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Proximity Effect in Nb/Gd Layers

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Abstract

We have grown a Nb/Gd bilayer on a SiO_2/Si substrate by using a DC magnetron sputtering system, which was fabricated *in situ* with silicon stencil masks. In order to investigate proximity effect of the Nb/Gd bilayer, we used a planar tunnel junction with an AlOx tunnel barrier by oxidizing the Al ground electrode at the bottom. A $Co_{60}Fe_{40}$ backing of Al was deposited so as to reduce the superconductivity of the Al, ensuring a normal counterelectrode. With a 50-nm-thick Nb layer, we have measured dI/dV (dynamic conductance) by varying the thickness of Gd, which can reveal the density of states (DOS) of the Nb/Gd bilayer as a function of the Gd thickness resulting from the proximity effect of a superconductor/ferromagnet bilayer (S/F). The SF proximity effect in Nb/Gd will be discussed in comparison to our previous results of the CoFe/Nb, Ni/Nb and CuNi/Nb proximity effect; Gd is expected to show different effects since Gd has f-electrons, while CoFe, Ni, and CuNi have only d-electrons. Our studies will focus on the triplet correlation in a superconducting pair.

Keywords : Proximity, bilayer, Nb, Gd

I. Introduction

The interaction between magnetism and superconductivity and their coexistence remain one of the unsolved problems in conventional superconductivity. This can be seen in the superconductor/ferromagnet (SF) bilayer structure where the critical temperature (T_c) oscillation occurs which are explained as zero and π state of superconducting order parameter known as the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) effect [1-2] which was first proposed over 40 years ago. Zero state means that the real part of the order parameter is positive, and π state means the real part is negative. Unfortunately, the oscillation of the critical temperature alone is not enough to reveal the physical state of bilayers. It is known that the measurement of superconducting density of state (DOS) in a ferromagnet will provide more insight for the state of the ferromagnet/superconductor bilayers.

When a ferromagnetic metal is placed in contact with a superconductor, the exchange field gives additional center of momentum to the Cooper pairs moving into the ferromagnetic region and the wave function of the Cooper pair in the ferromagnet picks up the oscillation term. Therefore the oscillating phenomenon of the T_c is anticipated as a function of the thickness of the ferromagnet in the SF layer.

Since ferromagnetism is not compatible with superconducting singlet pairs with two opposite spins, in an SF bilayer system it is believed that the exchange field in the ferromagnetic metal breaks the Cooper pairs and the superconducting order parameter as a function of the thickness of ferromagnetic metal layer will be reduced. Therefore

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the critical temperature of SF bilayer system is much lower than that of superconductor single layer system and the bilayer system shows oscillatory behavior in their critical temperatures [3-5] and DOS as a function of the thickness of the ferromagnetic metal layer. These phenomena are not limited to bilayer systems and several studies that investigated multilayer systems reported similar behavior.

Although there have been numerous proposals [6-8] aiming at the satisfactory explanation for the proximity effect, the origin of the proximity effect is not clear. Also, the previous proximity effect experiments deal with the CoFe/Nb, CuNi/Nb [9] and Ni/Nb [10] where CoFe, CuNi and Ni have only d-electrons. In these experiments, various unusual phenomena are reported previously including an anomalous double peak structure in S/F tunneling density of states [11] and lack of oscillation in the density of states as a function of ferromagnet thickness [12] which was predicted by the Usadel equations. All these diverse behavior may come from the properties of the interface between Nb and the ferromagnet. Since Gd has f-electrons, it may exhibit effects different from that of the d-electron ferromagnetic metals. Additionally, there are not many experiments investigating the properties of Gd in the field of superconductivity. We hope these junction fabrication and measurement would serve as not only preliminary examination of the properties of a junction but also in and of itself precursors to those of the Nb/Gd bilayer tunneling spectroscopy at about 0.3 K.

II. Experimental setup

Silicon stencil masks, which were used when making a junction in a DC magnetron sputtering system, are fabricated by wet anisotropic etching method preceded by another lithographic process using a photoresist and an ultraviolet light aligner, a well-known process in bulk micromachining technique.

