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REVIEW ON PERFORMANCE PERSPECTIVES OF DIELECTRIC MATERIALS USED IN ADVANCED SEMICONDUCTOR DEVICES FOR VARIOUS APPLICATIONS

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ABSTRACT

Dielectric materials are important for use in micro- and nanoelectronics systems, as well as in devices like Thin Film Transistors (TFT), planar waveguides, solar elements, and Light Emitted Diode (LED). The synthesis of such materials, alongside the acquisition of physical information. On their structural, optical, and electronic properties, is very important for the development of new stable devices based on them. The new special issue of “Materials” will include research articles and review papers written by leading scholars in field of materials science and technology. Actually, dielectrics have the thin layer created have good insulating qualities and an effective dielectric constant. Adapted single, binary, and perovskite oxides can be manufactured to provide dielectric materials with high dielectric constant. The benefits of using nanomaterial of using nanomaterial structures in energy storage devices with distinct performance are reviewed and discussed. The advancements in dielectric materials derived from a thin-materials methodology are assessed.

KEYWORDS

Dielectric materials, HK dielectric, SiO_2, HfO_2, Permittivity.

1. INTRODUCTION

The development of new practical materials to satisfy device-scaling needs has been greatly aided by the computational research of electronic device materials .Dielectric materials that can function steadily in high-temperature and complicated electric field settings are necessary for powerful electronics and power equipment (Liu et al., 2022).The majority of the microelectronics and nanoelectronics devices require dielectric materials as necessary components, and these materials have been crucial rule to the tremendous growth the semiconductor industry has seen over the past five decades. The market's growing demand for better performance in electronic devices has made it more difficult to guarantee the stability of the dielectric materials. Due to its significant technological importance, the deterioration and breakdown of dielectric materials during regular device operation are extensively studied in ought to be explored more in new dielectric materials that could be utilized in the future (e.g., HfO_2, and TiO_2) (Mandal and Mukherjee, 2023). The primary role of dielectric materials is to produce electrical fields and capacitance effects, which are essential for transistors and capacitors to work correctly. For investigating dielectric characteristics of materials, a parallel-plate Metal-Insulator-Metal (MIM) device is usually used, in which the dielectric is enclosed inside two metal pads. The dielectric polarizes when a voltage bias (V) occurs between the two electrodes because an electric field is created, causing a total positive charge (+Q) at one electrode's interface and a total negative charge (-Q) at the other electrodes As a result of the huge demand for energy sources and the rapid advancement in the microelectronic sector, there has been a great deal of attention paid to the researchers for dielectric materials with colossal permittivity (CP) for use in electronic and energy storage device applications (Nandi et al., 2023). Materials with colossal permittivity (CP), also known as colossal dielectric constant, have real permittivity values exceeding a 1000, which is significantly higher than that of normal solid dielectrics by multiple orders of magnitude. Increasing the permittivity of dielectric materials is a simple and effective way to get high capacitance for practical uses. Due to the large dielectric response for the paraelectric-ferroelectric changeover temperature, standard ferroelectric oxides have high permittivity (Mgbemere, Henry E., 2024). To enhance the electrical characteristics and permittivity of the dielectric materials known high permittivity, involved the introduction of dopants and site-engineering techniques. It was shown that HfO_2 thin layers doped with lanthanum, nitrogen or fluorine could significantly improve their electrical characteristics. Similarly, it was discovered that Ta_2O_5 layers' dielectric characteristics and leakage current densities can be enhanced by carbon doping in various oxides(Tayal et al., 2022). SiO_2 may be replaced with certain binaries or mixes of metal oxides, such as ZrO_2, Ta_2O_5, Nb_2O_5, TiO_2, or Al_2O_3. TiO_2, HfO_2, and Al_2O_3 are three of these metal oxide compounds that have received a lot of attention as potential replacements for SiO_2 thin layers because of their high resistance, broad band gap, and strong thermodynamic stability with silicon(Guo et al., 2020). Because the layers were better controlled, the laminate structure's qualities were predictable. Degradation voltages and leakage currents in laminate architectures similarly showed a monotonic dependence on layer thicknesses (Ramaswamy et al., 2022). The most popular of insulating materials can be categorized as follows in Figure 1(Lin et al., 2023).

