PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 58, Nos 5 & 6
May & June 2002
pp. 919–924

Commensurability oscillations in $NdBa_2Cu_3O_y$ single crystals

H KÜPFER[1,*], G RAVIKUMAR[1,2], TH WOLF[3], A A ZHUKOV[4] and H WÜHL[1]
[1]Forschungszentrum Karlsruhe, Institut für Technische Physik and Universität Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany
[2]Technical Physics and Prototype Engineering Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
[3]Forschungszentrum Karlsruhe, Institut für Festkörperphysik, Postfach 3640, 76021 Karlsruhe, Germany
[4]Department of Physics and Astronomy, Southampton University, Southampton, SO17 1BJ, U K and Chemistry Department, Moscow State University, Moscow 117 234, Russia
*Email: heinz.kuepfer@itp.fzk.de

Abstract. Commensurability between inter-vortex distance and crystal lattice constant is investigated by angular dependent magnetization in very pure twinned and twin-free $NdBa_2\,Cu_3\,O_y$ single crystals. With increasing temperature the incommensurate states split up and become finally commensurate with half the vortex distance. These new commensurate states are related to a substructure of the intrinsic pinning potential within the unit cell and discussed with respect to temperature, field, anisotropy, and twin structure.

Keywords. Magnetization hysteresis; commensurability oscillations; $NdBa_2Cu_3O_7$.

PACS Nos 74.25.Dw; 74.60.Ge

1. Introduction

The layered structure and the c-axis coherence length, $\xi_c \approx 4$ Å, smaller than the lattice constant, $d = 11.7$ Å, are the source of intrinsic pinning in $YBa_2Cu_3O_y$ (Y123) for vortices oriented parallel to the a, b plane or within a lock-in angle of 0.2°. The variation of the order parameter along c direction with a minimum between the CuO_2 layers results into an intrinsic pinning potential [1] causing a maxima in pinning force when the inter-vortex distance is commensurate with the lattice constant d.

If the field B is oriented within the lock-in range, commensurability between the vortex lattice and the layered structure occurs when the condition $na_0 = kd$ (1) is satisfied [2,3]. Here n, k are integer numbers, $a_0 = (\sqrt{3}\phi_0/(2\Gamma B))^{1/2}$ is the inter-vortex distance where Γ is the anisotropy parameter. The lowest energy solution $n = 1$ where each vortex is intrinsically pinned corresponds to a maxima in pinning force. Also in an incommensurate state, the vortices are placed between the CuO_2 layers, but the energy necessary for the elastic distortion of the periodic vortex distance makes it less favorable. Such oscillations between commensurate and incommensurate states were first observed in de-twinned Y123 single crystals by magnetization measurements [4]. The quality of these crystals must be extremely good because background pinning from random disorder decreases the difference between commensurate and incommensurate states and makes the ratio between background and oscillations less favorable for an observation of the latter.

With increasing temperature thermal excitations first cause a one-dimensional melting of the solid vortex state in a direction parallel to the a, b plane. This smectic phase – a liquid in one direction parallel to the a, b plane and a solid in c-direction – exists up to the melting of the remaining solid at the melting line [5,6]. Such a transition from a solid vortex state into a smectic phase was demonstrated by analyzing commensurability oscillations [7]. The melting line between smectic and liquid phase, measured resistively, also shows oscillatory behavior from commensurate states in the smectic phase [8].

While commensurability oscillations are observed, so far, only in pure Y123 [4,7,9] we demonstrate that $NdBa_2Cu_3O_y$ (Nd123) crystals are also stoichiometric and sufficiently pure to show these features. Even in twinned Nd123, commensurability oscillations are present in contrast to Y123. The main purpose of this paper is to show that besides the periodicity of the magnetization commensurate with the lattice constant, there is a new periodicity commensurate with half the lattice constant which requires an extension of the picture given above.

