Investigation of the Off-Diagonal Thermoelectric Effect on Textured YBa$_2$Cu$_3$O$_{7-\delta}$

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Both the off-diagonal Seebeck effect and the off-diagonal Peltier effect were investigated on the same textured sample YBa$_2$Cu$_3$O$_{7-\delta}$, and with the use of the same experimental setup. The effectiveness of several kinds of heat-conductive media was studied for the measurement. The flatness of both the sample and the heat-conducting block, and the matching between them were found very important for the reduction of the heat resistance of the interfaces. A reasonable agreement was found between the off-diagonal Seebeck coefficient measured by the off-diagonal Seebeck effect and that by the off-diagonal Peltier effect. The steplike feature in the relation between the off-diagonal Seebeck coefficient and the annealing temperature may imply a nonmonotonic change of the Seebeck coefficient along the $c$ axis ($S_c$) with oxygen content.

KEY WORDS: Thermoelectricity; high-$T_c$ texture superconductor; anisotropy; oxygen content.

1. INTRODUCTION

Large-amplitude transient transverse voltages induced by pulsed laser irradiation on $c$-axis oriented thin films of YBa$_2$Cu$_3$O$_{7-\delta}$ at room temperature were reported by Chang et al. [1]. From then on, the voltage was improved from about 1 to about 200 V by several groups [2,3]. There was a controversy over the mechanism of this phenomenon. By applying the thermodynamics to a low-symmetry crystalline system, Testardi [4] explained the phenomenon with a model of off-diagonal thermoelectricity. In this model, an anisotropic sample with thickness $d$ and a tilt angle of $\theta$ with respect to the $z$ axis, (see Fig. 1) can produce both the off-diagonal Seebeck effect and the reverse effect, the off-diagonal Peltier effect. For the Seebeck effect, the induced voltage $V_x$ is proportional to the $S_{xz}$, the temperature difference along $z(\Delta T_z)$, and the heating length along $x(L)$ respectively, but it is inversely proportional to $d$:

$$V_x = S_{xz}\Delta T_z L/d$$  \hspace{1cm} (1)

where $S_{xz} = \frac{1}{2}(S_{ab} - S_{c}) \sin 2\theta$, and $S_{ab}$ and $S_c$ are the Seebeck coefficients in and out of the CuO$_2$ plane, respectively. For the Peltier effect, the heat flux $h_x$ is proportional to $S_{xx}$, the electrical current density $j_x$ passed through the sample in the direction $x$, and the sample temperature $T$:

$$h_x = j_x S_{xx} T$$  \hspace{1cm} (2)

Strong experimental evidence was found supporting the model of thermoelectricity in our previous work [5,6], performed separately for the Seebeck effect and the Peltier effect, on two different YBa$_2$Cu$_3$O$_{7-\delta}$ textured samples. Since quantitative comparison was not suitable between the two effects investigated on two different samples separately, a more careful and systematic study was called for to draw a more reliable conclusion. In this paper, we made a closer investigation of both effects on the same sample, and with the same experimental setup.

2. EXPERIMENTAL

2.1. Choice of Heat Conductive Medium

The effect of thickness $d$ on the Seebeck voltage $V_x$ was studied previously [6]. It was found that the
measured results are greatly affected by the properties of the sample surface and the heat conductance between the interface of the sample and the heater, and that between the sample and the heat sink, especially when the sample becomes too thin. We also found strongly experimental evidence for the effect of the flatness of the interfaces. To minimize such surface effect, the surfaces of the heater, the heat sink, and the sample should be as smooth and as flat as possible. In other words, the heat resistance of the interface should be as close to that of the bulk as possible. The heat conductive medium should be carefully selected to meet the requirement. Several materials, such as Vanish glue, alcohol, oil, industrial grease and its mixture with MgO powder, and heat-conductive grease, were tested systematically. It is found that the heat-conductive grease had the highest heat conductance while the Vanish glue had the lowest. Alcohol made the output unstable, because it evaporated during the measurement. Industrial grease was found to be a proper candidate and was selected as the heat conductive medium for the measurements.

2.2. Preparation of the Textured Sample

The sample was prepared by directional solidification using the modified MTG process [7]. The samples were cut, with a diamond saw, from the raw sample into a rectangular shape of $5 \times 10 \times 1 \text{ mm}^3$ for measurement. Alcohol was applied as coolant during the cutting process. The cut sample was of single-domain. The value of the tilt angle was determined by measuring the angle between the cleavage plane and the sample surface. The superconducting transition temperature $T_c$ was measured to be 91 K, and $\Delta T_c$ was about 1 K, by employing the four-lead technique.

2.3. Measurement Instruments

The Seebeck voltage, which was along the $c$-axis projection $V_x$, was recorded by an X–Y recorder (Type 3086) or a Keithley 191 digital multimeter. For the Peltier effect measurement, a Keithley 2001 multimeter was employed to detect the voltage signal from a pair of differential Cu–Constantan thermocouples, measuring the temperature difference between the two surfaces.

3. RESULTS AND DISCUSSIONS

3.1. Seebeck Effect

For the Seebeck effect, HB in Fig. 1 was a piece of copper. The voltage $V_x$ was measured by the leads, for the HB at different lengths. The typical thickness of the sample was 1 mm to minimize the influence of the deteriorated surface mentioned in [6]. It was comparable to the typical heating lengths from 2 to 9 mm. The temperature distributions inside the sample were then simulated by a computer for different heating lengths. Details of the simulation are given in Appendix 1. Figure 2 shows the contours of the simulated temperature for different heating lengths. It is obvious that the temperature gradient along the $z$ direction does not vanish immediately beyond the heating area. This temperature gradient also contributed to the detected Seebeck voltage. Integrating the