TEMPERATURE DEPENDENCE OF THE VISCOSITY COEFFICIENT IN TYPE II SUPERCONDUCTORS

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The differential resistance ρ_f is measured in 76 at.% Pb and 24 at.% In alloy samples over a broad range of temperature T and magnetic field strength H. It is shown that the empirical laws formulated by Kim[2] do not hold. Treatment of the experimental results by use of the variable $H/H_{c2}(t)$ made it possible to find new regularities in the behavior of the differential resistance of type II superconductors. The dependence of ρ_f/ρ_n on $H/H_{c2}(t)$ is linear up to a field strength of 0.5 $H_{c2}(t)$ at all temperatures. The dependence of the viscosity coefficient η on temperature is determined from the slope of these straight lines. The value of η and its temperature dependence are interpreted by taking into account the dissipation related to normal currents and the dissipation due to the finite relaxation time for the order parameter to reach its equilibrium value. The experimental values of η are in good agreement with the minimum value of the viscosity coefficient determined on the basis of the microscopic theory.[5,7]

INTRODUCTION

In the mixed state of type II superconductors, the energy dissipation and the appearance of resistance when the current flow exceeds the critical value J_c are connected with the motion of the vortex lattice under the action of the Lorentz force, which is counterbalanced by the viscous force[1]. Kim and coworkers[1,2] and Bardeen and Stephen[3] have shown the motion of the vortices induces in their cores an electric field and the normal current connected with it, which leads to energy dissipation. Tinkham[4] developed a phenomenological theory, which was later developed along microscopic lines by Gor'kov and Kopnin,[5] according to which another energy dissipation mechanism ought to exist in the vortex motion, along the mechanism of Bardeen and Stephen. This mechanism is connected with the fact that the finite time τ of relaxation of the ordering parameter Δ towards its equilibrium value can lead to a retardation of the ordering parameter; therefore when the vortex moves the value of Δ at each point differs from the equilibrium value by an amount proportional to τ and v_L (v_L is the velocity of the vortex). This circumstance leads to losses comparable in order of magnitude with the dissipation losses of Bardeen and Stephen.

A third theoretical model, due to Clem,[6] is based on the assumption that there exists an additional energy dissipation, which is determined by the local temperature gradient near the core of the moving vortex. Finally, Kupriyanov and Likharev[7] have shown within the framework of the model of Gor'kov and Kopnin[5] that the results both of Tinkham and of Bardeen-Stephen could be obtained from the microscopic theory. It should be noted that if each of the enumerated mechanisms of vortex retardation in type II superconductors really existed, then the value of the viscosity coefficient measured experimentally would be the sum of the absorption coefficients due to each of the possible mechanisms.[7]

In all the theoretical works mentioned, type II superconductors were considered in the range of relatively small magnetic fields, when the vortices can be regarded as individual, i.e., $d \gg \xi(T)$, where d is the distance between vortices and $\xi(T)$ the coherence length. In the range of fields shown, the value of the viscosity coefficient does not depend on the magnetic field.

It was shown in[2] that the viscosity coefficient η and the differential resistance of the type II superconductor ρ_f are connected by the simple relation

$$\eta = \phi_0 H / \rho_f c^2, \tag{1}$$

where φ_0 is the magnetic flux quantum. Therefore, the experimental determination of the viscosity coefficient in bulk type II superconductors reduces to the measurement of the differential resistance.

The rather large amount of experimental researches in which the energy dissipation has been measured in the resistive state of type II superconductors have not, in our opinion, led to any definite confirmation (or refutation) of any particular model. This is evidently connected with two circumstances: first, the insufficiently clearly determined dependences of the differential resistance ρ_f on the temperature and the field, and, second, the inadequate interpretation of the experimental data, which is already manifest in the fact that comparison is made with the Bardeen-Stephen theory, which was constructed for pure type II superconductors, while the experiment has been carried out for the most part (with the exception perhaps, of niobium) on dirty type II superconductors, where the free path length is $l \ll \xi_0$.

In the present work, a detailed study is made of the dependences of the differential resistance on the magnetic field and the temperature for superconducting 76 at.% Pb—24 at.% In alloy, with the aid of ascertaining the temperature dependence of the coefficient of viscosity in the vortex motion and the experimental testing of the existing models of energy dissipation in type II superconductors.

