Restructuring of Abrikosov vortex in a superconductor with a void superlattice

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The interaction between a vortex lattice and an ordered defect structure—a void superlattice—has been studied. If the vortex–defect interaction is sufficiently strong, structures with a constant vortex density are generated in some ranges of magnetic field, and the symmetry of their structures may differ from that of the void-superlattice symmetry. First-order phase transitions in which the structures are changed and second-order phase transitions in which additional vortices or vacancies are generated take place on the boundaries of these ranges. © *1996 American Institute of Physics.* [S1063-7761(96)01302-2]

1. INTRODUCTION

The most remarkable feature of type II superconductors is the creation of the Abrikosov vortex lattice in a magnetic field ranging between the first ($\mathscr{H}_{c1}$) and second ($\mathscr{H}_{c2}$) critical fields.[1,2] In this magnetic-field range the critical supercurrent is determined by the strength of pinning due to the interaction between the vortices and various structural defects. This interaction is strongest in the case of columnar defects generated by heavy ions with an energy of several gigaelectronvolts[3–8] if the magnetic field is aligned with the defect axis of symmetry.[9–11]

It is obvious that the pinning strength has a resonant peak when the defects are ordered and the period of the defect structure is equal to that of the vortex lattice. A detailed analysis of research of the mixed state of superconducting films with periodic defect structures is given in the review by Lykov.[12]

Under certain irradiation conditions, three-dimensional ordered structures—void superlattices—with a symmetry similar to that of the host lattice are generated in metals. A structure of this kind was first discovered by Evans[13] in molybdenum exposed to 2-MeV neon ions. Similar lattices were later detected in various metals, including niobium and its alloys, which are type II superconductors.[14,15]

In a uniform type II superconductor, the mixed state is a regular hexagonal vortex lattice, but the energies of the lattices with different symmetries are only slightly different (e.g., the energy of a hexagonal lattice is 2% higher than that of a tetragonal lattice). Therefore we may expect that the interaction between vortices and an ordered structure of defects can alter the symmetry of the vortex lattice.

The aim of the present work was to study structural phase transitions in an Abrikosov vortex lattice in type II superconductors with a void superlattice under a magnetic field around $\mathscr{H}_{c1}$. We have found that the interaction between voids and vortices may be sufficiently strong to "freeze" a flux lattice commensurable with the void lattice in some interval of the magnetic field. When the magnetic field is changed beyond this range, the vortex lattice may change its symmetry abruptly (a first-order phase transition) or gradually by generating extra vortices or vacancies (a second-order phase transition).

2. FREE ENERGY OF THE SYSTEM

Let us consider properties of a porous superconductor in a magnetic field $H_{c1} \leqslant H \leqslant \kappa H_{c1}$, where H_{c1} is the first critical field and $\kappa = \lambda/\xi$ is the Ginzburg–Landau parameter. In this range the overlap of vortex cores is negligible and the superconductor free energy can be expressed in the pair-interaction approximation:

$$F = \mathscr{E}_0 NL + \frac{L}{2}\sum_{ij} E_{vv}^{ii} + \sum_{ik} E_{vd}^{ik} - \int dV \frac{\mathbf{B}\cdot\mathbf{H}}{4\pi}, \tag{1}$$

where N is the number of vortices in a sample, $\mathscr{E}_0 = (\phi_0/4\pi)H_{c1}$ is the core energy, ϕ_0 is the magnetic flux quantum, E_{vv}^{ij} is the energy of interaction between vortices per unit length, E_{vd}^{ik} is the vortex–void interaction energy, $\mathbf{H}$ is the external magnetic field, $\mathbf{B}$ is the magnetic induction inside the sample, and L is the sample dimension in the field direction.

In the limit of low vortex density, the interaction between vortex lines can be described with high accuracy by the London approximation:[16]

$$E_{vv}^{ij} = \frac{\phi_0^2}{8\pi^2\lambda^2} K_0\left(\frac{|\boldsymbol{\rho}_i - \boldsymbol{\rho}_j|}{\lambda}\right), \tag{2}$$

where $K_0(z)$ is the zero-order modified Bessel function and $\boldsymbol{\rho}_j$ are two-dimensional coordinates of vortices.

