実験報告書様式（一般利用課題・成果公開利用）

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Experimental Report

Experimental Report	承認日 Date of Approval 2013/05/21 承認者 Approver Masavasu Takeda 提出日 Date of Report 2013/05/20
課題番号 Project No. 2012B0139 実験課題名 Title of experiment Observation 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, Low Temperature Physics Laboratory	装置責任者 Name of Instrument scientist Masayasu Takeda 装置名 Name of Instrument/(BL No.) BL17 実施日 Date of Experiment 16 March 2013 – 20 March 2013

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/Au/Fe with a cap of Au by neutron reflectometry technique. A single crystal of $Al_2O_3(11\bar{2}0)$ (15×15mm^2 ×0.5mm) 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. A schematic diagram of the sample structure is shown in Fig. 1 together with the layer thicknesses. The Nb layer shows superconductivity below T_c~8.0 K, and the Fe layer is ferromagnetic. Below ~8.0 K, the Au layer is supposed to be in a superconducting state due to a proximity effect to the Nb layer.

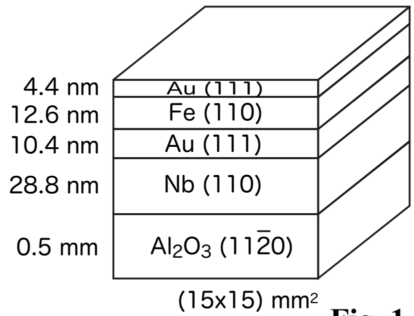


Fig. 1

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 plane (see Fig. 2), neutron reflectivity measurements were performed at BL17 (Sharaku). Firstly, the sample was cooled down to 3 K under zero magnetic field ($|H|$<0.1 Oe) to achieve a superconducting state. Measurements typically for 0.006≤Q≤0.5 Å^{-1} were carried out in sequence as shown in Fig. 3: [3 K, 0 kOe]→[3 K, 0.5 kOe]→[3 K, 2 kOe]→[10 K, 2 kOe]. Thus we obtained the data for three types of conditions:

(*S*, *H*=0) a superconducting state without field,

(*S*, *H*≠0) a superconducting state with a field applied,

(*N*, *H*≠0) a normal state with a field applied.

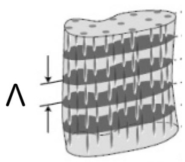


Fig. 2

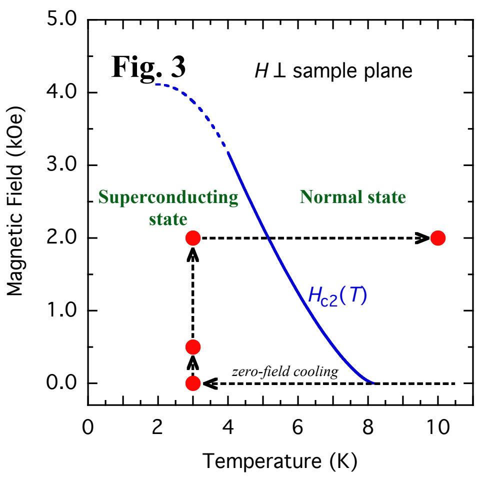
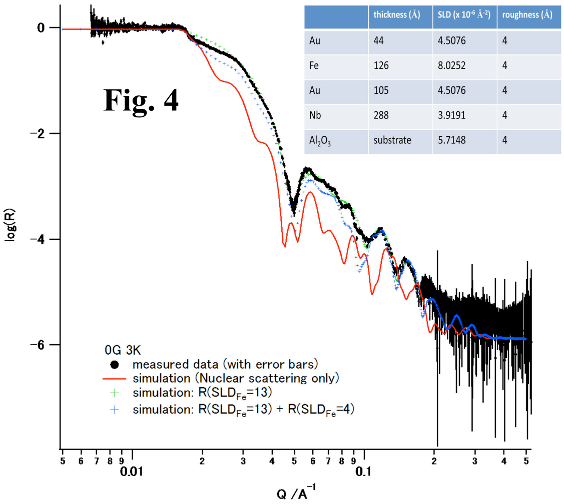


Fig. 3

II. Results

Obtained reflectivity (R) as a function of Q was, as a whole, successfully reproduced by the theoretical calculations based on a usual scattering model including the contributions from nuclear and magnetic scattering. From the fitting of a theoretical curve to the experimental data, we estimated layer thicknesses and interface roughness of the sample. Typical result of the fit is shown in Fig. 4 for the [3 K, 0 kOe] data.