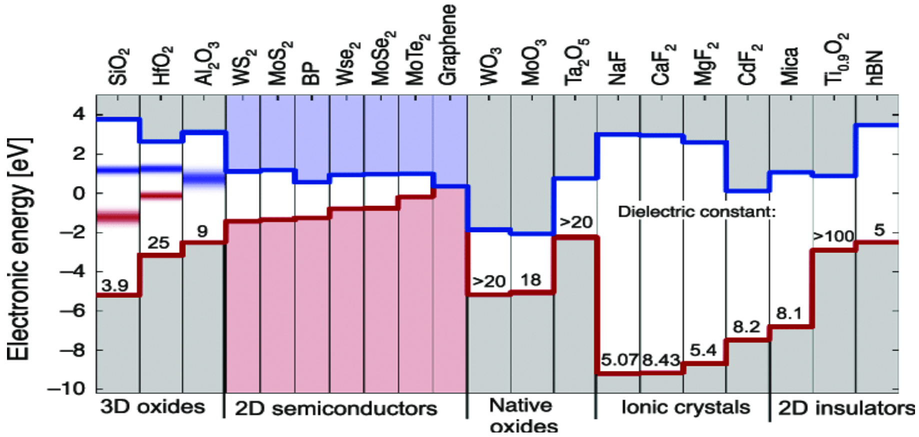

Fig. 1. Band diagrams for different types of insulating materials

The chemical production of high-k dielectrics has drawn a lot of attention in recent years. The typical dielectric materials are treated in a solution processed includes Titanium dioxide (TiO_2), Gadolinium oxide (Gd_2O_3), Aluminum Oxide (Al_2O_3), Ytterbium oxide (Yb_2O_3), Tungsten trioxide (WO_3), Yttrium oxide(Y_2O_3), Neodymium oxide (Nd_2O_3), Lithium oxide (Li_2O), Zirconium dioxide (ZrO_2), Silicon nitride (Si_3N_4), Hafnium Oxide (HfO_2), Molybdenum trioxide (MoO_3), Gallium oxide (Ga_2O_3), Scandium oxide (Sc_2O_3) and lanthanum doped zirconium oxide ($LaZrO_2$)(Shukur, 2021).Hexagonal boron nitride (HBN) is the most frequently used for two-dimensional insulators, providing semiconductor/insulator interfaces that are atomically smooth and free of hanging bonds.

Breakdown phenomena (BD) are an undesirable event that can cause a partial or complete failure of these components. However, in a certain device (such as memristors and electronic for artificial neural networks), BD has a beneficial effect and facilitates the performance of many operations (i.e., resistive switching (RS)(Pérez-Escribano and Márquez-Segura, 2021).

In this work, we present a review of a different dielectric materials and high permittivity dielectric materials that using in advanced semiconductor devices. The technological use of these materials is aimed towards the electrical materials field of high efficiency energy storage devices.

2. DIELECTRIC MATERIALS

2.1. Structure of dielectric materials

Dielectrics materials show a dipole structure where an electric field is not delivered, the dipole structures will typically be oriented randomly. Electrical polarization happens if a voltage is coupled to a dielectric because the dipoles spin and arrange themselves in the field. The polarization of a dielectric in an electric field that is external is seen in Fig.2 (Azadmanjiri et al., 2014).

