FRAM Guide Book
FRAM Guide Book

FUJITSU LIMITED
Preface
FRAM * has the same low-voltage, high-speed random access characteristics as DRAM and SRAM, while maintaining the nonvolatile data characteristics of Flash Memory and EEPROM. At the same time, FRAM is a media that features a different storage method that allows it to consume less power during operation.

FRAM, which represents the crystallization of Fujitsu’s semiconductor technologies, is an ideal memory that should prove an integral part of the social infrastructure and systems of the future. Specifically, we expect FRAM to prove indispensable for new equipment that applies wireless communications and high-security technologies, such as contactless smart cards and mobile communications equipment.

*: FRAM is a registered trademark of Ramtron International Corporation of the United States.

Purpose and Target Readership of This Guidebook
This guidebook aims to promote an overall understanding of FRAM. Specifically, it is designed to resolve technology-related questions, distinguish between DRAM, Flash Memory and other currently existing types of memory, and indicate appropriate applications for FRAM.

Consult the Sales Department or the Support Department of Fujitsu Limited for mass production.

Overall Design of Guidebook
This guidebook comprises the following seven chapters.

Chapter 1 Outline
This chapter provides an outline of FRAM.

Chapter 2 Technical Explanation
This chapter describes FRAM simply from a technical perspective.

Chapter 3 Introduction to Fujitsu FRAM Products
This chapter describes Fujitsu FRAM product introduction.

Chapter 4 Applications
This chapter describes FRAM applications.

Chapter 5 Security Technology
This chapter describes security technologies that are applied for smart cards.

Chapter 6 Customer Support
This chapter describes FRAM business models.

Chapter 7 Greening FRAM
This chapter describes Fujitsu’s activity to reduce the environmental impact of electronic devices and demonstrates several activities for greening FRAM.
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This chapter outlines ferroelectric RAM (FRAM) to provide you its basic understanding. In addition, the chapter describes the position of FRAM among all types of memory and describes its difference from other types.
1.1 What is FRAM?

FRAM is a type of ferroelectric random access memory that uses a ferroelectric thin film. Ferroelectric film is polarized by the electric field applied from an external source and remains polarized even with the external electric field removed (this polarization is referred to as remanent polarization). With this nature, FRAM does not lose data when power is removed from it (this characteristic is called non-volatility). Changing the direction of the applied electric field inverts the direction of polarization of the ferroelectric material, capable of updating data. Polarization is an extremely short phenomenon caused by the ionic displacement of atoms making up the ferroelectric crystal structure. Therefore FRAM is superior memory very fast in data read/write speeds.

1.2 History of FRAM

The first successful experiment of using a ferroelectric material’s polarization materials to control a semiconductor’s surface charges was conducted by Mr. Moll and Mr. Tarui at Stanford University (announced in 1963). In 1974, Mr. S. Y. Wu et al. reported a memory using a ferroelectric film as the insulator for a MOS (Metal Oxide Si) transistor on silicon. In 1987, Krysalis Corp. announced a method of detecting a reverse current in a ferroelectric material. The Krysalis’ memory had a structure of stacked MOS transistors and ferroelectric capacitor. In 1988, Ramtron International Corporation released the first commercial FRAM product based on a similar method. With the progress of FRAM Technology, the memory size and structure of FRAM have been changed. Fujitsu has started mass-producing FRAM since 1999 and shipped over one hundred million chips as of October, 2003.

1.3 Comparison between FRAM and other Memories

Semiconductor memory is divided into two major types. One is volatile memory which loses stored data unless it remains supplied with power from an external source. The other is nonvolatile memory which retains stored data even with its external power supply disconnected.

DRAM (Dynamic Random Access Memory) and SRAM (Static Random Access Memory) are typical volatile memories. DRAM is inexpensive memory but it must regularly update (refresh) its contents with stored data to ensure data is retained. Therefore, it is suitable for systems which require large capacities. SRAM is faster in read/write access and requires no refreshing but it takes up a larger area than DRAM. Therefore, it is suitable for relatively small or medium-capacity applications and embedded in MPUs (MicroProcessing Units) and systems. Some types of SRAM use EEPROM (Electronically Erasable and Programmable Read Only Memory) described later to back up data (NVRAM: Non-volatile RAM) or use a battery to back up the power (BBSRAM: Battery Back-up SRAM) in case the power is turned off or the power supply causes a power failure.

Nonvolatile memory is divided into ROM (read-only memory) that can only be read and RAM (random access memory) that can be read or written. Further ROM is divided into reprogrammable and non-reprogrammable types. A typical non-reprogrammable type of ROM is masked ROM. Masked ROM is shipped after being programmed during manufacture in general. Reprogrammable types of ROM include EEPROM and Flash Memory, to which data is written by the user in general. Nonvolatile types of RAM include NVRAM and BBSRAM are mentioned above, which pretend to be nonvolatile in combination with another type of memory and a battery for backup purposes, FRAM is an ideal memory that can serve as either RAM or ROM by itself.

The following section compares features of FRAM and other types of memory.
### Table 1.1 Comparison between FRAM and Other Memories

<table>
<thead>
<tr>
<th>Item</th>
<th>FRAM 2T/2C, 1T/1C</th>
<th>FRAM SRAM Type</th>
<th>EEPROM</th>
<th>Flash Memory</th>
<th>EPROM</th>
<th>MASK ROM</th>
<th>DRAM</th>
<th>SRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data retention</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
<td>Volatile</td>
<td>Volatile</td>
<td></td>
</tr>
<tr>
<td>Period data retained</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
<td>Unlimited</td>
<td>–</td>
<td>1 year (battery operation)</td>
<td></td>
</tr>
<tr>
<td>Cell structure</td>
<td>2T/2C</td>
<td>1T/1C</td>
<td>6T/4C</td>
<td>2T</td>
<td>1T</td>
<td>1T</td>
<td>1T/1C</td>
<td>6T</td>
</tr>
<tr>
<td>Read time</td>
<td>110 ns</td>
<td>200 ns</td>
<td>200 ns</td>
<td>&lt;120 ns</td>
<td>&lt;150 ns</td>
<td>&lt;120 ns</td>
<td>70 ns</td>
<td>70 to 85 ns</td>
</tr>
<tr>
<td>Write voltage</td>
<td>3.3 V</td>
<td>3.3 V</td>
<td>20 V</td>
<td>12 V</td>
<td>12 V</td>
<td>Unnecessary</td>
<td>3.3 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Data rewriting</td>
<td>Rewrite method</td>
<td>Overwrite</td>
<td>Erase or write</td>
<td>Erase or write</td>
<td>Ultraviolet light erase + write</td>
<td>Not possible (written during manufacture)</td>
<td>Overwrite</td>
<td>Overwrite</td>
</tr>
<tr>
<td>Rewrite cycle</td>
<td>180 ns</td>
<td>Equivalent to SRAM</td>
<td>10 ms (by byte)</td>
<td>1 s (by sector)</td>
<td>Write *3</td>
<td>-</td>
<td>70 ns</td>
<td>70 to 85 ns</td>
</tr>
<tr>
<td>Data erasure</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Necessary (byte erase)</td>
<td>Necessary (sector erase)</td>
<td>Necessary (ultraviolet erase)</td>
<td>0.5 ms (by byte)</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
</tr>
<tr>
<td>Number of write cycles</td>
<td>PZT: 10⁹ to 10¹²</td>
<td>Unlimited</td>
<td>100,000</td>
<td>100,000</td>
<td>100</td>
<td>Not possible</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Current to retain data</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
</tr>
<tr>
<td>Standby current</td>
<td>5 μA</td>
<td>Equivalent to SRAM</td>
<td>20 μA</td>
<td>5 μA</td>
<td>100 μA</td>
<td>30 μA</td>
<td>1000 μA</td>
<td>7 μA</td>
</tr>
<tr>
<td>Read-time current</td>
<td>4 mA</td>
<td>Equivalent to SRAM</td>
<td>5 mA</td>
<td>12 mA</td>
<td>40 mA</td>
<td>40 mA</td>
<td>80 mA</td>
<td>40 mA</td>
</tr>
<tr>
<td>Write-time current</td>
<td>4 mA</td>
<td>Equivalent to SRAM</td>
<td>8 mA</td>
<td>35 mA</td>
<td>40 mA</td>
<td>–</td>
<td>80 mA</td>
<td>40 mA</td>
</tr>
</tbody>
</table>