In order to reduce noise of the data, we took an average of five data points: $[R(Q_{n-2})+R(Q_{n-1})+R(Q_n)+R(Q_{n+1})+R(Q_{n+2})]/5$ as a value of $R(Q_n)$, and then the ratios $R_{[\mathbf{3\ K,\ 2\ kOe}]}/R_{[\mathbf{3\ K,\ 0\ kOe}]}$, $R_{[\mathbf{10\ K,\ 2\ kOe}]}/R_{[\mathbf{3\ K,\ 0\ kOe}]}$, and $R_{[\mathbf{3\ K,\ 2\ kOe}]}/R_{[\mathbf{10\ K,\ 2\ kOe}]}$ are plotted as a function of Q in log-log scale in Fig. 5. These ratios indicate changes of reflectivity corresponding to the changes in conditions: **(S, H=0)→(S, H≠0)**, **(S, H=0)→(N, H≠0)**, and **(N, H≠0)→(S, H≠0)**, respectively.



	thickness (Å)	SLD (x 10^{-6} Å^{-2})	roughness (Å)
Au	44	4.5076	4
Fe	126	8.0252	4
Au	105	4.5076	4
Nb	288	3.9191	4
Al_2O_3	substrate	5.7148	4

Fig. 4

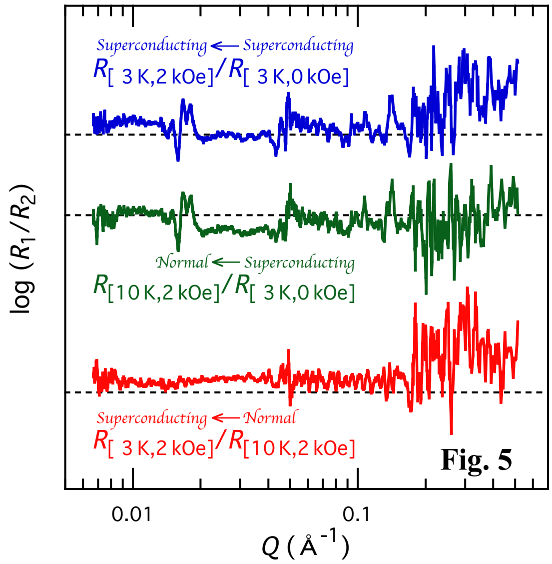


Fig. 5

III. Discussion

In Fig. 5, the data of $R_{[\mathbf{3\ K,\ 2\ kOe}]}/R_{[\mathbf{3\ K,\ 0\ kOe}]}$ and $R_{[\mathbf{10\ K,\ 2\ kOe}]}/R_{[\mathbf{3\ K,\ 0\ kOe}]}$ (i.e., for **(S, H=0)→(S, H≠0)** and **(S, H=0)→(N, H≠0)**) show that the peaks appeared in the region Q<0.2 Å^{-1} are due to a change in magnetic scattering by applying a magnetic field. These peaks, therefore, have nothing to do with the superconducting transition of the sample, rather they originate from a change in the ferromagnetic Fe layer. In fact, the variation in $R_{[\mathbf{3\ K,\ 2\ kOe}]}/R_{[\mathbf{10\ K,\ 2\ kOe}]}$ that corresponds to **(N, H≠0)→(S, H≠0)** shows no apparent peaks for Q<0.2 Å^{-1}.

Here we direct our attention to a broad peak at ~0.3 Å^{-1}. This peak can be seen for **(S, H=0)→(S, H≠0)** and **(N, H≠0)→(S, H≠0)**, and *not* for **(S, H=0)→(N, H≠0)**. This result suggests that the peak at ~0.3 Å^{-1} appears when the sample is in a superconducting state and, *simultaneously*, a field (<H_{c2}) is applied to the sample. We tried to fit the broad peak to a Gaussian function (Fig. 6). The result of fit shows $\Lambda=2\pi/Q_0$=19.7 Å and (coherence length)~30 Å. The value of the obtained Λ is close to a distance (~20 Å) of expected FFLO-like nodal planes. The fluctuation in $\log(R_1/R_2)$ seen typically in Fig. 6 has a component of periodic variation as a function of Q. Fast Fourier Transform (FFT) was carried out on the $\log(R_{[\mathbf{3\ K,\ 2\ kOe}]}/R_{[\mathbf{10\ K,\ 2\ kOe}]})$ data (see the inset of Fig. 6). Before FFT was applied, a linear-extrapolation was done to have data points with an equal interval of 0.001 Å^{-1} in Q. The peak at n=22 in power spectrum indicates a period of 0.022 Å that corresponds to λ=283 Å. This length is in good agreement with the Nb-layer thickness, suggesting the emergence of triplet-pairs at the Nb/Au interface for the transition ***N*→*S***.

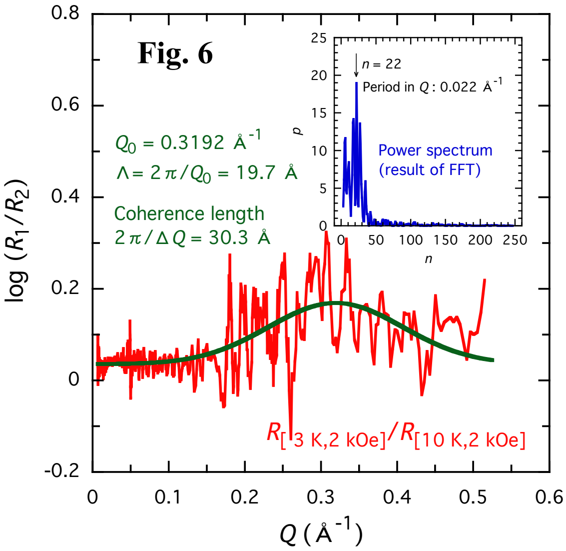


Fig. 6

IV. Conclusion

The results of neutron reflectivity measurements were explained in terms of the FFLO-like nodal planes. For more conclusive evidence, we may need more beam time in J-PARC.