$  to be constant within the whole volume, so

$$T = T_e + \Theta \cdot (V_{FM} - V_p)/V. \tag{17}$$

As was mentioned above, this approach is correct in the vicinity of the percolation threshold when  $(V_{FM} - V_p)/V \ll 1$ . Therefore, taking into account that the material temperature in a phase separated state is close to  $T_c$ , it follows from (17) that:

$$\frac{V_{FM} - V_p}{V} \sim \frac{T_c - T_e}{\Theta} \ll 1. \tag{18}$$

This condition can be satisfied in various ways, for example, by increasing the system thermal insulation or raising the electric field intensity.

Thus, expressions (5) and (17) give the solution of the problem under consideration, which makes it possible to determine the temperature  $T$  and the fraction of the FM phase  $V_{FM}/V$  in the sample using the preset intensity values of the electric and magnetic fields:

$$\begin{aligned} \frac{V_{FM} - V_p}{V} &= \frac{H/4\pi M - V_p/V + (T_c - T_e)/T_M}{\Theta/T_M + 1} \\ \frac{T - T_c}{T_M} &= \frac{H/4\pi M - V_p/V - (T_c - T_e)/\Theta}{1 + T_M/\Theta}. \end{aligned} \tag{19}$$

The condition (16) for the applicability of the theory results, i.e. the condition which determines if the temperature distribution over the sample can be considered as homogeneous over the whole volume, takes the form:

$$\frac{H/4\pi M + (T_c - T_e)/T_M - V_p/V}{1 + T_M/\Theta} \ll \frac{4\kappa_{eff} h}{\kappa_0 L}. \tag{20}$$

In other words, this result implies that high heat conductivity of a material and good thermal insulation of a system, both favor the homogeneous temperature distribution over the sample volume.

It follows from Fig. 2 that for great values of  $\Theta/T_M$ , the film temperature responds weakly to the temperature of the surrounding medium. So, for  $\Theta/T_M \sim 150$ , even the change of the temperature of the surrounding medium by  $\Delta T_e \sim 20T_M \sim 50$  K results in the film temperature



change by  $\Delta T \sim 0.1T_M \sim 0.25$  K. At the same time, the film temperature can be effectively tuned by means of external magnetic field. For the case where  $\Theta/T_M$  is sufficiently great, an asymptotical approximation

$$T - T_c = T_M \cdot \left( H/4\pi M - V_p/V \right) \quad (21)$$

can be used. According to this approximation, the magnetic field strength increase by  $\Delta H = 4\pi M$  brings about the rise of the film temperature by  $\Delta T \sim T_M$ .

### 5. Conclusion

Thus, the active thermal stabilization regime can be realized in the systems with combined magnetic and resistive phase transition of the first order placed in a perpendicular magnetic field with electric current flowing through the film.

As a concluding remark, let us note that electric current influences the system magnetic susceptibility. In fact, as the system average magnetization is  $\langle M_z \rangle = M \cdot V_{FM}/V$ , we can find

$$\chi = \frac{d\langle M_z \rangle}{dH} = \frac{1}{4\pi(\Theta/T_M + 1)}, \quad (22)$$

with taking into account expression (19). It follows from Eq. (22) that the system susceptibility decreases with the increasing heat parameter  $\Theta/T_M$ .

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## **Автостабілізація температури у матеріалі з резистивно-магнітним фазовим переходом першого роду при протіканні електричного струму**

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Показано, що на основі матеріалів з комбінованим резистивно-магнітним фазовим переходом першого роду може бути реалізований режим активної термостабілізації, коли під час протікання електричного струму у зразку автоматично підтримується температура поблизу порогу  $T_c$  ( $T_c$  – температура фазового переходу). Розраховано залежності частки феромагнітної фази та температури у зразку від електричного та магнітного полів. Визначено робочі параметри системи, за яких реалізується режим активної термостабілізації. Встановлено, що за визначених умов магнітне поле ефективно впливає на температуру системи.