Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp440-441

Progress of STT-MRAM Technology and its application to low-power memory systems
A key Technology and Prospect of Normally-off memory systems

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Abstract

Intensive works on STT-writing technology with P-MTJ reduced the electric charge necessary to write data to below 100fC/bit and led to a 70-80% reduction in power consumption in normally-off memory systems.

1. Introduction

An ideal memory, a fast and dense nonvolatile memory with unlimited endurance, does not exist. Consequently, all of memory systems use a combination of fast volatile working memories and dense non-volatile storages as shown in Fig.1(a) and (b).

However, those volatile working memories consume a lot of power. L2, L3, and L4 cache memories become common more and more in these days and their power consumption and their performances become critical issues.

Ultra-low power systems, called normally-off systems, were proposed which used relatively fast nonvolatile MRAM as working memories [1]. Spin-transfer-torque writing (STT)-MRAM with perpendicular anisotropy MTJ (simply expressed as P-MTJ) has successfully reduced the write current and made the normally-off systems realistic [2], [3], [4], [5], [6].

In this study, the progress of P-MTJ in terms of write current and electric charge is reviewed and the effect on the normally-off systems and its prospect are discussed.

2. Normally-off memory systems

Fig.1 (a) shows the functionality of logics and memory devices in conventional memory systems. The memory system does not always need to work with their full capability. There exist appreciable intervals called stand-by mode between active-modes. In the stand-by mode, electricity for the core part in Fig.(b), can be turned off to save power consumption. This is called power gating.

However, the conventional systems waste a lot of energy even during the stand-by modes, because lower levels of SRAMs (L2,L3,L4) leak current and in the case of main memory, DRAM refreshes all the time in order just to keep data.

By using nonvolatile working memories, those wasting power can be saved. However, it should be noticed that the writing charge in MRAM cells is much larger than that in SRAM ones. For example, the charge for state- of-the-art MRAM cells is estimated 100fC/bit and that for typical SRAM cells is about 0.1fC/bit. Therefore, simple replacement of volatile devices in the core by MTJs result in an increase in power consumption.

Therefore, a proposed normally-off system has non-volatile STT-MRAMs with P-MTJ at lower levels of cache memories and at a main memory level as shown in Fig1(c), while in the core part, volatile devices remain to be used[4].

2. Reduction in required STT-writing charge by P-MTJs

Writing power consumption is proportional to Iw * tw * Vdd where Iw, tw, and Vdd are writing current, wrting pulse-width, and drain voltage. Iw is about 1.5 * Ic to attain acceptable error-rate of 10^{-11},where Ic is switching current at the writing-pulse width. Therefore, with given Vdd in order to save the power consumption, a product of Ic and tw ,i.e. electric charge necessary for writing should be minimized.

Fig. 2 shows the switching current density reduction trend. P-MTJ successfully reduced the current density to below 1MA/cm^2 with 5msec. pulse-width[4].

However, there exists a intrinsical trade-off relationship between Ic and tw.

Recently, switching voltage and Ic at short pulse-width have been improved as shown in Fig.3. The switching voltage becomes as small as 0.3-0.45V for new P-MTJ-2 which is far below the break-down voltage of 1.2-1.4V [7].

As a result, necessary writing-charge was reduced to almost 1/10 as shown in Fig.4. Most of the previous demonstrations shown as circles sit in the energy wasting region. Only the recent two demonstrations shown as stars sit in energy saving region.

4. The effect on lowering power consumption in memory systems

Performance and power consumption of the normally-off system with the P-MTJs were evaluated by a processor emulator for ARM-core based CPU on Linux OS while running MPEG and video game.

The reduction in power consumption was confirmed to be 70-80% without any performance degradation[8].

5. A possible future evolution of MRAM

Even though the trade-off relationship between Ic and tw was eased as seen in Fig.3, it is still there.

There appears a new writing scheme which may break this trade-off relationship. It is voltage writing or voltage assisted writing[9],[10],[11].

5.Conclusion

Intensive works on P-MTJs overcame the major obstacle of large write current. As a result, normally-off systems were confirmed to save power consumption by 70-80%.

Since the writing current is still under improvement and recently potential disruptive technology of voltage writing is under development, the normally-off systems is thought to becme realistic more and more.