1. METHOD OF MEASUREMENT

The measurements were carried out on polycrystalline samples and single crystals of the 76 at.% Pb—24 at.% In alloy. High purity Pb and In were used as initial materials. The samples were prepared in the form of cylinders and plates. The volt-ampere characteristics (VAC) were studied as functions of the magnetic field and the temperature. In all the measurements, the transport current was directed along the long axis of the sample, and the magnetic field was perpendicular to the current. The accuracy of the measurement and the stability of the temperature is equal to 0.003°K for $T < 4.2$°K and 0.1°K for $T > 4.2$°K, ($T_c = 6.85$°K). The error in the determination of the relative temperature near T_c is ±2%.

To perform the measurements as close as possible to H_{c1}, where the vortices can assuredly be regarded as independent, it was necessary to take steps to decrease the pinning forces and consequently the critical currents J_c. As has been shown previously,[8] J_c in this case is determined in the ground state of the surface layer and is considerably reduced by chemical polishing of the surface. Here the anisotropy of the critical current on the single-crystal samples is seen to be comparatively small, while there is only a single linear portion on the VAC of samples with polished surfaces in practically every case. This is in contrast with samples with large values of the surface pinning forces, where there are two linear portions.[9] For this reason, the interpretation of the results is simple. In the experiments that were carried out, most of the samples were subjected to chemical polishing. The orientation of the samples relative to the magnetic field was so chosen that the values of J_c were minimal. In the case of plates, the field was perpendicular to the broad faces, which also corresponds to minimal J_c.

For accurate determination of the location of the linear portion on the volt-ampere characteristics, direct recording of the values of the derivative dV/dJ as a function of the current was carried out in many cases, in addition to graphic differentiation of the volt-ampere characteristics.

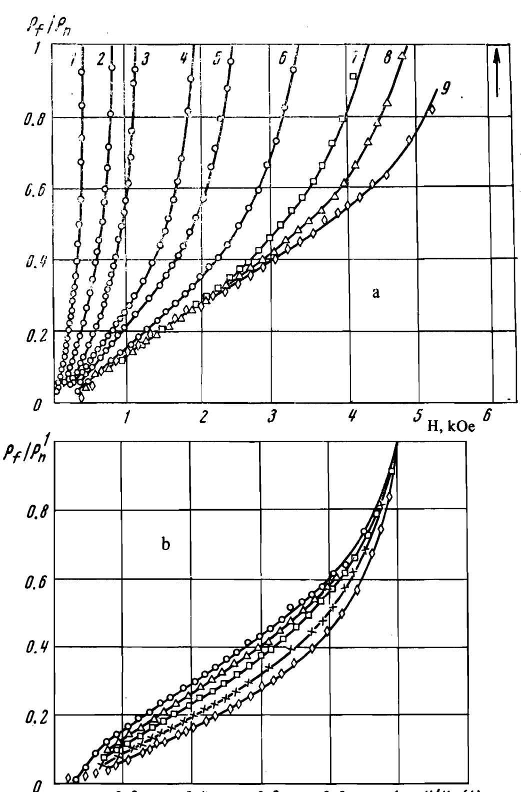

FIG. 1a. Dependence of the differential resistance on the magnetic field in sample I (plate 13 × 2 × 0.2 mm) at different temperatures (in °K): curve 1—T = 6.53; 2—6.24; 3—5.96; 4—5.36; 5—4.97; 6—4.22; 7—3.456; 8—2.8; 9—2.034. The magnetic field was perpendicular to the broad side of the sample. The arrow indicates the value of $H_{c2}(0)$. 1b—Dependence of the differential resistance on the reduced magnetic field $H/H_{c2}(t)$ in sample I for various temperatures (in °K); ○—T = 2.034; △—2.8; □—3.456; +—5.36; ◇—6.53.