*2T/2C: 2 transistors/2 capacitors
1T/1C: 1 transistor/1 capacitor
6T/4C: 6 transistors/4 capacitors
1T: 1 transistor
2T: 2 transistors
6T: 6 transistors
4T+2R: 4 transistors + 2 resistor elements

*1: FRAM - number of write cycles: Because of reading is destructive, this is the total number of cycles for reading and rewriting.
*2: Flash Memory - Rewrite cycle: Excludes pri-programing time inside of the chip.
*3: EPROM-Ultraviolet erase: Ultraviolet light at 2,537 Å, irradiation amount is 10-15Ws/cm² for 15 to 20 minutes
*4: The time is assumed when it's Battery Back-up type SRAM.
1.4 FRAM Structure and Ferroelectric Thin Film Materials

PZT (Pb(Zr,Ti)O3) and SBT (SrBi2Ta2O9) are now known for ferroelectric films used for FRAM. As PZT has been widely used for piezoelectric devices in printers, its characteristics have been known for a long time. PZT is one of the materials suitable for mass production because of its large amount of polarization. On the other hand, SBT is a ferroelectric material which has recently been studied for research and development toward application to FRAM. It says that its high frequency rewriting is relatively large while its amount of polarization is small.

The circuit configuration of memory cells can be either a reliable 2T/2C type (two transistors and two capacitors) or a 1T/1C type (one transistor and one capacitor) that allows higher integration. These configurations are used for relatively high capacity FRAM. 6T/4C FRAM (six transistors and four capacitors) is also available, which is made nonvolatile by integrating ferroelectric capacitors into the SRAM circuit. This 6T/4C FRAM was launched by Fujitsu as the first product of its kind in the world. Although it needs a large area, but it can operate at the same speed of SRAM. We are also developing a 1T type (single transistor) FRAM that uses a ferroelectric thin film for the gates of the transistor. This is expected for the realization of FRAM with extremely high integration.
Chapter 2 Technical Explanation

This chapter provides a brief explanation of ferroelectric RAM (FRAM) technologies.
2.1 Cell Structure of FRAM

There are two major types of FRAM with ferroelectric films integrated as nonvolatile memory cells; (1) 1T/1C type (2T/2C type) and (2) MFSFET type. For release to the market, the 2T/2C type of FRAM is currently ahead of the others.

(1) 1T/1C (2T/2C) Type : 1 Transistor / 1 Capacitor (2Tr/2Cap)
This structure is organized by two parts, which are a storage capacitance to retain and a transistor to access like a DRAM cell. However, different from DRAMs, which use such paraelectrics as silicon oxidized film or silicon nitride film for the storage capacitance, this structure uses incorporating ferroelectrics. As a result, FRAM technologies having this cell configuration are extremely similar to DRAM cell technologies, and the two can be integrated relatively easily.

Cell information is detected by reading the change in current which results from the change in polarization charges when a voltage is applied to a cell (Refer to “2.5 Writing and Reading Cell Data”). Therefore, inevitably cell information is lost in each reading cycle during information is read. And because of the destructive reading, cell information must be rewritten during the same cycle.

(2) MFSFET : Metal Ferroelectric Semiconductor FET
This configuration can be achieved by using a ferroelectric film instead of silicon oxidized film for the gate oxidized film. Cell’s information is written by applying a voltage between the gate electrode and substrate, which polarizes the ferroelectric film. This causes the threshold value of the transistor to change in accordance with the direction of polarity. When a fixed gate voltage is applied, the cell information will be retrieved according to the drain current that corresponds to the transistor threshold caused by the direction of polarity. As a result, the design technologies for this memory has an increased compatibility with those of EEPROM and Flash Memory technologies. The major advantages are that non-destructive reading is possible and that cell area is small.

However, the MFSFET type has some problems preventing the product from being commercialized. They include: nonconformity in the crystal surfaces at the boundaries between the silicon substrate and the ferroelectric, making it difficult to gain stable control of the transistor threshold value, and the significant characteristic deterioration of the ferroelectric film, causing its non-volatility to be lost. To solve these problems, MFMIS (Metal Ferroelectric Metal Insulator Semiconductor) has been suggested, which grows a ferroelectric film on the floating gate. This approach, however, involves difficulties such as voltage division that decreases the amount of polarization and problems such as difficult integration. These issues are still remained.
2.2 Ferroelectric Materials

■ Perovskite Structure and PZT

Many ferroelectrics are chemically expressed as ABO$_3$, with an octahedron constructed by six oxygen atoms including a smaller metallic element near their center. ABO$_3$ type ferroelectric crystals are divided into the perovskite, ilmenite and tungsten-bronze types. Most ferroelectrics that are candidates for storing charges in FRAM are of the perovskite type, which is depicted in the figure below. The tetragonal crystal system perovskite structure is a cubic lattice with one face of the lattice with a (001) direction extended, with the other two direction shrinking. In the extended direction, the displacement of plus ions (A and B), minus ions and their valence electrons separates the center of gravity of the positive and negative electric charges, which allows an electrical polarization moment to occur. The charge amount of electrical polarization moment per unit area is electrical polarization ($\mu$ C/cm$^2$). The extended direction is the c axis <001>, while the a axis <100> and b axis <010> directions are the shrunken direction. Electrical polarization occurs along the c axis direction.

One representative ferroelectric material having a perovskite structure is PZT. PZT is a solid solution of PbZrO$_3$ and PbTiO$_3$. This solution is commonly known as PZT - a name created by taking the first letter from the name of each cation element. The distinguishing feature of PZT material is that the addition of each type of ion (La, for example) causes substantial changes in its material properties. The figure below depicts a perovskite compound having a PZT: Pb(Zr,Ti)O$_3$ crystalline structure.
Other Ferroelectric Materials

Many PZT research has been done for ferroelectric thin film capacitor materials for use in FRAM. This is because PZT has high remnant polarization values ($2P_r$), it obtains ferroelectric characteristics relatively easily, and it has coercive field values that suits it for use in FRAMs. Conversely, SBT: SrBi$_2$Ta$_2$O$_9$, a Bi layer compound, has a low $E_C$, enables an operating voltage decrease by making the film thinner, and exhibits little fatigue even after polarization has been reversed $10^{12}$ times.

The figure below depicts the crystal structure of SBT.
2.3 FRAM Process Flow (Combination with CMOS Process)

A cross-sectional diagram of FRAM memory cell and a description outlining process flow are shown below. First, a standard CMOS processes is used to create a transistor. Next, SiN, SiO₂ is deposited. Next, using an peculiar FRAM process, a capacitor is formed by placing a ferroelectric film between a bottom electrode and a top electrode. TiN is used for connecting the transistor plug and the ferroelectric capacitor. Finally, wiring and a cover film are added in a process similar to that used for standard CMOS logic devices.

The greatest advantage of the FRAM process in the process flow described above is that it is highly compatible with the CMOS logic process, allowing the FRAM capacitor to be mounted without altering the CMOS process significantly.

![Cross-Section of FRAM Memory Process Flow](image)

2.4 Cell Operating Principles

FRAM is a memory that uses ferroelectric materials to take advantage of the polarization phenomenon of ferroelectrics. To understand the principals of FRAM cell operation, one must first understand the characteristics of ferroelectrics or the hysteresis characteristics that exhibit voltage dependency of a polarized electric charge Q and how these characteristics correspond to polarization conditions of a ferroelectric capacitor.

If the voltage applied to the ferroelectric capacitor is Vf, and the voltage level of the bottom electrode is plus (+) with respect to the top electrode, the figure below depicts the relationship between the hysteresis loop and the charge that accumulates in the ferroelectric capacitor.

In “Figure 2.5 Hysteresis Loop and Ferroelectric Capacitor Polarization Conditions”, six points are indicated on the hysteresis loop, indicating the condition of a ferroelectric capacitor. At Vf = 0 V, points A and D describe different polarization conditions with a remnant polarization of +/-Pr. At Vf = +/-Vc, points B and E indicate a polarization of 0, and points C and F describe the conditions of Vf = +/-Vcc.

