Anisotropic Upper Critical Fields of Disordered Nb_{0.53}Ti_{0.47}−Ge Multilayers

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Studies are reported of the upper critical fields of Nb_{0.53}Ti_{0.47}−Ge multilayers consisting of thick Ge layers and varying-thickness Nb_{0.53}Ti_{0.47} layers. Both the angular dependence and the temperature dependence of the upper critical fields indicate a dimensional crossover at a Nb_{0.53}Ti_{0.47} layer thickness near 200 Å. All the 2D samples display a cusplike upper critical field angular dependence with a sharper cusp for thinner Nb_{0.53}Ti_{0.47} layers. The parallel upper critical fields are tentatively fitted with an expression combining the 2D field dependence of Rickayzen, the paramagnetic limiting behavior of Maki, and the disorder-related Coulomb interaction effects of Maekawa and Fukuyama. The perpendicular fields are fitted with the Maekawa, Ebisawa, and Fukuyama theory; better agreement is obtained for thinner Nb_{0.53}Ti_{0.47} sublayers when the paramagnetic limiting effect is included.

1. INTRODUCTION

The anisotropy of the upper critical fields $H_{c2}$ of layered superconductors has attracted much interest in recent years. Anisotropy in $H_{c2}$ can arise from the properties of the individual layers\textsuperscript{1–5} if they are well isolated by barriers, or it may reflect the coupling of the superconducting layers through the barriers. The coupling involves the Josephson effect for insulating barriers\textsuperscript{6–8} and the proximity effect for metallic barriers;\textsuperscript{9,10} the presence of magnetic moments in the barriers also has a pronounced effect.\textsuperscript{11,12}
detailed theory exists for the Josephson coupled superlattice in the limit of a vanishing thickness for the superconducting layers, and the proximity coupled system has been examined recently. Two representative systems that have been studied experimentally are Nb-Ge and Nb-Cu; both involve the "clean" superconductor Nb. However, additional phenomena can arise when studying a multilayered superconductor that consists of "dirty" superconductors or when the superconducting layers are made ultrathin. It is now generally recognized that disorder results in the appearance of various quantum effects, such as electron localization and Coulomb interaction, and that these will greatly influence $T_c$, $H_{c2}$, and $J_c$.\(^{13-17}\)

The present paper is concerned with the highly anisotropic upper critical fields of superconducting Nb$_{0.53}$Ti$_{0.47}$-Ge multilayers with thick Ge layer barriers. Evidence for a dimensional crossover was observed at a Nb$_{0.53}$Ti$_{0.47}$ layer thickness $D_s$ near 200 Å, as revealed by the differing temperature dependence of the parallel upper critical fields $H_{c2\parallel}$ and a cusplike structure in the angular dependence of $H_{c2\parallel}$. A proper theory for $H_{c2\parallel}$ of a dirty, quasi-2D superconductor is not available. Therefore, we have (somewhat arbitrarily) combined various theoretical expressions that individually treat orbital, spin-orbit, and localization-interaction effects into a single expression in order to discuss our experimental data. We constructed a generalization of Rickayzen’s expression\(^5\) for a finite-thickness superconducting slab to account for paramagnetic limiting and $T_c$ degradation due to weak localization and interaction effects,\(^{12}\) which satisfactorily describes the $H_{c2}$ temperature dependence for different samples.

The perpendicular critical field data, on the other hand, can be fitted with the theory of Maekawa et al.,\(^{14}\) with an improved fit if a paramagnetic limiting term is included.

## 2. SAMPLE PREPARATION AND CHARACTERIZATION

The Nb$_{0.53}$Ti$_{0.47}$-Ge samples were prepared by dc magnetron sputtering with a multishubstrate four-gun sputtering system.\(^{18}\) The layering was achieved by alternatively positioning the substrate above Nb$_{0.53}$Ti$_{0.47}$ alloy and pure Ge targets, respectively. Typically 60 consecutive bilayers were deposited on an ~200°C sapphire substrate. The deposition parameters and the layer-thickness determination are described elsewhere.\(^{17}\) High-angle $\theta$–$2\theta$ diffractometer scans show a textured growth of the Nb$_{0.53}$Ti$_{0.47}$ layers with the bcc (110) plane parallel to the substrate. The Ge is amorphous due to the low deposition temperature. The existence of distinct and intense low-angle diffraction peaks indicated good layering in the film normal direction (Fig. 1). The position and relative intensities of these low-angle