# Creating non-volatile electronics by spintronics technology

## — Toward developing ultimate green IT devices —

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**[Translation from *Synthesiology*, Vol.2, No.3, p.211-222 (2009)]**

We have been promoting *Full Research* to develop ultimate green IT devices based on non-volatile electronics. A core technology of non-volatile electronics is a non-volatile memory possessing features such as large capacity, high-speed operation, and high endurance. To develop such an ultimate non-volatile memory, we developed a novel high-performance magnetic tunnel junction device based on magnesium oxide (MgO) and its mass-manufacturing technology. These technologies have already been commercialized for the production of the magnetic heads of ultra-high density hard disk drives (HDD). Now we are also performing intensive R & D activities for developing the ultimate non-volatile memory called Spin-RAM.

*Keywords* : Spintronics, magnetoresistance, hard disk drive (HDD), MRAM, Spin-RAM, non-volatile electronics, green IT

## 1 Introduction

### *1.1 The need for non-volatile electronics*

Current electronic memory devices are built around a core of silicon LSI technology and are basically “volatile,” which means that recorded data is erased when the power supply is cut off. That happens because the DRAM[Term 1] general-purpose high-capacity memory and SRAM[Term 2] high-speed memory used by computers and IT home electronics use volatile recording techniques, and the logic unit in the CPUs and other such electronic devices are also all volatile (Fig. 1). Generally, electronic equipment has very long input “standby time.” When creating documents with personal computers, for example, the computer is idle for most of the time from one key input to the next key input, and is not doing any work at all. Even during such “standby” times, however, the power to the electronic equipment remains on and power is consumed. The volatility of electronic equipment means that the power cannot be turned off. If the electronic devices that constitute computers and IT appliances could be made “non-volatile” (i.e., memory is retained even when power is disconnected), then basic designs in which the power could be turned on or off instantly, as needed, (“quick-on”) or in which the basic state is “normally off” and the power is turned on only when computation is being performed would be possible (Fig. 1). “Normally off”, in particular, is a new concept that is completely the opposite of the current electronics concept of power on as the basic state and holds out the promise of ultimate green IT equipment that consumes almost no power.

To realize this dream of normally-off electronic equipment requires development of non-volatile electronics technology for the main memory (DRAM and SRAM) and for the logic unit of computers. As the first stage of research and development aiming at normally-off electronics, AIST is doing R & D to achieve the first of those two requirements, a large-capacity, high-speed and highly-reliable non-volatile computer memory. Here, high reliability mainly refers to rewrite durability. To replace the DRAM and SRAM that serve as the main memory of computers, it is necessary to attain the practically limitless write endurance of $10^{15}$ rewrite cycles without failure. Incidentally, the write endurance of the flash memory used in current external storage devices is only $10^4$ to $10^6$ rewrite cycles, and so is not usable as main memory. The ferro-electric memory devices (FeRAM), typical non-volatile memory devices that are already on the market, have a write endurance of $10^8$ rewrite cycles, still inadequate to serve as computer main memory. The phase change memory (called PRAM or PCRAM) devices currently under development as non-volatile memory also have limited rewrite times. Spintronics technology (explained below), on the other hand, enables the development of non-volatile memory that has unlimited rewrite times.

The main non-volatile, large-capacity external storage device currently in use is the hard disk drive (HDD) (Fig. 1). In the future, SSD[Term 3] based on flash memory is expected to replace the HDD in small-capacity and high-end applications, but the HDD is expected to remain the primary device for large capacity and low cost storage applications that have a large market for some time into the future. However, high power

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Original manuscript received May 11, 2009, Revisions received June 30, 2009, Accepted July 1, 2009

consumption is a problem with the HDD. Reduction of the size (diameter) of the recording medium disk called “platter” is generally an important factor in reduction of HDD power consumption, and the key to that is higher recording density. At this time, HDDs that have platters that are 3.5-inches in diameter are mainstream, but those drives consume a great deal of power (typically 5 W per unit). The smaller 2.5-inch drives, on the other hand, consume only about one-fifth the power required by a 3.5-inch drive. If the current 3.5-inch HDDs can be replaced by 2.5 inch drives that have a higher recording density, the overall power consumption of HDDs could be greatly reduced. AIST is also doing R & D aimed at increasing the recording density of HDDs.

### *1.2 Spintronics technology for non-volatile electronics*

Spintronics is a new field in which new functions are created by using both the electrical (charge) and magnetic (spin) properties of electrons (Fig. 2). Silicon-based electronic devices that use only electron charge are the foundation of information technology, but they are inadequate for implementing non-volatile memory. Magnetics, which uses only electron spin on the other hand, is good for non-volatile memory, but does not perform well in terms of logic operations or power consumption. For future technology, spintronics opens up the possibility of realizing non-volatility together with features such as high reliability, low power consumption and logic operations at the same time. Non-volatile memory that offers large capacity, high-speed and high reliability together will be the core technology for non-volatile electronics for the ultimate normally-off computers.

Spintronics uses quantum mechanical phenomena to correlate electron charge and spin. Of those phenomena, the most important is magnetoresistance. Magnetoresistance (MR) is the change in the electrical resistance of a solid or a solid-state device when a magnetic field is applied to it. The relative rate of change in electrical resistance is referred to as the magnetoresistance ratio (MR ratio). The magnetoresistance effect can be used to convert a magnetic field signal into an electrical signal, so it can be applied to sensing magnetic fields in the design of magnetic read heads for hard disk drives (HDDs). Furthermore, magnetic hysteresis characteristics of ferromagnets can be used to implement the same kind of non-volatile memory as is possible with magnetic recording.

For devices that use the magnetoresistance effect, the MR ratio at room temperature and low magnetic fields (below a few milli-tesla) serves as an index of performance, because the magnetic fields that can be generated in ordinary electronic circuits are small, several milli-tesla at most. Larger MR ratios at room temperature and low magnetic field mean that devices of higher performance can be developed. This important metric of practical application had values of only from 1 to 2 %, which was never considered as having potential for practical use. Then, A. Fert *et al.* and P. Grünberg *et al.* discovered the giant magnetoresistance effect (GMR effect) of metallic magnetic multi-layers in 1988, achieving an MR ratio at room temperature and low magnetic field of about 10 %, an order of magnitude higher than any previous value. That discovery earned Fert and Grünberg the 2007 Nobel Prize in Physics. About ten years after its discovery, GMR was applied to the magnetic read head of hard disk drives (GMR head), after which the capacity of HDDs increased rapidly (Fig. 3). Furthermore, the discovery of the GMR effect stimulated vigorous research and development on magnetoresistance around the world. It was also linked to achievement of the TMR effect (explained below) at room temperature (Fig. 3). We do not cover GMR here; for more information on that subject, see the formal paper for the 2007 Nobel Prize in Physics[1]. The TMR effect is described in more detail in the next section.