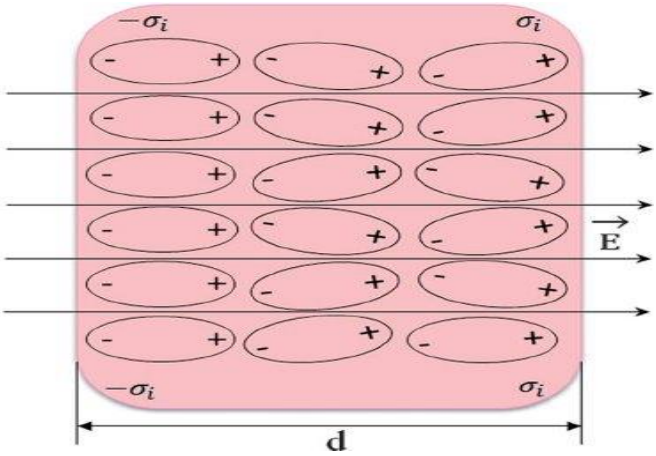

Fig. 2. Polarization of a dielectric in an external electric field

A dipole's negative charges are minutely displaced in the opposite direction from the dipole's positive charges, which are minutely displaced in the direction of lesser voltage. When polarisation occurs in a dielectric, the active electric field among the plates is reduced, and the parallel plate structure's capacitance is increased (De Visser et al., 2021). When frequency applied is low, there is sufficient time for the electrons and dipoles to react to the alternating electromagnetic field. The actual permittivity as an indicator of frequency decreases as the external field's frequency increases because the polarizability cannot be maintained. Based on the way that dielectrics polarize, these materials can be separated into two groups. Metal oxides having nonpolar atomic configurations, such as Ta_2O_5, TiO_2, Al_2O_3 Nb_2O_5, ZrO_2, and HfO_2, provide the basis of one category (Imran et al., 2023). This class of dielectrics allows for the persistence of residual polarization long after the voltage that was applied has been removed. We refer to this phenomenon as dielectric relaxation. Second groups are ferroelectrics materials which are a different class of dielectric materials that mostly exhibit perovskite structures and have residual dipoles from static atomic displacements such as materials [$Pb(Zr,Ti)O_3$] and [$PbMg_1/3Nb_2/3O_3$] (Mohammed et al., 2021).A collection of the contemporary dielectric materials that have different compositions and high dielectric constants can be found in Table 1.(Azadmanjiri et al., 2014).

Table 1 Dielectric constants (k) of typical materials (Yang et al., 2023)

Composition	Constant
SiO_2	3.9
AL_2O_3	9
ZrO_2	29
HfO_2	25
$HfSiO_4$	11
Ta_2O_5	26
La_2O_3	30
$LaALO_3$	30
Nb_2O_5	35
TiO_2	95

2.2. Properties of dielectric materials

Material categorization by accounting for a homogenous material's permeability (μ) and permittivity (ε). Consequently, if ε and μ are both concurrently negative, some aberrant physical phenomena take place, including the inversion of the Doppler Shift, the Cherenkov Effect, and the Snell Law. The following is the relationship between the refractive index (n), ε, and μ component parameters as showed in Eq.1 (Chen et al., 2021)

$$n = \pm\sqrt{\mu r \varepsilon r} \tag{1}$$

The capacitance per unit area (C), leakage current density (Jleak) and breakdown voltage (Vb) are still significant performance metrics on dielectrics materials and can be tested with comparable metal-insulator-metal (MIM) capacitor topologies. Two electrical double layers (EDLs) occur at the electrode/electrolyte junctions of the capacitor when a voltage bias is made available. The electrolyte polarizing causes this due to ion migration. The formula for the EDL capacitance per unit area can be expressed by Eq.2 (Irfan et al., 2024).

$$CEDL = \frac{\varepsilon r \varepsilon o}{\lambda} \tag{2}$$

ϵr = Permittivity of materials

ϵo= Permittivity of vacuum

λ = Wave length

The capacitance (C) can be used to estimate the dielectric constant (ε) at low frequencies. This theoretical research suggests that the dielectric constant of Al_2O_3–TiO_2 is between 3 and 750 times greater than that of Al_2O_3. Because of leakage current that occurs when the sub-layers get thinner due to electron hopping in the TiO_2 sub-layers, it was proposed the true dielectric constant of this thinner structure could not be that high (Abdul-kadir et al., 2023).

3. TYPES OF DIELECTRIC MATERIALS

3.1. High dielectric constant materials

In the past ten years, high dielectric materials (high-κ) oxides have quickly supplanted SiO_2, and polysilicon gates have been replaced with metal gates(Ke et al., 2024). Metal oxides, including ZrO_2, TiO_2, Ta_2O_5, HfO_2, and ferroelectric oxides have been investigated as high permittivity materials with high dielectric constants. Keep in mind that the dielectric constant, also known as the relative permittivity (εr), is represented by the symbol k. The ratio of the permittivity of the dielectric (ε) to the permittivity of vacuum (ε_0) is known as the dielectric constant. One of the most important challenges for microelectronic materials is the creation of integrated devices using novel composite materials that can exhibit high permittivity levels and good insulating qualities (Lokanathan et al., 2021). Doping is a useful technique for raising permittivity and lowering dielectric loss. The primary benefits of employing high-κ dielectric (HK) dielectric materials are that the leakage current magnitude through it would be lower, enhancing the device's reliability and extending its lifespan. HfO_2 and Al_2O_3 are the most commonly used as high dielectrics materials in MOSFET construction. Even though the idea sounds straightforward, there are a lot of manufacturing challenges when using a HK dielectric to replace the SiO_2 gate oxide of a Metal-Oxide-Semiconductor-Field-Effect-transistor (MOSFET) (Chou et al., 2020). HK dielectrics first create a large number of faulty bonds at the interfaces by reacting with the nearby Silicon (Si) bulk and poly-Si gate electrode. Second at the temperatures applied in the MOSFET manufacture process, high dielectric materials can become polycrystalline, increasing the material's inhomogeneity and making defect-rich areas like grain boundaries (GBs) easy to generate (Smaani et al., 2023).

