Development of a Non-volatile Logic Technology Aiming at Electronic Equipment without the Need for Standby Power

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Abstract

NEC is attempting to develop electronic equipment featuring both convenience and without standby power consumption by means of non-volatile logic technology using spintronic devices. NEC also expects that applying this technology in the wireless sensor terminals used for example in energy management systems will extend the battery replacement intervals significantly and thereby render the systems virtually maintenance-free.

Keywords

spintronics, non-volatile, energy saving, logic IC, energy management system

1. Introduction

Expectations for the energy saving technology have been raised more than ever as a means for realizing a sustainable society by protecting the global environment as well as offering countermeasures to offset the electricity shortages that have been prevalent since the 2011 Great East Japan Earthquake. Such trends require that the standby power of electronic equipment can be reduced to near zero because it is essentially an unwanted factor. The standby power of electronic equipment can be eliminated by the user unplugging the power cord, but this would compromise the convenience of the equipment. NEC is attempting to achieve both the elimination of electronic equipment standby power and a high level of convenience by applying the non-volatile logic technology described below.

One of the assumed applications of this technology is in the terminal equipment of the energy management system (EMS). As discussed elsewhere in this special issue, NEC offers EMS using a variety of terminal equipment. A reduction of the power consumption of the terminal equipment is not only necessary for enabling the energy saving effect brought about by the introduction of EMS, but it also has significance otherwise. The first priority for the sensor terminals is to install them in the locations in which they can sense the physical quantities (including temperature and consumed wattage) required by the EMS. For this purpose, some EMSs improve the freedom of installation layout by using battery-driven sensor terminals that transmit sensor data via wireless communications. If the standby power of the electronic equipment is reduced to zero, it should be possible to extend the battery replacement intervals of such sensor terminals. Moreover, if the battery replacement interval can be extended to more than ten years, some systems may become virtually free of the need for battery replacement (i.e. to be maintenance free). If it is not required to consider battery replacement work in the layout of the sensor terminals, it should then become possible to implement more advanced and diversified EMSs.

In section 2 below, we will discuss how the non-volatile logic technology can offer both system convenience and power reduction. On the other hand, the element technology that is at the core of the non-volatile logic technology is that of spintronics. Section 3 will describe the operating principles of this technology that makes use of a previously unexploited property of electrons, which is the property of fine magnetic elements. Section 4 will report on the results that we have achieved so far in the development of non-volatile logic technology.

2. The Effects of the Non–volatile Logic Technology

Fig. 1 shows an example of the configuration of electronic equipment. While the user may think that the power supply is off, most electronic equipment still consumes standby power in order to hold the computations underway in the logic IC. If pending computations are saved in a storage that does not lose memory, even after the power supply is shut down, such as a flash memory or hard disk, the time taken for recalling the saved data increases the time after power on until the equipment can actually be used, thereby degrading the

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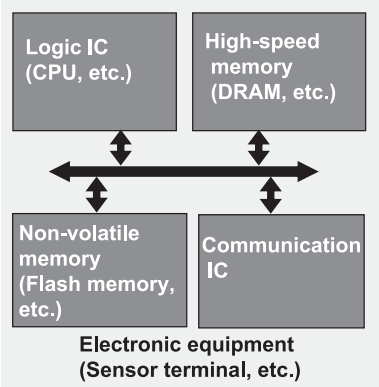

Fig. 1 Example of the electronic equipment configuration.

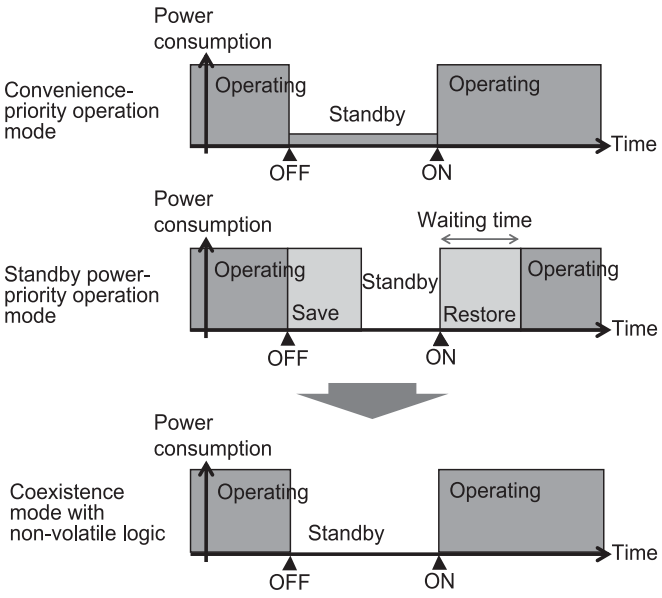

Fig. 2 Coexistence of convenience and power saving provided by non-volatile logic technology.

convenience. The current situation is a trade-off between the convenience and standby power reduction functions as shown in **Fig. 2** . However, the pending computations required for the convenience remain in both the high-speed memory and the logic IC. If these can be made capable of retaining the latter status even after the power supply is shut down (i.e. if they can be made non-volatile), the waiting time after turning the power on becomes unnecessary. This applies even when the standby power is eliminated by completely shutting down the power supply in the standby mode and the degradation of convenience after power recovery can be avoided.

