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Irreversible magnetostriction and magnetization of the superconduting $2H$-$NbSe_2$ single crystals in a peak-effect regime

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Magnetostriction measurements in the mixed state of superconducting $2H$-$NbSe_2$ single crystals under in-plane magnetic fields 0–12 T have revealed a peak on the magnetostriction versus magnetic field dependences in the vicinity of the upper critical field H_{c2} . The peak value of the longitudinal magnetostriction is higher by more than an order of magnitude in comparison with that of the transverse magnetostriction when measured along the hexagonal axis. Analysis of the measured field dependences of the magnetostriction and magnetization of $2H$-$NbSe_2$ allows one to relate the observed peculiarities of magnetostriction with the loss of order in the lattice of Abrikosov vortices, which occurs by a first-order phase transition.

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1. Introduction

The observation of giant magnetostriction in high-temperature superconductors [1–3], along with establishing its relation to the interactions between the crystal lattice inhomogeneities and the arrangement of Abrikosov vortices [4], enables one to use magnetostriction measurements as the tool for examination of a variety of phenomena in the vortex assembly, which results from magnetic flux pinning. An important direction in this field of investigation is elucidation of the origin of the peak effect, which is the peak on the field dependences of the critical current near the upper critical field H_{c2} , manifested as the maximum on the field dependences of the irreversible magnetization [5], and of its connection with the phase transitions in a flux-line lattice [6]. It should be mentioned that an advantage of magnetic studies of the peak effect is that they provide direct data on the thermodynamic parameters of the transition.

Many years of research on the field dependences of the critical currents and magnetization of type-II superconductors have shown that in general the peak effect is observed in different ranges of magnetic fields between the lower H_{c1} and upper H_{c2} critical fields, and the shape of the peak is described by an expression $(H_{c2})^n f(b)$, with $f(b)$ similar at all temperatures below T_{SN} , where b is the reduced magnetic induction in the sample, and $n = 1$–3, depending on the type of pinning center and the pinning mechanism involved [5]. The peaks on the field dependences of the magnetostriction were observed in [2,7,8] on single crystals of high-temperature superconductors (HTSCs) of the 1-2-3 type with rare-earth substitutions, polycrystals of Nb–Ti alloys, and single crystals of the layered compound 2*H*-$NbSe_2$, respectively. For HTSCs it was shown [2] that the peaks in the intermediate field range correspond to the traditional mechanisms of pinning ($n = 2.5$). For explanation of the observed value $n = 4.5$ for the magnetostriction peak in Nb–Ti the field dependence of the Young's moduli of the crystal lattice was taken into account. The value $n = 6.5 \pm 0.2$ for the magnetostriction in 2*H*-$NbSe_2$ will be analyzed in the present work.

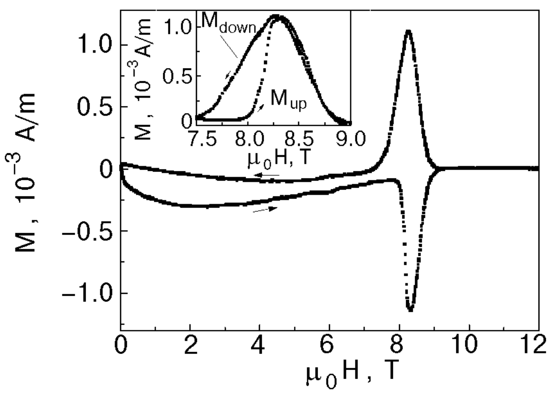

Fig. 2. Absolute magnetization measurements along the *c* direction for an in-plane direction of the magnetic field. The inset shows the enlarged region of the peak effect.

2. Experimental results

The measurements were performed on high-quality single crystals of the superconducting compound 2*H*-$NbSe_2$ with the superconducting transition temperature $T_{SN} = 7.2$ K.

2.1. Magnetostriction measurements

The magnetostriction measurements were performed in a cryogenic capacitance dilatometer [8]. The longitudinal $\lambda(a,a)$ and transverse $\lambda(c,a)$ magnetostriction values were measured in a field applied in the basal plane of the sample along the *a* axis. The measurements of $\lambda(c,a)$ and $\lambda(a,a)$ in increased field at temperature $T = 1.5$ K are presented in Fig. 1. It is clearly seen that at fields near H_{c2} a pronounced peak is observed, and the absolute values of $\lambda(c,a)$ are much lower than those for $\lambda(a,a)$.

