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# CHARACTERIZATION, PREPARATION& ANALYSIS OF OXIDE BASED CAPACITORS FOR GATE OF MOS CHARACTERISTICS

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**Abstract**—*Over the past three decades, CMOS technology scaling has been a primary driver of the electronics industry and has provided a path towards both denser and faster integration. The transistors manufactured today are 20 times faster and occupy less than 1% of the area of those built 20 years ago. The number of devices per chip and the system performance has been improving exponentially over the last two decades according to Moore's law. As the channel length is reduced, the performance improves, the power per switching event decreases, and the density improves. But the power density, total circuits per chip, and the total chip power consumption has been increasing. The need for more performance and integration has accelerated the scaling trends in almost every device parameter, such as lithography, effective channel length, gate dielectric thickness, supply voltage, device leakage, etc.*

***Keywords***—*Impedance Spectroscopy, Scanning electron microscopic, Thermo gravimetric Analysis Cyclic Voltammetry.*

## I. INTRODUCTION

Silicon dioxide has been used as a gate oxide material for decades. As transistors have decreased in size, the thickness of the silicon dioxide gate dielectric has steadily decreased to increase the gate capacitance and thereby drive current, raising device performance. As the thickness scales below 2nm, leakage currents due to tunneling increase drastically, leading to high power consumption and reduced device reliability. Replacing the silicon dioxide gate dielectric with a high-K material allows increased gate capacitance without the associated leakage effects. Since it becomes necessary to replace the $SiO_2$ with a physically thicker layer of oxides of higher dielectric constant (K), there are various oxides under consideration for this purpose such as hafnium oxide ($HfO_2$), hafnium silicate, zirconium oxide and various lanthanides and it was found that in many respects they have inferior electronic properties than $SiO_2$, such as a tendency to crystallize and a high concentration of electronic defects. New high quality electronic materials developed from these oxides are on the way of extensive research.
There are also some problems associated with high-k such as increased threshold voltage and decreased mobility. These problems can be solved by replacing poly Si gates with doped metal gates which improves mobility.

## II. METHODOLOGY

**Techniques Used for Material Characterization**

***A. Impedance Spectroscopy***

The conductivity measurements of electrode and electrolyte are generally carried out using a.c. signal Impedance Spectroscopy (IS). IS actually refers to study the impedance response of the solid state ionic materials under a small amplitude sinusoidal (ac) signal of varying frequencies ranging from few mHz to several MHz.(Randles,1947; Macdonald,1987).

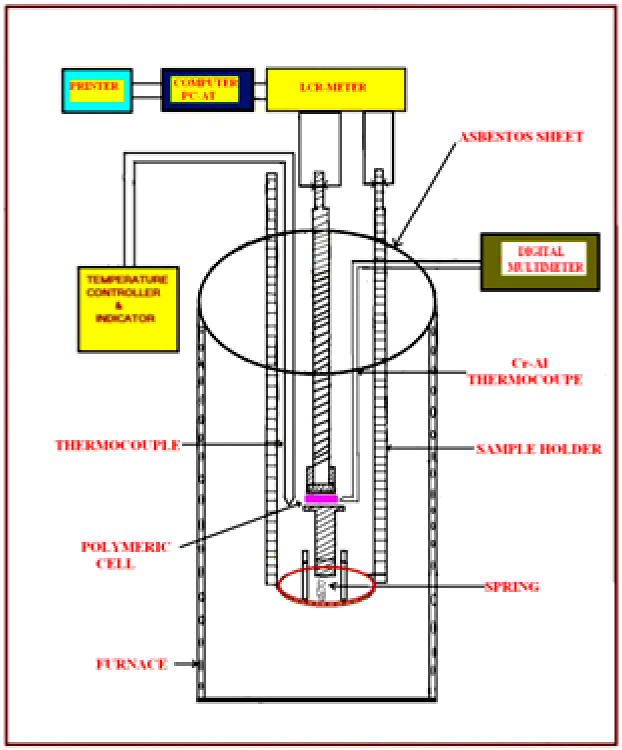



*Fig. 1: Experimental Arrangement of Dielectric Measurement by IS Technique.*

This technique has several advantages over the d.c. measurements. Some of the definite advantages include: absence of polarization effects, true bulk resistance of the test sample can be separated out from the other resistance contributions viz. grain boundary resistance, electrode - electrolyte interfacial resistance etc.
The electrochemical cells consisting of a test sample pallet, sandwiched between bulk / non-bulk electrodes, the typical complex impedance (Z' - Z") responses and corresponding ideal equivalent circuits are shown in Fig. 2.

