Ferroelectricity in Memory Devices

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Abstract— *Ferroelectrics are characterized by spontaneous polarization, the direction of which can be reversed by an external electric field. These two states of spontaneous polarization are used as the logic states of a memory device that does not require power backup to maintain the stored information. The basic physics, properties and the role of ferroelectric materials as non-volatile memory devices is discussed.*

Keywords — *Ferroelectric, polarization, non-volatile, FeRAM , hysteresis loop***.**

INTRODUCTION

Ferroelectric materials are the research subjects which have led to new discoveries in the field of both science and technology. Furthermore, these materials are likely to offer new kinds of devices and functionality, because of their size-dependent properties, which have motivated a lot of current research activity in the area of ferroelectric materials. Ferroelectric materials possess a spontaneous electric polarization, the direction of which can be switched with an applied electric field. In fact, in the case of ferroelectric materials, the 'ferro' part of the name arises from their electrical properties which are similar to the magnetic properties of iron-based magnetic materials; most of them, however, are not ferrous, since they do not contain iron. Ferroelectrics are used to make capacitors with high dielectric constant materials, and also have applications in non-volatile data storage etc.

FERROELECTRIC MATERIALS

Ferroelectrics are a class of materials exhibiting spontaneous polarization below the ferroelectric Curie temperature (T_C), and the polarization direction can be changed by an applied electric field. At temperatures above T_C, the crystals are non-polar and no longer ferroelectric and behave like normal dielectrics. Generally there may exist more than one Curie temperature, although most of the ferroelectrics have one Curie point. The Rochelle salt $KNaC_4H_4O_6\cdot 4H_2O$, for example, has two Curie points, one at 24°C and one at −18°C, so that the ferroelectric state exists in the temperature range from −18 to +24°C [1]. The dielectric constants of ferroelectric materials are extremely high, especially near the Curie temperature. A ferroelectric crystal consists of domains; i.e., regions with uniform spontaneous polarization. In the absence of an electrical field, the domains are randomly oriented, which results in near complete compensation of polarization. When an external electric field is applied, the domains become oriented along the field causing polarization of the material. The switching of domain orientation proceeds through domain-wall motion.

Hysteresis Loop and logical states

Ferroelectrics are a special group of ceramics that have a spontaneous polarization reversible by an applied electric field, yielding a hysteresis loop on a polarization–electric field (P–E) graph [5]. The presence of "up" and "down" polarized states allows usage in memories as "1" and "0" bits [6, 7]. The reversibility of permanent polarization, which results in a hysteresis loop in the dependence of polarization P on electric field E is analogous to magnetization curves in ferromagnetic materials. A typical view of a hysteresis P-E loop is shown in Figure 1. The hysteresis loop is characterized by saturation polarization P_s, remanent polarization P_r, and coercive field E_c. Saturation polarization is the maximum polarization that can be reached, remanent polarization is the polarization present when no electric field is applied, and coercive field is a value of electric filed that is required to bring the polarization to zero.

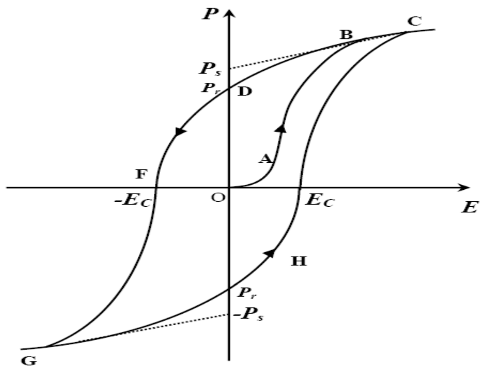

Fig. 1 Typical polarization vs. electric field (*P*-*E*) hysteresis loop of ferroelectrics Fig1: Hysteresis loop with up and down polarized states

A. Switching in Ferroelectrics

Switching is the process by which the remanent polarization is reoriented to a new position of remanent polarization; P_r. It is possible to induce switching both by an electric field and mechanical stress. The polarization switching phenomenon is usually studied using bipolar square wave form pulses. This signal has two advantages: (i) the field is constant during the switching and (ii) this arrangement is similar to that used for memory applications [13]. At zero applied field, there are two states of polarization, $\pm P_r$ furthermore, these two states of polarization are equally stable. Either of these two states could be encoded as a “1” or a “0” and since no external field is required to maintain these states, the memory device is non-volatile. To switch the state of the device, a threshold field greater than $\pm E_c$ is required. Additionally, in order to reduce the required applied voltage (to within 5 V) for a given E_c, the ferroelectric materials need to be processed in thin films. In most of ferroelectric memories, the memory cell is read destructively by sensing the current transient that is delivered to a small load resistor when an external voltage is applied to the cell

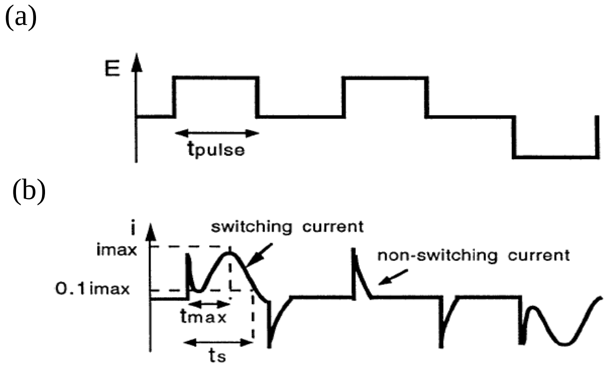

Fig. 2: Shows a typical (a): input pulse and (b): output switching current for a ferroelectric [12].