2.2. Magnetization measurements

The magnetization measurements were performed along the crystallographic *c* direction by means of a magnetic capacitance torquemeter technique [9]. The absolute values of the magnetization were obtained using a calibration coil [10].

The measurements at temperature $T = 1.5$ K are shown in Fig. 2. Figure 3 presents irreversible component of magnetization for different temperatures. Figure 4 demonstrates irreversible magnetostriction and magnetization in reduced coordinates. For the magnetostriction and magnetization measurements the scaling law with $n = 6.5 \pm 0.2$ is fulfilled.

3. Discussion

The unit cell of this compound comprises two sandwiches. Each of them is a hexagonally packed plane of Nb between two hexagonally packed planes of Se. The planes are shifted with respect to each other, and atoms of Se form a trigonal environment of the Nb atoms. The Nb planes are respon-

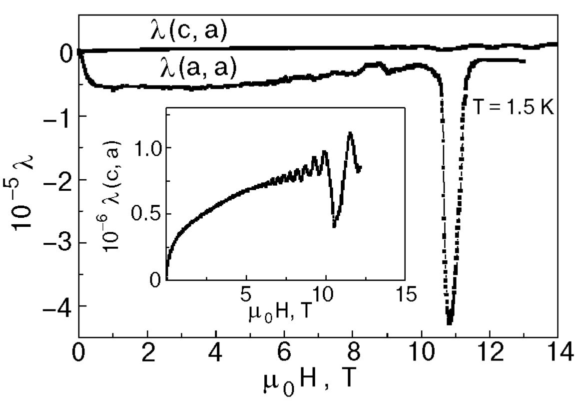

Fig. 1. Magnetostriction λ versus magnetic field measurements.

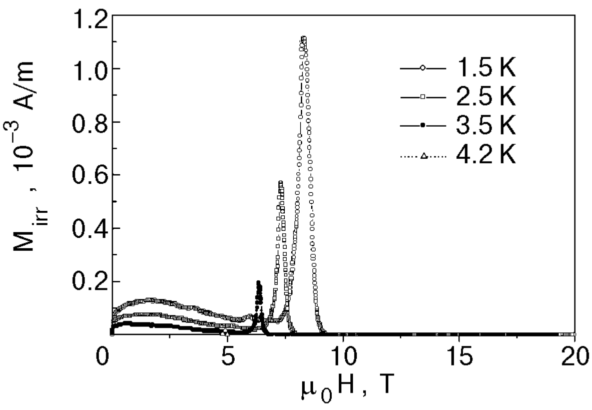

Fig. 3. Field dependence of the irreversible magnetization.

sible for the superconductivity of this compound. The distance between the nearest Nb planes is $d = c/2 = 6.27$ Å where c is the lattice spacing along the hexagonal axis. The in-plane lattice parameters are $a = b = 3.45$ Å. The ratio of the lattice parameters attests to pronounced crystallographic anisotropy. At the same time $2H$-NbSe$_2$ should not be considered as quasi-two-dimensional superconductor, as its superconducting coherence length along the hexagonal axis is twice the interplane spacing $\xi_c > d$ ($\xi_c(0) = 23$ Å). This is a typical highly anisotropic superconductor ($\xi_{ab}(0) = 78$ Å), which is characterized by an anisotropy parameter $\gamma = (M/m)^{1/2} = \xi_{ab}/\xi_c \approx 3$, or in alternative definitions $\varepsilon^2 = m/M \approx 0.09$ ($m = m_1 = m_2$ and $M = m_3$ are the effective electron masses along and normal to the crystallographic planes). Such high values of the anisotropy parameters of $2H$-NbSe$_2$ provide an adequate description of its superconducting properties by the Ginzburg–Landau equations [11] with the anisotropic mass tensor ([12] and references therein). For our case $m_1 = m_2 < m_3$; $m_1/m_3 = [H_{c2}(\|c)/H_{c2}(\perp c)]^2$. We take into consideration the following expression

$$H_{c2}(\theta) = \Phi_0 / [2\pi(\sin^2\theta + \varepsilon^2 \cos^2\theta)^{1/2}\xi_{ab}^2] \quad (1)$$

(Φ_0 is the quantum of magnetic flux, and θ is the angle between the direction of the applied magnetic field and the c axis), which defines the coherence length values.

Validity of this approach significantly simplifies analysis of the angular dependences of the measured properties, which in part will be considered in this paper.