Since a non-volatile logic IC does not need saving or recalling of data, the equipment can be turned on-off in the short time of less than 1/100th of the period of a single movie frame. A property that is set based on the limit of human vision (approx. 0.04 sec.). This makes it possible to implement equipment that can turn itself on-off frequently upon its own judgment without being noticed by the user and therefore power consumption may be saved significantly. For example, when the user types “ABC” on the keyboard, the electronic equipment can save power by turning the power supply to the unnecessary circuitry even in the short period between the typing of “A” and “B.” A similar power saving effect can also be obtained with the sensor terminals of EMSs because the temperature and brightness functions that they control change much more slowly than the operation of the non-volatile circuit, at a level equivalent to that of human motion.

In the above, we described the advantages of the implementation of a non-volatile logic IC assuming that optimum operations are performed. Nevertheless, the software of the currently available electronic equipment is designed assuming that the operations underway in the logic IC are lost when the power supply is shut off. This means that, in order to bring non-volatile logic technology to perfection, it is not required merely to develop a device or IC technology, but a comprehensive technological development comprising software designed to control the algorithms is necessary.

3. Spintronics

We will now consider the device technology of the non-volatile logic IC. **Fig. 3** summarizes the concept of spintronics. An electron has two properties, that of a negative charge and as a fine magnet. Since the early development of electronic equipment, electronics has not been positive in utilizing its property as a fine magnet (called the spin). However, following significant progress in magnetic material technology in recent years, spintronics has been advancing by aiming at the

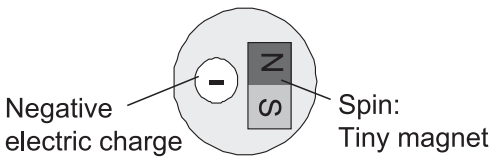

Fig. 3 Two properties of an electron.

positive utilization of the spin property. In the development of spintronics devices and IC technologies, NEC is engaged in leading-edge R&D by participating in the national project "The Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST)" of the Cabinet Office (Subject name: "Research and Development of Ultra-low Power Spintronics-Based VLSIs", Principal investigator: Prof. Hideo Ohno, Tohoku University).

One of the most attractive features of the spintronic device is that its rewrite count is not limited in spite of it being a non-volatile device that retains previous status even after the power supply is shut off. With the non-volatile storage elements used in logic ICs previously, such as in the flash memory, the rewrite count has been limited to around 100,000 times because the element is damaged by the high internal voltage. This limit does not pose a problem as far as the element is being used in the memory card of a digital camera because the user would not release the shutter for 100,000 times. However, it is not enough to control the rewrite count of elements used to switch the logic IC located in electronic equipment to the non-volatile status. Because the spintronic element holds the memory based on the orientation of fine magnets and is rewritable with low current under low voltage, it is not damaged and therefore the rewrite count is without limit.

NEC is developing a vertical domain wall element as a spintronic element for use in the domain of non-volatile logic technology that features vertical magnetization with respect to the magnetic body as shown in **Fig. 4** . As the magnetization on the two extremities of the magnetic body called "the free layer" is fixed in opposite directions by the magnetic body called "the pinning layer," an area where the magnetization orientation changes suddenly is produced around the center of the free layer. This area is called the domain wall. Data "1" or "0" is stored depending whether the domain wall is located on the left or right in the area in which magnetization is not fixed. The data can be rewritten by the current.

When a current flows between two extremities of the magnetic body, an electron stream is produced in the direction opposite to the current. As the electron spin trend is in the same direction, the area in the magnetization direction on the side of the free layer to which the electrons flow increases. This phenomenon appears to indicate that the domain wall is displaced by the pressure of the electron stream. The technology for producing this "domain wall motion" makes use of the interaction between the magnet-like properties of individual electrons and the current that flows, because electrons have negative charges as shown in **Fig. 5** . It is a typical spintronics-based technology.

Data of "1" or "0" of the vertical domain wall element is converted into a resistance value in the logic IC before being read out. The element used for the readout is also based on the spintronic technology called the magnetic tunnel junction (MTJ).

