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Ferromagnetic resonance in nanotwinned Ni–Mn–Ga film undergoing martensitic transformation

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The ferromagnetic resonance (FMR) in the shape memory alloys (SMAs) exhibiting structural cubic-tetragonal phase transition has been studied. The influence of instability and spatial inhomogeneity of crystal lattice on the FMR spectra of twinned ferromagnetic SMAs films has been analyzed using statistical model of ferromagnetic martensite. It has been shown that the abnormally strong temperature dependence of lattice parameters of martensitic film gives a noticeable contribution to the temperature dependence of the resonance value of external magnetic field. The narrowing of the resonance peak, which had been experimentally observed on cooling of the film slightly below the Curie temperature, has been explained. It is argued that the martensitic films are good candidates for the experimental study of local elastic strains influence on the shape of the FMR peak.

Keywords: ferromagnetic resonance, martensitic transformation, thin film, crystal lattice instability.

1. Introduction

The numerous practical applications of shape memory alloys (SMAs) are based on their unusual deformational properties due to the structural phase transformations from high-temperature austenitic phase to the low-temperature martensitic state [1–3]. The martensitic transformation (MT) is the first order phase transition characterized by the spontaneous deformation of crystal lattice arising on cooling of SMA. This transformation is considered in the framework of Landau theory of phase transitions as the phase transition of ferroelastic type. The ferromagnetic SMAs form a special class of solids undergoing the cubic-tetragonal or cubic-orthorhombic MTs. The cubic-tetragonal martensitic transformations of ferromagnetic SMAs are most widely studied theoretically in the framework of Landau-type theories of phase transitions (see, e.g., Refs. 4, 5 and references therein). All practically important properties of this class of alloys are strongly related to the microstructure of martensitic phase. In particular, the quasi-periodic twin structures with the twin width of the order of 100 nm or less can arise in the martensitic phase. Such twin structures are under special attention of researchers [6–8].

MT is one of the consequences of instability of crystal lattice. The lattice instability also leads to the abnormal temperature dependence of lattice parameters below the MT temperature and pronounced softening of elastic modules in the wide temperature range near MT temperature (see, e.g., Refs. 9, 10).

The large number of SMAs undergoes the phase transition to ferromagnetic phase below the Curie temperature, T_C, which can be higher or lower than MT temperature, depending on chemical composition of alloy. The lattice instability has a strong influence on the magnetic properties of SMAs. In particular, cubic-tetragonal MT results in the appearance of uniaxial magnetocrystalline anisotropy and the anisotropy parameter is proportional to the tetragonal distortion of crystal lattice $1-c(T)/a(T)$, where $c(T)$ and $a(T)$ are the temperature-dependent lattice parameters.

The ferromagnetic resonance (FMR) measurements are considered as the powerful method to obtain an information about the unusual magnetic and magnetoelastic properties of SMAs [11,12]. The magnetic anisotropy is one of the key factors, which predetermine value of FMR frequency. Therefore, not only the temperature dependence of magnetization value (as in the case of ferromagnetic solids with the stable crystal lattice), but the temperature dependence of lattice parameters should contribute to the temperature dependence of FMR frequency. If the microwave frequency is fixed, the temperature dependence of lattice parameters should result in the temperature shift of the resonance field value. It has been shown theoretically that

the magnetic anisotropy parameter of uniform SMA crystal is strongly different from anisotropy parameter of mesoscale twinned SMA [13]. This theoretical prediction was confirmed by the FMR experiments on twinned Ni–Mn–Ga thin films with the period of twin structure of about 100 nm [8]. The spatial inhomogeneity of crystal lattice also can result in the dispersion of the local values of magnetization, and leads to the broadening of the resonance peak.

In this communication, the theoretical evaluation of the influence of instability and spatial inhomogeneity of crystal lattice on the FMR spectra of twinned ferromagnetic SMAs films is obtained.

2. Theoretical and experimental backgrounds

The electron microscopy investigation [8] showed a formation of quasiperiodic crystallographic twin structure in Ni–Mn–Ga martensitic films with the period of about 100 nm. The twinning reduces the magnetic anisotropy field of the film by factor 1/2 [13]. The free energy density of twinned film in the magnetic field **H** can be presented as

$$F(T)=\frac{1}{2}K_u(T)m_z^2+2\pi(\mathbf{mn})^2M^2(T)-\mathbf{mH}M(T), \qquad (1)$$