3.1. Anisotropy of magnetostriction at $H_{c1} < H << H_{c2}$

The observed differences of $\lambda(c,a)$ and $\lambda(a,a)$ in the fields below the peak values may be explained in the following way. In fields applied along the extended surface of the sample in the a axis direction, magnetic flux penetrates the sample along the b axis. Under this condition the penetration is postponed by a surface barrier until the magnetic field H is increased to the value $H \approx 2.7H_c$ [5], where H_c is the critical field, which is determined by the difference of free energy values in the normal and superconducting states, and which is much higher than H_{c1}. The low-temperature limit of H_c for the compound under investigation is $H_c \approx 0.14$ T [13]. In this range of magnetic fields the magnetostriction is determined by the pressure of the magnetic field and by the ratio of elastic constants in different crystallographic directions. From the theory of elasticity the relation between $\lambda(c,a)$ and $\lambda(a,a)$ may be derived:

$$\lambda(c,a)/\lambda(a,a) = -C_{13}(C_{11} - C_{12})/(C_{11}C_{33} - C_{13}^2).$$

The right side of this relation includes the components of the elastic-modulus tensor of the crystal lattice. Introducing their values from [13], one obtains the ratio $\lambda(a,a)/\lambda(c,a) = -0.76/0.12 = -6.3$, which is in good agreement with the measurements in fields well below H_{c2}. When the magnetic flux penetrates the sample along the b axis, the values of $\lambda(c,a)$ are determined by the ratios of the volumes of the normal and superconducting parts of the sample [8] and are proportional to the size differences $\delta_T(\|c)$ in the normal and superconducting states along the distinguished crystallographic direction in the absence of magnetic field. This quantity is determined by relation $\delta_T(\|c) \sim H_c[\partial H_c/\partial P(\|c)]$, or according to [13] $\delta_T(\|c) \sim H_c^2/T_{SN}[\partial T_{SN}/\partial P(\|c)]$. Substitution of the values $\partial T_{SN}/\partial P(\|c) \approx \approx 1.8 \cdot 10^{10}$ from [14] gives a satisfactory agreement with the measurements [8] $\delta_T(\|c) \approx 2 \cdot 10^{-7}$. It is known [14] that the in-plane pressure dependence of T_{SN} differs significantly from that in the c direction. Pressure along the c axis weakly increases the transition temperature, while in-plane pressure increases it significantly. In first approximation it should be assumed that the below peak values, $\lambda(a,a)$ is also defined by the volumetric ratio of the normal part of the sample due to weak pinning (the ratio of the critical currents of depinning and depairing $j_c/j_0 \approx 10^{-6}$ [15] is surprisingly small). Therefore, the ratio of $\lambda(c,a)$ to $\lambda(a,a)$ in the field below peak is defined by the relation $[\partial T_{SN}/\partial P(\|c)]/[\partial T_{SN}/\partial P(\perp c)] \approx 0.45$ [15], which satisfies the experimental data for the reversible component of the magnetostriction [8]. It appears that for explanation of the irreversible magnetostriction we cannot neglect the pinning in the basal plane parallel to applied magnetic field.

3.2. Magnetostriction in the fields near H_{c2}

In [16,17] the peak effect in the field dependences of the critical currents near H_{c2} was attributed to the change of the elastic moduli of the flux-line lattice when the field approaches H_{c2}. In [16] it was the decrease of the shear modulus C_{66}, which occurs faster than the decrease of the pinning force. As a result, the vortexes redistribute in accordance with the spatial distribution of pinning centers or the pinning potential relief. This situation corresponds to a loss of spatial order in the flux-line lattice and, in principle, resembles melting processes. It was described in [18] in terms of the correlation volume V_c of the flux-line lattice regions which can move independently of each other. The results of this work have been used successfully for examination of transformations in the vortex arrays of anisotropic superconductors. The possibility of transformations developing via a first-order phase transition was analyzed in [19]. It was suggested that the transition is realized in the fluctuation regime when the Lindemann criterion [20] is fulfilled, i.e. when the mean-square amplitude of the vortex fluctuation displacements amounts to about $0.2a_0$, where a_0 is the vortex lattice parameter. It is a result of the loss of order in the vortex lattice or the decrease of V_c when the magnetic field approaches H_{c2}. A comparative analysis of the magnetostriction and magnetization measurements allows us to check if this situation is characteristic for our case. It should be noted that a fluctuation contribution to the behavior of superconducting $2H$-$NbSe_2$ is probable, as the Ginzburg number [21], which characterizes importance of the fluctuation contribution, is rather high: Gi $= k_B T_{SN} / H_c^2 \varepsilon \xi^3 \approx 10^{-4}$. For HTSCs it is of the order of 10^{-2}, and for other conventional superconductors it is of the order 10^{-8} [15]. This is, in part, the reason for the noticeable difference between the fields H_{c2} and H^*, where H^* is the field above which all irreversible characteristics vanish ($H^* \approx H_{c2}$). The advantage of $2H$-$NbSe_2$ for analysis of the transition processes is that, in contrast to HTSCs, there is no flux creep in it, notwithstanding the high level of thermal fluctuations. In addition, the inset in Fig. 2 demonstrates that in the peak regime the magnetization run (the low-field arm of the peak) is irreversible. It may be a proof of the first-order phase transition, on the one hand, and a manifestation of vortex lattice disordering and the consequent spread over pinning centers, on the other. So, the experimental data do not contradict the proposed description.

