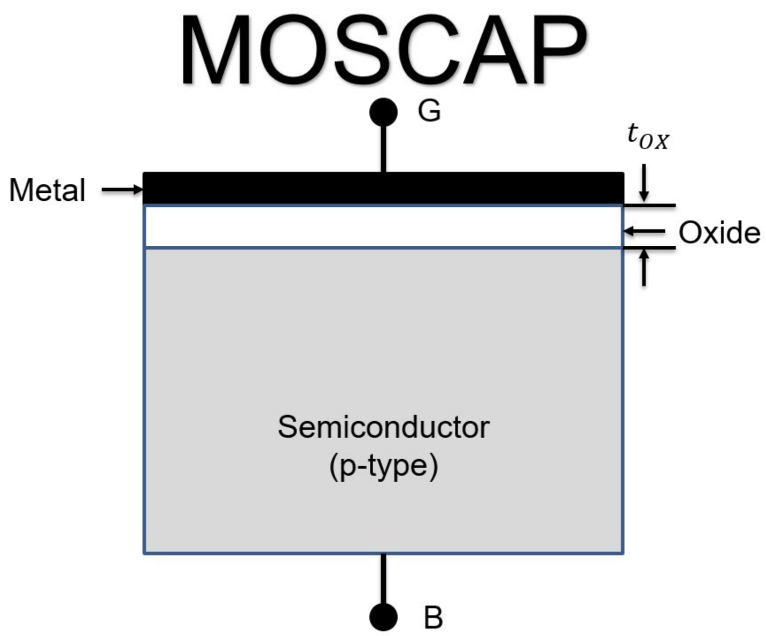
1.Introduction to MOSCAP

A MOSCAP, or metal-oxide-semiconductor capacitor, is an essential device in semiconductor technology. It consists of a semiconductor base, an oxide insulator, and a metal electrode. This report focuses on the creation of a MOSCAP using HfO_2 as the dielectric layer, known for its high dielectric constant ($\varepsilon r \sim 23$), which is pivotal for improving the capacitance of memory devices like DRAM.



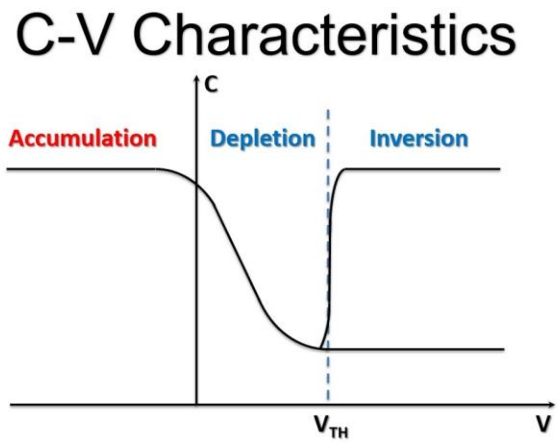
2.Working Principles of MOSCAP

The MOSCAP operates by adjusting the charge distribution within the semiconductor based on voltage applied at the gate terminal. This modulation leads to three operational states: accumulation, depletion, and inversion. Each mode affects the device's capacitance, which plays a crucial role in DRAM functionality.

In accumulation mode, the capacitance of the MOSCAP is high because the accumulated charge is close to the oxide layer, and the distance between the effective capacitor plates is minimal.

In depletion region, the capacitance decreases, because the gate voltage repels majority carriers away.

The capacitance stabilizes in the inversion layer as it behaves like a conductive region beneath the oxide layer, and the capacitance becomes dominated by the oxide layer's thickness.



3.Key Properties

The flat-band voltage of a MOSCAP reflects the point at which the energy bands of the semiconductor flatten. This parameter depends on the metal-semiconductor work function difference and any fixed charges within the oxide layer. The capacitance, dictated by the oxide thickness, underpins the MOSCAP's performance in DRAM systems. dictated by the oxide thickness, underpins the MOSCAP's performance in DRAM systems.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

From the above formula “$\boldsymbol{\varepsilon}_r$” is the dielectric constant value of HfO_2 that we calculated.