where the first, the second and the third terms describe the magnetocrystalline anisotropy, magnetostatic energy, and Zeeman interaction, respectively; $\mathbf{m}=\mathbf{M}(T)/M(T)$, $\mathbf{M}(T)$ is the magnetization vector, $\mathbf{n}\parallel z$ is the unit vector directed perpendicular to the film plane, z is perpendicular to the easy magnetization axes, x and y, of crystallographic twins, parameter $K_u(T)$ is the uniaxial magnetocrystalline anisotropy parameter of the martensitic phase. The magnetic anisotropy field is equal to $2K_u(T)/M$ for the uniform crystal lattice and $K_u(T)/M$ for the twinned film. For the cubic austenitic phase $K_u=0$, while for the tetragonal martensitic phase the value of this parameter is determined by the dimensionless magnetoelastic constant δ and temperature-dependent lattice parameters $a(T)$ and $c(T)$ as

$$K_u(T)=-6\delta[1-c(T)/a(T)]M^2(T). \qquad (2)$$

(For more information about the magnetic anisotropy of martensitic alloys see review article Ref. 13 and references therein.) For the tetragonal martensitic phase of Ni–Mn–Ga alloys undergoing MT in ferromagnetic phase $c(T)<a(T)$, $\delta<0$, and therefore, $K_u>0$. The easy magnetization axes are parallel to **n** for z-domains of tetragonal phase and perpendicular to **n** for x- and y-domains.

The FMR frequency can be found from the standard equation

$$\frac{1}{\gamma}\frac{d\mathbf{M}}{dt}=\frac{\partial F}{\partial\mathbf{M}}\times\mathbf{M}. \qquad (3)$$

For the perpendicular to the film plane magnetic field this equation has nontrivial solution if

$$H=\frac{\omega}{\gamma}+4\pi M(T)+H_A(T), \qquad (4)$$

where $H_A(T)=K_u(T)/M(T)$ is the magnetocrystalline anisotropy field of the film.

The temperature dependence of magnetization value $M(T)$ can be quantitatively described by the standard equation

$$M(T)=M(0)\tanh\left(\frac{T_C M(T)}{TM(0)}\right) \qquad (5)$$

in both austenitic and martensitic phases [14]. In the case of paramagnetic austenite–ferromagnetic austenite–ferromagnetic martensite phase transitions sequence the $T_C=T_{CA}$ is Curie temperature of austenitic phase, which is directly measured in experiments, while $T_C=T_{CM}$ is Curie temperature of martensitic phase, which can be evaluated theoretically from the temperature dependence of magnetization below MT temperature. The difference between the temperature dependences of magnetization measured in the austenitic and martensitic phases is a result of the difference in the energies of spin-exchange interaction in austenitic and martensitic phases and spatial inhomogeneity of martensitic state of alloy [14].

The ferromagnetic SMAs films are spatially inhomogeneous. The statistical model was developed to take into account the inhomogeneity of the film. It was successfully used for the description of magnetic and magnetocaloric properties of ferromagnetic SMA [14,15]. According to this model, the ferromagnetic SMA is considered as the ensemble of N spatial domains undergoing the phase transition from paramagnetic (PM) to ferromagnetic (FM) state at different Curie temperatures $T_C(n)$, where $n=1, 2, ..., N$. The dispersion of magnetization values $M(T,n)$ can be calculated from Eq. (5) taking into account different values $T_C(n)$. The difference in magnetization values leads to the difference in the local resonance fields:

$$H_R(T,n)=\frac{\omega}{\gamma}+4\pi M(T,n)+H_A(T,n). \qquad (6)$$

The volume fraction of domains with the Curie temperature $T_C(n)$ and the magnetization $M(T,n)$ can be described by the Gaussian function

$$p_n=\frac{\exp\left[-\dfrac{T_C(n)-T_C(N/2)}{2T_G^2}\right]}{\displaystyle\sum_{n=1}^{N}\exp\left[-\frac{T_C(n)-T_C(N/2)}{2T_G^2}\right]}. \qquad (7)$$

The theoretical value $T_C(N/2)\equiv T_C$ corresponds to the Curie temperature of spatially inhomogeneous film measured in the experiment. The average magnetization value is

$$M(T)=\sum_n p_n M(T,n). \qquad (8)$$

The more pronounced is the spatial inhomogeneity of the film, the larger are the Gaussian parameter T_G and the dispersion of the resonance field values $H_R(T,n)$. The values $T_G = T_{GM}$ and $T_G = T_{GA} < T_{GM}$ were accepted for martensitic and austenitic phases and substituted into Eq. (7) to take into account that the spatial inhomogeneity of martensitic phase is larger than of austenitic one.

