Spin polarization measurements in ferromagnetic SrRuO$_3$ using point-contact Andreev reflection technique

Masanobu Shiga$^1$, Naoto Nishimura$^1$, Yuji Inagaki$^1$, Tatsuya Kawae$^1$, Hiroshi Kambara$^2$ and Kenichi Tenya$^2$

$^1$Department of Applied Quantum Physics, Faculty of Engineering, Kyushu University, Motooka, Fukuoka 812-8581, Japan
$^2$Faculty of Education, Shinshu University, Nagano, 380-8544, Japan

E-mail: 2TE15295Y@s.kyushu-u.ac.jp

Abstract. Using the point-contact Andreev reflection (PCAR) technique, we have performed spin polarization measurements in a polycrystalline SrRuO$_3$ to study the difference of the spin polarization between the ballistic and diffusive transport samples. PCAR spectra were measured with Nb tips for $T = 4.2$ K with changing the contact area mechanically. The results were well fitted by the modified Blonder-Tinkham-Klapwijk (mBTK) model. We estimate the spin polarization $P \approx 0.59$, which is slightly larger than that of a single crystal film with $P \approx 0.51$ due to the change of transport property.

1. Introduction

After the discovery of the giant magnetoresistance (GMR), intensive efforts have been devoted to fabricate spintronics devices. Since magnetoresistance is sensitive to the spin polarization of ferromagnetic electrode, studying the spin-polarized transport properties of ferromagnetic materials is crucial for the development of spintronics devices. Spin polarization $P_n$ is defined by difference between minority-spin and majority-spin bands at the Fermi level $E_F$. Hence, it is possible to define $P_n$ by the following equation [1],

$$
P_n = \frac{<N^\uparrow(E_F)v^\uparrow_F>_n-<N^\downarrow(E_F)v^\downarrow_F>_n}{<N^\uparrow(E_F)v^\uparrow_F>_n+<N^\downarrow(E_F)v^\downarrow_F>_n},
$$

where $N^\uparrow(E_F)$ and $N^\downarrow(E_F)$ are the density of states (DOS) of majority and minority spins at the Fermi level, and $v^\uparrow_F$ and $v^\downarrow_F$ are the Fermi velocity, respectively. Spin-resolved photoemission experiments measure the spin polarization $P_0$, which is determined only by the difference of DOS between the majority and minority spins at the Fermi level. On the other hand, transport experiments measure a different spin polarization including the Fermi velocities. When the contact size $d$ at the surface is smaller than mean free path $L$ ($d << L$), electron transport is ballistic. In this case, the DOS is weighted linearly with $v_F$, and $P_1$ ($n = 1$) is measured. In diffusive electron transport ($L < d$), the weighting is quadratic in $v_F$, and $P_2$ is measured.
Therefore, the spin polarization $P_n$ depends on the transport properties of samples; if $v_{F\uparrow}^n$ is larger than $v_{F\downarrow}^n$, $P_2$ is larger than $P_1$.

Owing to the structural simplicity and remarkable chemical stability, SrRuO$_3$ is a good candidate to investigate the transport spin polarization $P_n$ including the Fermi velocities. SrRuO$_3$ has a ferromagnetic transition temperature at $T_c = 160$ K and a saturation magnetization of 1.6 $\mu_B$ [2]. To measure the spin polarization, the point contact Andreev reflection (PCAR) technique has been used because the $I-V$ characteristics due to Andreev reflection at a ferromagnet-superconductor interface changes significantly depending on the spin polarization of the ferromagnet.

In this paper, we report the spin polarization of a polycrystalline SrRuO$_3$ in the diffusive transport region with changing the contact area mechanically using PCAR technique where Nb is utilized for a probe tip. By fitting the experimental results to the modified Blonder-Tinkham-Klapwijk (mBTK) model [3], the spin polarization is estimated to be $P \approx 0.59$, which is slightly larger than that of a single crystal film with $P \approx 0.51$ [4].

2. Experiments

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].

![Fig. 1. Temperature dependence of electrical resistivity $\rho$ for polycrystalline SrRuO$_3$.](image)
The conductance versus voltage \((G-V)\) characteristics of the Nb-SrRuO\(_3\) point contact were measured at 4.2 K in vacuum with conventional lock-in technique with modulation frequency of 2 kHz. The Nb tip was fabricated by mechanically polishing a wire with the diameter of 0.2 mm. The sample was mounted in \(^4\)He cryostat after polishing its surface. The point contact was prepared by using a stacked piezo actuator, enabling the precise control of the contact size. The spin polarization \(P_n\), interface scattering parameter \(Z\) and superconducting energy gap \(\Delta\) are obtained from fitting the differential conductance \(dI/dV\) to the mBTK function.

### 3. Results and discussion

Fig. 1 shows the temperature dependence of electrical resistivity \(\rho\) for the polycrystalline SrRuO\(_3\). An anomaly due to the ferromagnetic transition is visible at \(T \sim 160\) K. The residual resistivity of \(~ 420\ \mu\Omega\text{cm}\) is about 8 times larger than that in a single crystal, suggesting the existence of many grain boundaries.