4.Applications in Electronics

MOSCAPs serve critical roles in:

- Dynamic Random-Access Memory (DRAM)
- Voltage-controlled devices
- Bioelectronics and sensors
- Energy storage solutions

Dynamic Random-Access Memory (DRAM):

DRAM is a type of volatile memory used in computers and digital devices to store data temporarily. Its fast access times make it ideal for running applications and multitasking. DRAM relies on capacitors to hold binary data, requiring frequent refreshing to maintain information, which is where MOSCAP structures play a vital role.

Voltage-Controlled Devices:

Voltage-controlled devices, such as MOSFETs and capacitors, regulate current or signal flow in response to voltage changes. These devices are essential in electronics, enabling amplification, switching, and precise control in circuits. MOSCAPs serve as variable capacitors in such systems, dynamically adjusting capacitance based on applied voltage.

Bioelectronics and Sensors:

Bioelectronics integrates electronics with biological systems for medical applications, like biosensors and neural implants. MOSCAP structures enhance signal detection and processing in biosensors, enabling them to sense minute biological signals, improving accuracy in medical diagnostics, environmental monitoring, and wearable health devices.

Energy Storage Solutions:

Energy storage solutions include devices like capacitors and batteries that store and release energy as needed. Capacitors with high dielectric constants, such as MOSCAPs with HfO_2, increase energy density, allowing for compact, efficient energy storage. This is critical in renewable energy systems and portable electronic devices where energy efficiency is paramount.

5.Lab equipment's:

RF-DC sputtering machine

The below image is of RF/DC Machine used in the nanotechnology lab

Components:

1. Vacuum chamber
2. Target material
3. Power supply
4. Substrate holder
5. Inert gas supply
6. Magnetron
7. Cooling system
8. Gas controller

Components specifications:

Vacuum Chamber:

Provides a controlled environment with low pressure (usually in the range of 10^{-3} to 10^{-7} Torr) to minimize contamination and allow for efficient sputtering.

Target Material:

The cathode or target is the material from which atoms are ejected and deposited on the substrate. It is made from the material intended to form the thin film. Target materials can be metallic (for DC sputtering) or non-metallic (for RF sputtering).

Power Supply:

A DC power supply is used for sputtering metallic or conductive materials, while an RF power supply is used for sputtering insulating materials.

Substrate Holder:

The substrate (such as silicon wafers or glass) is placed opposite to the target, where it receives the sputtered material. It also has the ability to rotate to ensure uniform film deposition.

Inert Gas Supply:

Argon is the most commonly used sputtering gas, as it is inert and easy to ionize. The gas pressure within the chamber is carefully controlled to regulate the energy of the ions bombarding the target.

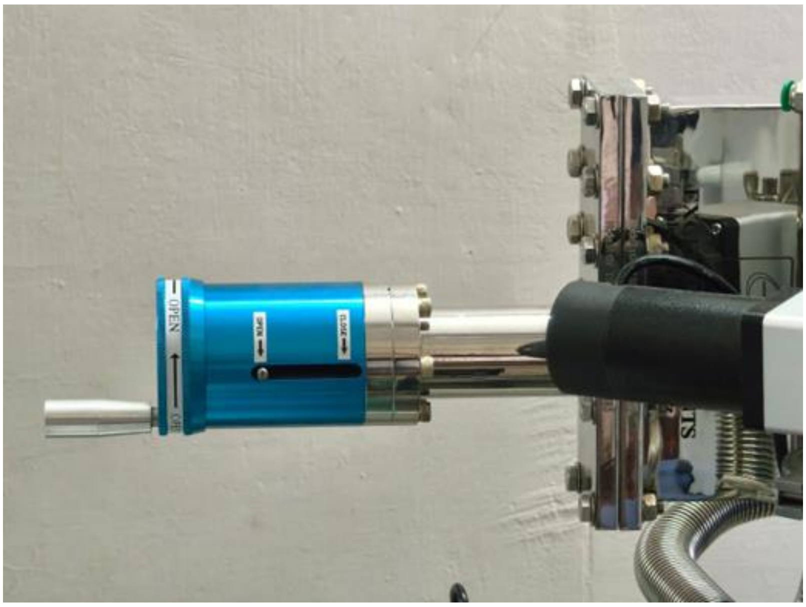
Magnetron:

In many modern sputtering systems, a magnetron is used to create a magnetic field near the target to trap electrons. This increases ionization efficiency, resulting in a more stable sputtering process and better film quality.