We express the pinning energy E_{vd}^{ik} due to the interaction between a void with a radius R ($R \leqslant \xi$) and a vortex as a Gaussian with a width ξ:[17]

$$E_{vd}^{ik} = -\frac{V_{\text{void}}}{\pi\xi^2}\mathscr{E}_0 \exp(-(\boldsymbol{\rho}_i - \boldsymbol{\rho}_k)^2/\xi^2), \tag{3}$$

where $\boldsymbol{\rho}_k$ are two-dimensional radius vectors of defects and V_{void} is the void volume.

3. FREEZING OF VORTEX DENSITY CLOSE TO THE CONDITION FOR COMMENSURABLE LATTICES

Next we discuss the interaction between a vortex lattice and a cubic superlattice of defects with a parameter d when the magnetic field is aligned with one principal crystal axis of the defect superlattice. In the plane perpendicular to the magnetic field, the defects form a tetragonal lattice of pins

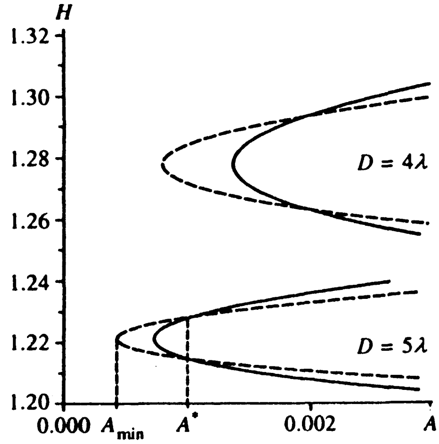

FIG. 1. Critical fields ($\mathscr{H}_{36}$, dashed lines and $\mathscr{H}_{46}$, solid lines) versus the vortex–defect interaction amplitude A in superconductors with different periods of the void superlattice.

with a parameter D ($D=d/2$ for a face-centered cubic superlattice, $D=d/\sqrt{2}$ in a body-centered cubic superlattice, and $D=d$ in a simple cubic superlattice). The conditions for restructuring a hexagonal flux lattice to a tetragonal one are obviously most favorable when the tetragonal-superlattice parameter a_4 is equal to the void-superlattice parameter D, and all the vortices are pinned at defects. In this case the free energy per unit volume for the tetragonal ($i=4$) and hexagonal ($i=6$) vortex lattices can be conveniently presented in a dimensionless form:

$$\mathscr{F}_i=n_i[(\mathscr{H}_{c1}-\mathscr{H})-AS_i+W_i/2], \tag{4}$$

where $\mathscr{F}=F/(\phi_0^2/8\pi^2D^2)V$, V is the sample volume, the magnetic field is expressed in units of $\phi_0/2\pi\lambda^2$, n is the surface density of vortices ($n_6=\sqrt{4/3(D/a_6)}^2$, $n_4=1$), $A=(4R^3/3\xi^2d)\mathscr{H}_{c1}$ is the amplitude of the vortex–defect interaction,

$$W(a)=\sum_j K_0(\rho_j/\lambda)$$

is the interaction energy of one vortex with other vortices, and S_i is the mean number of vortexes in a void ($S_4=1$).

The hexagonal lattice parameter a_6 is determined by minimizing the free energy at a fixed external field ($\partial\mathscr{F}_6/\partial n_6=0$). In calculating S_6 we assume that the flux lattice is not deformed and the vortices are distributed randomly with respect to the ordered defect lattice, from which it follows that $S_6=(\xi/D)^2/2$. In reality, the energy of a destorted hexagonal lattice is slightly lower.

An equation for the critical field $\mathscr{H}_{46}(A)$ at which the tetragonal lattice is transformed to the hexagonal one (solid lines in Fig. 1) is derived from the equality between $\mathscr{F}_6$ and $\mathscr{F}_4$:

$$A(n_6)=\frac{(W_4-W_6)n_4+n_6\partial W_6/\partial n_6(n_6-n_4)}{n_4(S_4-S_6)}, \tag{5}$$

$$\mathscr{H}_{46}(n_6)=\mathscr{H}_{c1}+\frac{n_4(S_4W_6-S_6W_4)+n_6\partial W_6/\partial n_6(n_4S_4-n_6S_6)}{n_4(S_4-S_6)}. \tag{6}$$

Note that besides the tetragonal lattice, another pattern with an equal vortex density can be formed by shifting vortices by half a lattice parameter in odd rows. We shall call this structure a trigonal lattice. It has an elementary cell shaped as an isosceles triangle, which is nearly equilateral since the angle at its base is $\tan^{-1}2$. The energy W_3 of interaction between the vortices in the trigonal lattice is smaller than in the tetragonal one ($W_6<W_3<W_4$), but only half of the vortices are pinned at voids.