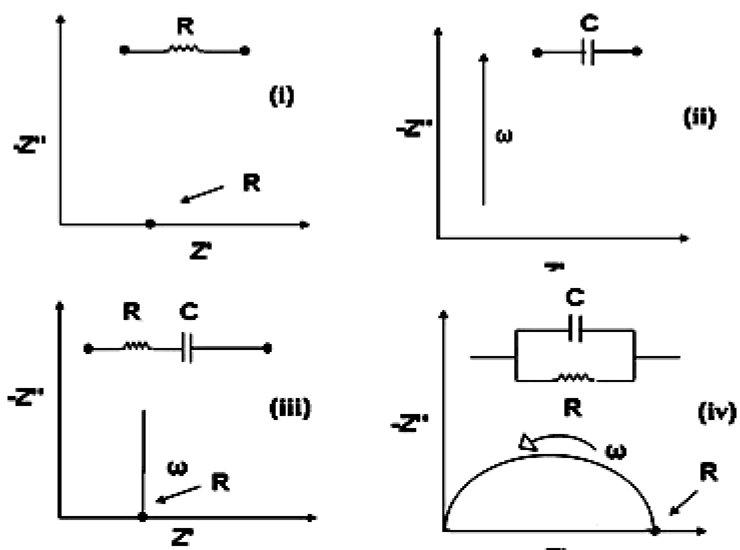



*Fig.2: Complex Impedance Plots for Some Elementary R, C and RC Circuits.*

***B. Scanning electron microscopic (sem)***

The concept of an SEM was first described by M. Knoll (1935) in Germany working in the field of electron optics. The improvement of the secondary electron detector used in SEM was accomplished by Everhart and Thornley in 1960 named as Everhart-Thornley Detector. It has been available since the fifties, but remains the most frequently used detector in SEMs. The first commercial scanning electron microscope became available in 1965 by Cambridge Scientific Instruments. It produces a highly magnified

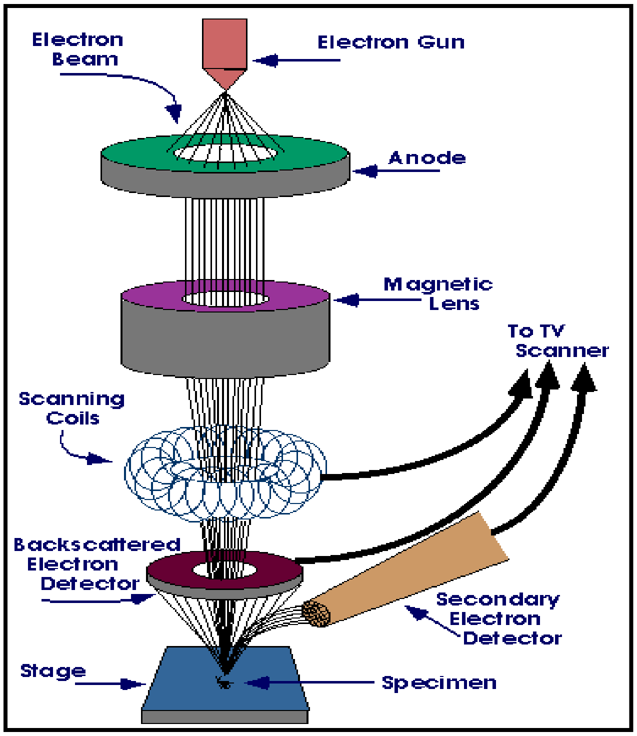



***Fig. 3: Schematic Diagram of Scanning Electron Microscope.***

image by using electrons instead of light. A beam of electrons is produced at the top of the microscope by an electron gun. The electron beam follows a vertical path through the microscope, which is held within a vacuum.