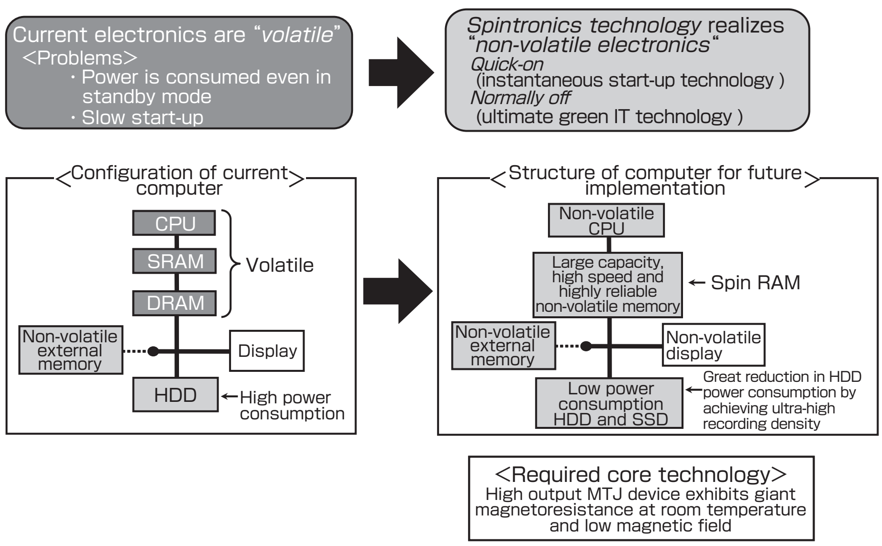


**Fig. 1 Current electronics and future non-volatile electronics.**

### *1.3 Room temperature TMR effect and its applications*

A magnetic tunnel junction (MTJ) device consists of an insulation layer that is no thicker than a few nanometers (tunnel barrier) sandwiched between two ferromagnetic metal layers (ferro-magnetic electrodes) (Fig. 4). Insulators do not normally carry current, but when the insulation is less than a few nanometers thick, minute currents flow due to quantum effects, a phenomenon called the "tunneling effect." The current and electrical resistance generated by this effect are referred to as the tunnel current and the tunnel resistance. If the electrode layers are ferro-magnetic, the tunnel resistance is small in the parallel magnetization state (P state: Fig. 4(a)) and a larger current flows. In the anti-parallel magnetization state (AP state: Fig. 4(b)), on the other hand, the tunnel resistance is large and the tunneling current is small. That phenomenon is called the tunnel magnetoresistance (TMR) effect. MTJ devices can be switched between the P state and the AP state by application of a magnetic field (Fig. 4(d)), creating magnetoresistance. Also, because ferromagnets possess a magnetic hysteresis characteristic, they are bistable at zero magnetic field, having a P state or an AP state. An MTJ device can thus act as a non-volatile memory to store one bit of information.

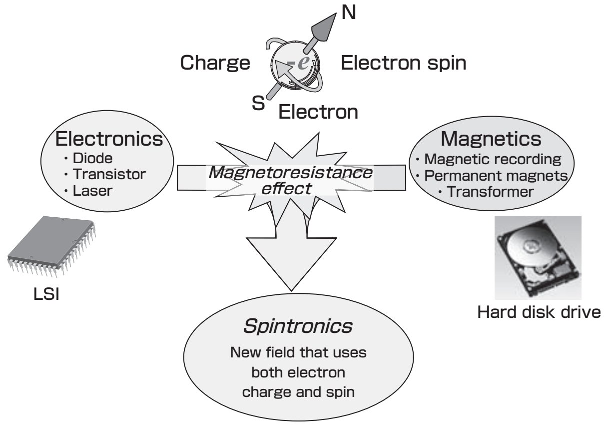


**Fig. 2 Spintronics and magnetoresistance effect.**

The low-temperature TMR effect has been known since the 1970s, but room-temperature magnetoresistance had not been obtained and there was little interest in the phenomenon in the following ten years. With the discovery of GMR in 1988, however, came much R & D on magnetic sensors (HDD magnetic heads, etc.) and TMR also began to attract interest again. In 1995, Miyazaki *et al.*[2] and J. Moodera *et al.*[3] used amorphous (random arrangement of atoms) aluminum oxide (Al-O) for the tunnel barrier and polycrystalline transition metals such as Fe or Co for the ferromagnetic electrodes to fabricate MTJ devices that had MR ratios of close to 20 % at room temperature and low magnetic field (Fig. 3). That was the highest room temperature MR ratio at the time, and the achievement thrust the TMR effect into the limelight. Subsequently, there was vigorous work on optimizing the method for making the Al-O tunnel barrier and the electrode material, resulting in achievement of room temperature MR ratios of over 70 % for the TMR effect.

The room temperature TMR effect was put to practical use in an HDD magnetic read head (TMR head) in 2004, about ten years after it had been implemented (Fig. 5). Combining that TMR head with a perpendicular magnetic recording medium achieved a high recording density of 100 Gbit/inch$^2$. Furthermore, a relatively low capacity (4 Mbit to 16 Mbit) non-volatile MRAM (Fig. 6) product based on the MTJ device was commercialized in 2006. That product drew attention as a unique non-volatile memory that featured high reliability (unlimited write endurance). The reason for the unlimited write endurance of the MRAM is that reversal of the spin direction (the rewrite operation) causes no degradation of the material at all. In addition, MRAM operation is faster than DRAM and nearly as fast as the high-speed SRAM used in the CPU. However, there remains little margin for improvement in the performance (room temperature MR ratio) of MTJ devices based on an amorphous Al-O tunnel barrier, and that was a serious problem for achieving higher

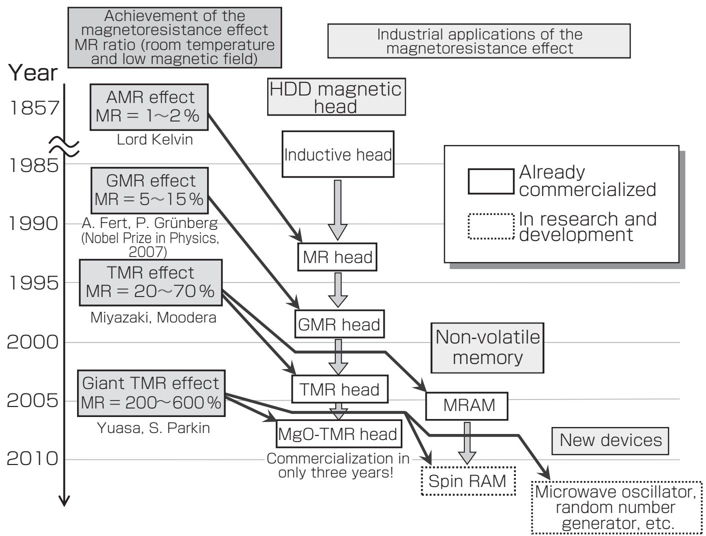


**Fig. 3 History of the magnetoresistance effect and its industrial applications.**

performance in hard disk drives and MRAM. With an MTJ device that uses an amorphous barrier, development of an HDD recording density higher than 200 Gbit/inch$^2$ and gigabit-class large-capacity MRAM was difficult (Fig. 4). To overcome that limitation and develop next-generation devices that have a higher integration scale, higher speed and less power consumption, even higher MR ratios were essential.

First-principle theoretical calculations for a single-crystal MTJ device that uses a crystalline tunnel barrier rather than the amorphous barrier that had previously blocked further progress were published around 2001, and a huge theoretical MR ratio of over 1000 % was predicted. In 2004, AIST was the first in the world to experimentally achieve a giant room temperature TMR effect in an MTJ device using a crystalline magnesium oxide (MgO) tunnel barrier, making a great step forward in applied research on the TMR effect. Beginning with the next section of this paper, we describe the stages of *Type 1 Basic Research*, *Type 2 Basic Research*, and commercialization in the R & D of a high-performance MTJ device that uses a crystalline MgO tunnel barrier, and explain how the *Full Research*[4] was conducted.