2. EXPERIMENTAL RESULTS

Figure 1a shows the dependence of the differential resistance on the magnetic field at various temperatures for one of the samples. The same data are plotted in Fig. 1b in the coordinates ρ_f/ρ_n vs $H/H_{c2}(t)$, where ρ_f is the differential resistance, ρ_n the specific resistance of the alloy in the normal state, $t = T/T_c$ the reduced temperature, and $H_{c2}(t)$ the upper critical field for the given temperature. As will be shown below, such a choice of variables guarantees a significantly better possibility of analysis of the experimental data and comparison with theory than in the case of the coordinate H usually employed by other authors. Figure 2 shows the dependence of ρ_f/ρ_n on the reduced magnetic field for another sample. The value of H_{c2} for a given temperature was determined both from measurements of the magnetization and from curves of the dependence of $\rho_f/\rho_n(H)$ and $J_c(H)$. All three methods of determination of H_{c2} give good agreement. Our data on $H_{c2}(t)$ agree well with the published values.[10]

Figure 3 gives the dependence of ρ_f/ρ_n on temperature for various fixed values of the magnetic field H for sample II. In the range of comparatively low temperatures, a small minimum of ρ_f/ρ_n is observed that is similar to that found in the researches of other authors.[11-13] The experimental results shown in Figs. 1a and 3 are in qualitative correspondence with the literature values. Analysis of the results by means of construction of the curves of $\rho_f/\rho_n(H/H_{c2}(t))$ (see Figs. 1b and 2) allow us to establish certain new regularities, however, along with the known ones. These regularities reduce to the following.

1. The dependence of ρ_f/ρ_n on the reduced magnetic field is shown to be linear in the range of small fields (with the exception of the immediate vicinity of the origin of the coordinates) up to field values $0.5\,H_{c2}(t)$ for all temperatures, and is well approximated by the function

$$\rho_f/\rho_n = a + bH/H_{c2}(t), \tag{2}$$

where a and b are constants which depend only on the temperature.

2. For $H/H_{c2}(t) > 0.5$, the dependence $\rho_f/\rho_n(H/H_{c2}(t))$ departs from linear; ρ_f/ρ_n increases with $H/H_{c2}(t)$ more rapidly than in the small field region.

3. A similarity is observed for curves $\rho_f/\rho_n(H/H_{c2}(t))$ pertaining to different temperatures. A comparison of the values of ρ_f/ρ_n in the same relative field shows that the change in the temperature of the sample over a wide range leads only to a comparatively small (and monotonic) change in the differential resistance for a fixed value of the reduced magnetic field.

The origin of the first term a in the expression (2) is not entirely clear but its relative value is small. Taking this into account, it is easy to see in (2) the generalization of the well-known formula of Kim:[2]

$$\rho_f/\rho_n = H/H_{c2}(0). \quad (3)$$

In fact, transforming (3), we obtain

$$\frac{\rho_f}{\rho_n} = \frac{H_{c2}(t)}{H_{c2}(0)} \frac{H}{H_{c2}(t)}. \quad (4)$$

If the condition (3) is satisfied, then it follows from a comparison of (4) and (2) that $b = H_{c2}(t)/H_{c2}(0)$. However, the dependence of the quantity b on the temperature and the temperature dependence of $H_{c2}(t)/H_{c2}(0)$ do not agree anywhere with the exception of a single point. Therefore one must undoubtedly write the empirical law of Kim in the form

$$\frac{\rho_f}{\rho_n} = \frac{H}{H_{c2}(0)} f(t), \quad (5)$$

where, in contrast with the assumption of Kim,[2] one cannot assume $f(t) = 1$ even for low temperatures.

Thus, in the most general form, the empirical dependence of the differential resistance on the magnetic field can be written in the form (2). The advantage of such a way of writing is that, in contrast with the variables $H/H_{c2}(0)$ and $f(t)$ that enter into (5), the variable $H/H_{c2}(t)$ has the explicit physical meaning of the fraction of the normal phase, inasmuch as $H/H_{c2}(t) = 2\pi\xi^2(t)/d^2$.

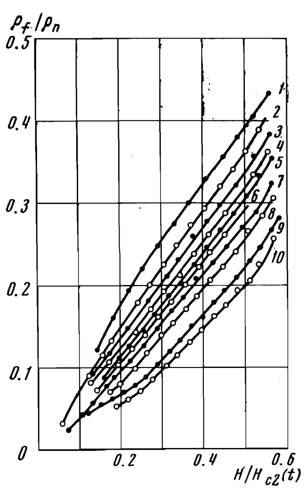

FIG. 2

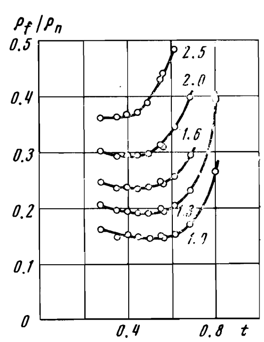

FIG. 3

FIG. 2. Dependence of the differential resistance on the reduced magnetic field $H/H_{c2}(t)$ for different temperatures (in °K) in the range of fields to 0.5 $H_{2c}(t)$ for sample II (a single crystal of cylindrical shape, diameter 0.75 mm, length 12 mm): curve 1–1.9; 2–2.735; 3–3.056; 4–3.4; 5–3.782; 6–3.871; 7–4.22; 8–4.72; 9–5.5; 10–6.06. The scale on the ordinate is increased relative to Fig. 1a, in order to locate the greater number of curves.

