Development of point-contact spectrometer for spin polarization measurements

M. Shiga\textsuperscript{1}, N. Nishimura\textsuperscript{1}, H. Takata\textsuperscript{1}, Y. Inagaki\textsuperscript{1}, H. Kambara\textsuperscript{2}, K. Tenya\textsuperscript{2}, and T. Kawae\textsuperscript{1}
\textsuperscript{1}Department of Applied Quantum Physics, Faculty of Engineering, Kyushu University, Motooka, Fukuoka 819-0395, Japan
\textsuperscript{2}Faculty of Education, Shinshu University, Nagano, 380-8544, Japan

e-mail 2TE15295Y@s.kyushu-u.ac.jp

Abstract. We construct a “needle-anvil” type point-contact spectrometer for spin polarization measurements, which is installed in a $^4$He-cryostat. Two types of piezo devices are used to control the contact size precisely between a sample ferromagnet and a superconductor. An attocube piezo-based positioner is mounted for coarse movement of the tip, while a stacked-type piezo device is used for fine control of the contact size. This enables to change the contact size between the tip and sample from sub micro-meters to atomic-size contacts continuously. By suppressing thermal flow into the sample space and mechanical vibration, we can keep the contact over hours, enabling the precision measurements. To examine the performance of the spectrometer, we study the spin polarization of polycrystalline SrRuO$_3$ with the point-contact Andreev reflection measurements. The polarization is estimated to be $\approx 0.59$ at the clean limit of the interface, which is consistent with previous study.

1. Introduction
Point-contact spectroscopy (PCS) is used to study the interaction of conduction electrons with excitations of quasiparticles [1]. When the contact size $d$ is smaller than electron mean free path $l$, the conduction electron is accelerated by the bias voltage and moved without energy dissipation in the contact, which is known as “ballistic transport”. Then, the ballistic electrons lose their energy by interacting with a variety of excitations such as phonons. When the ballistic electron enters from metal to superconductor, the characteristic features is expected to appear at superconductor/metal interface depending on the energy of ballistic electron. In the region that the energy of incident electron is lower than the superconductor energy gap $\Delta$, the electron can form the cooper pair at the interface as shown in figure 1. Simultaneously, the hole reflects from superconductor to metal. This phenomenon is called as Andreev reflection.

At the superconductor/ferromagnet interface, the Andreev reflection is suppressed due to the difference of density of state (DOS) between the up spin and down spin at the fermi surface. This difference of the DOS resulting in the spin polarization expressed by the following equation,

$$P = \frac{D_{Ef}^U - D_{Ef}^D}{D_{Ef}^U + D_{Ef}^D} \quad (1),$$

$D_{Ef}^U$ and $D_{Ef}^D$ represent the DOS of up spin and down spin at the fermi energy, respectively.
where \( D_{\uparrow}^{\uparrow} E_f \) and \( D_{\downarrow}^{\uparrow} E_f \) are the density of state of up spin and down spin at the fermi surface. This implies that the spin polarization in ferromagnetic materials can be investigated through Andreev reflection between the ferromagnet and superconductor [2]. By using the point-contact Andreev reflection (PCAR) measurements, the spin polarization \( P \) and superconducting energy gap \( \Delta \) are demonstrated to be estimated by fitting the differential conductance \( (dI/dV) \) spectra between superconductor and ferromagnetic material to a modified Blonder-Tinkham-Klapwijk (mBTK) model [3, 4]. Figure 1(b) shows \( P \) dependence of the conductance calculated from mBTK model, which is largely changed with the magnitude of \( P \).

In this study, we develop a “needle-anvil” type point-contact spectrometer for PCAR measurements, which is mounted in a \(^4\text{He} \) cryostat. By using two types of piezo devices, the contact size of the superconductor/ferromagnet interface can be controlled very precisely. We have measured the spin polarization of ferromagnet iron and polycrystalline SrRuO\(_3\), which exhibits a ferromagnetic transition at \( T \sim 160 \) K, with this spectrometer. The present results provide high resolution compared to previous works.

2. Experimental setup

Figure 2(a) shows a schematic illustration of the spectrometer. To control the contact size of the interface accurately, we use two types of piezo devices. An attocube piezo-based positioner (ANPz51 Attocube systems AG) is mounted for coarse movement of the tip, while a stacked-type piezo device is used to control the contact size. A superconducting tip is positioned to be \( \sim 3 \) mm apart from a sample at room temperature as depicted in left panel of figure 2(a). After cooling the temperature to \( T \sim 4 \) K, the tip is approached to contact softly with the sample by using the attocube positioner. Then, the contact size between the tip and sample is changed finely by the stacked-type piezo device as shown in the right panel of figure 2(a). Owing to this method, we can perform the PCAR measurements with changing the contact size without breaking the contact during the measurements, resulting in the smooth variation of interface scattering parameter. Figure 2 (b) shows a schematic diagram of cryostat (left panel) and an experimental setup (right panel). Note that thermal flow into the sample space is anchored at each thermal stage to keep the contact with the same size over a few hours.

