Magnetic properties of polycrystalline $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$

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The temperature and magnetic-field dependence of the magnetization in $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$ samples have been measured in different temperature ranges in order to study the magnetic-field penetration depth $\lambda_L(T)$, the thermodynamic critical field $H_c(T)$, and the critical fields $H_{c1}(T)$ and $H_{c2}(T)$. The λ_L determined from the powder magnetization data is 803 Å at zero temperature. The H_{c2} derived from the resistivity measurement is 15.4 T at zero temperature. This corresponds to a coherence length of $\xi(0) = 45.3$ Å. The H_c estimated from the magnetization curve is 0.25 T at zero temperature. H_{c1} , H_{c2} , and H_c are discussed in the framework of Ginzburg-Landau theory.

$\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ is of current interest because it is a non-copper oxide compound with T_c values of about 26 K (Ref. 1) at a 50% resistive transition. This system is also of interest because it is a simple system with a cubic crystal structure and there is no anisotropy. There have been several studies of the superconducting properties of this system.¹⁻⁴ In this work, we report measurements of the magnetic-field penetration depth, the thermodynamic critical field H_c , and the critical fields H_{c1} and H_{c2} of the $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$.

The samples were prepared by mixing powders of BaO, K_2O , and Bi_2O_3 thoroughly. The following three steps were used: (1) The powders were first annealed in flowing N_2 at 700°C for 1 h, at a heating rate of 4°C per minute. (2) The powders were then annealed in flowing O_2 at 450°C for two hours and furnace cooled to room temperature. (3) The powders were pressed into pellets and steps (2) and (3) repeated once more. The samples were then cut into rectangular bars for electrical and magnetic measurements. Since K_2O is very deliquescent, great care must be taken in the processing of the samples. In our preparation of $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$, the samples are processed in a N_2 atmosphere from beginning to end, so that the samples are dry and easy to handle.

Figure 1 shows a typical powder x-ray-diffraction pattern for the samples reported here. The data were taken using a Siemens powder x-ray diffractometer (model D500). The sample is single phase with a lattice constant of 4.29 Å and an x-ray density of 7.29 g/cm³ at room temperature.

Figure 2 shows M/M_{max} data as a function of temperature for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$ in a field of 5 G measured in a superconducting quantum interference device magnetometer (Quantum Design) on powders of $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$ sieved through 400 mesh. For a superconducting sphere, the relation between M/M_{max} and $x = \lambda_L/a$ has been reported in Ref. 5, i.e.,

$$M/M_{\text{max}} = 1 - 3x \coth(1/x) + 3x^2, \quad (1)$$

where λ_L is the London penetration depth and a is the diameter of the particle. Some authors^{5,6} have used ac susceptibility to study the magnetic-field penetration depth and the results are in reasonable agreement with other reported data. Here we have used dc susceptibility to derive the magnetic-field penetration depth and the results are shown in Fig. 3. Using the average size of the particle, which is about 2 μm here, we get $\lambda_L(0) = 803$ Å at zero temperature. In the free-electron model the carrier con-

FIG. 1. X-ray diffraction data for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$.

FIG. 2. M/M_{max} as a function of temperature for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$.

FIG. 3. Magnetic-field penetration depth $\lambda_L(T)/\lambda_L(2\text{ K})$ as a function of temperature for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$. Also shown is the prediction $\lambda_L(T)/\lambda_L(0)=1/[1-(T/T_c)^4]^{1/2}$ in the two-fluid model and $\lambda_L(T)$ in the GL theory, which is normalized to the field-penetration depth at zero temperature.

centration n and the Fermi velocity v_F are given by

$$n = m/(\lambda_L^2 e^2 \mu_0), \quad (2)$$

$$v_F = (\hbar/m)(3\pi^2 n)^{1/3}, \quad (3)$$

where m is the electron mass, e is the electronic charge, and μ_0 is the permeability in vacuum. Putting $\lambda_L(0)$ into Eq. (2) and using Eq. (3), we obtain $n = 4.38 \times 10^{21} \text{ cm}^{-3}$ and $v_F = 5.86 \times 10^7 \text{ cm/sec}$ for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$. Also shown in Fig. 3 are the predictions of λ_L in the two-fluid model and $\lambda_L(T)$ in the Ginzburg-Landau (GL) theory in the dirty limit, i.e., $\lambda_L = 0.615\lambda_L(0)(\xi_0/l)^{1/2}(1-T/T_c)^{1/2}$ Å,⁷ where ξ_0 is the BCS coherence and l the mean free path.

Figure 4(a) shows the magnetization as a function of magnetic field at 5 K. The irreversible magnetization data H^* estimated from these data are similar to those reported by McHenry *et al.*¹ We note that the H^* at 5 K is five times larger than McHenry's value. The data indicate that the samples reported here have stronger pinning forces than those reported in Ref. 1. Figure 4(b) shows the magnetic-field dependence of $\ln \Delta M$ at several temperatures. A linear temperature dependence was found in $\ln \Delta M$ vs H . Because the critical current J_c is proportional to ΔM in the Bean model,⁸ the data suggest that the critical current density is related to the field by $J_c = J(0) \times \exp(-cH)$ for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$, where $J(0)$ is the critical current density and c is a constant. The value of the critical current density determined from the Bean model is about $1.5 \times 10^5 \text{ A/cm}^2$ with $c = 1.119 \times 10^{-4} \text{ G}^{-1}$ at 5 K. Also shown in Table I are values of $J(0)$ and c at other temperatures.