3.2. Low dielectric constant materials

Low dielectric elements have been the subject of extensive investigation by ceramic and polymeric researchers during the last fifty years. But these elements have a wide range of mechanical, chemical, thermal, and electrical characteristics that are equally important as their classification. Consequently, these additional characteristics frequently determine the uses of small dielectric constant materials, and the selection of a low dielectric material can significantly impact a device's lifetime and performance(Xu et al., 2023).

Dielectrics with low permittivity are employed as microwave dielectric materials, conduction polymers, semiconductors, and their composites, as well as carbon-based materials (Graphene, reduced Graphene oxide (rGO), carbon nanotubes (CNTs)(Xu et al., 2020). The dielectric constant is closely related to polarization processes, such as dielectric polarization and several other polarization mechanisms including Maxwell-Wagner-Sillars (MWS) polarization and lattice polarization. The real component of permittivity (ε), in accordance with the traditional electromagnetic theory, indicates a material's capacity to polarize in the presence of an oscillating electromagnetic field (Iyer, Alu and Epstein, 2020).

4. DIELECTRIC MATERIALS USED IN MOSFET

Between the beginning of the 1970s and the beginning of the 2000s, silicon dioxide (SiO_2) was chosen as the. insulating gate oxide for MOSFET transistors fabrication (Abdul-Kadir, Mohammad and Hashim, 2020). This was attributed to its superior insulating properties, as well as its affordability, ease of fabrication, and superior compatibility with silicon bulk. Moore's law has led to an aggressive scaling down of device sizes, particularly for MOSFETs, in the microelectronics industry as an approach to improving the performance (energy consumption, computing capacity and speed) of commercial electronic devices (computers and TVs) in accordance with societal and technological demands Field-Effect Transistors are fabricated on different types of substrates as shown in Fig.3 (Dutta et al., 2023).

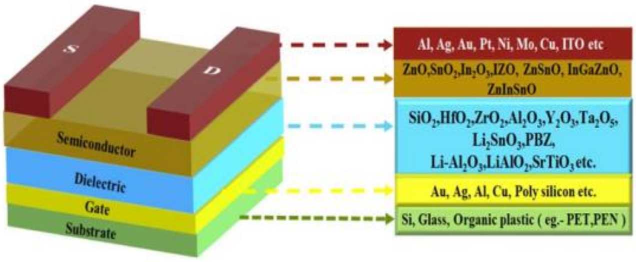

Fig. 3. Schematic diagrams of a thin film transistor

Both the voltage value and SiO_2 thickness of a MOSFET must decrease as its dimensions are shrunk. SiO_2 thickness is decreased almost proportionately to the channel length of the gate to prevent negative 2D electrostatic effects on threshold voltage, also known as short-channel effects (SCE). However, when the insulators material thickness reduces, the direct tunneling current over the gate dielectric increases exponentially.(SiO_2) thinner than 0.8 nm causes leakage currents that are excessively large and directly affect by the chip's power and gate oxide credibility. To overcome this inconvenient state, proposals will have been adopted to deal with the problem by including insulators with a high dielectric constant (HK) (Panwar et al., 2023).

5. IMPACT DIELECTRIC MATERIALS PERFORMANCE ON MOSFET

High-k materials can be used as channel materials or micro dimension transistors due to their high mobility. In Field-Effect-Transistor(FET) devices, high-k materials can be effect on the electrical parameters of device such as threshold Voltage (Vth) , transconductance (gm), sub-threshold slop (SS), Off-current (Ioff) and Drain Induced Barrier Lowering (DIBL) (Abdul-Kadir and Taha, 2022).

5.1. Impact dielectric materials on threshold voltage (Vth)

As the channel length gets shorter, the threshold voltage drops. where TiO_2 provides improved Vth since it has a higher Vth level than these minerals. In the vicinity, the gate needs to transport less charge, which lowers Vth and lowers performance. Table 2 lists the Vth variations for a variety of high-gate dielectric materials (Acharya, Agarwal and Mondal, 2023).

