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Josephson and tunneling junctions with thin films of iron based superconductors

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Abstract

We produced planar hybrid Superconductor - Normal metal - Superconductor (SNS') junctions and interface-engineered edge junctions (SN'S' or SIS' with normal metal (N') or insulating (I) barrier) with various areas using Co-doped Ba-122 as base electrode. Varying the thickness of the Normal metal (gold) barrier of the planar junctions, we can either observe Josephson behavior at thinner gold thicknesses or transport dominated by Andreev reflection. The edge junctions seem to form a SN'S'-contact.

Keywords: Josephson junctions; tunneling effect; Andreev reflection; pnictides

1. Introduction

To study the properties of iron-based superconductors we investigate the electrical transport in different kinds of junctions with pnictide thin films as base electrode. Planar hybrid Superconductor - Normal metal - Superconductor (SNS') junctions with various areas are realized with Co-doped Ba-122 (S), an Au layer (N) and a PbIn counter electrode (S'). For larger thicknesses of the N layers the electrical transport is dominated by Andreev reflections while for thinner N layers a Josephson current is observed. Our results on planar Josephson junctions demonstrated a quite usual behavior of Josephson junctions in *c*-direction of the pnictide unit cell [1]. Results on Josephson junctions with various pnictide electrodes summarized in [2] show such behavior for different kinds of junctions, prepared by other groups, too.

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Such experiments can be a helpful tool to determine the superconducting gaps and their temperature dependence. To determine the influence of the unusual pairing symmetry of the pnictide electrode one way is utilizing an edge junction geometry. The coupling to the PbIn counter electrode is realized by the interface barrier, thus mainly by the surface region of the pnictide film edge. While the planar junction is sensitive in the *c*-direction, the edge junction will be sensitive in the *ab*-direction of the pnictide. We just started to investigate such junctions and compare their properties with those of planar junctions.

2. Preparation

To prepare the junctions, thin films of Ba-122 were used, which were fabricated by pulsed laser deposition (PLD) on a (La,Sr)(Al,Ta)O_3 (LSAT) substrate. The films had thicknesses of approximately 80 nm. Details of the deposition process can be found in [3]. The surface showed a good quality with a root mean square (RMS) roughness of less than 1nm enabling a complete coverage with gold. This normal metal layer is tunable in thickness and forms the barrier between the two superconducting electrodes as well as it avoids possible degradation of the Ba-122 by air, photo resists and other chemicals used in subsequent preparation steps.

The planar junction areas were confined by frameworks of insulating SiO_2, so that different areas between 3x3 µm² and 100x100 µm² are formed. A counter electrode made of a lead indium alloy (PbIn), deposited by thermal evaporation was prepared on top (Fig. 1). The junction design precisely allows the determination of T_C and I_C for both electrodes, separately as well as for the junction itself in four-point geometry. Therefore, it is possible to investigate the temperature dependent electrical properties for each electrode independently and determine their influence on the junction.

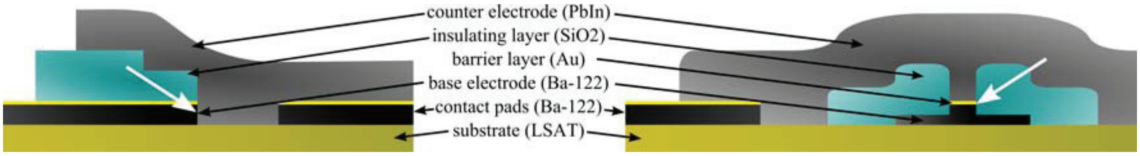

Fig. 1. Schematic cross-sections (a) of an edge junction and (b) of a planar junction. The white arrows mark the junction areas.

The edge junction geometry (Fig. 1a) allows electrical transport processes in the *ab*-plane of the iron pnictide. Therefore, an insulating SiO_2 layer was deposited on top of the Ba-122 base electrode to prevent possible contact in *c*-direction. The contact area is formed via ion beam etching of the iron pnictide and thermally evaporated lead indium. Its size is defined by thickness of the Ba-122 layer (80 nm) and the width of the PbIn bridge (tunable between 3 µm and 20 µm). The edge contact is also measureable in four-point geometry. Its barrier is determined by the interface between the pnictide edge and the counter electrode film. Thus the preparation of the interface has a strong influence on barrier properties like it is know from “interface-engineered” junctions with cuprate superconductors, see e.g. [4,5]. All pads of one junction (eight at the planar ones, four at the edge junctions) were contacted via ultrasonic bonding technique with gold wires (diameter of 25 µm) providing the connection to the measurement equipment.

