実験報告書様式（一般利用課題・成果公開利用）

MLF Experimental Report

提出日 Date of Report
2014/8/19

課題番号 Project No.
2014A0102

装置責任者 Name of responsible person
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実験課題名 Title of experiment
Error rate evaluation of MRAM with perpendicular magnetic tunnel junction under fast neutron irradiation

装置名 Name of Instrument/（BL No.）
NOBORU (BL No. 10)

実験責任者名 Name of principal investigator
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実施日 Date of Experiment
2014/6/14〜2014/6/15

所属 Affiliation
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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, 1170 magnetic tunnel junctions (MTJs) with perpendicular magnetic easy-axis (p-MTJ) devices that were equipped with an MgO/CoFeB/Ta/CoFeB/MgO double-interface recording structure formed on a 40 × 40 mm area (3-inch) SiO_2/Si wafer (Fig. 1) were fabricated at Tohoku University. Each p-MTJ has a stacked profile structure from the SiO_2/Si substrate side: Ta (5)/Ru (10)/Ta (5)/Pt (5)/[Co (0.4)/Pt (0.4)]$_6$/Co (0.4)/Ru (0.4)/[Co (0.4)/Pt (0.4)]$_2$/Co (0.4)/Ta (0.3)/CoFeB (1.0)/MgO (1)/CoFeB (1.6)/Ta (0.4)/CoFeB (1.0)/MgO (1)/Ta (5)/Ru (5), where the numbers in parentheses are the nominal thickness in nanometers, and the subscripts indicate the number of Co/Pt multilayers. The stack is processed into circular D = 40 nm MTJs using electron beam lithography and Ar ion milling, and then annealed at 300 °C under vacuum conditions and in a perpendicular magnetic field of 0.4 T for 1 h. Post-fabrication, devices with tunnel magneto-resistance (TMR) ratios above 70% were defined as good devices. The yield ratio of such devices is about 37.6% (= 440 MTJs / 1170 MTJs), as shown in Fig. 3.

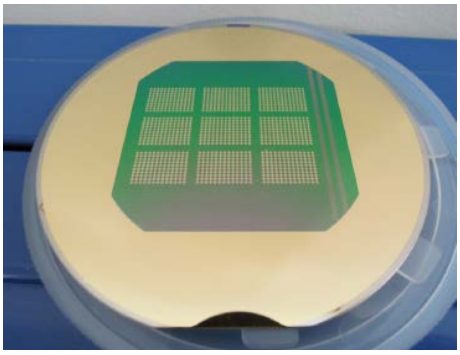
Fig. 1: p-MTJ device photograph

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 cut from the neutron beam using two 5 mm-thick B4C slits while gamma radiation was blocked using a 25 mm-thick Pb block. During irradiation, gamma radiation was monitored using an alanine dosimeter set near the p-MTJs within the beam irradiation area.

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

Figure 2 shows the experimental setup used in this study. The p-MTJs shown in Fig. 1 were irradiated with neutrons for 1400 min. The total neutron flux (1 MeV equivalent neutrons/cm^2) was estimated to be 4.1×10^{11} neutrons/cm^2, which corresponds to 2.05×10^{10} h irradiation with atmospheric fast neutrons (20 neutrons/h/cm^2) and the number of neutrons irradiated at one junction was approximately 5.15. The absorbed dose of gamma radiation was 19 Gy, as measured by alanine dosimeter.

Fig. 2 Experimental setup at the BL-10.

The TMR ratio of each p-MTJ was determined from resistance-magnetic field (*R-H*) measurements. The hard error rate is estimated from the differences in TMR ratios measured before and after neutron irradiation. After neutron irradiations of 4.1×10^{11} neutrons/cm^2 to a wafer, we conducted *R-H* measurements for 440 p-MTJ devices with TMR ratios above 70%. Figure 3 shows the TMR ratio result for each p-MTJ. In this figure, the black boxes indicate MTJ devices with TMR ratios less than 70% (and thus broken) before neutron irradiation. The white boxes indicate MTJ device with TMR ratios above 70% before the neutron irradiation, and the red box indicates an MTJ device with a TMR ratio above 70% before neutron irradiation that was discovered to be broken after the neutron irradiation experiment.

Of the 440 devices irradiated, we found one broken p-MTJ device, which was believed to be caused by the neutron irradiation. However, there was little TMR ratio change observed in the other 439 devices (within ~4%). Therefore, the hard error rate was calculated as (1 device $\times$ 10^9 h)/(440 devices $\times$ 2.05×10^{10} h) = 0.0001 FIT, where the unit adopted to quantify failures in time is the FIT, which is equivalent to one hard error per 10 trillion hours under atmospheric fast neutron irradiation. Hence, in order to investigate the damage at the MTJ interface, structural characterization of the interfaces in the broken p-MTJs will be conducted using high-resolution cross-sectional transmission electron microscopy (TEM). To obtain more reliable error rate results, we will continue this experiment in the 2014B proposal round.

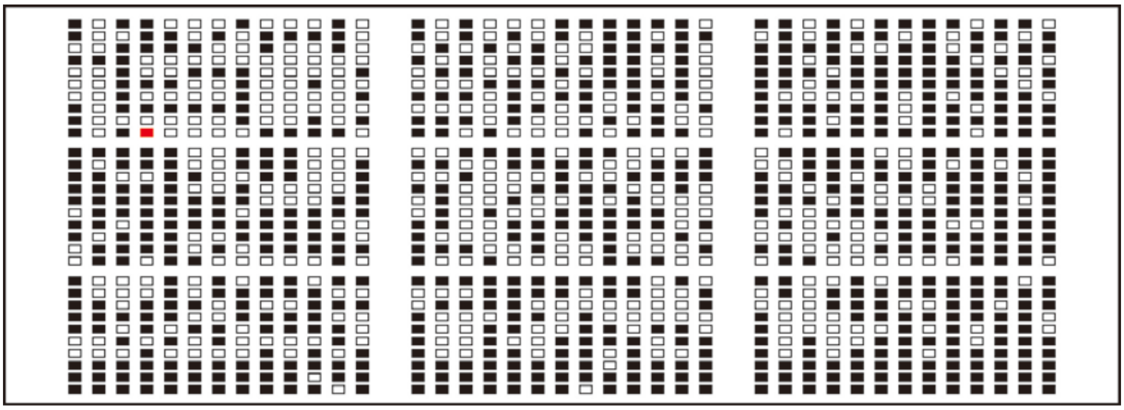

Fig. 3: TMR ratio results for all p-MTJ devices measured by *R-H* measurement.