Let us consider the alloy undergoing the first-order phase transition. The alloy is in the austenitic state if $T > T_{MS}$, in the twinned martensitic state if $T < T_{MF}$, and in the mixed austenitic-martensitic state if $T_{MF} < T < T_{MS}$. In this case, the resonance peak can be modeled by the function

$$I(n,T) = I_0\left\{\alpha(T)p_n^{(M)} + [1-\alpha(T)]p_n^{(A)}\right\}, \qquad (9)$$

where

$$\alpha(T) = \frac{1}{2}\left[1 + \tanh\left(\frac{T_0 - T}{\Delta}\right)\right] \qquad (10)$$

is the volume fraction of martensite, $T_0 = (T_{MS} + T_{MF})/2$ is the middle point of the temperature interval of MT, $\Delta = (T_{MS} - T_{MF})/2$. The temperature interval of MT is $T_0 - \Delta < T < T_0 + \Delta$.

Equations (6) and (9) provide the parametric representation of the function $I(H,T)$. The resonance peak maximum should be observed at

$$H_R(T) \equiv H_R(T, N/2). \qquad (11)$$

As it was mentioned above, one of the most important features of ferromagnetic SMAs is the lattice instability resulting in the martensitic transformation and abnormally strong temperature dependence of lattice parameters in the martensitic phase. It is convenient to characterize this dependence by the tetragonal distortion of crystal lattice in the martensitic phase $1 - c(T)/a(T)$. The value of tetragonal distortion measured immediately after the finish of cubic-tetragonal MT, varies from 0.03 to 0.6 for the different representatives of Ni–Mn–Ga, Co–Ni–Ga and some other alloy systems [16–18]. The further decrease of the alloy temperature results in the gradual increase of tetragonal distortion with the rate $\sim 10^{-4}$–10^{-3} K^{-1}. The low-temperature magnetization of the bulk specimens of such alloys, $M(0)$, is about of 500–700 emu/cm^3 (200–300 emu/cm^3 at room temperature, see, e.g., Refs. 14, 19), the Curie temperature $T_C = T_{CA}$ is close enough to 400 K for Ni–Mn–Ga and near 300 K for Co–Ni–Ga bulk specimens. The value $T_{CM} - T_{CA} \approx 30$ K was obtained for $Ni_{52.6}Mn_{23.5}Ga_{23.9}$ alloy in Ref. 14. Taking into account that for the Ni–Mn–Ga films the $M(0)$ value usually is lower than for the bulk specimens, let us consider the representative film characterized by the "typical" values $M(0) = 450$ emu/cm^3, $T_{CA} = 400$ K, $T_{CM} = 430$ K.

The experimental curves $M(T)$ obtained for the films undergoing the phase transition from paramagnetic to ferromagnetic phase in the martensitic state have the pronounced "high-temperature tails" [8], which show that the maximal difference between the local Curie temperatures is of about 50 K or even larger. This feature of magnetization behavior is also inherent to the bulk Ni–Mn–Ga with $T_{MF} > T_C$ [14]. Such statistical spread of Curie temperatures in the martensitic state can be modelled by the Gaussian function, Eq. (7), with $T_{GM} = 30$ K. (The correspondence between $M(T)$ curve computed for this value of Gauss parameter and experimental $H_R(T)$ curve obtained for the film with $T_{MF} > T_C$ is illustrated in the Supplement.) In the case if MT temperature is noticeably lower than T_C, the high-temperature tail of magnetization is hardly observable [14], and therefore, small value of Gauss parameter $T_{GA} = 3$ K can be taken for austenitic phase.

The MT temperatures are different for different nonstoichiometric Ni–Mn–Ga alloys. To illustrate the peculiarities of FMR in the austenitic and mixed martensitic-austenitic phase, the realistic values of MT start and MT finish temperatures, $T_{MS} = 360$ K and $T_{MF} = 300$ K, respectively, can be taken. Figure 1 illustrates the typical temperature dependence of tetragonal distortion of crystal lattice of SMA, which undergoes MT at these temperatures. This theoretical dependence was obtained from the theory of ferroelastic phase transitions as explained in the Supplement. The inset shows that this theory satisfactorily describes experimental temperature dependence of tetragonal distortion of crystal lattice reported in Ref. 20 for the martensitic phase of Ni_2MnGa. This function will be used in the following computation of the temperature-dependence of the resonance field $H_R(T)$. When the temperature in-

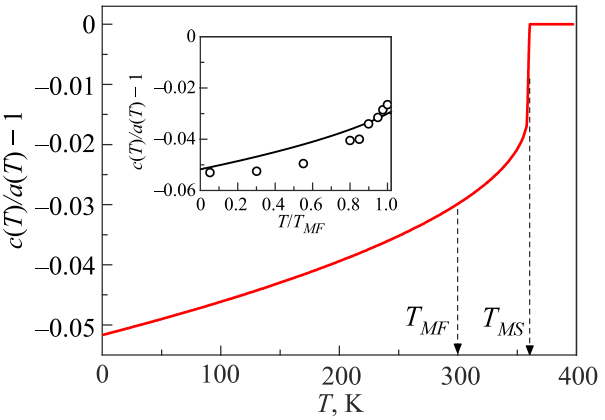

Fig. 1. The temperature dependence of the tetragonal distortion of crystal lattice computed from the Eqs. (13), (14) for the representative film. Inset: the tetragonal distortion taken from experimental dependences of lattice parameters presented in Ref. 16 for the martensitic phase of Ni_2MnGa alloy (circles) and the model function (line) used here for the computations; the tetragonal distortion is presented versus T/T_{MF} because there is a difference between the MT temperatures of the Ni_2MnGa alloy investigated in Ref. 16 and representative film.

