Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Phase-dependent heat current of granular Josephson junction for different geometries

Elaheh Afsaneh *, Heshmatolah Yavari *

Department of Physics, University of Isfahan, Hezar Jarib, Isfahan 81746, Iran

ARTICLE INFO

Article history:
Received 8 January 2018
Received in revised form 28 May 2018
Accepted 30 May 2018
Available online xxxx
Communicated by L. Ghivelder

Keywords:
Heat current
Granular superconductor
Magnetic field
Geometry

ABSTRACT

We theoretically investigate the phase-dependent heat transport of a temperature-biased granular Josephson junction in the presence of a perpendicular magnetic field. We illustrate the influence of geometry of the junction on the thermal current. The use of granular Josephson junction rather than bulk one makes significant changes in the heat current behavior. The heat current diffraction pattern of the rectangular, circular and annular geometries with no trapped fluxons demonstrates similar to the current of s-wave superconducting junction. By increasing the number of trapped fluxon, the pattern of current behaves such as d-wave superconducting junction. The feasibility of using granular superconductors, with different geometries, controlled by the magnetic field provides an appropriate tool to obtain the desired result for a specific application.

1. Introduction

Advances in condensed matter physics and technology have provided the significant progress on the thermal transport of nanosystems [1,2]. The improvement of heat current has proposed the quantum heat machines [3], quantum refrigerators [4] and thermoelectronic devices [5]. In the past decades, the heat current through the Josephson junction has been attracted much interest.

For the first time Maki and Griffin proposed the interference term in addition to the quasiparticle one for the heat current through the Josephson junction [6]. It was predicted that the interference current was depending on the superconducting phase and was due to an interplay between the quasiparticles and cooper pairs. For years, a plenty of projects was proposed to demonstrate the anomalous interference term [7–10]. In spite of extensive attempts, no experiment could observe this phase-dependent term until 2012. Ultimately, F. Giazotto and M.J. Martinez-Perez proved the predicted phase-dependent term of thermal current in a heat interferometer dc-SQUID experiment [11]. The modulation of phase-dependent thermal current through the temperature-biased Josephson junction was analyzed by means of magnetic flux similar to the electrical current through voltage-biased Josephson junction [12]. In a temperature-biased Josephson junction, thermal current diffraction patterns were observed in a flux driven junction for the first time [13]. Manipulation of heat currents based on phase-coherent caloritronics devices was proposed for several nanostructures [14] and was investigated by mastering the superconducting quantum phases in temperature-biased Josephson junctions [15]. Recently, thermal hysteresis behaviors were discussed in temperature-biased SQUID to provide thermal memory devices [16,17].

In order to improve the transport properties through the Josephson junction, the granular superconductor can be applied rather than the bulk one. Recently, a great deal of interest has been paid to understanding the properties of the granular superconducting systems [18–20]. Different characteristics of electron transport and other electric responses to the external field have been studied on the superconducting granular systems [21].

The two-dimensional granular superconductor was arranged in honeycomb structure to investigate the phase oscillations [22]. A granular multilayer of superconducting-ferromagnetic structure was supposed to achieve the proximity effect [23]. The characteristics of a superconducting granular structure were demonstrated by fluctuation spectroscopy close to the critical temperature [24]. In studying the transport properties of the d-wave granular superconducting system under the electric field, the critical current is increased by the applied strong electric field [25]. A two-fluid model was proposed to describe the transport characteristics of the granular superconductors which was well agreed with the different

---

* Corresponding authors.
E-mail address: el.afsaneh@gmail.com (E. Afsaneh).

https://doi.org/10.1016/j.physleta.2018.05.053
0375-9601/© 2018 Published by Elsevier B.V.

Please cite this article in press as: E. Afsaneh, H. Yavari, Phase-dependent heat current of granular Josephson junction for different geometries, Phys. Lett. A (2018), https://doi.org/10.1016/j.physleta.2018.05.053

high-Tc superconductors [26]. For the weak coupling, the conductivity of granular superconductors was investigated in the insulating regime and it was found that the charging energy of each grain could grow up the superconducting gap magnitude [27]. In two-dimensional granular superconductors, the Nernst effect was studied using simulations with Langevin and RSJ dynamics [28].

In recent years, the different characteristics of thermal transport in granular superconductors have been found much interest. In a temperature-biased long Josephson junction, it was shown that the maximum phase-dependent heat current behaves similarly to the superconducting critical current [29]. The length and the damping of LJJ affect the behavior of the diffractions patterns. The lobes configuration of the thermal transport diffraction patterns is strongly related to solitons. In turn, the number of solitons depends on the both length of junction and the intensity of the external magnetic field. In a thermally-biased LJJ, the influence of solitonic dynamics and excitations on the phase-coherent heat transport through the junction was studied [30]. In this study, new coherent caloritronics devices were proposed which are based on the motion of solitons and can be controlled by the external magnetic field. The interplay between phase-coherent caloritronics and solitonic dynamics was explored to introduce fast caloritronic devices providing the control of local temperature and heat power in solitonic manipulation procedure [31]. In this strategy, heat oscillators were proposed to be applied in nano-heat engines and coherent-heat machines.

