Journal of Alloys and Compounds 724 (2017) 413–420

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Origin of photovoltaic effect in (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ /Ag heterostructure

Z. Chu [a, b, c], Z.P. Ma [a, b], F. Yang [a, b], L. Han [a], N. Zhang [a, b], F.G. Chang [a, b, *]

[a] College of Physics and Materials Science, Henan Normal University, Xinxiang, Henan, 453007, People's Republic of China
[b] Henan Key Laboratory of Photovoltaic Materials, Xinxiang, Henan, 453007, People's Republic of China
[c] Department of Materials Engineering, Henan Institute of Technology, Xinxiang, Henan, 453003, People's Republic of China

A R T I C L E I N F O

Article history:
Received 13 April 2017
Received in revised form
30 June 2017
Accepted 2 July 2017
Available online 3 July 2017

Keywords:
Photovoltaic effect
Open circuit voltage
Built-in electric field
Bi-2223/Ag heterostructure

A B S T R A C T

We report *I-V* characteristics and remarkable photovoltaic effect of (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$/Ag (Bi-2223/Ag) heterostructure in the temperature range between 50 K and 340 K induced by purple-laser irradiation, which is closely related to the superconductivity of Bi-2223 and the charge transfer between silver electrode and the superconductor. Obvious photo-induced voltage has been observed in the whole temperature range with two polarity reversals at a critical temperature (T_{pr1}) above room temperature and at the superconducting transition temperature (T_c). A maximum value of the photo-induced voltage appears at the onset of superconducting transition temperature (T_m). We confirm that there exists a built-in electrical field at the interface of Bi-2223/Ag heterostructure, similar to that found in YBCO/Ag systems, which provides the separation force for the photo-induced electron-hole pairs. The origin of the built-in electric field below T_c is a result of charge diffusion or redistribution between silver and the superconducting Bi-2223 associated with the Proximity effect and Andreev reflection. The direction of the field is always pointing from the superconductor to the metallic electrode. Between T_c and T_{pr1}, the interface field pointing from metal to superconductor arises from the diffusion of electrons in the metal and holes in the superconductor. The additional polarity reversal of photo-induced open circuit voltage (V_{oc}) at T_{pr1}, which was not observed in YBCO/Ag system, implies a possible change of charge carrier type in Bi-2223. Our data provide a new dimension of information for depicting a more comprehensive picture of Bi-2223/Ag heterostructure and may lead to new applications of this high temperature superconductor in the field of photo-electronic sensing devices.

1. Introduction

Interfacial heterostructures between metal and unconventional superconductors have recently been a research focus [1–8], as the ability to precisely create interfaces providing a wealth of new possibilities to discover new physical phenomena and generate novel photoelectric devices. High temperature superconductor (HTSC)/metal interfaces in particular are an essential part of high T_c electronic devices since they provide the basis for making wiring connections to the devices. The electrical integrity of the interface plays an important role for the intended applications. Recent progress in interface superconductivity [9,10], photovoltaic effect of HTSC/semiconductor heterostructure [11–13] and light-induced superconductivity [14,15], generates wide research interests in superconductor based interfaces under light illumination [1,2,11–14]. It is thus essential to understand the physical mechanisms of the interface conduction process.

In the early 1990's, photo-induced voltage in the interfacial heterostructures of HTSC/metal was first reported and has been extensively studied ever since, yet the nature of the interface remains far from settled [16–19]. Opinions vary on the mechanism of this photo-induced phenomena, such as photo-carrier injection effect [13], thermoelectricity [16,18,20,21], asymmetry of photo-excitation [22] and so on. Recently, prominent photovoltaic effects in metal/unconventional superconductor heterostructures, i.e. YBa$_2$Cu$_3$O$_{6.96}$/Ag and SmO$_{0.7}$F$_{0.3}$FeAs/Ag have been reported and a new mechanism for the origin of this photo-induced voltage has been proposed [1,2]. It has been concluded that there is a built-in electrical field in the interface between metal electrode and

* Corresponding author. College of Physics and Materials Science, Henan Normal University, Xinxiang, Henan, 453007, People's Republic of China.
E-mail address: fanggaochang@163.com (F.G. Chang).

http://dx.doi.org/10.1016/j.jallcom.2017.07.007
0925-8388/

superconductor, which provides the driving force to separate the photo-induced electron-hole pairs. This interfacial field may arise from the Proximity effect of metal/superconductor structure in superconducting state and the charge carrier diffusion near the interface above the superconducting transition temperature [23–27].

Optimally doped Bi-based superconductor Bi-2223 has rather similar electrical transport properties as to those of YBCO, yet Bi-2223 has a much higher superconducting transition temperature. Similar to YBCO, the perovskite-type feature and the presence of CuO_2 layers also exist in this superconductor. However, unlike YBCO, Cu-O chains are not present and there are three instead of two CuO_2 layers in Bi-2223. The YBCO superconductor has an orthorhombic structure, whereas the other high-T_c superconductors have a tetragonal structure. These structural difference would affect the features of the superconductor/metal interface, leading to a different built-in electric field. It is generally accepted that the charge carriers are holes for optimally doped Bi and Y based superconductors at normal states. All the Fe based superconductors such as $SmFeAsO_{1-x}F_x$, however, have electrons as their majority charge carrier. It is expected that these high temperature superconductors would behave rather differently under laser irradiation. Systematic study of the photovoltaic (PV) effect in Bi-2223/Ag heterostructure would help to understand the mechanism of built-in electric field in the interface of HTSC/metal in general. In addition, the PV behavior of high temperature superconductors above room temperature, as far as the authors know, has never been investigated.