Since the vortex densities in the trigonal and tetragonal lattices are equal ($n_3=n_4$), the free energies of these states are equal and do not depend on the external magnetic field. These determines the threshold value $A^*=W_4-W_3$ below which the lattice is trigonal.

For $A<A^*$ the magnetic-field range in which the lattice is trigonal (shown by dashed lines in Fig. 1) is determined by Eqs. (5) and (6) with parameters of the tetragonal lattice substituted with those of the trigonal lattice.

Curves of transition fields for superconductors with different defect-superlattice parameters are given in Fig. 1. One can see that for $A<A_{min}$ the lattice is hexagonal at all magnetic fields. For $A_{min}<A<A^*$ the trigonal structure with a constant vortex density has a lower free energy in the field ranges between the rising and falling parts of the dashed curves ($\mathscr{H}_{36}^-<\mathscr{H}<\mathscr{H}_{36}^+$). For $A>A^*$ the tetragonal vortex lattice has a lower energy than the hexagonal lattice in the magnetic field range $\mathscr{H}_{46}^-<\mathscr{H}<\mathscr{H}_{46}^+$. But in this range it may be less costly in free energy to generate additional vortices or vacancies in the tetragonal lattice, and the free energy of this structure may be lower than in a defect-free superconductor.[18]

4. GENERATION OF DEFECTS IN A VORTEX LATTICE

4.1. Additional vortices

Extra magnetic-flux quanta may be introduced into a superconductor by generating two-quantum vortices.[19] But this configuration has a higher energy if the voids are small, and an additional flux line may be located in a tetragonal lattice in two ways (Fig. 2):

(i) at the center of an elementary cell (Fig. 2a) with an additional interaction energy $\mathscr{E}_1$ between vortices;

(ii) by shifting one host vortex from its equilibrium position and forming a bound pair ("dumb-bell") with the additional vortex (Fig. 2b); in this case we denote the additional energy as $\mathscr{E}_2$.

It follows from the comparison between free energies that generation of additional vortices saves free energy when $\mathscr{H}\geqslant\mathscr{H}_a=\min\{\mathscr{H}_1,\mathscr{H}_2\}$ holds, where

$$\mathscr{H}_j=\mathscr{H}_{c1}+\mathscr{E}_j. \tag{7}$$

The system behavior is determined by the parameters $\mathscr{H}_{46}^+$, $\mathscr{H}_1$, and $\mathscr{H}_2$, which are plotted against the vortex–defect

