FERROELECTRONICS

ELECTRONIC DEVICES

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ABSTRACT

The rapid evolution of semiconductor technology, driven by Moore's law, has propelled the industry for six decades, yet the imminent constraints of device miniaturization pose a pivotal moment for information storage. This paper delves into the forefront of innovation with a focus on Ferroelectric Field-Effect Transistors (FeFETs) and Ferroelectric Tunnel Junctions (FTJs) in the realm of ferroelectric memory technologies.

FeFETs, disrupting traditional scaling challenges, redefine spatial efficiency by substituting the gate dielectric with ferroelectric materials. Offering non-destructive read-out capabilities, they emerge as compelling candidates for cutting-edge non-volatile memory applications, such as Flash memory and storage-class memory.

FTJs, operating on ultrathin ferroelectric layers between metallic electrodes, exhibit a distinctive fusion of non-volatility, resistive switching, and scalability. Overcoming inherent challenges, their potential extends to non-volatile memories, 3D neuromorphic computing, and logic devices, positioning them as pivotal components in the future of memory technologies.

This integration of ferroelectric materials into memory technologies not only confronts existing challenges in information storage but also propels electronic devices into an era characterized by heightened efficiency, unprecedented compactness, and unparalleled versatility.

CONTENTS

APPENDIX

Parameters:

- W - Electrical channel width (m).
- L - Electrical channel length (m).
- μ - Channel mobility [$m^2/(V \cdot s)$].
- n_i - Intrinsic carrier concentration (mm^3).
- N_d - Donor doping concentration (assumed uniform) (m^{-3}).
- N_a - Acceptor doping concentration (assumed uniform) (m^{-3}).
- n - Free carrier concentration (m^{-3}).
- q - Charge unit ($-1.6 \times 10^{-19}\,C$).
- T - Absolute temperature (K).
- k - Boltzmann's constant ($1.38 \times 10^{-23}\,J/K$).
- β - $q/(kT)$ (V^{-1}).
- ε_0 - Permittivity of free space ($8.85 \times 10^{-12}\,\mathrm{F/m}$)

Polarization:

- P_r - Remanent polarization (C/m^2), occurs at zero electric field on a saturated hysteresis loop.
- P_s - Spontaneous polarization (C/m^2), maximum ferroelectric dipole polarization on a saturated hysteresis loop.
- E_c - Coercive field (V/m), electric field at which ferroelectric dipole polarization is zero on a saturated hysteresis loop.

Chapter 1

INTRODUCTION

The relentless march of technology, marked by the iconic Moore's law, has propelled the semiconductor industry for over six decades, with an estimated annual value ranging from 600 to 700 billion dollars. However, as we approach the physical limitations dictated by the miniaturization of devices, the landscape of information storage faces a crucial crossroads.

The semiconductor industry, in its pursuit of increased efficiency, has collectively decided to lower Si-logic levels from 5V to an unprecedented 0.5V. This significant reduction, combined with the demands of the electronic age, poses challenges to existing FLASH memory technologies, particularly when operating at such diminished voltages. As charge pumps struggle to cope, the quest for new materials and functionalities intensifies, seeking integration within the current CMOS process flow or as standalone memory devices.

While the key attributes of high storage density and signal-to-noise ratio remain paramount, challenges of reliability, costs, fatigue, and rapid read-write capabilities persist. In this ever-expanding landscape, the characteristics of ferroelectrics emerge as a promising frontier. Renowned for their non-volatility and ability to operate at low voltage thresholds, these devices offer advantages such as data integrity during power interruptions, energy efficiency, rapid data access, high storage density, potential cost reductions in manufacturing, and versatility in applications beyond memory devices.

It becomes clear that ferroelectric materials not only offer solutions to the immediate challenges of information storage but also open avenues for fundamental research into ferroelectricity itself. The intricacies of ordered spontaneous polarization, bistable states, and switchable charge centers become apparent in the design of functional devices, including sensors, ferroelectric-RAMs (feRAMs), ferroelectric-field effect transistors (FeFET), and ferroelectric tunnel junctions (FTJ).

Ferroelectric (FE) materials exhibit two stable polarization states that can be switched by applying an electric field, making them suitable for various applications such as capacitors, memory cells, sensors, actuators, and energy storage. The remanent polarization at zero applied field is a defining property of ferroelectrics, and their temperature-dependent nature also makes them pyroelectric. The intrinsic properties of ferroelectrics include spontaneous polarization, hysteresis in the polarization-electric field curve, and phase transitions associated with the development of spontaneous polarization. Additionally, the field-dependent volume change in these materials results in piezoelectric properties.

