

Transformation from flux tube to labyrinthine stripe pattern in the intermediate state of superconducting Indium

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Abstract

Intermediate state structures in Type I superconductors are observed by the magneto-optical imaging technique. A $10 \mu\text{m}$ thick Indium film submitted to a perpendicular applied magnetic field presents two kinds of normal state domains : flux tubes and labyrinthine stripes. We show that the tube pattern disappears when the field increases. The fraction of the surface area occupied by tubes is observed to depend on the magnetic flux penetration mechanism. This indicates that the observed tube-to-stripe transformation is hysteretic.

Key words: Magnetic flux structures ; Intermediate state ; Type I superconductivity

1. Introduction

The spontaneous formation of domain structures has been predicted and observed in various diphasic two-dimensional systems [1-3]. These structures result from a competition between long-range repulsive interaction between domains and short-range attractive interaction associated to a positive interface energy between the two phases. Almost-circular domains and stripe shaped domains may coexist in the system with relative concentrations depending on experimental parameters.

The intermediate state (IS) structure in Type I superconductors present such characteristics [3]. In this case the two phases are the normal state (NS) and superconducting state (SS) domains. The tube-to-stripe transformation of the NS domains is not well understood. The purpose of this paper is to determine experimentally the applied magnetic field range in which the two kinds of domains are present and to show that the observed patterns are correlated to the flux penetration mechanism.

2. Experimental set-up

The IS structure is studied by the magneto-optical (MO) technique using a CdMnTe semimagnetic quantum well heterostructure as a probe [4]. A superconducting $10 \mu\text{m}$ thick Indium film is evaporated directly onto the MO probe. The sample is immersed into the He bath maintained at 1.8K and submitted to an increasing applied magnetic field H perpendicular to its plane.

The optical set-up is similar to a reflection polarizing microscope. Linearly polarized light from a Ti-Sapphire laser is focused onto the sample. It penetrates into the MO layer and is reflected by the superconductor. The beam polarisation plane is rotated by Faraday effect within the MO layer above the flux bearing NS regions of the superconductor.

3. Discussion

Fig. 1 shows the IS structures on one edge of the Indium film for two H values. The normal component of

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the local magnetic field is zero in the SS (grey) regions and equal to the thermodynamical critical field H_c in the NS (black) regions.

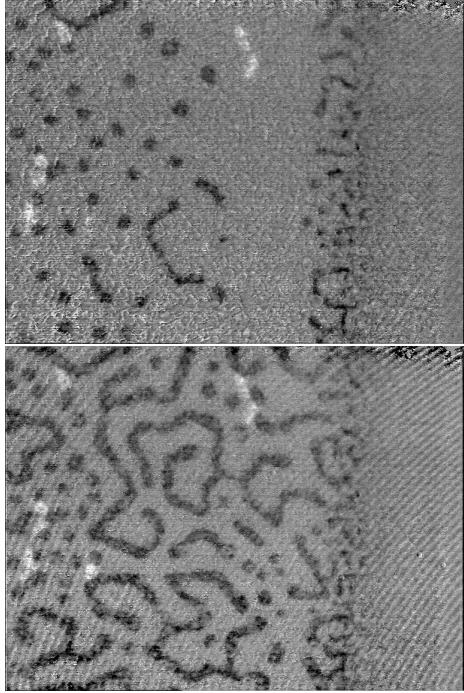


Fig. 1. Magnetic flux pattern on the edge of a $10 \mu\text{m}$ thick superconducting Indium film revealed by the magneto-optical technique. The images size is $264 \times 191 \mu\text{m}^2$. The grey band on the right of the pictures (width $\approx 50 \mu\text{m}$) correspond to the exterior of the film. The normal and the superconducting state regions appear in black and in grey respectively. The two images have been obtained for increasing h values (top: $h = 0.1$, bottom: $h = 0.24$).

For $h = 0.1$ (top image) where $h = H/H_c$ and $H_c(1.8K) = 20.2mT$, the IS does not fill the full surface area. This indicates that the flux distribution is not an equilibrium distribution. A diamagnetic band (width $\approx 40\mu\text{m}$) separates the IS structures present on the edge and in the interior of the film. The diamagnetic band is associated with a geometrical metastable energy barrier [5] which prevents spontaneous flux migration from the edges towards the film interior. The interior IS structure is essentially composed of NS tubes (dark spots) (diameters $\approx 7\mu\text{m}$) and by several stripes. For $h = 0.24$ (bottom image) (i) the total surface area occupied by the NS has increased, (ii) the diamagnetic band has disappeared : flux can penetrate continuously from the edges.

However, as it is shown in Fig. 2, increasing h reduces the relative area fraction of tubes F (defined as the ratio of the surface area occupied by the tubes over the NS total area (tubes + stripes)). For $h \approx 0.5$, F becomes almost equal to zero. Whereas the IS model

developed in Ref. [3] predicts a tiny difference between the free energy associated to the tube and the stripe pattern, this result indicates that the tube pattern becomes less favourable for the highest h values.

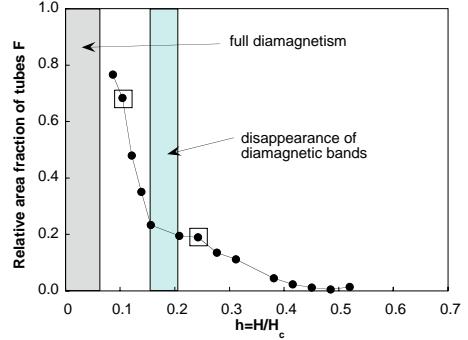


Fig. 2. Relative area fraction of tubes F versus reduced magnetic field $h = H/H_c$. The framed points correspond to the two pictures of Fig. 1. The two decay regimes are correlated with the presence and absence of the diamagnetic band with the increase of h .

Two decay regimes of F can be distinguished and correlated with the presence and absence of the diamagnetic band, i.e., correlated to the magnetic flux penetration mechanism. F decays rapidly when the diamagnetic band is present ($h = 0.03 - 0.16$). In this field range, flux tubes unfasten from the IS edge structure and penetrate irreversibly into the film [5]. F decays more slowly when the diamagnetic band is absent ($h > 0.2$). In this range, flux can penetrate continuously into the stripes which are reaching the edge. The fact that the decay of F depends on the flux penetration mechanism indicates that (i) the measured F values are not equilibrium values and (ii) the tube-to-stripe transformation is most probably hysteretic. This suggests that equilibrium IS models [6] may be not accurate to describe the observed tube-to-stripe transformation.

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