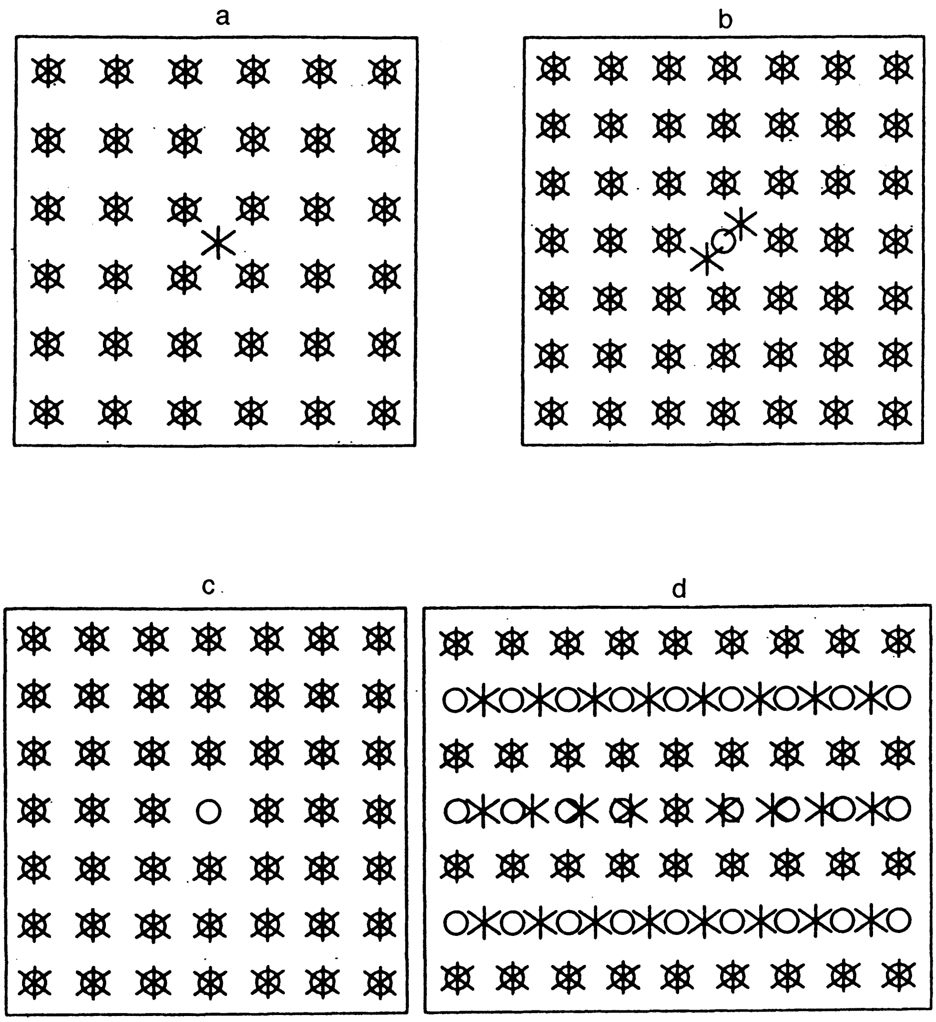

FIG. 2. Generation of defects in a vortex lattice: a) a vortex in the cell centrum; b) displacement of a host vortex from its site and formation of a "dumb-bell" pair with an additional vortex; c) vacancy in a tetragonal lattice; d) trigonal lattice with an extra vortex.

interaction amplitude in a type II superconductor with $\kappa=10$ and a void superlattice with $D/\lambda=5$ in Fig. 3.

The generation of an additional vortex leads to relaxation of the host vortices. It is evident that the "dumb-bell" configuration should occur at a smaller A than that with a vortex at a cell center because it is obvious that a vortex can be more easily torn from its void at a lower interaction amplitude. The function $\mathcal{H}_2(A)$ is linear since the relaxation of other vortices is negligible.

The form of the function $\mathcal{H}_1(A)$ (curve *4* in Fig. 3) can be easily understood using Fig. 4, which shows the free energy as a function of the displacement of neighboring host vortices. The curve of the free energy has two minima. When A is sufficiently large, the narrow minimum is dominant (curve *1* in Fig. 4), which corresponds to the location of the additional vortex near a void (the plateau on curve *4* of Fig. 3). The wider minimum is dominant at a smaller interaction amplitude since in this case the energy of interaction with the additional vortex is sufficient to displace surrounding vortices from their sites at voids (curve *3* in Fig. 4). It is clear that at some A the depths of the two minima are equal (curve *2* in Fig. 4), which corresponds to the cusp in Fig. 3.

4.2. Vacancies

At a lower magnetic field, vacancy generation is thermodynamically favored (Fig. 2c). In this case the free-energy density in a vortex lattice containing M vacancies may be expressed as

$$\mathcal{F}_{N^*-M}=\left(\mathcal{H}_{c1}-A-\mathcal{H}_0+\frac{W_4}{2}\right)-\frac{M}{N^*}(W_4+\mathcal{H}_{c1}-A-\mathcal{H}_0+E_r)+\frac{1}{2N^*}\sum_{ij}^{M}\mathcal{E}_{ij}, \tag{8}$$

where N^* is the number of vortices in a sample with full commensurability. This yields the condition for the critical field $\mathcal{H}_v$ for vacancy generation:

$$\mathcal{H}_v=\mathcal{H}_{c1}-A+W_4+E_r, \tag{9}$$

where $E_r(A)$ is the relaxation energy of the vortex lattice around one vacancy. As follows from Fig. 3, the function $\mathcal{H}_v(A)$ is nearly linear at all interaction amplitudes since the vortex displacement in this system is small and the relaxation energy is low. The point of intersection between the curves $\mathcal{H}_v(A)$ and $\mathcal{H}_{46}(A)$ defines the critical vortex–defect inter-

