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# Film-cooling-induced phase transitions in magnetic bubble lattices

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**Abstract.** A theoretical study of the transitions taking place in magnetic bubble lattices (MBLs) on cooling the film has been performed. It is shown that, if the MBL was formed at room temperature, then, on cooling the film, spontaneous transitions occur from the initial MBL to a lattice with a larger domain period and diameter. The nature of these transitions is that of first-order phase transitions and they are accompanied by a change in the total number of domains in the specimen. The phase diagram for the MBL formed in thin bismuth–thulium garnet films is calculated; there is good agreement with experimental results.

## 1. Introduction

Experimental and theoretical studies concerning the effect of increasing the temperature upon the bubble lattices formed in thin ferrite–garnet films have previously been carried out [1, 2]. Increasing the temperature was shown to induce a first-order phase transition in a magnetic bubble lattice (MBL), the initial MBL turning into a structure consisting of two coexistent phases: blocks of a new MBL characterized by smaller values of the parameters $d$ (bubble diameter), and $a$ (the lattice period), and striped domain areas. The explanation is that the MBL is only in equilibrium at the temperature $T_f$ of formation and corresponds to an energy minimum only for specific values of the parameters $l(T_f)$ and $M(T_f)$ ($M$ is the saturation magnetization and $l$ the characteristic length defined as the ratio of the surface density of the domain wall energy to $\mu_0 M^2$); if the parameters are varied, the lattice becomes metastable. With increasing temperature the degree of metastability also increases, approaching the critical value at which MBL instability in relation to decomposition into phases occurs. The decomposition temperature is determined according to [1] by the initial MBL parameters, the value of the bias field and the rate of change in the film characteristic length with temperature.

The purpose of this paper is to investigate the MBL behaviour on cooling ferrite–garnet films. Thermodynamic analysis of the MBL state stability will be performed on the basis of studying the temperature dependence of the bubble chemical potential in the lattice derived in [1] as $\mu = \partial U/\partial N$, where $U$ is the MBL energy and $N$ the number of domains in the lattice.

## 2. Experimental results

The experiments were carried out in a magneto-optical installation where the sample could be cooled to liquid-nitrogen temperature. The observations were carried out on

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bubble lattices formed in epitaxial ferrite–garnet films $(TmBi)_3(FeGa)_5O_{12}$, grown on GGG substrates on (111) surfaces. The MBL was formed from the labyrinth structure by a pulsed magnetic field at room temperature and in a zero bias field. Then the film was cooled, and the MBL parameters measured. The MBL formed at $T_f = 300$ K in a sample with $h = 5.0\ \mu m$, $l(T_f)/h = 0.11$ and $M(T_f) = 50\ kA\ m^{-1}$ had the parameters $d = 12\ \mu m$ and $a = 16\ \mu m$. In the temperature range between 300 and 215 K the bubble diameter and the lattice period do not change. With $T_1 = 215$ K a spontaneous transition to a new MBL with a larger period and domain diameter ($d_1 = 21\ \mu m$ and $a_1 = 29\ \mu m$) takes place. If at the temperature $T_1 = 215$ K we form a new lattice in this sample using a pulsed field, then its parameters turn out to be very close to those of the lattice that was spontaneously formed in the cooling process from the MBL formed at $T_f = 300$ K. Cooling the film further from $T_1 = 215$ K, we found that at $T_2 = 180$ K a similar transition occurred to a lattice with parameters $d_2 = 81\ \mu m$ and $a_2 = 110\ \mu m$.

In the course of direct observations of the kinetics of transformations into MBLs it was determined that the essential difference between the transitions in the MBL (which are induced by the temperature increase) and those studied in [1, 2] lies in the fact that the transition from an MBL to a lattice with larger parameters occurs with a change in the number of domains in the specimen. Some of the domains in the initial lattice are collapsing and the diameters of the rest of the bubbles are increasing, and forming a new lattice. The cooling-induced transitions in the MBL occur without the formation of nucleation centres, in contrast with transitions induced by heating.

The temperature dependence of the characteristic length was obtained from the equilibrium period of stripe structures (figure 1). The static coercivity of the sample, measured at room temperature, is $H_c = 62\ A\ m^{-1}$. Figure 1 also shows the increase in coercivity on cooling the sample to $T = 180$ K. A similar dependence of $H_c(T)$ for other bubble materials were given in [3, 4]. As shown in [5] the saturation magnetization of thulium iron garnets is almost constant in the temperature range between 300 and 100 K.

