Mixed State in Layered Superconductors(Abstracts of Doctral Dissertations)

Mixed State in Layered Superconductors

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Abstract

Chap. 1. Introduction

Artificially prepared multilayered superconductors, such as Nb/Cu, have layered structures where superconducting layers and nonsuperconducting layers are alternately stacked. Cuprates with high superconducting critical temperature (Tc) are also intrinsic layered superconductors having crystal structures where the CuO_2 layers responsible for the high-Tc superconductivity and the other nonsuperconducting layers, such as LaO, BaO, and CuO chain layers, are periodically stacked. In these layered superconductors, the superconducting properties under a magnetic field strongly depend on the layered structures when the coherence length perpendicular to the layers at T = OK is comparable to or shorter than the period of the layered structures. Due to the layered structure, the mixed state of these layered superconductors shows not only large anisotropic properties but also peculiar behavior which is unable to be explained by the theory of the conventional homogeneous type-II superconductors. For example, concerning the observed temperature dependence of the upper critical field parallel to the layers, H_{c2}'', the dimensional crossover behavior from 3D to 2D is seen as temperature decreases. Furthermore, the experimental results indicate that the layered structure causes the unusual behavior of the physical properties, such as the angular dependence of the upper critical field H_{c2}, the temperature dependence of the lower critical field H_{c1}, the flux line structure, and the flux line state. To understand these peculiar properties in the mixed state, a new theoretical approach is required which takes into account the effect of the periodic layered structure on superconducting properties, in particular the proximity effect and the periodicity dependence. Hence in this thesis by introducing a new phenomenological Ginzburg-Landau (GL) model for layered superconductors, we develop a phenomenological theory based on the GL theory. Using this model, we investigate qualitatively the general characteristics of the effect of the layered structure on the mixed state in superconducting multilayers and high-Tc cuprates. In this chapter the background and the purpose of this study are presented. The organization of this thesis is also given.

Chap. 2. New Ginzburg-Landau Model for Layered Superconductors and Its Application to Not Weak Link Limit

In this chapter we first present a new phenomenological GL model (continuous model) for general layered superconductors which include superconducting multilayers and high-Tc cuprates. This continuous model assumes that the GL coefficients, which depend on the material parameters characterizing the properties of the mixed state, vary periodically and continuously in the direction perpendicular to the layers. Using the GL equations derived from our continuous model, we deal with a layered superconductor composed of an alternating array of strongly superconducting (SSC) layers and weakly superconducting (WSC) (or normal) layers of almost equal thickness. The physical properties numerically calculated are the spatial and temperature dependences of the superconducting

order parameter in the Meissner state. The amplitude of the order parameter at WSC layers is rapidly enhanced with decreasing temperature, in particular at low temperatures, not only by the proximity effect but also by the influence of the periodically arrayed layers. The system hence becomes closer to a homogeneous superconductor as temperature decreases. We also numerically calculated the temperature dependence of H_{c2} and H_{c1} in the directions perpendicular and parallel to the layers, and the angular dependence of $H_{c2}(\theta)$. Here, θ denotes the angle measured from the direction perpendicular to the layers. The proximity effect and the periodic layered structure cause these properties to be qualitatively different from those of homogeneous type-II superconductors. The angular dependence of $H''_{c2}(\theta)$ around $\theta = 90°$ is correlated with the dimensionality appearing in the temperature dependence of H_{c2}. In the 3D regime the H_{c2} versus θ curve shows a bell-shaped curve similar to that in the effective mass model. On the other hand, in the 2D regime the $H_{c2}(\theta)$ has an angular dependence similar to that in the Tinkham formula for a thin film, that is, a curve with a cusp at $\theta = 90°$. As to the global angular dependence of $H_{c2}(\theta)$ ($0° < \theta < 90°$), even in the 3D regime H_{c2} versus θ curve shows a clear difference from that of the homogeneous anisotropic type-II superconductors. This difference is much more pronounced at high temperatures than at low temperatures. The calculated results for $H_{c2}(\theta)$ explain qualitatively the observed angular dependence of H_{c2} in Nb/Cu multilayers. The H_{c1} is anomalously enhanced with decreasing temperature. The calculated temperature dependence of H_{c1} reproduces qualitatively the observed one in Nb/Cu multilayers and high-Tc cuprates.

Chap. 3. Weak Link Limit (Josephson-coupled Layered Superconductors)

In Chap. 2, we considered the layered superconductors where the interlayer coupling is not so weak. This chapter is concerned with a treatment for a layered superconductor whose interlayer coupling is very weak, such as $Bi_2Sr_2CaCu_2O_{8+y}$. This type of superconductor may be considered to be a Josephson-coupled layered superconductor. In this case our continuous model of the weak link limit may be applied. This specific formalism is equivalent to the generalized Lawrence-Doniach (LD) model. The original LD model is used to describe an array of equivalent superconducting layers stacking equidistantly. The generalized LD model has additional inequivalent superconducting layers. Using the GL equations for our model in the weak link limit, we first numerically calculated the temperature dependence of the superconducting order parameter in the Meissner state and the temperature dependence of H_{c1} in the directions perpendicular and parallel to the layers. It is found that when the interlayer coupling is weak enough, the amplitude of the order parameter at WSC layers is rapidly enhanced with decreasing temperature, in particular at low temperatures, both by the proximity effect and by the influence of the periodically arrayed layers. This enhancement of the order parameter causes the anomalous enhancement of H_{c1} at low temperatures as mentioned in Chap. 2, and is consistent with the experimental results. We also carried out the numerical calculations for the structure of a single flux line and the magnetization process in a magnetic field parallel to the layers. The structure of a single flux line parallel to the layers is extremely anisotropic when the interlayer coupling is weak enough as follows: the distribution of the magnetic field extends along the layers in a macroscopic scale. As a result, the increasing rate of the flux line density for raising magnetic field is small. The magnetization in this case decreases with increasing the magnetic field near H_{c1} in contrast to the magnetization increase in the homogenous type-II superconductors. The self-energy of a single flux line depends on the position of the flux line in the layers. This dependence brings about the intrinsic pinning force for the flux line moving in the direction perpendicular to the layers. When the in-plane penetration depth of WSC layers is much greater than that of SSC layers, the first order phase transition occurs in the magnetization process even in the large GL parameter case.

Chap. 4. Summary and Further Outlook

This chapter summarizes this thesis and remaining problems are also presented.