The masks come in two types; one lined and four lined ones as in the above picture. These two masks are used in a perpendicular manner to maximize the number of junctions on a substrate. The line widths range from about 40 to 100 micrometers, which can be controlled by the etching time, temperature and mass density of the etchant. We held the temperature and the concentration constant and varied the time for simplicity.

The junction is fabricated using the DC (direct current) magnetron sputtering system with the base vacuum pressure 1×10^{-8} Torr. Since the system has two vacuum chambers and an *in situ* mask changer, the fabrication by sequential depositions and oxidation can be done without breaking vacuum; the main chamber is for the metal deposition, the preparation chamber is for RF (radio frequency) plasma oxidation and the middle connecting tube is for changing stencil masks. Base pressure is on the order of 10^{-8} Torr for the main chamber and 10^{-7} Torr or lower for the preparation chamber.

The junction on a SiO_2 substrate consists of a bottom electrode of aluminum, an interlayer of oxide, a ferromagnetic layer of Gd and a superconducting layer of Nb, as can be seen in the Fig. 1 below.

For the bottom electrode, an aluminum layer of 10 nm thickness is deposited; 5 mTorr Ar gas pressure and 20 W DC power induces Ar ions and the magnetic field around the aluminum target creates the plasma. As a result, the target bombarded by the Ar ions is sputtered and deposited on the SiO_2 substrate which was cleaned with acetone and mechanically fixed in a holder and put into the preparation chamber with a one-lined stencil mask on it.

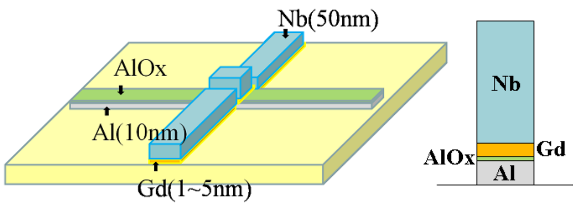

Fig. 1. The quarter and cutaway view of the junction.

The mask is not mechanically fixed for convenience of changing, but is held lightly in place by the wedge-like geometry of the holder.

The electrical measurement is performed with a lock-in amplifier. The equipments are controlled by a Labview application via GPIB interfaces. The substrate with the junctions on it is placed on the tip of a dipstick and put into liquid helium in a cryogenic storage dewar. The four-point probe method is used and small amounts of indium are applied on the electrodes, in this case one-lined AlOx/Al and four-lined Nb, so that each of them makes robust contact with gold-tipped probes.

We first measured the resistance versus temperature (R-T) curve of an Nb layer on a 2 mm × 7 mm silicon substrate by the four-point probe method, as shown in Fig. 2, manually dipped in the liquid helium in a cryogenic storage dewar. In this case a lock-in amplifier is not necessary, as the signal is fairly stronger than ambient noise. It shows very reproducible superconducting transitions for Nb layers.

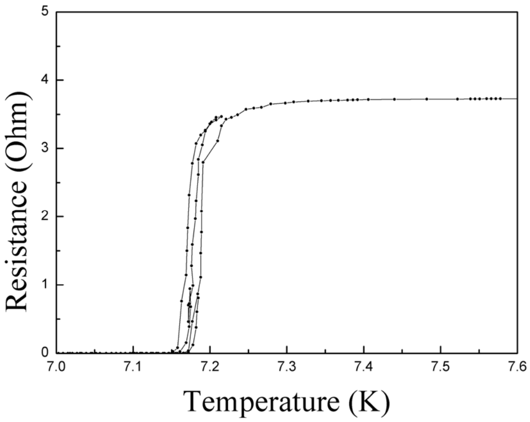

Fig. 1. Resistance-Temperature curve of the bulk Nb from 7.0 K to 7.6 K.

The Fig. 3 shows the normalized conductance of the junction without the Gd layer at 4.2 K. The four curves correspond to the four junctions respectively and the normalized conductance property of the junctions is fairly consistent, as can be seen.

The normalized conductance curves of the junctions with the 1 nm thick Gd layer are shown below in Fig. 4. The depth of the conductance dip at the zero bias is slightly reduced from the conductance of pure Nb.