The Spintronics Group of the AIST Electronics Research Division did R & D on the two outcomes described below in the second research strategy period of AIST.

(1) A practical next-generation magnetic head for the ultra-high-density HDD

The objective is a next-generation magnetic head for ultra-high-density HDDs that have a recording density of over 200 Gbit/inch$^2$ to reduce power consumption by achieving an ultra-high-density, compact HDD.

(2) Basic technology for ultimate non-volatile memory (spin RAM)

The goal is basic spin RAM technology for the large-capacity, high-speed and highly-reliable ultimate non-volatile memory that will be the core technology for non-volatile electronics.

To produce these two outcomes, we target two R & D goals: (i) development of a landmark high-performance MTJ device and (ii) development of mass production technology for it.

## 2 Elemental technology

### *2.1 Theory of the magnesium oxide (MgO) tunnel barrier TMR effect*

This section explains the physical theory behind the TMR effect. The good crystal lattice-matching between the (001) surface of the body-centered cubic crystal (bcc) Fe and the (001) crystal surface of magnesium oxide (MgO) allows experimental fabrication of a fully epitaxial MTJ thin film that has a high quality Fe (001)/MgO (001)/Fe (001) structure. Even combining a bcc (001) electrode layer of an alloy whose main constituents are Fe and Co and a MgO (001) tunnel barrier allows formation of high-quality single-crystal MTJ thin film in the same way. In 2001, Butler *et al.*[5] and Mathon *et al.*[6] performed first-principle theoretical calculations for a single-crystal MTJ that has an Fe (001)/MgO (001)/Fe (001) structure, showing that a giant MR ratio of over 1000 % can be expected in theory. The physical mechanism of this giant TMR effect differs from that when the conventional amorphous Al-O tunnel barrier is used as described below.

The difference in the electron tunneling process for the

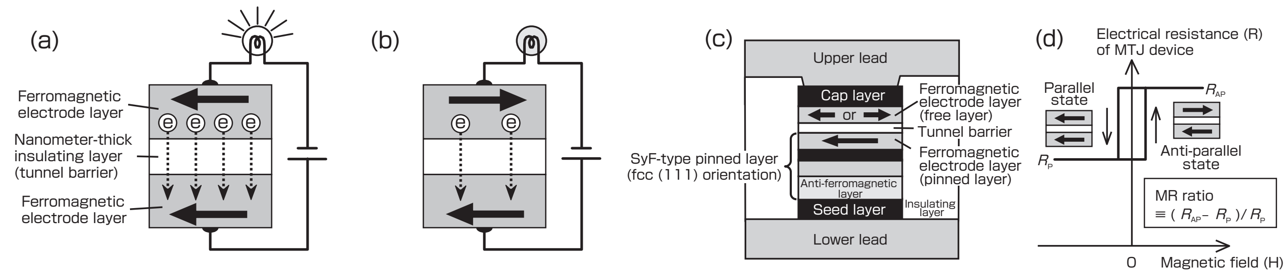


**Fig. 4 Tunnel magnetoresistance (TMR) effect of magnetic tunnel junction (MTJ) device.**

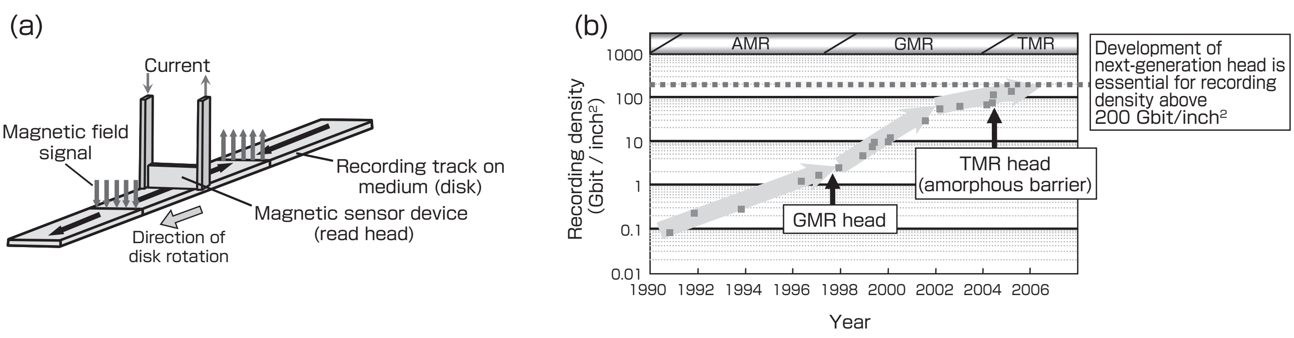


**Fig. 5 (a) Hard disk drive (HDD) magnetic read head, (b) Evolution of HDD recording density and magnetic read heads**

conventional amorphous Al-O tunnel barrier and the crystalline MgO(001) tunnel barrier is illustrated in Fig. 7. Conduction electron states that have various wave function symmetries (Bloch states) exist in the ferromagnetic electrode. For an amorphous Al-O tunnel barrier, the symmetry of atomic arrangement in the barrier is broken, so the various Bloch states are mixed up within the electrode and tunneling conduction occurs (Fig. 7(a)). Each Bloch state in the electrode generates a positive or negative MR ratio, depending on its orbital symmetry. With an amorphous Al-O barrier, those Bloch states are mixed and all are subject to tunneling conduction. Therefore, the mean MR ratio of the Bloch states (which is to say the MR ratio of the MTJ device) cannot attain a high value, and an MR ratio that greatly exceeds 70 % cannot be attained at room temperature.

If the tunnel barrier is crystalline MgO (001), on the other hand, an entirely different characteristic is predicted by theory. The single-crystal MTJ device tunneling process is illustrated in Fig. 7(b). The tunnel electron is often assumed to be a free electron, but the evanescent states of electrons that are in the actual band gap of the insulating tunnel barrier have a special orbital symmetry and a special band dispersion that differ greatly from free electrons. Three kinds of evanescent states exist within the MgO (001) band gap: $\Delta_1$ (*spd* hybridized high symmetry state), $\Delta_5$ (*pd* mixed state), and $\Delta_{2'}$ (*d* low electronical symmetry state). The attenuation rates of the density of states of these states within the tunnel barrier depend greatly on the orbital symmetry of the state. The $\Delta_1$ evanescent states have the slowest attenuation in the tunnel barrier (i.e., the longest attenuation length). Accordingly, the tunneling current via this $\Delta_1$ states is dominant (Fig. 7(b)). In an ideal tunneling process, only the $\Delta_1$ Bloch states in the Fe (001) electrode can couple with the $\Delta_1$ evanescent states in the MgO, so the dominant tunneling path is Fe-$\Delta_1 \leftrightarrow$ MgO-$\Delta_1 \leftrightarrow$Fe-$\Delta_1$. What should be noted here is that the $\Delta_1$ Bloch state in the Fe (001) electrode is a special electron state that can generate a very large positive MR ratio. From the fact that only electrons that have the $\Delta_1$ symmetry selectively pass through the MgO tunnel barrier, as we see in Fig. 7(b), we can theoretically expect a huge MR ratio of over 1000 %. The theoretical prediction for such a huge MR ratio is not limited to the bcc Fe (001) electrode, but is predicted also for Fe and Co based ferromagnetic alloys that have the bcc structure.