When applying voltages from 0 V to +Vcc and from 0 V to -Vcc, the polarization state changes progressively around the loop from point A to B to C, and point D to E to F, respectively. When applying voltages from +Vcc to 0 V and from -Vcc to 0 V, the polarization state changes, moving from point C to D and from point F to A, respectively. In this situation, the amount of polarization decrease slightly, without reversing its direction. The amounts of polarization at points C and F are designated as Qs and -Qs, respectively, which are referred to as the amounts of saturation polarization.
To apply these ferroelectric characteristics to a memory, call the two polarization conditions "0" and "1" with "0" the upward polarization and "1" the downward polarization. Also, when the voltage impressed to ferroelectric capacitor is adjusted to 0V (power off), the polarization becomes D and A point in the hysteresis loop like figure. In other words, the remnant polarization charge is +Pr or −Pr, allowing data to be stored.

Indicates the change in ferroelectric polarization if voltage changes according to 0 → +Vc → +Vcc → 0 → −Vc → −Vcc → 0.

Figure 2.5 Hysteresis Loop and Ferroelectric Capacitor Polarization Conditions
Relaxation characteristics

Up to this point, the hysteresis characteristics of ferroelectric capacitors have ignored time dependency (as indicated in Section 2.4) to draw a smooth, continuous curve. These hysteresis characteristics have been observed to follow the curve depicted in the figure below. In other words, with $V_f=0\,\text{V}$ as the point of remnant polarization, polarization charge has been observed to fall off as time dependence moves $A' \to A$ or $D' \to D$. This can be seen as the decrease in $Q$ over a short period of time that corresponds to the retention characteristics that cause $Q$ to deteriorate over a long period of time. Over time this characteristic follows the path $D \to C \to D' \to D$ or $A \to F \to A' \to A$, rather than $D' \to C \to D'$ or $A' \to F \to A'$.

![Figure 2.6 Hysteresis Loop](image-url)
2.5 Writing and Reading Cell Data

■ Writing

Writing "1" or "0" data to a cell requires the application of the voltage +Vcc or −Vcc to both electrodes of the ferroelectric capacitor.

In “Figure 2.7 Fundamentals of Writing and Reading a 1T/1C Cell, Writing”, the actual writing to the 1T/1C cell, the word line (WL) is selected (meaning that the transistor is on) and a voltage (Vcc) is applied between the bit line (BL) and the plate line (PL). Adding this voltage to the ferroelectric capacitor causes data to be written. Writing "0" data is accomplished by making BL = 0 V and PL = Vcc, whereas "1" data is written by making BL = Vcc and PL = 0 V.

After writing, data is retained even if the selected word line becomes unselected (meaning that the transistor is off). In other words, the data is nonvolatile.

As described in “2.4 Cell Operating Principles”, the polarity remains as remnant polarization (+Pr, −Pr) even if the applied voltage is removed.

■ Reading

When reading "1" or "0" data from a cell, prior to selecting WL, BL must be precharged to 0V to retain the high-impedance condition. Next, WL is selected and Vcc is applied to PL. By applying a voltage to the ferroelectric capacitor, the data can be read out. In “Figure 2.7 Fundamentals of Writing and Reading a 1T/1C Cell, Rewriting after reading”, if the cell holds "0" data, the polarization is not reversed but the relatively slight movement of the electric charge (j0) causes BL to charge up by ΔVL. If another cell holds "1" data, polarization is reversed, causing a major movement of the electric charge (j1). This causes BL to charge up by ΔVH. The sense amp, which holds the reference voltage (Vref) established between ΔVL and ΔVH, is connected to BL. In this manner, ΔVL - which has a lower voltage level than Vref - can be further reduced to 0V, and ΔVH - which has a higher voltage level than Vref - can be raised further to Vcc.

The post-amplification bias states of the ferroelectric capacitor are: when reading "0", Vf = +Vcc (the same state as for writing "0") with BL = 0 V and PL = Vcc. When reading "1", Vf = 0 V, meaning that the cell has a 0 (zero) bias, with BL = Vcc and PL = Vcc.

■ Rewriting after reading

When reading "1" data, the reversal in polarity causes the data to be destroyed, creating a "0" data state. Therefore, the "1" data needs to be written again to restore the data to its correct value prior to reading. After reading "1" data, the BL voltage level is Vcc. At this time, PL voltage level becomes 0 V, causing "1" data to be rewritten. Then, when WL is turned off, the bias of the ferroelectric capacitor becomes "0", and the "1" data is stored. In this way, the stored data returns to the original "1" data. When reading "0" data, since no reversal of polarity occurs, the data is not destroyed and a value of "0" is retained.
Chapter 2 Technical Explanation

Figure 2.7 Fundamentals of Writing and Reading a 1T/1C Cell
2.6 Reliability of Ferroelectrics

The ferroelectric materials used for FRAM cells have two main characteristics that affect the reliability of data retention.

1) Data retention characteristics

The figure below depicts data retention characteristics. As time (t) elapses, the polarization charge (Q) decreases (deterioration). This characteristic determines the data retention capability of non-volatile memory. This characteristic can be acceleration tested by temperature. This characteristic is greatly affected by materials. From a design standpoint, this characteristic can be improved by optimizing the write voltage to the ferroelectric capacitor. Fujitsu designs FRAM circuits to maintain the polarization charge in order to improve retention performance.

![Figure 2.8 Data retention characteristics](image)

2) Fatigue characteristics

A fatigue characteristic refers to the tendency for the amount of polarization (Q) to decrease (be degraded) as a result of repeated polarization reversal. The graph below shows this tendency. The horizontal axis of the graph (the number of cycles) indicates the number of times polarization is reversed. The fatigue characteristic is highly dependent on the operating voltage, so the degradation is slower at lower operating voltages. The fatigue characteristic can therefore be further improved by future reduction in the voltage ratings of FRAM devices.

![Figure 2.9 Fatigue characteristics](image)
Chapter 3

Introduction to Fujitsu FRAM Products

This chapter is introducing simply about the various FRAM products of Fujitsu, such as a FRAM stand-alone memory.
3.1 FRAM Stand-alone Memory

Fujitsu has commercialized stand-alone memory with FRAM features that are nonvolatile, high-speed re-writing, low power consumption and high rewriting endurance.

i. Compared with SRAM

SRAM can be replaced to Fujitsu stand-alone memory FRAM because it uses pseudo SRAM I/F. There are advantages by replacing SRAM with FRAM as written below.

(1) Total cost reduction

- Reduction of maintenance burden: The battery exchange is unnecessary
- Downsizing the device: Battery sockets and some other parts are unnecessary
- Reduction in manufacture process: Built-in process and some other process are unnecessary

In general, we need to replace the batteries every one to ten years on Battery Backup SRAM system, but it can be shorter than that cycle, so we have to take care of the battery conditions constantly. There is also the possibility of leaking problem. You will be free from battery leaking problems and maintenance troublesome of using batteries by replacing SRAM with FRAM. We need some extra spaces on substrates and parts like battery sockets and backflow prevention diode other than SRAM and batteries, however, FRAM, one chip can be replaced for them and it also help to reduce manufacturing process and to downsize devices.

(2) For environment

- Battery dispose is unnecessary
- Reduction in manufacture burden

There is an important advantage to make them batteryless for environment, such as environmental impact in FRAM manufacturing process of CO₂ emission conversion is less than half compare to manufacturing SRAM, batteries and sockets and these used batteries would be also industrial waste.

ii. Compared with EEPROM/Flash Memory

Major three features of FRAM are high-speed, low power consumption and high-rewiring endurance compared with existing nonvolatile memories like EEPROM and Flash Memory. There are advantages by replacing SRAM with FRAM as written below.

(1) Total cost reduction

- Extending the life of products/reduction of parts: High-rewriting frequency
- Improvement of delivery efficiency by reduction in writing time: High-speed writing

We can improve manufacture and delivery efficiency by reduction in writing time compared with using EEPROM and Flash Memory in the situation of writing parameter in products one by one.

(2) Performance improvement of embedded products

- Capable of using for a long time in the case of battery drive devices because of the low power consumption
- Improvement in transaction by high-speed writing
- Capable of high-frequency recording because of the high-rewriting frequency

EEPROM and Flash Memory require high voltage internally and high-power consumption for writing, however, FRAM doesn't need high voltage and high-power consumption. Therefore, it is capable of using for a long time compared to EEPROM for battery drive devices. It also can store far exceeded information compared existing EEPROM with FRAM for the use of writing data in very short period. We expect the accuracy to be improved by recording data more frequency than EEPROM and Flash Memory in management of device conditions and records.