The non-volatile logic IC is implemented by fabricating spintronic elements on a general IC. This is equivalent to incorporating an element with a non-volatile storage function in the logic IC. The previous mainstream procedure in logic IC design was to separate it from the memory because this was believed to improve the cost efficiency of information processing. Today, however, it is thought that the integrated fabrication of non-volatile logic ICs with memory not only has the potential of changing the mainstream of the information processing mechanism, but by crossing the current limits of IC

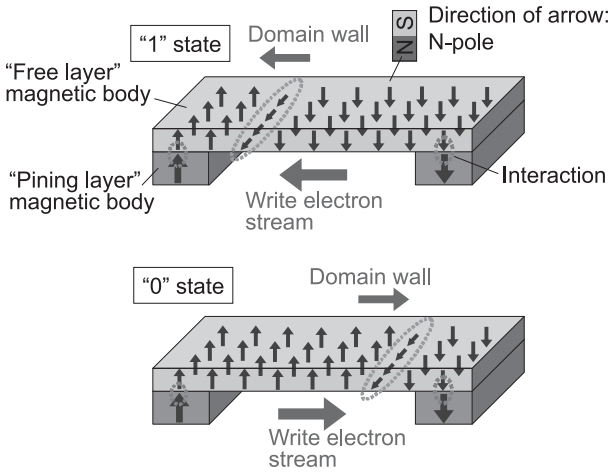

Fig. 4 Domain wall motion of vertical domain wall element.

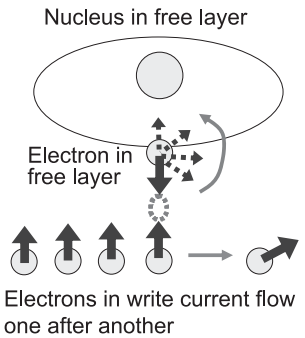

Fig. 5 Magnetization reversal by spin interaction.

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technology it represents a paradigm shift in the developing architecture of electronic equipment.

4. Non–volatile Logic IC Technology

Under the framework of the funding program, we have developed and demonstrated an innovative content addressable memory (CAM) processor for use in the CPU for the first time in the world. It features both high-speed operation, equivalent to existing ICs, and non-volatile memory operation that holds data in the IC even when the power supply is shut off during processing. Employing the vertical domain wall element described above that we have long been developing this technology makes it possible to hold the data being processed in the CAM processor. This is the circuit used for referencing temporarily saved data of the same status, without saving the data to a memory when the power supply to the CAM is shut off. **Photo** shows the CAM processor applying the vertical domain wall element.

We selected the CAM processor as the tool for demonstrating the operation of non-volatile logic technology because the CAM combines logic and memory circuits and in demonstrating its operations we open up the perspective for implementing an entirely non-volatile CPU.

The newly developed CAM processor features the capability of data search at an equivalently high speed to the previous processors. To transform a CAM processor into a non-volatile device without losing its high speed, we connected two spintronic elements each with an opposite spin direction in each cell of the chip. Other spintronic elements are not capable of direct connection between two elements due to the circuit structure and therefore to batch write data in them is difficult. On the other hand the newly developed vertical domain wall elements use separate paths for the write and read currents, thereby making it possible to connect two elements in series and to write data in them simultaneously.

This structure makes it possible to omit one of the two write switches that had to be provided per element. As a result, the cell can be implemented in a more compact size, while achieving a fast 5-ns search cycle time equivalent to the previous CAM processors composed only of CMOS transistors at the same time as offering low power consumption.

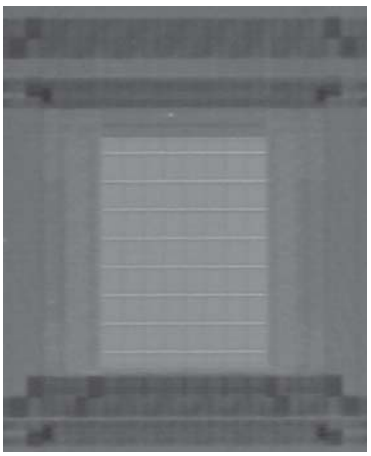

Photo Content addressable memory processor applying 140 nm wide vertical domain wall elements.

5. Conclusion

Development of a non-volatile logic technology in order to entirely transform an electronic device is being advanced as described above. In the future, under the collaboration with Tohoku University, we will set targets to bring the element and circuit technologies to perfection. Meanwhile, we have also started work on the development of suitable control algorithms and software for use with entirely non-volatile electronic equipment. The results of the upcoming development will be published sequentially.

Non-volatile logic technology can provide electronic equipment for use directly by users that features the coexistence of energy saving and convenience. On the other hand, with the EMS mounted, it can be free of restrictions related to battery replacement, optimize the installation layout of the sensor terminals and improve their performance. We are developing non-volatile logic technology that can contribute to energy saving in the field of information communications by targeting completion of development and provision of marketable products by the year 2015.

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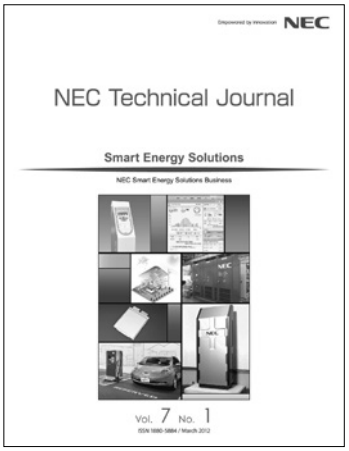

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