(※本報告書は英語で記述してください。ただし、産業利用課題として採択されている方は日本語で記述していただいても結構です。)

CROSS TOKAI **Experimental Report** J-PARC	**承認日**Date of Approval 2014/7/19 **承認者**Approver Masayasu Takeda **提出日**Date of Report 2014/7/10
課題番号 Project No. 2014A0131 実験課題名 Title of experiment Confirmation of the FFLO-like nodal planes in the Au layer of Nb/Au/Fe trilayers 実験責任者名 Name of principal investigator Hiroki Yamazaki 所属 Affiliation RIKEN, Nishina Center	装置責任者 Name of responsible person Masayasu Takeda 装置名 Name of Instrument/(BL No.) Sharaku/BL17 実施日 Date of Experiment 7 May 2014 – 10 May 2014

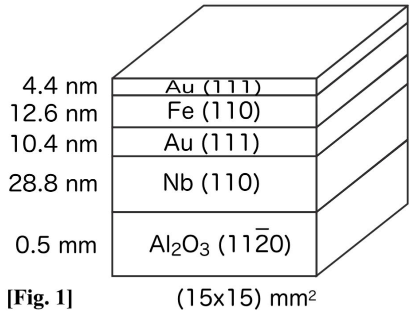
試料、実験方法、利用の結果得られた主なデータ、考察、結論等を、記述して下さい。(適宜、図表添付のこと)

Please report your samples, experimental method and results, discussion and conclusions. Please add figures and tables for better explanation.

1. 試料 Name of sample(s) and chemical formula, or compositions including physical form.

Sample: Nb/Au/Fe trilayer

We measured a trilayer of Nb(28.8nm)/Au(10.4nm)/Fe(12.6nm) with a cap of Au(4.4nm). A single crystal of $Al_2O_3(11\bar{2}0)$ ($15\times15mm^2\times0.5mm$) was used as a substrate when the trilayer was prepared using molecular beam epitaxy (MBE) technique. Each layer showed epitaxial layer-by-layer growth, and the preferential orientations of Nb(110), Au(111) and Fe(110) have been confirmed. The Nb layer shows superconductivity below T_c~8.0 K, whereas the Fe layer is ferromagnetic. Below T_c, the Au layer is supposed to be in a superconducting state due to a proximity effect to the Nb layer.



[Fig. 1]

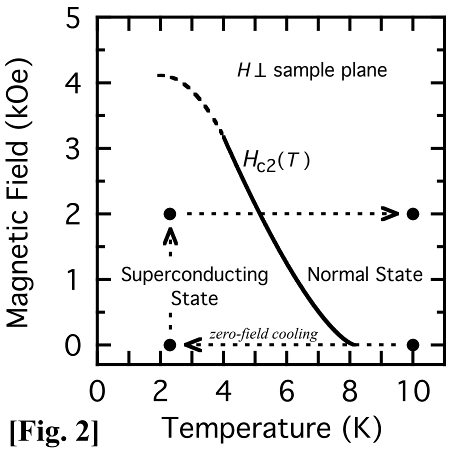
2. 実験方法及び結果(実験がうまくいかなかった場合、その理由を記述してください。)

Experimental method and results. If you failed to conduct experiment as planned, please describe reasons.

I. Experimental Method

In order to observe possible FFLO-like nodal planes, where paramagnetic moments appear when a magnetic field is applied perpendicular to the planes, neutron reflectivity measurements were performed for $0.07<Q<6$ nm^{-1} at BL17 (Sharaku). Firstly, measurements were performed at [10K, 0 kOe], then the sample was cooled down to 2.3 K under zero magnetic field ($|H|<0.1$ Oe) to achieve a superconducting state. Measurements were carried out in sequence as shown in Fig. 1: [2.3 K, 0 kOe]→[2.3 K, 2 kOe]→[10 K, 2 kOe]. We adopted a wider Q range compared to the previous experiments (2012B0139). The data for four different types of conditions were obtained:

- **(*N*, *H*=0)** a normal state without field,
- **(*S*, *H*=0)** a superconducting state without field,
- **(*S*, *H*≠0)** a superconducting state with a field applied, and
- **(*N*, *H*≠0)** a normal state with a field applied.