We will expand the variation of density and interface of our products in near future.
3.2 FRAM Embedded Secure Processor

The recent dramatic popularization of the Internet has focused attention on E-Commerce, virtual shopping, virtual offices, and other web-based activities. Practical application of these concepts requires the use of security systems using public key encryption.

The FRAM embedded secure processor integrates a Fujitsu 8-bit microcontroller, elliptic curve encryption (public-key encryption) coprocessor, and FRAM into a single chip. The coprocessor enables processing over 1,000 times faster than software processing. The use of FRAM enables updating of essential security-related information on the security chip at higher speed and lower power consumption and dramatically increases the maximum allowable number of times memory can be updated, compared to existing memories such as EEPROM.

This product enables encrypt/signature processing of confidential information inside the chip. The product is therefore expected to significantly contribute to achieving secure systems in the mobile terminals, digital home appliances, and smart cards in the future.

Detail of the public key cryptography is described in “Chapter 5 Security Technology”.

Figure 3.1 Security LSI (for Mobile Application)

- 8Bit CPU + FRAM 4KByte + Crypto Co-processor
- Operating frequency 3.58 MHz
- Min. command operating time 0.28 µs
- Available for Elliptic Curve Cryptography
  - Key length 239 bit (max)
  - Digital signature creation/confirmation, encryption/decryption,
    key exchange is available by firmware
- 8bit CPU
- 32KByte Mask ROM
- 1KByte SRAM
Chapter 3 Introduction to Fujitsu FRAM Products

3.3 FRAM embedded LSI for Smart Cards

Whereas the EEPROM is primarily applied to memory for storing data for the current IC cards (smart cards), by introducing FRAM that features the speed of writing in data which is 10 thousand times faster, electricity consumed which is roughly one 400th and the number of rewriting which is 100 thousand times as much, compared to the EEPROM, Fujitsu has succeeded in giving shape to the LSI for smart cards.

By adopting 0.35 µm FRAM technology, the LSI chip incorporates 32-bit RISC processor, 32 Kbytes FRAM, interface for contact/contactless communication and processor for encryption into a single chip.

By incorporating 32-bit RISC processor, this LSI chip is able to incorporate the operating system that can manage multiple applications. In addition, FRAM with capacity as large as 32Kbytes incorporated allows more than one application to be executed at high speed and with low power consumption and the data to be stored. For communication interface, the contact (ISO/IEC 7816 class A)/contactless types (ISO/IEC 14443 type-B) that meet ISO/IEC standards are adopted.

With a shingle chip, a combination card that can deal with both contact and contactless communication can be realized. Furthermore, by adopting Elliptic Curve Cryptography (ECC), DES, RSA and others as encryption circuits for authentication, a high level of security has been attained. This allows encryption of data required by electronic commerce via the Internet and others or safe security systems for personal authentication by means of public key encryption.

The LSI chip makes use of such features of FRAM as high speed, low power consumption and the high overwriting frequency and consolidates all functions indispensable to smart cards into a single chip; thereby bringing into corresponding to the demand in the broadband, Internet age.

If the multiple applications are not necessary for you, we also have the 8-bit micro controller embedded LSI for smart cards.

They embed 4 Kbytes FRAM and have the advantages of FRAM such as high-speed operation, low power consumption and high rewriting endurance.

3.4 LSI for RFID tags

RFID tags have the advantages of "data writable", "anti-collision", and "the possible to process into various configurations". They get a lot of attention as key parts to bring out new system, which barcode applications couldn't realize.

Fujitsu is mass-producing LSI for RFID tags named "MB89R118" that have the major features written below.
1. Correspond to ISO/IEC15693
2. Read and write high-density data (2Kbyte)
3. High-speed writing
4. Readable and writable as much as 10 billion times

We will develop our products as "FerVID family™" including UHF band based on FRAM mass production technology that we have been leading the world.
3.5 FRAM embedded Custom ICs

Fujitsu provides Custom ICs with embedded FRAM, which combines the best features of both RAM and ROM.

For many circuit designers, "special writing operation is unnecessary, high-speed and capable of random access nonvolatile memory" = "nonvolatile RAM" is very ideal. But existing RAM is volatile, and writing operation speed for ROM is slow and troublesome. Now we can realize the improvement of convenience, and the development burden reduction because of unnecessary to distinguish between RAM and ROM by embedding FRAM. It is also possible to embed various IP such as ROM, RAM, encrypt Macro, MCU Core by utilizing design environment as same as our ASIC.

![Figure 3.2 FRAM embedded custom ICs](image)

We can utilize the features of Custom ICs with embedded FRAM, which are nonvolatile, high-speed rewriting, low-power consumption, and high rewriting endurance for various applications like embedding security operation, identification data, and the storage of the environmental variable for electric household appliances, office equipment machines and portable handsets.

![Applications of FRAM Macro](image)

**Applications of FRAM Macro**
- Storage of product identification data, ID code
- Storage of encryption key for security
- Storage of various mechanical parameter
- Storage of backup data
- Storage of record management and history data
- Storage of boot up program and data

![Figure 3.3 FRAM macro applications](image)
This chapter describes FRAM applications. Currently, there is a growing demand for FRAMs for data storage in the field of smart cards.
4.1 What are Contactless Smart Cards?

Smart cards in which data is transmitted by an electromagnetic field with no contact parts are called contactless smart cards.

Magnetic cards, such as cash cards, credit cards, telephone cards, and train tickets, are already part of our everyday lives. Recently, those smart cards have earned significant attention, which have an LSI chip embedded to store a large amount of information and to read/write data. Train tickets and electronic money are good examples.

Beginning several years ago, smart card feasibility studies have been conducted at several locations throughout the world, and some smart cards have already been put to practical use. Because of the volume of information that can be stored on smart cards and the ease and flexibility of reading and writing the information, smart cards are also ideally suited to security applications. In particular, contactless smart card - which allows data to be transferred without making contact - is a focus of attention because they can be used even while moving.

Contact smart cards to transfer data through electrical contact were introduced to eliminate the need to handle small change. Most so-called "electronic money" uses contact smart cards. However, cards used as train tickets are currently magnetic, and friction caused by contact with the card reader/writer frequently results in problems at ticket gates. Contactless smart cards have gained attention as a way of overcoming such problems. Users of this type of card merely hold it up as they pass a ticket gate. The convenience to passengers has accelerated the development of contactless smart cards.

4.2 About Electric Power Transfer and RF Technologies

Since smart cards do not have batteries, electric power must be supplied from outside of the card.

Electric power transfer methods can be divided broadly into two categories; contact and contactless.

Contact smart cards receive power directly from the reader/writer via gold-plated terminals (electrical contact) contactless smart cards, on the other hand, electric waves from the reader/writer is received by an antenna (coil), and electric waves is then obtained through an RF (Radio Frequency) circuit.

Contactless smart cards use either wireless or optical communication systems, but smart cards generally use wireless communication systems. As the communication distance may be tens of centimeters depending on the communication system, smart cards require lower operating voltages and currents even for memory access.

EEPROM requires not only a booster but also much time for updating data. In contrast, FRAM is suitable for low-power operations as it updates data at high speed and operates at low voltage.

In addition, FRAM can incorporate ferroelectric capacitors to eliminate the need for external capacitors, thereby reducing the number of components and the costs.

Communication methods include (1) the single streaming communication method, in which the transmitter communicates to the receiver, (2) the "talk first" method, whereby transmitter and receiver communicate intermittently, and (3) the simultaneous interactive communication method, in which both devices communicate simultaneously. At present, the most common method is the reader/writer "talk first" method, whereby the smart card responds to the request of a reader/writer.

Modulation types used include (1) ASK modulation levels of 10% and 100%, (2) BPSK, and (3) FSK. These methods support lower power consumption in such limited sizes as smart cards.

