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ANOMALOUS SURFACE IMPEDANCE IN REENTRANT FERROMAGNETIC SUPERCONDUCTORS

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For $ErRh_4B_4$, owing to the critical spin fluctuations just above T_s ($>T_{c2}$), the critical temperature at which surface ferromagnetism appears, the reciprocal penetration depth, λ^{-1}, decreases smoothly as T decreases toward T_s. For $Er_{0.5}Ho_{0.5}Rh_4B_4$, the decrease in λ^{-1} for $T > T_{c2}$ is very small, and λ^{-1} decreases abruptly at T_{c2}.

$ErRh_4B_4$ has been investigated intensively. It becomes superconducting at $T_{c1} = 8.7$ K and reenters the normal state at $T_{c2} \sim 0.8$ K. The persistent current screens the long-wave components of the exchange interaction between rare earth magnetic moments, giving rise to the onset of a spin-periodic phase at $T_p (>T_{c2})$.(1,2) However, due to the reduction of the persistent current screening in the neighborhood of the sample surface, it has been shown theoretically (3) that uniform ferromagnetism within a magnetic penetration depth of the surface appears below T_s ($>T_{c2}$). In view of the fact that microwaves sample a volume near a surface determined by the penetration depth, λ, they would be expected to provide a useful probe in the search for this surface ferromagnetic state.

We have employed a microwave spectrometer with a sample ($\sim$0.5 mm x $\sim$2 mm x $\sim$6 mm) glued to one side of a rectangular TE_{103} cavity operated at $\sim$9.3 GHz. The temperature dependence of λ changes the effective size of the cavity, and, hence, gives rise to the shift of the resonance frequency of the cavity, allowing λ to be obtained simply by measuring the frequency shift of the cavity. (4) Our system is stable enough to measure a frequency shift as small as $\sim$50 Hz, which enables us to measure λ to an accuracy of a few Å. In addition to $ErRh_4B_4$, for comparison, we have also investigated $Er_{0.5}Ho_{0.5}Rh_4B_4$ ($T_{c1} = 7.35$ K), because only its Ho magnetic moments order ferromagnetically at T_{c2} (2.70 K)(5,6) with a mean-field type of transition. Figures 1 and 2 show our results. The effects of the absence of spin fluctuations in $Er_{0.5}Ho_{0.5}Rh_4B_4$ is clearly displayed by the sharp drop in λ^{-1} at T_{c2}, indicating that $T_s < T_{c2}$. The gradual decrease of λ^{-1} in $ErRh_4B_4$ as T is decreased toward T_{c2} is consistent with the prediction that $T_{c2} < T_p < T_s$. In a non-magnetic superconductor the surface impedance may be expressed as a simple relation involving the London penetration depth. (7) However, this formula is no longer valid in a magnetic superconductor owing to the effect of the spin fluctuations. For our calculation, we consider a semi-infinite superconductor filling the half-space $z > 0$, with a surface at $z = 0$. From the definition of the surface impedance, we define the effective penetration depth as (7)

$$\lambda(\omega) = \mathrm{Re}\int_0^\infty dz\, b(\omega;z)/h(\omega;0) ,$$

where b and h are the amplitudes of B and H, respectively.

By assuming that the effects of the pair breaking associated with the spin fluctuations and the polarization of the superconducting electrons induced through the d-f interaction are negligible, the London penetration depth $\lambda_L(T)$ may be computed using the standard BCS formula. Utilizing the Maxwell equations, we obtain in the paramagnetic state

$$\lambda(w) = \mathrm{Re}\,(F/G) \qquad (1)$$

where

$$F = \lambda_L(T)[\alpha_+\alpha_-(\alpha_+ + \alpha_- + \mu\lambda_L(T) + \eta\mu\lambda_L(T)]$$

$$G = \eta\,[\alpha^2 + \alpha_+\alpha_- + \alpha^2 + \mu\lambda_L(T)(\alpha_+ + \alpha_-) - \eta]$$

Here α_+ and α_- are given by
$\alpha_\pm^2 = (\epsilon + d\eta - ic_0\gamma \pm [(\epsilon - d\eta - ic_0\gamma)^2 - 4c_0 d\eta]^{1/2})/2d$, in which $\eta = 1 - i(\lambda_L^2(T)/\delta^2)$, $d = D/T_m\,\lambda_L^2(T)$, $\epsilon = T/T_m - 1$, $c_0 = 4\pi C/T_m$ and $\gamma = \omega\tau/4\pi$. T_m is the normal state Curie temperature, C the Curie constant, and D the stiffness constant. Near T_s, $\lambda(0) \propto (T-T_s)^{-1}$.