Table 2 lists the Vth variations for a variety of high-gate dielectric (Prokopchuk et al., 2021)

Dielectric materials	Threshold Voltage (Vth)
SiO_2	0.42 V
Si_3N_4	0.44 V
Sapphire	0.45 V
Ta_2O_5	0.47 V
TiO_2	0.49 V
HfO_2	0.46 V

The results obtained from Table 2 show that the threshold voltage (Vth) is directly proportional to the dielectric constant (ϵr). Specifically, an increase in (ϵr) results in an increase (Vth).

5.2. Impact dielectric materials on sub-threshold slop (SS)

Table 3 shows the sub-threshold slop levels for the various dielectric materials demonstrating that TiO_2, with its higher dielectric and lower leakage current, has a lower SS. The SS values for several dielectric materials are listed in Table 3. Table 3 Various gate dielectric materials have sub-threshold swing variation (Prokopchuk et al., 2021).

Table 3 lists the SS variations for a variety of high-gate dielectric (Prokopchuk et al., 2021)

Dielectric materials	Sub-threshold Swing (SS)
SiO_2	67.6 mV/decade
Si_3N_4	63.7 mV/decade
Sapphire	62.3 mV/decade
Ta_2O_5	61.3 mV/decade
TiO_2	60.8 mV/decade
HfO_2	64.5 mV/decade
Al_2O_3	68.2 mV/decade

The results acquired from Table 3 show that the sub-threshold slop (SS) is inversely proportional to the dielectric materials constant (ϵr) according to Eq. 3 and 4 (P.S. Raja1, 2012). Practically, an increase in the dielectric material constant (ϵr) results in a corresponding decrease in sub-threshold slop (SS).

$$SS = 60\left(1 + \frac{Cdep}{Cox}\right) \tag{3}$$

$$Cox = \frac{\varepsilon o\, \varepsilon r}{Tox} \tag{4}$$

5.3. Impact dielectric materials on (DIBL)

Drain Induced Barrier Lowering (DIBL) in MOSFETs meant that as drain voltage increased, the threshold voltage of the MOSFET would decrease. When compared with other insulator gate materials, TiO_2's DIBL value shows that it has a better flow of current control across the channel (Abdul-kadir et al., 2023). The source barrier intersection shrinks when deployment ions are in the channel, making it difficult to get the gate voltage to govern the drain current. Table 4 lists the DIBL amounts for Several dielectric materials.

Table 4 lists the DIBL variations for a variety of high-gate dielectric (Prokopchuk et al., 2021)**.**

Dielectric materials	DIBL mV/V
SiO_2	42.5 mV/V
Si_3N_4	41.1 mV/V
Sapphire	41.5 mV/V
Ta_2O_5	41.3 mV/V
TiO_2	42.1 mV/V
HfO_2	42.2 mV/V

6. NOVEL DIELECTRIC MATERIAL

6.1. $LaZrO_2$

Compared to dielectric constant SiO_2 (3.9), $LaZrO_2$ are inert chemically when in contact with silicon (Si), have a greater crystallization temperature, a broad energy band gap of 6 eV, and a high dielectric constant (40). $LaZrO_2$ has been utilized for 14 nm FinFETs in an inverter model. In gate high-k dielectric material, the Ion raised by 2.7 and the Ioff reduced by 101 compared to regular SiO_2. Improvements in charge carrier efficiency have led to additional improvements in the current ratio Ion/Ioff, increased capacitance at the gate terminal and increased electron mobility on the source terminal (Kulkarni, Tambe and Joshi, 2020).

6.2. HfO_2

In order to reduce SCE impacts like GIDL (Gate Induced Drain Lowering) and GISL (Gate Induced Source Leakage) current, SiO_2 is placed between the (source and drain) S/D regions to constrain the gate control concerning S/D regions. HfO_2 (promising material), serves as the gate dielectric to improve gate controllability Figure 4(Merizgui et al., 2021).