For a crystal to exhibit ferroelectricity, it must have a non-centrosymmetric structure and the ability to switch the position of ions in the lattice between two stable states.

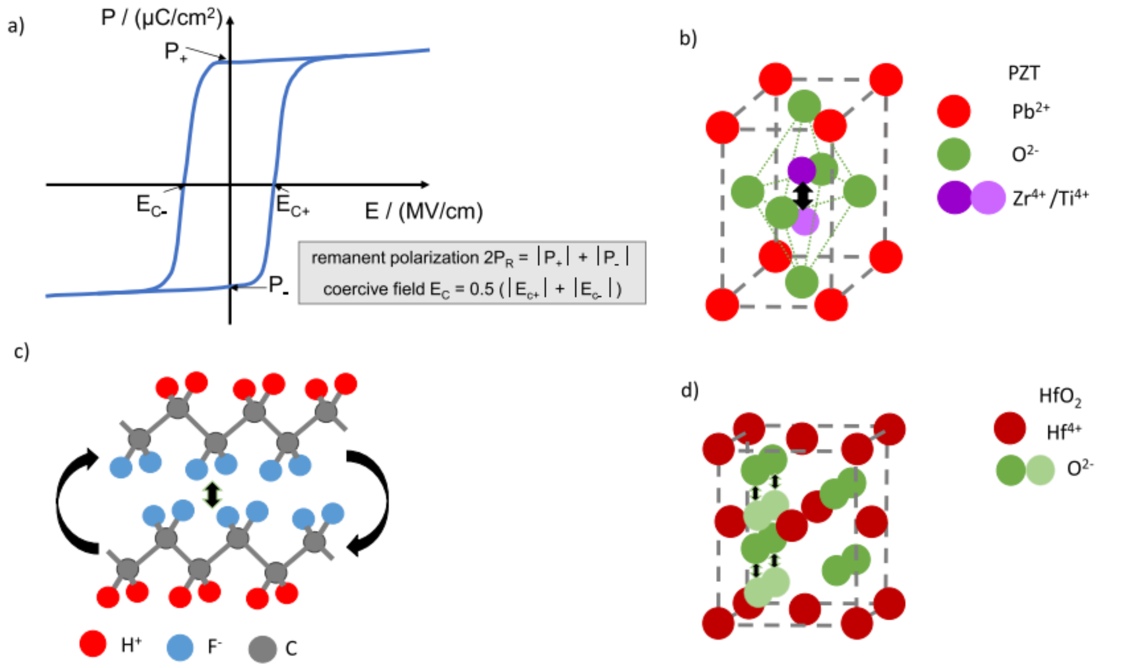

Fig. 1. Ferroelectric hysteresis and typical ferroelectric crystals. (a) Typical hysteresis curve of a ferroelectric material showing the most important properties remanent polarization and coercive field. (b) Sketch of a PZT crystal showing the two stable positions of a central Zr^{4+} or Ti^{4+} ion. (c) Sketch of a PVDF polymer chain with the two orientations that can generate the ferroelectric polarization. (d) Sketch of an orthorhombic hafnium oxide crystal indicating the switching of O_2-oxygen ions in the crystal.

Figure 1.1: Ferroelectric Hysteresis[10]

The earliest ferroelectric materials explored for electronic devices primarily comprised complex crystal structures, notably perovskites, characterized by their non-centrosymmetric arrangement of ions in the lattice. Despite their inherent ferroelectric properties, the intricate nature of these crystal structures posed formidable challenges for seamless integration into semiconductor manufacturing processes. The complexities included difficulties in controlling crystal growth, precise doping, and ensuring compatibility with established fabrication techniques.

In 2011, ferroelectricity was reported in doped hafnium oxide (HfO2), a standard material in complementary metal–oxide–semiconductor (CMOS) processes. This discovery opened up possibilities for integrating ferroelectrics into semiconductor technologies. More recently, AlN's piezoelectricity was transformed into switchable ferroelectricity in AlScN, showing promise for integration with GaN technology and CMOS back-end processes. Additionally, efforts to incorporate ferroelectrics into electron devices using 2D materials have yielded interesting results.

Chapter 2

FERROELECTRICITY

Ferroelectric materials play a crucial role in the development of capacitors with high dielectric constant materials, contributing significantly to non-volatile data storage and various applications.

These materials exhibit a spontaneous polarization shift below the ferroelectric Curie temperature (T_C). Above T_C, these crystals behave as non-polar dielectrics. Notably, certain ferroelectrics possess multiple Curie temperatures, each linked to unique properties.

Ferroelectric crystals consist of domains—regions with uniform spontaneous polarization. In the absence of an electric field, these domains are randomly oriented, nearly completely compensating for polarization. Upon applying an electric field, domain orientation changes, inducing polarization through domain wall motion.