A reasonable fraction of the electrons emitted can be collected by appropriate detectors, and the output can be used to modulate the brightness of a CRT whose x- and y- inputs are driven in synchronism with the x-y voltages rastering the electron beam.. Every point that the beam strikes on the sample is mapped directly onto a corresponding point on the screen. As a result, the magnification system is simple and linear magnification is calculated by the Eq.:

$$M = L/l \tag{1}$$

where L is the raster's length of the CRT

### *C. Thermogravimetric Analysis*

Thermogravimetric Analysis (TGA) is an analytical technique that measures the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. TGA was developed in the early 1900's, but has only been applied to polymeric materials since 1960s.

*Mechanisms of Weight Change*: At low temperatures, weight loss may originate from evaporation of residual moisture or solvent, but at higher temperatures weight loss can arise from a various processes including:
*Decomposition:* The breaking apart of chemical bonds.
*Evaporation:* The loss of volatiles with elevated temperature.
*Reduction*: Interaction of sample to a reducing atmosphere (hydrogen, ammonia etc).

Weight gain processes may also be observed and measured with TGA.
*Oxidation:* Interaction of the sample with an oxidizing atmosphere.

**Technique Used for Gate Capacitance Characterization**
There are various techniques which can be used for capacitor characterization. Some of them used in this study are as follows.

***A. Cyclic Voltammetry***

Cyclic voltammetry is the most widely used technique for acquiring qualitative information about electrochemical reactions. It offers a rapid location of redox potentials of the electroactive species. It concerns with the scanning of working electrode potential between the potential limit of $V_1$ and $V_2$ at a known scan rate v, in both forward and reverse direction and measuring the current of the electrochemical cell. The resultant current of the system involves the faradic current which is due to various electrochemical phenomena (Ellis, 1985; Bard et al., 2001). A plot of measured current as a function of applied potential is known as "cyclic voltammogram". Normally the shape of the cyclic voltammotry dependence on the type of redox reactions.A voltage sweep applied to an ideal capacitor creates a current given by Eq.

$$I = C\frac{dV}{dt} \tag{2}$$

dV/dt is the scan rate of the linear voltage ramp.
The average specific capacitance is evaluated by

$$C = \frac{Q}{V_r}\frac{1}{m} \tag{3}$$

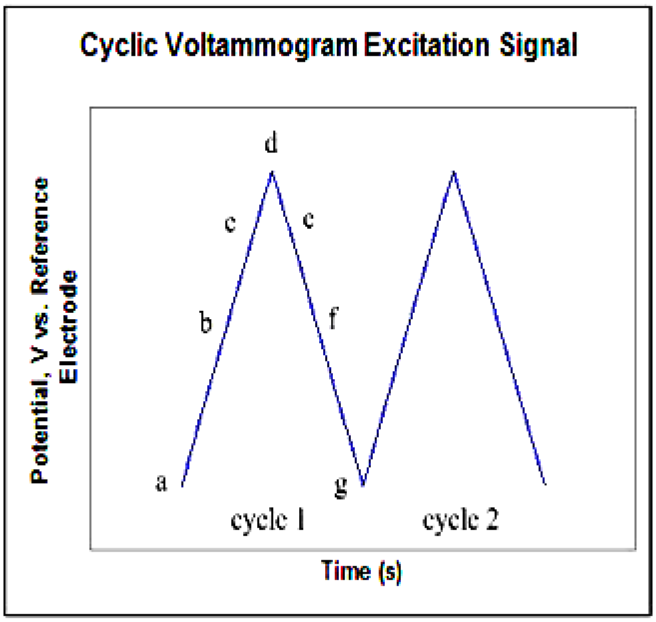



***Fig. 4: V-t Curve of Cyclic Voltammetry.***

Where $V_r$ is the potential range, $Q$ is the total charge in a half cycle, $I$ is the current, and $m$ is the mass. The specific power is calculated by Eq.

$$P = \frac{Max\ (i \times V)}{m} \tag{4}$$

Where *Max* stands for maximum value of current and voltage of CV curve.

***B. Discharge Curve and Leakage Current***

The discharge curve and leakage current also used to differentiate between Capacitor and battery. A battery has high energy density, and it has ability to hold charge for longer time. Therefore it discharges at constant voltage the discharge curve is parallel to time axis. Capacitor has higher power density, it releases their whole charge in very short duration of time, it will drop their voltage as they discharge their stored energy.