Five methods have been adopted for bit coding: "NRZ", "Manchester", "Modified Miller", "Pulse Width", and "Pulse Position".
Chapter 4 Applications

Figure 4.1 Power Transmission in Contact Smart Card

- Electric power
- Gold-plated terminal
- Contact Smart Card
- R / W

Figure 4.2 Power Transmission in Contactless Smart Card

- Magnetic field
- Antenna coil
- LSI chip
- Contactless Smart Card
- R / W
- Electric waves
- Control circuit
- Power supply to controller

Figure 4.2 Power Transmission in Contactless Smart Card
Table 4.1 RFID Technologies Using the 13.56 MHz Frequency

<table>
<thead>
<tr>
<th>Format</th>
<th>Proximity type</th>
<th>Vicinity type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO</td>
<td>14443</td>
<td>15693</td>
</tr>
<tr>
<td>Type</td>
<td>Type A</td>
<td>Type B</td>
</tr>
<tr>
<td>Communication Distance</td>
<td>&lt;10 cm</td>
<td>&lt;10 cm</td>
</tr>
</tbody>
</table>

Transfer from reader/writer to card (Downlink)

<table>
<thead>
<tr>
<th>Carrier Frequency (fc)</th>
<th>13.56 MHz</th>
<th>13.56 MHz</th>
<th>13.56 MHz</th>
<th>13.56 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Modulation Type</td>
<td>ASK</td>
<td>ASK</td>
<td>ASK</td>
<td>ASK</td>
</tr>
<tr>
<td>AM Modulation (Modulation Level)</td>
<td>100%</td>
<td>8 to 14%</td>
<td>100%</td>
<td>10 to 30%</td>
</tr>
<tr>
<td>Subcarrier Frequency</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Required Bandwidth</td>
<td>+/- (1/Power Pause Time)</td>
<td>+/- Communication Speed × 1</td>
<td>+/- (1/Power Pause Time)</td>
<td>+/- Communication Speed × 2</td>
</tr>
<tr>
<td>Data Rate</td>
<td>105.9375 (fc/128) [211.875 (fc/64)]</td>
<td>105.9375 (fc/128) [211.875 (fc/64)]</td>
<td>1 out of 256 : 1.65 (fc/8192)</td>
<td>1 out of 4 : 26.48 (fc/512)</td>
</tr>
<tr>
<td>Bit Coding</td>
<td>Modified Miller</td>
<td>NRZ-L</td>
<td>Pulse Position (PPM)</td>
<td></td>
</tr>
<tr>
<td>Self-clock in Data</td>
<td>Self-clock</td>
<td>No self-clock</td>
<td>Self-clock</td>
<td>Self-clock</td>
</tr>
<tr>
<td>Peak Difference between Main and Sideband</td>
<td>Approx. 14 dB</td>
<td>Approx. 28 dB</td>
<td>Approx. 14 dB</td>
<td>Approx. 28 dB</td>
</tr>
</tbody>
</table>

Transfer from card to reader/writer (up link)

<table>
<thead>
<tr>
<th>13.56 MHz transmission Transfer from card to reader/writer</th>
<th>Load Modulation</th>
<th>Load Modulation</th>
<th>Load Modulation</th>
<th>Load Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication with reader/writer</td>
<td>Talk first Reader/ writer Talk first *</td>
<td>Talk first Reader/ writer Talk first *</td>
<td>Talk first Reader/ writer Talk first *</td>
<td>Talk first Reader/ writer Talk first *</td>
</tr>
<tr>
<td>Digital Modulation Type</td>
<td>ASK Subcarrier</td>
<td>BPSK Subcarrier</td>
<td>FSK Subcarrier</td>
<td>ASK Subcarrier</td>
</tr>
<tr>
<td>Subcarrier Frequency</td>
<td>847.5 kHz (fc/16)</td>
<td>847.5 kHz (fc/16)</td>
<td>423.75 kHz (fc/32)</td>
<td>423.75 kHz (fc/32)</td>
</tr>
<tr>
<td>Data Rate</td>
<td>105.9375 (fc/128) 211.875 (fc/64)</td>
<td>105.9375 (fc/128) 211.875 (fc/64)</td>
<td>6.67 (fc/2032) 26.69 (fc/508)</td>
<td>6.62 (fc/2048) 26.48 (fc/512)</td>
</tr>
<tr>
<td>Bit Coding</td>
<td>Manchester</td>
<td>NRZ</td>
<td>Manchester</td>
<td>Manchester</td>
</tr>
</tbody>
</table>

* : Transmits after recognizing a specific code from the reader/writer
4.3 Reader/Writer

A smart card reader/writer is a equipment that communicates data (reading and writing) between the system and smart card. Some such equipment transmit electric power to smart cards that do not have internal lithium batteries or other operating power sources. The relationship between the reader/writer and the smart card is illustrated below.

The data transmitter sends data to and receives data from the smart card while supplying power to it. The contactless smart card reader/writer has an antenna coil to communicate data and transmit power by radio. The data transmission controller performs control processing to allow data communication with the smart. The system interface exchanges data with the host system and performs the encryption process.

![Figure 4.3 Relationship between Reader/Writer and Smart Card](image)

4.4 Contactless Smart Card Market

There are two types of smart cards - contact and contactless - although currently, most are contact type. The market for these cards has been expanding steadily, particularly in Europe.

A number of possible applications for smart cards are listed below. Recently, there has been an increasing demand for contactless smart cards, and feasibility experiments have been conducted with regard to use of these cards in place of tickets for trains, airplanes, and other modes of transportation. Among the smartcard-related fields listed below, the market for contactless smart cards can be expected to include these transportation ticket replacements, as well as ID cards and tags for the distribution field.

**<Applications for Smart Cards>**

- **Transport:**
  - Railways, Undergrounds, Buses, Taxis (Tickets, Commuter passes, Prepaid cards)
  - Electronic Toll Collection systems on toll highways
  - Airlines (Member management systems, Frequently flyer program)

- **Distribution:**
  - Tags for freight, tools, etc.

- **Identification:**
  - Student and company employee identification cards (Entry/exit of buildings, Cashless payment at cafeterias, Library use, etc.)
Chapter 4 Applications

- Public services:
  Cards issued by local government, Resident cards, Drivers licenses, Passports, Telephone cards, etc.
- Payment function:
  Bank cash cards, Credit cards issued by banks and credit loan companies, Electronic money, Amusement cards, etc.
- Wireless communications:
  SIM cards for GSM
- Broadcasting:
  Receiving fee-based television broadcasts at home
- Medical insurance:
  Health insurance certificate, recording medical information, etc.
- Others:
  - Member cards issued by companies, department stores, shopping areas, etc.
  - Purchase and sale of products and provision of services over the Internet (E-Commerce), etc.

4.5 About Battery Backup

One of the necessary conditions of work memory for equipments used on production lines is that it has non-volatile data. This is required besides random accessibility to cope with equipment breakdowns and sudden power outages.

At present, SRAM is commonly used for work memory, with lithium batteries or other power sources for data storage. In general, batteries need to be replaced approximately once a year, but battery life is sometimes shorter. It is therefore necessary to constantly monitor battery conditions. In addition, mechanical vibrations from motors and other device inside a system can lead to battery leakage, possibly causing equipment to break down. Therefore, replacing battery-backed-up SRAM (BBSRAM) with FRAM frees operators from the troublesome maintenance or leakage problems that batteries present.
The most significant feature of the smart card is the high level of security attainable.

There is a growing trend toward smart cards as a replacement for magnetic cards, in order to prevent such illegal activities as unauthorized access to confidential data and falsification of personal information.

This chapter provides an outline of the security technologies featured in the smart card.
5.1 Security

Smart cards are continuing to evolve as a part of the social infrastructure, and it is essential to establish fundamental technologies maintain security and ensure peace of mind. As the range of information and functions contained by smart cards increases, security to prevent unauthorized access or falsification of data will become more important than ever before. This security falls into two categories - hardware security geared toward tamper resistance, and software security, which involves digital encryption technology.

■ Hardware Security (Tamper Resistance)

In order to maintain hardware security, it is necessary to protect non-volatile memory against unauthorized access, and to prevent the analysis of the LSI’s internal logic through reverse engineering. Reverse technology involves such methods as 1) peeling off the LSI chip; 2) analysis using operational test circuits; and 3) analysis using low-frequency clocks.

■ Software Security (Encryption Technology)

Smart cards offer a variety of security functions, including authentication, safe communications (encryption technology), data read/write protection, and protection of confidential data. Encryption technology is central to all of these functions. "Common key (private key) cryptography" and "public key cryptography" are two types of encryption functions that are effective in preventing illegal access to the LSI’s internal information.

