Order-disorder transition in the vortex lattice induced by anisotropy of the YBaCuO superconductor

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Abstract. Pinning force $F_p$ variation with the magnetic field $H$ and the angle $\alpha = \angle H, ab$ is investigated in crystals having different concentrations of point defects $n_{pd}$. Comparison between the functions $F_p(H)$ and $F_p(\alpha)$ strongly suggests that the minimum position in the $F_p(\alpha)$-curve corresponds to the angle $\alpha_{OD}$, which separates the ordered vortex lattice (VL) formed at $\alpha < \alpha_{OD}$ and the disordered VL formed at $\alpha > \alpha_{OD}$. This conclusion is confirmed by variation in the $E(J)$-curve shape in the vicinity of the angle $\alpha_{OD}$, and by hysteresis behavior of the $E(J)$-curves measured for increased and decreased transport current at angles $\alpha > \alpha_{OD}$. This order-disorder transition arises, because the elastic energy of the disordered VL decreases with an increased $\alpha$, while the pinning energy is independent of $\alpha$.

1. Introduction
The phase state and pinning of the VL in high-T$_c$ superconductors have long been the subject of theoretical and experimental investigations. Correlation between the phase state and the pinning force $F_p$ of the VL was determined in single-crystalline samples BiCaSrCuO and YBa$_2$Cu$_3$O$_{7-\delta}$ through variation of magnetic field $H$. Visualization of the VL structure in BiCaSrCuO [1] and YBa$_2$Cu$_3$O$_{7-\delta}$ [2] crystals has revealed that the low-field ordered VL is replaced by disordered VL as the magnetic field increases. Comparison of field variations of the force $F_p$ in the BiCaSrCuO [3] and YBa$_2$Cu$_3$O$_{7-\delta}$ [2,4] crystals with the VL structure in these crystals shows that the force $F_p$ decreases with an increasing field $H$ for the ordered VL, but the force $F_p$ increases with the field for the disordered VL. It is supposed that the order-disorder (OD) transition in the VL occurs provided that lateral displacements $u_t$ satisfy the Lindemann criteria $u_t = c_L a_0$, where $a_0 \equiv \sqrt{\Phi_0/B}$ is the intervortex distance, and $c_L$ is the Lindemann number. These displacements increase the elastic energy of the VL by $E_{el} \equiv c_L^2 \varepsilon a_0 \propto 1/\sqrt{H}$ [5,6]. In the presence of point defects, the pinning energy increases with the field slower, $E_p \propto 1/H^{0.1}$ [7]. Therefore, in low fields the energy $E_{el}$ exceeds the pinning energy.
and the ordered VL is formed, while in high fields the pinning energy compensates the energy $E_{el}$ and the disordered VL is formed.

It is well known that in layered superconductors, specifically, in the YBa$_2$Cu$_3$O$_{7-\delta}$ [8-10], the pinning force non-monotonically varies with $\alpha = \angle \mathbf{H}, ab$. It has recently been suggested that the minimum position $\alpha_{OD}$ in the $F_p(\alpha)$ curve separates the ordered VL formed at angles $\alpha < \alpha_{OD}$ from the disordered VL formed at angles $\alpha > \alpha_{OD}$. The OD transition arises, because the energy $E_{el}$ decreases with an increase in the angle $\alpha$ [10], while in the presence of point defects the energy $E_p$ is independent of the angle $\alpha$ [7]. Experimental evidence for the transition was provided by a decrease in the angle $\alpha_{OD}$ with an increase in the point defect concentration $n_{pd}$ [10]. In this paper we present the experimental results for the effect of defect concentration on field and angular variations of the pinning force, and on the evolution of vortex dynamics in the vicinity of the angle $\alpha_{OD}$. The present results strongly suggest that the angle $\alpha_{OD}$ really corresponds to the OD transition induced by structural anisotropy of the superconductor.

2. Experimental results

Measurements were carried out on two YBa$_2$Cu$_3$O$_{7-\delta}$ crystals with $T_c = 93.3$ K and $\Delta T_c = 0.3$ K (sample S1), and with $T_c = 93.5$ K and $\Delta T_c = 0.4$ K (sample S2). The transport current vector $\mathbf{J}$ was parallel to the $ab$-plane, and the magnetic field vector was perpendicular to the vector $\mathbf{J}$. The temperature stability was better than 5 mK. The measurements in the normal state have shown that overheating of the sample at the highest dissipation level of 50 $\mu$W did not exceed 10 mK. Additional defects like «vacancy-interstitial» were introduced by irradiation with 2.5 MeV electrons at $T < 10$ K, as it was described elsewhere [11]. After irradiation with doses $\phi = 10^{18}$, $2 \cdot 10^{18}$, and $3 \cdot 10^{18}$ 1/cm$^2$ the $E(J)$-curves were measured without heating the sample over 110 K to exclude clustering of the defects. A dose of $10^{18}$ 1/cm$^2$ produced the defect concentration $n_p = 10^4$ dpa [11], averaged over all sublattices. The pinning and dynamics of the VL were investigated through direct-current measurements of current - voltage characteristics $E(J)$.