creases from zero to T_{MF}, the tetragonal distortion varies from –0.05 to –0.025. This fact is very important to understand the influenc of lattice instability on the temperature dependence of FMR field.

The dimensionless parameter of magnetoelastic coupling $\delta = -23$ was evaluated from magnetic measurements carried out for the number of Ni–Mn–Ga alloys in Ref. 14. This parameter is involved into Eq. (2), which will be used below to determine the magnetocrystalline anisotropy parameter of martensitic phase.

3. Results

Figure 2 shows the $H_R(T)$ curves computed for the temperature-dependent tetragonal distortion (Fig. 1) and constant values of lattice parameters. It is seen that the contribution Δ_1 of temperature dependence of magnetization to the total temperature dependence of resonance field is close in value to the contribution Δ_2, caused by the strong temperature dependence of lattice parameters: $\Delta_2/\Delta_1 \approx 1.14$. Different martensitic alloys are characterized by different temperature dependences of magnetization and lattice parameters, nevertheless, it can be concluded, that the values Δ_1 and Δ_2 are of the same order of magnitude for all martensitic films. This is the manifestation of lattice instability in the resonance properties of SMA.

As it was said above, the SMAs are spatially inhomogeneous and spatial inhomogeneity is more pronounced in the martensitic phase than in the austenitic one. It is commonly recognized that the inhomogeneity of ferromagnetic SMA and thermal fluctuations predetermine the width of FMR peak. The influence of spatial inhomogeneity of the film on the half-width of the peak was estimated from the Eqs. (6) and (9): if

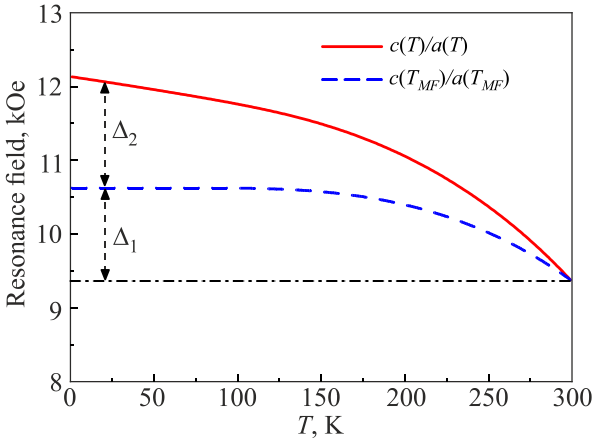

Fig. 2. Temperature dependence of the resonance field computed from the Eqs. (6), (11) and (14) for the twinned martensitic film with temperature-dependent lattice parameters (solid line). The resonance field computed for the constant values of lattice parameters, i.e. u = const (dashed line), is shown for comparison. Two-side arrows show the changes of the resonance field caused by the temperature dependences of magnetization (Δ_1) and lattice parameters (Δ_2). Horizontal dash-dotted line shows the resonance field value calculated for MT finish temperature.

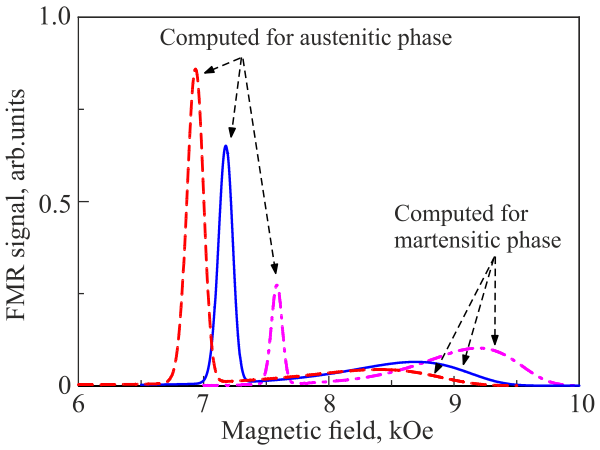

Fig. 3. Resonance peaks computed using the Eqs. (6)–(10) for 310 K (dash-dotted line), 330 K (solid line) and 340 K (dashed line).

the temperature of alloy is fixed, these equations provide the parametric representation of the function $I(H)$.

