Anomalous Metal Interface Effect of Iron-based Superconductors

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Abstract: We report the results of the Andreev spectroscopy of the (Co-doped Ba-122 single crystals)/metal/Pb junctions with a metal layer of Al, Pb, Ag, and Sn. We observed Andreev-like spectra for each metal layer and the junctions were identified to be (superconductor)/(normal metal) type. The spectra showed different behaviors for each metal layer. Especially in the case of Sn, the junction showed complex structure where different S/N type features were folded. We consider this behavior is due to a chemical reaction, in the interface between an iron-based superconductor and a layering metal.

Keywords: Iron-based superconductor, Tunnel junction, Conductance spectroscopy, Andreev reflection

1. Introduction

In iron-based superconductors (IBS), the pairing symmetry of the superconducting order parameter is particularly important to investigate its pairing mechanism. The Josephson effect measurements, which have actually been used to determine the symmetry of cuprate superconductors as d-wave [1], is one of the most effective methods for determining the pairing symmetry.

We have studied the junctions, in which one electrode was a Fe[Te,Se] single crystal and the counter electrode was metal/(metal oxide)/Pb double (triple) layers, because the proximity effect between IBS and a conventional metal is expected to be another sensitive tool to investigate the pairing symmetry of IBS. However, an abnormally large gap was observed in some combination of the electrodes [2]. Then, we estimated this structure as the interface effect between IBS and a specific metal (in this case, Pb). Since the proximity effect is strongly affected by the condition of the
interfaces between electrodes, it is very important to clarify what is happening in the interfaces. It is also important for the Josephson effect criteria to be effective. Moreover, the existence of a large gap in Fe[Te,Se] case may suggest the stabilization or the formation of the higher $T_c$ phase/material due to the interface, especially in the FeSe system.

In this paper, we report the results of the Andreev spectroscopy of the Co-doped Ba(FeAs)$_2$ (Ba-122) single crystals, using a junction structure same as described in our previous report [2]. Here, a Ba-122 crystal surface has a direct contact with a proximity layer metal. Ba-122 has been known to give good contact with the metal electrode and show the Josephson effect in the combination with Pb [3]. Therefore, it is suitable to investigate the material dependence of the proximity layer. We report here the results of Al, Pb, Sn, and Ag metal layers. In addition to conventional Andreev spectra, we will show the very anomalous spectra both in the structure and in the temperature dependence in a junction with a metal contact.

2. Experiment

In this work, we used the single crystals of Ba(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ grown by a flux method. ‘Figure 1’ shows a typical temperature dependence of the resistivity of a crystal. The $T_c$ onset occurred at $\sim$ 22 K, and the transition width was $\sim$ 3 K.

A Ba(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ crystal was first set on the sapphire substrate and cleaved in a vacuum. Next, an Al, Ag or Sn proximity layer with the thickness of $\sim$2 nm was deposited on the clean surface immediately after the cleavage. Then after taking the substrate out of the vacuum chamber, the junction window was formed by a resin in the air. Finally, the Pb counter electrode with a thickness of $\sim$800 nm was deposited to form a cross-shape via a metal mask. The typical size of the junction area was $\sim$0.3×0.3 mm$^2$. During depositions, a pressure was kept under $\sim$10$^{-6}$ torr. In this process, we did not intentionally oxidize the metal surface before depositing Pb electrode, so that oxide layer was not expected on the proximity layer. ‘Figure 2’ shows schematic view of our junction.

We measured $I$-$V$ characteristics and their temperature dependences using a four-probe geometry. The differential conductance was obtained by a numerical differentiation of $I$-$V$ characteristics.
3. Result and discussion

‘Figure 3’ shows the results of $\text{d}I/\text{d}V$-$V$ characteristics for junctions with various proximity layer materials. Each curve was normalized by the data above $T_c$, where the all the $\text{d}I/\text{d}V$-$V$ curves were folded. In ‘figure 3(d)’, the origins of the data were shifted in a vertical direction according to their temperature. Our junctions were considered to be a (superconductor)/(normal metal) type, because the effect of the superconducting transition of the Pb counter electrode was not clearly observed. One reason can be that the conductance between the Ba-122 and the proximity layer is expected to be much lower than that between the proximity layer and the counter electrode. Another reason is that the gap value of Pb is very small compared to that of Ba-122 and can be neglected if major gap structures are concerned.

We found the features, which may be accounted by the Andreev reflection, in each junction. However, the detailed shapes were evidently dependent on the material of the proximity layer. In the case of the Al layer in ‘figure 3(a)’, a typical Andreev spectrum was obtained. The spectra showed a small gap structure at ~3 mV and a large gap structure at ~8 mV. These values are approximately consistent with the previous reports [5]. However, above 10 mV no structure was observed. Since they might be well interpreted by the two gap BTK model [5], we assure that our device is well described as an S/N junction.