FIG. 3. Dependence of the differential resistance on the relative temperature for different fixed values of the magnetic field on sample II. The numbers on the curves give the value of the magnetic field in kilooersteds.

Using (1), we can easily express the quantity b in terms of the viscosity coefficient

$$b = \frac{\partial(\rho_f/\rho_n)}{\partial(H/H_{c2}(t))} = \frac{\phi_0 H_{c2}(t)}{\eta\rho_n c^2}, \quad (6)$$

and thus 1/b represents the value of the viscosity coefficient in units of $\varphi_0 H_{c2}(t)\sigma_n c^{-2}$, which can be compared with the conclusions of the various theories if 1/b does not depend on the coupling forces.

Figure 4 shows the dependence of 1/b on the temperature for several samples of the Pb (76 at.%) – In (24 at.%) alloy. There is excellent agreement between the values of 1/b for samples of various geometry even with different coupling forces. (The linear density of the surface critical current for sample II amounts to 2.7 A/cm; for sample III–3.7 and 6.6 A/cm at minimum J_c, respectively; all the values were taken for $T = 4.22$°K and $H = 0.4H_{c2}(t)$. The values of 1/b for the minimum and maximum J_c on sample II agree with with[14].

As is seen from the drawing, the viscosity coefficient (in units of $\varphi H_{c2}(t)\sigma_n c^{-2}$) increases with increase in temperature.

3. DISCUSSION OF RESULTS

In this section, we pause to consider the behavior of the differential resistance and the viscosity coefficient in the region of comparatively weak small fields, and compare the obtained results with the existing theoretical representations on the viscosity coefficient in the case of motion of individual vortices.

We must first make several preliminary remarks.

1. The condition $d \gg \xi(t)$ for the superconductor studied by us ($\kappa(1) = 4.8$; $\kappa(0) \approx 6.5$; $H_{c2}(0) = 6.1$ kOe) is strictly observed only in a small range of fields; however, the fact that up to $0.5H_{c2}(t)$ a linear dependence of ρ_f on $H/H_{c2}(t)$ exists, and consequently, no change in the viscosity coefficient takes place, gives us a basis for assuming that the interaction between the vortices still does not play an important role, and becomes significant only for fields $> 0.5H_{c2}(t)$.

2. In all the theories that consider the viscosity, it is assumed that all the vortices participate in the motion and that the current is uniformly distributed over the sample. In comparison of the experimental results with the theoretical, one must be sure that these conditions are observed in the experiment.

It is known that the critical current corresponding to the onset of motion of the vortices flows principally in the surface layer.[15,8] with increase in the transport current and the magnetic field, the current distribution over the sample becomes more homogeneous.[14,16-18] Evidently, the very motion of the vortices leads to an averaging of the current over the entire volume. It can be assumed that the current distribution in the region of linear portions of the VAC is sufficiently homogeneous.

The differential resistance is determined from the linear sections of the VAC. The initial parts of the VAC are nonlinear. A number of explanations have been advanced to account for the nonlinearity of the

VAC at currents close to critical.[19-24] It seems to us that the principal reason for the nonlinearity of the VAC in this section is the mechanism considered by Baixeras and Fournet,[22] which is that in the region of current change, an increase takes place in the number of moving vortices with increase in the current. The results of experiments on the study of noise in type II superconductors serve as a confirmation of this.[25] Evidently, the straightening of the characteristics signifies that all the vortices take part in the motion.

Thus, for values of the current not too close to J_c, and in the region of the linear portions of the VAC, it can be assumed that the fundamental premises of the theory are satisfied. The considerations set forth above show that the value of $1/b$ obtained from experiment (Fig. 4) can actually be compared with the corresponding values obtained theoretically.

