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A Brief Overview of Present and Future Random Access Memories

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Abstract – Smart phones in our pockets today are thousands of times more powerful than the computer used to put a man on the moon. The advancement in technology over the past few decades has been nothing short of astounding, but this rate of progress is declining as we reach the limits of our current technologies. In this mini review article, we explore some of the current technologies used in computing - specifically Random Access Memory (RAM), and seek to make improvements to the core structure by using a new and exciting class of materials known as multiferroics. We also look at how these materials interact, what makes them interesting for our purposes, and how they can improve our technological prowess.

Keywords – RAM; Mutltiferroics; Information storage.

1. Introduction

It is not controversial to say that our modern world revolves around computing. Almost everything we do involves some form of electronic device, and there are countless additional technologies that would be impossible without the electronic processing and storage of data that we all rely on. Indeed, try to imagine a modern world without computers, or, perhaps more strangely, what the world would look like if we had not drastically increased our computing speed over the past few decades. Of course, this all requires hugely complex infrastructure, with multiple separate components to allow standardised communication with these devices, and create a seamless experience for the user. At a fundamental level, these devices work by storing data as a set of 1s and 0s, but due to the variety or roles electronic components can fill, there is a need for a similar amount of variety in their functionality. But how does this technology work? What are its current limitations? And is there a way we could expand past these limitations in the future? In this mini review paper, we will be looking specifically at RAM - Random Access Memory; how RAM is used in computers today, the advantages and disadvantages of RAM, and how we can improve the current technology using new and exciting materials.

2. What is RAM?

RAM stands for Random Access Memory, and is a key component of modern computers. It is faster than other electronic data storage solutions such as HDDs and Optical Storage, because the information held can be accessed very quickly, and in any order. This is a very important requirement for computers, as increased speed almost universally guarantees a better user experience and allows heavy calculations to be performed faster. RAM can often be considered the ‘working memory’ of the computer, storing the boot OS and active files and applications, and communicating directly with the central processing unit (CPU). This makes faster speeds and stability even more important.

In addition, as technology has improved over the years, the components involved have been reduced to unimaginable sizes, on the order of millionths of a millimetre, drastically improving the storage density, or the amount of information that can be stored in a given space. Due to the limitations of working at such scales, many feel we are reaching a limit to how small we can actually go, and we will explore some of these limitations later [1]. As we approach this limit then, we must seek other ways to continue improving the storage density of our components.

3. How does RAM work?

RAM stores data using a combination of transistors and capacitors. In the most common type of RAM today, DRAM, each bit is composed of a single capacitor and a single transistor as shown in figure 1.

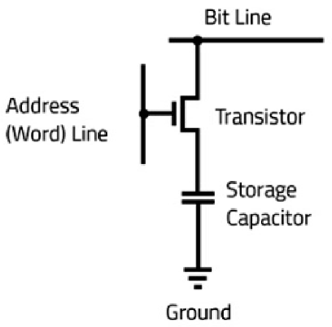

Figure 1. A single RAM bit cell [2].

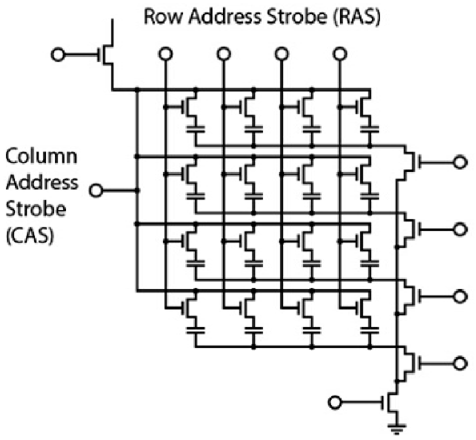

Figure 2. A multi component RAM array [2].

These bits are the arranged in a 2-dimensional grid as shown in figure 2 (this extends to billions of bits in modern devices), and each bit can therefore be in one of two states, charged or discharged. A charged state in the capacitor represents a 0 and discharged is 1, and this state can be read or written via interaction with the transistor.

