Vortex Dynamics at the Transition to the Normal State in $YBa_2Cu_3O_{7-\delta}$ Films

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Abstract **- We propose a description of the vortex dynamics for $YBa_2Cu_3O_{7-\delta}$ films. According to this description : i) the vortex motion is thermally activated along the twin boundaries of the films; ii) pinning is due to intersections of twin boundaries and iii) the transition to the normal state is due to vortex depinning. The predictions of this description are compared to data published by González *et al.* [Phys.Rev.B68,054514 (2003)].**

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I. VORTEX DYNAMICS IN THE CRITICAL STATE

In the physics of YBCO films, the role of extended planar defects, such as low angle grain boundaries and twin boundaries (TBs), has been discussed for a long time [1,2]. Many authors have pointed out that since the width of these planar defects is in the range of $\xi_{ab}(T)$, the superconducting coherence length in the a-b planes of YBCO, some type of Josephson behavior could be expected [3, 4]. In this contribution, we discuss the flux-pinning contribution of twinning in epitaxially grown YBCO films (see also Ref.[5]). According to electron microscopy observations, the TBs can stretch over several micrometers in this type of samples [6]. Different types of measurements suggest that the TBs planes act as grooves channeling the vortices [7,8], but the TBs are highly disordered at the scale of a few interatomic distances, as revealed by High Resolution Electron Microscopy [9,10]. It is reasonable to suppose that the modulation of the TBs width by disordered areas has a strong effect on their Josephson behavior. We suggest that the separation between the superconducting banks of the TBs can be locally large enough with respect to $\xi_{ab}(T)$ to cause a disruption of the tunneling current. This results in the splitting of the TBs into rows of Josephson weak links with length δ (see Fig.1). Considerations on the vortices and TBs energies and the fact that disordered areas are also certainly included in the weak links along the TBs suggest that, in the critical state, the weak link energy is equal to k_BT. Then, each weak link, whatever its length, carries the same net current that is equal to

$$I_J = \frac{2\pi k_B T}{\phi_o} \qquad (1)$$

where ϕ_o is the flux quantum. An experimental verification of this prediction is reported below. Consequently, the critical current takes the form :

$$I_{cr} = \frac{w}{\delta} I_J \qquad (2)$$

where w is the width of the investigated sample. Another consequence of Eq.(1) is that the amplitude of the vortex screening current flowing across each weak link is also equal to I_J , since a current amplitude smaller than I_J is in the range of the current thermal fluctuations [11]. Dissipation occurs through thermally activated vortex motion along the TBs. Magnetic susceptibility measurements suggest that vortex pinning occurs at the TBs intersections [12]. Fig.2a represents schematically two perpendicular vortex rows in the vicinity of a TB intersection. The upper vortex in the vertical row can move forward over distance δ only if screening current lines enter both its core and the core of the first vortex in the horizontal row (see Fig.2b). The corresponding energy barrier takes the form

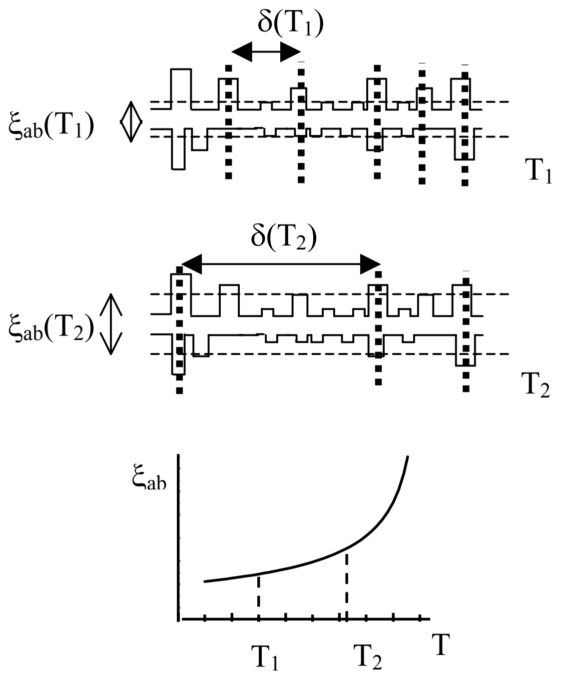

Fig.1 : Schematic representation of a twin boundary section at two different temperatures ($T_1<T_2$) and sketch of the dependence on temperature of the coherence length, ξ_{ab}. The rectangular peaks represent disordered areas (or defects) lying along the TB that change locally its width. The tunnneling current is disrupted wherever the effective separation between the superconducting banks is much larger than the coherence length. As a result the TBs consist of rows of weak links bounded by large disordered areas (at the atomic scale) . The thick dashed lines represent the limits of these weak links. Since at temperature T_1 the coherence length is shorter than at temperature T_2, more defects or disordered areas are large enough to disrupt the superconducting current at T_1 than at T_2. Consequently, the weaks links are shorter at T_1 than at T_2.