First of all, we compare the value of the viscosity coefficient obtained in the present work with the microscopic theory.[5,7] For superconductors with a high concentration of nonmagnetic impurities, and as $T \to T_c$, it follows from this theory that

$$\eta = \tfrac{1}{2}a(\gamma_0 + \beta T_c/\Delta)\varphi_0 H_{c2}(t)\sigma_n c^{-2}. \qquad (7)$$

The factor in front of $\varphi_0 H_{c2}(t)\sigma_n c^{-2}$ is the theoretical value of $1/b$. In Eq. (7), β is a free parameter ($\beta > 0$), the value of $\tfrac{1}{2}\alpha\gamma_0$, which determines the lower limit of the viscosity coefficient, is equal to ≈ 1.47.[7] This quantity is represented by the dashed line in Fig. 4. For small β and at temperatures not too far from T_c, the value of $1/b$ should approach 1.47. The experimental values of $1/b$ for $t \leq 0.4$ agree well with this quantity. It is seen from Fig. 4 that, in qualitative agreement with (7), an increase is observed in the viscosity coefficient with increase in temperature; however, there is no proportionality between $\eta(t) - \eta(0)$ and $1/\Delta(t)$ over the entire temperature range.

It is of interest to note that comparison of the experiment with the earlier phenomenological theories shows good agreement. It should be emphasized that the alloy studied in the present work belongs to the class of dirty superconductors. The value of the parameter $\rho = 0.882\,\xi_0/l$, which was introduced by Gor'kov[26] and which characterizes the degree of purity of the sample, is equal to 17 for the alloy with 24 at.% In, i.e., the condition for the dirty limit $l \ll \xi_0$ is well satisfied.

As Galaĭko has shown[27] mention of this is contained in[3]), in the case $l \ll \xi_0$, and within the framework of the Bardeen-Stephen mechanism, the dissipation outside the core of the vortex is about one half that in the core, which ought to lead also to a value of the viscosity coefficient half the size of that in the case $l \gg \xi_0$, the case considered by Bardeen and Stephen. According to the estimates of Galaĭko, for $l \ll \xi_0$, the viscosity coefficient associated with normal losses is

$$\eta_n \approx 0.55\, H_{c2}(t)\varphi_0\sigma_n c^{-2}. \qquad (8)$$

The value of η computed in this fashion is much less than that obtained experimentally (see Fig. 4). One can therefore draw the conclusion that account of one of these mechanisms is insufficient for the explanation of the experimental data.

We now estimate the viscosity coefficient, taking into account the mechanism of energy dissipation proposed by Tinkham as well as the Bardeen-Stephen mechanism. (The Tinkham method is briefly described in the introduction of this paper.) This is made more necessary by the fact that Eq. (8) does not give the temperature dependence of $1/b$. According to Tinkham, in the presence of relaxation losses only, the following expression is obtained for the viscosity coefficient:

$$\eta_\tau = \tfrac{1}{4}\alpha H^2_{cm}(t)\,G^2(H,T)\tau, \qquad (9)$$

where $G^2(H, T) = |\Delta(H, T)/\Delta(0, T)|^2$ is a quantity which reflects the change in the order parameter with magnetic field, $H_{cm}(t)$ is the thermodynamic critical field, τ is the relaxation time, and α is a numerical factor of the order of unity. Replacing $H_{cm}(t)$ by $H_{c2}(t)$ and the penetration depth $\delta(t)$, and expressing $\tau/\tau(0)$ in terms of $H_{c2}(0)/H_{c2}(t)$,[28] we obtain the following expression for η_τ

$$\eta_\tau = \frac{\alpha\pi}{4}\frac{H_{c2}(0)}{H_{c2}(t)}\frac{\delta^2(0)}{\delta^2(t)}G^2(H,T)\varphi_0 H_{c2}(t)\sigma_n c^{-2}. \qquad (10)$$

Tinkham proposed to approximate $G^2(H, T)$ by the expression $1 - (H/H_{c2}(t))^2$. Inasmuch as $(H/H_{c2}(t))^2$ is small in comparison with unity in the range of fields under consideration, and the experimental data are well described by a linear dependence on H, this factor in (10) will be omitted in what follows. The total viscosity coefficient η is a sum of the two coefficients:

$$\eta = \eta_n + \eta_\tau. \qquad (11)$$

Figure 4 shows the values of the viscosity coefficient calculated from Eq. (11), in addition to the experimental data. Here we have used the temperature dependence of δ for the dirty limit in the form[29]

$$\delta^2(t) = \frac{c^2}{4\pi^2}\frac{\hbar}{\Delta\sigma_n\,\mathrm{th}\,(\Delta/2kT)}, \qquad (12)$$

and the coefficient α is so chosen that the best agreement is obtained between the experimental and theoretical curves ($\alpha = 0.93$). As is seen from Fig. 4, the agreement between the experimental and theoretical values of $1/b$ is quite satisfactory.