Ideal capacitors maintain constant voltage without current flow from an external circuit but real capacitors require a leakage current, $I_{leakage}$, to maintain constant voltage.This process is called self discharge. $I_{leakage}$ can be calculated using Eq.

$$I_{leakage} = C\frac{dV}{dt} \quad (5)$$

Leakage current can be modeled as resistor that is parallel with a capacitor. This model is a simplification of the voltage and time dependence of leakage current. The typical charging, discharging curve and leakage current curve of Capacitor are shown in Fig. 6 and 7 respectively.

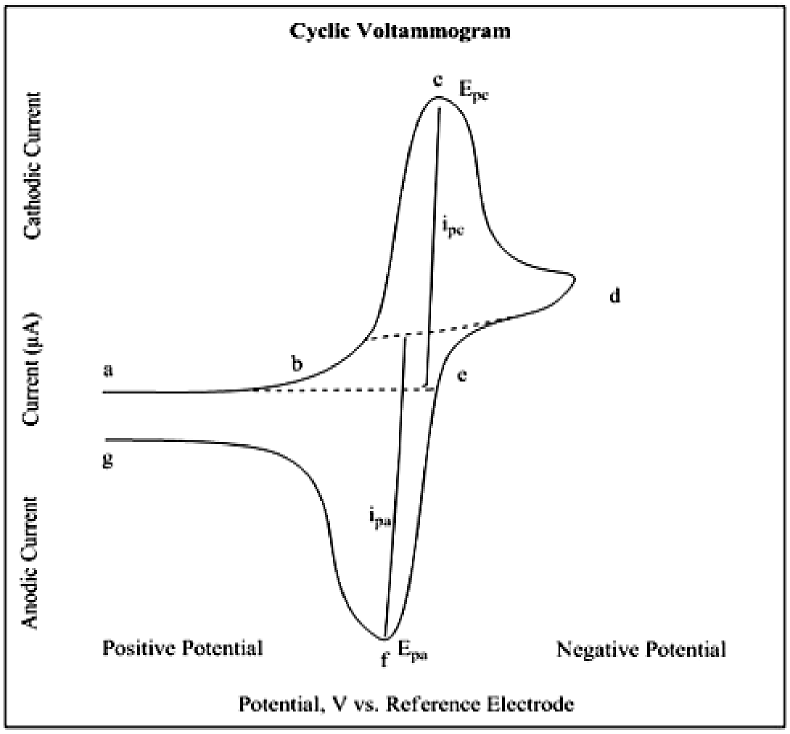



*Fig 6: Discharge Curve of Capacitors.*

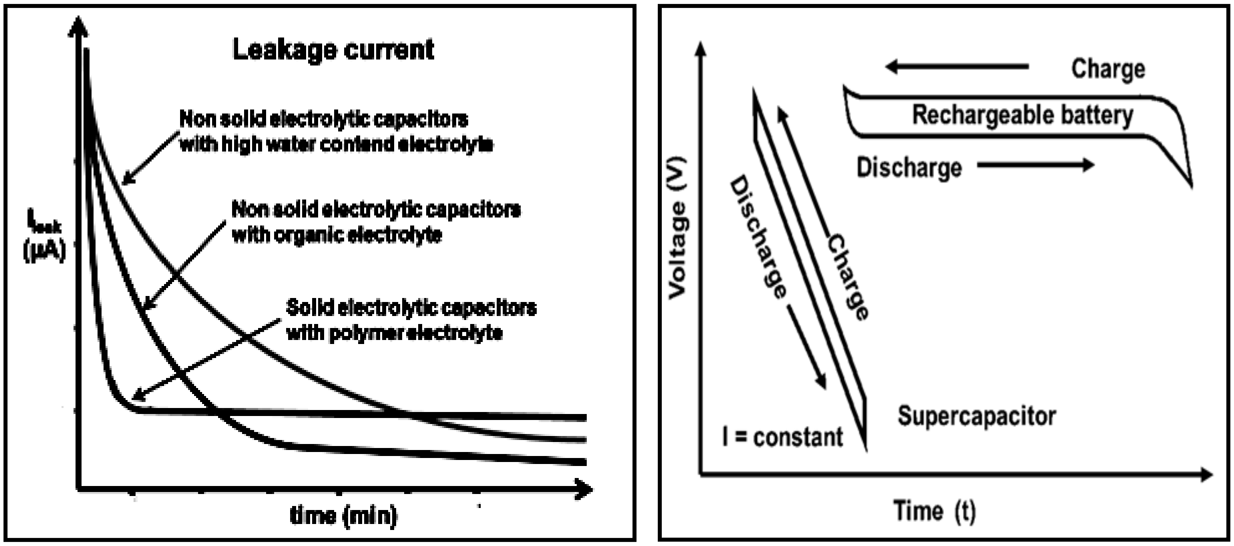



*Fig. 7: Leakage Current of Capacitors.*

## III. EXPERIMENTAL RESULT

**Preparation and Characterization of Dielectric Material**

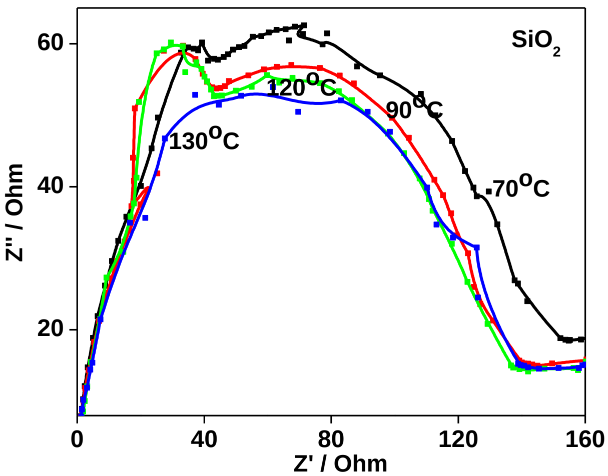
We use three different type oxide materials $SiO_2$, $TiO_2$ and $Al_2O_3$ as dielectric for gate capacitance. All the materials are analytical grade and purchase for Sigma Aldrich. The description of oxide materials are as Nano size $SiO_2$ (size <100 nm, purity ~ 99% Sigma-Aldrich), $Al_2O_3$ (~100nm purity ~ 98% Sigma-Aldrich ) and $Al_2O_3$ (10 µm purity ~ 98% Sigma-Aldrich ). These particles are insulating and insoluble in water. All the materials are grounded separately in ball mill for six hours to increase anodize and missed homogeneously.

***A. Impedance Spectroscopy Behavior of Dielectric***

**Temperature dependent impedance study**

To establish the impedance mechanism of oxide nano material, impedance spectroscopy is employed widely in this study. The typical impedance plot (Z' vs. Z") for $SiO_2$ , $TiO_2$ and $Al_2O_3$ at different temperatures are shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3 respectively. The impedance plot of both dielectric system shows normal impedance behavior, depressed semicircular arcin the high frequency range followed by a linear arc in the low frequency range.
The high frequency semicircle corresponds to the bulk properties of the dielectric films. The increase in temperature decreases the diameter of the semicircle dominantly in the intermediate frequency region and becoming well defined from the original depressed shape and similarly the interfacial resistance in the low frequency region decreases proportionally. At lower temperatures< $80^0$ C, the shape of the plots tends to straight linewith a large slope indicating the low conducting behavior of the sample. With the increase in temperature the slope of the curve decreases, bowing up to the real axis with a well defined semicircle. These results suggest that the migration of ions may occur through the volume of polymer matrix, which can be represented by a resistor.



