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Anomalous superconducting phase diagram in UBe_{13}

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Abstract. Surface impedance measurements Z_s , where Z_s consists of surface resistance R_s and surface reactance X_s, were carried out for a single crystal UBe_{13}. R_s exhibits unusual field dependence with a significant hump around the H^*,which is nearly equal to $0.6H_{c2}$. This behavior indicates that the strong vortex pinning occurs around H^*.

1. Introduction

The heavy-Fermion superconductor UBe_{13} has attracted much attention because of unusual normal and superconducting properties. The electronic specific heat coefficient $\gamma_e \approx 1.1$ J/mol·K^2 is extremely large, reflecting the large effective mass associated with the uranium $5f$ electrons. The superconducting transition occurs at $T_c \approx 850$ mK with a large specific heat jump, $\Delta C(T_c)/\gamma_e T_c \approx 1$, indicating that the heavy-quasiparticles are responsible for superconductivity[1, 2]. The unconventional nature of the superconducting state in this material, such as power-low behaviors of various thermodynamics, strongly suggests that the superconducting (SC) symmetry has nodal SC gap structure. Especially, the behavior of the superconducting upper critical field H_{c2} is unusual, e.g., the SC phase diagram does not follow the simple Werthamer-Helfand-Hohenberg (WHH) theory [3, 4], but has an anomalous $H^*(T)$-line inside in the H-T SC phase diagram. In fact, the previous radio frequency (RF) surface impedance measurements revealed anomalous H-T SC phase diagram including the H^*-anomaly[9]. Furthermore, $U_{1-x}Th_xBe_{13}$ shows a second phase transition at T_{c2} below a SC transition at T_{c1} by Th-doping of 2∼4 % [5]. It has been argued that T_{c2} is either an ordering of antiferromagnetic (AF) spin density wave (SDW) state[6] or two coexisting SC order parameters, i.e., multiple superconducting (SC) phases, in Th-doped and pure UBe_{13}. Recently, Shimizu et al. reported from the results of dc magnetization measurements that the H^*-line is attributed either to an increase of the superfluid density below H^* or to a short-range FM ordering with the weak magnetic moment below H^*. However, the origin of the $H^*(T)$-anomaly is still unclear at present.

In order to understand the unconventional superconductivity in UBe_{13}, we have carried out surface impedance measurements on UBe_{13}. Although the previous RF surface impedance measurements revealed H^*-anomaly, the lowest temperature is limited down to 360 mK by the experimental setup [9]. Therefore, here we re-examine reproducibility of the previous results of the RF surface impedance measurements and extend the temperature region down to 100 mK. And we will draw up the H-T SC phase diagram from the view point of the vortex dynamics.

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Note that the surface impedance is useful technique for detection of the electromagnetic response of metallic materials and is generally given by $Z_s = (i\omega\mu_0/\tilde{\sigma})^{1/2}$ for highly conductive material, where $\tilde{\sigma}$ is the complex conductivity $\tilde{\sigma} = \sigma_1 - i\sigma_2$, ω is the angular frequency, and μ_0 is the permeability of vacuum. In the superconducting state, the surface impedance can be expressed as $Z_s = R_s + iX_s = i\omega\mu_0\tilde{\lambda}(\omega, B, T)$, where $\tilde{\lambda}$ is a complex field penetration depth, B is the magnetic field density[10]. The field dependence of the surface impedance Z_s in the vortex state of type II superconductors have provided information of the dynamical properties of vortices, e.g., pinning properties, vortex dynamics, electronic structure of the vortex core, and dynamics of the quasiparticles[11].

