Flux flow measurements in irreversible type II superconductors

J.M. Lumley, J.E. Evetts, C.H. Chao

Classification
Physics Abstracts
74.60G

FLUX FLOW MEASUREMENTS IN IRREVERSIBLE TYPE II SUPERCONDUCTORS (*)

J. M. LUMLEY, J. E. EVETTS and C. H. CHAO (**)

Dept. of Metallurgy and Materials Science, University of Cambridge, Pembroke Street, Cambridge, U.K.

(*Reçu le 23 août 1978, accepté le 20 septembre 1978*)

Résumé. — Nous décrivons de nouvelles mesures des caractéristiques de courant-tension dues au mouvement des lignes de flux dans des lames d'un supraconducteur de type II en présence d'un champ magnétique transverse. En utilisant une technique de détection de phase pour mesurer la résistivité différentielle, nous montrons que les courbes intensité-voltage présentent une structure fine remarquable dont les caractéristiques principales sont proportionnelles à la valeur du courant critique.

Abstract. — We report new measurements of the flux flow characteristics of irreversible type II superconducting foils in transverse magnetic fields. Using a phase sensitive detection technique to measure differential resistivity it is found that the current-voltage curves exhibit remarkable fine structure the main features of which are shown to scale with the critical current.

1. **Introduction.** — The first serious measurements on the flux flow state of type II superconductors were performed by Kim *et al.* [1] who showed that their current-voltage (*v-i*) curves were linear and that their slopes, i.e. their flux flow resistances, were related to the normal state resistivity and the applied magnetic field but not to the pinning present in the sample. Since then a number of people have observed non-linear *v-i* characteristics which have largely been explained in terms of specimen non uniformity producing a spread in j_c values [2, 3]. More recently it has been realized that the form of the *v-i* relation is affected by and can provide information about the type of pinning and depinning mechanisms operating in a given superconductor [4, 5]. Further there is growing evidence, both experimental and theoretical [5, 6, 7], that in the presence of pinning the flux lattice will tend to flow along its high symmetry directions. The driving force for such an orientation of the flux lattice comes from the pinning distribution the dominant Fourier components of which are those having the same wavenumbers as the low index reciprocal lattice vectors of the flux lattice. This suggests that at large currents the flux lattice will rotate to such an orientation from the one imposed on it by the pinning potential structure at the critical current. A reorientation of this sort may be expected to produce a *kink* or a change of slope of the *v-i* characteristic because the flux lattice will experience slightly different pinning for each orientation. This was the motivation for the accurate differential resistivity measurements reported here.

2. **Experimental.** — Both current-voltage and differential resistivity measurements were obtained using standard four terminal methods. For the differential resistivity measurements the phase sensitive detection [PSD] techniques used could accurately detect slope changes $\lesssim 1\,\%$ in the *v-i* curves, changes which would otherwise probably go unnoticed. Because we were looking for very small slope changes we selected samples having *linear v-i* characteristics reaching their full flux flow resistivity close to the critical current. For all specimens used this also meant taking measurements at fields not too close to H_{c2} [7, 8], a feature we shall discuss in a future publication. Further, because heating could cause spurious curvature of the *v-i* curves all samples were immersed in superfluid helium and power dissipation levels were kept below that required to produce ~ 10 mK (estimated) tem-

(*) This paper has been presented at the LT-15 Conference as a post deadline paper.

(**) Present address : Institute of Physics, Academia Sinica, Peking, China.

perature difference between the sample and the superfluid.

We have obtained detailed differential resistivity measurements on a number of Nb/Ta and Pb/Bi alloys and *v-i* curves for a wider range of superconducting alloys. All the samples measured exhibited moderate bulk pinning with critical current densities $\sim 5 \times 10^6$-10^8 A/m^2.

3. **Results and discussion.** — In figure 1 we reproduce some effectively linear *v-i* curves for a Pb-12 at % Bi foil (1.5 mm × 0.1 mm, $B_{c2} = 0.9$ T, voltage contacts $\simeq 3$ mm apart). The magnetic field was applied perpendicular to the wide foil dimension. For the same sample we present in figure 2 a family of differential resistivity curves obtained using a 5.6 Hz, 14 mA p-p ripple current. It is clear from this figure that fine structure exists which is not evident from the d.c.