### 3. Thermodynamical analysis

Let us study the temperature change in the MBL thermodynamic state using the following expression for the MBL chemical potential [1]:

$$\mu(T, H) = (4\pi M)^2(h^3/4)[xl/h - I(x) + x^2H/8\pi M + 5k(p)x^4z^{-3}] \qquad (1)$$

where $x = d/h$, $z = a/h$, $H$ is the bias field strength, $I(x)$ is the function proposed in [6], and $k(p)$ is a numerical parameter (for hexagonal MBLs, $k(p) = 0.172$). The range of applicability of (1) is limited to $z > 1$, $x/z < 1$. If the equilibrium MBL is formed at $T = T_f$, then $\mu(T_f) = 0$ [1]. If the film is cooled, the MBL will no longer remain in equilibrium because of the temperature dependences of $l$ and $M$, i.e. $\mu(T) \neq 0$ for $T < T_f$. If $\mu(T) < 0$, then the number of bubbles in the lattice is less than in the equilibrium MBL for the given temperature. For $\mu(T) > 0$ the number of bubbles exceeds that required for the equilibrium structure and therefore the system tends to the state with fewer domains. Thus, analysing the change in MBL chemical potential with temperature, one can obtain some information on the trends of the possible transition to the equilibrium state.

The dependence $\mu(T)$ is found from (1), taking into acount that $M(T) \approx$ constant, $x(T)$, $z(T)$ do not vary up to the transition point, and $\mu(T_f) = 0$:

$$\mu(T) = (4\pi M)^2(h^2x/4)[l(T) - l(T_f)]. \qquad (2)$$

Since $l(T) > l(T_f)$ for $T < T_f$ (figure 1), we have $\mu(T) > 0$. This means that with

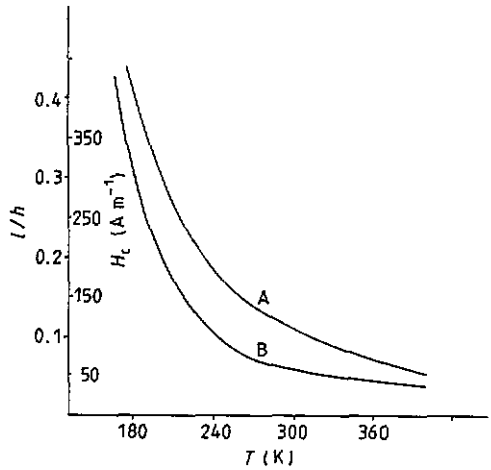


**Figure 1.** Characteristic length (curve A) and coercivity (curve B) as functions of temperature for a $(TmBi)_3(FeGa)_5O_{12}$ film.

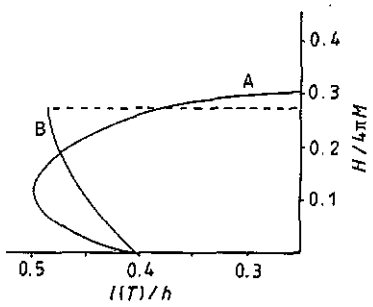


**Figure 2.** Phase diagram of the MBL formed with $l(T)/h = 0.25$: curve A, stability boundary of MBL-1; curve B, stability boundary of MBL-2.

decreasing temperature the lattice becomes metastable in relation to the equilibrium MBL′ having $\mu'(T) = 0$. It follows from (2) that the degree of metastability of the MBL increases steadily on cooling the film, the number of domains in the lattice thus being excessive at any temperature $T < T_f$. Therefore the above analysis of the change in $\mu(T)$ allows one to conclude that, as the temperature decreases, the transitions in the MBL must tend to reduce the number of domains in the MBL, as observed experimentally.

In order to calculate the transition temperature and the conditions for the existence of this transition, let us consider the MBL-to-MBL″ transformation. The increase in the characteristic length with decreasing film temperature leads to an increase in the surface tension force of the domain walls (DWs), compressing the bubbles. However, because of the large coercivity no change occurs in the MBL diameter. In this case the coercivity $H_c$ acts as a static frictional force in the DW temperature shift process. The lattice becomes non-equilibrium with respect to both the number of domains in the structure ($\mu > 0$) and the bubble diameter ($\partial U/\partial x \neq 0$). For a transition to the equilibrium domain diameter for a given lattice period it is necessary to overcome the energy barrier of the coercive field.

A possible mechanism of the transition to the equilibrium MBL on cooling the film is the following. Because of spatial fluctuations in the magnetic parameters of the film along its surface, one or more of the bubbles in the vicinity of a surface defect may first collapse because of the increase in DW surface tension force with decreasing temperature. With the collapse of one bubble the energy of the structure changes by the value of its chemical potential determined by (2) and is transferred to the degree of freedom of MBL fluctuations. If this energy is sufficient for overcoming the coercivity barrier, then the nearest DWs may move to their equilibrium positions appropriate to the given temperature. When the DWs tear away pulsations and translation fluctuations occur in the MBL. In this case a deformation wave propagating in the MBL may initiate a process of a dynamic collapse of some bubbles if the film temperature has attained a value for

which the MBL equilibrium condition [7] is violated:

$$l/h \leqslant S_0(x) - 8k(p)(1 - 1/\sqrt{3})x^3 z^{-3} \tag{3}$$

where $S_0(x)$ is the Thiele function. The condition (3) having been violated, a process of a dynamic collapse of some bubbles starts. The number of the rest of the domains in the MBL is determined by the equilibrium condition $\mu(T) = 0$. In the process of the domain collapse the pressure in the MBL decreases, this being the reason for expansion of the rest of the bubbles up to diameters corresponding to the given field and the new lattice period.