![Figure 1. Field variations of current $J_y$ in the sample S1, measured at angles $\alpha = 0$ (empty symbols) and $\alpha = 14^\circ$ (filled symbols) before irradiation (squares) and after irradiation with doses of $10^{18}$ (circles), $2 \cdot 10^{18}$ (triangles), and $3 \cdot 10^{18}$ (diamonds).]
The pinning force is usually characterized by a transport current density $J_V$ corresponding to a low voltage $V$ across the sample. Figures 1 and 2 show, respectively, the field and angular variations of the current density $J_V$ determined at voltage criteria of $0.5\mu V$. It can be seen that $J_V$ non-monotonically varies with both the field and the angle $\alpha$. As it has been mentioned above, the minimum position in the $J_V(H)$ curves corresponds to the field $H_{OD}$, which separates the low-field ordered VL and the high-field disordered VL [1-4]. As is evident from figure 1, the field $H_{OD}$ decreases with an increased $n_{pd}$, that agrees with the previous experimental studies [4]. This behavior is explained by the fact that the pinning energy increases with the defect concentration [7], $E_p \propto n_{pd}^{1/3}$, while the elastic energy of the concentration $n_{pd}$ remains unchanged. Therefore, a higher pinning energy can compensate a higher loss in the elastic energy, and the increase in the concentration $n_{pd}$ results in a decrease of the field $H_{OD}$. Figure 3 also shows that for the same concentration $n_{pd}$ the field value $H_{OD}$ at $\alpha = 14^\circ$ is always lower than the one at $\alpha = 0^\circ$. This regularity is easy to understand considering that the energy $E_{el}$ decreases with an increase in the angle $\alpha$ [10], while the energy $E_p$ is independent of the angle $\alpha$ in the presence of point defects [7]. Therefore, for the same concentration $n_{pd}$, and consequently, for the same pinning energy value, the OD transition should shift to lower fields with an increase in the angle $\alpha$. This regularity has previously been observed in experimental studies of pinning force anisotropy in YBa$_2$Cu$_3$O$_{7-\delta}$ crystals [8,9].

![Figure 2](image.png)

Figure 2. Angular variation of current $J_V$ in samples S1 (a) and S2 (b), measured before irradiation (squares) and after irradiation with doses of $10^{18}$ (circles), $2 \cdot 10^{18}$ (triangles), and $3 \cdot 10^{18}$ (diamonds).
In the nonirradiated sample the minimum in the $J_V(H)$ curve for the angle $\alpha = 14^\circ$ is observed in the field $H = 15kOe$. This means that for the given parameter values the equality $E_p = E_{el}$ is satisfied. Considering that the elastic energy increases with a decrease in the angle $\alpha$, and the pinning energy is independent of the angle $\alpha$, the ordered VL in the nonirradiated sample should be formed at angles $\alpha < 14^\circ$, while the disordered VL should be formed at $\alpha > 14^\circ$. As it is seen in figure 2, the pinning force of the ordered VL decreases with an increase in the angle $\alpha$, but it increases with angle $\alpha$ for the disordered VL. The pinning force increase for the disordered VL is supported by the results of measurements after irradiation with a dose of $3 \cdot 10^{18}$. It can be seen in figure 2 that at $\alpha = 0^\circ$ the OD transition occurs in the field $H_{od} \approx 12kOe$. Considering that the elastic energy decreases with increasing $\alpha$, the disordered VL should be formed in the magnetic fields $H_{od} > 12kOe$ for all angles $\alpha$. It is evident from figure 2 that for this vortex state the pinning force increases with the angle $\alpha$, with the exception of a narrow interval of angles $\alpha \leq 0.3^\circ$. The reason of this behavior will be discussed later. For intermediate irradiation doses, $\phi = 10^{18}$ and $\phi = 2 \cdot 10^{18}$, in the magnetic field of 15 kOe the ordered VL is formed at $\alpha = 0^\circ$, while at $\alpha = 14^\circ$ the disordered VL is formed. Therefore, one can expect the occurrence of the OD transition with an increased $\alpha$ in the angular range $0 < \alpha < 14^\circ$. Considering that the pinning force of the ordered VL decreases with an increased $\alpha$, and the pinning force of the disordered VL increases with $\alpha$, it is natural to suppose that the minimum position in the $J_V(\alpha)$ curve corresponds to the OD transition.

