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THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

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Triangular flux line lattices have been observed by electron microscopy on Pb-4at% In and niobium specimens in the remanent state. These lattices contain various kinds of defects.

The Abrikosov solution [1] of the Ginsburg-Landau equations [2] for the mixed state of type II superconductors predicts a periodic arrangement of flux lines (flux line lattice) penetrating the specimen parallel to the applied field. Neutron diffraction studies [3,4] on niobium and nuclear magnetic resonance studies on vanadium [5] give evidence for the existence of a close packed arrangement of flux lines.

In this paper we present results on the flux line arrangement obtained by sirect observation of individual flux lines. As was shown in previous papers [6-8], the magnetic structures on the surfaces of ferromagnets and superconductors can be revealed with a resolution of about 500 Å or better by depositing small ferromagnetic particles on the specimen and observing the resulting patterns in the electron microscope by means of a replica technique.

We report here the magnetic structures of Pb-4at%In ($\kappa = 1.35$ at 1.1°K [8]) and niobium in the remanent state at 1.1°K based on observations on the end surfaces of well-annealed mono- or polycrystalline rods (4 mm diameter, 50 mm length) that had been magnetized parallel to the rod axis in a field of 3000 Oe. Parts of the surfaces exhibited a quite well defined triangular lattice of "points of exit" of the magnetic flux (fig. 1). In polycrystalline Pb-4at%In the lattice parameter (nearest neighbour separation) is $a = 3500$ Å. If each of the indivudual spots is as-

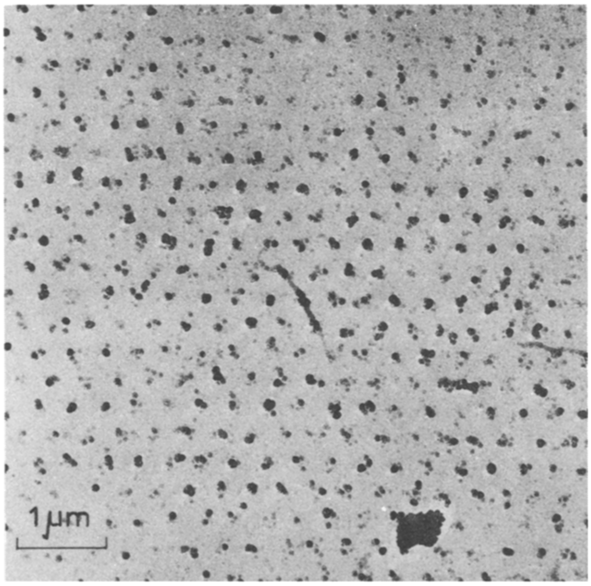

Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at%indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

signed to an intersection of the surface with a flux line carrying one fluxoid quantum $\Phi_0 = hc/2e = 2.06 \times 10^{-7}$Gcm^2, an average induction of $B = 195$ gauss is calculated in good agreement with the measured induction B [8]. The surface of a monocrystalline niobium rod showed a flux line lattice near the axis only. The measured lattice parameter $a = 2200$ Å corresponds to a local induction of 450 gauss. This corroborates recent neutron diffraction studies [4] on niobium, which indicate that for an average induction B smaller than 500 gauss the flux line lattice parameter is almost independent of B. In accordance with our observations by light microscopy this can be accounted for by the fact that in relatively small external fields the induction is not homogeneous.

If larger areas are considered, one finds various kinds of imperfections of both "elastic" and "plastic" nature in the flux line lattice (fig. 2). The elastic distortions give rise to deviations of the lattice parameter from the mean value up to about 50% and to strong curvatures of the close packed directions. Over a distance of about 20 μm a close packed line may deviate from the original direction by as much as 30°. There seems to be no correlation between the orientations of the magnetic lattice and the crystal lattice.

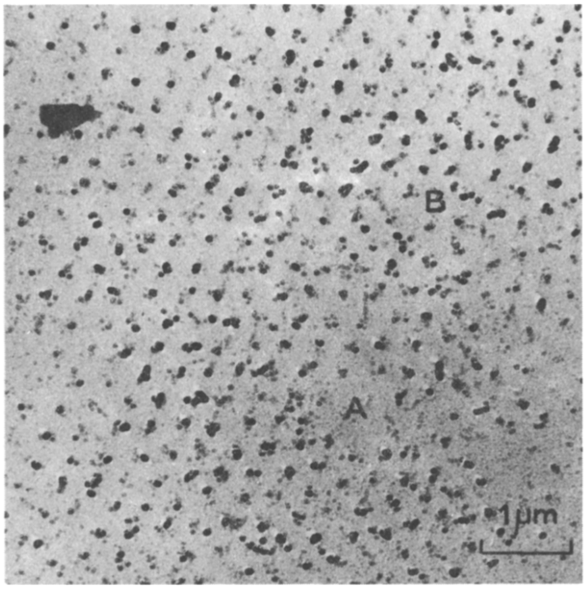

Fig. 2. Flux line lattice on the surface of a lead-4at% indium rod at 1.1°K showing a high density of defects in the flux line lattice (A: Hole, B: Flux line dislocations).

The "plastic" distortions include a variety of "lattice" defects", namely
a) Flux line dislocations (FLD) of different types (see fig. 2), as already discussed by Labusch [9]. These dislocations often arrange themselves to form "grain boundaries". b) "Stacking faults".
c) "Point defects" (interstitials and vacancies).
d) Holes in the lattice where a number (typically 5 to 20) of flux lines are missing.

It should be noted that the analogy of the observed "defects" to those known from crystal physics is incomplete in the sense that the defects in the flux line lattice are imbedded in a lattice exhibiting very large elastic distortions. A detailed discussion of the observed structures including the field dependence will be published elsewhere.

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