Figure 5(a) shows typically the temperature dependence of resistivity for $\text{Ba}_{0.5}\text{K}_{0.5}\text{BiO}_3$ under different magnetic fields. The resistivity was measured by a four-point technique. The current in the sample is 0.1 mA in the electrical measurement. The sample shows a sharp resistive transition with $T_c(90\text{--}10\%) = 23\text{--}24 \text{ K}$. The critical magnetic fields, H_{c2} 's derived from a 10% resistive transition ($0.9\rho_n$ criterion) are shown in Fig. 5(b). The shape of the phase boundary determined this way is a straight line. A linear temperature dependence of H_{c2} in

FIG. 4. (a) Magnetization as a function of temperature at 5 K; (b) $\ln \Delta M$ as a function of magnetic field at several temperatures, where $\Delta M = M_+ - M_-$ was obtained from the hysteresis curve.

$(1-T/T_c)$ was found at T near T_c with $dH_{c2}/dT = -0.916 \text{ T/K}$. The value of H_{c2} at zero temperature is 15.4 T if one uses the relation $H_{c2}(0) = -0.69T_c(dH_{c2}/dT)T_c$. This corresponds to a coherence length $\xi = [\phi_0/(2\pi H_{c2})]^{1/2} = 45.3 \text{ Å}$, where ϕ_0 is the flux quantum.

Figure 6 shows the thermodynamic critical field H_c (●) obtained from doing the integration $\int M dH$ using the data in the magnetization curve and setting $\int M dH = H_c^2/8\pi$. A linear temperature dependence of H_c was found for T near T_c . This linear behavior is consistent with the prediction of H_c in the GL theory. In the GL theory, H_c is

TABLE I. The magnetic-field dependence of the critical current derived by fitting magnetization data to $J(H) = J(0)\exp(-cH)$ at several temperatures, where $J(0)$ and c are constants and H is the magnetic field.

T (K)	$J(0)$ (A/cm ²)	c (G ⁻¹)
5	1.5×10^5	1.119×10^{-4}
7.5	1.44×10^5	1.181×10^{-4}
10	1.0×10^5	1.796×10^{-4}
15	5.0×10^4	2.145×10^{-4}
17.5	4.7×10^4	8.450×10^{-4}
20	1.0×10^4	9.679×10^{-4}

FIG. 5. (a) Magnetic-field dependence of electrical resistivity; (b) H_{c2} as a function of $1 - T/T_c$, a linear temperature dependence in H_{c2} vs $1 - T/T_c$ was found at T near T_c .

also given by

$$H_c = \phi_0 / [2\pi\sqrt{2}\lambda_L(T)\xi(T)], \quad (4)$$

so it is interesting to compare the data of H_c calculated from Eq. (4) and that obtained from the magnetization curve. Putting the data of $\lambda_L(T)$ and $\xi(T)$ into Eq. (4), one obtains the temperature dependence of H_c as shown in Fig. 6. Symbols + and ∇ were H_c calculated from 10% and 50% resistive transitions, respectively. A reasonable agreement between the data obtained from the magnetization curve and that derived from Eq. (4) was found. We note that the discrepancy is about 30% for T near T_c .

FIG. 6. Temperature dependence of critical field H_c , obtained from the M vs H curve. The H_c data calculated from GL theory based on 10% and 50% resistive transitions are also shown.

if the calculation is based on the 10% resistive transition. This discrepancy is due to minor differences in the magnetic and electric measurements.

Regarding the magnetic properties of $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$, Kwok *et al.*⁹ have performed the magnetic and resistive measurements of superconducting critical fields of melt-cast $\text{Ba}_{0.65}\text{K}_{0.35}\text{BiO}_3$. They found a Ginzburg-Landau parameter $\kappa = 59$, coherence length $= 36.3 \text{ \AA}$, and field penetration depth $\lambda_{GL} = 2200 \text{ \AA}$ at zero temperature. In this work we have studied the temperature dependence of λ_L from the powder magnetization data (M vs T) and the temperature dependence of $H_c(T)$ from the magnetization curve (M vs H). We found a field penetration depth $\lambda_L(0) = 803 \text{ \AA}$ and $H_c(0) = 0.25 \text{ T}$ at zero temperature. The temperature dependence of H_{c2} obtained from the resistivity measurements shows a linear behavior in $(1 - T/T_c)$. This linear temperature dependence of H_{c2} in $(1 - T/T_c)$ for T near T_c has been predicted in the GL theory of superconductivity. This corresponds to a coherence length $\xi(0) = 45.3 \text{ \AA}$. Using the expression $\ln\kappa/2\kappa^2 = H_{c1}/H_{c2}$ in the GL theory, we found $H_{c1} = 8 \text{ G}$, where κ is the GL parameter which is equal to 21 at 22 K.

In summary, the magnetic-field penetration depth λ_L , the thermodynamic critical field H_c , the magnetic critical fields H_{c1} and H_{c2} , and the coherence length have been determined and discussed within the framework of the Ginzburg-Landau theory of type-II superconductors.

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