In this paper, we report remarkable PV effect induced by purple-laser (λ = 405 nm) illumination in Ag/Bi-2223 heterostructure between 340 K and 50 K. We show that the PV effect is directly related to the superconductivity of Bi-2223 and the nature of the interface of Bi-2223/Ag heterostructure. Two polarity reversals of V_{oc} have been observed in the vicinity of superconducting transition as well as in a temperature range from 314 K to 323 K. The results have been discussed in terms of a built-in electric field at the Bi-2223/Ag heterostructure. Our findings shed further light on the origin of PV effect in the interface of metal/superconductor heterostructures and provide a novel alternative method to study the interface related phenomena such as the Proximity effect.

2. Experiment

$(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10+\delta}$ high temperature superconducting ceramics were synthesized by the conventional solid states reaction technique [28]. The resistivity measurements of the samples between 300 K and 50 K were carried out by using the standard four probe method. The required temperatures were achieved with the help of the vibration sample magnetometer (Versa-Lab, Quantum Design). The zero resistance superconducting transition temperature of the Bi-2223 ceramic used in this work is determined to be T_c = 107 K. The crystalline structural of the Bi-2223 sample was characterized by X-ray diffractometer using Cu-K_α radiation (XRD, Bruker D8 Advance). XRD analysis showed that the superconducting ceramic is pure 2223 phase.

The Photo-induced voltage experiments were performed on Bi-2223/Ag heterostructure. A Bi-2223 sample of 1.5 mm thickness and 10.5 × 5.8 mm^2 rectangular shape, on which the copper lead wires were cohered with silver paste forming four circular electrodes about 1 mm in diameter, was illuminated by continuous wave purple-laser with laser spot size of 1.5 mm in diameter. The distance between the two voltage electrodes was about 5.5 mm. *I-V* characteristics of the heterostructure were measured using Versa-Lab with a quartz crystal window. Standard four-wire method was employed to obtain the *I-V* curves of the sample in the temperature range from 340 K to 50 K. The relative positions of silver electrodes were shown in Fig. 1(n). Laser intensities up to 72.9 mW/mm^2 were applied to the samples at selected temperatures in the cooling process.

3. Results and discussion

3.1. Results

Fig. 1(a–c) shows the *I-V* characteristics of Bi-2223/Ag heterostructure at 340 K. Normal *I-V* behavior is obtained without light illumination: a straight line crosses the origin. This straight line moves downwards with increasing laser intensity irradiating at the cathode electrode [Fig. 1(a)], leading to a negative photo-induced voltage at zero current (often called open circuit voltage V_{oc}). Light irradiation on HTSC can generate electron-hole pairs (e–h) [29,30]. To produce an open circuit voltage V_{oc}, however, it is necessary to spatially separate photo-generated e-h pairs before recombination occurs [31]. The negative value of V_{oc}, relative to the electrode configuration given in Fig. 1(m), strongly suggests that there exists a build-in electric field at Bi-2223/Ag interface pointing from Bi-2223 to the silver electrode, which sweeps the electrons to the anode and holes to the cathode. Consequently, a positive V_{oc} would be obtained if the sample area near the anode is illuminated, as can be seen in Fig. 1(c). It is not a surprise that there is no V_{oc} is observed when the laser spot being pointed to the center of the sample (about 2 mm apart from the Bi-2223/Ag interfaces), up to the maximum laser intensity available [Fig. 1(b)]. These observations provide strong evidence that there exists an interfacial electric field pointing from the superconductor to the silver electrode at this temperature.

I-V characteristics of Bi-2223/Ag heterostructure at 120 K are given in Fig. 1(e–g). As can be seen in Fig. 1(e), a straight line moves upwards with increasing laser intensity irradiating at the cathode leads, resulting in a positive V_{oc} opposite to that obtained at 340 K. Similarly, when the laser beam is pointed at the center of the sample no PV effect appears in Fig. 1(f) up to the maximum laser intensity available. Although light illumination will certainly produce electron-hole pairs, no V_{oc} is obtained because there is no built-in interface field available at the center of the sample to separate them [1,2]. *I-V* curves move to the opposite direction as the anode electrode is irradiated [Fig. 1(g)]. All these results obtained for this Bi-2223/Ag system at 120 K indicate the existence of a built-in interface electric field opposite to that observed at 340 K.

Fig. 1(i–k) depict the *I-V* characteristics of Bi-2223/Ag heterostructure at 50 K. As can be expected from a superconducting material, the voltage across the sample remains at zero independent of current without light illumination. *I-V* curves parallel to the *I*-axis moves downwards with increasing laser intensity when laser beam is directed at cathode [Fig. 1(i)]. Obviously, we have a negative V_{oc} and the zero slope of the *I-V* curves implies that the sample is still in superconducting state under laser illumination. The negative V_{oc} suggests that there exists an electrical field directing from the superconductor to the silver electrode. Again, no V_{oc} can be obtained with increasing laser intensity to the maximum value available [Fig. 1(j)], as the laser spot points to the center of the sample. Positive V_{oc} is observed when anode is illuminated [Fig. 1(k)]. *I-V* characteristics of Bi-2223/Ag heterostructure at 50 K with laser irradiated at different positions of the sample lead us to an interface field opposite to that observed at 120 K but consistent with that observed at 340 K.

To investigate the effect of temperature on the photovoltaic properties of the Bi-2223/Ag system, the sample was irradiated at the cathode with purple laser of intensity 63.4 mW/mm^2. *I-V* curves obtained at selected temperatures between 340 K and 50 K are