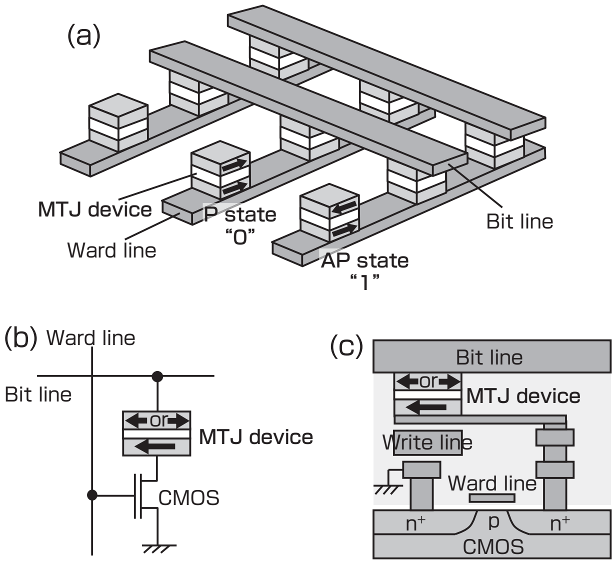


**Fig. 6 Non-volatile memory MRAM (a) Schematic diagram, (b) Circuit diagram, (c) Cross-section**

### 2.2 Achieving the MgO tunnel barrier giant TMR effect

When the theoretical prediction of the giant TMR effect for a crystalline MgO tunnel barrier appeared in 2001, there were experimental attempts to actually fabricate MTJ devices that had the single-crystal Fe (001)/MgO (001)/Fe (001) structure, mainly by public research organizations in Europe, but there was no success. Room temperature MR ratios that exceeded those of conventional amorphous Al-O tunnel barrier were not attained, so the expectations for the crystalline MgO tunnel barrier were not met and the theoretical predictions for the giant TMR effect came to be viewed with skepticism. Under those circumstances, AIST continued experimental research on crystalline MgO tunnel barriers, and succeeded in fabricating a high-quality single-crystal Fe (001)/MgO (001)/Fe (001) MTJ device using molecular beam epitaxy (MBE) in 2004 (Fig. 8)[7][8]. That single-crystal MgO-MTJ device was used to achieve the world's first room temperature MR ratio that exceeded that of an amorphous Al-O barrier in the beginning of 2004 (Fig. 9, 1))[7]. That paper also verified high reproducibility, excellent voltage characteristics and other aspects of practicality, and was thus a historical turning point that brought the crystalline MgO tunnel barrier back into the limelight. After that, AIST achieved an even higher room temperature MR ratio of 180 % by further improving the quality of the crystalline MgO tunnel barrier in the latter half of 2004 (Fig. 9, 2))[8]. On the other hand, at about the same time that AIST produced those results, Parkin *et al.* of IBM fabricated an MTJ device that used a preferred-oriented polycrystalline (textured) MgO (001) tunnel barrier with

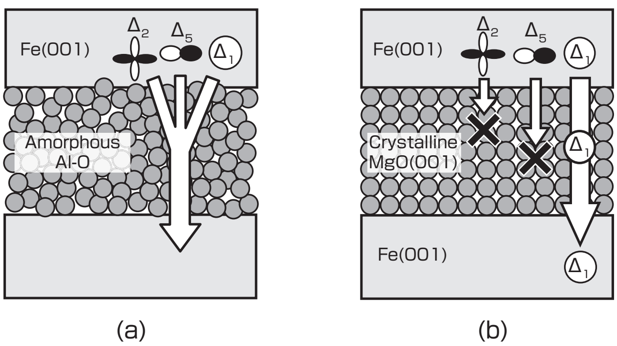


**Fig. 7 Electron tunneling transport.**
**(a) Amorphous Al−O tunnel barrier, (b) crystalline MgO(001) tunnel barrier**

a preferential orientation of (001) crystal plane formed by sputtering. That device attained a room temperature MR ratio of 220 % (Fig. 9, 3))[9]. Viewed microscopically, the textured MTJ device has basically the same structure as the single-crystal MTJ device, so it can be considered to manifest the giant TMR effect by the same mechanism. To distinguish it from the conventional TMR effect, we call this kind of very large TMR effect exhibited by the crystalline MgO tunnel barrier the giant TMR effect (nomenclature of the authors). The results shown in Fig. 9 1), 2), and 3) (references[7]-[9]) are also presented in the 2007 Nobel Prize in Physics paper[1] and recognized worldwide as historical papers.

AIST is conducting various types of *Type 1 Basic Research* using a high-quality single-crystal MgO tunnel barrier and has succeeded in observing new phenomena not seen with an amorphous Al-O tunnel barrier, such as the oscillation phenomenon of the TMR effect relative to the thickness of the MgO barrier[8][10], interlayer exchange coupling mediated by the tunnel electron[11], and a complex spin-dependent tunneling spectra[12] in addition to the giant TMR effect. Progress in understanding the physical mechanism of these phenomena should lead to further development of the physics of the tunneling effect.

### 2.3 Mass production technology for crystalline MgO-MTJ devices

As described above, AIST achieved the landmark *Type 1 Basic Research* result of the giant TMR effect in 2004, but at that time the skeptical outlook on industrial applications for the crystalline MgO-MTJ device was still dominant. The main reason is that neither the single-crystal MgO-MTJ device developed by AIST nor the textured MgO-MTJ device developed by IBM had a device structure suitable for application in practical devices. For application to HDD magnetic heads or MRAM, the lower structure, the "SyF type pin layer" (Fig. 4(c)), is necessary (details are omitted here). However, the basic structure of the SyF-type pin layer is (111) oriented face-centered cubic (fcc) crystal, which has three-fold rotational in-plane symmetry, and it is not possible to grow a MgO (001) layer of different crystal symmetry (an in-plane four-fold rotational symmetry structure) over it. That fundamental problem in crystal growth was a serious problem for fabrication of a MgO-MTJ device over this "practical lower structure".

At first, AIST took the viewpoint of developing a new lower structure that had in-plane four-fold rotational symmetry and tried to sell device manufacturers the idea of MgO-MTJ device technology. However, the reaction from device manufacturers was, "The reliability of the lower structure is directly related to product (HDD and MRAM) reliability. The highly reliable SyF-type pin layer lower structure is the result of ten years or so of research and development, so the development of a new lower structure now is not possible (there is no margin for it)." To be sure, commercialization depends on satisfying many requirements. For example, even for new technology that has outstanding capabilities, just one fatal flaw would prevent commercialization and bring death to the technology, as the word in "valley of death" implies. While we know that to be the greatest difficulty to overcome in *Full Research* in our minds, the reality of the matter comes when we actually experience it. At the time, there were two straightforward solutions: (i) brute-force development of a new lower structure that has in-plane four-fold rotational symmetry structure and (ii) development of a new tunnel barrier that can be formed above a SyF-type pin layer that has in-plane three-fold rotational symmetry. Either of those solutions, however, would require at least five to ten years of development. Furthermore, the requirement of device manufacturers for "mature technology at a level that can be immediately developed and introduced to the production line" meant that it was practically impossible for AIST to independently develop such a solution. Faced with that situation, AIST began joint development with the production system manufacturer Canon ANELVA Corporation and achieved the "landmark solution" described below.