In comparing the data on the magnetostriction and magnetization we should keep in mind that in the latter case the torque was registered in a tilted field, which is a necessary condition for application of such a measuring technique. The chosen value $\theta = 77°$ corresponds to the maximum signal [22]. Analysis of the angular dependences and comparison of the data obtained at different θ is possible due to applicability of Ginzburg–Landau theory with an anisotropic mass tensor to the compound under study (the relations are presented in [6]).

3.3. Phase transition

In order to analyze the possibility that a first-order phase transition in the vortex array is manifestated in the peak effect, the relation derived for the flux-line lattice from the Lindemann criterion [19,20] will be used:

$$H_m(T) = \beta_m (c_L / \mathrm{Gi}) H_{c2}(0) (T / T_{SN})^2 \times$$
$$\times [1 - (T / T_{SN}) - H_m / H_{c2}(0)]^2 , \qquad (2)$$

where $\beta_m \approx 5.6$, $c_L = 0.23$–0.15 is the Lindemann criterion in systems with variable pinning, and H_m is the melting field of the flux-line lattice. The location of the measured high-field magnetostriction and magnetization peak-effect curves, namely H^*, suits well the value of $H_m(T)$ if the superconducting parameters of $2H$-$NbSe_2$ are substituted into Eq. (2). The experimentally observed jump in the equilibrium magnetization near H^* at $T = 1.5$ K is $\Delta M \approx 5$ G, and the corresponding elongation is $\Delta L \approx 2 \cdot 10^{-8}$ mm. Therefore, the pressure derivative of the transition field may be estimated using the Clapeyron–Clausius relation: $\Delta L(||c) / \Delta M = \partial H^* / \partial P(||c)$. Substitution of the magnitudes obtained gives a reasonable [14] estimate $\partial H^* / \partial P(||c) \approx 0.6$–$0.8$ G / bar.

3.4. Scaling law for isothermal field dependences of magnetostriction

The analysis of the magnetostriction measurements in the peak regime according to the scheme [2,7] have shown that the field dependences of the irreversible component of the magnetostriction $\lambda_{\mathrm{irr}}(c,a)$ measured at different temperatures follow the scaling laws $M_{\mathrm{irr}} \sim (H^*)^n$ and $\lambda_{\mathrm{irr}} \sim (H^*)^n$ with the same power $n = 6.5 \pm 0.2$. Consequently, for analysis of the observed dependences the concepts developed for the trivial peak effect may be used, and the field dependences of the elastic moduli of the crystal lattice may in our case be excluded from consideration of the magnetostriction peak. In view of the softening of the flux-line lattice in a peak effect regime and the independent displacements of its parts with the correlation volume V_c, the relation for collective pinning in the peak region [18] may be used for description of the irreversible magnetization:

$$M_{\mathrm{irr}} \sim (n_p f_p^2 / V_c)^{1/2} , \qquad (3)$$

where n_p is the density of pinning centers, f_p is the elementary pinning force, and $n_p^{1/2} f_p$ is the volume density of the pinning force. Usually, the latter is characterized by a power-law dependence on H_{c2}

with a power of 1–3 for different types of pinning centers [5]. Its contribution to n may be also estimated from analysis of the broad maximum of the magnetization in fields of about $H = 2.4$ T. The nearly same position of the maxima at different temperatures suggests a matching between the flux-line lattice spacing and the distance between the pinning centers involved [5]. The flux-line lattice spacing may be estimated from the well known relation $a_0 \approx (\Phi_0 / B)^{1/2} = 178$ Å, which can easily correspond to the distance between the stacking faults in Nb planes arising below the charge-density-wave transition ($T_{CDW} = 34$ K), with the appearance of an incommensurate structure of niobium atoms, characterized by a lattice spacing of about $3a_0$ [23]. Estimation of the corresponding pinning force from [24] gives the power $n_1 \approx 2.5$.