$$U_o = 2 I_J \nu \phi_o = 4\pi \nu k_B T \qquad (3)$$

where $\nu\phi_o$ is the flux carried by each vortex, with $\upsilon > 1$ when the vortex carries more than one flux quantum.

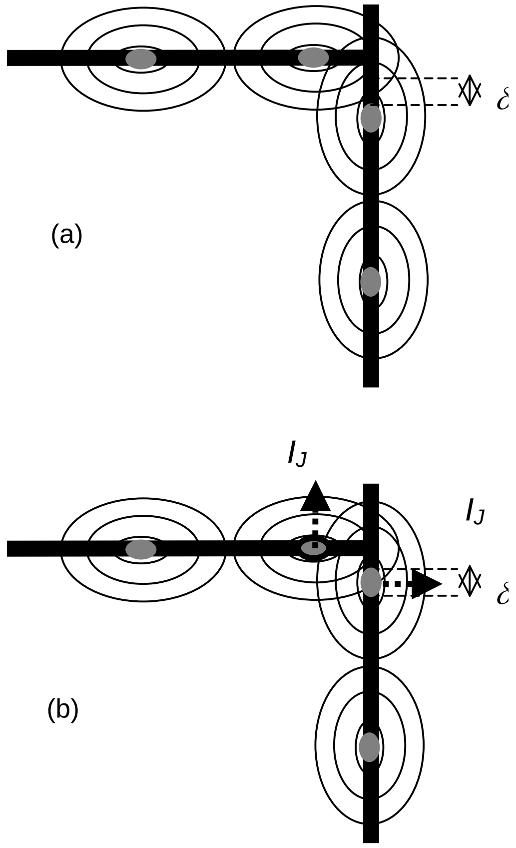

Fig.2 : a) Schematic representation of vortices located along two intersecting twin boundaries. The thick lines, the grey areas and the ellipses represent the twin boundaries, the vortex cores and the screening current lines, respectively; b) the first vortex in the vertical row can move forward over distance δ only if screening currents I_J , represented by the dashed arrows, enters both its core and the core of the first vortex in the horizontal row.

II. TRANSITION TO THE NORMAL STATE

Depinning of an individual vortex line occurs if the total force $\vec{F}$ acting on the vortex is equal to the maximum value of the pinning energy gradient [13]. According to Brandt, [14,15] the pinning energy is an elastic energy. Then, the maximum intensity of force $\vec{F}$ can be written as

$$F = J_{core} \nu \phi_o d = 2\frac{U_o}{\delta} \quad (4).$$

In Eq.(4), J_{core} is the current density carried by the vortex core when depinning occurs. From Eqs.(1-4), we have

$$J_{core} = 4J_{cr} \qquad and \qquad I_{core} = 4I_J \quad (5)$$

since current I_J flows across the weak links in the critical state.

Let's consider a sketch of the vortices lying in the vicinity of the annihilation line along a TB. In the critical state (Fig.3a) and in absence of any external field, the TB is completely penetrated by the vortices and the antivortices. The mean distance between the vortex cores is equal to 2λ and there is no vortex interaction. When each weak link carries current $3I_J$, the mean distance between neighboring vortices is equal to $2\lambda/3$. The total screening current flowing across the vortex cores is equal to zero, except across the cores of the vortices located at $\pm\lambda/3$ that carry a screening current equal to $2I_J$ due to their next neighbors (see Fig.3c). However, due to its first and second neighboring vortices, the weak link located on the annihilation line carries a total screening current that is equal to $4I_J$, the depinning value. As the current goes on increasing, more weak links carry current $4I_J$ and we expect a sudden vortex depinning when current $4I_J$ flows across the cores of the vortices neighboring the TBs intersections in the vicinity of the annihilation line. It is reasonable to assume that this brutal depinning process ignites a thermal runaway and the transition to the normal state.