(1) Common key (Private key) cryptography:

With common key cryptography, both the sender and receiver have the same key, which allows each of them to encrypt and decrypt information. Although these systems allow processing speeds ranging from several MB/s to 100 MB/s, both parties need to keep the common keys in a safe location beforehand. Commonly used systems include DES and Triple-DES. AES has been standardized as a next-generation encryption function to replace DES.

(2) Public key cryptography:

With public key cryptography, both the sender and receiver have different keys to encrypt and decrypt information. The cryptography is used mostly to distribute common keys over networks. Different from common key cryptography, public key cryptography does not require users to have the same key beforehand, which make keys easier to manage. However, the processing speeds are slower (from several KB/s to 100 KB/s), meaning that circuits become larger if systems are hardware-based. One such system is RSA. Typical systems of this type are RSA and elliptic curve cryptography.
5.2 Elliptic Curve Cryptography and RSA cryptography

In terms of encryption algorithms, RSA cryptography uses unique factorization from arithmetic theory for key creation and data encryption and decryption; as a result, the encryption strength characteristics are such that the unique factorization questions are extremely difficult to solve. Calculations in the case of Elliptic Curve Cryptography is based on the points of an elliptic curve, resulting in encryption strength characteristics in which it is difficult to solve the discrete logarithm problems from these points. In both of these schemes, it is extremely difficult for a third party (cracker or hacker) to decipher the private key or plain text from the public key or ciphertext. Given these characteristics, a high level of security can be achieved through the use of either of these schemes.

There are many application examples of public key encryption schemes; RSA cryptography is currently in wide use on the Internet. RSA cryptography is used as the public key encryption method in smart cards as well, but problems arising from the processing time have led to increased interest in Elliptic Curve Cryptography for these applications.

In comparison to RSA cryptography, Elliptic Curve Cryptography has the following advantages:

- Equivalent encryption strength achieved with shorter key lengths Key lengths can be reduced significantly by using Elliptic Curve encryption. For example, with a key length of 1024 bits in the case of RSA encryption, the equivalent key length using Elliptic Curve encryption would be 160 bits; with an RSA key length of 2048 bits, the Elliptic Curve encryption key length would be 211 bits.
- Reduced key length growth rate
  
  In the previous example, where the key length in the case of RSA encryption is doubled (1024 → 2048), the key length for Elliptic Curve encryption increases by only $1.3 \times (160 \rightarrow 211)$.
- Because of the shorter key length, processing time decreases, and higher encryption processing speeds become possible.
- Because the computation processing volumes are reduced, the scale of the hardware can be reduced as well.
- Elliptic Curve encryption is perfectly suited to improved encryption strength on the limited surfaces of semiconductor chips.

Fujitsu has led the world with the commercial release of a microcontroller with on-board FRAM - an original FRAM product with an embedded Elliptic Curve encryption coprocessor that incorporates next-generation Elliptic Curve encryption and FRAM into a single chip. For further details, refer to “Chapter 3 Introduction to Fujitsu FRAM".
Chapter 6 Customer Support

This chapter outlines ferroelectric RAM (FRAM), to provide a basic understanding. In addition, the chapter describes the position of FRAM among all types of memory and describes its difference from other types.
6.1 Firmware Development Support
Fujitsu offers a development kit to support customer firmware development.

Table 6.1 Development kit

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Support</th>
<th>PC Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chip only (customer develops OS)</td>
<td>ICE</td>
<td></td>
</tr>
<tr>
<td>2. Chip + OS (customer and FJ develop OS)</td>
<td>ICE</td>
<td>Depend on customer</td>
</tr>
<tr>
<td>3. Chip + OS + ISO command</td>
<td>Already implemented</td>
<td></td>
</tr>
<tr>
<td>4. Chip + OS + (ISO command) + user command</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.1 System configuration

6.2 Chip Supply
Fujitsu employs leading-edge technologies in its manufacture of semiconductor ICs. We also supply chips using a wafer process that is designed to contribute to our customers’ businesses. In addition to this wafer process, we offer integrated testing and assembly services.

Our chip supply business models comprise a COT support and a wafer manufacturing service. For details, see “6.4 COT Support” and “6.5 Wafer Manufacturing Service”, respectively.
6.3 COT Support

Fujitsu performs mask making and wafer processes for products whose logic and layout are designed by customers using their own tools. Fujitsu also supports customers by providing necessary design documents and data.

With demand for top-down design increasing each year, Fujitsu actively supports a variety of third-party tools.

We provide our COT support services according to the flow described below.

Figure 6.2 LSI Design System

- Mask Design Rules
- Process Parameters
- Permitted Current
- Hot Carrier Rules
- Antenna Rules
- SPICE Models
- Drawing Guide
- FRAM Macro (Cell Information)
- Mask Making
- Wafer Process (Optional)
- Wafer Sort
- Assembly
- Final Test

Design Kits for FRAM & MCU
- Mask design rule
- Drawing guide & Design guide
- Process parameter
- Permitted current
- SPICE parameter
- etc.

Development tools for MCU
- Software
  - Development Manager SOFTUNE™
  - 8bit, 16bit family OS
- Hardware
  - Emulators, for 8bit, 16bit

10 weeks TAT
0.5μm, 5V Technology is ready
0.35μm, 3V Technology is ready

Figure 6.3 COT Service
6.4 Wafer manufacturing service

Fujitsu provides the following types of wafer manufacturing service.

Standard service
Based on GDS II data resulting from customer’s designs, Fujitsu performs mask making and wafer processes, and ships wafers which have been subjected to PCM tests.

Mask making
Fujitsu also makes masks based on GDS II data provided by customers. By linking these operations with wafer processes, we supply masks in a timely manner.

Wafer processes
At present, Fujitsu’s wafer manufacturing service include wafer processes provided by its Mie, Wakamatsu, Iwate plants and Akiruno Technology Center. The wafer manufacturing service for FRAM is supported by Iwate plants.

Option #1
In addition to its standard services, Fujitsu offers wafer testing. Using testing programs provided by customers, Fujitsu performs wafer testing by using logic, analog, and memory testers according to device functions and then ships the wafers.

Option #2
In addition to its standard services and those mentioned in Option #1, Fujitsu provides assembly services. Based on assembly wiring diagrams and leadframe information provided by customers, Fujitsu assembles devices and ships them to the customers.

Option #3
In addition to its standard services and those described in Option #1 and Option #2, Fujitsu provides LSI testing services. Based on LSI testing programs provided by customers, Fujitsu performs LSI testing by using logic, analog, and memory testers according to device functions. Once testing is completed, Fujitsu ships these devices to the customers.

Figure 6.4 Flow of Foundry Services
Figure 6.5 Wafer Plants
Wakamatsu plants (Logic)
ISO9001: 2000 Acquisition
ISO/TS16949: 2002 Acquisition
ISO14001 Acquisition

Iwate plants (Memory & Logic)
ISO9001: 2000 Acquisition
ISO/TS16949: 2002 Acquisition
ISO14001 Acquisition

Wakamatsu plants
Iwate plants
Mie plants
Akiruno Technology Center

Mie plants (Memory & Logic)
ISO9001: 2000 Acquisition
ISO/TS16949: 2002 Acquisition
ISO14001 Acquisition

Akiruno Technology Center
(Leading-edge technology development)
ISO9001: 2000 Acquisition
ISO/TS16949: 2002 Acquisition
A ferroelectric random access memory (FRAM) is non-volatile and it does not require any power in order to retain stored data. This feature is ideally suitable for reducing environmental impact of electrical and electronic equipment (EEE).

This chapter describes Fujitsu’s activity to reduce the environmental impact of electronic devices and demonstrates several activities for greening FRAM.
Chapter 7 Greening FRAM

7.1 Introduction

Current products of electrical and electronic equipment (EEE) have become more oriented for personalized and mobile usages. Accordingly, faster operation and lower power consumption is required.

FRAM is a non-volatile memory device that utilizes a ferroelectric material in the memory cell. An electrically activated polarization state in this material changes its direction up to down, and vice versa when an external electric field is applied. The direction of the polarization is retained even after the external electric field is removed. This means that FRAM can hold binary data without any power consumption. Restore and rewriter operation in memory cells are carried out by switching the polarization direction of the ferroelectric material. The switching speed of the ferroelectric has been shown to occur on the order of nanoseconds, which is one billionth of a second.