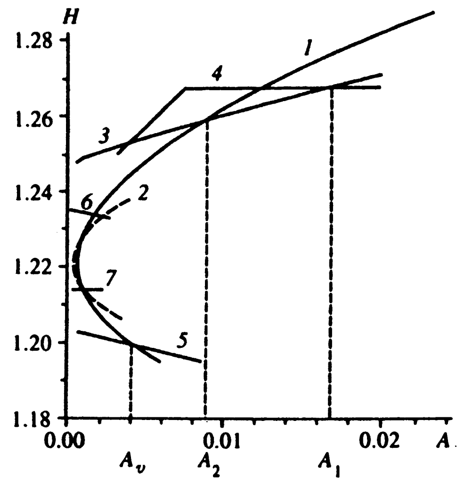

FIG. 3. Fields corresponding to phase transitions versus the vortex–defect interaction constant at $D/\lambda=5$, $\kappa=10$: (1) field $\mathscr{H}_{46}$ of the tetragonal-to-hexagonal lattice transition; (2) field $\mathscr{H}_{36}$ of the trigonal-to-hexagonal transition; (3) field $\mathscr{H}_2$ at which "dumb-bells" are generated; (4) field $\mathscr{H}_1$ generating an interstitial vortex; (5) field $\mathscr{H}_v$ generating a vacancy in a square lattice; (6) field $\mathscr{H}_3$ generating an extra vortex in a trigonal lattice; (7) field $\mathscr{H}_{3v}$ generating a vacancy in a trigonal lattice.

action constant A_v beyond which vacancies are generated. Additional vortices (Fig. 2d) or vacancies might be generated in the trigonal lattice, but this would lead to a higher free energy since the respective transition fields $\mathscr{H}_3$ and $\mathscr{H}_{3v}$ (curves 6 and 7 in Fig. 3) are outside the range of existence of the trigonal structure.

Thus the system behavior at higher magnetic fields is determined by the vortex–void interaction amplitude. At low amplitudes the trigonal ($A_{\min}\leqslant A\leqslant A^*$) and tetragonal ($A^*\leqslant A\leqslant A_v$) vortex lattices abruptly transform to the hexagonal structure (a first-order phase transition), which interacts weakly with the void superlattice and gradually changes its vortex density. But at larger interaction amplitudes it is preferable to generate additional vortices or vacancies in the tetragonal lattice. The additional vortices may either be interstitial ($A\geqslant A_1$) or form a "dumb-bell" with a host vortex ($A_2\leqslant A\leqslant A_1$) (Fig. 2a and 2b).

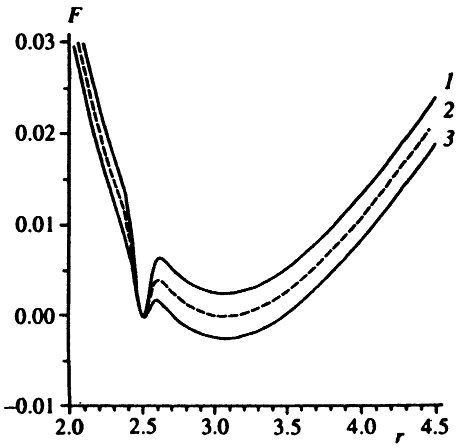

FIG. 4. Free energy versus displacement of vortices from an additional vortex: $D/\lambda=5$, $\kappa=10$: (1) $A=0.01$; (2) $A=0.0075$; (3) $A=0.005$.

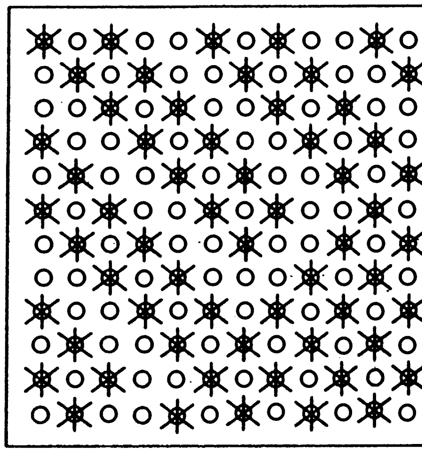

FIG. 5. Transition from a vortex density of 1/2 to one of 2/5 through generation and motion of dislocations.

The defect generation is a second-order phase transition similar to that at $\mathscr{H}=\mathscr{H}_{c1}$. In this case the interaction between new vortices or vacancies must be taken into account at higher fields. This interaction is discussed in the next section.