HYSTERESIS LOOP AND LOGICAL STATES

Ferroelectrics are characterized by a hysteresis loop in the Polarization–Electric field (P–E) graph, crucial for applications. This loop includes saturation polarization (P_s), remanent polarization (P_r), and coercive field (E_c). Saturation polarization represents the maximum achievable polarization, P_r is the polarization retained with no applied electric field, and E_c is the field required to reset polarization to zero.

These hysteresis loops enable the representation of logical states, where reversible spontaneous polarization facilitates encoding information in "up" and "down" polarized states, analogous to "1" and "0" bits.

SWITCHING IN FERROELECTRICS

Switching, the reorientation of remanent polarization, can be induced by an electric field or mechanical stress. The presence of two stable polarization states at zero applied field—$\pm P_r$—provides the basis for encoding "1" or "0." Switching requires a threshold field greater than $\pm E_c$.

Miller et al.[11] proposed a model to fit the experimental P–E relationship in a ferroelectric capacitor.

$$P^+(E) = P_s \tanh\left(\frac{E - E_c}{2\delta}\right) + \epsilon_F \epsilon_0 E \tag{2.1}$$

$$\delta = E_c \left(\ln\left(\frac{1 + \frac{P_r}{P_s}}{1 - \frac{P_r}{P_s}}\right)\right)^{-1} \tag{2.2}$$

$$P^-(E) = -P^+(-E) \tag{2.3}$$

Here, P^+ indicates the lower (positive-going) branch, and P^- is the upper (negative-going) branch. The model fits well into the P–E relation of the saturated hysteresis loop but cannot describe the nonsaturated (minor) situation.

The graph plotted from above equations is given as (Parameters are given in Table 2.1):

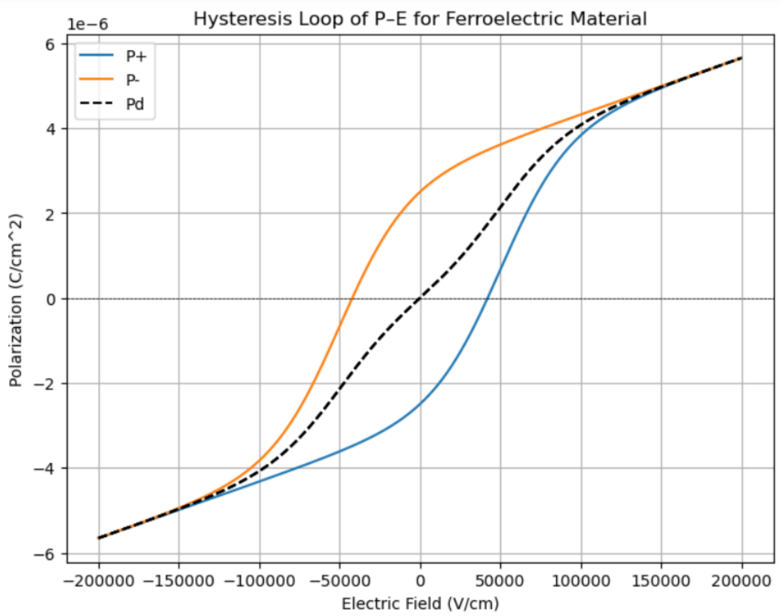

Figure 2.1: P-E graph for the ferroelectric materials

A new expression for the minor hysteresis loop is constructed, determined by a parameter E_m, the maximum electric field that the ferroelectric layer may undergo:

$$\begin{aligned} P^+(E, E_m) = {} & P_s \tanh\left(\frac{E - E_c}{2\delta}\right) \\ & + \epsilon_F \epsilon_0 E + \frac{1}{2}\left(P_s \tanh\left(\frac{E_m + E_c}{2\delta}\right) - P_s \tanh\left(\frac{E_m - E_c}{2\delta}\right)\right) \end{aligned} \tag{2.4}$$

$$P^-(E, E_m) = P_s \tanh\left(\frac{E + E_c}{2\delta}\right) \\ + \epsilon_F \epsilon_0 E - \frac{1}{2}\left(P_s \tanh\left(\frac{E_m + E_c}{2\delta}\right) - P_s \tanh\left(\frac{E_m - E_c}{2\delta}\right)\right) \tag{2.5}$$

The polarization as a function of the maximum electric field is defined by:

$$P_d(E_m) = \epsilon_F \epsilon_0 E_m \\ + \frac{1}{2}\left(P_s \tanh\left(\frac{E_m + E_c}{2\delta}\right) + P_s \tanh\left(\frac{E_m - E_c}{2\delta}\right)\right) \tag{2.6}$$