Now the contribution of the correlation volume V_c will be estimated. It goes as the inverse square of the tilt and shear moduli of the vortex lattice, or $(H_{c2})^{-4}$, which means that expression (3) comprises a multiplicativefactor with the power $n_2 = 2$.

And, finally, the thermofluctuational character of the transition near H^* means that expression (3) should be supplemented by a temperature-dependent factor [25]. It is determined by temperature dependence of the depinning energy for thermal fluctuations, which to a first approximation is linear in the temperature [5]. Using the temperature dependence of the critical fields, a factor with $n_3 = 2$ is obtained.

In this way a total power $n = 6.5$ is obtained, which agrees with that derived from magnetostriction and magnetization measurements in the peak-effect regime.

Conclusions

It was found that the maximum on the field dependences of irreversible magnetostriction in superconducting $2H$-$NbSe_2$ corresponds to the field range of structuraltransformations in the vortex array, which is realized after a first-order phase transition scenario. The measured field dependence in the peak region is described by a scaling law $\lambda_{irr} \sim (H^*)^{6.5\pm0.2}$, similar to that for the irreversible magnetization $M_{irr} \sim (H^*)^{6.5\pm02}$. It is shown that the power $n = 6.5 \pm 0.2$ is determined by the field dependences of the elementary pinning force and correlation volume and by thermal fluctuations near the upper critical field. It should noted that the analysis presented is the first one of this kind, but the similar dependences may be expected for the irreversible magnetostriction in HTSCs in the high-field peak-effect regimes. According to the arguments proposed, in conventional superconductors with a low probability of thermal fluctuations the power of H_{c2} in the high-field-peak scaling law should be a few times lower.

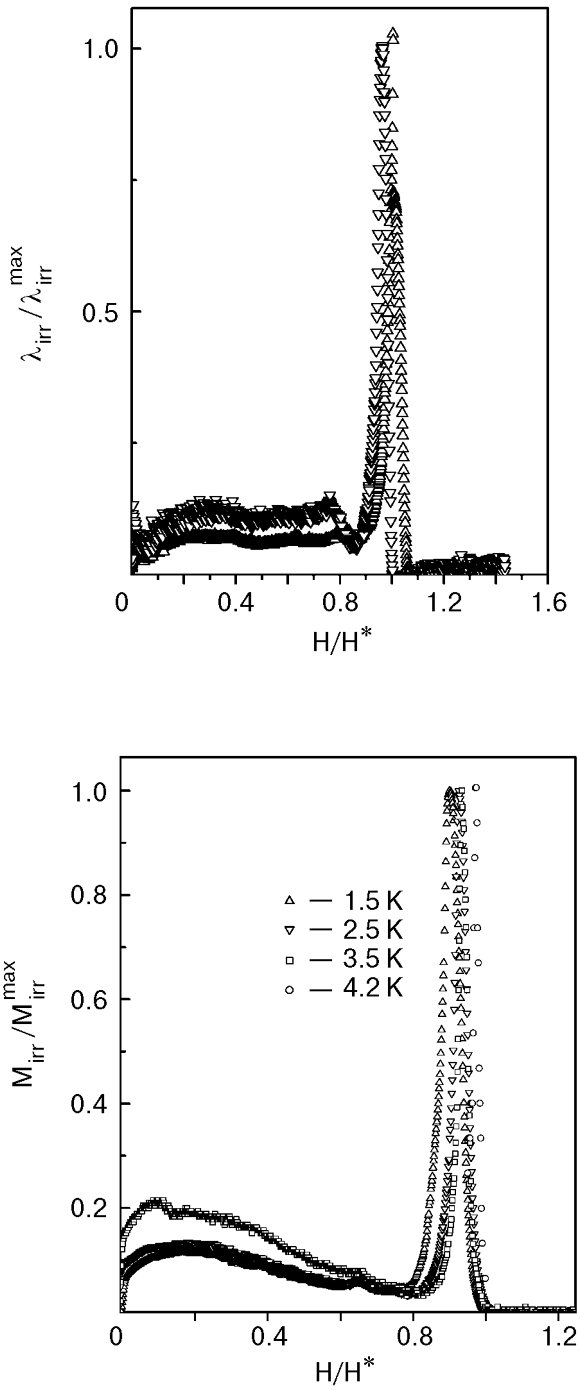

Fig. 4. Reduced field dependence of the irreversible magnetostriction [8] and magnetization, normalized to their values at the peak.