5. RESTRUCTURING OF THE VORTEX LATTICE

Let us consider the magnetic field range in which the vortex density is smaller than that of the defects. One can see in Fig. 3 that the relaxation energy of host vortices due to vacancies is negligible, and all the vortices may be pinned at voids. In this case the free-energy density is

$$\mathscr{F}=\frac{N_1}{N^*}(\mathscr{H}_{c1}-A-\mathscr{H}_0)+\frac{1}{2N^*}\sum_{i,j=1}^{N_1}\mathscr{E}_{ij}, \qquad (10)$$

where N_1 is the number of voids at which vortices are pinned, and the first critical field is obviously modified:

$$\mathscr{H}_{c1}^*=\mathscr{H}_{c1}-A. \qquad (11)$$

At $\mathscr{H}>\mathscr{H}_{c1}^*$ vortices form lattices with different vortex densities. It follows from Eqs. (8) and (10) that structures with vortex densities n_1 and $1-n_1$ are similar to each other, and their ranges are symmetrical on the magnetic-field interval extending from $\mathscr{H}_{c1}^*$ to $\mathscr{H}_v$. Therefore we may discuss only the interval between $\mathscr{H}_{c1}^*$ and the field $\mathscr{H}_m=(\mathscr{H}_{c1}^*+\mathscr{H}_v)/2$ at which the structure around $\mathscr{H}_m$ is half-filled.

When the magnetic field deviates from $\mathscr{H}_c$, then either vacancies can be generated in the half-filled lattice (similarly to the case of full filling) or a different structure can be generated. Calculations for a type II superconductor ($\kappa=10$) with a void superlattice ($D/\lambda=5$) demonstrate that generation of single defects in the half-filled structure is not favorable from the thermodynamic viewpoint because the required magnetic field is lower than the fields corresponding to transitions to striped patterns with fillings of 3/7, 2/5, and 1/3 (Fig. 5) through generation and motion of dislocations. The magnetic field ranges corresponding to phases with fillings of 3/7 and 2/5 are very narrow, and the differences between the free energies of these phases and of the 1/3 phase

TABLE I. Structural and energy parameters of vortex lattices and magnetic fields corresponding to transitions among them. Transition fields in the range of $n > 1/2$ are mirror reflections of those at $n < 1/2$ around the point $\Delta\mathscr{H}_l = 8.22675 \cdot 10^{-3}$, e.g., $\Delta\mathscr{H}_{1/2 \to 4/7} = 2\Delta\mathscr{H}_l - \Delta\mathscr{H}_{3/7 \to 1/2} = 1.47809 \cdot 10^{-2}$.

Vortex density	Lattice parameters			Average energy of vortex-vortex interaction	Transition fields
n_1	a/D	b/D	α	W	$\Delta\mathscr{H} = \mathscr{H} - \mathscr{H}^*_{c1}$
1/2	$\sqrt{2}$	$\sqrt{2}$	$\pi/2$	$1.6473 \cdot 10^{-3}$	
3/7	5	$\sqrt{5}$	$\tan^{-1}(1/2)$	$1.3677 \cdot 10^{-3}$	$1.662576 \cdot 10^{-3}$
2/5	5	$\sqrt{5}$	$\tan^{-1}(1/2)$	$4.1290 \cdot 10^{-3}$	$1.662574 \cdot 10^{-3}$
1/3	3	$\sqrt{2}$	$\pi/4$	$8.09 \cdot 10^{-4}$	$1.661000 \cdot 10^{-3}$
1/3	3	1	$\pi/2$	$7.4183 \cdot 10^{-3}$	$1.533600 \cdot 10^{-3}$
1/4	2	2	$\pi/2$	$7.2076 \cdot 10^{-5}$	
1/4	2	$\sqrt{5}$	$\tan^{-1}2$	$5.6266 \cdot 10^{-5}$	$9.895226 \cdot 10^{-5}$
1/5	5	1	$\pi/2$	$7.4179 \cdot 10^{-3}$	
1/5	5	$\sqrt{5}$	$\tan^{-1}(1/2)$	$2.0856 \cdot 10^{-5}$	
1/5	5	$\sqrt{2}$	$\pi/4$	$7.8794 \cdot 10^{-4}$	$3.526000 \cdot 10^{-5}$
1/6	3	2	$\pi/2$	$3.5775 \cdot 10^{-5}$	
1/6	3	$\sqrt{5}$	$\tan^{-1}2$	$1.1017 \cdot 10^{-5}$	

are insignificant. Therefore it is highly probable that at nonzero temperatures disordered striped patterns with random widths of stripes will be generated. The energetic and structural parameters and transitions fields are listed in Table I.