Cooling System:

The target can heat up during the sputtering process, and cooling mechanisms (such as water or air cooling) are used to prevent overheating of the target and maintain consistent sputtering.

Gas Control: Flow controllers and pressure sensors are used to manage the inert gas flow and maintain the required pressure inside the chamber for optimal sputtering.

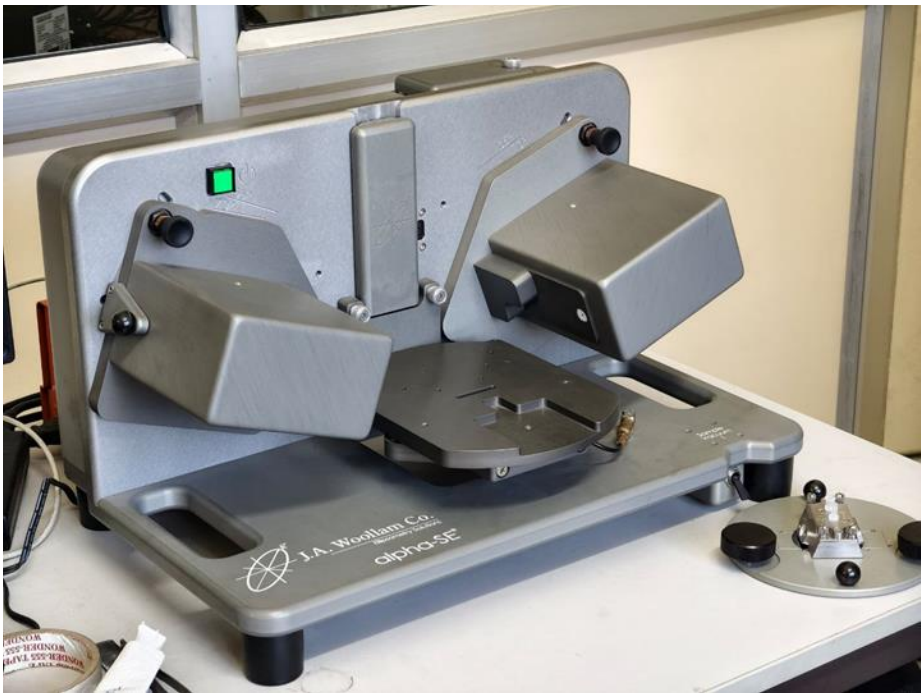


- this is the valve to control the vacuum in the chamber

- RF-DC sputtering machine controls and display

Ellipsometer:

An **ellipsometer** is an optical instrument used to measure the thickness and optical properties of thin films. It operates by analyzing changes in the polarization of light as it reflects off a sample surface. Typically, polarized light is directed at the sample, and the reflected light's amplitude ratio (Ψ) and phase shift (Δ) are measured. These values help calculate the film's thickness, refractive index, and absorption coefficient.