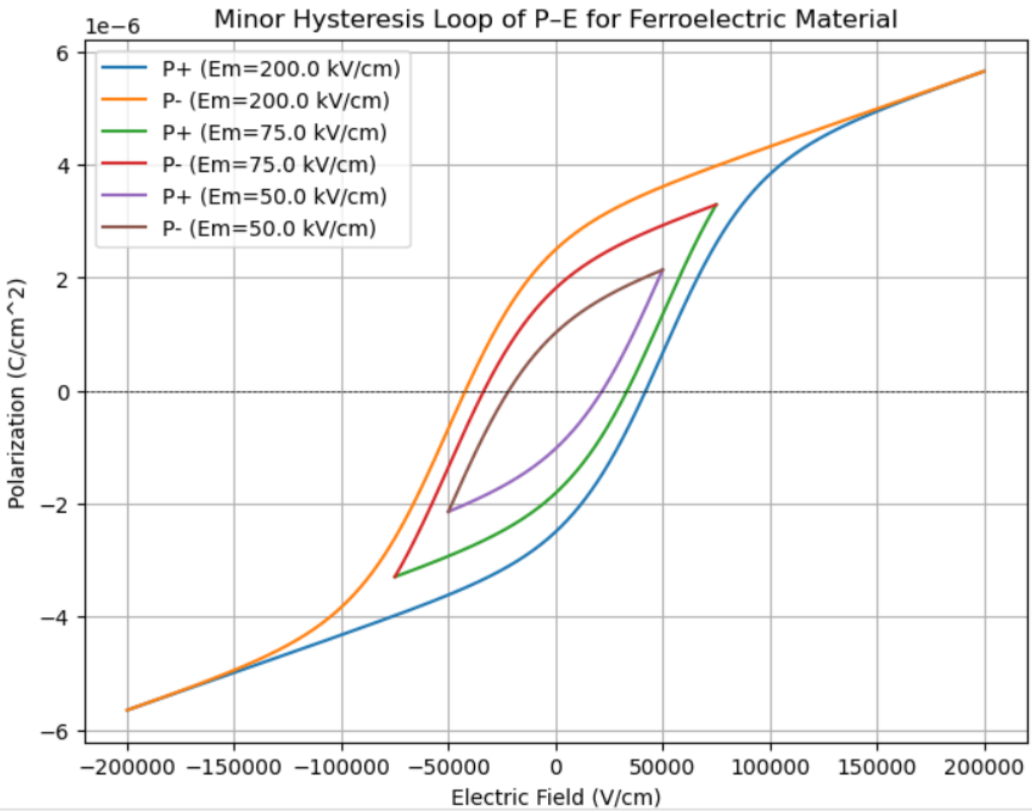

Figure 2.2: P-E graph for the ferroelectric materials under various maximum electric fields

These equations provide a simple and analytical approach to simulate characteristics for a ferroelectric-based device, though they may not be suitable for arbitrarily asymmetrical applied voltage scenarios.

Parameter	Value
Remnant polarization (P_r)	2.5×10^{-6} C/cm^2
Saturation polarization (P_s)	3×10^{-6} C/cm^2
Coercive field (E_c)	50×10^3 V/cm
Dielectric constant of ferroelectric (ϵ_F)	150

Table 2.1: Device parameters for P-E plot for FeMFET simulation.

Ferroelectric Materials: Ferroelectric materials come in various types, each exhibiting unique structures and properties. Inorganic ferroelectrics, such as lead zirconium titanate (PZT) or barium titanate (BTO), feature central ions switching between stable positions. Organic ferroelectrics, like polyvinylidene fluoride (PVDF), employ rotating polar polymer chains for polarization. Fluoride structure ferroelectrics, found in hafnium oxide, witness oxygen ions switching between positions.

READOUT MECHANISMS FOR FERROELECTRIC MEMORIES

Implementing ferroelectric materials into memory cells necessitates effective readout mechanisms. Three prominent approaches have been explored:

1. **Capacitor-Based Readout:**
   - Utilizes charge during switching/non-switching operations.
   - Ferroelectric material serves as the dielectric in a biased capacitor.
   - Destroys stored information, requiring a write-back.
   - Commonly employed in Ferroelectric Random Access Memories (FeRAMs).
2. **Ferroelectric Field Effect Transistor (FeFET):**
   - Ferroelectric integrated into the gate dielectric of a transistor.
   - Polarization-induced shift in the transistor's I–V curve determines ferroelectric state.
   - Nondestructive readout.
3. **Ferroelectric Tunnel Junction (FTJ):**
   - Thin ferroelectrics or a double-layer structure with a thin tunneling layer.
   - Polarization state directly read out as current flowing through the capacitor.
   - Nondestructive readout, still in the basic research phase.