Although we might think of production system manufacturers

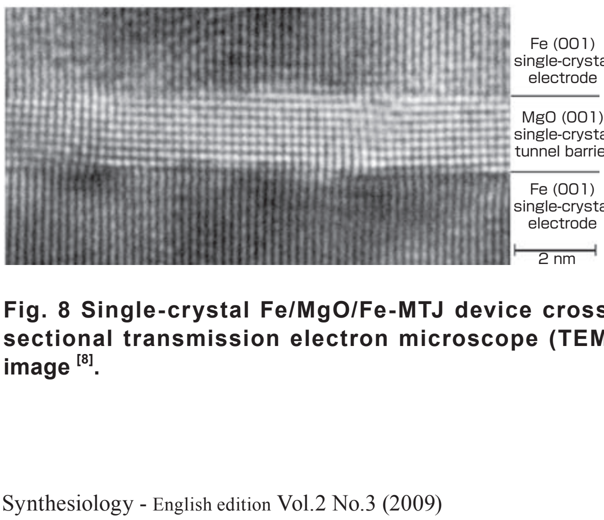


**Fig. 8 Single-crystal Fe/MgO/Fe-MTJ device cross-sectional transmission electron microscope (TEM) image [8].**

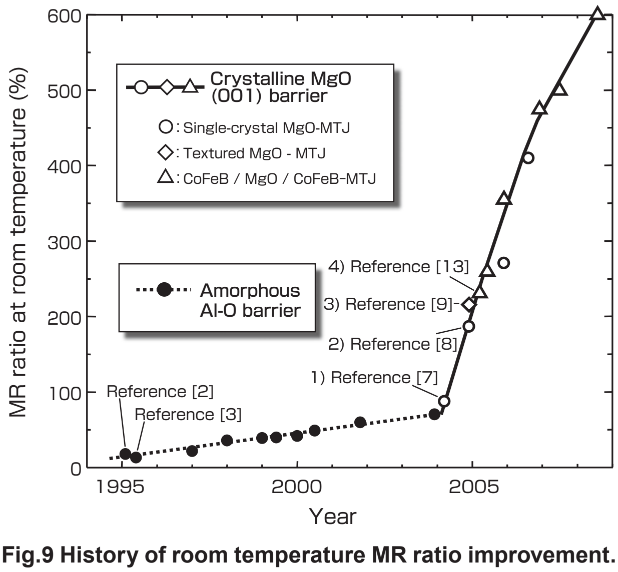


**Fig.9 History of room temperature MR ratio improvement.**

as simply builders of production systems, current production system manufacturers play the important role of developing new materials and new device production process technology in addition to building the systems. In this R & D, we aimed for a solution to the difficult problem described above by integrating AIST's superior material and device technology seeds and the excellent production process technology and equipment possessed by the production system manufacturer (Fig. 10). In particular, the production sputtering system of that company is a world-standard system in the HDD industry, so if mass production technology can be developed using it, that technology can be rapidly transferred to the production lines of device manufacturers.

In the joint research with the Canon ANELVA Corporation, we discovered that if amorphous CoFeB alloy is used for the lower ferromagnetic electrode, a high-quality oriented polycrystalline (textured) MgO (001) tunnel barrier layer can be grown over it at room temperature (Fig. 11(a))[13]. A CoFeB/MgO/CoFeB structure MTJ device that uses this very special manner of crystal growth can be fabricated over any base layer because the lower electrode layer is amorphous. Moreover, it is formed by room temperature sputtering, so it is ideal in terms of production process compatibility and production efficiency. When that CoFeB/MgO/CoFeB-MTJ device is heat-treated at 250 °C or above, crystallization of the amorphous CoFeB layer begins from the interfaces (Fig. 11), and a bcc CoFeB(001) structure that has good lattice matching with the MgO (001) layer forms[14]. The device structure shown in Fig. 11(b) is basically the same as the single-crystal MgO-MTJ device and the oriented polycrystalline MgO-MTJ device, so giant TMR effect manifests by the same physical mechanism (Fig. 9, 4))[13]. This thin film fabrication process is an original method that counters the common-sense understanding that crystal growth proceeds upwards from the base layer.

That CoFeB/MgO/CoFeB MTJ device has now become the mainstream technology in spintronics applications, and various types of vigorous R & D that use it are proceeding on a worldwide scale. That work has so far achieved a room temperature giant MR ratio of 600 %. Incidentally, success in developing the CoFeB/MgO/CoFeB-MTJ device was achieved in barely one year from the beginning of the joint research with Canon ANELVA. That achievement was largely dependent on the "good lineage" of the crystalline MgO tunnel barrier, but it also verified that the combination of AIST and a production system manufacturer engaging in *Type 2 Basic Research* was a highly suitable approach.

## 3 Creating Outcomes

### *3.1 Commercialization of the ultra-high-density MgO-TMR HDD head*

The CoFeB/MgO/CoFeB MTJ device developed jointly by AIST and the Canon ANELVA Corporation and that company's production system were quickly introduced to HDD manufacturers' product development lines and energetically used in mass production of HDD magnetic heads (Fig. 10). The result of vigorous product development was the successful commercialization of the second-generation TMR head (MgO-TMR head) using the MgO-MTJ device by various HDD manufacturers in 2007. The MgO-TMR head had greatly higher performance than the