3. Planar junction geometry

3.1. Thin normal metal barriers

The *I-V* characteristics of junctions with a gold layer thickness of 5 nm show hysteretic behavior (Fig. 2), that can be described using the resistively and capacitively shunted Josephson junction (RCSJ) model. It seems that there are multiple branches and sometimes the junction jumps between them. There is an asymmetry between the positive and the negative critical current, which may be caused by trapped flux.

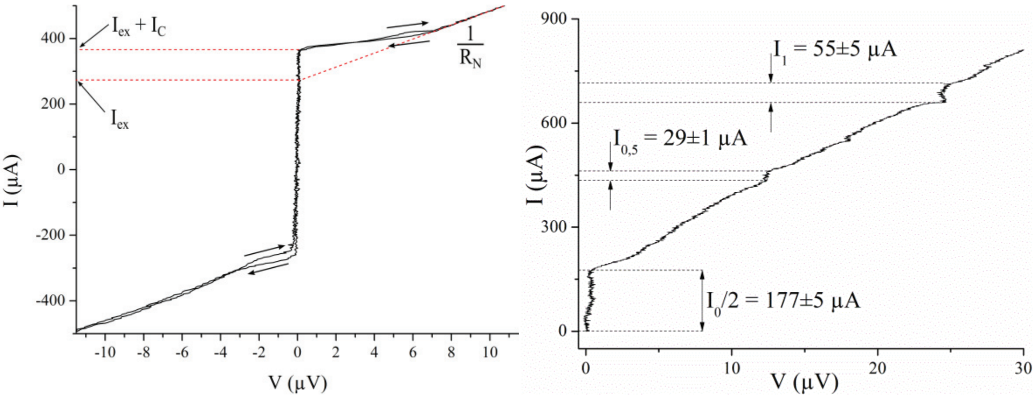

Fig. 2. (a) *I-V* characteristics of the Josephson junction with a gold barrier thickness of 5 nm and a junction area of 30x30 μm² measured bidirectional at 4.2 K in current bias mode. A hysteretic difference between increasing and decreasing bias currents is visible in the negative branch [1]. (b) Distinct Shapiro steps occur under microwave irradiation (f = 12 GHz). The indices of I denote multiples of 2eV/hf. $I_0/2$ corresponds to the microwave suppressed value of $I_{ex}+I_C$.

To get rid of fluctuation effects, we determined the critical current from several *I-V* characteristics at constant temperatures. At 4.2 K, the formal critical current $I_{ex}+I_C$ is about 360 μA (Fig. 2(a)), decreases nearly linear with the temperature and reaches zero at 7.2 K, which corresponds to the T_C of the PbIn counter electrode. Extrapolating the linear part of the *I-V* characteristic (Fig. 2(a)) to zero voltage gives rise to assume an excess current, I_{ex}, of about 270 μA, lowering the effective I_C to 90 μA. The normal state resistance, R_N, of the junction is 47 mΩ and thus the effective $I_C R_N$ product is 4.2 μV. From the junction area size the critical Josephson current density, J_C, may be calculated to 10 Acm^{-2}, while the sheet resistance, ρ_N, of the junction is 5200 Ωcm^{-2}. Having that small value of J_C and that high value of ρ_N, it can be ruled out that the Josephson junction is formed by a grain boundary. We rather assume the junction to be of the SNS', SINS', or SINIS' type, with N as normal metal, I as insulating, S and S' as superconducting layers.

Under microwave irradiation Shapiro steps were observed. Depending on the microwave frequency and power, steps up to the fifth order occur. Also subharmonic steps can be observed matching to step indices of 1/2 and 1/3. The steps follow the Bessel behavior when increasing the microwave amplitude. For further details see Ref. [1].

3.2. Thicker normal metal barriers

To characterize a junction with thicker barriers (10 nm) and its electrodes, information about their electrical behavior is required. We obtained the differential conductance in respect to the applied voltage and the differential resistance in respect to the biased current, respectively by numerical derivation of measured *V-I* characteristics. The PbIn counter electrode has a critical temperature of 7.2 K and critical current of 20 mA at 4.2 K, which corresponds to a critical current density of 1.7 × 10^5 Acm^{-2}. For $T \geq T_C$ the differential resistance is independent of the biased current and slightly increases with temperature. The Ba-122 base electrode behaves differently as shown in Ref. [6]. The *V-I* curve shows hysteretic behavior up to 6.6 K. At 4.5 K the critical current is 3.75 mA and its density is 6.7 × 10^4 Acm^{-2}. Increasing the temperature changes the shape of the differential resistance. At temperatures above 10.6 K v-shaped behavior occurs for low currents instead of the u-shaped one at lower temperatures. This nonlinear current dependency appears also in the conductance spectra of the junction (Fig. 3a). The normal state of the Ba-122 thin film with constant resistance R_N = 150 Ω is reached at 18.6 K.

