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Above-gap and subgap differential conductance anomaly in concentrated magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb superconductor hybrid junctions

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ABSTRACT

The $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb hybrid junctions were prepared, where the concentrated magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$ is in the region of variable range hopping transport instead of the ballistic or diffusive transport. The high differential conductance peak at gap voltage and two above-gap peaks were observed below the superconducting critical temperature. Moreover, both the zero bias conductance peak and the finite bias conductance peak were observed below the gap voltage. All these differential conductance peaks systematically evolve and finally disappear as the temperature or the magnetic field increases. These transport phenomena were explained by phase coherent Andreev reflection in the presence of strong disorder, magnetic impurity scattering, and spin polarization.

1. Introduction

Normal metal/superconductor and semiconductor/superconductor hybrid junctions have gained considerable attention in recent years because of the novel transport phenomena and potential technological applications. In such hybrid junctions, a well known two electrons process is Andreev reflection (AR) [1], i.e., one electron with energy lower than superconductor gap can penetrate into superconductor while a hole is retro-reflected along its time-reversed path at the same time. The AR process was theoretically accounted by Blonder et al. in 1980s and was observed subsequently by experiments [2,3]. In 1990s, the zero bias conductance peak (ZBCP) was observed in InGaAs/Nb and InAs–AlSb quantum wells/Nb junctions with strong disorder in the semiconductor region [4,5]. This phenomenon was interpreted in term of phase coherent Andreev reflection by scattering matrix method or quasiclassic Green function [6–10]. According to this model, an electron is reflected off the superconducting interface after failing an Andreev reflection process, but it can be multiply scattered coherently by impurities or defects in the normal region without lose its phase memory. Therefore, the electron has more chances to try Andreev reflection to enhance the conductance. In the case of tunneling junctions of metal/insulator/superconductor, the phase coherent Andreev reflection can decrease the barrier effect at low bias, and it is called reflectionless tunneling [7]. Later, ZBCP and the finite bias conductance peak (FBCP) were observed in many normal metal/superconductor and semiconductor/superconductor hybrid junctions by experiments [11–15], which were well explained by phase coherent Andreev reflection. In these works, the ballistic transport or diffusive transport was considered near the interface of the normal metal/superconductor and semiconductor/superconductor hybrid junctions, and mainly ordinary scattering from impurity or magnetic scattering from paramagnetic particles was considered.

On the other hand, spin dependent transport in ferromagnet/superconductor junctions has been an important subject in the field of spintronics recently [16]. The Andreev reflection is a direct method to determine the spin polarization of various ferromagnetic materials such as Co metal [17], CrO_2 half-metal [18], $Ga_{1-x}Mn_xAs$ [19], Mn and Al co-doped ZnO [20], and Cr-doped In_2O_3 [21] magnetic semiconductors. The Andreev reflection in these junctions is suppressed due to the exchange interaction and spin polarization of the ferromagnet [22–24]. The retroreflectivity is broken by the exchange field of the ferromagnet, and the Andreev reflection channels are limited by the minor spin channels near the Fermi level due to the spin polarization. In these ferromagnet/superconductor junctions, the ferromagnet is usually ferromagnetic metal, or magnetic semiconductor which shows metallic transport behavior. However, little attention has been paid to the

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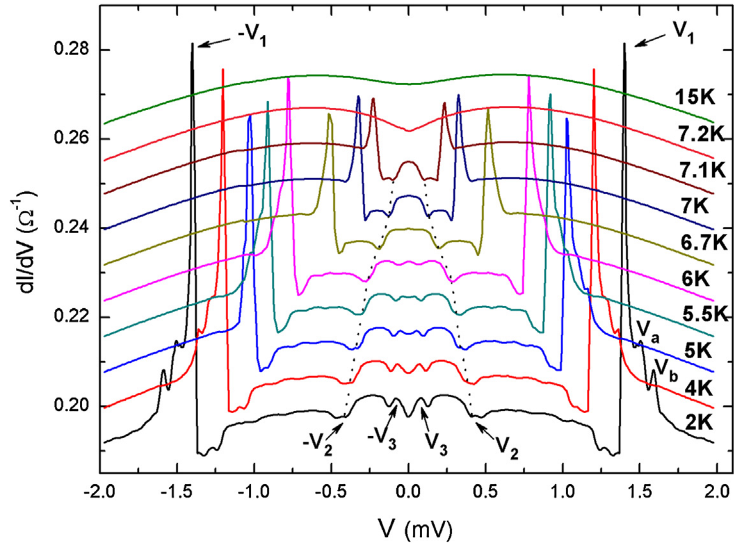

Fig. 1. The differential conductance spectra dI/dV–V curves of magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb superconductor hybrid junctions, which were measured at different temperatures without magnetic field. Three characteristic voltages are marked in the picture, which denote the strongest peak at gap voltage $\pm V_1$, the wide zero bias conductance peak between the dips at $\pm V_2$, and the finite bias conductance peak at $\pm V_3$. The dI/dV curves were vertically shifted an equal distance from the neighboring curves for clarity. The voltage signal from a resistance of 4.7 Ohm in series in $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb junctions was deducted from the raw data.

ferromagnetic semiconductor/superconductor junctions where the ferromagnetic semiconductor is not in the metallic transport region but in hopping transport region. In this case, the ferromagnetic semiconductor in hopping region usually has localized spin polarized carriers and show strong magnetic scattering due to large quantity of defects, which are expected to have significant effects on the Andreev reflection.