The resonance peaks computed for the temperatures belonging to the temperature range of mixed austenitic-martensitic state of the film, $T_{MF} < T < T_{MS}$, are presented in Fig. 3. The figure obviously shows the variation of the amplitudes of FMR signals corresponding to austenitic and martensitic phases. This feature of FMR is caused mainly by the temperature dependences of volume fractions of coexisting martensitic and austenitic phases. The peaks corresponding to martensitic phase are much wider than those computed for austenitic phase due to the difference between parameters of Gauss functions T_{GA} and T_{GM} characterizing the spatial inhomogeneity of alloy specimen in the austenitic and martensitic phases, respectively. Figure 3 shows, moreover, that the austenitic peak becomes narrower when the temperature decreases.

Figure 4 shows that the narrowing of the resonance peaks during the cooling of film takes place in the martensitic state, as well.

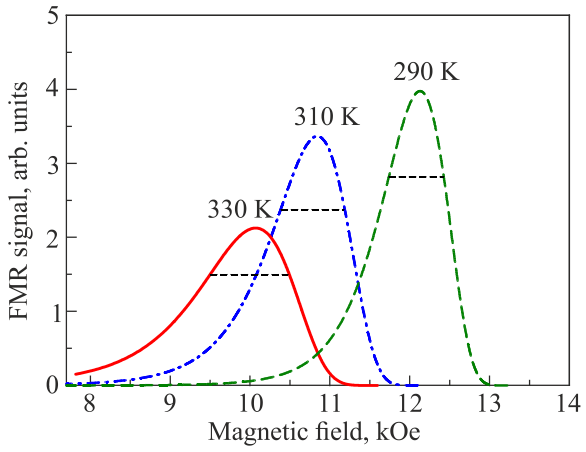

Fig. 4. The evolution of the half-width (horizontal dashed line) of the resonance peaks corresponding to martensitic phase with temperature.

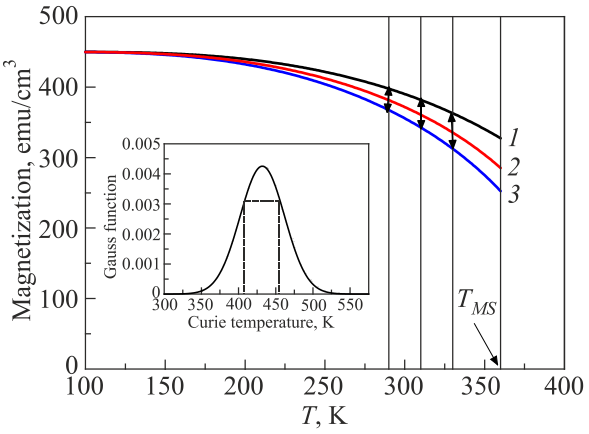

Fig. 5. Magnetization functions $M(T,n)$ computed for the martensitic phase. The curves *1* and *3* are calculated for the numbers n corresponding to the half-width of Gauss function shown in the inset. The curve *2* depicts the average magnetization value (Eq. (8)).

Figure 5 illustrates that the decrease of half-width of the resonance peaks on cooling of martensitic film is caused by the differences between the local magnetization values $M(T,n)$, and these differences decreases with lowering of temperature. The magnetization curves *1* and *3*, depicted in Fig. 5, are computed for the spatial domains of martensitic phase whose Curie temperatures correspond to the half-width of Gauss distribution with $T_G = T_{GM} = 30$ K. The intermediate curve *2* depicts the temperature dependence of average magnetization value $M(T)$ expressed by Eq. (8). The narrowing of the resonance peaks is caused by the convergence of curves *1* and *3* in the low-temperature range (see Fig. 5).

4. Conclusion

The presented above theoretical model of FMR in the film, which undergoes MT, is based on the statistical model of ferromagnetic martensite. This model was formulated in Refs. 14, 15 to describe the magnetic properties of SMA in the saturating magnetic field. In accordance with this model, the martensitic alloy is the statistical ensemble of small spatial domains with the different values of Curie temperature. It is considered that the difference in Curie temperatures of domains is caused by the difference in local values of magnetic exchange parameter, while the difference in the local values of magnetic anisotropy parameters is disregarded. Such simplification of the model is acceptable in the case of the free-standing films or thick relaxed films deposited on the proper substrate. In this case the model results in two conclusions:

i) the strong temperature dependence of lattice parameters of martensitic film gives a noticeable contribution to the temperature dependence of the resonance value of external magnetic field;

ii) the difference in the local values of Curie temperature leads to the narrowing of the resonance peak on cooling of the film.