In Fig. 3(a) conductance spectra in dependence on the temperature are shown for such a planar SNS’ junction with an area of 10x10 µm². One can see the change from SNS’ to a SN-like behavior when the temperature exceeds 7.2 K. Below this value the differential conductance shows a central peak for voltages $|V| \leq 3$ mV. Within the slope of this peak there are many features which are caused by multiple Andreev reflections and maybe other unknown processes due to the SNS’ structure in this temperature region. Unfortunately we are not able to describe the conduction spectra within a complete model for temperatures below the critical one of the PbIn electrode.

When increasing the temperature above 7.2 K, the central peak changes, its height decreases while its width increases. This is due to the normal state resistance of the PbIn electrode, which is 4.2 Ω at 7.3 K. A correction of the spectra can be performed by subtracting this resistance from the measured conductances [6]. For even higher temperatures, also the Ba-122 base electrode influences the spectra as mentioned above. One can see, that the curves above $T = 10.2$ K exhibit a sharp central peak in contrast to the round shape below. This behavior can also be seen in the differential resistance of the pure Ba-122 electrode, so we assume that this is an intrinsic effect of the pnictide. Due to this nonlinear dependence on the electrodes resistance one cannot, unlike for the counter electrode, derive the junction spectra from the measured one, which hinders a detailed analysis of the spectra for these temperatures.

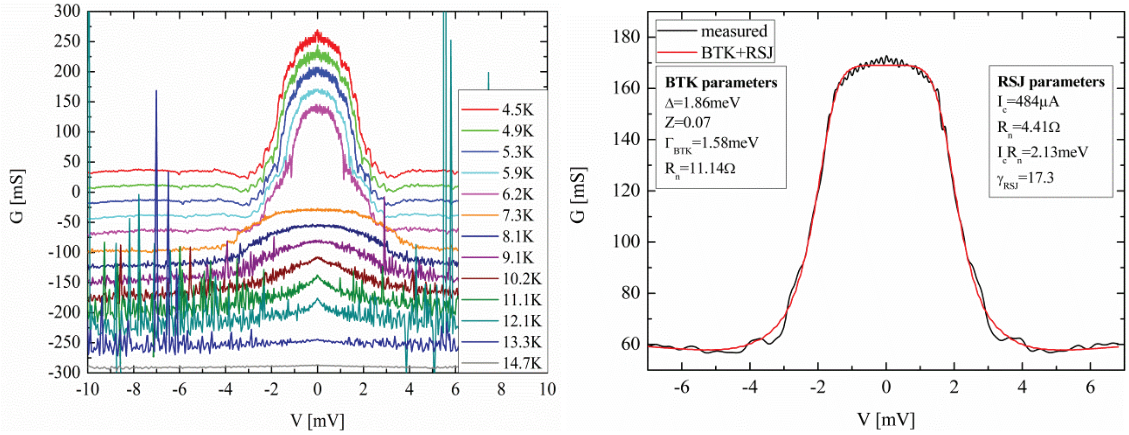

Fig. 3. (a) Differential conductance versus applied voltage of a planar SNS’ junction with a gold barrier thickness of 10 nm and a junction area of 10x10 µm² calculated by numerical differentiation. Each curve is shifted by 25 mS against the higher one. (b) Corrected conductance spectrum at 7.3 K (black) and a fit with a combined BTK and RSJ model (red) of the same junction.

To describe the conduction spectrum of a single superconductor-normal metal junction one can use a model by Blonder, Tinkham and Klapwijk (BTK [7]) with quasiparticle lifetime extension parameter Γ [8,9]. A detailed description about the used model and possible extensions for iron-based superconductors (e.g. two-gap superconductivity) is given by Daghero and Gonelli [10]. In this model, the maximum ratio is $G(V=0)/G(\infty) = 2$. Fig. 3(b) shows the corrected spectrum of the junction at 7.3 K. It is clearly noticeable, that the ratio is higher (≈3). To describe this, former works on other superconducting junctions [11-13] assumed a serious shunt of a SN-junction and a Josephson junction which can be described within the RSJ model [14]. In this model the applied voltage over a Josephson junction (1) and the according conductance of the complete series circuit (2) are given by

$$V = \frac{2}{\gamma} R_N I_C \frac{\exp(\pi\gamma\alpha)-1}{\exp(\pi\gamma\alpha)} T_1^{-1}, \tag{1}$$

with $$T_1 = \int_0^{2\pi} d\varphi I_0\left(\gamma sin\frac{\varphi}{2}\right) \exp\left[-\left(\frac{\gamma}{2}\right)\varphi\right], \alpha = {}^{I}/_{I_C}, \gamma = \frac{\hbar I_C}{e k_B T_n}.$$

$$G_{BTK+RSJ} = \left[\left(\frac{dV}{dI}\right)_{BTK} + \left(\frac{dV}{dI}\right)_{RSJ}\right]^{-1} \tag{2}$$

R_N is the normal state resistance of the junction, I_C its critical current, T_n the effective noise temperature and $I_0(x)$ the modified Bessel function. Such a model was used for our sample in Fig. 3(b) for T = 7.3 K and it can be seen, that there is a good agreement between the measured data and the model. However, from the obtained $I_C R_N$ product it cannot be concluded on the origin of the Josephson junction. Either a grain boundary in the Ba-122 or an intrinsic effect along its *c*-axis is possible up to now.