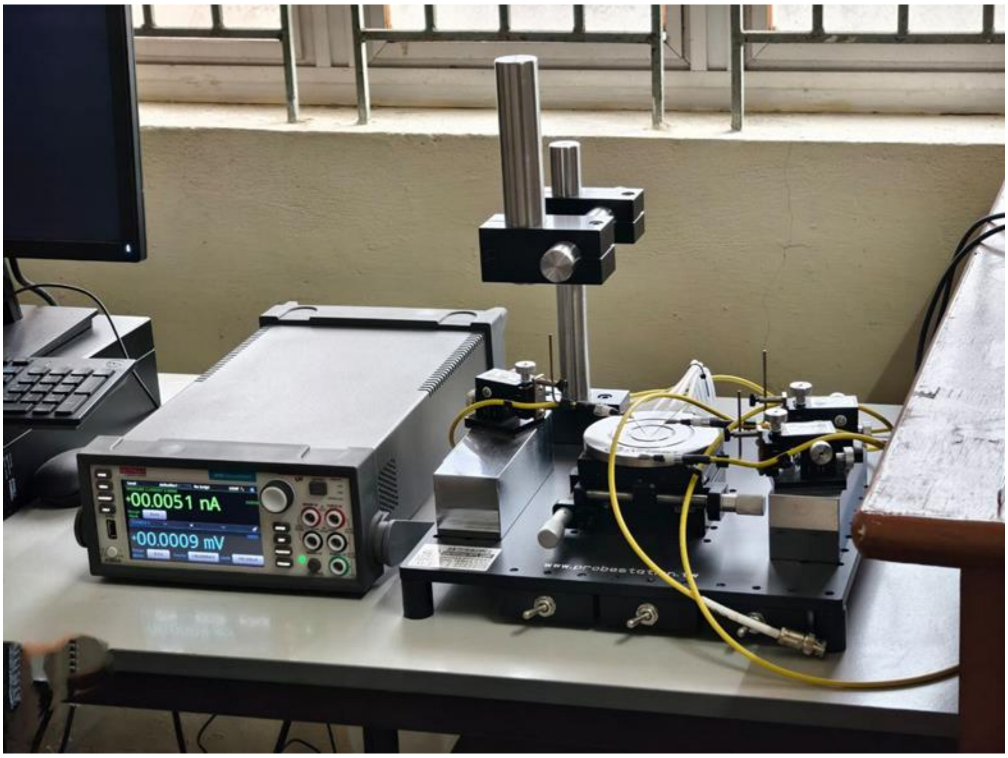
- The above image is the ellipsometer used in our TFT lab

The two key quantities measured are:

Ψ(Psi): The amplitude ratio between the polarized light components.

Δ(Delta): The phase difference between the polarized light components

Probe station:

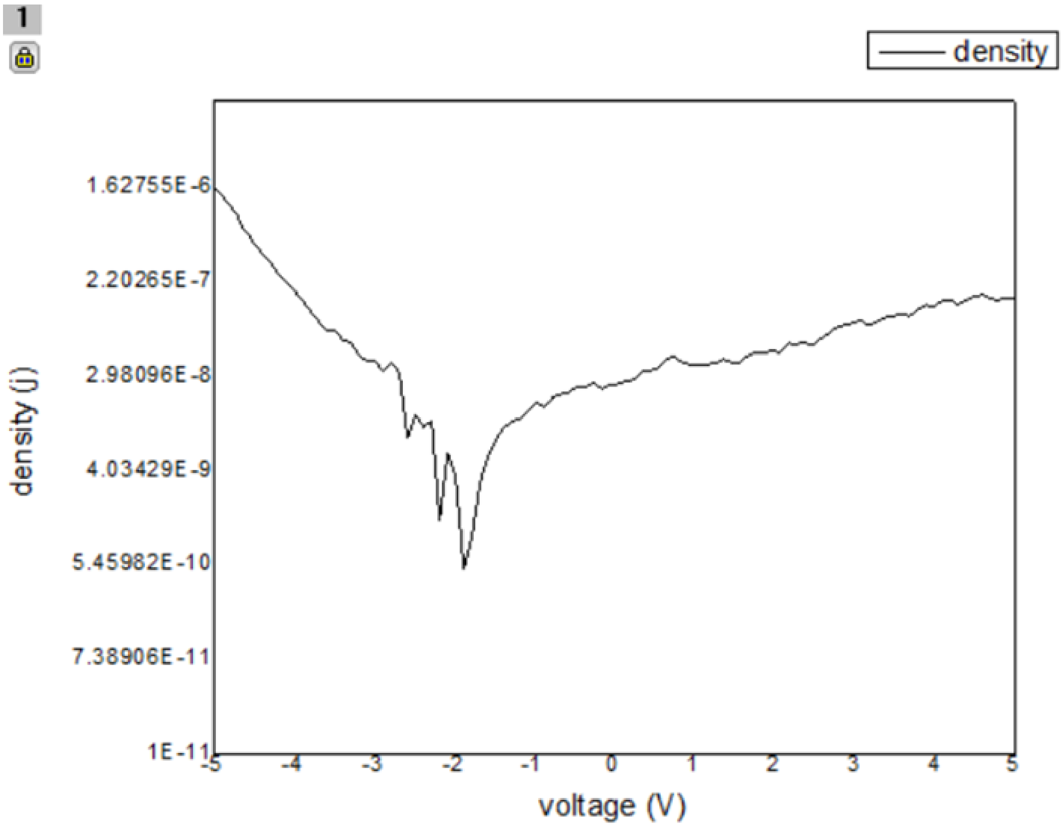


- Probe station used to measure the characteristics of mos-cap

A probe station is a sophisticated instrument used to measure the electrical properties of individual semiconductor devices or chips, such as transistors, diodes, and capacitors, throughout various phases of design, fabrication, and testing. It allows precise probing of microscopic components, enabling engineers and researchers to analyse parameters like current, voltage, and resistance. This is crucial in assessing device performance, identifying defects, and validating manufacturing quality. Probe stations are integral in research and development, as well as in quality control for semiconductor production, as they facilitate in-depth analysis at the wafer level, ensuring that devices meet the desired specifications before mass production.

Result of probe station:

The values obtained from the probe station is fed into the origin software and the following graph is plotted



- The graph is a plot between the current density j and voltage v.

The **J-V curve** helps characterize a device's electrical properties, showing how current density changes with applied voltage. This analysis is commonly used for diodes, MOSCAPs, solar cells, and other semiconductor devices to determine properties like threshold voltage, breakdown voltage, and leakage current.

6.Fabrication of MOSCAP

Materials used:

1. Silicon substrate (Si)
2. Hafnium dioxide (HfO_2)
3. Silver (Ag)
4. Shadow mask

3.1 Shaping of the Substrate

A silicon block is carefully selected and cut to the desired dimensions using a diamond cutter to ensure precision. The silicon surface is then thoroughly cleaned with hydrogen fluoride (HF) and acetone to remove any organic or inorganic contaminants. Extra precautions are taken throughout the process to prevent any recontamination of the substrate surface, ensuring optimal conditions for the subsequent fabrication steps.

3.2 RF/DC Sputtering Process

- **Loading the Substrate:** The substrate, typically a silicon wafer or glass, is securely placed on the substrate holder inside the sputtering chamber. It is positioned at an optimal distance from the target material to ensure uniform deposition.
- **Creating a Vacuum:** The sputtering chamber is evacuated to a low-pressure environment to minimize contamination. This is achieved in two stages: first, a rotary pump reduces the pressure from atmospheric levels to 10^{-3} torr, and then a turbo pump further reduces the pressure from 10^{-3} to 10^{-9} torr.
- **Introducing Gas:** A controlled flow of inert gas, usually argon, is introduced into the chamber. The argon gas ions bombard the

target surface, causing atoms to be ejected and directed toward the substrate, facilitating the deposition process.

- **Gate Valve Control:** The gate valve regulates the chamber's pressure by controlling the isolation between the chamber and the pump. When open, there is no isolation, allowing for full vacuum control; when closed, the chamber is completely isolated from the pump.
- **Deposition:** An electric field is applied between the target (anode) and the substrate (cathode). The high polarity difference generates plasma at the anode, which accelerates atoms from the target toward the substrate, forming a thin, uniform layer. During this stage, we deposited an oxide layer, followed by a silver layer for 4 minutes. A shadow mask with 1 mm diameter holes was used to pattern the metal layer accurately.
- **Cooling and Unloading:** Cooling is achieved by circulating water through a coil around the target. The water temperature, initially at 24°C, rises to around 28-29°C during deposition. To ensure safe handling and minimize thermal stress, the substrate is left to cool for 30 minutes before removal from the chamber.