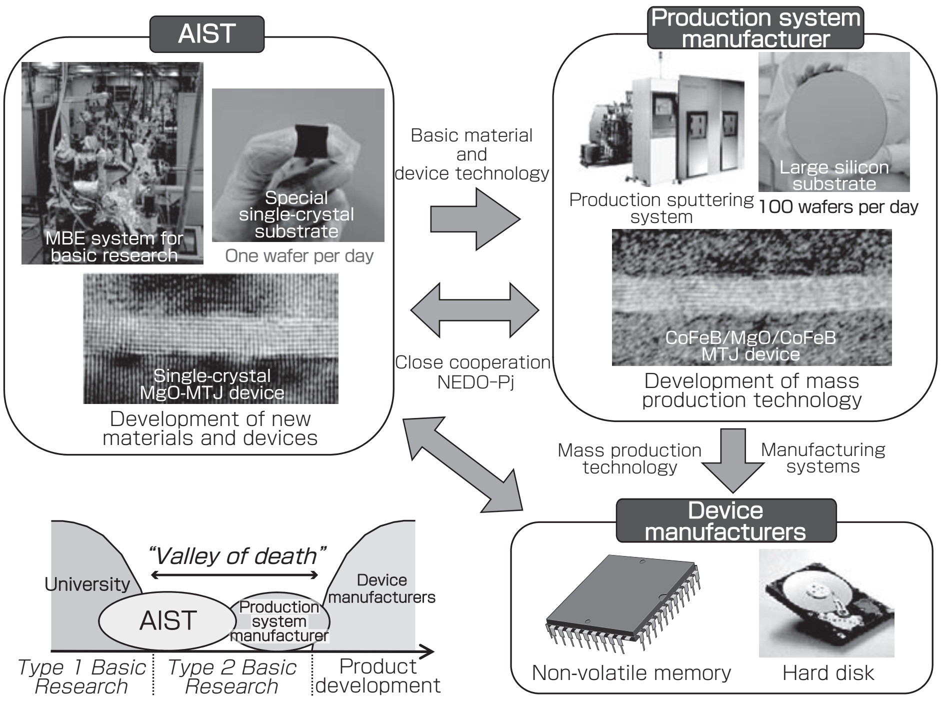


**Fig.10 *Full Research* on MgO-MTJ device.**

first-generation TMR head, and when combined with the latest perpendicular magnetic recording medium, realized an ultra-high-density HDD with a recording density above 250 Gbit/inch$^2$ (twice the previous value)[15]. The future potential for development extends up to the 1 Tbit/inch$^2$ next-generation HDD. By achieving such high HDD recording density, the 3.5 inch drives that are the main devices in use can be replaced with 2.5 inch drives that have adequately high capacity. As a result, 2.5 inch drives are expected to come into mainstream use, even in the market for large-capacity HDD. As described in section 1.1, 2.5 inch drives consume only one-fifth power of the 3.5 inch drive, so replacing 3.5 inch drives with 2.5 inch drives will greatly reduce overall HDD power consumption. The HDD industry has a huge market that compares in scale with DRAM and CPUs (about 3 trillion yen per year). The magnetic head is the most expensive component in a disk drive, and the market value for the magnetic head alone is a huge six hundred billion yen per year. The fact that nearly all of the drives currently being produced are equipped with MgO-TMR heads is the best indication of the social impact of these research results.

### *3.2 Ultimate non-volatile memory "spin-RAM" R & D*

With the objective of implementing the "spin RAM" ultimate non-volatile memory that provides large capacity, high speed and high reliability and will serve as the core technology of non-volatile electronics, AIST is working together with Toshiba Corporation and other companies on the NEDO Spintronics Non-volatile Devices Project. Spin-RAM is an MRAM that uses a new physical phenomenon called "spin torque switching" in the data write technique, achieving a higher capacity than the conventional magnetic field write MRAM. To realize a gigabit-class large capacity spin-RAM requires both increased read out by the giant TMR effect of the MgO-MTJ device and a low-power write technique that uses spin torque switching. Spin torque is the torque generated by the transfer of spin angular momentum from the conduction electrons to the local magnetic moment of the magnetic layer when a current flows in the MTJ device. That spin torque can be used to reverse the direction of spin of the ferro-magnetic electrode (i.e., write). Spin torque switching has been implemented before using GMR devices and Al-O barrier MTJ devices, but the current density needed for switching is very high, so achieving a practical effect was considered difficult. AIST implemented spin torque switching in a MgO-MTJ device for the first time in the world in 2005[16][17]. Furthermore, AIST and Osaka University are collaborating to develop a method for quantitative estimation of spin torque[18][19] and have succeeded in verifying a high output microwave oscillator that uses spin torque[20]. Also, Sony, Tohoku University and many others have been doing vigorous research and development on attaining spin torque switching at lower current.

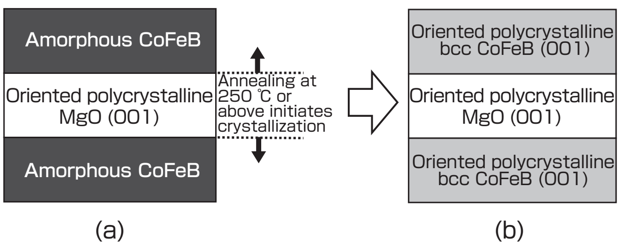


**Fig.11 Structure of the CoFeB/MgO/CoFeB MTJ device.**

Currently, AIST is moving forward with development of the ultimate spin RAM that uses a perpendicularly magnetized MgO-MTJ device that combines newly developed perpendicularly magnetized electrodes and a crystalline MgO tunnel barrier in collaboration with Toshiba Corporation and with the support of the NEDO project. Because this project involves industry, the government and academia and is currently in progress, there are many confidential aspects, so we must omit the details of research and development here, but we have already verified low current and high speed spin torque write operations and excellent data retention characteristics. We are continuing this R & D with the near-term objective of an ultimate non-volatile memory that uses this perpendicularly magnetized MgO-MTJ device and with the long-term objective of implementing ultimate green IT devices through normally-off computer.

## 4 Conclusion

We have described here our impressions based on our own experience of *Full Research* achievements. The *Full Research* scenario put forth by AIST is ultimately a conceptualism, and the actual specific methods for executing it must rely on a groping search by the individual persons engaged in R & D in the laboratories. Although conceptualisms are also important, they are not immediately useful in the R & D labs where difficult and pressing problems are being dealt with. Actually linking the results of basic research to commercialization, involves the problem of matching research with social needs and problems of dealing with complex elements such as the difference in interests between organizations and interpersonal relations in addition to the technological problems. Particularly the difference of interests between organizations may create a deadlock, even when the matter is left to the upper levels of the organizations, and there is no progress. In the end, the people in the labs must work within organizations to solve problems, so a relationship of trust among the people doing the R & D in the laboratory is important. That is to say, it is ultimately an interpersonal problem.

Speaking of the technical problems, the "valley of death" that lies between basic research and product development is wider and deeper than is imagined, and it is probably impossible for AIST to cross it alone. Particularly in mature industries such as electronics, there is an advanced separation of labor such as among manufacturing systems manufacturers, raw materials producers, device manufacturers, and foundries. Therefore, cooperation with appropriate partners at each stage of R & D is essential. The tag-team approach used by AIST and the manufacturing system manufacturer in this case can be called a model case for *Type 2 Basic Research*. The importance of production system manufacturers is generally still not fully recognized, and we feel that AIST should actively send out that message through examples of success such as this.

As a final matter, we attempt to analyze the factors of success relating to commercialization in a mere three years from obtaining the results of *Type 1 Basic Research* in the R & D reported here. We can say that the key to success is measured by "the potential of technology seeds." When *Type 1 Basic Research* produces some remarkable capability, it is thrust into the limelight and draws great praise. In product development, however, all of ten or more important item tests must be passed, and even one failure can be a fatal defect that makes commercialization impossible. Even if it is a "landmark new technology" that gets published in a well-known scientific journal, there is most often some fatal defect, and in nearly all cases, the valley of death cannot be crossed. Although only the rare technology seeds that have true potential can cross the "valley of death", and even for those cases the stage of practicality cannot be reached without many collaborators and endorsers brought together from the industrial world. The key here is how to bring together capable collaborators and endorsers. Our feeling is that if the technology seed has strong potential and suitable results are announced with appropriate timing, "People will naturally gather together." Technology seeds that have strong potential draw capable people. In industry, most people are conservative, and views of new technology are most often skeptical and critical, but there are certainly also developers and managers who can see the potential and appropriately evaluate new technology. If technology seeds fail to bring together collaborators even after a number of announcements and industry is completely unmoved, it is best to first consider whether one's own technology seeds might have weak potential before putting the blame on the conservatism of industry.

## Note

This research was done in part with support from the Japan Science and Technology Agency (JST) and also from the New Energy and Industrial Technology Development Organization (NEDO) Nanotech Challenge Project and the NEDO Spintronics Non-volatile Devices Project. Parts of this work were done in joint research with Canon ANELVA Corporation and Toshiba Corporation.