III. COMPARISON TO EXPERIMENTAL RESULTS

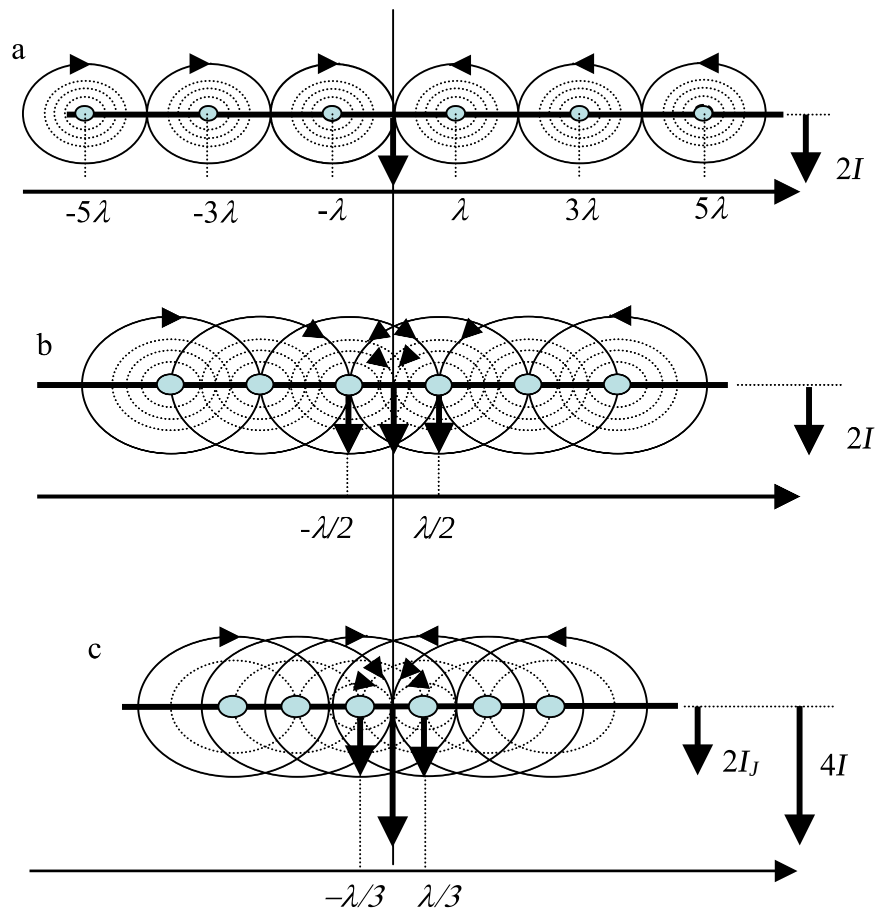

Fig.3 : Schematic representation of the vortices and antivortices lying along a twin boundary in the vicinity of the annihilation line : (a) each weak link carries current I_J (critical state); (b) each weak link carries current $2I_J$; (c) each weak link carries current $3I_J$. The ellipses represent screening current lines and the grey areas in the ellipses represent the vortex cores. The thick horizontal lines and the vertical line represent the twin boundary and the annihilation line, respectively. Only the screening currents flowing across the weak links located on the annihilation line and at the vortex cores are shown (full arrows).

The work carried out by the force due to the transport current acting on a vortex line that moves over distance δ takes the form $W = Jv\phi_o d\delta$. According to the Kim-Anderson model, in the flux creep regime we have

$$V\alpha\, e^{-\frac{U_o}{k_B T}} sinh\left(\frac{W}{k_B T}\right) \qquad (6)$$

where V is the voltage at the terminals of the sample. Then, the length δ can be determined from the current-voltage curves. The inset in Fig.4 shows the δ values for two films respectively 190nm and 150nm thick measured by Gonzàlez *et al.* [16]. As expected, (see Fig.1) the δ values increase as the temperature increases. At a given temperature, an estimation of I_{wl}, the current flowing across the weak links in the critical state, can be obtained with Eq.(2) from the experimental values of I_{cr} and δ. The main part of Fig.4 shows the values calculated for both samples. Except near T_c, the experimental I_{wl} values are in the range of $I_J = \frac{2\pi k_B T}{\phi_o}$, as predicted by the model. Fig.5 shows $J^*(T)$, the current density at the transition to the normal state measured by Gonzàlez *et al.* on both samples, as well as the values calculated supposing that the current at the transition takes the form $I^* = 3I_J \frac{w}{\delta}$.
There is a very good agreement between calculated and measured values in the whole range