If the lattice parameters of the film are temperature-independent, the $H_R(T) - \omega/\gamma$ value is proportional to $M(T)$ with the temperature-independent coefficient of proportionality (see Eqs. (2), (4)). This fact is commonly used for the determination of the $M(T)$ function, which is inherent to the thin film. However, the temperature dependence of the resonance field measured for the free standing film is contributed by the temperature dependence of lattice parameters (see Eqs. (2), (6), (11)), and therefore, the first conclusion can be used for determination of the temperature dependence of tetragonal distortion of the crystal lattice in the martensitic phase of such film. In this connection, it should be mentioned, first, that the straightforward measurement of magnetization of the thin film encounters the formidable obstacles, and so, needs special experimental facilities. Second, the substrate impedes the expansion/contraction of thin martensitic film deposited on the substrate, reduces the abnormally strong temperature dependence of lattice parameters, which is inherent to SMAs in their martensitic state, and therefore, minimizes the influence of this factor on the resonance field value. However, the mechanical stress induced by substrate in the film exponentially decreases with increasing of the film width, so the temperature dependence of lattice parameters may be well-pronounced in the thicker films.

The narrowing of the resonance peak on cooling of the film is experimentally observed only in the austenitic phase of Ni–Mn–Ga film, at the temperatures, which are close to the Curie temperature (see Fig. 6), because the higher is temperature, the more pronounced is difference between the local magnetization values (Fig. 5). The Inset in Fig. 6 shows that the theory adequately describes the experimental data if the Gauss parameter is equal to 7 K for austenitic phase.

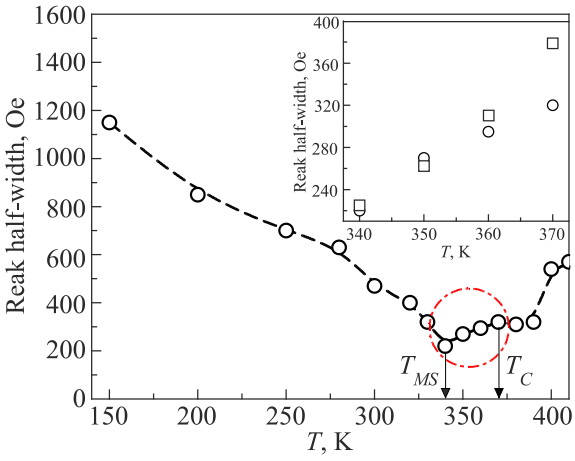

Fig. 6. The experimental temperature dependence of the half-width of resonance peak measured for the Ni–Mn–Ga thin film with $T_C < T_{MF}$ (circles) [21]. The dashed line is the guide for eye. The dash-dotted line encircles the experimental points exhibiting the narrowing of the resonance peak on cooling below the Curie temperature T_C. The inset shows that the theory (squares) satisfactorily describes experimental data (circles) at $T_{MS} < T < T_C$.

The experiment shows that after the start of martensitic transformation (in the temperature range from 150 K to 340 K) the cooling of alloy results in the drastic widening of the resonance peak (see Fig. 6). This fact is caused, seemingly, by the axial straining of the film because of the appearance of MT strain and due to the difference between the temperature expansion coefficients of the film and substrate: the cooling of martensitic film, which was deposited on the substrate at elevated temperature, induces the temperature-dependent elastic strain. The local strain values may by noticeably different due to the spatial inhomogeneity of the film in the martensitic state. The temperature dependence of lattice parameters of SMAs in the martensitic state is abnormally strong, and therefore, this fact shows that the martensitic films are good candidates for experimental study of the influence of local elastic strains on FMR. To develop statistical model for the description of magnetic properties of locally strained/stressed martensitic film one must take into account the difference in the values of magnetic anisotropy constant and different directions of easy magnetization axes inherent to small spatial domains of the film. This non-trivial problem needs special consideration.

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Supplement

Estimation of Gauss parameter

As it is known, the magnetization value of uniform crystal lattice and magnetic anisotropy field abruptly fall to zero when the temperature reaches Curie point. In this case the resonance field abruptly decreases to the value $H_R = \omega/\gamma$ (see Eqs. (4), (6)). Figure 6 shows, however, that the experimental value of the resonance field obtained in Ref. 8 slowly decreases in the wide temperature range $375\ \text{K} < T < 425\ \text{K}$, that is in the temperature interval $\Delta T = 50$ K above the temperature of 375 K, which can be interpreted as the Curie temperature of the unstressed film experimentally studied in Ref. 8. The same behavior is inherent to the magnetization function computed for the representative film in the temperature range $\Delta T = 50$ K above the Curie temperature of austenite $T_{CA} = 400$ K (see Fig. 7). Taking into account that the effective field is proportional to magnetization value, one can conclude that the Gauss function with $T_G = 30$ K is adequate to the influence of spatial inhomogeneity of martensitic state on the temperature dependence of magnetization of the film. It should be noted that the $H_R(T)$ and $M(T)$ curves are not congruent because of the i) difference between the Curie temperature of the representative film considered above and the Curie temperature of martensitic film studied in Ref. 21; ii) temperature dependence of lattice parameters interrelated with $H_R(T)$ function.