2. Experimental

Single crystal of UBe_{13} were grown by Al-flux method. Details of sample preparation techniques for single crystals of UBe_{13} were reported elsewhere[8, 12]. Samples were characterized to be a single crystal by a Laue photograph as well as X-ray diffraction. The residual resistivity is $\rho_0 \approx$ 140 $\mu\Omega$cm [12]. The RF impedance Z was measured by the LC resonator method at frequency $f \approx 6$ MHz by using a spectrum analyzer (Advantest R3131A) with a tracking generator and an NMR probe circuit. Details of the surface impedance ($Z_s = R_s + iX_s$) measurements were reported elsewhere [12], where R_s and X_s are the surface resistance and surface reactance, respectively. Here $\rho_0 \approx 140$ $\mu\Omega$cm is sufficient to detect Z_s in the observed temperature range[9]. A top loading type ^{3}He-^{4}He dilution refrigerator was utilized down to $T = 100$ mK with a 120 kOe superconducting magnet. The sample temperature was monitored using a calibrated RuO_2 resistor at low $T's$ (50 mK - 20 K). The sample investigated was fixed on a Bakelite holder and located in a pick up coil having dimensions of 4 mmϕ diameter and 5mm length. Here we focus on R_s, which is connected with the flux flow resistivity ρ_f in the SC state.

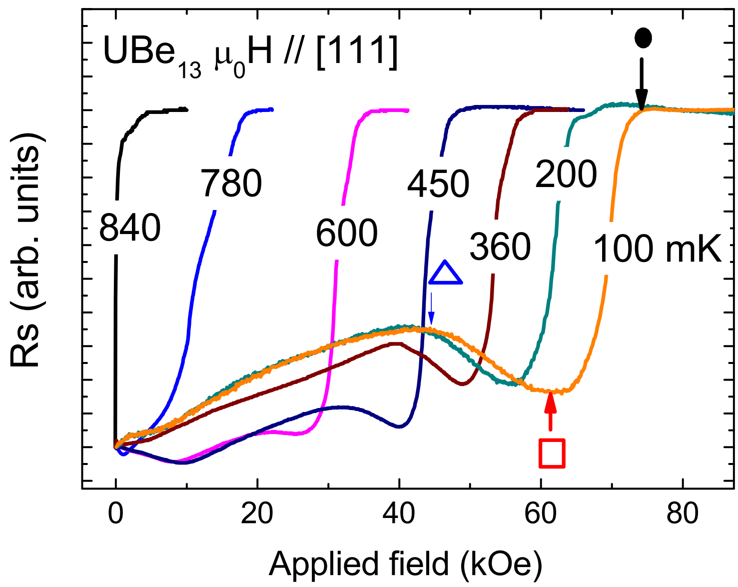

Figure 1. Field dependence of $Rs(H)$ at various temperature. Closed circle, open square and triangle indicate H_{c2}, H_1^*, H_2^* respectively.(see text)

3. Results and Discussions

Figure 1 shows the H dependence of $R_s(H)$ of UBe_{13}, where the dc magnetic field H was applied parallel to the crystal [111] axis, while RF field is applied perpendicular to the [111] axis. $T_c(H)$ was tentatively defined by linear extrapolations of the temperature linear region in $R_s(H)$ curves, as indicated by the closed circle. As clearly seen in the figure, $R_s(H)$ has a hump at around 40 kOe. The square and triangle in the figure correspond to the bottom (H_1^*) and peak (H_2^*) found in $R_s(H)$. Figure 2 shows the H-T SC phase diagram. Note that H_2^* is relatively higher than H_{Mag}^* obtained from the magnetization measurements [13]. The upper critical field can be estimated as $H_{c2}(T = 0\mathrm{K}) \approx 85$ kOe from the linear extrapolation of the $H_{c2}(T)$ curve. The overall feature of the SC phase diagram agrees well with the previous result [9].