In order to ensure sustainable development we must take it into consideration when producing future products how these products will interact with the environment. Consequently, it is important to reduce the environmental impact of EEE and electronic devices as well as their components. The non-volatility feature of FRAM is an inherent property which results in devices which are battery (drycell)-less and maintenance-free. As a consequence, FRAM contributes to reduce the environmental impact.

To take advantage of the characteristics of FRAM, it must be attempted for greening, which means to reduce the environmental impact. This chapter discusses the substances used in the production of FRAM and those contained in the FRAM devices. We demonstrate Fujitsu’s activity for greening FRAM, and our efforts in producing lower environmental impact products.

7.2 Fujitsu’s Group Guideline for the restriction of environmentally hazardous substances

We describe the Fujitsu group guideline for the restriction of environmentally hazardous substances involved in all product line-ups and any parts of the production process.

The Fujitsu group classified three groups of hazardous substances, as listed below, and prohibits their use in the production process and their presence in any products. This guideline applies to all Fujitsu electronic devices, including FRAM. Restriction of these specified hazardous substances has been strictly observed in the stage of raw material purchasing and production. By the end of FY2005 at the latest, Fujitsu group plans to completely abolish the use of the specified hazardous substances described below.

■ Substances prohibited in all products

Table 7.1 lists a total of 27 chemical substances that are prohibited in all products. These substances include bis (tributyltin) oxide (TBTO), CFCs (chlorofluoro carbons), and polybrominated biphenyls (PBBs), which are listed in the relevant laws and directives such as the Law Concerning the Examination and Regulation of Manufacture, etc., of Chemical Substances (LERMCS) [1], the Montreal Protocol on Substances that Deplete the Ozone Layer [2], and the EU RoHS Directive [3].

■ Substances prohibited in all production processes (Ozone-Depleting Substances)

Table 7.2 lists seven chemical substances that are prohibited in all production processes. These substances include CFCs and specific halons, which are listed in the Montreal Protocol on Substances that Deplete the Ozone Layer.

■ Substances eliminated in all products

Table 7.3 lists four chemical substances that are to be eliminated in all products, in accordance with the EU RoHS Directive. These chemical substances include cadmium and its compounds, and hexavalent chromium compounds. In practice, however, certain substances and specific applications are exempted from the requirements of elimination in all products because of a lack of suitable alternatives, in accordance with the RoHS Directive (Table 7.4).
Table 7.1 Hazardous Substances Prohibited

<table>
<thead>
<tr>
<th>No.</th>
<th>Restricted unit substance (group)</th>
<th>CAS No.</th>
<th>Major applicable legal regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>Polychlorinated Biphenyls</td>
<td>1336-36-3</td>
<td>EU Directive</td>
</tr>
<tr>
<td>002</td>
<td>Polychlorinated Naphthalenes (with more than 3 chlorine atoms)</td>
<td>70776-03-3</td>
<td></td>
</tr>
<tr>
<td>003</td>
<td>Asbestos</td>
<td>1332-21-4</td>
<td></td>
</tr>
<tr>
<td>004</td>
<td>CFCs *1</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>007</td>
<td>1,1,1-Trichloroethane</td>
<td>71-55-6</td>
<td>Montreal Protocol</td>
</tr>
<tr>
<td>008</td>
<td>Chlorobromomethane</td>
<td>74-97-5</td>
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<td>009</td>
<td>Methyl bromide</td>
<td>74-83-9</td>
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</tr>
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<td>HBFC *1</td>
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</tr>
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<td>011</td>
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<td>59536-65-1</td>
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<td>85535-84-8</td>
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<td>Bis(tri-n-butyl)oxide</td>
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<td>015</td>
<td>Tributyl tins &amp; Triphenyl tins</td>
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<td>LERMCS Class 2</td>
</tr>
<tr>
<td>016</td>
<td>Amines *3</td>
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</tr>
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<td>017</td>
<td>Azo compounds *4</td>
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<td>018</td>
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<td>020</td>
<td>Aldrin</td>
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<td>021</td>
<td>Endrin</td>
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<td>022</td>
<td>Dieldrin</td>
<td>60-57-1</td>
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<td>Hexachlorobenzene</td>
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<tr>
<td>024</td>
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<td></td>
</tr>
<tr>
<td>025</td>
<td>2,4,6-tri-tert-butylphenol</td>
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</tr>
<tr>
<td>026</td>
<td>Toxaphene</td>
<td>-</td>
<td></td>
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<tr>
<td>027</td>
<td>Mirex</td>
<td>2385-85-5</td>
<td></td>
</tr>
</tbody>
</table>

*1: See “Table 7.5 Ozone-depleting substance detailed list”
*3: See “Table 7.6 Specific Amin detailed list”
*4: Azo dyes and azo pigments that form specified amines and are used on locations that will be in direct contact with the skin for a long period of time.

: Ozone-depleting substances
Table 7.2 Fujitsu Group Specified Hazardous Substances Prohibited for Use in all Production

Table 7.2 Hazardous Substances Prohibited During Manufacturing

<table>
<thead>
<tr>
<th>No.</th>
<th>Restricted unit substance (group)</th>
<th>CAS No.</th>
<th>Major applicable legal regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>CFCs *</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>002</td>
<td>Halons *</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>003</td>
<td>Carbon tetrachloride</td>
<td>56-23-5</td>
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<tr>
<td>004</td>
<td>1,1,1-Trichloroethane</td>
<td>71-55-6</td>
<td>Montreal Protocol</td>
</tr>
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<td>005</td>
<td>Chlorobromomethane</td>
<td>74-97-5</td>
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</tr>
<tr>
<td>006</td>
<td>Methyl bromide</td>
<td>74-83-9</td>
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</tr>
<tr>
<td>007</td>
<td>HBFC *</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

* : See “Table 7.5 Ozone-depleting substance detailed list”

Table 7.3 Hazardous Substances to be Eliminated

<table>
<thead>
<tr>
<th>No.</th>
<th>Restricted unit substance (group)</th>
<th>CAS No.</th>
<th>Major applicable legal regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>Cadmium and its compounds</td>
<td>-</td>
<td>RoHS Directive</td>
</tr>
<tr>
<td>002</td>
<td>Hexavalent chromium compounds</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>003</td>
<td>Lead and its compounds</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>004</td>
<td>Mercury and its compounds</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4 Applications of the Restricted Hazardous Substances Exempted from Prohibited Substances

<table>
<thead>
<tr>
<th>substance</th>
<th>Purpose that makes the substance exempt as a substance to be totally abolished</th>
</tr>
</thead>
</table>
| Lead(Pb)           | Lead in high melting temperature type solders (i.e. tin-lead solder alloy containing more than 85% lead)  
|                    | Lead in glass of cathode ray tubes, electronic components and fluorescent tubes  
|                    | Lead in electronic ceramic parts (e.g., piezoelectronic devices)  
|                    | Lead as an alloying element in steel containing up to 0.35% lead by weight  
|                    | Lead as an alloying element in aluminum alloy containing up to 0.4% lead by weight  
|                    | Lead as an alloying element in copper alloy containing up to 4% lead by weight  |
| Mercury(Hg)        | Mercury in compact fluorescent lamps not exceeding 5 mg per lamp  
|                    | Mercury in straight fluorescent lamps not exceeding 10 mg per lamp  
|                    | Mercury in other lamps not specifically mentioned in this table  |
| Cadmium(Cd)        | Cadmium for the surface treatment of electric contact points required to ensure high reliability  |
| Hexavalent chromium (Cr ⁶⁺) | Hexavalent chromium as an anti-corrosion of the carbon steel cooling system in absorption refrigerators |
Table 7.5 Ozone-depleting substance detailed list

<table>
<thead>
<tr>
<th>Regulation unit substance (group)</th>
<th>Detailed substance</th>
<th>CAS No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
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<td>CFC-115</td>
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<td>CFC-13</td>
<td>75-72-9</td>
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<td>CFC-111</td>
<td>354-56-3</td>
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<td>CFC-112</td>
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<td>Halon-1301</td>
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<td></td>
<td>Halon-2402</td>
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<td>Carbon tetrachloride</td>
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<td>71-55-6</td>
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<td>Chlorobromomethane</td>
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<td>74-97-5</td>
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<tr>
<td>Methyl bromide</td>
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<td>74-83-9</td>
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<td>Tribromodifluoroethane</td>
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<td>Bromotetrafluoroethane</td>
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<td>Dibromofluoroethane</td>
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<td>Bromofluoroethane</td>
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<td>Chlorobromomethane</td>
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### Table 7.6 Specific Amin detailed list