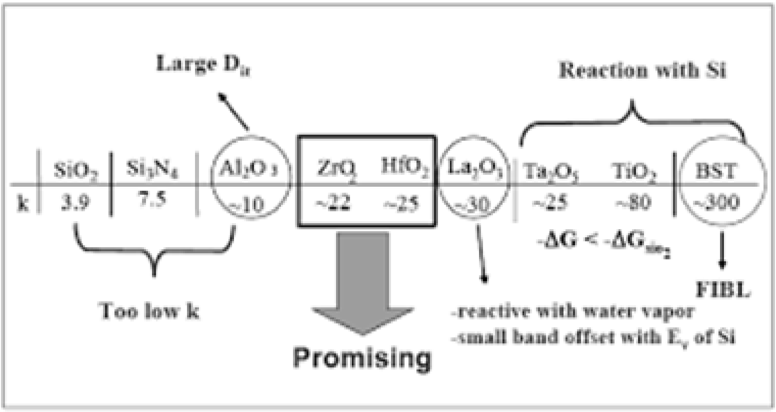

Fig. 4. Dielectric of promising high-k dielectrics

Compared to SiO_2, HfO_2 has a higher k dielectric, greater physical thickness, lower leakage current and improved electron mobility. Mobility deterioration in MOS transistors with HfO_2 can be decreased by a factor of two. Table 5 summaries the mathematical parameters of the mechanism applied to the calibrated SiO_2 and HfO_2 dielectrics (Merizgui et al., 2021).

Table 5 Calibrated parameters of SiO_2 and HfO_2 (Lim et al., 2023)

Parameter	Value	
	SiO_2	Hf O_2
Zero-field activation energy (Ea)	4.1(eV)	3(eV)
Molecular dipole moment(P0)	4.1(eÅ)	5.2(eÅ)
Number of initial weak bond(N0)	1.4 x 10^{21}(/cm3)	1x10^{19}(/cm3)
Dielectric constant (k)	3.9	25

6.3. BaTiO3

The initial perovskite oxide in which a ferroelectric property was identified is called $BaTiO_3$. $BaTiO_3$ is the most appropriate choice when taking into account the dielectric permittivity (has a comparatively greater value of εr) and working temperature, as a result, ordinary multilayered ceramic capacitor (MLCC) that has been constructed are based on $BaTiO_3$.The dielectric permittivity versus the temperature of the ferroelectric materials in Fig.5 (Ramaswamy et al., 2022).

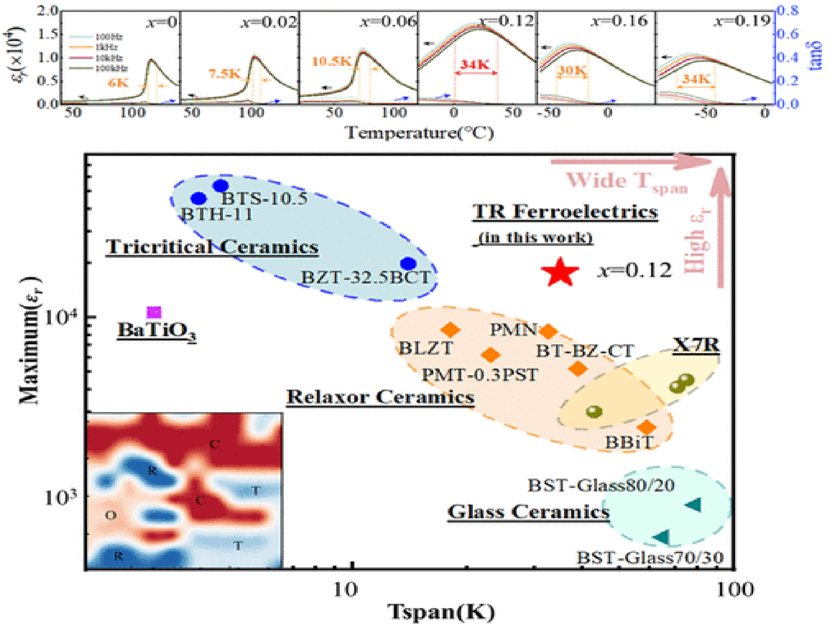

Fig. 5. The dielectric permittivity and temperature of various ferroelectric materials

7. CRITICAL REVIEW AND ANALYSIS

The microelectronics industry has developed high- and low-k dielectrics to facilitate the ongoing miniaturization of integrated circuits (ICs) in both horizontal and vertical dimensions. The use of low-k materials reduces gate leakage current and heat dissipation while also decreasing propagation delay and crosstalk. This allows devices to operate at higher frequencies, including in the terahertz range(Acharya et al., 2023). As device features continue to shrink, conventional gate oxides encounter significant issues, necessitating the development of new gate dielectric materials. These new materials must have properties akin to silicon dioxide (SiO_2) and be compatible with current complementary metal-oxide-semiconductor

(CMOS) technology. When the thickness of SiO_2 falls below 1.5 nm, leakage currents exceed 1 A/cm^2, and tunneling currents increase dramatically. Therefore, new materials with a dielectric constant higher than 30, an interface-state density less than 1×10^{11}/cm^2-eV, a tunneling current below 10 mA/cm^2, and negligible hysteresis are required.