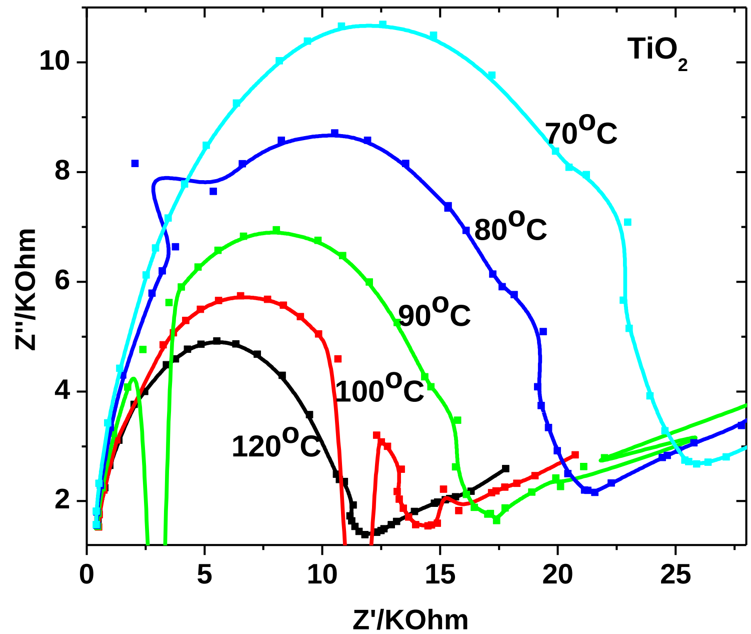




*Fig. 8: Cole Cole plot of $SiO_2$ dielectric at different temperature* *Fig. 9: Cole Cole plot of $TiO_2$ dielectric at different temperature*

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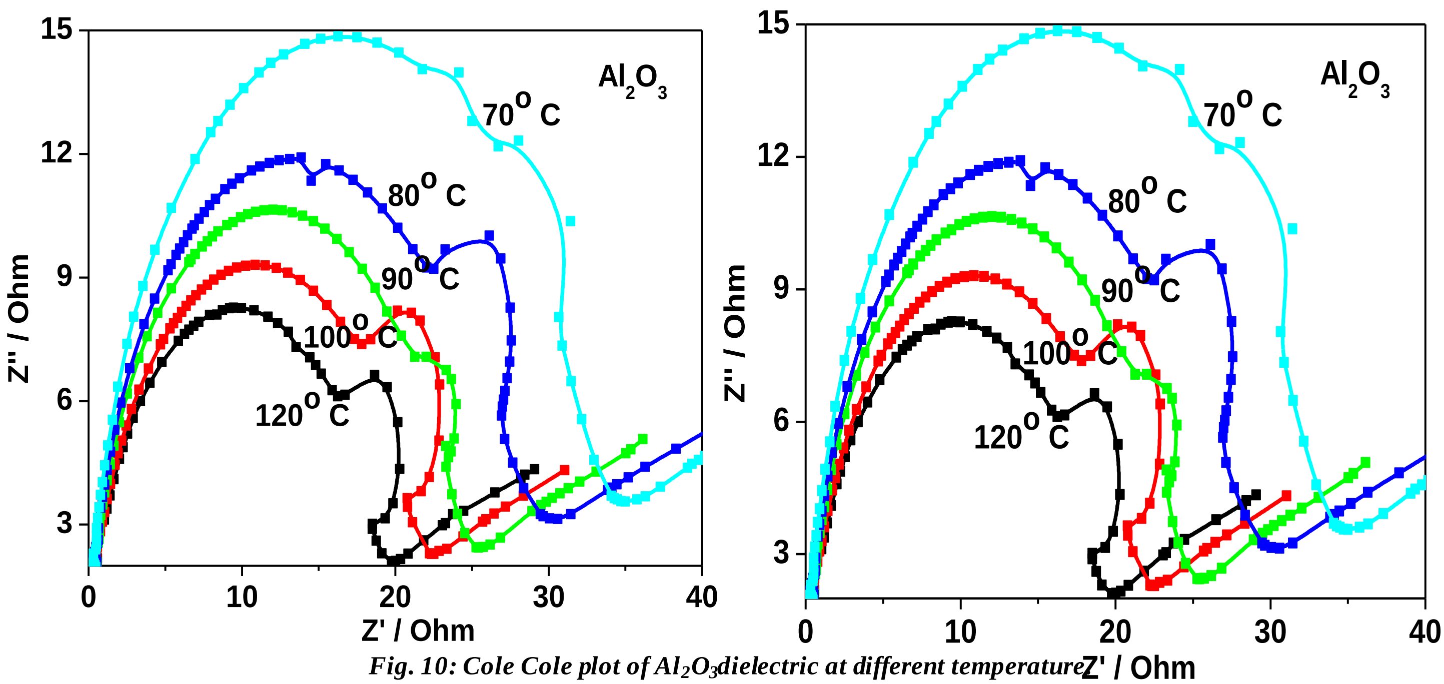


*Fig. 10: Cole Cole plot of $Al_2O_3$ dielectric at different temperature*

 

### *B. Dielectric loss of oxide material*

Variation of loss tangent of $SiO_2$, $TiO_2$ and $Al_2O_3$ dielectric film with logarithmic frequency is shown in Fig. 11, Fig. 12 and Fig. 13. It shows that the loss is high at low frequency region which related to high conductivity and it decrease below unity for frequency in kHz range. The high value losses at low frequency region can be explained by Maxwell – Wagner phenomena for complete analysis of relaxation phenomena.