COMMERCIAL STATUS AND FUTURE PROSPECTS

While capacitor-based readout and FeFET have gained significant attention and found their way into low-volume products, challenges such as depolarization field and low coercive field have impacted their widespread commercial success. Ferroelectric tunnel junctions, a newer approach, are still in the early stages of basic research.

Chapter 3

DEVICES

Memory devices leverage material properties exhibiting hysteresis, allowing switching between states with external stimuli. For ferroelectrics, the application of an external field/voltage facilitates the transition between polarized states.

Key requirements for memory devices include fast read/write speeds, stability for over 10^{12} writing cycles, data retention for at least a decade, and cost-effectiveness. Despite being considered non-volatile, ferroelectrics face challenges in retention due to leakage at the interface with electrodes/semiconductors. While many ferroelectrics are integrated into memory devices, they can also function as standalone high-capacitance non-volatile memory.

In recent research, there is a growing focus on integrating ferroelectric materials into memory devices for artificial neurons and synapses, especially in neuromorphic computing. Conventional CMOS technology, while an option, encounters challenges in energy efficiency and device integration due to the need for numerous unit devices.

Hafnium-based ferroelectric materials, with their bistable polarization state, offer non-volatile memory functions regulating binary information through electric field strength. Notably, Hf-based ferroelectric devices demonstrate stochastic switching and multi-value polarization control, providing advantages like unexpected switching behavior and a larger band gap.

The emergence of two-terminal ferroelectric memory devices, such as Ferroelectric Tunnel Junctions (FTJs), has opened new avenues for high-performance, low-power, and large-scale parallel memory computing applications. These devices, with superior analog switching characteristics, high nonlinearity, and uniformity, bring unique advantages to the field of memory technology.

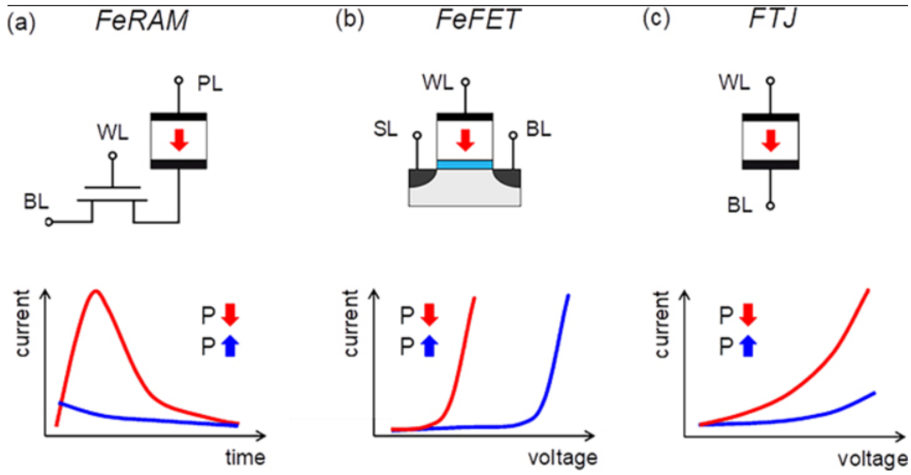

Figure 3.1: Three ferroelectric memory concepts and their respective current-response as a function of time or voltage for both polarization directions: (a) FeRAM, (b) FeFET, and (c) FTJ.[6]

3.1 FERROELECTRIC RANDOM-ACCESS MEMORY (FERAM)

Ferroelectric RAM (FeRAM) is a distinctive non-volatile memory technology characterized by its 1T-1C structure, utilizing a ferroelectric material as the capacitor-based component.

OPERATION OF FERAMS

FeRAM's fundamental operational architecture lies in the 1T-1C structure, comprising a transistor and a ferroelectric capacitor. The ferroelectric material serves as the storage medium for binary information.

The non-volatile characteristics of FeRAM emanate from the application of ferroelectricity in storing binary data. However, a key distinction lies in the destructive characteristics associated with read pulses. The read pulse determines whether the polarization state is inverted, necessitating a subsequent cell recovery process.

ADVANTAGES OF FERAMS

FeRAM boasts several advantages, rendering it a compelling candidate for certain applications. Its fast access time positions it as an efficient solution for applications demanding rapid data retrieval. Moreover, FeRAM exhibits low power consumption, making it energy-efficient. High-security features, excellent retention and endurance times, and remarkable radiation tolerance enhance its suitability for deployment in diverse sectors.