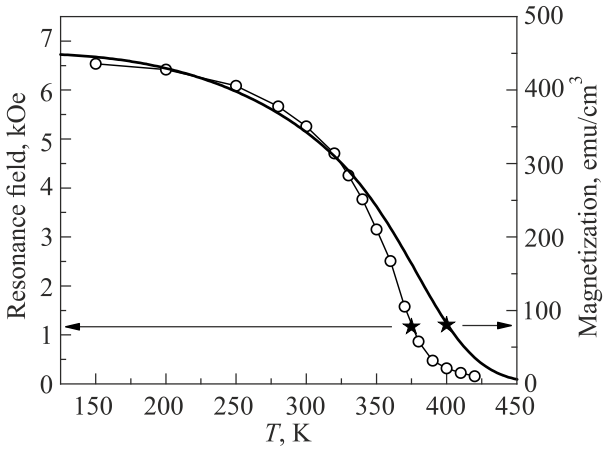

Fig. 7. The theoretical temperature dependence of magnetization of martensitic film ($T_M < T_C$) computed for $T_C = 400$ K (bold line) and experimental values of magnetization of martensitic Ni–Mn–Ga film (circles, thin line is the guide for eye) reported in Ref. 8. Asterisks mark the "high-temperature tails" of $M(T)$ and $H_R(T)$ curves. The horizontal arrows point to the values M^* and H^* mentioned in the text.

Explanation of temperature dependence of tetragonal distortion of the crystal lattice

The theoretical temperature dependence of spontaneous tetragonal distortion of crystal lattice caused by the cubic-tetragonal phase transition is obtained by the minimization of elastic energy of the crystal. This energy is expressed as

$$F = \frac{1}{2}c_2(T)u^2 + \frac{1}{3}a_4u^3 + \frac{1}{4}b_4u^4, \qquad (12)$$

where $u(T) = 2[c(T)/a(T) - 1]$, the coefficients a_4 and b_4 are the linear combinations of third-order and fourth-order elastic modules [22]. The coefficient $c_2(T)$ is a decreasing function of temperature, $c_2(T) > c_t$ in the cubic phase, $0 < c_2(T) < c_t$ in the temperature range of MT and $c_2(T) < 0$ in the tetragonal phase. As so, the temperature dependence of tetragonal distortion was computed using the expression

$$c_2(T) = c_t \frac{T - T_{MF}}{T_{MS} - T_{MF}} \qquad (13)$$

and values $a_4 = 30$ GPa, $b_4 = 500$ GPa. These values provide realistic temperature dependence of shear elastic modulus and $u(T)$ [22].

The energy is minimal if $u(T)$ satisfies the condition $\partial F/\partial u = 0$, which results in the expression

$$u(T) = \begin{cases} -(a_4/2b_4)\left[1+\sqrt{1-c_2(T)/c_t}\right], & T \le T_{MS}, \\ 0, & T > T_{MS}, \end{cases} \quad (14)$$

where $c_t = a_4^2/4b_4 > 0$. The tetragonal distortion depicted in Fig. 1 is equal to $u(T)/2$.