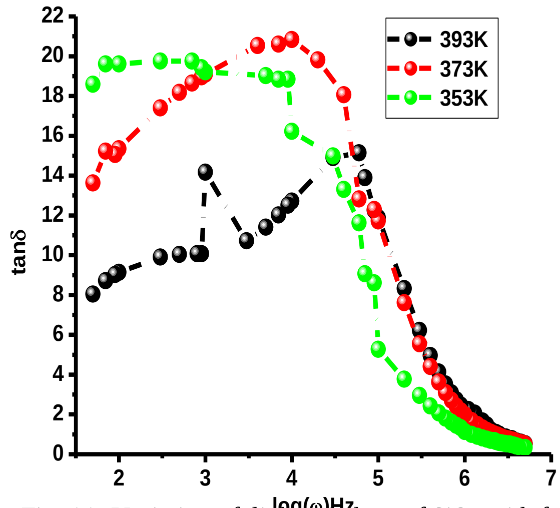


Fig. 11: Variation of dielectric loss of $SiO_2$ with frequency.

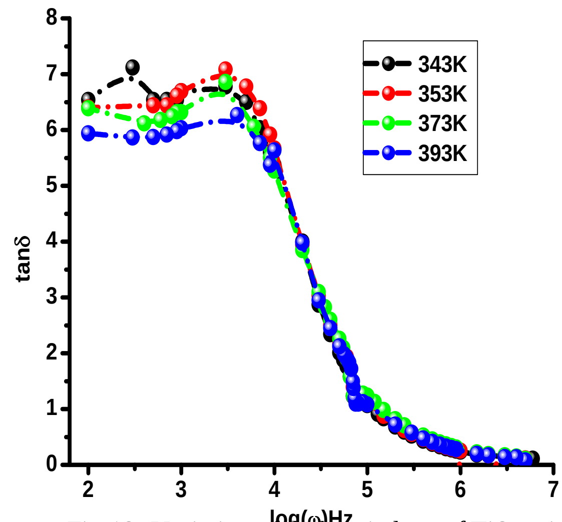


Fig.12: Variation of dielectric loss of $TiO_2$ with frequency.

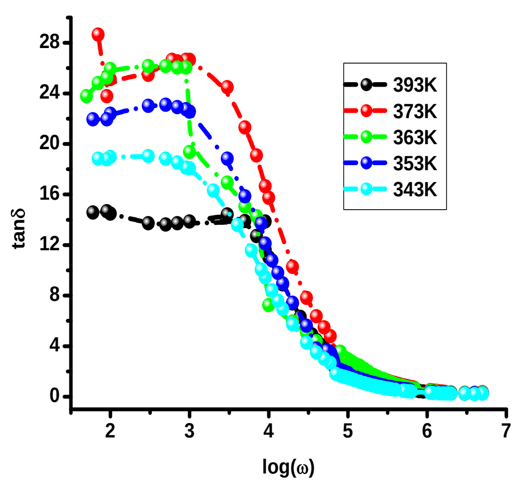


***Fig. 13: Variation of dielectric loss of $Al_2O_3$ with frequency***

### *C. Thermal Characterization by TGA*

Fig. 14 shows the TG curves of dielectric materials used for capacitance preparation. All the curves exhibit one main weight loss region but the temperature varies with respect to the additives involved. The TG curve of the $SiO_2$ (Fig.4.7a) film appears to be quite dry with the weight loss of about 1.5 to 3% until 150 °C. This could be attributed to a dehydration and presence of chemically strong $H_2O$ bonding.