2. Results and discussion

Two Nd123 crystals from the same batch were investigated: FK, twinned, transition temperature $T_c = 95.3$ K, sample size $3 \times 2.35 \times 0.43$ mm^3 and FM, almost naturally twin-free, $T_c = 95.7$ K, $1.45 \times 0.54 \times 0.2$ mm^3. Both crystals were two times high-pressure oxidized (FM2, FM6, FK3, FK6). The high quality of both crystals is demonstrated by first-order melting at $B \parallel c$, a transition field at 77 K above 12 T, and low current density [10]. The magnetization was measured with a vector vibrating sample magnetometer (Oxford Instruments) equipped with two perpendicular pick-up coils. The angular resolution was better than 0.01°. The magnetization parallel to the applied field for $B \parallel a, b$ results from shielding currents $j_{a,b}$ flowing within the a, b plane and j_c flowing along c. While one expects a maximum $j_{a,b}$ in a commensurate state, j_c shows a minimum due to the easy flux motion parallel to the a, b plane from the large anisotropy of the shear modulus [11]. In the framework of anisotropic Bean model, contribution of j_c to the magnetic moment is dominant [7]. Therefore, a commensurate state corresponds to a minimum in the magnetization. The commensurability oscillations in the magnetization are placed on a considerably large background moment from random disorder. Therefore, we subtract a linear field-dependent part and, the resulting $\delta m(B)$ is shown for example in figure 1 for the decreasing field branch (thick line). For an even better analysis we used the differential susceptibility $\mathrm{d}m/\mathrm{d}B$ obtained by careful smoothing [7]. The amplitude of $\mathrm{d}m/\mathrm{d}B$ is used as a relative measure of the lock-in strength. It becomes smaller with decreasing B because the difference in energy between commensurate and incommensurate states shrinks with increasing distance between vortices. The commensurability condition (1) with $n = 1$ requires that the distance between neighboring oscillations should be periodic in $1/\sqrt{B}$ which is in good agreement with the plot of the amplitude of $\mathrm{d}m/\mathrm{d}B$ vs. k (dashed line

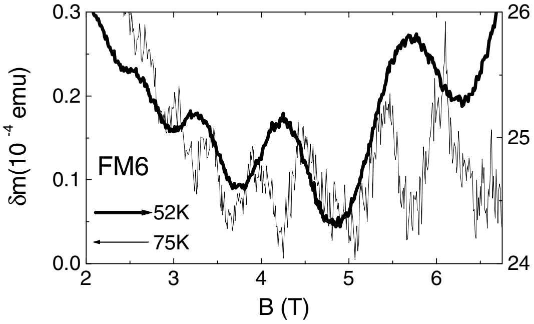

Figure 1. Commensurability oscillations of the magnetic moment δm vs. applied field B of the twin free crystal FM6 after a linear field dependent part was subtracted.

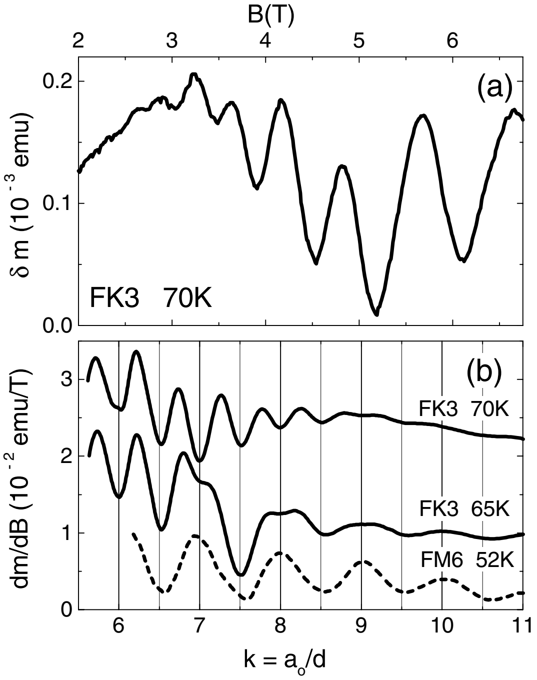

Figure 2. (**a**) Commensurability oscillations of the magnetic moment δm vs. applied field B in the twinned crystal FK3 after a linear field dependent part was subtracted. (**b**) Differential susceptibility $\mathrm{d}m/\mathrm{d}B$ vs. k which is the inter-vortex distance a_0 divided by the crystal lattice constant d. The values of Γ used for this plot are between 5 and 7, and they are in good agreement with values obtained from different methods.

in figure 2b). This means that the periodicity of the oscillations is commensurate with the crystal lattice constant d.

At 75 K, however, the maxima are split into a double peak (thin line in figure 1). The $m(B)$ minima which correspond to the commensurate states remain at about the same fields. Only the incommensurate states at 52 K change obviously into commensurate ones at 75 K. The splitting of the maxima becomes more pronounced at higher temperatures and at higher fields, the same dependences as for the usual oscillations. The development of the double peak starts in different crystals at different temperatures. In the twinned crystal FK the splitting becomes visible already above 50 K and its final state is reached at 70 K. Figure 2a shows the magnetization of the decreasing field branch after a linear field dependent part was subtracted. The number of oscillations has doubled with respect to the common lowest energy solution $n = 1$ (FM6 at 52 K in figure 1). The corresponding differential susceptibility of FK3 at 70 K is compared in figure 2b with a measurement at 65 K and with the usual commensurability oscillations of FM6 at 52 K. For clarity, the curves are shifted by a constant value along the $\mathrm{d}m/\mathrm{d}B$ axis. The development from a single into a double peak is a continuous process within a temperature region of about 10 K. The temperature dependence is shown in figure 3a where the fields of the original minima ($k = 6$, 7 and 8) and of the new ones (a and b) are plotted. The difference in $1/\sqrt{B}$ between 7 and 6, $\Delta B(7-6)$, as well as $\Delta B(8-7)$ are in agreement with the anisotropy parameter and the lattice constant. If the development of the splitting has finished, the differences $\Delta B(a-6)$ and $\Delta B(7-a)$ correspond however to half the lattice constant and the periodicity of the commensurate states has doubled.