DISADVANTAGES OF FERAMS

The read operations are destructive and need the re-write procedure. Despite its merits, FeRAM contends with certain drawbacks. Foremost among these is the larger cell size compared to alternative memory technologies. The incorporation of a plate line results in footprints, rendering FeRAM less compact compared to other ferroelectric memory devices. This larger footprint poses integration challenges, impeding FeRAM's viability for next-generation ferroelectric devices.

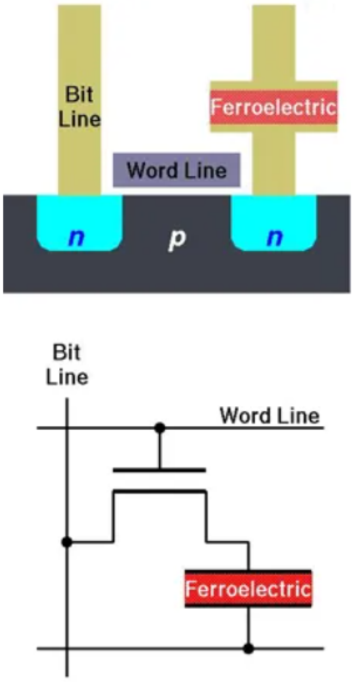

Figure 3.2: Ferroelectric memory concepts of FeRAM. Image source:[4].

APPLICATIONS OF FERAMS

IoT Devices: FeRAM's rapid access, low power use, and non-volatile storage make it ideal for small, power-efficient IoT devices.

Secure Identification (Smart Cards, RFID): FeRAM's high-security features and reliability suit secure ID applications like smart cards and RFID systems, ensuring fast and secure data handling.

Industrial Control Systems: FeRAM's resilience to harsh conditions and quick read/write access make it valuable for maintaining critical data integrity in industrial control systems.

3.2 FERROELECTRIC FIELD-EFFECT TRANSISTORS (FEFETS)

OPERATION OF FEFETS

Traditional ferroelectric capacitors encounter scaling challenges, where reduced surface area diminishes their switching current to undetectable levels. FeFETs emerge as a solution to this predicament, offering enhanced space efficiency and non-destructive read-out capabilities.

In a FeFET, the conventional gate dielectric is substituted with a ferroelectric material. The polarization of thE ferroelectric layer can be manipulated by applying a gate voltage. This polarization, induced by a positive voltage surpassing the coercive voltage, directs a positive charge into the ferroelectric layer.

In the case of a p-type semiconductor(in substrate), electrons accumulate at the interface to counterbalance the ferroelectric charge, creating a low-resistivity channel. Switching the polarization to its alternative state results in a negative ferroelectric charge, leading to the depletion of electrons near the gate and, consequently, a high resistivity.

The preference for high and low conductance states, dictated by ferroelectric polarization, persists even after removing the gate voltage. Reading the channel status involves applying a small drain voltage that does not disturb the ferroelectric polarization, yielding a source-drain current or none, corresponding to binary states (1 or 0). The resulting memory device is deemed non-volatile as long as the polarization maintains the charge accumulation/depletion at the gate.

Upon semiconductor depletion, the ferroelectric can either switch to reverse polarization, keeping the semiconductor depleted, or depolarize due to a lack of free electrons compensating the polarization charge at the semiconductor-ferroelectric interface.

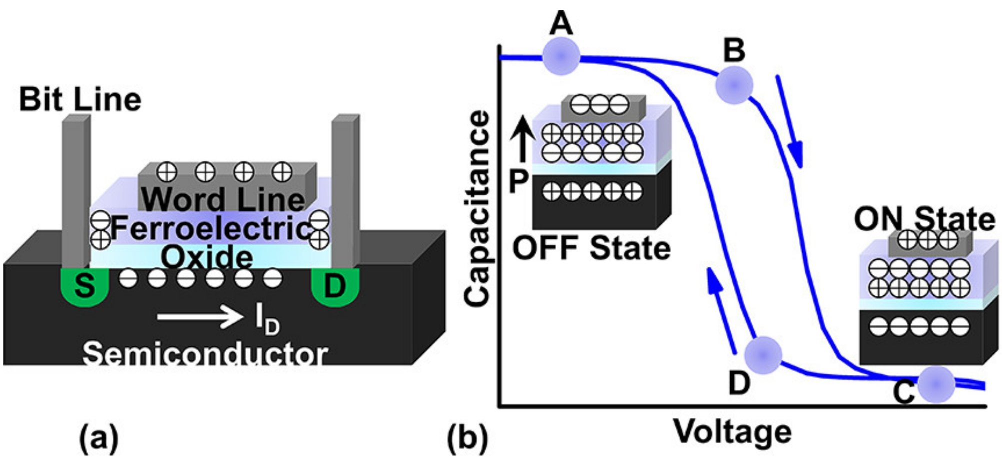

Figure 3.3: (a) MFIS structure of FeFET and (b) operation in the OFF and ON state.[7].