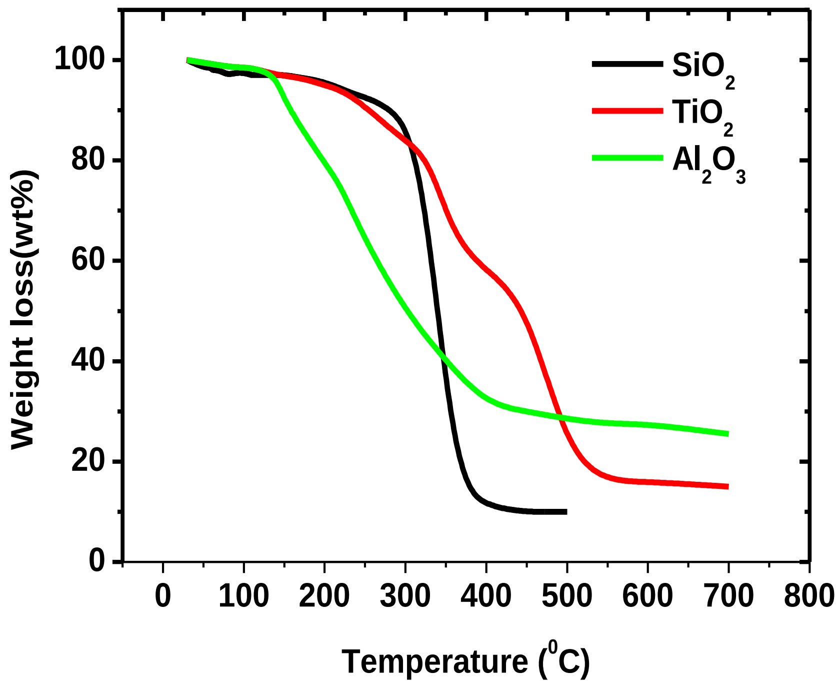


***Fig. 14: TGA Curve of dielectric material for gate capacitance.***

Fig. 14 shows percentage weight loss of $Al_2O_3$ at various temperatures. Till 100°C the weight loss is only 1.5% which is due to content of moisture. The weight loss is 13% upto 300°C , a remarkable weight loss obtain between temperature 320°C to 500°C, where weight loss of 76% is obtain, it shows that $Al_2O_3$ is more stable till 320°C. The weight between these temperature abruptly decreases and upto 700°C the 80% weight loss is observed. The slop of decomposition curve shows that the weight loss abruptly increases. The initial decomposition temperature and percentage of total weight loss is summarized in table 1.

Table 1: Total weight loss of dielectric studied via TG analysis

| Dielectric Materials | Initial weight loss | | First Transition Region | | Total weight loss(%) |
|---|---|---|---|---|---|
| | Temp($^oC$) | Loss(%) | Temp($^oC$) | Loss(%) | |
| $Sio_2$ | 97 | 7.4 | 280 | 82.6 | 90.0 |
| $TiO_2$ | 98.8 | 6.3 | 230 | 29.1 | 85.4 |
| $Al_2O_3$ | 98.5 | 1.5 | 300 | 75.0 | 76.5 |

## IV. RESULT

The choice of materials which could replace silicon dioxide and show the variations of threshold voltage with oxide thickness it is necessary to explain the effect of threshold voltage variation on reliability of CMOS and threshold voltage reduction on power and leakage current. We also cover techniques for threshold voltage scaling and explain body bias circuit technique as the one. Further research can be carried in finding methods to reduce threshold voltage in CMOS which is desirable. The effect of High K oxides on the mobility of charge carriers, accurate measurements and degradation mechanisms of charge carriers with $HfO_2$ as dielectric. The commonly encountered sources of error, like, trapping by high densities of interface traps leads to over counting of inversion charge carriers, high gate leakage current through ultra-thin high-k film could result in underestimation of mobility at high fields, the large channel resistance in weak inversion could result in high artificial mobility at low fields, error due to contact resistance for short channel MOSFETS. Certain mechanisms of mobility degradation have also been focused. Coulomb scattering due to interface traps is a major cause of mobility degradation. Soft optical phonons also contribute to mobility degradation.

## V. CONCLUSION

Scaling is necessary due to increasing demand in the technology sector but aggressive scaling of a device dimension and threshold voltage has significantly increased leakage value and its contribution to total power consumption. Also gate thickness has been scaled to maintain adequate control of the channel.

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