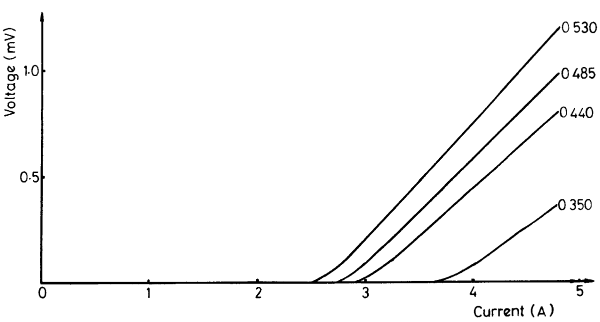

FIG. 1. — Current-voltage curves for Pb-12 at % Bi foil. The number alongside each curve is the magnetic field in tesla.

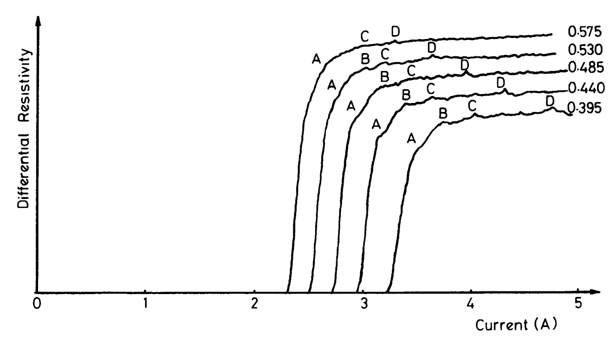

FIG. 2. — Differential resistivity curves for sample of figure 1. The number alongside each curve is the magnetic field in tesla.

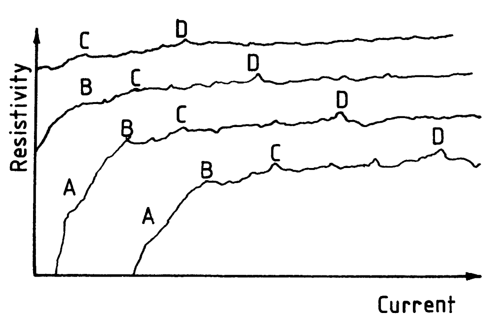

FIG. 3. — Part of the differential resistivity curves of figure 2 showing the fine structure in greater detail.

v-i plots and which is highly reproducible, each curve being the average of two or more chart recorder traces. In figure 3 we show an enlarged region of figure 2 to show this fine structure more clearly.

Although not obvious from figure 2 the structure is essentially independent of both frequency (1.2-13 Hz) and amplitude (2-30 mA p-p) of the ripple current used for the PSD measurements. This proves that we are picking out genuine features of the d.c. *v-i* curves which are simply unresolvable by inspection. The time taken for flux lines to cross the sample is also of no importance with the times involved being less than 1 % of the period of the ripple current used. Finally, the structure is also basically independent of the direction of the d.c. current through the sample and therefore of the direction of motion of the flux lattice across the sample.

From figure 2, by noting the currents at which the features A, B, C and D occur, we have constructed table I by dividing these currents by the relevant

TABLE I

The ratios of the current at which the features A, B, C, D *occur to the dynamic critical current as a function of field.*

Field (tesla)	A	B	C	D
—	—	—	—	—
0.35	1.03	—	1.18	1.39
0.395	1.03	1.10	1.18	1.40
0.44	1.03	1.10	1.18	1.40
0.485	1.03	1.11	1.21	1.39
0.53	1.05	1.14	1.22	1.40

dynamic critical currents. The constancy of these ratios is remarkable and gives indisputable evidence that the features scale to the critical current, i.e. are related to the pinning in the sample. We have obtained essentially the same ratios for measurements between different pairs of voltage contacts on this and other Pb/Bi samples of similar composition. For Nb-50 at % Ta foils the characteristic ratios are somewhat different (some appear to be quite close) although they too are independent of field. For each of the samples it is clear that the structure is not related to heating since this varies with magnetic field. Neither can it be related to nucleation of flux lines or to surface irregularities since, for these samples, the critical current is a bulk property.

What then is the crucial scaling quantity relevant to these results ? Is it the average flux velocity ($v \propto (J - J_c)\,\rho/H \propto (J - J_c)\,\rho N/H_{c2}(0)$ for $t \leqslant 0.3$ [1]) or is it a ratio between the total force and the pinning force on the flux lattice (i.e. to $JB/J_c\,B$) or is it some other pinning related field independent quantity ? Thus far it has not proven possible to obtain a sufficiently large range of ρ/H for a given specimen or specimen type to choose between velocity or force, but there is tentative evidence for the latter from our results on other Pb based alloys. Incidentally, the electric field cannot be the appropriate scaling quantity since it is a function of field ($\mathbf{E} = \mathbf{V} \times \mathbf{B}$).