Due to the scale of these capacitors, usually around 10^{-9}m in modern devices, the charge held by them will discharge rapidly over time, meaning it needs to be regularly refreshed, where the data is essentially rewritten thousands of times per second [3]. The discharge time for the capacitors is highly variable, but at room temperature is generally not more than a couple of seconds, often only a fraction, so loss of data occurs very quickly once power is lost [4]. This refreshing action leads to the term ‘dynamic’, hence the ‘D’ in DRAM, which is the most common type of RAM in use today.

This is a notable drawback of DRAM, in that it is ‘volatile’. That is to say, it requires power to maintain the information it holds, which leads to longer shutdown and boot times, along with the obvious loss of information in the event of an unexpected power failure. This is different to ‘static’, or SRAM, which uses a different type of technology and is larger and more complex, and thus unsuitable for high density data storage.

The advantages of DRAM then include its fast speed and versatility, but it also has many disadvantages. The need for the dynamic rewriting of data several thousand times per second requires a large amount of energy in the form of electric current, which makes the system significantly less efficient, suggesting a great degree of potential if this limitation were to be removed. The volatility of the system is also far from ideal, requiring the user to completely reload the ‘working memory’ whenever the system restarts, to say nothing of potential data loss in the event of power outages [5].

4. Other types of RAM

Many alternative solutions have been proposed over the years, the first of which was Ferro-Electric, or FERAM, in 1952. FERAM makes use of an interesting property called ferroelectricity. This is characterised by strong electric polarisation hysteresis loops as shown in figure 3. This allows the polarisation of the material to be adjusted via an applied electric field, or a voltage. Under an applied electric field, the electric dipoles within the ferroelectric material align with the electric field. A portion of this polarisation maintains its state even after the removal of this field, allowing retention of information without the need for refreshing. This is called ‘remanent polarisation’. P_r [6].

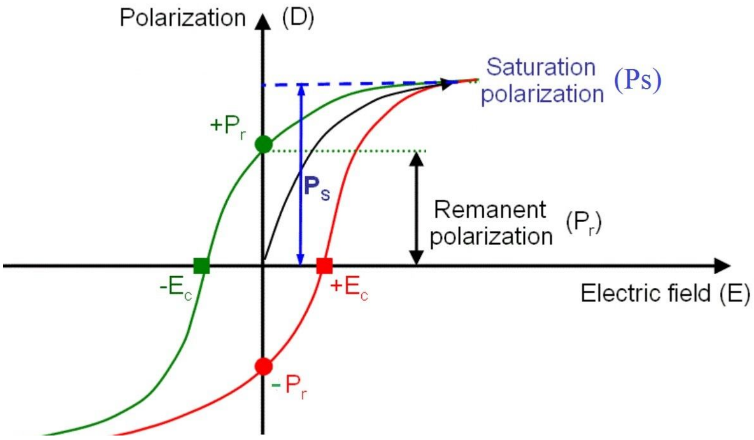

Figure 3. Hysteresis loop for a ferroelectric material.

Where before the capacitors used in DRAM contained a nonlinear dielectric, the capacitors in FERAM contain a highly nonlinear ferroelectric dielectric as in figure 4 (c.f. figure 1). This means that when an electric field is applied, the material attains a polarisation that remains even without the electric field. Indeed, this remanent polarization can be retained without power for up to 100 years [7]. This remanent polarization is now the medium used to store the data, rather than the charge state of the capacitor as before, with a positive polarisation representing a 1 and negative polarisation as 0.

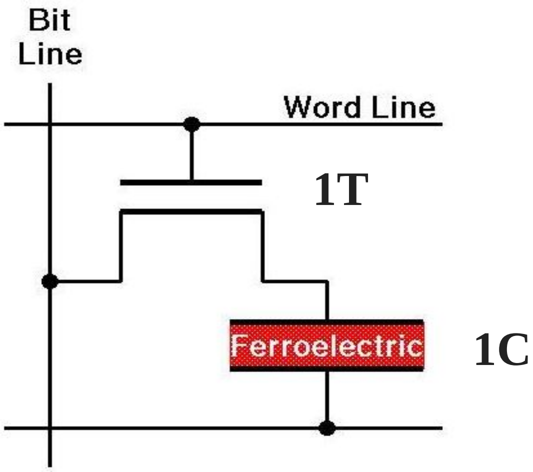

Figure 4. A single FERAM bit cell. Image adapted from [8].