In the case of Pb and Ag, in ‘figure 3(b)’ and ‘figure 3(c)’, we have observed Andreev spectra again. In the Pb junction, we could observe a small gap at ~5 mV and a large gap-like feature at ~10-12 mV, but not a sign of a peak splitting around 0 mV. In the Ag junction, we also saw a two gap feature with gap energies of ~3 mV and ~5 mV, so that large gap value seemed to be reduced compare to the Al and Pb case. In addition, a sharp zero bias peak was observed. Although the spectra are “typical” compared to our Sn layer case in ‘figure 3(d)’ or the case of FeSeTe/Pb junction in our previous report [2], there are clear material dependence in the spectra. At this stage, we could not well describe the reason of these variations. Since they originate from the difference in the layering materials, it is natural to attribute them to the chemical effect to the IBS at the interface. The interfacing metal may modify the complex band structure of IBS different way and modify a set of gap values associated to each band.
and/or the weights of electronic density of states. In some case, the interface metal may work as a carrier dopant at the interface.

One thing which characterizes interface effect and can be evaluated is the magnitude of contact resistance. The Al junction showed highest resistivity of \(~ 20 \Omega/cm^2\), the Pb and the Sn medium \(~ 10 \Omega/cm^2\), the Ag lowest. The IBS/Ag interface provided the best metallic contact. Thus, the observed zero bias peak in the Ag junction can be understood as a trace of a Josephson current \([3]\). On the other hand, pure Pb did not yield a sufficient contact with an IBS. This explains why we could not observe Josephson current.

Compared to the cases of Al, Pb, and Ag junctions, that of Sn in ‘figure 3(d)’, were very anomalous both in the structure and in the temperature dependence. There are three characteristic features; (1) the small peak structures observed below 8 K, (2) the conventional conductance enhancement due to the Andreev reflection, (3) the large peak with dip structure in the highest energy range. The feature 3 can

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**Figure 3.** Temperature dependence of the junction conductance normalized by the normal value using an (a) Al, (b) Pb, (c) Ag and (d) Sn electrode
be identified to that of the simple S/I/N tunnel junction, where the peak energy corresponds to the gap value. In ‘figure 4’, the temperature dependence of these three features was plotted. Since the feature 1 disappears at around a $T_c$ of Pb, it might be related to Pb superconductivity. The feature 2 disappeared at 19 K. Since $T_c$ of a bulk Ba-122 is around this temperature, we can identify it as an Andreev reflection spectrum due to bulk Ba-122 superconductivity, with a gap value about $\sim$8 mV. On the other hand, the feature 3 disappeared at $\sim$25 K, indicating the existence of a higher $T_c$ entity in this system. Actually, above 20 K, only feature 3 can be observed.

The Sn layer may glow on the Ba-122 crystal as an island. Then 2 nm of Sn layer would not fully cover the crystal surface. Then our junction can be interpreted as a parallel connection of a Ba-122/Sn/Pb junction and a Ba-122/Pb junction. The $I$-$V$ characteristics of latter Pb junction can be same as that in Fig.3 (b), therefore, it would give the feature 2 part of the Sn junction. Then the feature 3 can come from the $I$-$V$ characteristics of the "true" Ba-122/Sn/Pb junction. Then one hypothesis is that the deposited Sn reacts with a Ba-122 at the surface and makes some higher $T_c$ phase and an insulating layer on it. Our results of Fe[Te,Se]/Pb junctions suggested that the deposited Pb reacted with Fe[SeTe] and gave a large gap-like feature [2]. It is natural to consider that the similar reaction take place in the Ba-122 case. However, here, Pb is replaced by Sn. Higher $T_c$ may be due to an extra doping caused by a metal contact.

In this scenario, we assumed the existence of the higher $T_c$ phase. At present, only supporting fact is that temperature dependence of the associated gap follows BCS-like curve. To confirm superconductivity directly, it is important to measure electrode's resistivity in the present configuration that has not yet done. The heating effect may account for the nonlinear $I$-$V$ curve of this type. However, because the junction resistance is as high as that of Pb junction and our Pb junction did not show any such effect, it may not be the case.
4. Summary

We have studied the temperature dependence of the conductance spectra of S/N/S' junctions with a Co-doped Ba-122 single crystals as a base electrode. The spectra were N material dependent and indicated the existence of an interface effect between an iron based superconductor and a layering metal. Here, the interface effect means some chemical reaction, the carrier doping effect, and so on, between adjacent materials. Especially, for Sn, the effect is very large and the formation of a phase with $T_c$ of 25 K has been suggested.

5. References

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