ADVANTAGES OF FEFETS

- **Space Efficiency:** FeFETs overcome the scaling issues faced by traditional ferroelectric capacitors, providing enhanced space efficiency.
- **Non-Destructive Read-Out:** FeFETs distinguish themselves by offering non-destructive read-out capabilities, a significant advantage for memory applications.

DISADVANTAGES OF FEFETS

- **Write Endurance:** Despite improvements, FeFETs may still face challenges related to write endurance, especially in scenarios demanding frequent write cycles.
- **Dependence on Material Properties:** FeFET performance is highly dependent on the choice of ferroelectric material, and achieving the right material properties can be a complex task.
- **Complex Fabrication:** The fabrication process for FeFETs may be more intricate compared to traditional memory technologies, potentially impacting manufacturing costs. While FeFETs bring substantial advantages, challenges include depolarization effects, interdiffusion issues, and charge injection problems at metal-ferroelectric-semiconductor interfaces. Innovative solutions involve introducing insulating layers to mitigate depolarization effects and exploring designs like Metal Ferroelectric Metal Insulator Semiconductor (MFMIS) for improved performance.

APPLICATIONS OF FEFETS

- **Memory Applications:** FeFETs excel in nonvolatile memory applications, including Flash memory and storage-class memory. Their ability to retain data without continuous power makes them suitable for a variety of memory storage solutions.
- **Logic-in-Memory Systems:** FeFETs show promise in logic-in-memory systems, where the boundary between digital and analog computing is blurred. This could lead to more efficient and integrated processing architectures.
- **Neuromorphic Computing:** FeFETs are explored for neuromorphic computing, simulating the behavior of biological neural networks. Their ability to perform synaptic operations makes them potentially suitable for brain-inspired computing applications.

3.3 FERROELECTRIC TUNNEL JUNCTIONS (FTJS)

Ferroelectric Tunnel Junctions emerge as a promising frontier in memory technologies. Their unique combination of non-volatility, resistive switching, and compatibility with scaling make them a subject of intense research and development. While challenges persist, the advantages and potential applications position FTJs as key players in the future landscape of memory technologies, paving the way for more efficient and compact electronic devices.

OPERATION OF FTJS

FTJs operate on the principle of utilizing a thin ferroelectric layer sandwiched between two metallic electrodes. This ultrathin ferroelectric film, often less than 3 nm in thickness, becomes the focal point for the phenomena of resistive switching. The polarization of this ferroelectric layer can be reversed by applying an electric field, resulting in a change in conductance across the junction.

The key to FTJ operation lies in the intricate interplay of polarization reversal, depolarization fields, and the resultant changes in the potential barrier height. As an electric field is applied, the ferroelectric polarization is reversed, inducing a change in the electrostatic potential at the interfaces. This, in turn, alters the tunneling resistance, leading to a distinct ON/OFF state in the junction. The asymmetry in potential profiles, induced by factors such as screening lengths and interface effects, contributes to the Tunneling Electro Resistance (TER) effect, making FTJs a promising candidate for non-volatile memory.

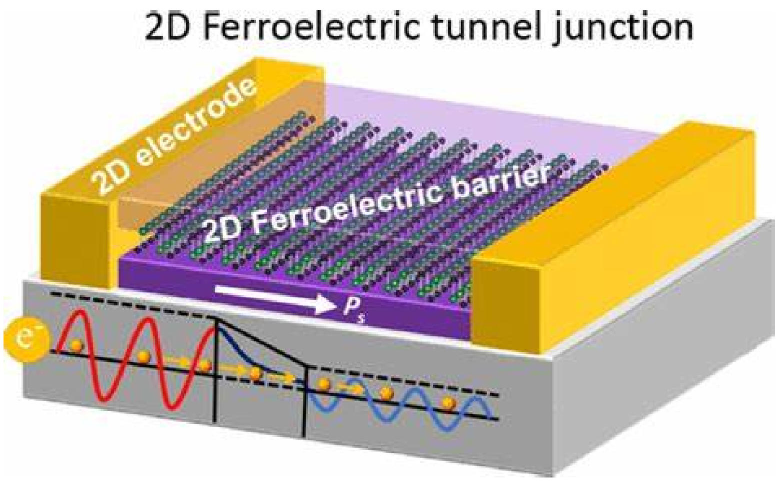

Figure 3.4: Ferroelectric Tunnel Juntion. Image source:[2].