![Fig. 2](image)

Fig. 2. The temperature dependence of the differential conductance spectra \(G(V)\), which is normalized by the conductance at the normal region \((G_n)\). Here, the contact resistance at the interface is controlled to be the same for all the measurements. When the temperature is higher than the Nb superconducting transition temperature \(T_C = 9.5\) K, the spectra shows 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 $E_F$. It is seen that the anomaly is well reproduced by the fitting curve calculated by the mBTK function. This indicates that the anomaly is understood by the Andreev reflection at the superconductor/ferromagnet interface.

Fig. 3. The representative spectra of differential conductance at $T = 4.2$ K. The spectra are measured with increasing the resistance at the interface without breaking the contact after preparing it. The solid line shows fitting by mBTK model.

We measure the evolution of the differential conductance spectra with increasing the resistivity at the interface, which corresponds to decrease of the contact size. It is important that the measurements are performed without breaking the contact after preparing it, which suppresses the scattering of data. We depict the representative spectra at $T = 4.2$ K for various resistances in Fig. 3(a)-3(d), where the fitting curve by the mBTK function and the parameters for the fitting are also shown. The superconducting gap of bulk Nb is 1.5 meV, which is larger than that estimated from the present experiments. The gap is suppressed by magnetic scattering at the superconductor/ferromagnet interface. Moreover, the scattering parameter $Z$ increases with decreasing the resistance $R$ at the contact as shown in the inset of Fig. 4. This implies that the effect of ferromagnetic scattering, which suppresses the superconducting current, is increased with increasing the contact size.
We plot $P_n$ versus $Z$ in Fig. 4, indicating that $P_n$ is suppressed with increasing $Z$ [6]. From the results, the value of spin polarization at $Z = 0$ is evaluated to be $P_n \approx 0.59$. The spin polarization of a single-crystal thin film, which is measured in the ballistic transport region, is reported to be $P_1 = 0.51$ at $T = 4.2$ K [4]. The spin polarization in the present experiments is slightly larger than the single-crystal thin film. The origin is likely due to the difference of transport properties between the samples as follows.

The electrical resistivity of the present sample is $\rho \sim 420$ $\mu\Omega$cm at $T = 4.2$ K as shown in Fig. 1. We can estimate the mean free path from the electrical resistivity $\rho$ to be $L \sim 0.8$ and 0.45 nm for minority and majority carriers, respectively [7]. Furthermore, the contact resistance $R_n$ is approximated by the following equation,

$$R_n \approx \frac{4 \rho L}{3\pi d^2} + \frac{\rho}{2d},$$

where $\rho$ is electrical resistivity [8]. When the contact is assumed to have a circular shape, the contact diameter of this sample is larger than several tens of nanometers, e.g., $d \sim 36$ nm at $R = 60$ $\Omega$, representing that the measurements are done in the diffusive transport ($L < d$) region. Thus, the spin polarization in the present experiments should be larger than that in the single-crystal as mentioned in Sec. 1 and we can conclude that the effect of the Fermi velocity in $P_n$ is different between the ballistic and diffusive transports for the Nb-SrRuO$_3$ interface. The similar results are found in the spin polarization of La$_{0.7}$Sr$_{0.3}$MnO$_3$ [9].

![Fig. 4. Spin polarization $P$ as a function of interface scattering parameter $Z$. Dotted lines were extrapolated to each data by a quadratic function. Inset: $R$ dependence of the interface scattering parameter $Z$.](image)
4. Conclusion
We have studied the spin polarization of a polycrystalline SrRuO$_3$ using point-contact Andreev reflection technique. The spin polarization $P_n$ at $T = 4.2$ K is obtained as a function of the interface scattering parameter $Z$, giving $P_n \approx 0.59$ at $Z = 0$. This value is larger than that in the single-crystal, which can be understood by the difference of the transport property between the ballistic and diffusive transports for the Nb-SrRuO$_3$ interface.

5. Acknowledgements
This work was supported by a Grant-in-Aid for Scientific Research (Grant Nos. 25220605, 25287076, and 26600102) from the Japan Society for the Promotion of Science.

References
[1] Mazin I I 1999 Phys. Rev. Lett. 83 1427
[2] Gao G, McCall S, Shepard M, Crow E J and Guertin P R 1997 Phys. Rev. B 56 321
[3] Mazin I I, Golubov A A and Nadogorny B 2001 J. Appl. Phys. 89 7576
[4] Raychaudhuri P, Mackenzie P A, Reiner W J and Beasley R M 2003 Phys. Rev. B 67 020411(R)
[5] Kawasaki I, Yokoyama M, Nakano S, Fujimura K, Netsu N, Kawanaka H and Tenya K 2014 J. Phys. Soc. Jpn. 83 0647712
[6] Ji Y, Strijkers J G, Yang Y F, Chien L C, Byers M J, Anguelouch A, Xiao Gang and Gupta A 2001 Phys. Rev. Lett. 86 5585
[7] Nadgory B, Osofsky S M, Singh J D Woods T G, Soulen J R, Jr, Lee K M and Eom B C 2003 Appl. Phys. Lett. 82 427
[8] Nikolic B and Allen B P 1999 Phys. Rev. B 60 3963
[9] Nadogorny B, Mazin I I, Osofsky M, Soulen J R, Jr, Broussard P, Stroud M R, Singh J D and Harris G V 2001 Phys. Rev. B 63 184433