First, the anisotropic Bean model involving j_c and $j_{a,b}$ as a possible explanation for the double peak behavior has been excluded. Based on the experimental observations de-

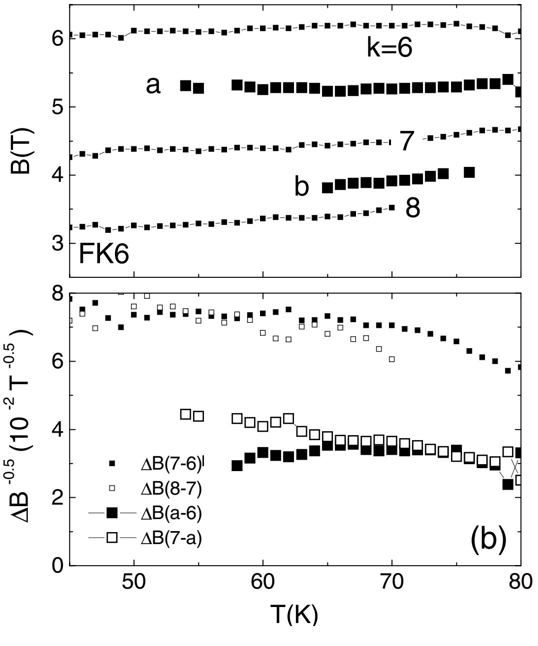

Figure 3. (**a**) Field at which the minima of the oscillations occur vs. temperature for $k = a_0/d$ of 6, 7 and 8 and for the new minima a and b. (**b**) Difference in $1/\sqrt{B}$ of two consecutive minima for instance $1/\sqrt{B}7 - 1/\sqrt{B}6 = \Delta B(7-6)$ vs. temperature.

scribed earlier, we propose the following explanation for this phenomenon. The double periodicity, after its development has finished at high enough temperatures, is described by $2a_0 = kd$ which corresponds to the second lowest energy solution. This means that minima with even numbers of k represent the original commensurate states, whereas odd numbers characterize the new ones. In these new commensurate states only every second vortex is pinned between the CuO_2 layers and the other vortices are placed in the middle of CuO_2 double layers where no intrinsic pinning potential is commonly expected. The strength of the new commensurate states increases with temperature and field as a result of lower background current and higher distortion energy. This dependences of the double periodicity on field and temperature are qualitatively the same as for the structure with the lowest energy solution. The new commensurate state with $n = 2$ – vortex pinned in the middle of the CuO_2 double layers – is energetically less favorable than the $n = 1$ state where each vortex is locked. Therefore, one expects for $n = 2$ oscillation amplitudes being smaller for an odd than for an even number of k, in contrast to the experimental observation of about similar amplitudes (figure 2), apart from the state where the double structure starts developing. This unexpected observation may be related to crystal imperfections like dislocations or stacking faults. They prevent a vortex to be pinned at the same element of the unit cell along the full length of the crystal. Thus, a vortex may be pinned alternately in the double planes and in the chain regions. This levels off the measured oscillation amplitudes expected to be larger from lock-in between the CuO_2 layers. The crossings of a vortex between chain regions and double layers, however, require a static kink structure which energetically is not stable in the lock-in range. The necessity to prevent a movement of the kinks demands interaction with defects, preferentially twin walls, which must be crossed if the kinks are moving. This pinning interaction between kinks and twin structure is probably responsible for the much more pronounced double periodicity in the twinned crystal FK than in the almost twin-free crystal FM.

Comparing the commensurate states in Y123 with that in Nd123 for the twin-free and twinned state, one expects a double periodicity also in Y123. But only some Y123 crystals show a tendency towards a double peak structure at higher fields [4]. In contrast to Nd123, commensurate oscillations have not been observed in twinned Y123. From measurements at $B \| c$ it is known that the twin structure in Nd123 is less efficient in pinning vortices. Possibly, a moderate interaction between kinks and twins is already sufficient for the stabilization of the new commensurate structure which may be therefore present also in ‘twin-free’ crystals, whereas heavy twinning is detrimental for the occurrence of commensurate states. From the four crystals showing a splitting, one may conclude that twins are absolutely necessary for this effect.

3. Conclusion

We report on the development of incommensurate states into new commensurate ones where the vortices may be pinned in the middle of the CuO_2 double layer. In this new vortex/crystal lattice configuration which does not correspond to a minimum energy solution, the periodicity of the commensurate oscillations has doubled and vortices are alternatingly locked in the CuO_2 double layers and in the CuO chain region.

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