There is no necessity of calling on the additional mechanism proposed by Clem (besides the mechanisms mentioned above) in order to interpret the experimental data, since the change in the viscosity coefficient with change in temperature is monotonic. The relative value of the minimum of ρ_f/ρ_n is small (Fig. 3) and, judging from the experimental data, its appearance is connected with different temperature dependences of the quantities a and b in (2). While b is the same for

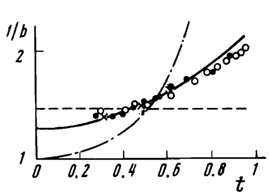

FIG. 4. Dependence of the viscosity coefficient on the relative temperature (samples I, II and III; sample III—single crystal with etched surface): ○—sample I, ●—II, ×—III. The solid lines gives the dependence of the viscosity coefficient on t from (11). The dashed line gives the minimum value of the viscosity from (7). The dot-dash line is the value of 1/b from the empirical formula of Kim (4). All the values of the viscosity coefficient are given in units of $\varphi_0 H_{c2}(t)\sigma_n c^{-2}$.

all the samples, the values of a for different samples are different. In particular, this determines the fact that the temperature at which the minimum of ρ_f is achieved is different for the various samples.

It must be observed that there is a small systematic error in the values of the viscosity coefficient that we have determined. This is connected with the difference between the magnetic induction B in the sample and in the external magnetic field H. One must replace H by the quantity B in the exact expression for ρ_f (Eq. (2)). Since the difference mentioned is small in the ranges of fields studied, this error is very insignificant.

Preliminary data obtained by us in samples of PbIn alloy with other concentrations of the components show that all the regularities discovered here are realized also for the other alloys of this system. It must be emphasized that the results obtained here in no way contradict the results of other investigations of the differential resistance in type II superconductors. On the contrary, a treatment similar to that carried out by us in this research, of all the existing experimental results of other authors (in those cases, of course, in which the published data allow such a treatment) shows that the regularities mentioned here are general; departures from the empirical law of Kim take place for all type II superconductors, and it must be assumed that for all temperatures up to T_c, a linear dependence of ρ_f/ρ_n on $H/H_{c2}(t)$ exists in the weak-field region. This was not noted in the other investigations for two reasons: first, because in the range of fields $<0.5H_{c2}(t)$ and at high temperatures, the quantity ρ_f was as a rule determined at two or three points (see, for example,[30,31]); second, that the particularly important assumption that ρ_f/ρ_n should satisfy the empirical law of Kim in the form $\rho_f/\rho_n = H/H_{c2}(0)$ leads to the result that the lack of correspondence to this law was perceived as the absence of linearity generally. It should be recalled that the special case of non-observance of the empirical law of Kim has already been noted in one of the recent papers.

CONCLUSIONS

1. Measurements of the value of the viscosity coefficient in the range of relative temperatures 0.27—0.95 were made on several samples of the PbIn alloy with concentration of 24 at.% In. Satisfactory agreement was found between the experimental data and the minimum value of the viscosity coefficient obtained from the microscopic theory.[5,7]

2. The value and the temperature dependence of the viscosity coefficient are well described by the phenomenonological theories[4,27] for the dirty limit under the assumption that the dissipation of energy is connected both with the normal and the relaxation losses.

3. It is shown that the differential resistance of all type superconductors does not obey the empirical rules of Kim.[2] New regularities have been found which give a good description of the differential resistance in the range of fields up to 0.5 $H_{c2}(t)$ for all temperatures.

In conclusion, the author thanks I. M. Dmitrenko for attention to the research, V. P. Galaĭko and K. K. Likharev for useful discussions, and also considers it his pleasant duty to give recognition to A. A. Konyukhov, in cooperation with whom the measurement of magnetization were carried out, and M. Yu. Kupriyanov and K. K. Likharev for making their results available before publication.

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