## Terminology

Term 1. DRAM: A type of large capacity memory used in computers. Information is stored by charging capacitors. When the power is cut off, the capacitor is discharged and the stored information is lost (volatile memory).

Term 2. SRAM: A type of volatile memory used for CPU cache memory, etc. that uses the bistable state of a flip-flop circuit to store data. It is fast and highly reliable, and also compatible with logic circuits, but it is not suited to increased integration scales and power consumption is high.

Term 3. SSD: An external storage device that uses flash memory as the recording medium. Unlike hard disk drives, it has no moving parts. SSD is an acronym for Solid State Drive. Compared to hard disk drives, it consumes little power and is resistant to physical shock. The cost per unit capacity, however, is an order of magnitude higher than current hard disk drives.

## References


[1] http://nobelprize.org/nobel_prizes/physics/laureates/2007/phyadv07.pdf

[2] T. Miyazaki and N. Tezuka: Giant magnetic tunneling effect in Fe/Al2O3/Fe junction, *J. Magn. Magn. Mater.,* 139, L231-L234 (1995).

[3] J.S. Moodera, L. R. Kinder, T. M. Wong and R. Meservey: Large magnetoresistance at room temperature in ferromagnetic thin film tunnel junctions, *Phys. Rev. Lett.,* 74, 3273-3276 (1995).

[4] Hiroyuki Yoshikawa: Dai 2 shu kiso kenkyu no gencho ronbunshi (A journal of *Type 2 Basic Research* original articles), *Synthesiology,* 1, 1-6 (2008).

[5] W. H. Butler, X.-G. Zhang, T. C. Schulthess and J. M. Maclaren: Spin-dependent tunneling conductance of Fe/MgO/Fe sandwiches, *Phys. Rev. B,* 63, 054416-1-12 (2001).

[6] J. Mathon and A. Umerski: Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe (001) junction, *Phys. Rev. B,* 63, 220403R-1-4 (2001).

[7] S. Yuasa, A. Fukushima, T. Nagahama, K. Ando and Y. Suzuki: High tunnel magnetoresistance at room temperature in fully epitaxial Fe/MgO/Fe tunnel junctions due to coherent spin-polarized tunneling, *Jpn. J. Appl. Phys.,* 43, L588-L590 (2004).

[8] S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki and K. Ando: Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions, *Nature Mater.,* 3, 868-871 (2004).

[9] S. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant and S.-H. Yang: Giant tunneling magnetoresistance at room temperature with MgO (100) tunnel barriers, *Nature Mater.,* 3, 862-867 (2004).

[10] R. Matsumoto, A. Fukushima, T. Nagahama, Y. Suzuki, K. Ando and S. Yuasa: Oscillation of giant tunneling magnetoresistance with respect to tunneling barrier thickness in fully epitaxial Fe/MgO/Fe magnetic tunnel junctions, *Appl. Phys. Lett.,* 90, 252506-1-3 (2007).

[11] T. Katayama, S. Yuasa, J. Velev, M. Y. Zhuravlev, S. S.

Jaswal and E. Y. Tsymbal: Interlayer exchange coupling in Fe/MgO/Fe magnetic tunnel junctions, *Appl. Phys. Lett.,* 89, 112503-1-3 (2006).
[12] Y. Ando, T. Miyakoshi, M. Oogane, T. Miyazaki, H. Kubota, K. Ando and S. Yuasa: Spin-dependent tunneling spectroscopy in single-crystal Fe/MgO/Fe tunnel junctions, *Appl. Phys. Lett.,* 87, 142502-1-3 (2005).
[13] D. D. Djayaprawira, K. Tsunekawa, M. Nagai, H. Maehara, S. Yamagata, N. Watanabe, S. Yuasa, Y. Suzuki and K. Ando: 230 % room-temperature magnetoresistance in CoFeB/MgO/CoFeB magnetic tunnel junctions, *Appl. Phys. Lett.,* 86, 092502-1-3 (2005).
[14] S. Yuasa and D. D. Djayaprawira: Giant tunnel magnetoresistance in magnetic tunnel junctions with a crystalline MgO(001) barrier, *J. Phys. D: Appl. Phys.,* 40, R337-R354 (2007).
[15] http: //www8.cao.go.jp/cstp/sangakukan/sangakukan2008/award.html
[16] H. Kubota, A. Fukushima, Y. Ootani, S. Yuasa, K. Ando, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe and Y. Suzuki: Evaluation of spin-transfer switching in CoFeB/MgO/CoFeB magnetic tunnel junctions, *Jpn. J. Appl. Phys.,* 44, L1237-L1240 (2005).
[17] H. Kubota, A. Fukushima, Y. Ootani, S. Yuasa, K. Ando, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and Y. Suzuki: Magnetization switching by spin-polarized current in low-resistance magnetic tunnel junction with MgO [001] barrier, *IEEE Trans. Magn.,* 41, 2633-2635 (2005).
[18] A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe and S. Yuasa: Spin-torque diode effect in magnetic tunnel junctions, *Nature,* 438, 339-342 (2005).
[19] H. Kubota, A. Fukushima, K. Yakushiji, T. Nagahama, S. Yuasa, K. Ando, H. Maehara, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe and Y. Suzuki: Quantitative measurement of voltage dependence of spin-transfer torque in MgO-based magnetic tunnel junctions, *Nature Phys.,* 4, 37-41 (2008).
[20] A. M. Deac, A. Fukushima, H. Kubota, H. Maehara, Y. Suzuki, S. Yuasa, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira and N. Watanabe: Bias-driven high-power microwave emission from MgO-based tunnel magnetoresistance devices, *Nature Phys.,* 4, 803-809, (2008).

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## Discussion with Reviewers

### 1 Achieving the breakthrough

**Question and comment (Naoto Kobayashi, Center for Research Strategy, Waseda University)**

I think this R & D is a rare example where the research results, through the two major breakthroughs of " 1) the giant TMR effect achieved using MgO" and " 2) the realization of CoFeB/MgO/CoFeB structure" are linked to the outcome of development of a product that is actually sold in the market in a short period of time. From this paper we can understand the most part why these respective breakthroughs could be achieved, but could we have an explanation of the process of selecting those processes and materials (including the reasons for excluding other materials and processes, etc., and, if necessary, the research and development system). Also, if there was an effective serendipity or other such factors, please also describe them.

**Answer (Shinji Yuasa)**

Half of the success factors were a matter of achieving set goals, and the other half involved good luck (serendipity). Theoretically, there are a number of promising crystalline tunnel barrier materials other than MgO. The first thing to consider is the problem of which theoretical prediction is correct (which prediction should we bet on). Furthermore, to reach a practical stage means the satisfaction of various requirements such as (i) fabricating thin films of nanometer order thickness without opening up pinholes, (ii) prevention of reaction and atomic diffusion at the interface with the metal electrode material, (iii) crystallization in low temperature layer formation, (iv) a sufficiently high breakdown voltage, and (v) product-level reliability. Based on the experience and knowledge we have accumulated and as the result of considering what material system would be the most promising from many angles, we came to the conclusion that using anything other than crystalline MgO would present difficulties even before we began any experimentation. However, that did not at all mean that there would be no problems if we chose to go with MgO. The most troubling problem before beginning the research and development was production process compatibility, but that problem was solved by the development of the CoFeB/MgO/CoFeB structure in joint research with Canon ANELVA Corporation. Serendipity was large among the success factors in forming the CoFeB/MgO/CoFeB structure, I believe, even with the active work done by the excellent engineers of the Canon ANELVA Corporation. Also, the inability to judge ultimate reliability at the product level until the final stage of research and development is reached is a problem, but we had the feeling from the initial stage of research and development that the reliability of MgO was high. That was not a conclusion based on theoretical consideration, but an intuition that can only be felt by people working in the lab.