Figure 2 shows a typical input pulse and the output switching current for a ferroelectric. The polarization switches from $-P_r$ to $+P_r$ when the field is applied antiparallel to the polarization ($-P_r$). The output current shows the spike and bell shaped curve. The former may be due to the fast linear dielectric response and the later is due to polarization switching. Once the ferroelectric is switched the same pulse may be applied again, this time parallel to polarization to obtain only the transient from the fast response of the dielectric.

FERROELECTRIC MATERIALS IN MEMORY DEVICES

Among many non-volatile memory devices, ferroelectric memory device has been considered as one of most attractive memory devices for the IT memory device, because it show several attractive memory properties such as fast access time of 45 ns, low read/ write voltage of 3V, and negligible standby current of 10 µs [3].

A. Different types of memories

(i) Volatile memory is computer memory that requires power to maintain the stored information. Most modern semiconductor volatile memory is either Static RAM (SRAM) or dynamic RAM (DRAM).

- SRAM retains its contents as long as the power is connected and is easy to interface to but uses six transistors per bit.
- DRAM uses only one transistor and a capacitor per bit.
- DRAM is used for desktop system memory.
- SRAM is common place in small embedded systems, which might only need tens of kilobytes or less.
- Forthcoming volatile memory technologies Z-RAM, A-RAM and ETA RAM.

(ii) Non-volatile memory is computer memory that can retain the stored information even when not powered. Examples of non-volatile memory include

- read-only memory (ROM),
- flash memory,

- magnetic computer storage devices (e.g. hard disks, floppy discs and magnetic tape),
- optical discs
- Forthcoming technologies include FeRAM (Ferroelectric RAM), CBRAM (Conductive Bridging RAM), PRAM (Parallel RAM), RRAM (Resistive RAM), Racetrack memory, NRAM (Nano RAM) and Millipede.

B. Status of FeRAM

The suitability of a memory device is decided by certain parameters eg. Cell size, read latency, write latency, endurance, energy. Almost from the onset of computing, digital information has been stored mainly in two kinds of structure: silicon transistors (for fast, volatile random-access memories) and magnetic media (for low cost, non-volatile mass data storage). Presently leading competing technologies in the long term for non-volatile computer memories are FRAM and magnetic random access memories (MRAM). These are supposed to replace EEPROMs (electrically erasable programmable read-only memories) and “Flash” memories in devices such as digital cameras. Flash, though proving highly commercially successful at the moment, is not a long-term technology, suffering from poor long term endurance and scalability. It will be difficult for Flash to operate as the silicon logic levels decrease from 5V at present to lower voltages in the near future.

Ferroelectric memories, which store data in a bistable electrical polarization state that can be switched by a short voltage pulse, are, like flash, non-volatile and provide random-access, yet are inherently faster and have greater operating lifetimes. Today's FeRAM uses lead zirconate titanate (PZT) and partially (SBT); other materials are being considered. The main developer of FeRAM is Ramtron International. FeRAM is the most common kind of personal computer memory with the ability to retain data when power is turned off as do other nonvolatile memory devices such as ROM and Flash memory. In a DRAM , the data periodically need refreshing due to the discharging of the capacitor, whereas FeRAM maintains the data without any external power supply.

However, it is a fast memory that can endure a high number of cycles e.g., 10^{14} (as per Ramtron International Corporation, 2009), meaning that the need for a write cycle for every read cycle will not result in short product lives in case of very low power requirement. It is expected to have many applications in small consumer devices such as personal digital assistants (PDAs), handheld phones, power meters, and smart cards, and in security systems. FeRAM is faster than Flash memory. It is also expected to replace EEPROM and SRAM for some applications and to become key component in future wireless products. Even after FeRAM has achieved a level of commercial success, with the first devices released in 1993, current FeRAM offer performance that is either comparable to or exceeding current flash memories, but still slower than DRAM[2].

The advent of increasingly sophisticated portable technologies demands reliable, high performance non-volatile memories, with ferroelectric random-access memories (FeRAMs) being developed as an alternative to current Flash memories [9-11]. Fujitsu clearly leads in the actual commercial use of its embedded FRAMs. The Fujitsu-embedded FRAM is that used in the SONY Playstation 2 [4]. FeRAM device with a capacity of 128 Mbits has been presented by Toshiba in 2009.

Challenges and Future Prospects

The main problem for FeRAM is the destructive read operation, which means that each read operation must be accompanied by a write operation leading to faster degradation of the device. As ferroelectrics can suffer from fatigue with repetitive cycling, this destructive read-out places a limitation on the reliability, though over the years fatigue resistance has been improved by the use of oxide electrodes. Low density of FeRAM devices is again a hindrance so research is focused on exploring new materials, composites with special attention at nano-scale properties. There is still also considerable interest in non destructive read-out devices, including ferroelectric field-effect transistors, or through the use of materials or composite structures where ferroelectric and ferromagnetic orderings are coupled and the electrical polarization direction can be measured from the magnetization. Since it is not still concluded yet which ferroelectric material is best for the ferroelectric products, efforts are being focused on developing and optimizing the current and new ferroelectric films. The advanced process technologies are enhanced by developing its own design technology.

Although there are distinct advantages for both ferroelectrics and ferromagnets but a leading class of fascinating materials- multiferroics has come forth. These are the materials that display both ferroelectric and magnetic ordering, the hope being that one could develop a material with a strong enough coupling between the two kinds of ordering so as to create a device that can be written electrically and read magnetically.

CONCLUSIONS

At present, ferroelectric memory devices have reached a point where they are beginning to appear in real commercial devices. At the same time, demand for faster, smaller, nano-scale devices put limits to existing dominating memory technology and prompting the research in direction to achieve better memory devices by either modifying the existing materials or by introducing new functional materials.

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