In this paper, we designed the $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb hybrid junctions, where the magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$ is in the region of variable range hopping transport [25,26] instead of the ballistic or diffusive transport. The high differential conductance peak at gap voltage and two above-gap peaks were observed below the superconducting critical temperature. Moreover, both the zero bias conductance peak and the finite bias conductance peak, which are below the gap voltage, systematically evolve as the temperature or the magnetic field increases. These transport phenomena were explained by phase coherent Andreev reflection in the presence of strong disorder, magnetic impurity scattering, and spin polarization.

2. Experimental

The glass substrate/Ag/$Zn_{0.32}Co_{0.68}O_{1-v}$/Pb hybrid junctions of 100 μm × 100 μm in area were prepared using shadow mask technique. First, a 30 nm Ag stripe was sputtered as the bottom electrode. Then the concentrated magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$ layer of 60 nm was prepared and exposed to air to form a very thin oxide barrier on the surface. Finally, the sample was moved back to the high vacuum chamber to deposit the crossed Pb stripe of 300–500 nm in thickness by thermal evaporation. The junction resistance varied from several Ohms to several hundred Ohms, depending on air exposure time of the $Zn_{0.32}Co_{0.68}O_{1-v}$ surface.

It is worthy to mention that the $Zn_{0.32}Co_{0.68}O_{1-v}$ concentrated magnetic semiconductor layer was prepared by alternately depositing 0.5 nm Co layers and 0.5 nm ZnO layers for 60 periods at 20 °C, and the end layer is 0.5 nm ZnO. The relatively low growth temperature and alternating sputtering are a thermal non-equilibrium process, which allows for a high solubility of Co in ZnO to form $Zn_{0.32}Co_{0.68}O_{1-v}$ concentrated magnetic semiconductor [25] due to significant oxygen vacancies.

All samples were measured by standard lock-in technique without or with magnetic field paralleled to the junction plane. The Pb single film shows the bulk superconducting critical temperature $T_C = 7.2$ K and the critical magnetic field $H_C = 800$ Oe, which are obtained by independent transport measurements.

3. Experimental results

Fig. 1 shows the differential conductance spectra dI/dV of the magnetic semiconductor $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb superconductor hybrid junctions at different temperatures. When temperature is above the superconducting critical temperature $T_C = 7.2$ K, the dI/dV spectra only show a tunneling background with a dip at zero bias voltage. Just below T_C, a high differential conductance peak at gap voltage $\pm V_1$ occurs, and it moves to bigger bias voltage and becomes higher in amplitude with decreasing temperature. Moreover, the high conductance peak clearly develops into one main peak as well as two above-gap peaks, which are marked as V_1, V_a, and V_b, respectively. It is worthy to note that the dI/dV curves were vertically shifted an equal distance from the neighboring curves to show clearly. In fact, the dI/dV curves almost overlap as the bias voltage is above the gap voltage for all temperatures between 7.2 and 2 K. This means that the tunneling background above the gap voltage hardly depends on the temperature between 7.2 and 2 K.

In addition to the high conductance peak at gap voltage, a wide ZBCP between the dips at $\pm V_2$ (thus the half width of ZBCP is V_2) occurs below the gap voltage. The ZBCP shows 1%–2% enhancement above the tunneling background in the temperature range of 2–7.1 K. Moreover, a small FBCP at $\pm V_3$ occurs and superimposes on the wide ZBCP. It is obvious that both the width of the ZBCP and the peak voltage of the FBCP increase monotonously with decreasing temperature.

Fig. 2 further shows the temperature dependence of the normalized gap voltage $V_1(H = 0, T)/V_1(H = 0, T = 0)$ and the normalized half width $V_2(H = 0, T)/V_2(H = 0, T = 0)$ of the ZBCP without magnetic field. Both of them decrease as temperature increases, and they disappear at the superconducting critical temperature $T_C = 7.2$ K, which can be well fitted by the BCS gap law. It means that both the high conductance peak at gap voltage and the zero bias conductance peaks are closely related to the superconducting transport of the $Zn_{0.32}Co_{0.68}O_{1-v}$/Pb hybrid junctions.