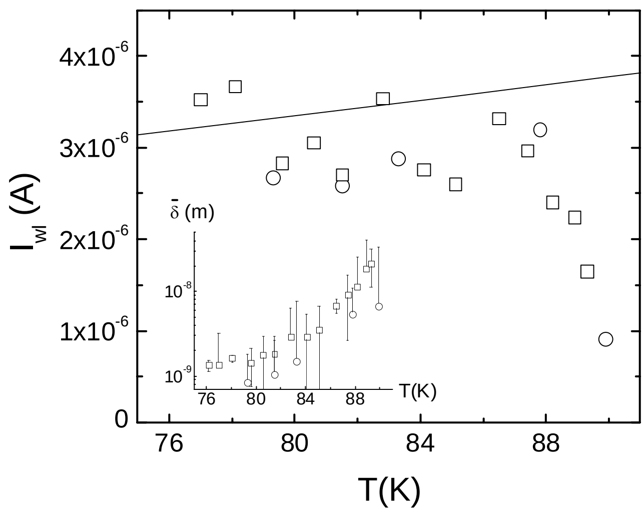

Fig.4: Current $I_{wl} = J_{cr} d\delta$ carried in the critical state by each weak link of the 190nm (circles) and the 150nm (squares) thick films measured by Gonzàlez et al., as a function of the temperature. The solid line shows the predicted values $I_{wl} = \frac{2\pi k_B T}{\phi_o}$ (Eq.1). The inset shows the δ values.

of the measurements, although J^* is different from $3J_{cr}$ near T_c [17] .

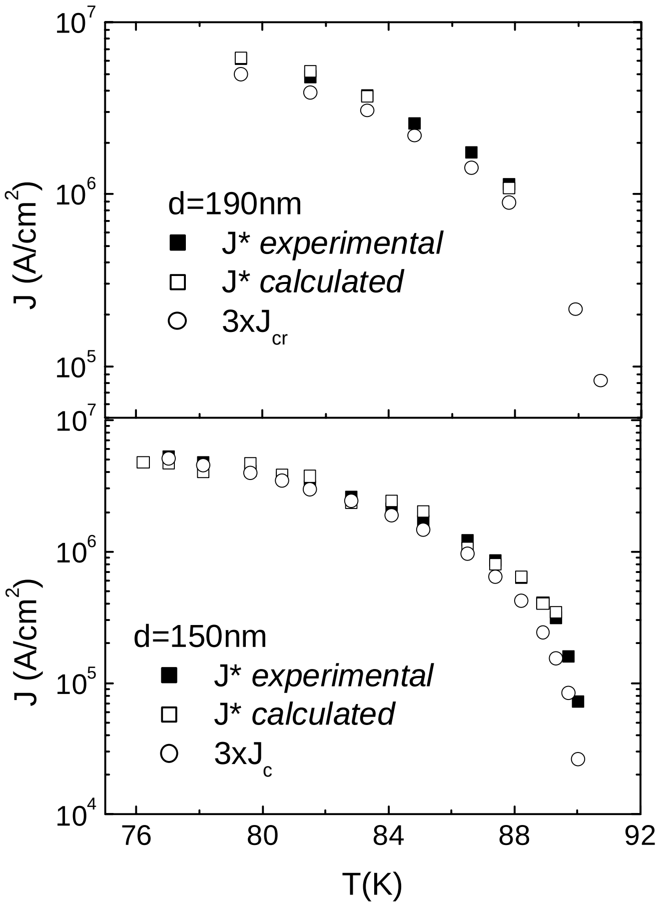

Fig.5: Experimental and calculated current densities at the transition to the normal state for the 190nm and the 150nm films measured by González et al. The experimental and calculated values are very near $3J_{cr}$ except near T_c.

IV. SUMMARY

We have proposed a description accounting for the behavior of twinned YBCO films in the critical state and at the transition to the normal state. According to this model, the vortices are in motion along the TBs that, due to disorder, behave as rows of weak links. Vortex pinning occurs at the TBs intersections. All the weak links carry the same current $I_J(T)$ in the critical state. The transition to the normal state occurs when each weak link carries current $3I_J$. It is triggered by vortex depinning at the TBs intersections neighboring the annihilation line. The model predictions are in good agreement with the data measured by Gonzàlez *et al.*[16].

References and Notes

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