<table>
<thead>
<tr>
<th>Regulation unit substance (group)</th>
<th>Detailed substance</th>
<th>CAS No.</th>
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<tbody>
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<td>Biphenyl-4-ylamine</td>
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<td>Benzidine</td>
<td>92-87-5</td>
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<tr>
<td>4-Chloro-o-toluidine</td>
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<tr>
<td>2-Naphthylamine</td>
<td>91-59-8</td>
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</tr>
<tr>
<td>o-Aminoazotoluene</td>
<td>97-56-3</td>
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</tr>
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<td>5-Nitro-o-toluidine</td>
<td>99-55-8</td>
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<td>p-Chloroaniline</td>
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<td>4-Methoxy-m-phenylenediamine</td>
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<td>4,4’-Methyleneedianiline</td>
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<td>3,3’-Dichlorobenzidine</td>
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<td>3,3’-Dimethylbenzidine</td>
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<td>4,4’-Methylene-di-o-toluidine</td>
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<td>2-Methoxy-5-methylaniline</td>
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<td>3,3’-Dichloro-4,4’-diaminodiphenyl methane</td>
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<td>o-Toluidine</td>
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<td>2,4,5-Trimethylaniline</td>
<td>137-17-7</td>
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<td>o-Anisidine</td>
<td>90-04-0</td>
<td></td>
</tr>
<tr>
<td>4-Aminoazobenzene</td>
<td>60-09-3</td>
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</tbody>
</table>
7.3 Implementation of lead-free FRAM

For greening FRAM, we observe the Fujitsu group guideline for the restriction of environmentally hazardous substances in the purchasing of raw materials, during the production process, and in products themselves. This section describes Fujitsu’s approach for eliminating lead, which is one of the specified hazardous substances.

Lead has been used in a number of materials as a joining material for electronic components in the form of lead solder (e.g., eutectic solder with a composition of Sn63%-Pb37%). Typical application is the solder alloy plating in order to join printed circuit boards to the package lead frame pins. FRAM, in particular, contains lead in an oxide form in the ferroelectric capacitor material (lead zirconate titanate: PbZrTiO₃, or PZT).

The other specified hazardous substances have never been used in FRAM; they are to be abolished in all Fujitsu products by the end of FY2005 at the latest.

Fujitsu’s plan to eliminate lead in FRAM is described as the following.

The potential effects of lead on human health have been reported in detail by the U.S. EPA (Environmental Protection Agency) and ATSDR (Agency for Toxic Substances and Disease Registry) [4], [5].

■ Lead-free Package

Packages that contain the electronic device are available in lead type and ball type depending on the circuit board mounting method.

Fig.7.1 shows a typical lead-type SOP (Small Outline Package). This type is widely used Sn90%-Pb10% lead solder as a plating material for joining the lead frame pins. This lead solder has already been eliminated and lead-free solder is being used. Currently, lead-free solder plated packages are available upon receiving a customer’s request. Note that the Fujitsu standard lead-free solder has a composition of Sn98%-Bi2%.

Fig.7.2 shows a typical ball-type FBGA (Fine Pitch Ball Grid Array) package. The previous composition of conventional solder ball was Sn63%-Pb37%. These lead solder balls have also been eliminated and lead-free solder balls are substituted. Lead-free solder ball packages are available upon request. Note that the Fujitsu standard solder ball composition is Sn96.5%-Ag3%-Cu0.5%.

We recommended the Fujitsu standard lead-free solders as the best solders, based on the total evaluation of whisker, wettability, strength, and cost. In addition, we verified the performance characteristics, which are equivalent to conventional solders through a variety of tests, including lead tensile strength in mounting temperature cycle, drop tests, and vibration tests. Furthermore, we verified secondary mountability in lead-free solders, which revealed as good of performance as the conventional solders have shown.

The lineup of typical surface mount packages is shown on the Fujitsu web site on the Technical Information of Electronic Devices page [6]. We guarantee the quality in the IR reflow temperature up to 250 °C as the guarantee temperature for heat resistance. The customers should pay attention to the specified IR reflow temperature in the soldering process.

---

![Figure 7.1 Schematic Cross-sectional View of an SOP](image)
Chapter 7 Greening FRAM

Figure 7.2 Schematic Cross-sectional View of a FBGA Package

■ Ferroelectric Capacitor

FRAM contains a lead oxide within the ferroelectric capacitors. Fig.7.3 presents a schematic cross-sectional view of FRAM. A ferroelectric layer is shown as the 200-nm-thick layer between the upper and lower metallic thin layers (electrodes). In this layer, lead is present in a crystalline metal oxide called PZT. Fig.7.4 shows a schematic structure of PZT crystal.

In the RoHS Directive that specifies the restrictions in the use of lead, PZT is regarded as electronic ceramic parts and is exempted from the list of prohibited substances. Accordingly, Fujitsu also deals with PZT as an exemption from our restrictions related to specified hazardous substances.

The lead concentration in FRAM devices varies among products, though it is no more than 30ppm in current FRAM devices. Let us examine the lead concentration in our living environment, compared with the lead concentration in FRAM.

Lead is one of the naturally occurring elements that exist in the earth’s crust. The concentration of the elements in the earth’s crust (extending about 10 miles below the surface) was estimated by F. W. Clarke (1924) and is known as the Clarke number. The concentration of natural lead ranges from 13 to 15ppm [7]. The concentration of lead present in the soil around our living environment, including residential areas and urban parks, is known to have a background level between 15 and 30ppm [8]. This means that the lead concentration in FRAM is almost equal to that in soil.

In Japan, contaminated soil must be reclaimed according to Japanese law when the lead concentration exceeds 150ppm (mg/kg) [9]. Hence, even if every FRAM is disposed of improperly and the lead would be inadvertently dispersed into the soil, the lead concentration will never reach the criterion needed for reclamation.

Livestock can ingest and plants (grains, vegetables and fruits) may extract lead from the soil during their growing processes. Consequently, every natural food contains lead, though the concentration is extremely small. The U.S. EPA published a well-organized survey report on their systematic investigation of the concentrations of major elements in foods in 1986 [10]. This report lists the lead concentrations to be 3 to 83 ppm (µg/g) in dairy products and 2 to 136ppm in grains. Although we would never expect for FRAM to be ingested, we note that FRAM has a similar lead concentration level to that in natural foods.
Lead Zirconate Titanate (PZT) Crystal Structure

1. Polarization occurs when an electric field is applied (Zr/Ti atoms move upward or downward in the crystal).
2. Polarization remains even after the electric field is removed.
3. Two stabilized states are stored in the form of "0" and "1" data.

Figure 7.3 Schematic Cross-sectional View of FRAM

Figure 7.4 Schematic Structure of PZT crystal
7.4 Subsequent approaches

As mentioned above, Fujitsu group prohibits the use and presence of the specified hazardous substances throughout their group-wide activities. For packages, we are ready to supply the packages using lead-free solders for mounting of electronic packages and solder balls.

Ferroelectric capacitors are exempted as electronic ceramic parts in the RoHS Directive. The lead concentration in FRAM devices is almost equal to the concentration in soil, which is similar to that present in foods.

As FRAM becomes more widely used in the future, the demand of FRAM is expected to increase. There is a potential that long-term use may result in an unfavorable increase in environmental impact, when FRAM devices are disposed of improperly. Therefore, in order to reduce the environmental impact, Fujitsu is considering the use of lead-free ferroelectric materials for the future generations of FRAM products. We will make continuous efforts to achieve this plan through research and development.

In the selection of new ferroelectric materials, we are going to introduce the method of integrated LCA (Life Cycle Assessment) \(^{[11]}\). Through a comprehensive evaluation of environmental impacts, including human health, ecological system, and effects on social assets due to resource depletion, Fujitsu will make every effort to develop products that truly minimize the environmental impact. This is our approach for greening FRAM and that meet the needs of our customers.

References


9. Enforcement Regulations for Soil Contamination Countermeasures Law (Ordinance No. 29 issued by the Ministry of the Environment on 26 December 2002).