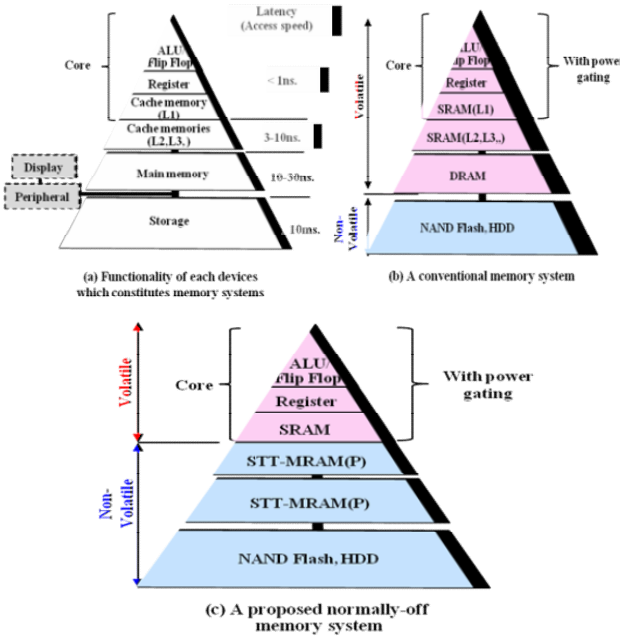

Fig. 1 Conventional memory systems and proposal of normally-off memory systems

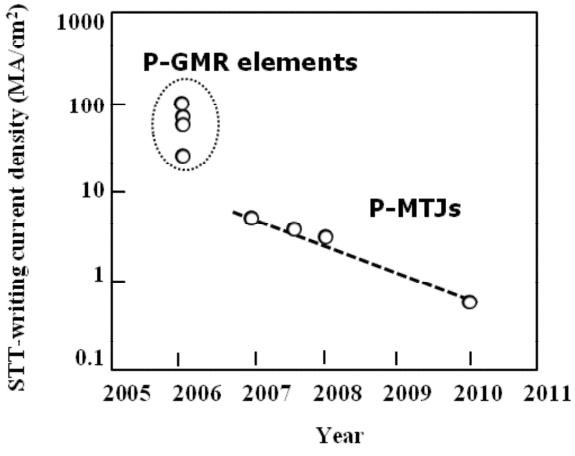

Fig. 2 STT-writing current density reduction trend[4]

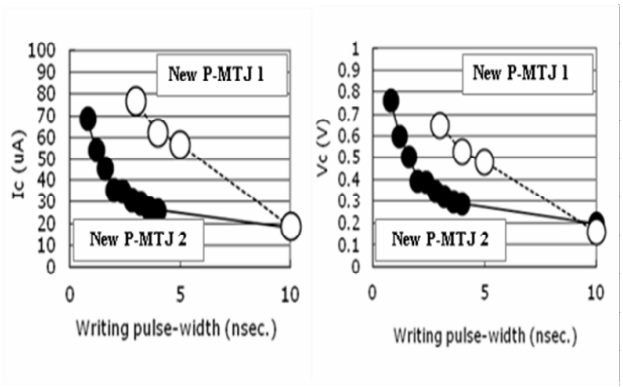

Fig.3 STT-writing pulse-width vs switching current (Ic) and switching voltage(Vc) of new P-MTJs

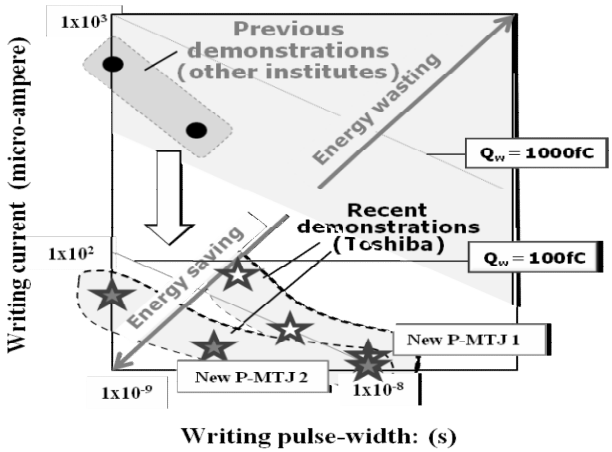

Fig.4 The effect of the writing energy reduction of P-MTJs

Acknowledgements

This study was partly supported by NEDO. We thank all the members of Spin-RAM working group of NEDO Spintronics Nonvolatile Devices project and of NEDO normally-off computing project.

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