Several materials with high dielectric constants have been identified as potential replacements for SiO_2, such as SiOxNy, Ta_2O_5, TiO_2, Y_2O_3, CeO_2, $SrTiO_3$, Al_2O_3, La_2O_3, and silicates of hafnium and zirconium. These materials show promise for use as gate dielectrics in sub-100 nm silicon technology. However, extensive research is needed to assess their compatibility with existing silicon IC manufacturing processes (Cheng et al., 2021).

Table 6. Performance comparison of different dielectrics materials in terms mobility and Ion/Ioff ratio (Acharya, Agarwal and Mondal, 2023).

Dielectric	K	T (°C)	μ($cm^2 V^{-1}s^{-1}$)	Ion/Ioff
Al_2O_3	6.3	300	33	108
ZrO_2	22.6	300	1.6	104
HfO_2	25	300	1.05	107
$Y2O_3$	25.4	300	0.1	102
$Ga2O_3$	10.1	250	4.1	105
Sc_2O_3	12.1	350	27.7	107
MgO	7.5	500	5.48	107
Li_2O	6.7	300	5.69	107
Nd_2O_3	11.3	400	65	107
Yb_2O_3	11.3	500	4.98	106
SrO	8.6	600	5.61	107
Zr−Al−O	11.8	250	51	104
La−Al−O	83	440	12	106
PBZ	12	830	4.5	103
Li-Al_2O_3	35	550	17	104
$Li2ZnO_2$	-	500	23	103
$LiAlO_2$	40	700	25	105
LiTO	-	550	5.6	104

8. CONCLUSIONS

To overcome the research gap in micro- and nanoelectronics devices, materials optimization, it was one of the most important solutions to facing the challenges in the semiconductor industry especially insulating materials. So, we provide an in-depth analysis of current research on the characteristics, physical workings, and performance of dielectric materials used in advanced semiconductor devices for a range of applications. The dielectric characteristics of thin materials should differ significantly from those of corresponding bulks due to a variety of prospective causes, including remaining stress, the interface between the electrodes and dielectric materials, defect states and the soft mode. Key material considerations discussed include permittivity, band gap, steadily in high-temperature, interface quality, and performance. Selecting high dielectric material is essential for creating high-performance FETs, and charge storage capacity. Oxide materials [(TiO_2), (Gd_2O_3), (Al_2O_3), (Yb_2O_3), (WO_3), (Y_2O_3), (Nd_2O_3), (Li_2O), (ZrO_2), (Si_3N_4), (HfO_2), (MoO_3), (Ga_2O_3), (Sc_2O_3) and ($LaZrO_2$)], present a great model for studying dielectric in nanosheet devices. The overall results on different materials clearly show: 1- that the high- k dielectric materials such HfO_2, ZrO_2 and TiO_2 are very important and can be promising materials in advanced devices industry .2- Doping is a useful technique for raising permittivity and lowering dielectric loss. 3- Polymeric and ferroelectrics dielectrics are currently being utilized as the dielectric layers for nanoelectronics devices. 4- the leakage current magnitude through it would be lower, enhancing the device's reliability and extending its lifespan. 5- Dielectric nanosheet technology may yield a novel formula for creating useful devices with high dielectric constants.

Now, the new global research is on her way towards the several new materials that can be considered promising in the future like:

1- Metal–organic frameworks (MOFs). are taken into account to be prospect candidates for verification the required dielectric feature of any given material into nanodevices.

2- Quantum materials (QMs) are a great of interest materials in distinctive features because of them have unusual phenomena and their potential to serve the foundation for ground-breaking new technology in contemporary science and technology.

3- Polymer materials like electrolytes, electrodes and separators are used as flexible energy storage devices (FESDs) including batteries and supercapacitors have been employed extensively.

4- Dielectric elastomers are electroactive polymers that can deform significantly under the applied electric stimuli through electromechanical coupling effect.

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