1. H. Ikuta, N. Hirota, Y. Nakayama, K. Kishio, and K. Kitazawa, *Phys. Rev. Lett.* **70**, 2166 (1993).
2. C. de la Fuente, A. del Moral, J. I. Arnaudas, and J. S. Abell, *Physica* **C244**, 214 (1993).
3. V. V. Eremenko, V. A. Sirenko, H. Szymczak, and A. Nabialek, *Fiz. Nizk. Temp.* **25**, 311 (1999) [*Low Temp. Phys.* **25**, 221 (1999)].
4. A. A. Abrikosov, *Zh. Eksp. Teor. Fiz.* **32**, 1442 (1957) [*Sov. Phys. JETP* **5**, 1174 (1957)].
5. A. M. Campbell and J. E. Ivetts, *Critical Currents in Superconductors*, Taylor and Francis LTD, London (1972).
6. G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, *Rev. Mod. Phys.* **66**, 1125 (1994).
7. U. Wyder, P. J. E. M. van der Linden, H. P. van der Meulen, A. Gerber, V. H. M. Duyn, J. A. A. J. Perenboom, A. de Visser, and J. J. M. Franse, *Physica* **B211**, 265 (1995).
8. V. V. Eremenko, V. A. Sirenko, R. Schleser, and P. L. Gammel, *Fiz. Nizk. Temp.* **27**, 412 (2001) [*Low Temp. Phys.* **27**, 305 (2001)].
9. D. Shoenberg, *Magnetic oscillations in metals*, Cambridge University (1984).
10. V. Eremenko, V. Sirenko, Yu. Shabakayeva, R. Schleser, and P. L. Gammel, *Fiz. Nizk. Temp.* **27**, 952 (2001).
11. V. L. Ginzburg, *Zh. Eks. Teor. Fiz.* **23**, 236 (1952).
12. V. G. Kogan and J. R. Clem, *Phys. Rev.* **B24**, 2497 (1981).
13. V. G. Kogan, L. N. Bulaevskii, P. Miranovic, and L. Dobrosavljevic-Grujic, *Phys. Rev.* **B51**, 15344 (1995).
14. T. Sambongi, *J. Low Temp. Phys.* **18**, 139 (1975); P. Molinie, D. Jerome, and A. J. Grant, *Adv. Phys.* **23**, 1091 (1974); M. A. Obolenskii, Kh. B. Chashka, V. I. Beletskii, and V. M. Gvozdikov, *Fiz. Nizk. Temp.* **15**, 984 (1989) [*Low Temp. Phys.* **15**, 544 (1989)]; R. E. Jones, H. R. Shanks, and D. K. Finnemore, *Phys. Rev.* **B6**, 835 (1972); K. Yamaya and T. Sambongi, *J. Phys. Soc. Jpn.* **32**, 1150 (1972).
15. M. J. Higgins and S. Bhattacharya, *Physica* **C257**, 232 (1996).
16. A. B. Pippard, *Philos. Mag.* **19**, 217 (1969).
17. R. Labush, *Phys. Status Solidi* **32**, 439 (1969).
18. A. I. Larkin and Yu. N. Ovchinnikov, *J. Low Temp. Phys.* **34**, 409 (1979).
19. D. R. Nelson and H. S. Seung, *Phys. Rev.* **B39**, 9153 (1989).
20. F. Lindemann, *Phys. Z. (Leipzig)* **11**, 69 (1910).
21. Â. Ë. Ãèíçáóðã, *ÔÒÒ* **2**, 2031 (1960).
22. V. G. Kogan, *Phys. Rev.* **B38**, 7049 (1988).
23. B. Gianbattista, A. Johnson, R. V. Coleman, B. Drake, and P. K. Hansma, *Phys. Rev.* **B17**, 2741 (1988).
24. H. C. Freyhardt, *Proc. Intern. Discussion Meeting on Flux Pinning in Superconductors*, Sonnenberg / Germany (1974), p. 98.
25. L. Niel, *Cryogenics* **32**, 975 (1992).