However, irrespective of the answer to this important question we believe that the structure in the differential resistivity is related to reorientations of the flux lattice to Fourier components of the pinning potential; the fine structure coming from such processes on a local scale and the more pronounced features from larger scale rotations or alignment of large regions of the flux lattice. At the critical current the flux lattice will contain many imperfections and will exhibit short range order only. As the current increases various regions of the flux lattice will reorient and the lattice will contain fewer dislocations until at high currents the flux lattice will become more or less perfect. With this model it is clear that, in addition to the strength and distribution of the pinning sites, rigidity of the flux lattice will play an important part; the more rigid the flux lattice the less it will be influenced by the pinning centres and the less fine structure we'll see in the differential resistivity curves. We would also expect much less fine structure for a nearly periodic pinning array. Thus different types of pinning distributions in different materials will produce both fine and coarse structure but the size of this structure and the characteristic ratios will be different. There is some evidence for this in table II which presents the characteristic ratios for a number of different specimens. These ratios are early results obtained by inspection of the relevant *v-i* curves.

Schmid and Hauger [6 : SH] treat the pinning distribution in terms of its Fourier components and they too effectively predict a reorientation at high velocities remarking that a stiff flux lattice favours their solution of a moving perfect lattice. Fiory [7] too observes that in order to obtain his r.f. excitation effects he needs weak pinning and must use currents $> 2\,j_c$ at which his flux lattice clearly becomes regular. Perhaps the most implausible argument of SH is that the only really effective Fourier components will be those with the same wavenumber as the smallest reciprocal lattice vectors of the flux lattice. For a realistic pinning distribution it is perhaps more reasonable to imagine reorientations of the flux lattice to different Fourier components in different regions of the sample and reorientations from one Fourier component to another as the current is increased. In fact Daldini *et al.* [5] claim to have observed the latter effect for a regular pinning array for a magnetic field intermediate between the two smallest matching fields. It is of interest to note that for a Nb-50 at % Ta foil exhibiting a peak effect (in some sense a matching situation) we have obtained structure in our differential resistivity curves very similar to those of Daldini *et al.*

Summarizing, the differential resistivity curves of bulk type II superconductors display a fine structure the main features of which scale with the critical current, and so are related to pinning. Although at this stage it is not clear whether the critical scaling quantity is a velocity or a force we believe the origin of the structure to be the small and large scale reorientations that the flux lattice undergoes due to its interaction with various Fourier components of the pinning potential. This belief receives some indirect support from the work of Fiory, Daldini *et al.*, Schmid and Hauger.

TABLE II

The characteristic ratios for different alloys. These ratios are not very accurate being obtained by inspection of the relevant v-i curves.

Material/sample	Characteristic ratios
Nb-50 at % Ta	1.32
Nb-50 at % Ta	1.33
Pb-35 at % Bi	1.25
Pb-35 at % Bi (annealed)	1.37, 1.86
Pb-6 wt % In	1.53
Pb-12 at % Bi	1.54, 1.75, 2.5
Pb-20 at % Bi	1.66, 2.5

References

[1] KIM, Y. B., HEMPSTEAD, C. F. and STRNAD, A. R., *Phys. Rev.* **139A** (1965) 1163.

[2] JONES, R. G., RHODERICK, E. H. and ROSE INNES, A. C., *Phys. Lett.* **24A** (1967) 318.

[3] BAIXERAS, J. and FOURNET, G., *J. Phys. Chem. Solids* **28** (1967) 1541.

[4] CAMPBELL, A. M. and EVETTS, J. E., *Adv. Phys.* **21** (1972) 199.

[5] DALDINI, O., LEEMANN, C. and MARTINOLI, P., *Solid State Commun.* **16** (1975) 509.

[6] SCHMID, A. and HAUGER, W., *J. Low Temp. Phys.* **11** (1973) 667.

[7] FIORY, A. T., *Phys. Rev.* **B 8** (1973) 5039.

[8] TAKAYAMA, T., *J. Low Temp. Phys.* **27** (1977) 359.