At a lower magnetic field, the system transforms to a phase with a filling of 1/4, which may have two configurations—tetragonal and trigonal—as in the case of full filling, and the energy of the trigonal structure is smaller since $W_3 < W_4$ and all the vortices are localized at voids. A similar structure occurs for the 1/6 phase, and the pseudohexagonal configuration has a lower energy than the tetragonal one.

In the magnetic field range where the vortex density is less than 1/6, the energy of vortex–vortex interaction is small, and it is senseless to calculate parameters of ordered structure because low-density ordered phases exist within very narrow intervals, and a disordered pattern of vortices localized at voids will be formed at nonzero temperatures.

For $A > A_1$ the situation for interstitial vortices will be similar for $\mathscr{H} > \mathscr{H}_1$, but unlike vacancies the potential well for interstitial vortices is flatter and the relaxation energy is more important. This leads to wider ranges of magnetic field corresponding to phases with fillings of 1/5 and 1/3.

6. CONCLUSION

We have studied the interaction between Abrikosov vortices and cubic void superlattices. If the vortex–defect interaction is sufficiently strong, the void lattice imposes a particular structure on the vortex lattice and may fix the vortex density in some magnetic-field intervals. Therefore the curve of $B(H)$ becomes piecewise constant, i.e., the magnetic field range around H_{c1} is divided into several intervals on which the vortex density is constant and equals a rational fraction of the voids density. Transitions between these intervals may be abrupt.

Our calculations demonstrate, as expected, that the widest interval corresponds to the total coincidence between the void and vortex lattices ($n = 1$), i.e., when the vortex density equals that of the void chains along the magnetic-field vector. If the vortex–void interaction is sufficiently strong ($A > A^*$), a tetragonal vortex lattice is formed with all the vortices pinned at voids and none of the voids vacant. There is, however, an interval of interaction amplitudes ($A_{\min} < A < A^*$) where a trigonal lattice is formed with half of the vortices localized at voids, but with the energy of interaction between vortices close to that of a hexagonal lattice. This structure is highly anisotropic because the pinning along chains of nonlocalized vortices is many times softer than in the orthogonal direction. A sample may be separated into many "vertical" and "horizontal" domains.

The system behavior as a function of magnetic field is determined by the vortex–void interaction. At small interaction amplitudes, both the trigonal and tetragonal lattices transform abruptly to a hexagonal phase (the first-order phase transition), which weakly interacts with the void lattice and whose density changes gradually. But at a higher interaction amplitude A, generation of additional vortices or vacancies is more favorable (the second-order phase transition), and additional vortices may be introduced in two ways, namely, by producing an interstitial defect or a "dumb-bell" pair with a host vortex (Fig. 2a and 2b).

At a lower magnetic field, the defects multiply and other structures are realized. The entire magnetic-field range between $\mathscr{H}^*_{c1} = \mathscr{H}_{c1} - A$ (the first critical field taking into account the creation of vortices in voids) and $\mathscr{H}_v$ (the magnetic field at which vacancies are generated) is divided into symmetrical subranges in which the filling factor is constant. The subranges corresponding to structures with fillings n and $1-n$ are symmetrical about the middle of the entire interval because the interaction between vortices is paired and vortices cannot be displaced far from their voids. The widest subrange (80%) corresponds to the tetragonal structure with the one-half filling, and those of trigonal structure patterns with fillings of 1/4 and 3/4, which are similar to the triangular structure at $n = 1$, occupy 8.7% each. The transitions from these structures and low-dimensional stripe-like structures (3/7, 2/5, 1/3) are of first order and, apparently, occur through generation and motion of dislocations (Fig. 5). Fluctuations may lead to melting of low-symmetrical and disordered structures, as well as structures with a low density of vortices or vacancies.[20]

If the magnetic field is slightly tilted with respect to the crystal axis, vortices may have a zigzag shape, jumping from one void chain to another so that the average direction should coincide with that of the magnetic field. The study of such objects, which are similar to kinks in layered high-T_c superconductors[21–23] is beyond the scope of this work.

In conclusion, we would like to note that for $\kappa \gg 1$, which is the most interesting situation, the range of the vortex–defect interaction is much shorter than that of the interaction between vortices and the specific shape of its potential is not important. Therefore the structure and phase transitions discussed here may occur in a vortex lattice interacting with any defects (for example, cylindrical defects or dislocations) provided that they form a regular tetragonal lattice, and type II superconductors present a convenient model for studies of two-dimensional interacting particles in a short-range periodic potential.

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