ADVANTAGES OF FTJS

Non-volatility: FTJs offer non-volatile memory capabilities, retaining their state even in the absence of an applied voltage. This characteristic is crucial for various memory applications.

High Resistive Switching: The resistive switching in FTJs can reach extreme levels, providing a wide range of resistance states. This property is exploited in multilevel memory and logic devices.

Low Power Requirements: FTJs demonstrate reduced power requirements, making them energy-efficient and suitable for low-power non-volatile memory applications.

Scaling Possibilities: With the ability to operate with ultra-thin ferroelectric films, FTJs provide opportunities for miniaturization, an essential aspect in modern electronic devices.

DISADVANTAGES OF FTJS

Dependence on Film Thickness: FTJ performance is intricately linked to the thickness of the ferroelectric film. Issues such as incomplete screening and instability arise with films that are too thin, limiting the practical thickness range.

Interface Effects: The properties of FTJs are significantly influenced by the interfaces between the ferroelectric film and the metallic electrodes. Achieving optimal interface characteristics can be challenging.

Limited Polarization Stability: The polarization stability of ultra-thin ferroelectric films can be compromised, affecting the resistive switching's retention characteristics.

APPLICATIONS OF FTJS

Non-volatile Memories: FTJs hold immense promise in the development of non-volatile memories, providing a combination of quick read and write capabilities with modest size and non-volatility.

Field Data Loggers: The compact nature of FTJ-based microcontrollers, especially with the integration of sensing capabilities, makes them suitable for field data loggers.

3D Neuromorphic Computing: The unique characteristics of FTJs, particularly in the realm of resistive switching, position them as potential candidates for 3D neuromorphic computing systems.

Logic Devices: The high resistive switching capability of FTJs makes them suitable for logic devices, offering programmable resistance and low operating power.

Chapter 4

CONCLUSION AND SCOPE

In conclusion, the evolution of memory technologies, particularly the advent of Ferroelectric Field-Effect Transistors (FeFETs) and Ferroelectric Tunnel Junctions (FTJs), marks a paradigm shift in the landscape of electronic devices. The relentless pursuit of increased efficiency in the semiconductor industry, driven by the iconic Moore's law, has led to a crucial crossroads as we approach the physical limitations imposed by the miniaturization of devices.

FeFETs, with their innovative approach of substituting the conventional gate dielectric with ferroelectric materials, address the scaling challenges faced by traditional ferroelectric capacitors. Their operation, relying on the manipulation of ferroelectric polarization, provides enhanced space efficiency and non-destructive read-out capabilities. The advantages of FeFETs, including space efficiency and non-destructive read-out, position them as compelling candidates for non-volatile memory applications, such as Flash memory and storage-class memory.

On the other frontier, FTJs emerge as a promising solution with a unique combination of non-volatility, resistive switching, and scalability. Operating on the principle of an ultrathin ferroelectric layer sandwiched between metallic electrodes, FTJs showcase high resistive switching capabilities and low power requirements. Their non-volatile memory capabilities, coupled with opportunities for miniaturization, make them crucial components for the future of memory technologies.

SCOPE AND FUTURE DIRECTIONS

The scope of ferroelectric materials extends beyond traditional memory applications. The exploration of these materials opens avenues for fundamental research into ferroelectricity itself. The characteristics of ferroelectrics, including spontaneous polarization, bistable states, and switchable charge centers, pave the way for the design of functional devices such as sensors, ferroelectric-RAMs (feRAMs), ferroelectric-field effect transistors (FeFET), and ferroelectric tunnel junctions (FTJ).

In future research, addressing challenges such as write endurance, material property dependence, and complex fabrication processes for FeFETs will be paramount. Innovative solutions, such as introducing insulating layers and exploring designs like Metal Ferroelectric Metal Insulator Semiconductor (MFMIS), could enhance their performance and manufacturability.

For FTJs, focusing on overcoming limitations related to film thickness dependence and interface effects will be crucial. Further advancements in understanding the intricacies of polarization reversal, depolarization fields, and potential barrier height changes will unlock the full potential of FTJs in non-volatile memory applications.

The applications of these ferroelectric devices extend to 3D neuromorphic computing, where the unique characteristics of FTJs in resistive switching can be harnessed for brain-inspired computing systems. Additionally, the integration of these technologies into logic devices showcases their versatility in programmable resistance and low operating power, paving the way for more integrated processing architectures.

In summary, the integration of ferroelectric materials into memory technologies not only addresses current challenges in information storage but also opens up exciting possibilities for the future of electronic devices, ushering in an era of efficiency, compactness, and versatility.

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