### 2 Reduction of power consumption

**Question and comment (Naoto Kobayashi)**

You have described that the development of non-volatile memory is linked to the realization of ultimate green IT devices. While practical non-volatile memory will greatly reduce the power needed to operate memories, I think that no overall reduction in power consumption can be expected unless the non-volatile CPU is realized as described in Fig. 1. Thus I have two questions: 1) As far as we know now, what are the approximate relative proportions of the power consumption decrease that can be achieved by implementing the spin RAM and that achievable by implementing the future non-volatile CPU? and 2) I believe that spin FETs is essential to implementation of future non-volatile CPUs. What do you think of the prospects for that field of research and development?

**Answer (Shinji Yuasa)**

1) Not much reduction in power consumption can be expected from simply replacing DRAM and SRAM with MRAM and spin RAM. As you point out, a radical reduction in power consumption would require achieving non-volatility for both memory and the CPU together as a set. While non-volatile DRAM and SRAM serve as the first stage, the merits of that in itself include (i) an opening up of the near-future SRAM and DRAM scaling limits and (ii) higher integration scale and lower cost achieved by on-chip system LSI memory consisting of spin RAM only.

2) While switching devices that have a non-volatile memory function such as spin FETs are ideal, one opinion that non-volatile logic circuits can also be designed by combining existing memory devices (MTJ devices and ferro-electric memory devices, etc.) and CMOS. In any event, achieving normally-off equipment with a non-volatile CPU is a grand plan that will require considerable time and investment, and so is expected to need R & D on a 20-year scale.

**Question and comment (Kazuhito Ohmaki, Department of Information and Computer Sciences, Toyo University)**

Particularly in the Introduction, TMR is proposed as a key technology for normally-off computers. With today's computers, it may look like the computer is idle between key inputs, but in the meantime, the computer is busy monitoring communication lines, scanning display devices, and occasionally computing encryption algorithms and other such tasks, and thus not necessarily idle. I think you need to strengthen the explanation of the architecture for normally-off computers a little.

**Answer (Shinji Yuasa)**

My desktop personal computer is connected to a liquid crystal monitor, two hard disk drives, a DVD drive, LAN cables, and USB memory. I have Windows running on it, and under Windows I run word processing software, an Internet browser, a mail program, presentation authoring software, and a spreadsheet program all at the same time. Still, monitoring the CPU use shows that the use rate is normally only 1 to 4 %, and rarely exceeds 5 %. In other words, even though various kinds of processing go on in the background, it's still true that most of the time the CPU is in the standby state. Current electronics that are based on volatility are designed to reduce power consumption by lowering the CPU clock frequency or the power supply voltage during times of low load, but those methods are naturally limited. We think that, in the long term, green IT technology implemented with normally-off technology is necessary.

## 3 Switching speed

**Question and comment (Kazuhito Ohmaki)**

I'm not an expert in this, but my feeling is that switching speed will be a problem when using magnetic operations. When aiming for energy conservation by using magnetism, as with the TMR device, I wonder about the prospects for switching speed compared to current silicon technology for implementing normally-off computers. Would you comment on that?

**Answer (Shinji Yuasa)**

The magnetic switching speed is essentially fast, and can be faster than a few nanoseconds. Non-volatile memory that operates about as fast as the fast memory SRAM that is currently used in CPUs is feasible. It does not, however, represent a landmark speed increase over current silicon technology. In other words, while we can expect about the same operating speed as with current technology, the objective for non-volatility is landmark low power consumption. We added a brief explanation concerning operating speed to section 1.3.

## 4 Theoretical background

**Question and comment (Naoto Kobayashi)**

You have explained that what provided the opportunity for the first breakthrough (giant TMR using MgO) was the first-principle computation by Butler and Mathon, but I would like to have some explanation of the research background of their dealing with MgO. Was there any theoretical contribution from Japan regarding this?

**Answer (Shinji Yuasa)**

It's not that Butler and Mathon were the first to predict the giant TMR effect, but that they were the first to choose the Fe/MgO/Fe structure as a representative example that strict first-principle computation was possible. With the conventional amorphous Al-O tunnel barrier, the unordered amorphous structure did not allow first-principle computation. The Fe/MgO/Fe structure, on the other hand, features good crystal lattice matching and the possibility of experimental implementation, and I heard that led them to consider the Fe/MgO/Fe structure. Thus, theoretical prediction of the giant TMR effect as a result of performing the Fe/MgO/Fe theoretical calculations could be called a kind of serendipity. In 2001, there were, unfortunately, no researchers who had performed those theoretical calculations in Japan. The computation itself is not particularly difficult, and I even remember it being called "a too-obvious theoretical calculation." However, this was a "Columbus's egg" kind of thing, and I think that to actually perform an obvious computation and present the results to experimenters is a praiseworthy achievement.

## 5 A critical eye on technology seeds

**Question and comment (Naoto Kobayashi)**

The statement in the conclusion that "the potential of technology seeds" is very important is highly interesting. 1) It is very clear that this R & D was a technology seed of very high potential, but I wonder if that might be considered "serendipitous". Or perhaps only the technology seeds that reach the final goal can be said to effectively have had potential. If that is not so, how should we cultivate the feeling or sense (Leo Esaki's taste?) for looking critically at the potential in advance? 2) I think that whether the technology seed has potential or not is, not knowable until technological development has proceeded to some extent. Getting across the valley of death requires passing over a number of hurdles, but how can we judge the potential of technology seeds in those respective stages? In other words, how should we decide whether to continue technological development or abandon it when taking the "critical view"?

**Answer (Shinji Yuasa)**

Let me respond to questions 1) and 2) together. As is also described briefly in discussion 1, of the various requirements for practicality, whether or not product-level reliability, yield, and other such requirements can be satisfied cannot be known until the final stage of *Full Research*. Accordingly, we can also say that whether it is good technology that has potential or not cannot really be known until commercialization is attempted. Nevertheless, concerning the opposite judgment that this technology has weak potential, we believe that it is possible to make a decision before beginning R & D or in the first stage. Out of the many technology seeds that appear, I, myself, try to quickly terminate work on weak technology in an early stage. I think that recognizing technology as strong or weak requires a sense that allows phenomena to be analyzed logically and from many viewpoints in a broad field of view. This is probably the opposite of the ability to drill down deeply into a particular phenomenon. While both of those capabilities are essential to conducting *Full Research*, it is probably too much to expect both from a single researcher. I believe that researchers who are able to drill down into a single phenomenon are in the majority, and those capable of analyzing phenomena from diverse viewpoints in a wide field of view are a smaller group. If researchers lack a sense that allows them to judge the relative potential of technology, the research and development manager should be able to compensate for it. I do not know how we can cultivate a sense for judging the potential of technology seeds, but I should hope that those who become research and development managers would have such a sense.