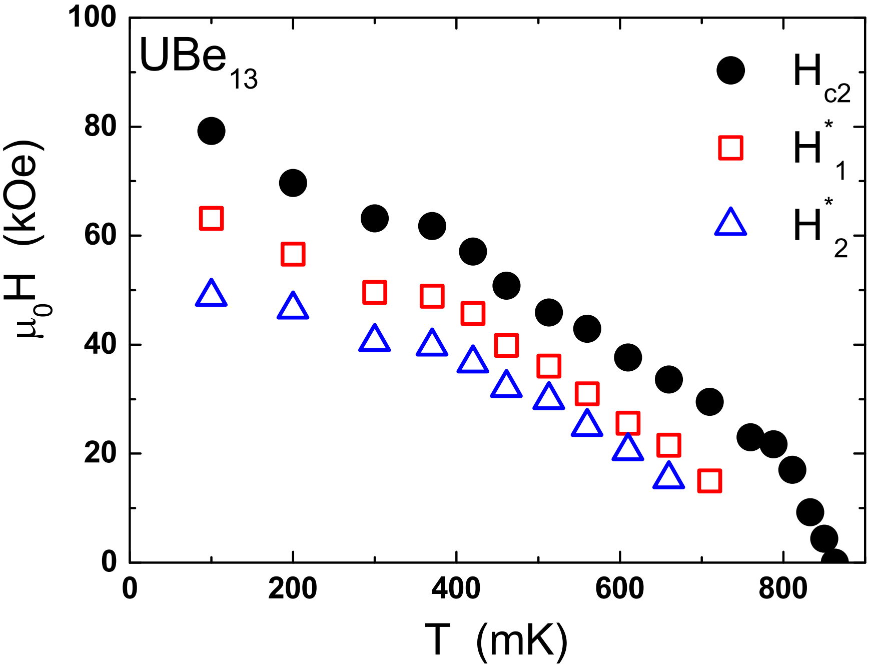

Figure 2. H-T phase diagram of UBe_{13} obtained from surface impedance measurements. Closed circles, open squares and triangles correspond to the symbols indicated in Fig.1.

In general, $R_s(H)$ in the superconducting state is in proportion to flux flow resistivity ρ_f, i.e., $R_s(H) \propto \rho_f$. In an s-wave superconductors without vortex pinning, the flux flow resistivity is proportional to the number of the vortex core in the magnetic field, i.e. $\rho_f = \rho_n H/H_{c2}$, where ρ_n is the nomal resistivity arising from the vortex cores. The present results considerably differ from the case for the conventional pinning-free superconductor. The hump-structure in $R_s(H)$ indicates that the strong vortex pinning occurs in the SC mixed state. In general, defects such as stacking faults in the crystal lattice cause the vortex pinning near H_{c2} ($H_p \approx 0.9H_{c2}$). However, $H_2^* \approx 0.6H_{c2}$ is quite lower than the conventional case, suggesting that the origin of the H^*-anomaly is probably different from the simple mechanism of the vortex pinning. For unconventional superconductors, the superfluid density n_s, the life time of the quasiparticles τ, and the SC gap structure Δ are involved in $\rho_f(H)$ [10]. If the present anomaly in $R_s \propto \rho_f(H)$ is attributed to the intrinsic nature of the SC state in UBe_{13}, any one of or some of these parameters change around H^*. Instead, Schmiedeshoff et al. reported that the measurements of magnetic torque reveals an anomalous contribution to the magnetic torque in the field range of 30-50 kOe, and this anomalous torque survives in the SC state[14]. They proposed that the anomalous torque reflects the coexistence of an intrinsic field induced magnetic transition. The field induced magnetic order is also a possible origin for anomalous suppression of $R_s(H)$. In any case, further detailed surface impedance measurements are needed.

4. Summary

In summary, the surface impedance Z_s was measured for heavy fermion superconductor UBe_{13}. The magnetic field dependence of the surface resistance exhibits anomalous hump in the superconducting state, different markedly from conventional s-wave superconductors. At present, the origin of the anomaly in $\rho_f(H)$ is still unclear. However, the H^* anomaly was confirmed from the surface impedance measurements. Further experiments are needed to clarify the nature of the anomaly.

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