![Figure 3](image-url)

Figure 3. The functions $E(J)$ and $\rho_d(J)$ measured in the sample S1 with increased (empty symbols) and decreased (filled symbols) transport current.
It is known that the shape of current-voltage curves changes in the vicinity of the OD transition caused by the increase in the magnetic field [12]. The ordered VL is characterized by a smooth increase of the electric field with current, while the disordered VL is characterized by an S-shaped $E(J)$ curve. Furthermore, directly above the transition point the $E(J)$ curves, measured with increased and decreased transport currents, show the hysteresis behavior. We have observed a similar evolution of the $E(J)$ functions in the neighborhood of the OD transition with increase of both the magnetic field and the angle $\alpha$. The last observation is demonstrated in figure 3, which shows the $E(J)$ functions and the current dependence of dynamic resistance $\rho_d = dE/dJ$ measured in sample S1 after exposure to a dose of $2 \cdot 10^{18}$. Irradiation with this dose results in the OD transition at $\alpha_{OD} \approx 1.5^\circ$, see figure 2. As is seen in figure 3, for the ordered VL ($\alpha = 1^\circ$) a smooth increase in the electric field with current takes place, this being confirmed by gradual increase in the dynamic resistance. For the disordered VL the dependence becomes concave, which is confirmed by the nonmonotonic $\rho_d(J)$ function. Besides, for $\alpha = 1^\circ$ the $E(J)$ curves measured with increased and decreased current coincide with each other, while for $\alpha = 2.5^\circ$ the curves show the hysteresis behavior. The hysteresis is not caused by sample overheating, because for the angle $\alpha = 1^\circ$ the measurements were performed at higher energy dissipation $W = E \cdot J$, yet there was no hysteresis observed. A nonmonotonic current variation of the dynamic resistance and the hysteresis behavior of the $E(J)$-curves are the characteristic dynamic features of the disordered VL. The disordered state of the static VL has been predicted to be replaced by a more ordered VL with an increase in the vortex velocity $v$ above some critical value $v_c$ [13,14]. Theoretical studies [13] and numerical calculations [15,16] show that the dynamic ordering manifests itself in the S-shaped $E(J)$ curves, and the local peak position in the $\rho_d(J)$ curves corresponds to the onset of ordering. As seen in figure 3, the current $J_{p,incr}$ corresponding to the peak position in the $\rho_d(J)$ curve measured with an increased current is higher than the current $J_{p,decr}$ corresponding to the peak position in the $\rho_d(J)$ curve measured with a decreased current. This difference reflects an “overheated” state of the ordered dynamic VL. Therefore, the transition of the ordered dynamic VL into the disordered static VL occurs at a lower current as compared with the transition of the disordered static VL into the ordered dynamic VL.

As it was mentioned above, after irradiation with a dose of $3 \cdot 10^{18}$ the OD transition at $\alpha = 0$ occurs at $H_{OD} \approx 12$ kOe. Therefore, in magnetic field 15 kOe one can expect formation of the disordered VL for all angles $\alpha$, and pinning force must increase with the angle $\alpha$. However, as is evident in figure 2, after irradiation with a dose of $3 \cdot 10^{18}$ local peak in the $J_v(\alpha)$ curve is observed at angles $\alpha < 0.3^\circ$. This remnant peak can arise due to lock-in of the vortex lines between superconducting planes. In layered superconductors the lock-in angle equals $\alpha_L \approx (H_{c1}d/H_w)$, where $H_{c1}$ is the lower critical field, $d$ and $w$ – respectively the thickness and width of the sample [7]. In our measurements $H = 15$ kOe, $d = 7 \mu$m, $w \approx 200 \mu$m and for reasonable value of $H_{c1} = 200$ Oe we obtain the angle $\alpha_L \approx 0.3^\circ$. At angles $\alpha > \alpha_L$ vortex lines have stepped structure [7]: vortex strings localized between the superconducting planes are connected by “pancake” vortex fragments which pierce through the superconducting planes and bring component of magnetic field along the $c$ axes. The “pancake” fragments can move along the $ab$-plane independently of the vortex strings and their pinning arises due to interaction with the structure defects [7]. At angles $\alpha < \alpha_L$ vortex lines are localized between the superconducting planes and their pinning arises due to both interaction with the structure defects and modulation of the superconducting order parameter along the $c$ axes. Therefore, local peak in the $J_v(\alpha)$ curve which is observed for the disordered VL at angles $\alpha < \alpha_L$ can be
explained by occurrence of additional pinning mechanism associated with modulation of the superconducting order parameter along the c axes.

3. Conclusions
Thus we have studied the effect of point defect concentration on field and angular variations of the pinning force in a moderately anisotropic superconductor YBa$_2$Cu$_3$O$_{7-δ}$. The comparison between $F_p(H)$ and $F_p(α)$ dependences, as well as the characteristic changes in the vortex dynamics testify that the minimum position in the $F_p(α)$ curve corresponds to the order-disorder transition in the vortex lattice. Remnant peak in the $F_v(α)$ curve which occurs for the disordered state of the VL at angles $α < α_L$ reflects additional pinning mechanism associated with modulation of the superconducting order parameter along the c axes. The ordered state of the VL is formed at angles $α < α_{OD}$, while the disordered state is formed at angles $α > α_{OD}$. The order-disorder transition is caused by the fact that in anisotropic superconductors the elastic energy of disordered VL decreases with a growing angle $α$, whereas the pinning energy is independent of the angle $α$.

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