MLF Experimental Report	提出日 Date of Report 2017/5/18
課題番号 Project No. 2015A0134 実験課題名 Title of experiment Error rate evaluation of MRAM with perpendicular magnetic tunnel junction under fast neutron irradiation 実験責任者名 Name of principal investigator Yuzuru NARITA 所属 Affiliation Yamagata University	装置責任者 Name of responsible person Kenichi OIKAWA 装置名 Name of Instrument/（BL No.） NOBORU (BL No. 10) 実施日 Date of Experiment 2015/11/7～2015/11/9 2016/6/18～2016/6/20

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.

In this study, we used 461 p-MTJ (magnetic tunnel junction with a perpendicular magnetic easy axis) devices equipped with a CoFeB-MgO recording structure. Each p-MTJ has a stacked profile structure from the SiO_2/Si substrate side: Ta (5)/Ru (10)/Ta (5)/Pt (5)/$[Co\ (0.34)/Pt\ (0.4)]_6$/Co (0.34)/Ru (0.44)/$[Co\ (0.34)/Pt\ (0.4)]_2$/Co (0.34)/Ta (0.3)/CoFeB/MgO/CoFeB/Ta (1)/Ru (7), where the numbers in parentheses are the nominal thicknesses in nanometers, and the subscripts indicate the number of Co/Pt multilayers. The stack is processed into circular p-MTJs using electron beam lithography and Ar ion milling, followed by annealing at 300 °C under vacuum with a perpendicular magnetic field of 0.4 T for 1 h. The junction diameter (D) of each p-MTJ was within the range of 46 to 64 nm. The p-MTJ devices having a tunnel magnetoresistance (TMR) ratio above 90% at room temperature were used.

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.

The neutron irradiation experiment was conducted using the BL10 beamline. The neutron beam irradiation area was approximately 80×80 mm^2. Low-energy neutrons were separated from the neutron beam using 5-mm-thick B_4C slits while gamma radiation was blocked using a 25-mm-thick Pb block. During irradiation, gamma radiation was monitored using an alanine dosimeter placed near the p-MTJs within the beam irradiation area. The effect of neutron irradiation was evaluated by comparing the resistance-magnetic field (R-H) curves of the p-MTJs before and after neutron irradiation.

In the 2015A0134 experiment, fast neutron irradiation of the p-MTJ devices was performed over 4 days. The beam time was utilized in two separate periods (2 days + 2 days) to measure the influence of the fast neutron irradiation. The beam powers for the first (2015/11/7 – 2015/11/9) and second (2016/6/18 – 2016/6/20) periods were 0.5 and 0.2 MW, respectively. The total fast neutron fluence (1 MeV equivalent neutrons/cm^2) at BL-10 was calculated to be 1.32×10^{12} neutrons/cm^2 in the 2015A0134 experiment. The total fluence of fast neutrons irradiated to the 461 p-MTJ devices was 3.79×10^{12} neutrons/cm^2 (proposal numbers 2014A0102, 2014B0120, and 2015A0134), which corresponded to 1.90×10^{11} h (approximately 22 million years) irradiation in fast neutron environments at ground level (20 cm^{-2}h^{-1}).

Figure 1(a) shows *R-H* curves for a p-MTJ with D = 48 nm and a TMR ratio of 108% following neutron irradiation up to 3.79×10^{12} cm^{-2}. In this figure, the dashed lines indicate the resistance values in the parallel and anti-parallel states prior to irradiation, R_P^{before} and R_{AP}^{before}, respectively. As can be seen, the resistance values and switching fields were unchanged from those prior to irradiation. Figure 1(b) shows a comparison of the TMR ratios of the 461 p-MTJs before and after irradiation of 3.79×10^{12} neutrons/cm^2. After the irradiation, the variation induced in the TMR ratios was in the range of approximately ±1%. Therefore, the properties of the CoFeB-MgO p-MTJ devices were not significantly affected by exposure to a neutron fluence of up to 3.79×10^{12} neutrons/cm^2.

We summarized the data obtained from the neutron irradiation experiments using BL-10 (proposal numbers 2014A0102, 2014B0120, and 2015A0134) and submitted an article to the *Japanese Journal of Applied Physics*.

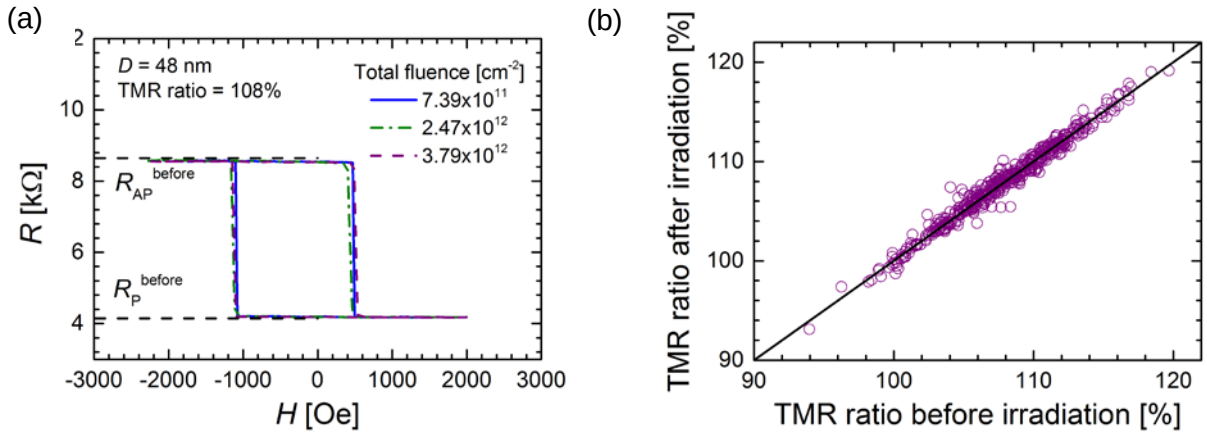

Fig. 1 (a) *R-H* curves for a p-MTJ with D = 48 nm and a TMR ratio of 108% following neutron irradiation up to 3.79×10^{12} cm^{-2}. (b) Comparison of TMR ratio before and after fast neutron irradiation of 3.79×10^{12} cm^{-2}.