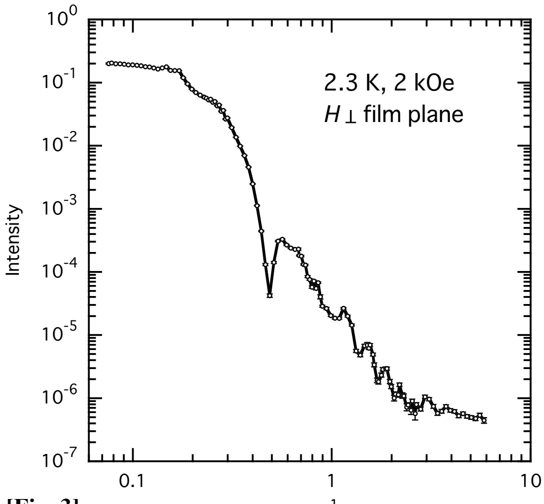


[Fig. 2]

2. 実験方法及び結果（つづき） Experimental method and results (continued)

II. Results

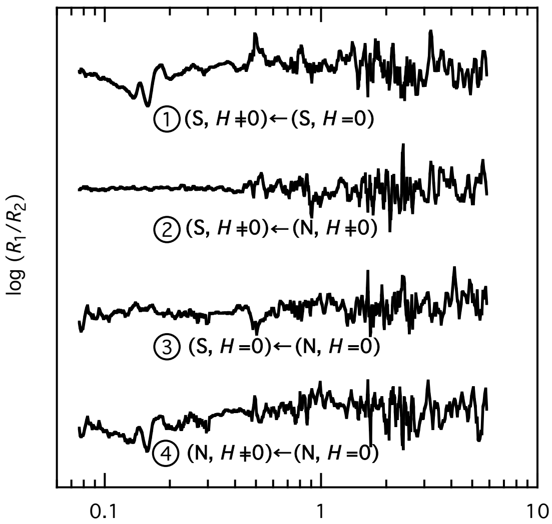
The reflectivity obtained as a function of Q almost exactly reproduced the previous results in 2012B0139. In the present experiment, we were particularly interested in the reflectivity at high Q's. To improve S/N ratio, signal was accumulated for a larger amount of counts than in the previous measurements. Typical result of the measurement is shown in Fig. 3 for **(S, $H \neq 0$)** at [2.3 K, 2 kOe]. We can see low-noise data even at high Q's.



[Fig. 3]

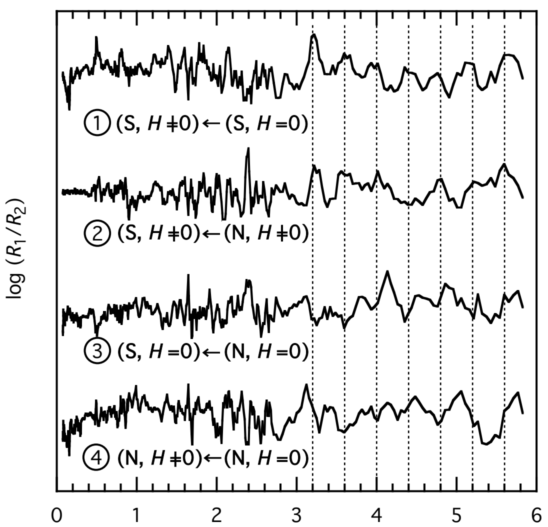
III. Discussions

In order to investigate the changes in reflectivity when measurement conditions were changed, the reflectivity ratios (R_1/R_2) were plotted on a log-scale as a function of Q in Figs. 4 and 5: [R(2.3 K, 2 kOe)/R(2.3 K, 0 kOe)], [R(2.3 K, 2 kOe)/R(10 K, 2 kOe)], [R(2.3 K, 0 kOe)/R(10 K, 0 kOe)], and [R(10 K, 2 kOe)/R(10 K, 0 kOe)] for ①**(S, $H \neq 0$)←(S, H=0)**, ② **(S, $H \neq 0$)←(N, $H \neq 0$)**, ③ **(S, H=0)←(N, H=0)**, and ④ **(N, $H \neq 0$)←(N, H=0)**, respectively. Base lines are shifted arbitrarily for clarity of comparison. The variations of log(R_1/R_2) are qualitatively the same as those obtained in the previous measurements. We see that the structure appeared for Q<0.5 nm^{-1} in ① and ④ (Fig. 4) is due to a change in magnetic scattering by applying a magnetic field. It likely originates from a change in the ferromagnetic Fe layer since in ② and ③ we have no corresponding structure.



[Fig. 4]

At high Q's in Fig. 5, regular and periodic peaks are observed particularly for ① and ② with an interval of 0.4 nm^{-1} (shown as broken lines), which corresponds to a period of 15.7 nm. Low-noise data in this experiment allows resolution of these peaks. At present, the origin of the 15.7 nm period is not clear. The thickness of the Fe layer is 12.6 nm, and we can really see a peak at 0.5 nm^{-1} that corresponds to a thickness of 12.57 nm reflecting a magnetic change in the Fe layer. For more elaborate analysis, we have to carry out reflectivity simulation based on an appropriate multilayer model including magnetic component not only in Fe but also in Au. The peak at 3.2 nm^{-1} in ① and ②, however, may prove the existence of the FFLO-like nodal planes.



[Fig. 5]

IV. Conclusion

We have successfully obtained a series of neutron reflectivity data on the Nb/Au/Fe trilayer. For more conclusive evidence of the FFLO-like nodal planes, we need elaborate simulation of reflectivity based on an appropriate model.