The polycrystalline sample of SrRuO\(_3\) is synthesized by the conventional solid-state reaction method. The powders of SrCO\(_3\) and RuO\(_2\) with stoichiometric compositions were carefully mixed and calcined.
in air at 1100°C for 24 hours. After careful mixing of the calcined samples, they were shaped into pellets and then sintered at 1100 °C for 24 hours [5].

Figure 2. (a) The schematic diagram of a needle-anvil spectrometer for point-contact spectroscopy. (b) The schematic diagram and photo of experimental setup.

The conductance versus voltage \((G-V)\) characteristics between a superconductor/ferromagnet interface are measured at \(T = 4.2\) K in vacuum with a conventional lock-in technique with modulation frequency of 2 kHz. The superconducting Nb tip is fabricated by mechanically polishing a wire with the diameter of 0.2 mm. The sample is mounted in \(^4\)He cryostat after polishing its surface. The spin polarization \(P\), interface scattering parameter \(Z\) and superconducting energy gap \(\Delta\) are obtained from fitting the differential conductance \(dI/dV\) to the m-BTK function.

Figure 3. The differential conductance of Nb/Fe interface at \(T = 4.2\) K. The circle and solid line are experimental data and fitting by m-BTK model. The fitting parameters are given in the figure.

3. Results and discussion

Figure 3 shows the differential conductance \((dI/dV)\) spectra of a Nb/Fe interface, which is normalized at normal state conductance at the bias voltage \(V = 5 mV\). The experimental data are well reproduced by the m-BTK model. From the fitting, the spin polarization of Fe is estimated to be \(P = 0.44\), which is in good agreement with the previous study \(P = 0.43 \pm 0.03\) [6]. These results indicate that we can measure the spin polarization of ferromagnet precisely with using the new spectrometer. Note the superconducting energy gap of Nb is obtained to be \(\Delta = 0.6\) meV, which is smaller than that of bulk Nb with \(\Delta_{Nb} = 1.5\) meV. The suppression of the energy gap is probably caused by the pair-breaking effect by ferromagnetic iron.
Next we show the temperature dependence of the differential conductance spectra at a Nb/SrRuO\textsubscript{3} interface. The representative spectra at $T = 4.2$ K for various resistances are plotted in figure 4(a)–4(d), where the fitting curve by the m-BTK function and the fitting parameters are also shown. Note that the measurements are performed without breaking the contact after preparing it, leading to a change of the differential conductance curve. The superconducting gap of bulk Nb is 1.5 meV, which is larger than $\Delta \sim 1.0$ mV estimated from the present experiments. As in the case of iron in figure 3, the gap is considered to be suppressed by magnetic scattering at the superconductor/ferromagnet interface. From these results,
the spin polarization of polycrystalline SrRuO$_3$ is evaluated to be $P \sim 0.59$ [7]. This value is larger than $P_1 = 0.51$ in a single crystal [8]. The difference of spin polarization between single and poly crystals can be caused by the changing the mean free path $l$ of the sample [9].

Finally, we show the temperature dependence of differential conductance between 2.0 K and 11 K at a Nb/ SrRuO$_3$ interface in figure 5. When the temperature is higher than the Nb superconducting transition temperature $T_c = 9.5$ K, the spectra show no anomaly. In contrast, as the temperature is decreased, a dip at around the zero bias voltage is grown rapidly because of the increase of the superconducting energy gap at Fermi surface. It is seen that the anomaly is well reproduced by the fitting curve calculated by the m-BTK function, representing fine control of the temperature. It is worthy to note that pumping a 1K pot to lower the temperature does not affect the differential conductance measurements, indicating that the spectrometer is mounted in $^3$He cryostat or dilution refrigerator to perform the measurements at very low temperature region.

4. Conclusion

We have developed a “needle-anvil” type point-contact spectrometer to measure the spin polarization of ferromagnet down to $T \sim 2$ K. Two types of piezo devices, attocube piezo-based positioner and stacked type device, are used to control the contact size precisely between a sample ferromagnet and a superconductor. Owing to this method, the contact size between the tip and sample is varied from sub micro-meters to atomic-size contacts continuously. By suppressing thermal flow into the sample space and mechanical vibration, we can keep the contact over hours, enabling the precision measurements. To examine the performance of the spectrometer, we study the spin polarization of polycrystalline SrRuO$_3$ with the point-contact Andreev reflection measurements. The polarization is estimated to be $\sim 0.59$ at the clean limit of the interface, which is consistent with previous study.

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