MLF Experimental Report	提出日 Date of Report 2017/6/27
課題番号 Project No. 2016A0012 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 2016/11/5～2016/11/14

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 employed 24 magnetic tunnel junction devices having a perpendicular magnetic easy axis (p-MTJ), each equipped with an MgO/CoFeB/Ta/CoFeB/MgO double-interface recording structure. Each p-MTJ also had a stacked profile structure on the SiO_2/Si substrate side consisting of Ta/Ru/Ta/Pt/$[Co/Pt]_6$/Co/Ru/$[Co/Pt]_2$/Co/Ta/CoFeB/MgO/CoFeB/Ta/CoFeB/MgO/Ta/Ru, where the subscripts indicate the number of Co/Pt multilayers. These stacks were processed into circular p-MTJs using electron beam lithography and Ar ion milling, followed by annealing at 300 °C under vacuum while applying a perpendicular magnetic field of 0.4 T for 1 h. The junction diameter (*D*) of each p-MTJ was less than 20 nm, and these devices exhibited a tunnel magnetoresistance (TMR) ratio above 50% at room temperature.

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 experiments were performed using the BL-10 beamline, applying a neutron beam irradiation area of approximately 80 × 80 mm. Low-energy neutrons were separated from the neutron beam using 5-mm-thick B_4C slits while gamma radiation was blocked by a 25-mm-thick Pb block. The effects of neutron irradiation were evaluated by comparing the resistance-magnetic field (*R*-*H*) curves of the p-MTJs before and after neutron irradiation.

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

In the 2016A0012 experiment, fast neutron irradiation of the p-MTJ devices was performed over nine days. Since the beam power was 0.15 MW, the fast neutron fluence (1 MeV equivalent neutrons/cm^2) generated by the BL-10 beamline was calculated to be 1.89×10^{12} cm^{-2}. Since the fast neutron irradiation to the 24 p-MTJ devices was conducted in the 2014B0120 and 2015A0134 experiments before this experiment, the total fast neutron fluence irradiated to the 24 p-MTJ devices was 5.21×10^{12} cm^{-2}, corresponding to exposure to a fast neutron environment at ground level at 20 $cm^{-2}h^{-1}$ over a time span of 2.60×10^{11} h (approximately 30 million years).

Figure 1(a) shows *R-H* curves obtained from a p-MTJ with D = 19 nm and a TMR ratio of 100% before and after a neutron irradiation up to 3.05×10^{12} cm^{-2}. As can be seen, the resistance value and switching field were unchanged from those prior to irradiation. Figure 1(b) plots the changes in the TMR ratios of 24 p-MTJs as a function of D following the same neutron irradiation. After irradiation, the variation induced in the TMR ratios was in the range of approximately ±3%. These data demonstrate that the properties of p-MTJ devices having an MgO/CoFeB/Ta/CoFeB/MgO double-interface recording structure and a D value below 20 nm were not significantly affected by exposure to a neutron fluence of up to 3.05×10^{12} cm^{-2}. In our previous study (Y. Narita *et al.*, JJAP **56**, 0802B3 (2017)), we demonstrated that the performance of CoFeB-MgO p-MTJs having a single-interface recording structure and D values between 44 and 64 nm was not degraded following irradiation with fast neutrons at a fluence up to 3.79×10^{12} cm^{-2}. These results together with our present data show that p-MTJ devices are unaffected by fast neutron irradiation at such levels, regardless of the junction size.

At present, our group is acquiring and analyzing the *R-H* curves of 24 p-MTJs following neutron irradiation up to 5.21×10^{12} cm^{-2} and the resulting data will be submitted for publication in a future paper.

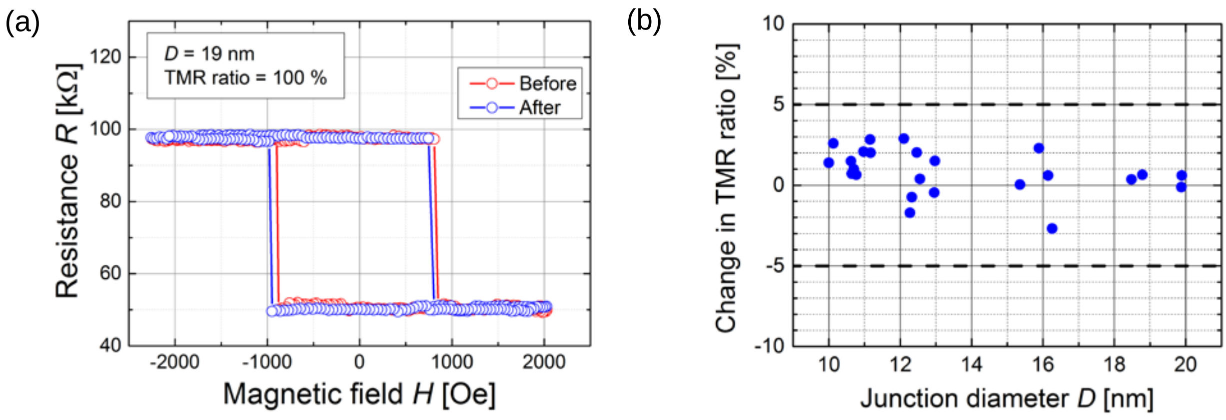

Fig. 1 (a) *R-H* curves for a p-MTJ with D = 19 nm and a TMR ratio of 100% before and after neutron irradiation of 3.05×10^{12} cm^{-2}. (b) Changes in the TMR ratios of 24 p-MTJs versus D following fast neutron irradiation at a fluence of 3.05×10^{12} cm^{-2}.