However, due to the mechanics of the hysteresis loop, it is very inefficient to read and write the data. This is because to change the state of a bit, say from positive to negative polarisation, the electric field must be varied to cycle through the hysteresis loop, rather than a straightforward charging of a capacitor. It is not possible to simply reverse the field, as a key feature of ferroelectricity is the reliance on previous states.

Another alternative is Magneto-Resistive, or MRAM. Unlike DRAM which stores information in the state of the capacitors (charged or discharged), and FERAM which uses the polarisation state of the dielectric material, MRAM uses the magnetic state of the material to induce a change in the resistance. The magnetic state can be carefully tuned to induce this change in resistance, and the data is then encoded in the resistance; a high resistance state would represent a 1, and a low resistance state a 0.

A general description of this sort of device is known as a TMR (Tunnelling Magneto Resistor) or GMR (Giant Magneto Resistor), which refer to devices with this common structure. Specifically, these terms refer to devices with two ferro-magnetic films separated by a non-magnetic material. Ferro-magnetic here simply refers to materials that display magnetic properties. TMR refers to devices that use an insulator for separation, while GMR describes the films as separated by a metal strip. They are very useful as sensors due to the fact they respond very well to changes in the local magnetic field. That in turn, is why they are so useful in MRAM.

As seen in figure 5, the current on the ‘bit’ and ‘word’ lines (terms also used to refer to the columns and rows in DRAM) is used to induce a magnetic field which alters the resistance of the layer in contact with it. When the two ferromagnetic layers are oriented in the same direction as each other, the resistance is in the ‘low’ state, and when they are aligned opposite to each other denotes the ‘high’ resistance state. The computer is then able to read the resistance and interpret the result as a 1 or 0. This state is permanent, and as such does not need to be refreshed, making MRAM non-volatile, similar to FERAM. These chips were first commercially released in 2004, making it a relatively new development [9].

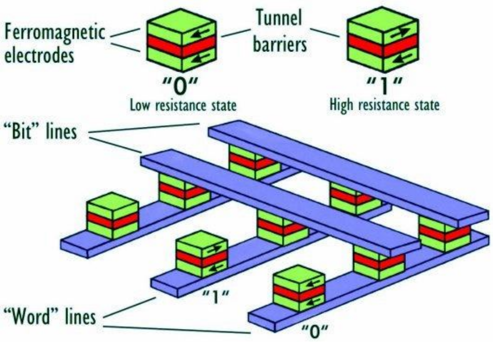

Figure 5. A multi component MRAM array [10].

However, even more so than FERAM, MRAM requires very high currents to manipulate the magnetic field and write data, which makes this solution somewhat inefficient in terms of energy consumption. This leads to issues surrounding excessive power consumption, and of course the corresponding heating/cooling issues that arise from dumping large amounts of energy into a system.

5. RAM based on multiferroic materials

So far, we have explored some of the existing types of RAM using materials that display magnetic or electric effects, leading to improvements on the ‘standard’ DRAM by removing the volatility that is such a hinderance. However, this comes at a cost of increased power usage, and corresponding thermal heating issues.

There exists however, a class of materials known as ‘multiferroics’, which means they can exhibit multiple ferroic properties, or order states, at the same time. These effects can interact with each other via a mechanism known as ‘exchange coupling’, seen in figure 6. As we can see, there exists 3 separate order states: ferromagnetic, ferroelectric, and ferroelastic [11]. For the purposes of this article, we will be focusing mainly on the interaction between the magnetic and the electric orders (the magneto-electric coupling effect), which is mediated by the stress/strain parameter. An inspection of figure 6 shows that applying an electric field (E) will affect the polarisation (P), but also the strain (ε). This in turn affects the stress (σ), which as shown, affects the magnetisation (M). Thus, via the strain mediated magneto-electric coupling, we have a material that can have an electric field applied to it, and subsequently undergo a change in magnetic orientation

If we look back to the drawbacks of MRAM, we recall that the large power consumption and corresponding thermal heating was due to the large currents needed to modify the magnetic state of the materials. If we can find a material that exhibits magneto-electric coupling effects as above, we would be able to use an applied voltage (electric field) to induce this magnetic alignment, which uses significantly less power and as such is more efficient.