In case of the junctions with the Gd layer of 2 nm thickness, the conductance dip at zero bias is further reduced.

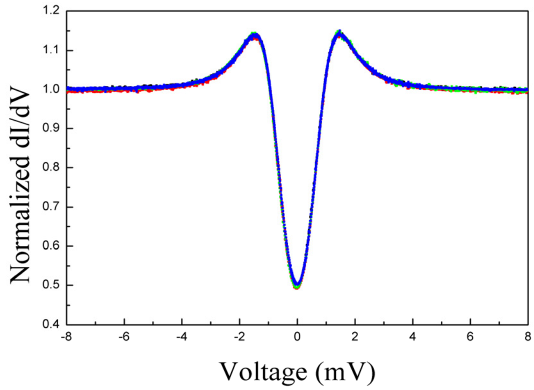

Fig. 3. Normalized conductance versus voltage of the bulk Nb.

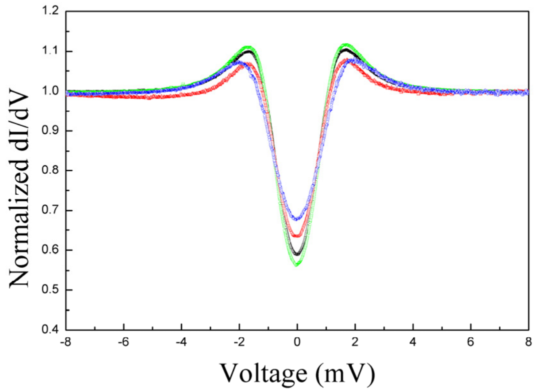

Fig. 4. Normalized conductance versus voltage of the junction with 1 nm Gd layer.

In another run for 2 nm thick Gd layer with a better Au/Ti contacts to the electrodes, the conductance curves in Fig. 6 turned out a little different from those of Fig. 5. The calibration for Gd layer thickness needs to be checked to confirm the results for 2 nm thick Gd layer.

When the Gd thickness is larger than 3 nm, no features in conductance were evident at 4.2 K. We will be conducting further investigation of the junctions with a probe designed for 0.3 K.

Since the gold is known to be stable in air or water, that is, not prone to oxidation, and the contact resistance is very small, a 14-holed mask will be used to make contacts to electrode by deposition of *in situ* Au/Ti to remove the indium completely to minimize possible unwanted side effects from indium contact at the ultra-low temperature.

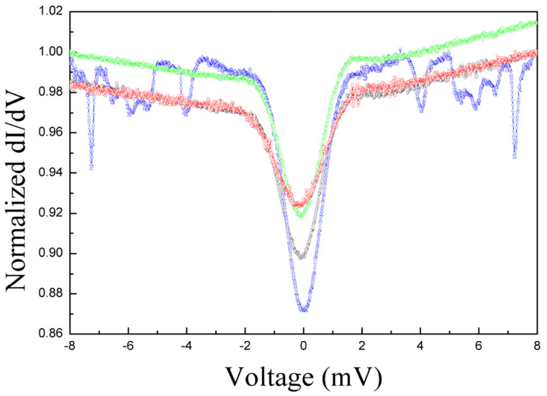

Fig. 5. Normalized conductance versus voltage of the junction with 2 nm Gd layer.

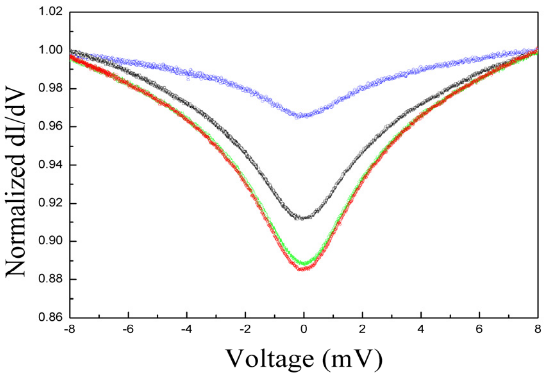

Fig. 6. Normalized conductance versus voltage of the junction with 2 nm Gd layer, Au/Ti electrode.

Acknowledgments

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