Here to progress the heat transport through the thermally biased Josephson junction, we consider electrodes made by granular superconductors. To this end, the effect of geometry on the granular superconductors was considered for both regular and irregular structures. The dynamics properties of thermoelectric effects and heat transport for two-dimensional granular superconductors were studied numerically under the influence of magnetic field [32].

Another protocol to enhance the transport properties becomes possible by applying different geometric frustration for the junction areas. The particular geometries used in junctions for studying the electrical transport [33,34] and thermal current [35] are rectangular, circular, and annular.

The aim of this paper is to study the phase-dependent heat current of the granular Josephson junction under the effect of a magnetic field control. Previously, we calculate the electric transport of granular s-wave [33] and d-wave [34] superconducting systems in an applied magnetic field. To obtain the thermal current of the granular Josephson junction in analogy with the electric current, firstly we consider the heat current of the bulk superconducting system with different geometries [35]. After that by applying the Meilikhov's method [36], we derive the thermal current of granular superconductor in rectangular, circular and annular geometries.

This paper is organized as follows: In Sec. 2, we describe a model to obtain the thermal transport of a granular Josephson junction under the perpendicular magnetic field. In Sec. 3, we calculate the heat current of Josephson tunnel junction with different geometries for the bulk superconducting contacts. In Sec. 4, we derive the thermal current through the granular Josephson junction for the rectangular, circular and annular geometries. In Sec. 5 to represent the results of this study, we compare the plots of granular heat current with bulk one for the various geometries. In Sec. 6, we conclude the obtained results in the present research.

2. Model

The physical system under study is shown schematically in Fig. 1. The proposed system is a long Josephson junction (LJJ) composed of a thin insulating barrier weakly coupled with two superconducting electrodes under the thermal bias. It means that the left and right leads are connected to the different heat baths with no bias voltage. Non-zero temperature difference between two contacts makes a heat current flowing through the junction. To neglect the effect of the edges, the Josephson junction is assumed symmetric. According to confinement of Josephson currents near the edges of junction, Josephson junctions can be identified into two classes of small and large ones. For LJJs, the edges of junction strongly confine the currents while in small junction, current distributes through the junction uniformly. A LJJ denotes a junction which has one dimension longer than the Josephson penetration length [37,38]. The superconducting phase of this junction is a function of spatial coordinates. On the other hand, a short Josephson junction is a junction with dimensions smaller than the Josephson penetration depth which is assumed as point-like in space.

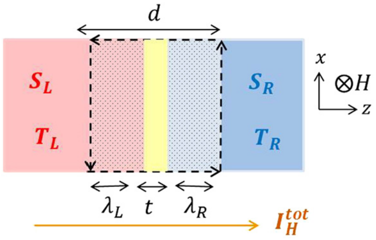

Fig. 1. Josephson tunnel junction in the presence of perpendicular magnetic field. Pointed area shows the closed integration. T_i and λ_i indicate the temperature and London penetration depth of superconducting contacts S_i $(i = L, R)$. t denotes the insulator thickness and $d = \lambda_L + \lambda_R + t$ represents the magnetic penetration depth.

Usually, when a bias voltage is applied to the reservoirs with common heat bath, electrons transport from one lead to another which flows the electric current. The total electric current through the junction yields three contributions as follows:

$$I^{tot}(T_R, T_L, \varphi) = I^{qp}(T_R, T_L) + I^{int}(T_R, T_L)\cos(\varphi) + I^{Jos}(T_R, T_L)\sin(\varphi) \qquad (1)$$

where the first, second and third parts are respectively the quasiparticle, interference and Josephson terms of the electric current. Also, $\varphi = \varphi_L - \varphi_R$ denotes the phase difference of superconducting reservoirs. Here, we obtain the heat current in analogy with the electric one [39–41].

Particularly for the heat current, the superconducting condensate carries no entropy in static situation. In other words, the Josephson current term which represents the condensate Cooper pairs has no contribution in the heat transport [6,11]. Therefore, when a temperature bias $(T_L > T_R)$ is applied to the electrodes, a steady-state heat current containing two terms flows from the left side to the right (Fig. 1):

$$I_H^{tot} = I_H^{qp}(T_L, T_R) + I_H^{int}(T_L, T_R)\cos\varphi \qquad (2)$$

in which, I_H^{qp} is the usual heat flux carried by quasiparticles [6,42,10,1] and $I_{int}(T_R, T_L)\cos(\varphi)$ denotes the interference term. The interference part of heat current as a function of the superconducting phase difference was predicted by Maki and Griffin [6,41].

The intrinsic superconducting phase-difference is influenced by the external magnetic field. So the only response of the heat current to the external magnetic field is the phase-dependent interference contribution. The phase difference of system as a function of the applied magnetic field is specified by integration along the closed contour illustrated in Fig. 1 [13,37,38]:

$$\varphi(x) = \frac{\Phi}{\Phi_0}x + \varphi_0 \qquad (3)$$

Please cite this article in press as: E. Afsaneh, H. Yavari, Phase-dependent heat current of granular Josephson junction for different geometries, Phys. Lett. A (2018), https://doi.org/10.1016/j.physleta.2018.05.053