The concept follows rather closely the principles of MRAM, but with an additional layer composed of a multiferroic material to induce a change in the magnetic orientation. As shown in figure 7, this material is placed underneath the lower ferromagnetic layer, and when a voltage is applied, it induces a strain in the material that conversely induces a change in the magnetisation of the lower ferro-magnetic layer.

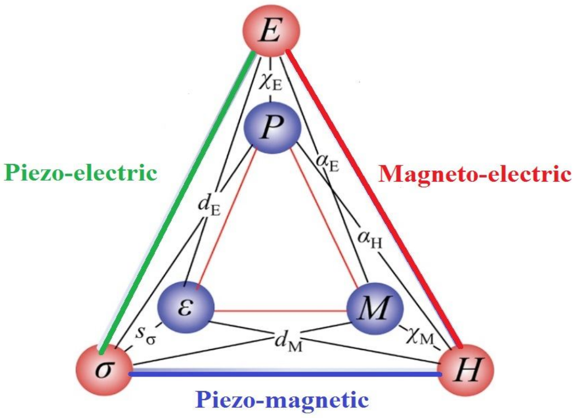

Figure 6. Diagram showing the intercoupling effects in a multiferroic material.

This method obtains the same result as MRAM, but by using an applied voltage to change the magnetic orientation rather than electric currents, we significantly improve the power consumption of the device [12].

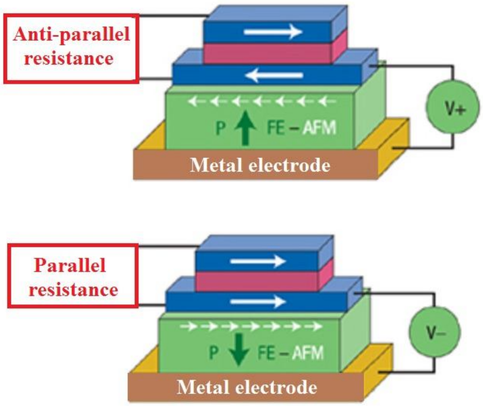

Figure 7. The two potential states of a multiferroic MRAM bit cell. Image adapted from reference [12].

There are a few other proposals for multiferroic MRAM (MFRAM), and of interest is the idea of multi state storage [11]. In figure 8, we see another design that utilises multiferroic materials. The upper portion (blue) is a ferromagnetic material, the lower portion (green) is the multiferroic material. They are separated by a spacer, which depending on the application could be either insulating (as a TMR) or metallic (as a GMR). The upper portion may be placed into either a positive or negative (opposite) alignment with the applied magnetic field, which will correspond to the constant magnetisation of the multiferroic portion. This is analogous to the mechanism used in MRAM, where an opposite alignment will result in a high resistance state (1), and a positive alignment will give a low resistance state (0).

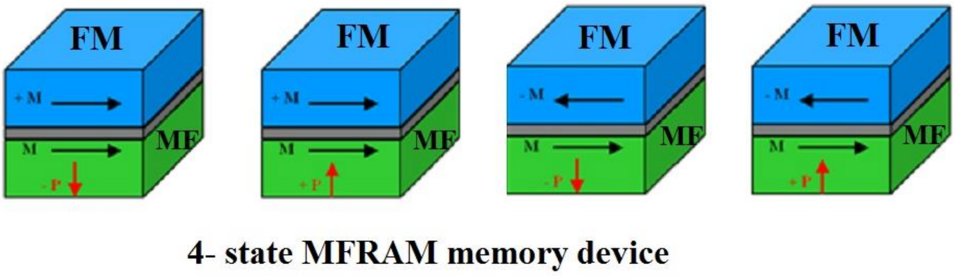

Figure 8. The 4 possible states for a 4-state MFRAM component.

The multiferroic material, as well as being permanently aligned with the magnetic field, may also display polarisation effects, as in FERAM. This results in 4 possible states for the bit, as seen in figure 8. As before, both of these states remain within the material even after the inducing field has been removed.

Thus, by utilising the incredible properties of multiferroic materials, we have been able to create a non-volatile MFRAM component that can retain information without the need for regular refreshing. On top of this, assuming we can achieve similar dimensions to current technologies, we will also have increased our storage density by increasing the total information that can be stored within the component.