4. Edge junction geometry

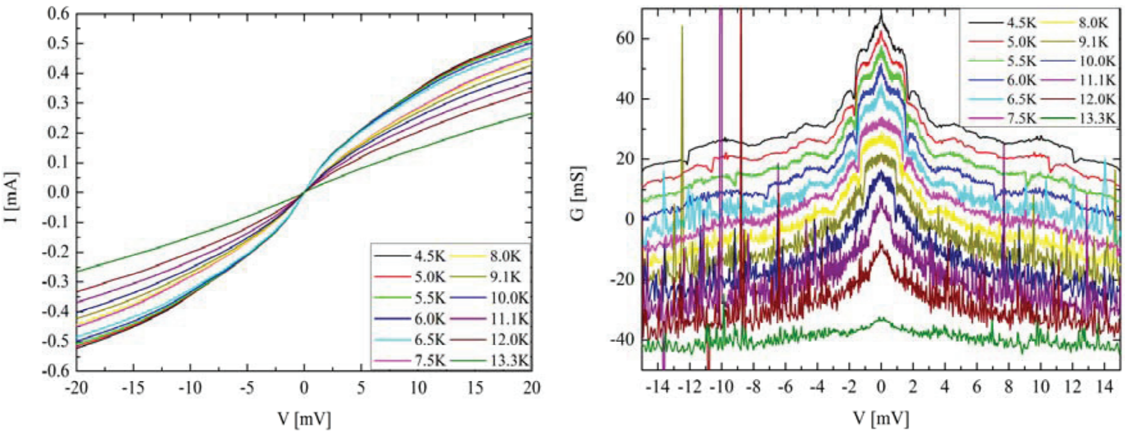

Fig. 4. (a) *I*-*V* characteristics of an edge junction with a width of 10 μm. (b) The differential conductance versus applied voltage of the same junction,obtained by numerical differentiation. Each curve is shifted downwards by 5 mS against the higher one. Also the curves for $T \geq 7.2$ K are corrected by the respective normal state conductance value of the PbIn counter electrode.

The edge junction shows similar behavior to the planar ones with thicker gold barriers. As clearly can be seen in Fig. 4 the conductance for low voltages is much higher than for high voltages, even for the case of $T \geq 7.2$ K, when the PbIn is in the normal state. Therefore one can assume a barrier which behaves more like a normal metal (N') than an insulator (I), thus most probably forming a SN'S' contact. Examining both electrodes in the superconducting state, a central peak can be observed, which vanishes at 7.2 K and might correspond to a Josephson current, but its origin stays unclear. Maybe it is due to a coupling between the electrodes through the interface-engineered barrier, but also a grain boundary junction within the PbIn electrode seems possible. Similar to the planar junctions, the influence of the Ba-122 electrode causes a change in the shape of the conductance spectrum for temperatures above 10 K. In contrast to the planar junctions, a description within a BTK-model, even with a series shunt of an additional Josephson junction, does not provide a sufficient fit. We assume, that the rise in conductance, occurring at around 2 mV for T = 4.5 K corresponds to a critical Josephson current. There are also features, which can be assigned to superconducting energy gaps. However, there is a background in the spectra, which cannot be described within a known analytical dependence, causing some additional features to the spectra and leading to a fail of modeling even within the combined BTK and RSJ model.

5. Summary

We have prepared hybrid junctions with a thin film pnictide electrode in different geometries and with different barriers. Planar SNS' junctions with thin N barriers of gold act as Josephson junctions connected to the *c*-direction of the pnictide showing a quite conventional behavior. For thicker N layers we get Andreev reflections but the behavior cannot be described by standard BTK theory even if two gaps are assumed. In some cases there seems to be a series connection of the SNS' junction and an additional Josephson junction. Up to now the origin is not known.

We also started to prepare hybrid edge junctions where the interface between Ba-122 and PbIn is used as barrier. The interface preparation determines the barrier properties ("interface-engineering"). The area of these junctions is quite small given by the film thickness times the width of the PbIn electrode. These junctions show a complex behavior but offer a way to realize combined *c*- and *ab*-oriented Josephson corner junctions for symmetry tests of the order parameter proposed in [15]. Further experiments will use other materials for the counter electrode as well as for the iron-based superconductor.

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