In Fig. 1 we present the theoretical values for the inverse of the characteristic length $\lambda(\omega)$ (solid curve) calculated from Eq. (1) for $ErRh_4B_4$ together with the experimental values (circles). The physical parameters used are

$T_m = 1.0$ K, $d_0 = 0.2529 \times 10^{-2}$, and $T_p \approx 0.85$ K. This gives a value for $\lambda_L(0) = 908$ Å. We also present the result of the static limit (dash-dotted curve) using a non-local kernel (3,8) together with the parameters $\kappa_B = 4$, $d_0 = 0.4254 \times 10^{-2}$ and $\lambda_L(0) = 749$ Å. The dashed curve is the BCS $\lambda^{-1}(T)$ with the parameter choice $\lambda_L(0) = 1184$ Å. We note that the effect of the spin fluctuations, as evidenced by the departure of the data from the BCS fitting, is quite pronounced, particularly at low temperatures.

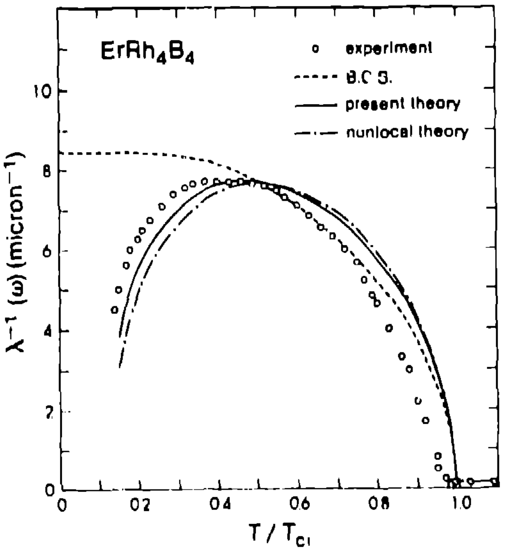

Fig. 1. Penetration depth $\lambda(\omega)$ for $ErRh_4B_4$.

In Fig. 2 the experimental data of $\lambda^{-1}(\omega)$ for $Er_{0.5}Ho_{0.5}Rh_4B_4$ are presented (circles) together with the BCS $\lambda^{-1}(T)$ (dashed curve) with the parameter choice $\lambda_L(0) = 1186$ Å. The experimental $\lambda^{-1}(\omega)$ shows a mild deviation from the BCS result above T_{c2} and a discontinuous jump to its normal value at $T = T_{c2}$, indicating that there is no additional magnetic transistion above T_{c2} (i.e., $T_s < T_{c2}$). C is given by the mean value of the values obtained in the Er and Ho case. The theory (solid curve) yields $d_0 = 1.0$, which is very large, indicating that T_s is well below T_{c2}. For comparison, the theoretical curve for $\gamma = 0$ (i.e. $\omega = 0$) is also presented, and shows a small decrease at lower temperature due to the fluctuation effect. Therefore, the present analysis suggests that the apparent suppression of the spin fluctuations in the superconducting state is due to $T_s \ll T_{c2}$ and also to the effect of the spin relaxation time.

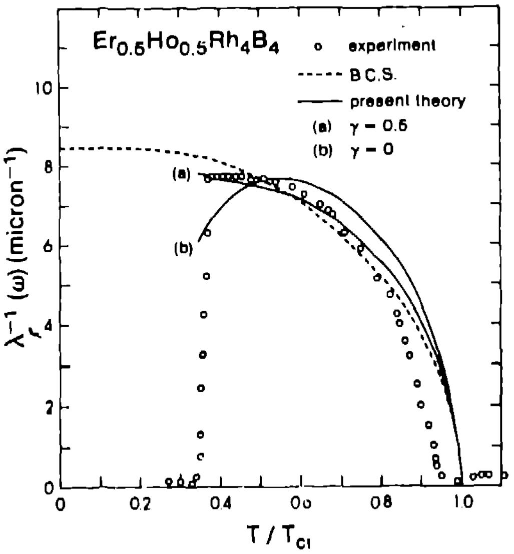

Fig. 2. Penetration depth $\lambda(\omega)$ for $Er_{.5}Ho_{.5}Rh_4B_4$.

In summary, the effect of the spin fluctuations can play an important role in determining the surface impedance in magnetic superconductors. In particular, the surface impedance of $ErRh_4B_4$ clearly manifests the effect of the critical fluctuations in the surface mangetization around T_{c2}. The surface impedance of $Er_{0.5}Ho_{0.5}Rh_4B_4$ exhibits a rather smooth dependence on the temperature down to T_{c2}, where it changes abruptly due to the first order magnetic transistion, indicating the suppression of the spin fluctuations in the superconducting state.

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