

Vortex Interactions with Twin Boundaries in $\text{YBa}_2\text{Cu}_3\text{O}_7$ Films

(A comment to "Vortex dynamics at the Transition to the Normal State in $\text{YBa}_2\text{Cu}_3\text{O}_7$ Films" by P. Bernstein *et al.*)

M.G. Blamire, A. Palau & J.H. Durrell,
Department of Materials Science, Cambridge University, UK
e-mail: mb52@cam.ac.uk

Abstract - This comment is intended to focus on the issues of twin boundaries and pinning introduced in the discussion document of Bernstein et al and subsequent comments; in particular the nature of vortices within the twin boundaries.

Manuscript received and accepted June 26, 2007; Reference No. ST1-D3, Category 2

Optimally-doped $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) is orthorhombic and so the material is highly likely to be twinned. In the case of the growth of (001) c-axis films on typical cubic substrates such as SrTiO_3 a high density of twin boundaries in thin films is observed if high resolution transmission electron microscopy or X-ray diffraction studies are performed. It is also true that YBCO thin films typically show much higher critical currents than bulk samples and the critical current density decreases significantly as film thickness is increased. The inference might, therefore, be drawn that twin boundaries are responsible for the high critical currents in thin film YBCO. In fact, the overwhelming evidence suggests that twin boundaries are *not* the dominant pinning mechanism in thin films. Recent evidence indicates that thickness dependence of the critical current density (J_c) is due to the generation of effective pinning centres at the substrate film interface. Films grown on very well matched substrates such as NdGaO_3 can show no thickness dependence at all. In this comment we give our views on the nature and role of twin boundaries in YBCO. We start by considering grain boundaries, with which some analogies have been drawn.

It is absolutely clear that the presence of grain boundaries in YBCO strongly degrades the overall J_c and that, at least for misorientation angles greater than a few degrees, there is a strong Josephson component in the electrical transport across them. Indeed large-angle boundaries have been extensively employed as Josephson junctions [1]. Low-angle grain boundaries are generally considered as retaining coherent superconductivity across at least a proportion of the boundary area, but this is locally suppressed at the cores of the dislocations required to accommodate the lattice distortions: as the misorientation angle is reduced, the separation of these dislocations increases and so the critical current density approaches that of the bulk. It is now well-established that these low-angle grain boundaries have radically different effects on vortex motion depending on the vortex angle. For vortices parallel to the plane of the grain boundary, the effective pinning force for motion parallel to the boundary is considerably lower than that normal to the

boundary - this leads to the channelling of vortices along the boundary for suitable directions of the Lorentz force and so a reduced overall J_c . Where vortices intersect obliquely with the grain boundary, critical currents can be considerably higher and indeed equal that of material without grain boundaries. For low angles to the boundary plane, vortex behaviour can be separated into strongly pinned vortex sections within the grains and weakly-pinned segments within the grain boundary; we hypothesised a cutting process which enabled motion of the grain boundary segments relative to the immobile intra-grain sections and a model based on this correctly fitted the angular dependence of the critical current in our experiments [2].

At least in terms of its superconducting properties, a twin boundary can be viewed as a special case of a grain boundary. Partly because the symmetry of the order parameter changes direction on crossing a twin boundary, and probably also because oxygen stoichiometry is reduced, the superconductivity and hence the local pinning strength is to some extent reduced at a twin boundary. This occurs without the presence of crystallographic defects which might enhance the vortex pinning. However, as we shall show, there is little direct evidence of any Josephson component in the coupling across twin boundaries and we believe that the best model for a twin boundary is that in which the pinning of Abrikosov vortices is locally reduced.

Experimentally, the study of the properties of twin boundaries in epitaxial films is simplified because they appear along definite crystallographic directions (110) and (110). It is thus possible to perform measurements, in which the direction of the applied field is changed and so identify the contributions of the twin boundaries to determining the overall J_c . We recently demonstrated that for certain angles, vortices can channel along twin boundaries in an analogous way to grain boundaries and that the same cutting model can be applied to model the behaviour for small oblique field angles [3]. However, our experiments also showed that depending on the magnitude of the field and temperature, twin boundaries could also give rise to an enhancement of the critical current for the same angles. It seems likely that this is associated with vortex motion along one twin direction being impeded by the presence of the orthogonal set of twin planes or at least by interaction with vortices associated with these orthogonal planes [3]. This gives rise to an excess pinning over that provided by the point and line pinning centres which lie within the material as a whole.

Bernstein *et al.* present a model based on Josephson coupling across a twin boundary which they use to model earlier data from melt-textured material. Without commenting on the particularities of the model, we have a number of general comments to make on the nature of coupling across extended planar defects. If we take the analogy with polycrystalline YBCO, it is clear that if the planar defects are Josephson-coupled then the result is a severe suppression of the critical current density. This is an inevitable consequence of the topology of such a system in which current must pass through the boundaries and so be limited by the tunneling critical current density. In contrast, point and line defects in which the order parameter is locally suppressed can act as efficient pinning centres without greatly disturbing the current flow in the material. As discussed by R. Woerdenweber in his comment (ST1-D1), a particular example of such a pinning centre is simply a hole in a thin film and it is comparatively straightforward to make artificial pinning arrays using electron-beam lithography and etching which significantly enhance the overall critical current of the material at the so-called matching field when

the vortex lattice is commensurate with that of the array. However, the extension of this structure to create extended 2-D pinning centres by patterning an array of linear cuts with a topology similar to that of twin boundaries would completely eliminate all conduction. A different sort of planar structure might be envisaged in which pinning properties were distributed such that vortex motion along the plane was relatively easy, but strongly resisted by pinning in the orthogonal direction. At least for fields applied parallel to the plane, a single planar structure such as this patterned across a conductor would substantially suppress the critical current across it but, because of the continuity of fundamental superconducting parameters such as critical temperature throughout the material, would not be a Josephson junction. Instead, the voltage generated by the "device" would be due to the motion of Abrikosov vortices within the plane. In many (but not all) respects the vortex channel structures fabricated by the Leiden group are a good model for such structures [4], albeit with a lower dimensionality. We would argue that twin boundaries are also reasonable approximation to this model, have probably a slightly reduced transition temperature associated with oxygen non-stoichiometry, and that such a model is perfectly consistent with the points noted in the comment by Bernstein and Hamet regarding the behaviour of twin boundaries.

Typically, twin boundaries appear with two orthogonal habits and so that even in the case where field is applied parallel to both twin planes the Lorentz force acting on them cannot be in the easy direction for all vortices. Thus there is the possibility for vortex flow along some twin boundaries to be blocked by entanglement with other vortices pinning within other twin boundaries. Just as in the case of the channelling of oblique vortices along low-angle grain boundaries, whether this entanglement is capable of enhancing the critical current or not depends on the relative magnitude of pinning and cutting forces at the field and temperature of the experiment. We believe that such a model is strongly favoured by the observation of a crossover between channelling and critical current enhancement associated with twin boundaries.

References

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