3.3 Annealing Process

Annealing is a thermal treatment applied to enhance the material properties of the fabricated substrate, improving its structural and electrical characteristics. This process involves gradually heating the substrate to a specified temperature to alter its physical and chemical properties.

- **Softening and Workability:** The primary goal of annealing is to soften the material, making it less brittle and more flexible. This enhanced malleability allows for easier machining, shaping, and forming of the substrate without the risk of cracks or fractures, ensuring a durable foundation for further processing.

- **Improving Electrical Conductivity:** Annealing also plays a crucial role in enhancing the electrical properties of the material. By heating the substrate, the process reduces crystal lattice dislocations and removes structural defects that could obstruct electron flow. This reduction in defects allows for improved electron mobility, resulting in enhanced conductivity across the substrate.
- **Heating and Temperature Maintenance:** In this procedure, the substrate is gradually heated to a target temperature of 500°C over a period of 30 minutes. Once this temperature is reached, it is maintained for an additional 30 minutes to allow complete thermal treatment, ensuring the substrate's atomic structure is realigned effectively.
- **Controlled Cooling:** After the annealing process, the substrate is allowed to cool to room temperature very slowly, which is essential to prevent thermal shock and avoid the reintroduction of stress or defects. This gradual cooling ensures a stable, well-annealed substrate with uniform electrical and structural properties, ready for subsequent fabrication steps.

7.Experimentation:

Ellipsometer:

An ellipsometer is a device used to measure the thickness of an oxide layer deposited on a sample.

- The sample is positioned on a stage that adjusts to ensure correct alignment between the polarized light and the analyzer.
- Both the polarizer and the analyzer are typically set at a 70-degree angle.
- The polarizer controls the polarization state of the incident light that interacts with the sample.
- After the light reflects from or transmits through the sample, the analyzer measures the polarization state of the reflected or transmitted light.
- The ellipsometer detects changes in the light's path and phase to determine the oxide layer's thickness.
- Results from the ellipsometer are analyzed using Origin software, which also generates graphs of the refractive index (n) and the absorption coefficient (k), along with the measured oxide thickness.

I-V characterization:

Probe station testing provided current-voltage relationships, critical for determining MOSCAP performance.

C-V characterization:

In a MOS (Metal-Oxide-Semiconductor) capacitor, the **Capacitance-Voltage (C-V) characterization** is essential for analyzing and understanding the properties of the MOS structure, such as doping concentration, oxide thickness, interface trap density, and threshold voltage. Here's a closer look at what C-V characterization entails and its importance in MOS capacitors:

C-V measurements provide vital information for MOS capacitor design and functionality in semiconductor devices:

- **Oxide Thickness Measurement**: C-V curves help calculate the oxide thickness by measuring the oxide capacitance Cox , especially in accumulation mode.
- **Doping Concentration Profile**: The semiconductor doping concentration can be extracted from the slope of the C-V curve in the depletion region, which affects the device's threshold voltage.
- **Flat-Band Voltage and Work Function Difference**: The flat-band voltage (the point at which the bands in the semiconductor are flat) indicates the work function difference between the metal and the semiconductor and any charge present at the oxide interface.
- **Threshold Voltage**: C-V characteristics allow for determination of the threshold voltage, an essential parameter for MOSFET operation.
- **Interface Trap Density**: Anomalies in the C-V curve, such as frequency dependence in the inversion region, reveal interface trap density, which affects charge carrier mobility and overall device performance.

8.Result

The fabricated MOSCAP showed a dielectric thickness of approximately 40 nm, with an effective area of 0.785 mm^2. Electrical testing indicated stable capacitance, although four of the seventeen devices fabricated showed layer damage, rendering them unusable.

9.Conclusion

This study successfully fabricated and characterized a **hfo2 mos-cap** device for dram applications. The device demonstrated favourable dielectric properties and capacitance, showcasing the potential of **hfo2** in high-performance memory technologies. Further improvements in layer uniformity and processing conditions could enhance device reliability and performance.