1. C. Lagoudas, *Shape Memory Alloys: Modeling and Engineering Applications*, Springer-Verlag, New York (2007).
2. M. Kohl, *Shape Memory Microactuators*, Springer-Verlag, Berlin (2004).
3. S.P. Hannula, O. Söderberg, T. Jämsä, and V.K. Lindroos, *Adv. Sci. Tech.* **49**, 109 (2006).
4. V.A. L'vov, E.V. Gomonaj, and V.A. Chernenko, *J. Phys.: Condens. Matter* **10**, 4587 (1998).
5. P. Entel, V.D. Buchelnikov, V.V. Khovailo, A.T. Zayak, W.A. Adeagbo, M.E. Gruner, H.C. Herper, and E.F. Wassermann, *J. Phys. D: Appl. Phys.* **39**, 865 (2006).
6. P. Muüllner, V.A. Chernenko, and G. Kostorz, *JMMM* **267**, 325 (2003).
7. Y. Ge, O. Heczko, O. Söderberg, V.K. Lindroos, and S.P. Hannula, *Appl. Phys. Lett.* **89**, 082502 (2006).
8. V.A. Chernenko, V.A. L'vov, V. Golub, I.R. Aseguinolaza, and J.M. Barandiaran, *Phys. Rev. B* **84**, 054450 (2011).
9. V.A. Chernenko, J. Pons, C. Seguí, and E. Cesari, *Acta Mater.* **50**, 53 (2002).
10. T. Fukuda and T. Kakeshita, *Metals* **7**, 156 (2017).
11. S.I. Patil, Deng Tan, S.E. Lofland, and S.M. Bhagat, *Appl. Phys. Lett.* **81**, 1279 (2002).
12. I.R. Aseguinolaza, V. Golub, J.M. Barandiarán, M. Ohtsuka, P. Müllner, O.Y. Salyuk, and V.A. Chernenko, *Appl. Phys. Lett.* **102**, 182401 (2013).
13. V. L'vov and V. Chernenko, *Mater. Sci. Forum*. **684**, 31 (2011).
14. V.A. Chernenko, V.A. L'vov, S.P. Zagorodnyuk, and T. Takagi, *Phys. Rev. B* **67**, 064407 (2003).
15. V.A. L'vov, A. Kosogor, J.M. Barandiaran, and V.A. Chernenko, *J. Appl. Phys.* **119**, 013902 (2016).
16. Y. Ma, S. Awaji, K. Watanabe, M. Matsumoto, and N. Kobayashi, *Solid State Commun*. **113**, 671 (2000).
17. N. Glavatska, I. Glavatskiy, G. Mogilny, S. Danilkin, D. Hohlwain, O. Soderberg, V. Lindroos, and A. Beskrovnij, *J. Phys. IV France* **112**, (2003).
18. V. Kireeva, C. Picornell, J. Pons, I.V. Kretinina, Yu.I. Chumlyakov, and E. Cesari, *Acta Mater*. **68**, 127 (2014).
19. Y.X. Li, H.Y. Liu, F.B. Meng, L.Q. Yan, G.D. Liu, X.F. Dai, M. Zhang, Z.H. Liu, J.L. Chen, and H. Wu, *Appl. Phys. Lett.* **84**, 3594 (2004).
20. P.J. Webster, K.R.A. Ziebeck, S.L. Town, and M.S. Peak, *Philos. Mag. B* **49**, 295 (1984).
21. V.O. Golub, V.A. Chernenko, A. Apolinario, I.R. Aseguinolaza, J.P. Araujo, O. Salyuk, J.M. Barandiaran, and G.N. Kakazei, *Sci. Rep.* **8**, 15730 (2018).
22. V.A. L'vov, V.A. Chernenko, and J.M. Barandiaran, *Magnetic Shape Memory Materials with Improved Functional Properties: Scientific Aspects*, in: *Novel functional magnetic materials, Series in Materials Science*, A. Zhukov (ed.), Springer International Publishing, Switzerland (2016), Vol. 231, Chapter 1.

Феромагнітний резонанс у нанодвійникованій плівці Ni–Mn–Ga при мартенситному перетворенні

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Досліджено феромагнітний резонанс (ФМР) в сплавах з ефектом пам'яті форми (СЕПФ), в яких відбувається структурне кубічно-тетрагональне фазове перетворення. За допомогою статистичної моделі феромагнітного мартенситу проаналізовано вплив нестабільності та просторової неоднорідності кристалічної гратки на спектр ФМР двійникованої феромагнітної плівки СЕПФ. Показано, що аномально сильна температурна залежність параметрів гратки мартенситної плівки робить значний внесок в температурну залежність зовнішнього резонансного поля. Також було пояснено звуження резонансного піку при охолодженні плівки, яке експериментально спостерігалося трохи нижче температури Кюрі. Підтверджено, що мартенситні плівки є цікавими об'єктами для експериментального дослідження впливу локальних еластичних напружень на форму ФМР піку.

Ключові слова: феромагнітный резонанс, мартенситне перетворення, тонка плівка, нестабільність кристалічної гратки.

Ферромагнитный резонанс в нанодвойникованной пленке Ni–Mn–Ga при мартенситном превращении

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Изучен ферромагнитный резонанс (ФМР) в сплавах с эффектом памяти формы (СЭПФ), испытывающих структурное кубическо-тетрагональное фазовое превращение. С помощью статистической модели ферромагнитного мартенсита проанализировано влияние нестабильности и пространственной неоднородности кристаллической решетки на спектр ФМР двойникованной ферромагнитной пленки СЭПФ. Показано, что аномально сильная температурная зависимость параметров решетки мартенситной пленки вносит существенный вклад в температурную зависимость внешнего резонансного поля. Также было объяснено сужение резонансного пика при охлаждении пленки, экспериментально наблюдаемое немного ниже температуры Кюри. Подтверждено, что мартенситные пленки являются интересными объектами для экспериментального изучения влияния локальных эластичных напряжений на форму ФМР пика.

Ключевые слова: ферромагнитный резонанс, мартенситное превращение, тонкая пленка, нестабильность кристаллической решетки.