6. Antiferroelectric RAM

Using antiferroelectric materials for RAM devices was first proposed in 2016 [13], and this technology was termed AFRAM. The operating principle of AFRAM is very similar to FERAM, except that the read / write protocol of AFRAM is rather different. Antiferroelectrics are crystals consisting of two equally and opposing ferroelectric sublattices, referred as A and B. Under no applied electric field, the antiferroelectric has zero polarization due to the self-cancellation of the opposing ferroelectric sublattices (figure 9.b). The application of an external electric field results in switching of the anti-ferroelectric from antipolar to polar state. Hence, unlike ferroelectrics, the antiferroelectrics display a double hysteresis loop (figure 9.b), where each loop represents the response of one of the two sublattices.

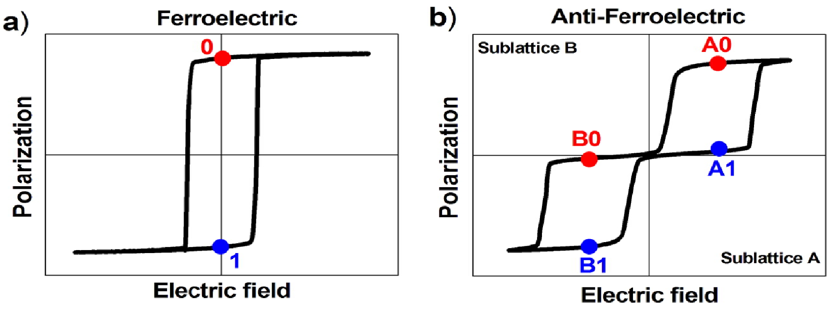

Figure 9. a) Ferroelectric hysteresis (2 states, 1 bit); b) Anti-ferroelectric double hysteresis (4 states, 2 bits).

FERAM chips encode data in their two remanent polarization states “0” and “1” (figure 9.a) of a ferroelectric. Unlike ferroelectrics storing digital data in their two remanent states, the antiferroelectric could potentially store data in the four quasi-remanent states of the two ferroelectric sublattices, as indicated schematically in figure 9. b. This results in a 4-state (A0, A1, B0, B1 in fig.2.b) non-volatile antiferroelectric random access memory, termed AFRAM [13], which doubles the storage capacity of the FERAM (i.e. it has two bits per cell instead of one).

The design architecture of the AFRAM memory cell is in fact identical to that of the FERAM cell, except the memory storage capacitor contains an antiferroelectric dielectric instead of a ferroelectric dielectric, as shown in figure 10.

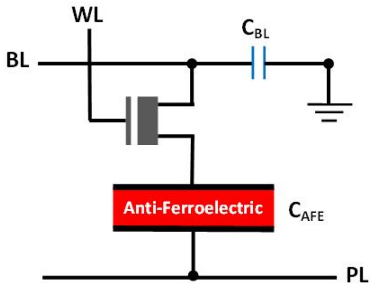

Figure 10. 1T-1C anti-ferroelectric (AFRAM) memory cell architecture.

More details about the AFRAM technology could be found in these references [14,15]. Moreover, this technology could soon enter the commercial high-tech industry, as Intel Corporation has filed a patent on the Antiferroelectric Capacitor Memory device [16].

6. Conclusions

The demands of a computer driven world are only increasing. We are reaching the limit of how far we can push ‘traditional’ computing systems, both in terms of efficient logic and power, but also the very real issue of space. Transistors and other components are at the nanoscale level, and it will soon be impossible to go smaller both due to technical limitations, and the fundamental issues involving inherently unpredictable quantum effects at these very small scales. Multiferroics will also share these issues, as they operate at similar scales, and although they are therefore not a perfect material, they are a relatively new class, and as such research is still very much ongoing. Many of them lose their exciting properties, or become unstable when not stored in the correct conditions, such as if the temperature gets too hot or cold. This could result in a loss of data, or even a complete system failure. However, the potential problems pale in comparison to the potential advantages if we are able to properly manipulate these properties, and solve the underlying issues. Computers would continue to increase in speed, data would no longer be lost during unexpected shutdowns, and long boot times would be a thing of the past. The common, but now outdated RAM is due for an upgrade, and new materials including multiferroic and antiferroelectrics are, hopefully, here to help with this technological development.

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