Thus for the transition to the equilibrium MBL it is necessary to satisfy two conditions:

(1) an excess of the degree of metastability of the MBL;
(2) a disturbance of MBL stability in relation to the dynamic collapse.

### 4. The MBL phase collapse

Let us calculate the temperature of the transition to the equilibrium MBL′ as a function of the bias field strength. Let the MBL be formed in equilibrium at $T = T_f$; then its parameters satisfy the equations:

$$\partial U(x, z, T_f)/\partial x|_H = 0 \qquad \partial U(x, z, T_f)/\partial z|_H = 0 \tag{4}$$

where $U$ according to [7] is

$$U = 2\pi M^2 - 8\pi^2 M^2 p^{-1}[I(x) - xl/h - x^2 H/8\pi M]z^{-2} + (4\pi M)^2 p^{-1} k(p) x^4 z^{-5}. \tag{5}$$

The transition temperature $T_0$ as a function of the field strength may be calculated from the equation

$$l(T_0)/h = S_0(x) - 8k(p)(1 - 1/\sqrt{3})x^3 z^{-3} \tag{6}$$

if we use the values satisfying (4) for $x(H)$ and $z(H)$. Note that it is not the temperature $T_0$ but its corresponding value $l(T_0)/h$ that is more conveniently found from (4) and (6). In this case the results obtained (values of $l/h$ corresponding to the transition temperature) do not depend on the composition and thickness of the film. The MBL-to-MBL′ transition temperature is found for each particular sample in accordance with the function $l(T)/h$ determined by experiment.

The results of the numerical solution of equations (4)–(6) are shown in figure 2 for two types of lattice formed at a temperature $T_f$ such that $l(T_f)/h = 0.25$. The type I lattice (MBL-1) was formed with $H = 0$; the bias field was then increased to a certain value of $H$, and subsequently the film was cooled. Figure 2 shows the phase diagram for MBL-1 as curve A. The MBL-1 phase exists to the right of this curve. As $l(T)$ increases (the temperature decreases) a transition occurs to the equilibrium phase for the given temperature and consists of MBL′ when curve A is reached.

If the lattice MBL-2 is formed in the presence of a bias field ($H \neq 0$), and the film is then cooled, the calculated phase diagram for such an MBL is presented as curve B in figure 2. Attention should also be paid to the difference in the thermal stability range of the MBL ($\Delta T = T_f - T_0$) as a function of $H$ for lattices of types I and II. The temperature of the transition from MBL-2 to the equilibrium lattice increases steadily with increasing bias field strength. This is because cooling for such lattices starts from states having $\mu(H, T_f) = 0$. For MBL-1, $\mu(H, T_f) = 0$ only when $H = 0$ and, on further increasing the field, $\mu$ becomes negative, passes through a minimum and then becomes positive [1].

The minimum $\mu(H, T_f)$ for $l(T)/h = 0.25$ is reached with $H/4\pi M = 0.11$. It is in this field that MBL-I has the widest range of thermal stability (figure 2, curve A).

Let us compare the computations with the experimental results for the MBL formed at $H = 0$. To do this we determine the temperature of the transition to the equilibrium MBL', making use of the diagram in figure 2. If the MBL was formed with $T = 215$ K, then $l/h = 0.25$ (figure 1). Figure 2 shows that the MBL formed with $l(T)/h = 0.25$ will be stable up to the value $l(T_0)/h = 0.4$. Using the curve $l(T)/h$ (figure 1) we find that the transition temperature $T_{01} = 185$ K corresponds to the value of $l/h = 0.4$. As stated above, the measured transition temperature value is 180 K. An analogous calculation of the transition temperature for an MBL formed at $T_f = 300$ K (using the phase diagram starting with $l(T_f)/h = 0.11$) yields the value $T_{02} = 212$ K.

## 5. Conclusions

Transitions in the MBL induced by decreasing the film temperature were theoretically and experimentally shown to occur at the MBL stability boundary and to be accompanied by the collapse of some of the initial lattice domains and the subsequent expansion of the rest of the bubbles up to the diameter corresponding to the new MBL bias field and period. The period of the MBL formed (or the number of the rest of the domains) is determined by the condition that the bubble chemical potential is zero in such a lattice. The temperature of the transition to the equilibrium MBL is determined by the rate of change in characteristic length with temperature (with $M(T) = \text{constant}$) and the bias field strength. The transitions to the equilibrium MBL are first-order phase transitions, i.e. they occur by changing the MBL specific volume and exhibit hysteresis. This hysteresis is due to the difference in the mechanisms of transitions which occur in the MBL on heating or cooling the film. For example, if the transition from MBL to MBL' occurred on cooling the film, then heating it could not lead to the inverse transition (MBL' to MBL). Indeed, in this case a transition to a two-phase structure (consisting of blocks of the new lattice and of stripes) takes place.

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