Effect of Ca Doping on the Lower Critical Field of YBa$_2$Cu$_3$O$_{7-d}$ Single Crystals

Shinjiro Tochihara$^1$, Masami Mashino$^1$, Hiroshi Yasuoka$^1$, Hiromasa Mazaki$^1$, Minoru Osada$^2$, and Masato Kakihana$^3$

$^1$Department of Mathematics and Physics, National Defense Academy, 1-10-20 Hashirimizu, Yokosuka-shi, Kanagawa 239-8686, Japan
$^2$RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
$^3$Materials and Structures Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama-shi, Kanagawa 226-8503, Japan

Abstract: The lower critical fields $H_{cl}$ of Ca doped YBa$_2$Cu$_3$O$_{7-d}$ single crystals have been investigated in terms of the magnetization curves measured using a SQUID magnetometer. The observed results were analyzed within the construct of the modified Kim-Anderson model, where $H_{cl}$ and surface barriers $\Delta H$ are explicitly taken into consideration. Analyses have revealed that $H_{cl}$ is closely correlated to the carrier concentration, and $H_{cl}$ increases of the carrier concentration in the CuO$_2$ plane.

Key Words: Lower critical fields, Modified Kim-Anderson model, Carrier concentration

INTRODUCTION

In cuprate based superconductors, substitution of elements with different valence electrons brings about a change in the hole density of the CuO$_2$ plane, and this results in variation of the critical temperature $T_c$ [1]. Interesting is that a change in the hole density is also expected to cause any effect on the magnetic properties of the sample. The lower critical field $H_{cl}$ is one of the key quantities of type-II superconductors. However, in the measurement of $H_{cl}$, other effects (demagnetization, volume flux pinning, surface barriers etc.) could be involved, and probably for that reason, the results of $H_{cl}$ are still conflicting.

Recently, we have fully derived the magnetization equations of type-II superconductors within the framework of the modified Kim-Anderson (KA) critical-state model [2], where $H_{cl}$ and surface barriers $\Delta H$ are explicitly taken into consideration. From the calculated initial magnetization curves and full-hysteresis loops, we found that magnetization curves are merely expanded up and down with $\Delta H$, while $H_{cl}$ introduces a step-like feature into the hysteresis loop. Besides, it has been revealed that this step width correctly corresponds to $2H_{cl}$ without involving surface barriers.

In order to reveal the correlation between $H_{cl}$ and the carrier concentration, we employed single-crystal Y$_{1-x}$Ca$_x$Ba$_2$Cu$_3$O$_{7-d}$ ($x = 0 - 0.20$) superconductors and measured the magnetization curves using a SQUID magnetometer. Analyses based on this theoretical prediction have revealed that $H_{cl}$ is closely correlated to the carrier concentration and is enhanced with the increase of the hole density. Details of the experiment and discussion are presented.
THEORETICAL

In the modified KA model, the critical-current density $J_c$ and the effective applied field $H_{eff}$ are respectively assumed as [3-5]

$$J_c = \frac{k}{B_0 + |B_i|},$$  \hspace{2cm} (1)

$$H_{eff} = H - \left(\frac{H}{|H|} H_{cl} - \frac{dH}{dt} \right) \frac{\Delta H}{H_{cl}}.$$  \hspace{2cm} (2)

In Eq. (1), $k$ and $B_0$ are material parameters, and $B_i$ is the local magnetic-flux density inside the specimen. We consider an infinitely long cylinder with $a$, and the applied field along the cylinder axis. A sample is located in an external field $H = H_{dc} + H_{ac} \cos(\omega t)$, where $H_{dc}$ is a dc magnetic field and $H_{ac}$ is an ac field. To complete hysteresis loops for any applied field $H$, it is necessary to consider 113 stages of $H$, and all the magnetization equations have been derived [2].

In Fig. 1, we demonstrate typical initial and hysteresis $M(H)$ curves calculated using the appropriate magnetization equations for $H_{dc} = 0$ and $H_{ac} = 4H_p$, where $M$ and $H$ are normalized to the full-penetration field $H_p$. The solid loop is for $\Delta H = 0$, $H_{cl} = 0.15H_p$ and the dashed loop is for $\Delta H = 0.1H_p$, $H_{cl} = 0.15H_p$. As shown in the figure, we find the central (solid) line shifted downward from the zero-magnetization line. This downward shift is caused by a nonzero value of $H_{cl}$, and the deviation of the central line corresponds to $H_{cl}$. We compare the cases of $\Delta H = 0$ and $\Delta H = 0.1H_p$. Comparison of the loop for $\Delta H = 0$ (solid loop) with that for $\Delta H = 0.1H_p$ (dashed loop) reveals that the loop is expanded up and down when $\Delta H$ has a nonzero value. Noteworthy is that the deviation of the central line for $\Delta H = 0.1H_p$ from the initial position ($M/H_p = 0$) is the same with that for $\Delta H = 0$. This implies that in the present method for determinations of $H_{cl}$, the effect of surface barriers is completely excluded.

Fig. 1. Theoretical $M(H)$ curves, scaled by $H_p$, for $H_{dc} = 0$ and $H_{ac} = 4H_p$. Solid loop is for $\Delta H = 0$, $H_{cl} = 0.15H_p$ and dashed loop is for $\Delta H = 0.1H_p$, $H_{cl} = 0.15H_p$. 

-0.5 0 0.5 1.0

-1.0 -0.5 0.0 0.5 1.0

-5 0 5

-5 0 5

$H / H_p$ $M / H_p$